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Renewable integration for remote communities: Comparative allowable cost analyses for hydro, solar and wave energy

Bryson Robertson[a,*], Jessica Bekker[b], Bradley Buckham[b]

[a] Pacific Marine Energy Centre, Civil and Construction Engineering, Ocean State University, Corvallis, OR, USA
[b] Institute for Integrated Energy Systems, University of Victoria (IESVic), BC, Canada

HIGHLIGHTS

- RCOM model developed for renewable energy system analyses in remote communities.
- Novel 'allowable cost LCOE' assessment for hydro, solar and wave energy systems.
- Diesel mitigation potential of variable renewable energy systems quantified.
- Wave energy as allowable LCOE of $0.59/kWh and $23,206/kW installed.
- Impact of resource variability, fuel cost, and emission pricing on allowable LCOE.

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ABSTRACT

Many remote communities are reliant on diesel-fueled electricity generation. The extra-ordinary logistical and financial complications in acquiring fuel often result in energy poverty. To alleviate these realities, and simultaneously mitigate noise and emissions, communities are focused on harnessing local renewable resources to achieve aggressive decarbonization and renewable energy penetration.

This study quantifies the diesel and emissions mitigation potential of micro-hydro, solar and wave energy; and defines 'allowable-cost' Levelized Cost of Energy (LCOE) targets. Through the application of a bottom-up, time domain energy systems model, Remote Community Optimization Model (RCOM), differing renewable options (including wave, micro-hydro and solar) are compared. The RCOM model formulates the community's energy system operation as a cost minimization optimization problem and generates an hourly dispatch strategy. Comparing hybrid renewables-based systems to the diesel only case, the maximum allowable LCOE values for each renewable energy system to provide economic benefit to the local community are quantified. Additional sensitivities to resource availability, emissions pricing and fuel costs are explored through scenario-based sensitivity analyses.

Utilizing RCOM for Hot Springs Cove (remote Canadian community), the diesel system results in LCOE of $0.76/kWh. The development of a small hydro system (225 kW) reduces the community's fuel costs by ~$5.2 M over the 30-yr. project lifetime. However, these savings are less than the upfront construction capital, and the associated LCOE increases to $1.36/kWh. Based on the novel 'allowable-cost' analysis, wave energy was found to provide economic benefit if the supplied power could be delivered for less than $0.59/kWh; with the added benefit of reducing diesel consumption by 40%, and returning $23,206/kW installed. Comparatively, integrating solar had an allowable-cost LCOE of $0.53/kWh, reduced diesel consumption by only 12%, and gave a return of $6844/kW installed.

1. 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 community's abilities 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

* Corresponding author.
E-mail addresses: Bryson.robertson@oregonstate.edu (B. Robertson), jbekker@uvic.ca (J. Bekker), bbuckham@uvic.ca (B. Buckham).

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Nomenclature

$TC_{system,PV}$	Total present value cost for a specific energy system
$C_{tech}(t)$	Cost at hour (t) for specific generation technology
$P_{tech}(t)$	Power output at hour (t) for specific generation technology
P_{d_max}	Maximum power output from the diesel generators
P_{h_max}	Maximum power output from the hydro generators
$X_{tech}(t)$	On/Off state for specific generation technology
$V_{fuel}(t)$	Volume of usage at time (t)
A	Diesel generator fuel consumption performance coefficient
$Q(t)$	Water flow rate through hydro facility
Q_o	Minimum flow rate required for hydro power output
A, B, C	Diesel and hydro generator performance coefficients (from linearized performance curves)
H_s	Hydro generator turbine start-up coefficient
$Y_{I/0}$	Hydro generator binary for turbine start.
PV	Present value
CRF	Capital Recovery Factor
d	Discount rate
N	Project lifetime
$LCOE$	Levelized Cost of Energy

points on the interactions between people and place. 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].

The built capacity of off-grid renewable energy has tripled in the last 5–10 years, reaching a global installed capacity of approximately 7000 MW in 2017 [5]. Amongst many drivers, the sustainable development and energy system decarbonization [6] goals set by the United Nations are motivating the use of local renewable energy supplies to mitigate, or eliminate, diesel fueled energy generation. For coastal communities, marine energy is the obvious renewable option. The wave energy resource is proximate, relatively stable and vast [7–9].

However, marine energy technologies remain pre-commercial. While there exists a wealth of literature on resources [10–15], specific technology concepts [16–19], control concepts [20,21], and utility-scale integration [21–29] there exists is little-to-no quantified research detailing the economic merit of wave energy systems relative to business-as-usual diesel only or hybrid systems (generally focussed on mature hydroelectricity or solar PV technologies) for remote communities. In addition, for the marine energy sector to advance, uncertainty in marine energy costs must be countered with greater certainty in the diesel displacement, allowable-cost Levelized cost of energy (LCOE), and any broader energy system savings accrued by integrating marine energy. In contrast to previous works on wave energy or tidal system LCOE [30,31], this study focussed on calculating the 'allowable' LCOE. By utilizing a 'bottom up' energy systems model [32], with exogenously defined zero cost solar and wave energy technologies, this work quantifies the maximum allowable costs at which a renewable energy generator creates economic benefit.

In general, broad research and understanding of Hybrid Renewable Energy Systems (HRES) is either completed via detailed measurement data [33], or via numerical energy system models. Getting a broad understanding of HRES solely via measured data, like Diaz et al. [33], is extremely data-intensive. This method suffers from two major drawbacks: 1) Getting consistent reliable data, and 2) the lack of ability to look forward to future scenarios. Utilizing numerical models, like HOMER, OSeMOSYS, R2HES, DER-CAM, TIMES/MARKEL [34,35], allow system operators, communities, and project developers to analyze the coupled nature of technical, economic and natural systems in both existing systems and future potential systems. There is a wide body of literature on Hybrid Renewable Energy Systems (HRES) energy system modelling – see comprehensive literature reviews in [33,35–39]

To provide an example parameter used to differentiate available HRES modeling tools is the system foresight available for dispatch; either myopic or perfect foresight. Myopic foresight reflects that the system operator makes decisions on energy dispatch from different sources with very limited knowledge of future resource availability and community demand. In a myopic foresight HRES model, dispatch is either simulated based on heuristic rules that ensure that supply and demand are always balanced [39], or are based on a full-factorial search, as used in HOMER, RETScreen and H2RES [40]. These tools compare all feasible system simulations to rank the most cost-effective energy system designs.

This study uses the Remote Community Optimization Model (RCOM), built on the General Algebraic Modelling System (GAMS) platform [41], to compare different energy system designs, associated 'allowable-cost' economics and diesel offsets. RCOM uses a perfect foresight approach in which the operation of a specific energy system design (e.g. a scenario with set generation technologies and capacities) is formulated as a cost-minimization optimization problem. By maintaining the system cost as a linear function of system state variables, and enforcing the supply-demand balance also as a linear function of the state variables, a minimum cost operation of the energy system can be determined using a mixed integer linear programming approach. The dispatch strategy follows no heuristic rules but is rather derived directly from the linear programming problem solution. Whereas myopic foresight tools allow for optimization across various system scenarios but sacrifice true optimality due to the heuristic dispatch, RCOM ensures optimal dispatch but only for the user specified scenario. Alternatives to RCOM include DER-CAM and MARKAL/TIMES as described in [29].

It is expected that a perfect foresight approach will yield the lower lifecycle cost boundary and is thus best suited to the calculation of 'allowable' costs. Due to massive uncertainties in the capital, operation and maintenance costs of wave energy devices, the front-end engineering design of wave energy projects are unable to resolve a value-proposition in terms of standard Levelized Cost of Energy (LCOE) calculations. In this work we use RCOM to consider a variety of HRES, including wave, solar and hydroelectricity options, to find the 'allowable-cost' LCOE values for each renewable option. Comparing allowable costs across the renewable options reveals the raw potential of each resource to serve decarbonization efforts; without introducing bias based on the maturity of each technology class or the ability to manage variability through storage. In this work we explicitly avoid including energy storage, as we are focussed on establishing the relative merits of wave energy technology and resources, not combinations of renewables and energy storage.

The RCOM framework is applied to a case study aimed at comparing diesel mitigation potential of a wave technology to that of solar and hydroelectricity alternatives for a coastal high latitude (north or south) community. Hot Springs Cove on the West coast of Vancouver Island, British Columbia (BC) Canada is indicative of these communities and can be characterized by high winter and low summer loads. Despite British Columbia's utility grid being more than 98% supplied by renewable hydro-electric generation, Hot Springs Cove is symptomatic of 32 BC coastal off-grid communities that remain reliant on diesel generation [42,43]. The Hot Springs Cove case is relatively unique in the sense that this community has access to local wave, solar and hydro resources, making it ideal for a comparison of the relative value proposition of emerging wave energy technology against established solar and micro-hydro competitors.

This paper is structured as follows: Section 2 introduces the Remote

Community Optimization Model, while Section 3 provides a detailed overview of the electricity demand and renewable resource options available for Hot Spring Cove, Canada. Section 4 details the representation (performance, cost, reliability, emissions) of the different generation options available at Hot Springs Cove. Section 5 details the results from the RCOM model at our case study location and quantifies the system performance over a year of operation. Section 6 provides a broader discussion of the results and includes contextual perspectives future work. Finally, Section 7 reviews the results and provides a concise overview for integrating hydroelectricity, solar and wave energy systems for a case-study high latitude remote community.

2. Remote Community Optimization Model (RCOM)

Energy system models are widely used for optimization of energy system capacity expansions, operational cost-minimization and detailed power flow analyses. These models inform operational efficiency, aid investment planning and identify policy opportunities/implications. As discussed in the Introduction, a wide variety of tools and models have been developed and are routinely utilized to answer specific questions of energy system composition and operational strategy (i.e. dispatch).

The Remote Community Optimization Model (RCOM) is used to produce *a priori* assessments of the economical, technical and operational impacts of candidate energy systems in small communities. Built on the General Algebraic Modelling System (GAMS) platform [41], RCOM optimizes the dispatch of known generation assets and resources to meet hourly electricity demands at the lowest cost (objective function), subject to a technology-specific operational and availability constraint. More technically, RCOM is a cost-minimization optimization that formulates the hourly resolved supply-demand energy balance problem as a linear, mixed integer programming problem [44]. The energy balance equation is an equality constraint for all generation sources, and includes a sink variable to equal the demand. Other constraints are defined by generator performance functions (from manufacturer data) or resource availability. Magnitude limits are defined for variables that represent the generator, or system capacity, and may also include minimum values. The mixed integer framework allows for on/off variables – very applicable to representing generator dispatch – whilst maintaining linear operational constraints. RCOM has perfect foresight for the entire modelling period.

Storage time domain variables are dependent on $(t-1)$ and $(t+1)$ states, which requires additional processing to optimize values in period (t). The addition of any time domain variables or constraints increase model complexity, yet impart more energy system attributes. To improve optimization efficiency, post processing calculates secondary system data. These include: CO2 emissions, fuel efficiency, capacity factors and annualized data sets.

Table 1
RCOM Objective function and operating constraints for hydro-diesel system.

Objective function	$minTC = \sum_0^n C_{hydro}(t) + C_{diesel}(t)$	(1)
Constraint #1	$P_{hydro}(t) + P_{diesel}(t) = P_{demand}(t)$	(2)
Constraint #2	$P_{d\_min} \leq P_{diesel}(t) \leq P_{d\_max}$	(3)
Constraint #3	$V_{fuel}(t) = (AP_{diesel}(t) + V_0)X_{diesel}(t)$	(4)
Constraint #4	$P_{h\_min}X_{hydro}(t) \leq P_{hydro}(t) \leq P_{h\_max}X_{hydro}(t)$	(5)
Constraint #5	$P_{hydro} = (B * Q(t) - C)X_{hydro}(t)$	(6)
Constraint #6	$(Q_0 + Q_{start}) \leq Q(t) \leq Q_{design}$	(7)
Binary Variables	$X_{diesel}, X_{hydro} = 0, 1$	

Fig. 1 illustrates the RCOM process flows for a simple hybrid hydroelectricity (hydro) and diesel-powered electricity system. RCOM requires input data on costs, demands, resource availability (diesel, water), then determines the cost minimal dispatch (subject to constraints) to meet the demand. Outputs include time series of generation, fuel use, emissions, costs, etc.

Given that generation resources and associated capacity are inputs to RCOM, any comparisons between different energy systems, installed capacities or technologies is completed via scenario-based studies. Scenarios could additionally include higher fuel costs, lower water flow years, emissions pricing, etc.

2.1. Technology operating constraints

Utilizing the hydro-diesel system (shown in Fig. 1) as an illustrative, Table 1 provides an overview of the objective function and technology-specific constraints. The objective is to optimize the dispatch of the hydro and diesel generators to minimize the Total Cost (TC) of generation.

All constraints must be met at every time step. Constraint #1 is the energy balance for the whole system, i.e. power generation from hydro (P_{hydro}) and diesel (P_{diesel}) must meet demand (P_{demand}) in each of the *n model* time steps (t). Constraint #2 represents the minimum and maximum output from the diesel generator; where P_{d_min} represents the start-up or minimum generation, and X_{diesel} is a binary variable and indicates whether the generator is available. Constraint #3 represents the diesel fuel consumption; which relies on the current power production (P_{diesel}), the generator fuel consumption performance (A), and the fuel consumption required for start-up (V_0).

The remaining constraints are associated with the hydro-electric generation. Constraint #4 shows the power from the hydro system stays between the maximum (P_{h_max}) and the 'shut-down' minimum (P_{h_min}). Constraint #5 indicates the power production for the specific hydro turbine; which is dependent on the turbine being available (X_{hydro}), the current water flow ($Q(t)$), the associated turbine performance (B), and the initial power losses required to run the turbine (C). The water

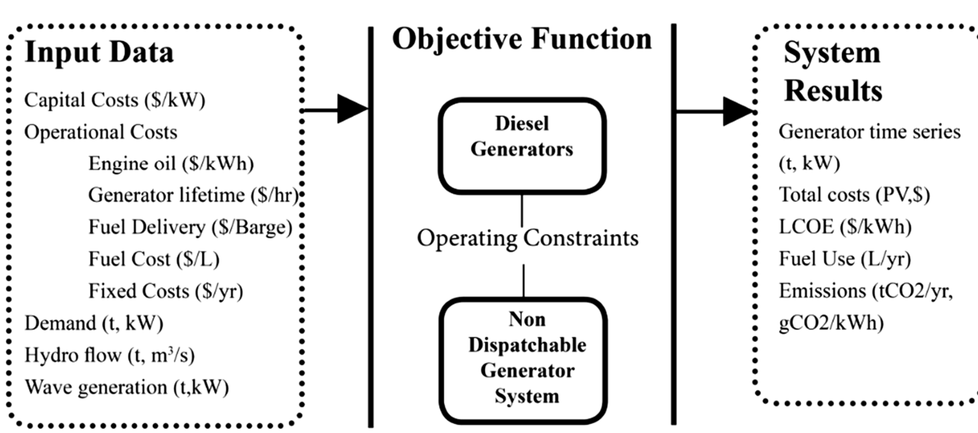

Fig. 1. RCOM process example – hybrid hydro-diesel energy system.

'consumption' for hydro is slightly more complex as 'start-up' and 'shut-down' flow rates differ. Constraint #6 enforces that flow rates are between the design (Q_{design}) and minimum (Q_0) water flow during operation. An incremental additional flow (Q_{start}) is required for turbine start-up (when $X_{hydro}(t-1) < X_{hydro}(t)$). Any generator in an RCOM model will feature a set of constraints similar to those demonstrated in Table 1.

For example, as wave and solar generators are added to the system, the set of constraints in Table 1 must be adapted. Constraint 1 must include the contributions of solar and wave to the supplied power. As is described in sections Section 4.3 and Section 4.4, the available output of the solar and wave plants at any time is set by exogenously defined resource profiles. RCOM determines how much of the available renewable to use at any time. This can be seen as an addition of solar and wave constraints similar to Constraint 2 where the lower bounds on solar and wave power are 0 and upper bounds are drawn from the resource annual profiles.

2.2. Technology economic constraints

For each generator, there are capital costs associated with project development, operations and maintenance (O&M) costs, and equipment overhaul costs. For existing generators, capital costs are considered sunk and only additional fuel costs (consumption and delivery) are included. For a diesel generator, the present value costs associated with generation are detailed in (8), and include fuel, O&M, overhaul and barging costs.

$$TC_{diesel,PV} = C_{Fuel,PV} + C_{DieselO\&M,PV} + C_{Overhaul,PV} + C_{Barge,PV} \tag{8}$$

For renewable energy generators, such as solar or wave, the fuel and delivery costs are general zero. However, total present value system costs ($TC_{system,PV}$) include upfront capital costs for construction and lifetime operating costs. Overhaul and O&M costs are dependent on usage, age, equipment, etc. In the case of hydroelectric system, water rental costs (capacity and output) can be included.

Utilizing the hydro-diesel system example, Fig. 2 provides an overview of the costs associated with the operation of the example hybrid electricity system.

Within this study, the Levelized Cost of Energy (LCOE - \$/kWh) and the cost of installed capacity (\$/kW) will be the primary economic metrics of comparison. The LCOE is calculated as:

$$LCOE = \frac{TC_{system,PV}\hat{A}\cdot CRF}{AnnualDemand} \tag{9}$$

where $TC_{system,PV}$ is the total present value cost for meeting the electricity demand.

Capital Recovery Factor (CRF) is calculated using (10):

$$CRF = d\frac{(1+d)^N}{(1+d)^N - 1} \tag{10}$$

where d is the discount rate and N is the selected project lifetime.

2.3. Allowable-cost methodology

For well-established generators, renewable or otherwise, the $TC_{system,PV}$ can be tabulated with historical site-specific performance data and input into RCOM. However, for nascent and emerging technologies, these baseline financial quantities are difficult to obtain or simply don't exist. Without quantified value proposition for new generators, it is difficult to determine the economic variability of the technology within a remote community electricity system.

In such scenarios, an allowable-cost cost analysis can be used to identify the TC_{newgen} allowable for the new generator. The allowable cost is the difference between the baseline system cost, and the scenario with the new generator; albeit with zero cost.

For example, the capital and operating expenses for a wave energy system are unknown. In order to identify the allowable-cost LCOE ($LCOE_{allow}$), a baseline scenario is modelled (TC_{diesel}) and a new system with wave energy is modelled (TC_{wave}) and calculated according to (11):

$$LCOE_{allow} = \frac{(TC_{diesel,PV} - TC_{newgen,PV})\hat{A}\cdot CRF}{WaveGeneration} \tag{11}$$

where *WaveGeneration* is the total site specific or local wave generation in kilowatt-hours (kWh). A similar methodology can be used to determine allowable-cost system capital costs if details on O&M are known.

In addition to allowable-cost LCOE, the total system-cost reduction (equally positioned as revenue opportunity) per kW of installed capacity provides insight into the value proposition for the various technologies investigated. The total system cost reduction is henceforth termed the 'return per kW'. See (12); where *capacity* is the total install capacity of wave, solar or wave + solar:

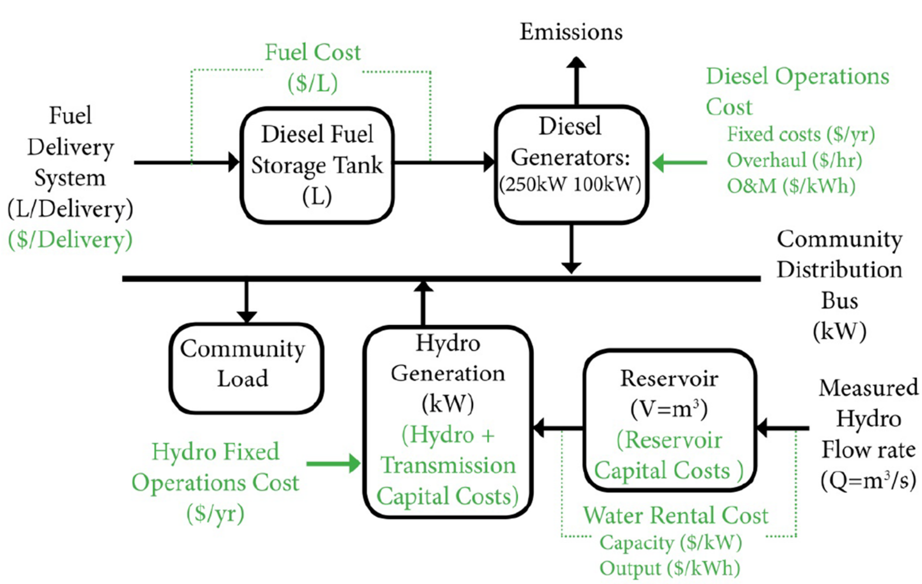

Fig. 2. RCOM economic analysis for hydro-diesel example system.

$$kW\_Return_{allow} = \frac{TC_{newgen,PV} - TC_{diesel,PV}}{Capacity} \quad (12)$$

3. Hot Springs Cove electrical system and resource options

Hot Springs Cove is a First Nations community, is located at 49°22′N, 126°16 W, and is only accessible by boat or seaplane. The community consists of ~123 people, 3 administrative and community buildings, and 30 residential homes. The electricity demand system at Hot Springs Cove is met through entirely through diesel generation, and is indicative of global remote communities. The community aspires to achieve 100% penetration of renewable energy and utilize their wealth of proximate, raw renewable energy resources [5] – hydro, solar and wave energy resources.

3.1. Existing demand and generation

In 2014, Hot Springs Cove installed electrical meters to record community electricity load data at 15 min resolution (shown in Fig. 3 for 2015). Hot Springs Cove features a winter peaking demand profile - representative of many high latitude locations. The winter demand peaks at 193.5 kW, while summer load averages just 50 kW. This demand profile is dominated by heating and lighting demands, as most cooking demands are met by propane gas.

The existing electricity system at Hot Springs Cove consists of two (2) Volvo 250 kW generators and two (2) 100 kW generators – schematically shown in Fig. 2. The larger 250 kW units are designed to meet winter peak loads, while the smaller 100 kW units are specified for summer operation; allowing the generators to run at more efficient, higher load regimes. The generator duplication is for redundancy and reliability concerns.

3.2. Renewable resource options

Hot Springs Cove has a unique but limited suite of renewable resource opportunities to draw from. Dominant amongst the options are traditional small scale hydroelectric (micro-hydro) generation and wave energy generation. However, given the rapidly decreasing capital costs and their modular nature, solar PV is additionally investigated to provide comparative analyses.

3.2.1. Hydroelectric power

Ahtaapq Creek is conveniently located 2 km from Hot Springs Cove and is currently being investigated by the Community for a small-reservoir run-of-river hydroelectricity system. Fig. 4 shows the creek discharge for a water average year (2006). The maximum flow occurs during the winter months whilst summer months feature very low flow conditions. Immediately evident is the variability in the flow conditions, associated with both short-term storm events (duration of days) and longer-term seasonal changes (duration of months). The extended low-flow conditions during winter, due to clear sky and below freezing climatic events, are notable (as noted in Feb-March in Fig. 4).

As noted, 2006 is represents an average Mean Annual Discharge (MAD = 0.39 m^3/s) year for Ahtaapq Creek. To investigate the impacts of increased/decreased water flow years on the electricity system operation, flow conditions for 1985 (MAD = 0.20 m^3/s) and 1997 (MAD = 0.55 m^3/s) will also be utilized.

3.2.2. Solar power

Solar data for this location was taken from the Government of Canada's *Canadian Weather Year for Energy Calculation (CWEC)* dataset [45]. CWEC datasets are collected from ground stations across Canada and compared against similar NASA and National Resources Canada's *Geostationary Operational Satellite system* datasets for validation [46]. Fig. 5 shows the normal solar irradiance for an average solar year in the Hot Springs Cove region. As shown the resource is maximal during summer months with significantly reduced resource during the winter. However, even during the summer, the resources maintains significant variability due to the presence of coastal 'fog'. The maximum resource of 914 W/m^2 is available during the spring (April/May) and an annual average of 138 W/m^2.

3.2.3. Wave power

Numerous studies have been conducted on assessing the future prospects of wave energy on the west coast of Canada [47–49]. For Hot Springs Cove, a location ~2 km from shore and in 40 m of water was identified based on a Simulation WAves Nearshore (SWAN) model [50].

Fig. 6 shows the gross wave energy transport (kW/m) over the 2015 period. As with the creek flow and solar resource, there is significant variability in the resource availability. The wave resource is dominated by seasonal trends – with highly active winters and relatively benign summers – and short-term storm events (multiple days). Generally, the wave energy resource is most active during the winter months with the gross wave energy flux reaching almost 250 kW/m. Note that wave energy flux is measure per m of wave crest; the energy flux through a 1 m diameter circle from the sea surface to the seafloor.

In order to maintain temporal coherence between community electricity demand and wave energy resources, 2015 wave data is used as the default. However, 2015 was a relatively active wave energy year on the West Coast of Canada, with an average wave energy transport of 21.4 kW/m. It is important that more benign wave conditions are also investigated for impact on the energy system. 2013 had an average wave energy transport of just 11.3 kW/m and the temporal characteristics are shown in Fig. 7 (note the y-axis scale difference)

Table 2 provides a quick overview of the average, minimum and maximum resource potential for hydro, solar and wave energy. The table provides a quick relative perspective of the opportunities for the

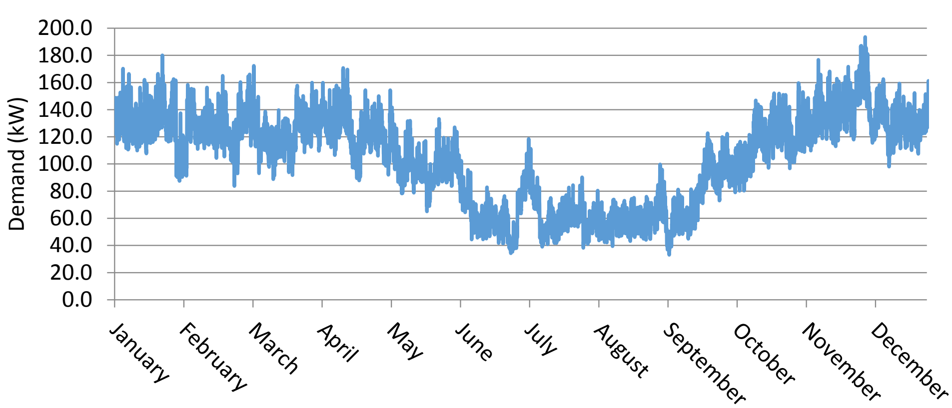

Fig. 3. Electrical demand for Hot Springs Cove (2015).

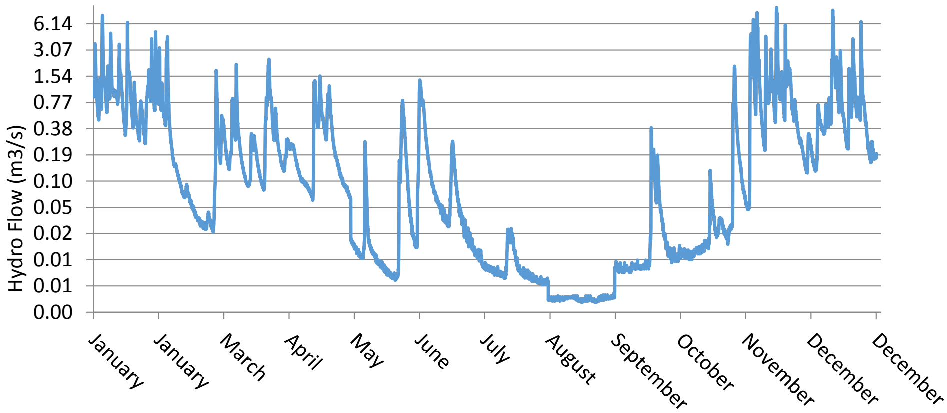

Fig. 4. Ahtaapq creek annual flow rates.

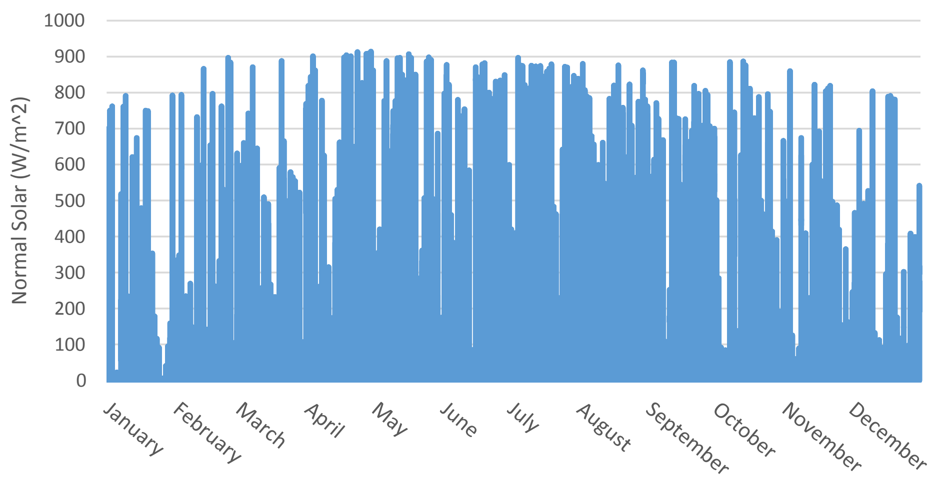

Fig. 5. Normal solar irradiance.

different resources, depending on the ability to reliability generate power from each.

4. RCOM scenarios and technology characterization

As previously discussed, RCOM inputs capital, fixed and variable operating costs, emissions intensity, and resource performance and availability for individual technologies. The following section details the technology representations and associated modelling constraints for the Hot Springs Cove resource and economic conditions.

A schematic of possible hybrid energy systems at Hot Springs Cove is presented in Fig. 8. The RCOM model optimized over 8760 h for representative or scenario-based years.

In order to elucidate the impacts and benefits of various energy systems, a scenario-based study is utilized. The results are presented for different hybrid energy systems, scenarios of installed capacities, and resource availabilities. Table 3 provides an overview of the systems and scenarios to be analysed.

In terms of economic analyses, all technologies were assumed to have a consistent 30-yr lifespan (slightly higher than [51] but utilized to maintain consistency with hydro system), a discount rate of 10% (as per [51]), and an inflation rate of 1.6% (mean of Canadian inflation rate over last decade [52]). For diesel fuel, a fuel escalation rate of 5.2% (mean of fuel increases in local community of Nanaimo between 2001

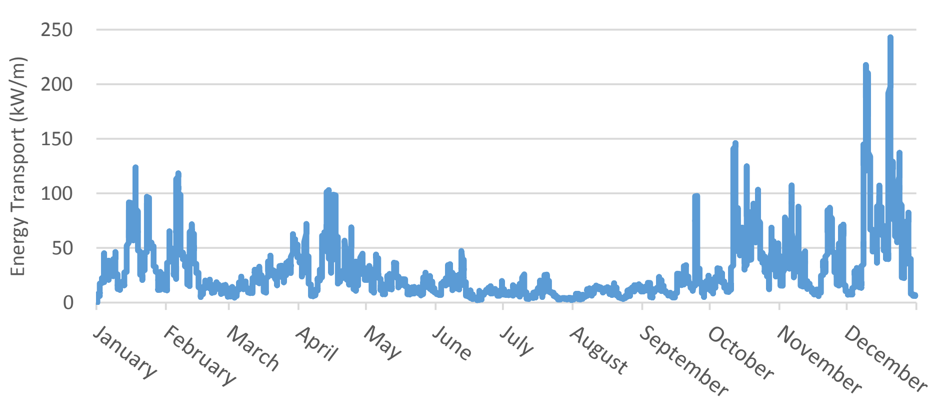

Fig. 6. Wave energy transport at Hot Springs Cove in 2015.

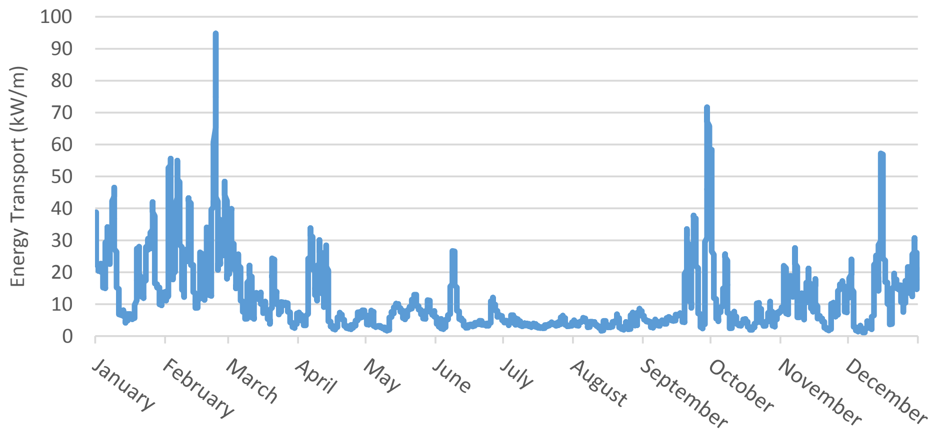

Fig. 7. Wave energy transport at Hot Springs Cove in 2013.

Table 2
Renewable resource options overview.

Renewable Resource	Hydroelectric (m^3/s)	Solar (W/m^2)	Wave (kW/m)
Average	0.39	138	21.4
Minimum (month)	0.05 (August)	0 (night)	0.2 (July)
Maximum (month)	7.5 (November)	914 (May)	248 (December)

and 2015 [53]) was utilized.

The community of Hot Springs Cove is currently exempt from carbon taxes so all default RCOM analyses do not include carbon pricing. However, in each scenario, the additional costs associated with carbon pricing at $30/tonne (current British Columbia provincial price), $50/tonne (Canadian federal price) and $100/tonne (possible future price) are investigated via post-system optimization processing.

4.1. Diesel system and constraints

The diesel fuel use for the 250 kW and 100 kW generators is based on Volvo performance curves [54] and linearized; based on the minimum generation, maximum generation and percentage load on the generator. See Table 4. As expected, operating the generator at higher percentage rated loads increases fuel efficiency per kW and reduces emissions per kWh.

The diesel system generation costs are detailed in Table 5, and the total costs (TC) formulated in (13). Additional fuel deliveries were at a unit volume of 49,400L/delivery (all fuel delivered by a barge carrying fuel trucks).

Table 3
Overview of energy systems and scenarios.

System/Scenario	Scenario Generation Capacities
Diesel System	- Diesel: 100 kW & 2x 250 kW
Hydro-Diesel System	- Diesel: 100 kW & 2x 250 kW - Hydro: 225 kW
Solar-Diesel System	- Diesel: 100 kW & 2x 250 kW - Solar: 100 kW or 200 kW
Wave-Diesel System	- Diesel: 100 kW & 2x 250 kW - Wave: 200 kW or 100 kW
Wave-Hydro-Diesel System	- Diesel: 100 kW & 2x 250 kW - Hydro: 225 kW - Wave: 200 kW (Sys. A)/100 kW (Sys. B)
Wave and Hydro Resource Sensitivity	- Diesel: 100 kW & 2x 250 kW - Hydro: 225 kW - Wave: 100 kW (Low/High hydro flow year: 1985/1997) (Low activity wave year: 2013)

Table 4
Diesel generator fuel consumption.

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

where $P_D(t)$ is the power generation at each time step.

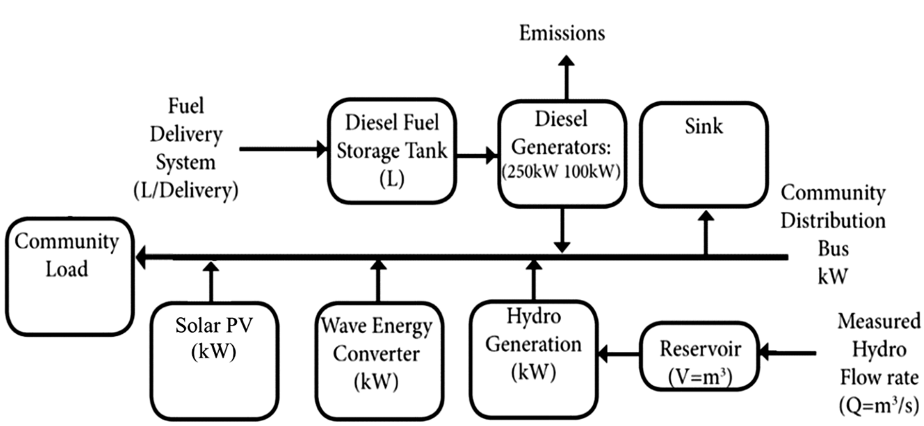

Fig. 8. Complete hybrid energy system options for Hot Springs Cove. Each energy system scenario includes/excludes certain generators from system as described in Table 3.

Table 5
Diesel System Generation Costs [55]

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

$$TC_{diesel,PV} = C_{Fuel,PV} + C_{DieselO\&M,PV} + C_{Overhaul,PV} + C_{Barge,PV} \quad (13)$$

Minimum generation was set to 20% of rated capacity and a minimum of 4hr 'up' time enforced to eliminate harmful cycling impacts on the equipment. No minimum 'down' time was included. It was assumed that the diesel generators could ramp to 100% capacity within the hourly time step. Emissions were based on Tier 2 off-road diesel engines as per [56] and CO_2 determined to be 5.0 and 3.5 g/kWh for the 250 kW and 100 kW generators respectively.

4.2. Hydroelectric system and constraints

Hydro generation is defined by the incoming creek flow rate, storage reservoir size, and the desired turbine capacity. The incoming creeks flow rates have been previously defined, and the reserve storage opportunity is limited to 6000 m^3 [55]. Additionally, in order to maintain the ecological biodiversity in the creek, an inflow stream requirement (IFR) is 0.011 m^3/s [57] must be met at every time step.

The investigated hydro system has a capacity of 225 kW 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. 9 illustrates the total efficiencies and power output for the 225 kW hydroelectric generation system. The RCOM hydro generation system representation includes turbine efficiency losses, power station losses, and transmission losses. Accumulating these losses, the total peak efficiency only reaches 80%.

The costs associated with hydroelectric plant design, construction, permitting are formulated in (14) and detailed in Table 6. Note that the water rental costs two contributions: a capacity (C_{hydro_cap})and a generation output cost (C_{hydro_gen}).

The capital and fixed costs (design, turbine and generator, construction, environmental monitoring, land lease, insurance, etc. costs), variable operation and maintenance costs (water rentals, management frees, vehicles, repairs and maintenance) are based on estimates from the local utility (BC Hydro [58]).

Table 6
Hydroelectric system generation costs.

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

$$TC_{hydro,PV} = C_{hydro\_cptl} + C_{hydro_{fix},PV} + C_{hydro_{cap},PV} + C_{hydro_{gen},PV} \quad (14)$$

Finally, the hydro system is given a 95% availability factor. To account for this availability factor, the RCOM model has 1.25% hrs per quarter assigned to zero hydro-electricity output (within the optimization framework).

4.3. Solar system and constraints

Locations for solar at Hot Springs Cove are somewhat limited by significant tree cover and limited suitable roof space. For this study, a potential 100 kW or 200 kW ground mounted systems was deemed favourable due to suitability of locations [46]. A panel slope of 34°, an azimuth of 180° (due South) and Canadian Solar 310 W panels were assumed. The resulting solar PV electrical output for the 100 kW system is shown in Fig. 10. This output was simple scaled to provide RCOM inputs for the 200 kW system.

4.4. Wave system and constraints

A wide variety of wave energy converters (WECs) are in development, all with differing energy capture and power-take-off concepts

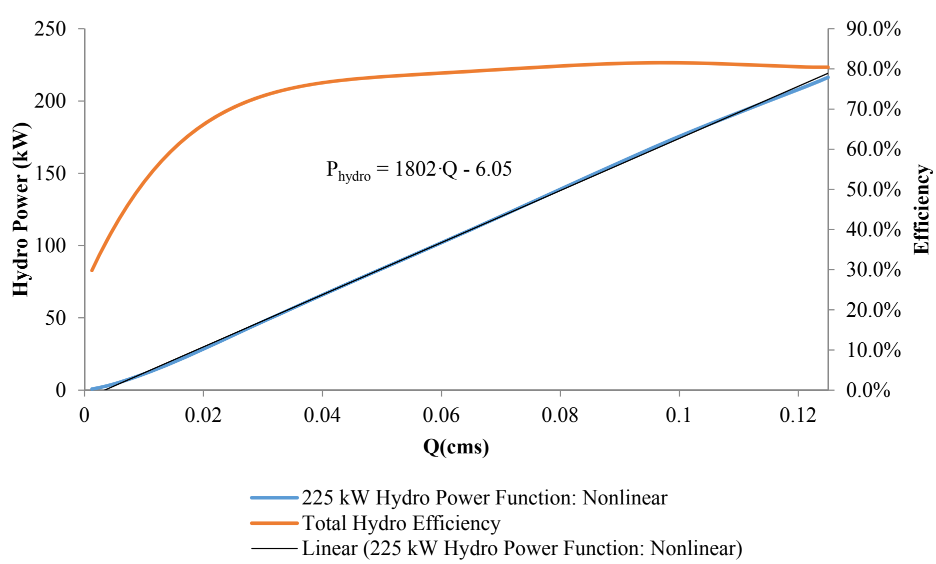

Fig. 9. 225 kW Hydro-electric generation power relationship.

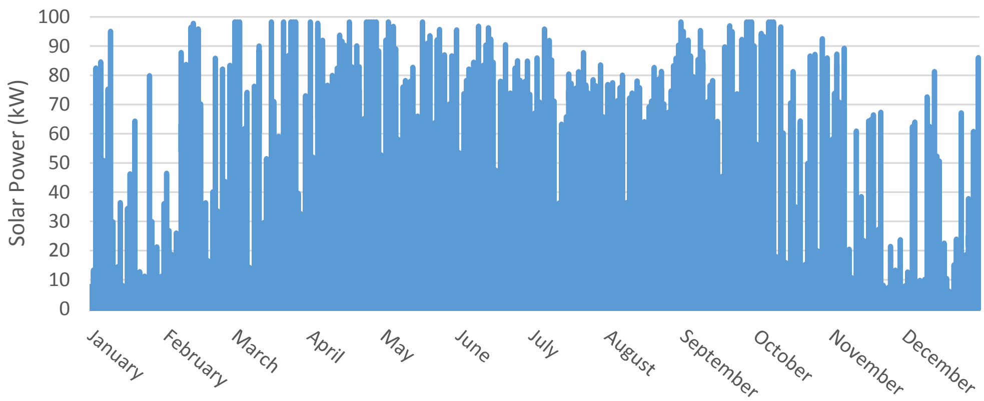

Fig. 10. Solar PV output at Hot Spring Cove.

[7,17,58–61]. For this study, WEC technology of choice was the SeaWood Designs 'SurfPower' system [62,63]. This choice was driven the relative simplicity of the concept and the ability to approximately scale WEC rated capacity with the buoyant wing width. Fig. 11 provides an overview of the system, and additional details on the numerical modelling can be found in Bailey et al. [19].

The power production potential from the SurfPower system 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 WEC power production (P_w) is sea state dependent power and calculated using (15):

$$P_w = \eta_{WEC} L * \left(\frac{\rho g^2}{64\pi}\right) H_s^2 T_e \tag{15}$$

where η_{WEC} is the efficiency of the WEC (Fig. 12), ρ is seawater density (1025 kg/m^3), g is gravity (9.81 m/s) 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; 24 m/200 kW and 12 m/100 kW. Whilst the rated power will not scale exactly with device width, the assumption provides an illustrative example of appropriate scale for integration. Fig. 13 shows the annual power production from a 200 kW WEC installed during 2015 at the chosen location off Hot Springs Cove. The wave energy system is given a 95% availability factor to mimic the hydroelectric facility (Note that the 95% availability is not shown in Fig. 13 since availability factor timing is endogenous to the RCOM framework).

Given the nascent nature of the WEC industry, costs are uncertain. As previously noted, a allowable-cost cost analysis is utilized for WEC generation system costs to identify the allowable \$/kWh and \$/kW for the community to benefit from wave energy.

5. Results

In the following sections, the impact of temporal compatibility and technology performance between local demand and a variety of renewable resources will be detailed. For nascent technologies, like wave energy, the system-wide economic allowable-cost point is based on diesel fuel consumption mitigation.

5.1. Diesel system

The costs and operational characteristics of the existing diesel system serve as the baseline system and the comparison point for all future energy systems. shows the seasonal and distribution of diesel system generation during 2015. The 250 kW generator primarily functions for winter peaks loads, while the 100 kW generator is dispatched during lower demand summer loads.

The total cost of running the diesel energy system is \$6.44 M, 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. Over the year, the 250 kW and 100 kW generators have capacity factors (CF) of 31% and 25% respectively. Finally, the diesel energy system emits 780 tonnes/yr. of CO_2.

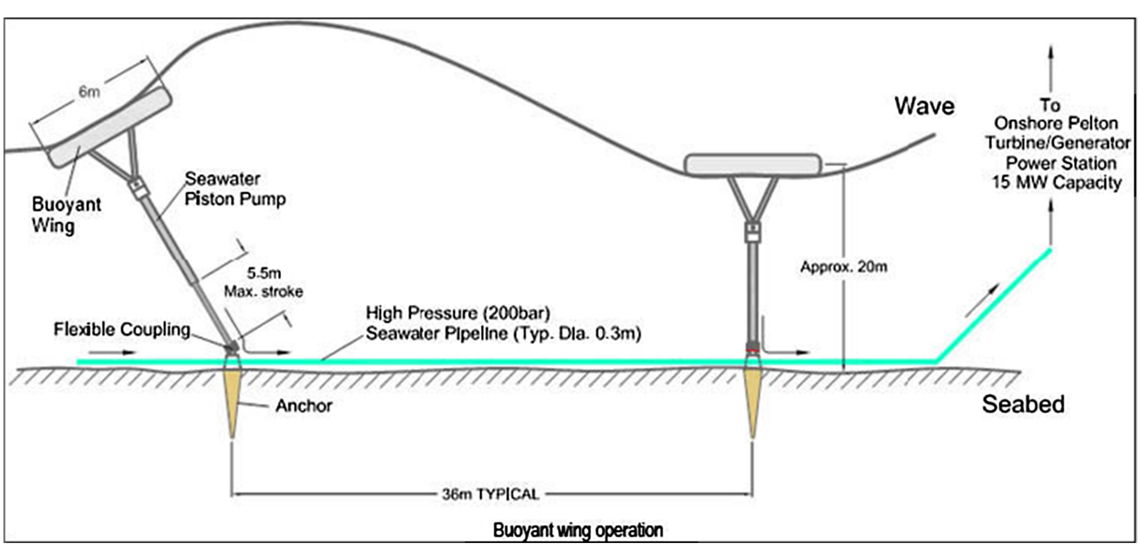

Fig. 11. Seawood designs 'Surfpower' WEC.

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. 12. WEC efficiency matrix.

If these emissions were subject to carbon prices at $30, $50 or $100/tonne, these emissions would increase the LCOE by $0.24/kWh, $0.40/kWh & $0.81/kWh.

Finally, fuel costs have been shown to dominate the system costs. In order to assess the impact of increased fuel costs, and associated reduced LCOE, the RCOM model was rerun using a high and low fuel cost ($2.0/L and $1.2/L). This 25% change in fuel costs results in a 20% increase/decrease in system LCOE ($0.90/kWh and $0.60/kWh respectively).

5.2. Hydro-Diesel system

Fig. 14 illustrates the significant renewable penetration potentially achievable by hydro-electricity at Hot Springs Cove. Based on an average rainfall year (MAD = 0.39 m^3/s), hydro can meet 65% of community electricity demand over the year.

The integration of hydroelectricity system saves ~193,000 L of diesel fuel (66% reduction) and 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 30 yr project lifespan, this accounts for $5.23 M of savings.

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 $7.73 M capital cost of developing the hydroelectric system – an upfront cost that is greater than the total diesel saving over the 30-yr. lifetime.

The CF of the 250 kW diesel generator being reduced to just 2%, yet it is still required in all seasons. This is partially due to the unavailability constraint assigned to the hydro-electric system. Conversely, the 100 kW generator CF increases to 31%. The 66% reduction in fuel use reduces carbon dioxide emissions to just 260 tonnes/yr.

If these emissions were subject to carbon prices at $30, $50 or $100/tonne, these emissions would increase the LCOE by $0.08/kWh, $0.14/kWh & $0.28/kWh. While substantial, these relative increases are much lower than those associated with a diesel-only energy system.

5.3. Solar-diesel system

As shown in Fig. 15, introducing 100 kW or 200 kW reduces the diesel generation by a marked amount during the summer, yet has limited impact during the winter months. For summer (Q2 and Q3), the penetration of solar for the 100 kW/200 kW systems are 23%/24%, while this drops to just 4%/7% in winter (Q3/Q4).

The solar systems save 36,485L and 58,385L of diesel fuel each year (12%/19%) for the 100 kW and 200 kW systems respectively. In order to provide comparative ability between wave and solar, solar has not been assigned any capital or operating costs. As such, the allowable-cost LCOE's for the 100 kW and 200 kW systems are $0.53/kWh and $0.44/kWh; the lower value for the 200 kW system is due to 7.7% of generation being curtailed.

The breakeven prices per kilowatt are $6844/kW and $5678/kW for the 100 kW and 200 kW solar system respectively.

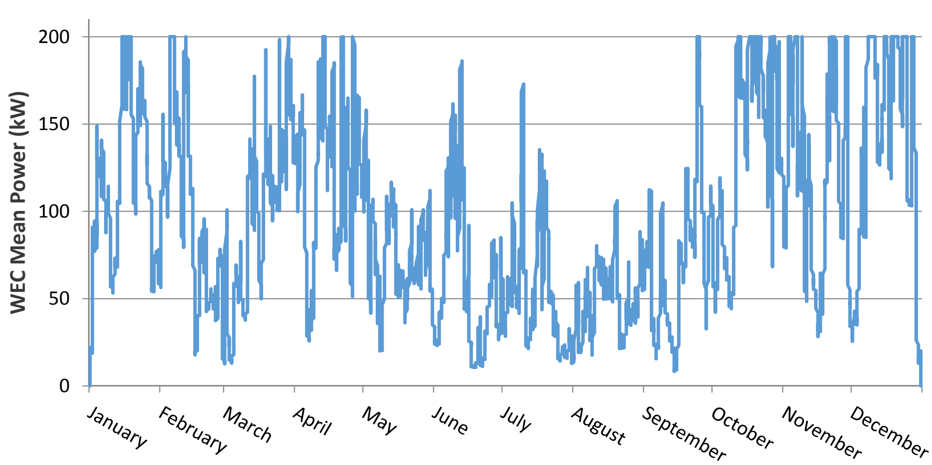

Fig. 13. 200 kW WEC power generation at Hot Spring Cove.

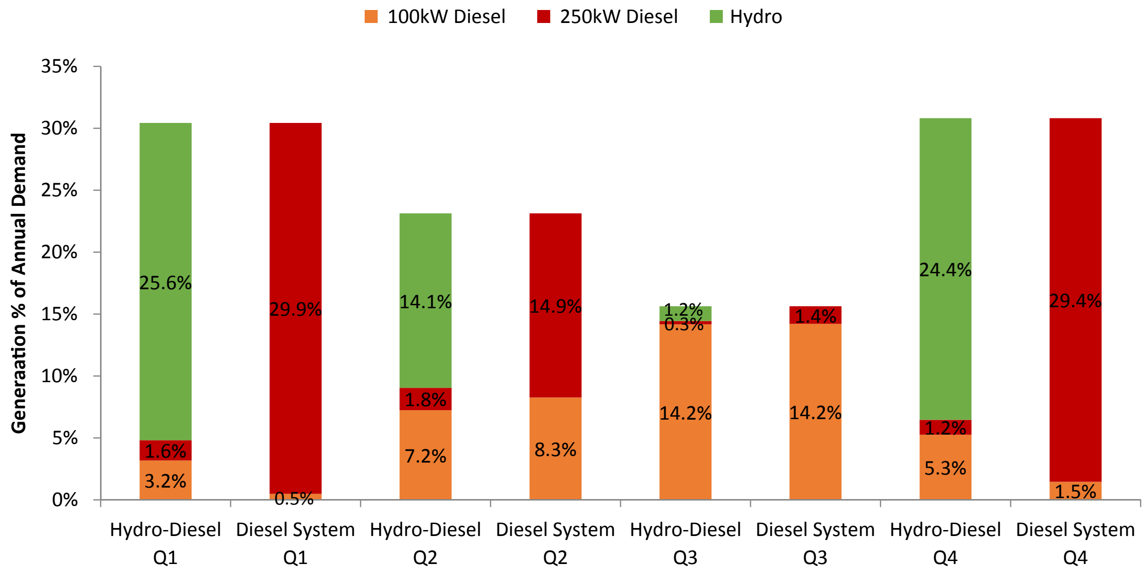

Fig. 14. Hydro-diesel system generation.

The CF's of both diesel generators are slightly reduced when solar is installed; between 5% and 6% for the 250 kW generator and 1%-4% for the 100 kW generator. Carbon dioxide emissions are slightly reduced to 1435 tonnes/yr. and 1313 tonnes/yr. for the 100 kW and 200 kW solar systems respectively.

If these emissions were subject to carbon prices at $30, $50 or $100/tonne, these emissions would increase the LCOE by $0.19/kWh, $0.32/kWh & $0.65/kWh for the 200 kW solar system. These carbon price impacts would increase the allowable-cost LCOE and price per kilowatt to $0.46/$0.47/$0.50 and $5899/$6046/$6414 respectively.

5.4. Wave-diesel system

As with the previous systems, the analysis of the wave-diesel system is based on operational and economic implications of installing differing levels of WEC capacity (detailed in Table 3).

Fig. 16 shows the system generation with a 200 kW and 100 kW WEC (same capacities as the solar systems). Wave energy penetration accounts for 43% to 71% of total annual energy demand for the 100 kW and 200 kW WECs respectively.

The 200 kW WEC reduces fuel consumption by 68% (total usage of 92,520L), but also generates excess electricity energy; up to 16% of annual demand. The 100 kW WEC reduces fuel consumption by 40% (total usage of 175,310L) and only generates 3% excess energy during the non-peak/summer seasons.

Financially, the 100 kW will save $2.32 M over a 30 yr. project, while the200kW will save $3.96 M. Using (10), the breakeven LCOE for a wave energy system can be calculated. For the 200 kW and 100 kW WEC systems, these are $0.51/kWh and $0.59/kWh respectively. The increased value for the 100 kW WEC is due to the higher utilization and reduced excess generation.

The breakeven price per kilowatt are $23,206/kW and $19,773/kW for the 100 kW and 200 kW wave systems respectively.

The CFs of the 250 kW generator drops to just 6% and 3%, while the 100 kW generator is more effective and has a CF of 44% and 21% respectively. The CO_2 final emissions for the 200 kW and 100 kW devices

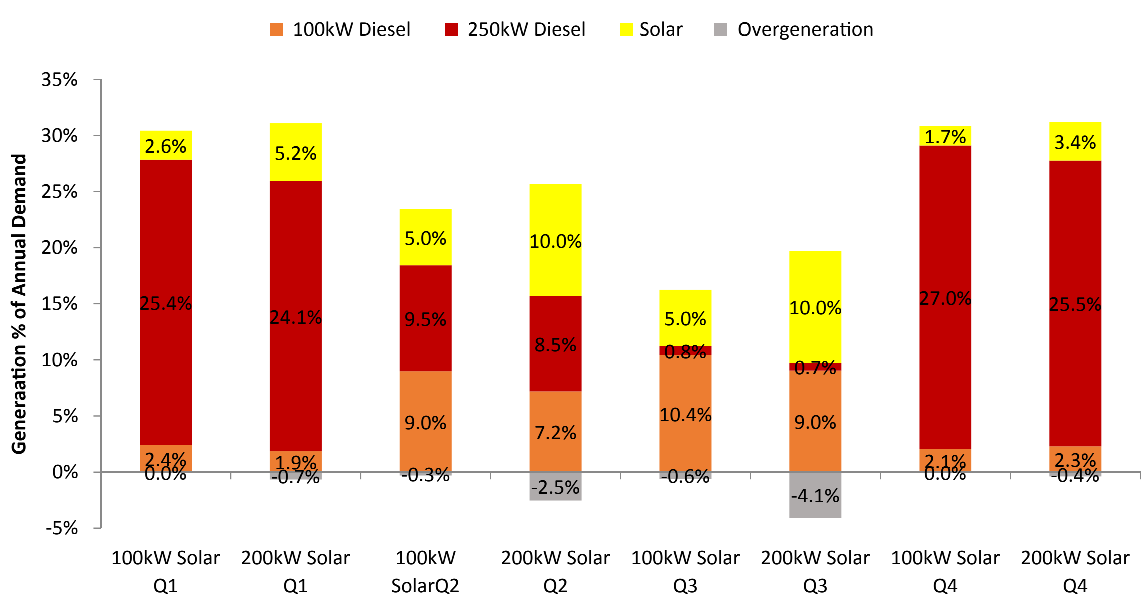

Fig. 15. Solar-diesel system generation.

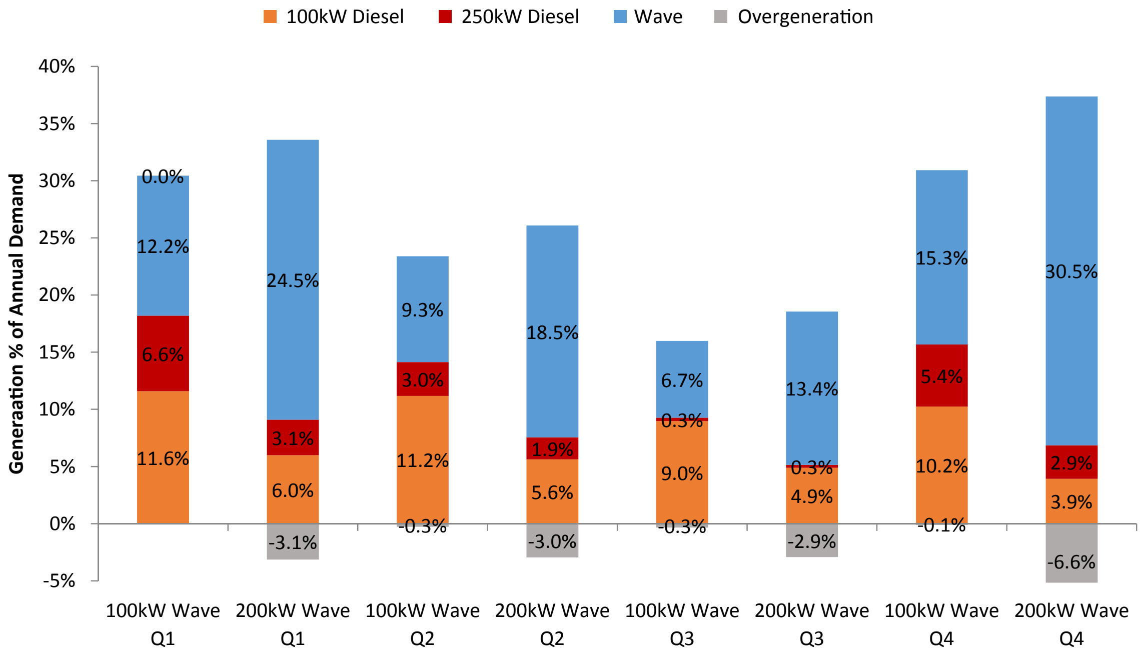

Fig. 16. Wave-diesel system generation.

are 246 and 467 tonnes/yr. respectively.

If these emissions were subject to carbon prices at $30, $50 or $100/tonne, these emissions would increase the LCOE by $0.08/kWh, $0.13/kWh & $0.25/kWh for the 200 kW WEC. These carbon price impacts would increase the allowable-cost LCOE and price per kilowatt to $0.52/$0.54/$0.57 and $20,529/$21,034/$22,294 respectively.

5.5. Wave-hydro-diesel system

Our case study location, Hot Springs Cove is moving forward with the 225 kW hydroelectric facility, so it is important to understand how a wave project will impact the performance of a hydro-diesel system. This activity is in line with the fact that hydroelectric systems dominate non-fossil fuel remote community electricity systems. Given this, and the temporality complementarity between wave energy and community demand, a 100 kW WEC and a 200 kW WEC scenario was investigated.

Fig. 17 shows the generation mix for each quarter. Overall, zero-carbon generation (e.g. 225 kW hydro + 200 kW wave) would account for 89% of total generation; a significant penetration. For the 100 kW and the 200 kW systems, wave energy accounts of 44% and 87% of renewable generation, vs. 37% and 16% respectively for hydro. This is partially driven by the merit order of the supply stack and wave being assigned zero costs for operation or maintenance. It is also evident that the larger 200 kW WEC system creates significant over generation (~16%) with the majority of this occurring during the fall months; a period of high rainfall and wave. This over generation is expected given that the system includes zero-carbon generation capacity that is ~218% higher than peak demand.

The 200 kW scenario results in $5.1 M in fuel savings, while the 100 kW system account for $4.5 M in savings. However, primarily due to the $7.73 M capital cost for the hydroelectric facility, the 200 kW system has a total cost of ~$14.4 M and the 100 kW system a total cost

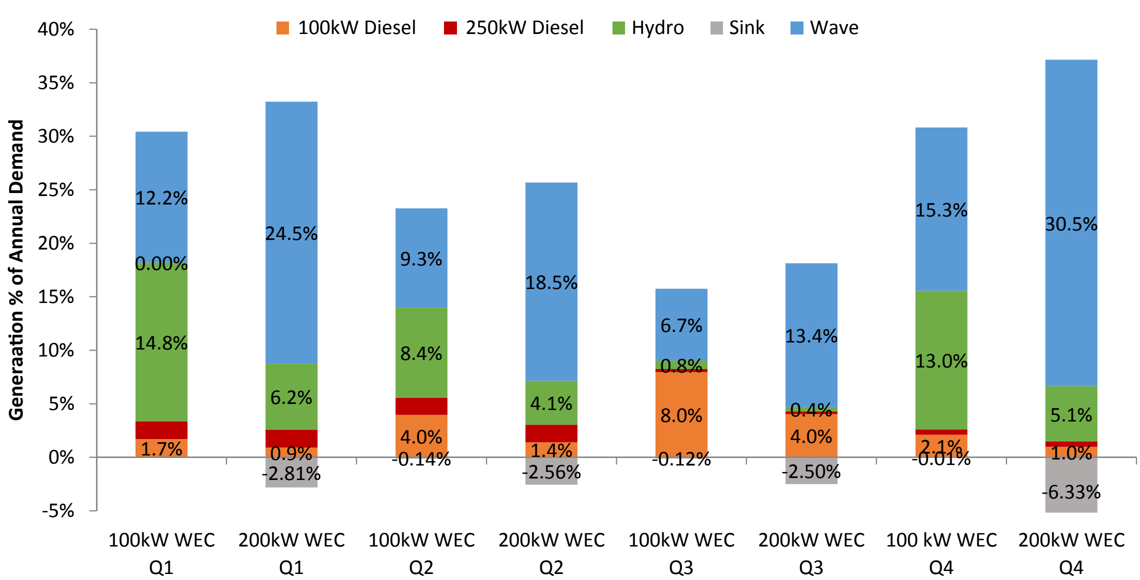

Fig. 17. Wave-hydro-diesel system generation.

Table 7
Diesel generation capacity factors.

DIESEL CF	200KW WEC	100KW WEC
250 kW *Diesel*	1%	8%
100 kW *Diesel*	3%	13%

of $13.2 M; significant numbers when compared against the $6.4 M cost to continue to operate the existing diesel system.

If the system emissions were subject to carbon prices at $30, $50 or $100/tonne, these emissions would increase the LCOE by $0.03/kWh, $0.05/kWh & $0.10/kWh for the 200 kW WEC and 225 kW hydro system. These carbon price impacts would increase the allowable-cost LCOE and price per kilowatt to $0.53/$0.55/$0.59 and $15,612/ $15,916/$16,676 respectively.

Interestingly, both systems still require the 250 kW and 100 kW diesel systems to ensure 100% reliability. The diesel generator CF's are shown in Table 7. Finally, total emissions are significantly reduced in these systems; varying between 78% and 88% reduction.

5.5.1. Impact of low/high water year

As with all renewable generators, the natural variability in resource availability (on a variety of temporal scales) drives the value proposition associated with integrating it into an electricity system. The previous sections quantified the impact of intra-annual variability, this section will utilize a scenario approach to quantify plausible best and worst cases for resource availability for hydro and wave energy systems (see Fig. 18).

Utilizing a 100 kW WEC, a 225 kW hydroelectric system and the existing diesel generation, annual water flow variability has significant impact on the performance of the system; in terms of penetration, cost and emissions.

Relative to MAD = 0.39 m^3/s average, a low flow of 0.20 m^3/s (experienced in 1985) would impact the system in a variety of interesting ways: (1) overall renewable penetration would increase slightly, (2) over-generation would increase, (3) cost would increase by ~ $0.16 M, and (4) emissions would increase by 50 tonnes/yr. At first glance, these results are counter intuitive and contradictory, yet this behavior is indicative of the complicated temporal aspects of realistic real-time supply-demand dynamics.

An increasing flow regime (MAD = 0.55 m^3/s), would impact the system by: (1) significantly increasing the renewable penetration (80% to 92%), (2) saving ~$0.74 M, and (3) decreasing emissions by 205 tonnes/yr. The results for high flow conditions follow expectation for increasing availability for hydro generation.

5.5.2. Impact of low/high wave energy year

Utilizing the same energy generation system as the high/low water flow years analyses, the impact of high/low wave energy years are now compared. 2013 represented a low wave year and features approximately half (50%) less available wave energy transport than the high wave energy case (2015). As shown in Fig. 19, the reduction of wave energy impacts the system in the following ways: (1) total renewable penetration drop by 6%, (2) overall system costs increase by $0.40 M, and (3) overall emissions increase by 115 tonnes/yr. The significant reduction in gross wave energy is buffered by the flexibility of the hydroelectric facilities.

A full overview of all scenarios and a breakdown of performance against the key metrics is shown in the Appendix A in Table 10.

6. Discussion

The presented results provide a host of interesting quantified implications for the integration of renewable energy resources into remote, diesel reliant energy systems; both for current systems and the next generation of systems. Table 10 in Appendix A provides a full overview of all scenarios and associated performance metrics.

Firstly, it should be noted that the existing diesel energy system at Hot Springs Cove supplies the community with reliable electricity. In none of the scenario's presented, despite increasing renewable energy penetrations to 218% of peak demand and 100% diesel generator ramping capabilities, does the need for diesel generation disappear. However, the associated costs, emissions, noise impacts, and dependence on marine transported diesel fuel are significant risks and limit the community's ability for economic development. Renewables reduce this diesel dependency and associated diesel consumption reduction is significant and immediately evident. Annually, the community burns 293,000 L of fuel, emits 780 tonnes of CO_2 and requires 6 deliveries of fuel. The resulting LCOE is $0.75/kWh (with a $1.6/L fuel cost), with fuel costs accounting for ~80% of this. It is important to note that these LCOE values do not account for capital previously invested to purchase and install the diesel generation systems.

On the hydroelectricity front, the development of a 225 kW 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

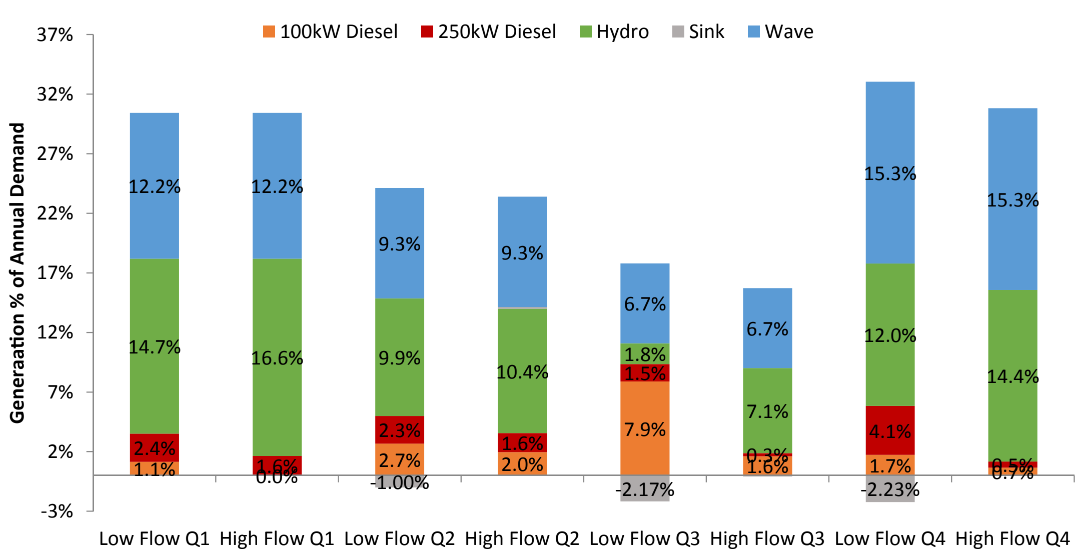

Fig. 18. Wave-hydro-diesel system generation – low and high flow scenarios.

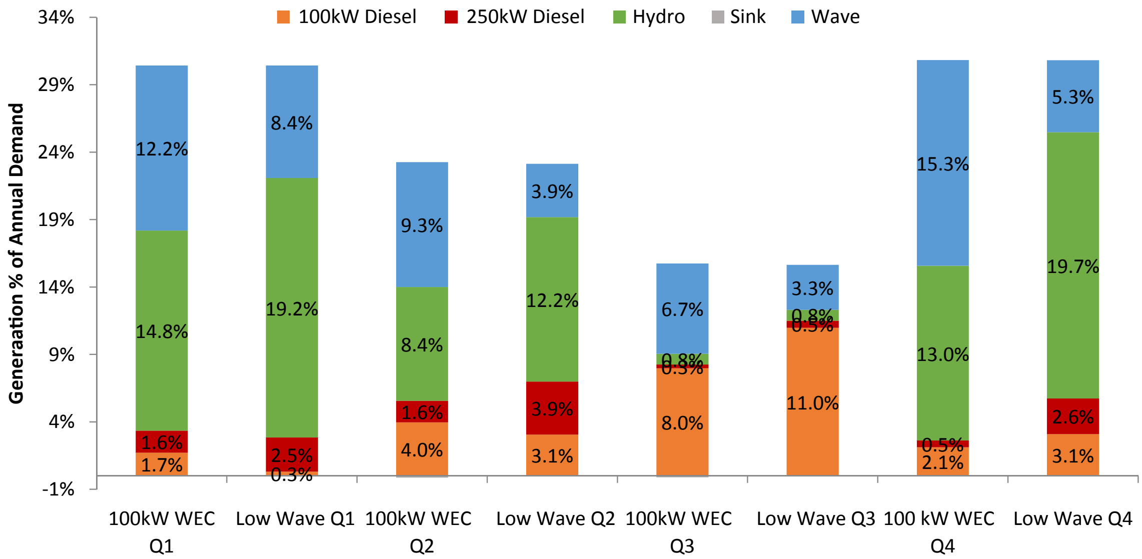

Fig. 19. Wave-hydro-diesel system generation – low and high wave scenarios.

construct the hydroelectric scheme are significant ($7.73 M). While the hydroelectric system is able to save $5.23 M over the next 30 years, the development of the hydro-diesel energy system actually increases the LCOE by 80%; to $1.36/kWh. It is important to note that, despite these known cost increases, small scale hydroelectric plants are the second most common generation resource for remote high-latitude communities (after diesel) and continue to be developed. In the Canadian and Hot Springs Cove context, the construction of energy systems in these remote communities has often been heavily subsidized through federal government funding and, as such, inclusion of capital costs in the economic analysis is valid but maybe not representative of project success.

For the 200 kW solar PV scenario, summer time renewable penetrations are high (20% of total), yet this useful energy is also curtailed due to over-generation (~7%). In the winter, very limited generation results from the solar PV (< 3%). Battery storage would undoubtedly provide significant assistance in reducing the former issue (summer over-generation) but would have little benefit in winter due to the natural seasonal variability of solar. The allowable-cost LCOE's for the 100 kW and 200 kW solar systems are shown to be $0.53/kWh and $0.44/kWh respectively.

Integrating the same capacity (200 kW) of wave generation increases total renewable penetration by 35% (up to 71% total) and reduces diesel demand by twice the amount as solar. For the 100 kW and 200 kW WEC systems, the allowable-cost analyses show higher values for wave energy ($0.59/kWh and $0.51/kWh respectively). Fig. 20 shows a comparison between the generation output from wave and solar. Cleary observable is the lack of generation from solar for 50% of the year (night) and a mean generation of less than 50 kW (25% of installed capacity) for 75% of the year.

Coupling wave and hydro allows the system to utilize the small storage reservoir to concurrently increase renewable penetration (up to 87%) while reducing over-generation compared to the wave-only scenario.

This research clearly quantifies the additional value of adding seasonally-compatible (in this case, wave) generation resources to the energy mix. Regardless of technology, the availability of the natural resource is a major driver in optimizing a HRES. As shown in Table 8, the annual solar energy profile exhibits negative correlation with the community energy demand while wave has a correlation co-efficient of +0.44 (Shown in Table 8).

Building on the presented results, there are a host of additional sensitivity factors will influence both the physical and economic metrics

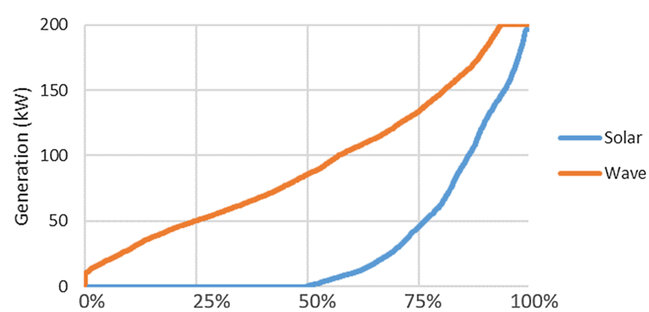

Fig. 20. Solar and wave sorted by generation output.

used to quantify system performance. Natural renewable resource variability, emissions pricing and fuel costs are detailed below.

Natural variability in renewable water and wave resource flows. Low-water years (1985) and high-flow years (1997) has expected results on systems with hydro generation – more water increases renewable penetrations and lowers LCOE, while less water reduces penetration and increases LCOE. However, it is interesting to note that the low-flow year actually has greater amounts of over-generation than the high flow year (5% vs. 1%). The temporal nature of energy systems is such that generation must occur to meet demand and any imbalance becomes excess. Low wave energy resource years increases the dependence on diesel and hydro, indicating the need to investigate a wide variety of historical, and plausible future, wave energy resource years when sizing the capacity of remote community systems.

Emissions pricing. In many jurisdictions, a monetary value is being placed on emissions from energy services. As presented, the impacts of $30/tonne, $50/tonne and $100/tonne emissions price on the LCOE and installed system costs are significant. As shown in the overview Table 9, the increased costs of burning fossil fuels increase the value proposition for each renewable system. However, even at $100/tonne, the associated increase in allowable-cost LCOE is below $0.06 (13%) for the 200 kW solar system. The impact is greater on systems including hydro. For the hydro-diesel system, the allowable LCOE increase is $0.28 (21%) and return per kilowatt increases by $7,816/kW (88%) for the wave-hydro-diesel system. In order to benefit from emissions pricing, the renewable energy system needs to have significant penetrations over the year – something solar is unable to do during winter months. Given that emissions pricing is on the rise globally, these costs should be accounted for when planning future energy systems.

Table 8
Correlation between demand and renewable resources.

Correlation Analyses	
Demand – Solar:	−0.13
Demand – Wave:	0.44
Demand – Hydro:	0.35
Solar – Wave:	−0.11
Wave – Hydro:	0.24
Solar – Hydro:	−0.11

Fuel pricing. Fuel prices can change dramatically due to a wide variety of global socio-economic and technical reasons. For this community, the fuel price was varied by +/− 25% to determine the associated impact on the costs of the current diesel system. The fuel cost increases have an almost linear response on increasing or decreasing the true system LCOE by 20%. Fuel cost impacts will be lower in the hybrid renewable energy systems and increase/decrease in tandem with the total amount of fuel brunt.

The are a number of important caveats that need to be notes as they provide important contextual information when assessing this research. This include temporal coherence, global applicability, and energy storage.

Temporal coherence and perfect foresight. In the baseline scenarios, the MAD data for Ahtaapq Creek is from 2006, the community demand from 2015 and the wave data from 2015. 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 result in increased electrical heating demand, but will also reduce stream flow (due to freezing) and reduced wave heights. During these times, the reliability of the energy system will rely on the diesel systems exclusively. These impacts are somewhat illustrated through the high/low water/wave scenarios, but a thorough examination is warranted for final system design. Additionally, it should be noted that the RCOM model has perfect foresight and can optimize the generator dispatch with perfect knowledge of future loads. This is not the case in reality and, as such, these results should be viewed as an impossible ‘perfect’ scenario.

Location and technology specific. Whilst this research does provide important results for integrating variable renewable resources into remote community electrical grids, they are not universally applicable. The quantified results are locational, technology and assumption specific (e.g. ability for diesel generators to ramp to 100% generation within an hour). The impacts could be significantly better, or worse, in differing communities, with differing renewable and demand profiles.

Energy Storage. As noted, energy storage was explicitly 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 allowable-cost analysis, then the avoided costs identified would have to be split between the WEC and the battery storage; this is not a simple task and make the beneficial defragmentation identification of comparative resources would be less clear. Finally, it should be noted that power quality impacts of HRES integration was beyond the study scope, yet is an ancillary service where battery storage provides significant system value.

7. Conclusion

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 community’s ability to provide reliable services and to seize on economic

Table 9
Impact of emissions pricing on system economics. The grey shaded LCOE values for the diesel and hydro-diesel systems are true LCOE values, not allowable-cost. Solar and wave technologies have 200 kW capacity.

Emissions Price ($/ton)	Diesel			Hydro-Diesel			Solar-Diesel			Wave-Diesel			Wave-Hydro-Diesel		
	30	50	100	30	50	100	30	50	100	30	50	100	30	50	100
Additional LCOE ($)	0.242858	0.404763	0.809526	0.083026	0.138376	0.276752	0.194348	0.323914	0.647828	0.076496	0.127493	0.254985	0.029852	0.049753	0.099506
Allowable Cost LCOE ($)	0.994337	1.156242	1.561005	1.444843	1.500193	1.638569	0.459305	0.470756	0.499382	0.524767	0.537659	0.569888	0.530189	0.546695	0.587961
$/kW Installed ($)							5898.917	6045.977	6413.626	20529.25	21033.59	22294.44	15611.97	15915.85	16675.55

development opportunities. As such, they are often cited as potential 'break-in' markets for wave energy projects or other nascent renewable energy technologies.

This study utilizes the Remote Community Optimization Model (RCOM) to study the full system dynamics for hydroelectricity, solar PV and wave energy for Hot Springs Cove; a remote community on the West Coast of Canada, and quantifies the 'allowable-cost' LCOE. This new metric indicates the maximum allowable system costs in order for energy new energy system to provide economic benefit to the community. The energy system fuels savings, 'allowable-cost' LCOE, emissions reduction are quantified. In addition, sensitivities to fuel cost fluctuations, emissions pricing and natural resource availability are investigated through scenario-based sensitivities studies.

The RCOM models quantified the total system costs of business-as-usual diesel-based generation at $0.76/kWh with 780 tonnes/yr. of emissions. Fuel price fluctuations of 25% result in almost linear 20% increases/decreases in the system LCOE. The development of a small scale 225 kW hydro-electricity system reduces the communities fuel costs by ~$5.2 M over the 30-yr. project lifetime. However, these savings are less than the associated capital required to build the hydro-system ($7.73 M), and the associated LCOE is increased to $1.36/kWh. However, the hydroelectric system reduces emissions by 1079 tonnes.

Based on a 'allowable-cost' LCOE analysis, and a 100 kW example system, wave energy and solar PV is cost optimal if it can be installed for $0.59/kWh and $0.53/kWh respectively. Wave energy conversion is additionally attractive when looking at the financial return per kilowatt installed; where wave would account for $23,206/kW while solar is just $6844/kW. Finally, wave energy integration would have a significantly higher impact on reducing annual emissions; 313 and 97 tonnes for wave and solar respectively. In jurisdictions with emissions pricing, the system-wide allowable LCOE increases and enhances the economic viability of integrating renewables.

The RCOM model and developed 'allowable-cost analysis, applied at the Hot Springs Cove community, have clearly identifies the diesel displacement, allowable-cost Levelized cost of energy (LCOE), and broader energy system savings accrued by integrating marine energy. While wave energy technology designs are still pre-commercial, this research clearly identifies the competitive advantages and economic opportunities needed to help the sector advance.

CRediT authorship contribution statement

Bryson Robertson: Writing, Conceptualization, Resources, Investigation, Funding acquisition. **Jessica Bekker:** Methodology, Software, Data curation, Investigation. **Bradley Buckham:** Conceptualization, Investigation, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Results overview

See Table 10.

Table 10
RCOM scenario results. The grey shaded grey with dashed borders indicates variations in calculation methodologies. For the hydro-diesel system, the known capital costs are included so 1.36 $/kWh is a <u>true</u> LCOE value. In the latter scenario's, the 'allowable-cost' values include multiple renewable resources so identification of specific resource impact cannot be isolated.

System: Scenario	Rated Capacity (kW)			Total Diesel Savings	Fuel Reduction	Capacity Factor					Renewable Generation	Emissions (tonnes)	'Allowable Cost' LCOE	$/kW Installed
	Hydro	Solar	WEC			100 kW Diesel	250 kW Diesel	**Hydro**	**Solar**	**WEC**				
Diesel						25.3%	31.4%					780		
Hydro-Diesel	225			$3.82 M	65.8%			30.1%			65.2%	293	1.36 (LCOE)	$11,103
Solar-Diesel		100		$0.68 M	12.4%	24.8%	26.1%		13.9%		13.4%	683	0.53	$6,844
Solar-Diesel		200		$1.14 M	19.9%	21.2%	24.4%		10.8%		20.9%	625	0.44	$5,678
WEC-Diesel			100	$2.32 M	40.2%	43.6%	6.4%			44.4%	42.7%	467	0.59	$23,206
WEC-Diesel			200	$3.95 M	68.4%	21.2%	3.4%			37.0%	71.3%	246	0.51	$19,773
Solar-WEC-Diesel		100	100	$2.93 M	50.5%	35.7%	5.1%		14.9%	45.1%	53.3%	386	0.56	$14,631
Solar-WEC-Diesel		100	200	$4.30 M	74.6%	16.4%	3.0%		14.9%	45.1%	76.9%	199	0.47	$14,333
Solar-WEC-Diesel		200	200	$4.42 M	76.7%	14.7%	2.9%		14.8%	45.1%	78.7%	182	0.43	$11,054
Solar-WEC-Diesel		200	100	$3.15 M	54.5%	32.2%	5.0%		14.8%	45.1%	56.9%	355	0.49	$10,512
WEC-Hydro-Diesel: High Wave	225		100	$4.58 M	79.3%	16.4%	1.7%	17.1%		44.9%	80.2%	162	0.45	$10,033
WEC-Hydro-Diesel: High Wave	225		200	$5.08 M	87.7%	7.6%	1.7%	7.3%		22.4%	88.6%	96	0.41	$8,860
WEC-Hydro-Diesel: Low Wave	225		100	$4.19 M	72.2%	18.1%	4.0%	24.0%		21.8%	72.9%	217	0.44	$8,819
WEC-Hydro-Diesel: Low Flow	225		100	$4.42 M	76.2%	14.0%	4.3%	17.7%		39.5%	76.3%	186	0.42	$9,535
WEC-Hydro-Diesel: High Flow	225		100	$5.32 M	91.8%	4.4%	1.7%	22.4%		44.9%	91.8%	64	0.48	$12,297

References

[1] Kempener R, d'Ortigue OL, Saygin D, Skeer J, Vinci S, Gielen D. Off-grid renewable energy systems: Status and methodological issues. Abu Dhabi; 2015.
[2] Kuang Y, Zhang Y, Zhou B, Li C, Cao Y, Li L, et al. A review of renewable energy utilization in islands. Renew Sustain Energy Rev 2016;59:504–13.
[3] Previsic M, Bedard R, Yakutat. Conceptual design, performance, cost and economic, wave power feasibility study. Electr Power Res Inst 2009;43:43.
[4] Walker B. Administrative order No. 289: Establishing Alaska Climate Change Strategy; 2017.
[5] International Renewable Energy Agency. Renewable capacity statistics 2018; 2018.
[6] UN. Sustainable Development Goals n.d. https://sustainabledevelopment.un.org/?menu=1300 [accessed September 30, 2019].
[7] IRENA. Wave energy technology brief. IRENA Ocean Energy Technol Br 2014; 4:28.
[8] Pinson P, Reikard G, Bidlot JR. Probabilistic forecasting of the wave energy flux. Appl Energy 2012;93:364–70. https://doi.org/10.1016/j.apenergy.2011.12.040.
[9] Veigas M, López M, Iglesias G. Assessing the optimal location for a shoreline wave energy converter. Appl Energy 2014;132:404–11. https://doi.org/10.1016/j.apenergy.2014.07.067.
[10] Cornett AM. A global wave energy resource assessment. In: Proc. 18th Int. offshore polar eng. conf., Vancouver, Canada; 2008.
[11] Robertson B, Bailey H, Clancy D, Ortiz J, Buckham B. Influence of wave resource assessment methodology on wave energy production estimates. Renew Energy 2016;86. https://doi.org/10.1016/j.renene.2015.09.020.
[12] Xu X. Identifying British Columbia's strategically important wave energy sites. University of Victoria; 2018. doi:10.22201/fq.18708404e.2004.3.66178.
[13] Soares CG, Rute Bento A, Gonçalves M, Silva D, Martinho P. Numerical evaluation of the wave energy resource along the Atlantic European Coast. Comput Geosci n.d. doi: 10.1016/j.cageo.2014.03.008.
[14] Ahn S, Haas KA, Neary VS. Wave energy resource classification system for US coastal waters. Renew Sustain Energy Rev 2019;104:54–68. https://doi.org/10.1016/j.rser.2019.01.017.
[15] Gunn K, Stock-williams C. Quantifying the global wave power resource. Renew Energy 2012;44:296–304. https://doi.org/10.1016/j.renene.2012.01.101.
[16] Dasari HP, Knio O, Hoteit I, Langodan S, Viswanadhapalli Y. A high-resolution assessment of wind and wave energy potentials in the Red Sea. Appl Energy 2016;181:244–55. https://doi.org/10.1016/j.apenergy.2016.08.076.
[17] Babarit A, Hals J, Muliawan MJ, Kurniawan A, Moan T, Krokstad J. Numerical benchmarking study of a selection of wave energy converters. Renew Energy 2012;41:44–63.
[18] Jenne DS, Yu Y-H, Neary V. Levelized cost of energy analysis of marine and hydrokinetic reference models. In: 3rd Mar energy technol symp; 2015.
[19] Bailey H, Robertson BRD, Buckham BJ. Wave-to-wire simulation of a floating oscillating water column wave energy converter. Ocean Eng 2016;125. https://doi.org/10.1016/j.oceaneng.2016.08.017.
[20] Hals J, Falnes J, Moan T. A comparison of selected strategies for adaptive control of wave energy converters. J Offshore Mech Arct Eng 2011;133.
[21] Bacelli G, Coe RG. Comments on control of wave energy converters n.d.; XX:1–4.
[22] Moazzen I, Robertson B, Wild P, Rowe A, Buckham B. Impacts of large-scale wave integration into a transmission-constrained grid. Renew Energy 2016;88. https://doi.org/10.1016/j.renene.2015.11.049.
[23] Parkinson S, Dragoon K, Reikard G, Garcia-Medina G, Ozkan-Haller T. Integration ocean wave energy at large-scales: a study of the US Pacific Northwest. Renew Energy 2015;76:551–9.
[24] Reikard G, Robertson B, Bidlot J-R. Combining wave energy with wind and solar: short-term forecasting. Renew Energy 2015;81:442–56. https://doi.org/10.1016/j.renene.2015.03.032.
[25] Fairley I, Smith HCM, Robertson B, Abusara M, Masters I. Spatio-temporal variation in wave power and implications for electricity supply. Renew Energy 2017;114. https://doi.org/10.1016/j.renene.2017.03.075.
[26] Kim C-K, Toft JE, Papenfus M, Verutes G, Guerry AD, Ruckelshaus MH, et al. Catching the right wave: evaluating wave energy resources and potential compatibility with existing marine and coastal uses. PLoS ONE 2012;7:e47598.
[27] Castro-Santos L, Garcia GP, Estanqueiro A, Justino PAPS. The Levelized Cost of Energy (LCOE) of wave energy using GIS based analysis: the case study of Portugal. Int J Electr Power Energy Syst 2015;65:21–5. https://doi.org/10.1016/j.ijepes.2014.09.022.
[28] Teillant B, Costello R, Weber J, Ringwood J. Productivity and economic assessment of wave energy projects through operational simulations. Renew Energy 2012;48:220–30. https://doi.org/10.1016/j.renene.2012.05.001.
[29] Segurado R, Krajačić G, Duić N, Alves L. Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde. Appl Energy 2011;88:466–72. https://doi.org/10.1016/j.apenergy.2010.07.005.
[30] Li Y, Willman L. Feasibility analysis of offshore renewables penetrating local energy systems in remote oceanic areas – a case study of emissions from an electricity system with tidal power in Southern Alaska. Appl Energy 2014;117:42–53. https://doi.org/10.1016/j.apenergy.2013.09.032.
[31] Esteban M, Leary D. Current developments and future prospects of offshore wind and ocean energy. Appl Energy 2012;90:128–36. https://doi.org/10.1016/j.apenergy.2011.06.011.
[32] Böhringer C. The synthesis of bottom-up and top-down in energy policy modeling. Energy Econ 1998;20:233–48. https://doi.org/10.1016/S0140-9883(97)00015-7.
[33] Díaz P, Arias CA, Peña R, Sandoval D. FAR from the grid: a rural electrification field study. Renew Energy 2010;35:2829–34. https://doi.org/10.1016/j.renene.2010.05.005.
[34] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 2014;32:192–205. https://doi.org/10.1016/j.rser.2014.01.035.
[35] Kannan R. The development and application of a temporal MARKAL energy system model using flexible time slicing. Appl Energy 2011;88:2261–72. https://doi.org/10.1016/j.apenergy.2010.12.066.
[36] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.
[37] Ringkjøb HK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev 2018;96:440–59. https://doi.org/10.1016/j.rser.2018.08.002.
[38] Jebaraj S, Iniyan S. A review of energy models. Renew Sustain Energy Rev 2006;10:281–311. https://doi.org/10.1016/j.rser.2004.09.004.
[39] Tezer T, Yaman R, Yaman G. Evaluation of approaches used for optimization of stand-alone hybrid renewable energy systems. Renew Sustain Energy Rev 2017;73:840–53. https://doi.org/10.1016/j.rser.2017.01.118.
[40] Mendes G, Ioakimidis C, Ferrão P. On the planning and analysis of Integrated Community Energy Systems: a review and survey of available tools. Renew Sustain Energy Rev 2011;15:4836–54. https://doi.org/10.1016/j.rser.2011.07.067.
[41] Corporation GD. General Algebraic Modeling System (GAMS), rel. 24.2. 1; 2013.
[42] Cook D, Candidate MA, Fitzgerald E, Candidate MA, Sayers J. First nations and renewable energy development in British Columbia; 2017.
[43] Natural Resources Canada. Remote Communities Energy Database n.d. https://atlas.gc.ca/rced-bdece/en/index.html [accessed September 30, 2019].
[44] GAMS. General Algebraic Modelling System. Model Solve; 2019. https://www.gams.com/latest/docs/UG_ModelSolve.html#UG_ModelSolve_ModelClassificationOfModels_MIP [accessed December 12, 2019].
[45] Government of Canada. Engineering Climate Datasets - Climate - Environment and Climate Change Canada n.d. https://climate.weather.gc.ca/prods_servs/engineering_e.html [accessed October 15, 2019].
[46] Group BP. Hot springs cover solar PV potential: pre-feasibility study; 2002:1–20.
[47] Robertson B, Hiles C, Buckham B. Characterizing the near shore wave energy resource on the west coast of Vancouver Island, Canada. Renew Energy 2014;71:665–78. https://doi.org/10.1016/j.renene.2014.06.006.
[48] Reikard G, Robertson B, Buckham B, Bidlot J-R, Hiles C. Simulating and forecasting ocean wave energy in western Canada. Ocean Eng 2015;103:223–36. https://doi.org/10.1016/j.oceaneng.2015.04.081.
[49] Moazzen I, Robertson B, Wild P, Rowe A, Buckham B. Impacts of large-scale wave integration into a transmission-constrained grid. Renew Energy 2016;88:408–17.
[50] Robertson B, Hiles C, Luczko E, Buckham B. Quantifying wave power and wave energy converter array production potential. Int J Mar Energy 2016;14. https://doi.org/10.1016/j.ijome.2015.10.001.
[51] International Energy Agency IEA. International levelised cost of energy for ocean energy technologies; 2015.
[52] StatsCan. Canadian consumer price index 2019. https://www150.statcan.gc.ca/n1/daily-quotidien/180126/cg-b001-eng.htm [accessed January 13, 2020].
[53] StatsCan. Monthly average retail prices for diesel 2019. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1810000101 [accessed January 3, 2020].
[54] Volvo Penta. Industrial power generation engines | Volvo Penta n.d. https://www.volvopenta.com/industrialpowergeneration/en-en/home.html [accessed August 15, 2019].
[55] Okada Y. Wuikinuxv nation: preliminary levelized cost of energy analysis report; 2016.
[56] BC Ministry of Environment. 2016 B.C. Best practices methodology for quantifying greenhouse gas emissions; 2016.
[57] Hatfield T, Lewis A, Ohlson D, Fisheries MB, Vancouver C. Instream Flow Guidelines for BC - Phase II; 2003.
[58] Van Dijk G, Crompton J. Community Electricity Plan for Refuge Cove; 2013.
[59] OES. International levelised cost of energy for ocean energy technologies; 2015:1–48.
[60] Drew B, Plummer AR, Sahinkaya MN. A review of wave energy converter technology. Proc Inst Mech Eng Part A J Power Energy 2009;223:887–902.
[61] Falcão AO. Wave energy utilization: a review of the technologies. Renew Sustain Energy Rev 2010;14:899–918.
[62] Bailey H, Ortiz J, Robertson B, Buckham B, Nicoll R. A methodology for wave-to-wire WEC simulations. Mar Renew Energy Technol Symp 2014:1–15.
[63] Bailey H, Robertson B, Buckham B. Variability and stochastic simulation of power from wave energy converter arrays. Renew Energy 2018;115. https://doi.org/10.1016/j.renene.2017.08.052.