At the End of the Line: Approaches for Adding Sustainable Energy to Rural Maritime Communities

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Abstract

Rural maritime communities are often located at the end of the line; adjacent to abundant marine resources but unable to transmit power due to ageing electrical infrastructure designed to transmit power from large thermal power plants. This paper draws experience from communities located adjacent to Grand Passage and Petit Passage, Nova Scotia and could be applied to similar maritime communities such as the Isle of Islay in Scotland.

The role of energy developers in these communities extends beyond the direct challenges of harnessing marine energy to supporting local economies and developing energy extraction that is sustainable.

This paper presents a model for the electric power supply required from the grid to meet the demand for fossil fuel replacement, with application to a case study of hybrid marine propulsion for passenger ferries that cross Grand Passage and Petit Passage. Fuel conversion from diesel combustion to power supply by an electric or ammonia hybrid ferry is shown to have a significant effect on available distribution capacity compared to the existing cap of estimated annual minimum load. An initial economic analysis suggests that electric hybrid ferries may be commercially viable at current residential power and diesel cost rates.

Keywords: Energy Storage, Hybrid Marine Propulsion, Marine Community, Tidal Energy

1. Introduction

With the decline of the ground fish industry on the east coast of Canada many rural maritime communities have dwindled, leaving behind ageing populations with vacant homes and minimal energy requirements. These communities are often located at the end of the line; adjacent to abundant marine resources but unable to transmit power due to ageing electrical infrastructure designed to transmit power from large thermal power plants.

Distribution connected projects in Nova Scotia, including those approved under the Community Feed-In Tariff (COMFIT) program [1] are limited such that the maximum system capacity cannot exceed the minimum annual load on the substation [2-3].

For the case of tidal energy developments in Grand Passage and Petit Passage, the annual minimum load of 0.9 MW is estimated by the Nova Scotia Power Inc. (NSPI) system operator to be approximately 25-30% of the annual peak load of 3.4 MW on the supply sub-substation and distribution feeder [4]. Estimates of maximum extractable power by an array of tidal turbines installed in these passages are 16 MW and 33 MW, respectively [5]. Karsten (2012) expects that extraction of 5.4 MW and 12 MW from Grand and Petit passages will result in only a 5% reduction in flow velocity.

Based on a comparison of available tidal energy to distribution capacity, if even a small fraction of the available energy is developed it will require heavy investment in transmission connection upgrades. Alternatively, the option of distributed power generation and community development could be a more economical route, with the additional benefit of establishing energy security. For the latter, we must evaluate and implement innovative approaches that involve energy storage and/or increased electrical load. Of course, fossil fuels are stored energy, thus for many scenarios distributed energy storage and increased electrical load are overlapping concepts.

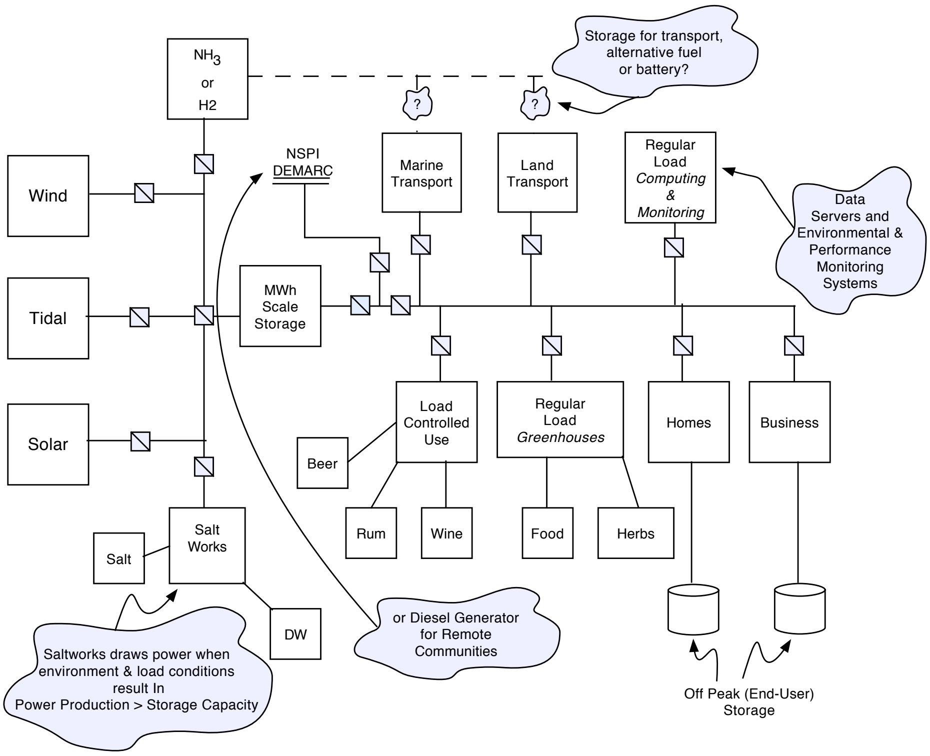

Fig. 1: Demand side power model

Potential approaches for adding sustainable energy to the distribution grid in rural marine communities include:

1) Increased minimum load through distributed energy storage, which includes replacing direct fossil fuel use with electric (or alternative fuel) options and creating off-peak energy storage (load shaping) [6]. Examples are:
   - Hybrid marine propulsion (ferries, fishing fleet, and other marine vessels);
   - Electric vehicles (buses, cars, trucks, and small vehicles such as ATVs for island transport);
   - Moving from oil based heating to electric for space and domestic hot water; and
   - Distributed (end-user) off-peak energy storage for home and business use.
2) Centralized MWh scale energy storage systems, such as batteries, compressed air, kinetic, pumped fluid, hydrogen and/or ammonia generation;
3) The addition of sustainable 'community-minded' built load, i.e., predictable and load-controlled energy use [6-7], such as:
   - Production of drinking water and salt for fisheries use through desalination (saltworks);
   - Greenhouses;
   - Brewery and/or distillery; and
   - Computing and monitoring systems.

As shown in Fig. 1, the overall solution will likely involve a combination of the above listed and additional options. The focus of this paper is on evaluating replacement to fossil fuel combustion systems, and includes a case study of hybrid marine propulsion for passenger ferries that cross Grand Passage and Petit Passage. The authors of this paper intend to address additional approaches in future works.

2. Power Requirement Modelling

A model describing the electric power supply from the grid required to meet the demand for fossil fuel replacement was developed. The model is assumed to be accurate to a second-order approximation. The model is extended to predict the installed capacity of a tidal turbine array that would meet this electrical demand. This model is general and can be used to predict the electrical requirement for replacing the use of fossil fuels for heat (space and hot water), marine and terrestrial transportation, and additional uses.

To calculate the electrical energy required to replace a volume (or flow rate) of fossil fuel, the amount of work (W_f) that is produced from the combustion of that fossil fuel must be considered. The efficiency (η_f) at which energy stored in the fossil fuel (E_f) is converted to useful mechanical work is defined as,

$$\eta_f = \frac{W_f}{E_f} \tag{1}$$

Knowing the amount of energy stored in the fuel, from Eq. (2):

$$E_f = \varepsilon_f V_f \quad (2)$$

where ε_f and V_f are the fossil fuel energy density (MJ/L) and volume (L), respectively. Both equations can be combined to determine the useful mechanical work resulting from fossil fuel combustion:

$$W_f = \eta_f \varepsilon_f V_f \quad (3)$$

where W_f is in this case given in MJ. Similarly, the average power produced by combustion is:

$$P_f = \eta_f \varepsilon_f \overline{Q_f} \quad (4)$$

where $\overline{Q_f}$ is the average fuel combustion rate (L/s) with P_f measured in MW.

In order to solve for various fossil fuel replacement scenarios, it is useful to define ratios: F_e as the fraction of fuel conversion, i.e., fraction of the work (or power) generated from alternative energy; F_f as the fraction of the work (or power) still generated from fossil fuel. Note that $F_e + F_f = 1$. Solving for the power required (P_e) to replace a fraction of the power coming from fossil fuel combustion, the assessment is bound to an existing system running entirely on fossil fuel through the following:

$$P_f = P_e + (1 - F_e)P_f \quad (5)$$

which rearranges to:

$$P_e = F_e P_f \quad (6)$$

Combining Equations (4) and (6), the average electrical power required ($\overline{P_e}$) for a fraction of fuel conversion (F_e) is:

$$\overline{P_e} = F_e \eta_f \varepsilon_f \overline{Q_f} \quad (7)$$

Defining $\overline{P_g}$ as the average electrical power drawn from the grid, the average electrical power transferred to work by a hybrid system would then be:

$$\overline{P_e} = \zeta_s \eta_s \overline{P_g} \quad (8)$$

where ζ_s and η_s are the efficiencies at which the grid power is stored and utilized for work by the hybrid system respectively.

The average grid power requirement $\overline{P_g}$ for the alternative fuel component of the hybrid system can then be met by:

$$\overline{P_g} = \frac{F_e \eta_f \varepsilon_f \overline{Q_f}}{\zeta_s \eta_s} \quad (9)$$

Tidal Power Requirement

The power produced by a tidal turbine (or an array of turbines), P_t, is calculated as follows [8]:

$$P_t = \frac{1}{2}\rho A \eta_t U^3 \quad (10)$$

where ρ is the density of water (kg/m^3), A is the capture area (m^2), η_t is the kinetic to electrical (water-to-wire) efficiency, and U is the effective flow speed (accounting for passive or active yaw) averaged over the capture area (m/s). Tidal turbine efficiency is a function of cut-in and cut-out speeds, power regulation, and any efficiency variation associated with rotor rotational velocity. Accounting for efficiency as a function of velocity, machine power curves are produced using Eq. (10).

To extend Eq. (10) from power production to total amount of energy produced over a period of time (t), Eq. (11) is used:

$$E_t = \sum_{n=1}^{t} \frac{1}{2}\rho A \eta_t U_n^3 \Delta t \quad (11)$$

where U_n is the average effective flow speed over the n^{th} time interval Δt.

In absence of accurate flow measurements and machine characteristics, the average power produced by a tidal turbine array is often predicted as follows:

$$\overline{P_t} = R C_p \quad (12)$$

where $\overline{P_t}$ is average power output (W), R is the turbine rated capacity (W), and C_p is the dimensionless turbine capacity factor. The capacity factor must be representative of the turbine rated velocity with respect to its maximum power output, any power regulation, and the flow speed distribution at the site. Equation (12) is extended to the total amount of energy produced (E_t), in J or Wh, over a period of time t, expressed in seconds or hours, as follows:

$$E_t = R C_p t \quad (13)$$

The rated capacity of a tidal power installation is related to the average grid power requirement to satisfy a fraction of fuel conversion (F_e) by the fact that the average power produced by the installation must equal the average grid power requirement ($\overline{P_t} = \overline{P_g}$), which using Eq. (12) for this initial assessment leads to:

$$R = \frac{F_e \eta_f \varepsilon_f \overline{Q_f}}{\zeta_s \eta_s C_p} \quad (14)$$

Note that site-specific assessment using Equations (10) and (11) is recommended following collection of flow data and validation of numerical models of fluid flow.

3. Case Study – Grand Passage and Petit Passage Passenger Ferries

The Grand Passage and Petit Passage ferries (Fig. 2) use approximately 6,000 L and 9,000 L of diesel fuel per week [9]. This extends to approximately 313,000 and 469,000 L/yr, which combines to 782,000 L/yr. This corresponds to flow rates ($\overline{Q_{f,d}}$) of approximately 0.010, 0.015, and 0.025 L/s, respectively.

Fig. 2: Passenger ferry crossing Petit Passage

Diesel fuel has an energy density of $\varepsilon_{f,d}$ = 38.5 MJ/L. Using this value, the energy requirement for the Grand Passage ferry is $E_{f,GP}$ = 12 × 10^6 MJ/yr (3,400 MWh/yr) and for the Petit Passage ferry, $E_{f,PP}$ = 18 × 10^6 MJ/yr (5,000 MWh/yr), for a total energy requirement of $E_{f,tot}$=30 × 10^6 MJ/y (8,400 MWh/yr). An additional useful metric for characterizing the energy use of the ferries is their average power use, which is 0.38 MW and 0.57 MW for the Grand Passage and Petit Passage ferries respectively.

Combustion efficiency is somewhat variable with respect to engine load. However, for the purpose of this initial assessment, efficiency is assumed to be constant. A typical gasoline internal combustion engine has an efficiency of approximately $\eta_{f,gas}$ = 0.25. Diesel engines have the highest thermal efficiency of any regular combustion engine due to a high compression ratio. For large medium speed diesel engines typically used for marine propulsion (where the acceptable range for weight can be large) efficiency is in the range of $0.4 < \eta_{f,d} < 0.5$. For this assessment, a middle value of $\eta_{f,d}$ = 0.45 is used.

For the alternative fuel component of the hybrid system, two alternatives are assessed: 1) battery storage for propulsion by an electric engine, and 2) ammonia (NH_3) storage for propulsion by combustion in a modified diesel engine.

Battery storage must consider the efficiency at which energy is transferred to the battery during charging and the efficiency at which the battery holds and discharges the energy. For this assessment, a combined (round-trip) battery storage efficiency of $\zeta_{s,b}$ = 0.75 is used. Electrical engines are more efficient than combustion engines in converting stored energy into useful mechanical drive [10]. Additionally, in the context of marine propulsion, electrical energy is not consumed when the vehicle is at rest or idling [11]. An estimate of diesel fuel used while the ferry is parked has not been factored into this initial assessment. Electrical engines are subject to a trade off between torque and efficiency, such that high torque produces high acceleration and reduces efficiency due to heat loss. The efficiency of a typical electric vehicle is approximately $\eta_{s,elec}$ = 0.80.

Ammonia (NH_3) can be generated from tidal energy, stored, and then used as a combustion fuel in a modified diesel engine [12]. Information from a Canadian supplier of ammonia storage systems suggests a renewable energy generator rated at 500 kW will produce 500 L of ammonia per day [13]. The energy density of NH_3 is approximately $\varepsilon_{s,NH3}$ = 11.2 MJ/L, thus from this generator, 5,600 MJ/day or 1.55 MWh/day of electricity is converted to NH_3. Using a capacity factor C_p of 0.33 for the renewable energy generator, 3.96 MWh/day of electricity would initially have been produced by this generator. This indicates an energy storage efficiency of approximately $\zeta_{s,NH3}$ = 0.39. With respect to combustion, for this assessment, it will be assumed that $\eta_{s,NH3} = \eta_{f,d}$ in the modified diesel engine.

The electrical requirements for replacement of diesel combustion in the Grand Passage and Petit Passage passenger ferries using battery storage converted to work by an electric engine (electric hybrid ferry) and using ammonia storage converted to work by mixed combustion in a modified diesel engine (ammonia hybrid ferry) are shown in Fig. 3.

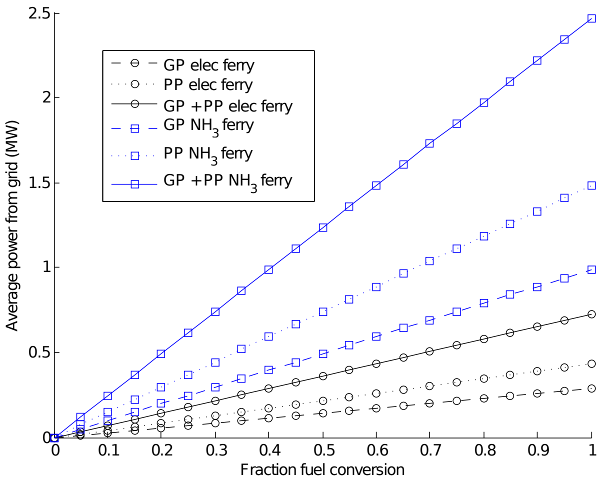

Fig. 3: Average power drawn from grid by electric and ammonia (NH_3) hybrid ferries (MW)

As shown in Fig. 3, fuel conversion from diesel combustion to power supply by an electric or ammonia hybrid ferry would have a significant effect on available distribution capacity compared to the existing cap of estimated annual minimum load (0.9 MW).

For the Grand Passage and Petit Passage ferries combined, an increase in the average power drawn from the grid equal to ¼ of the estimated annual minimum load (900 kW /4 = 225 kW) is reached at approximately 32% fuel conversion for use by an electric hybrid ferry. For an ammonia hybrid ferry this benchmark is reached at approximately 10% fuel conversion, and ¼ of the existing peak load of 3.4 MW (850 kW) is reached at approximately 35% fuel conversion.

Considering the size of tidal turbine installation required to meet this demand, it is important to note that maximum energy production from a tidal turbine occurs during large spring tides. Thus, under the existing limitation of maximum capacity for distribution connected generators not to exceed annual minimum load, a tidal array would meet the hybrid ferry energy requirement roughly every 14 days depending on the tidal turbine rated velocity and how much long-term tidal variation is considered.

The rated capacities of tidal turbine installations that would meet the average power requirements associated with replacement of diesel combustion for use in electric and ammonia hybrid ferries are shown in Fig. 4, using C_p = 0.33. This C_p value was used in the recent COMFIT calculations by Fundy Tidal Inc. and aligns well with the work of Bahaja et *al.* (2007) [14].

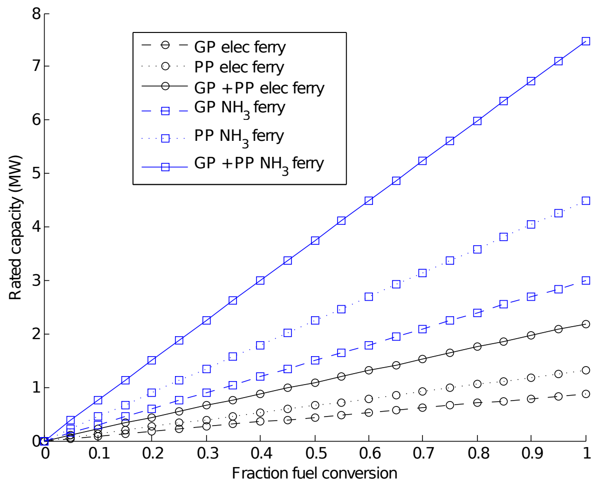

Fig. 4: Tidal energy rated capacity to supply power to electric and ammonia (NH_3) hybrid ferries (MW)

As shown in Fig. 4, the rated capacities of tidal turbine installations required to supply power for 32% and 10% fuel conversion in electric and ammonia hybrid ferries (¼ estimated annual minimum load benchmark above) and 35% fuel conversion in an ammonia hybrid ferry (¼ existing peak load benchmark above) are approximately 675 kW and 2.55 MW, respectively.

Economic Analysis

The volume of diesel fuel conserved by the hybrid ferry over a period of time *t* is:

$$V_{f,d} = F_e \overline{Q_{f,d}} t \tag{15}$$

The annual diesel fuel conserved is shown in Fig. 5.

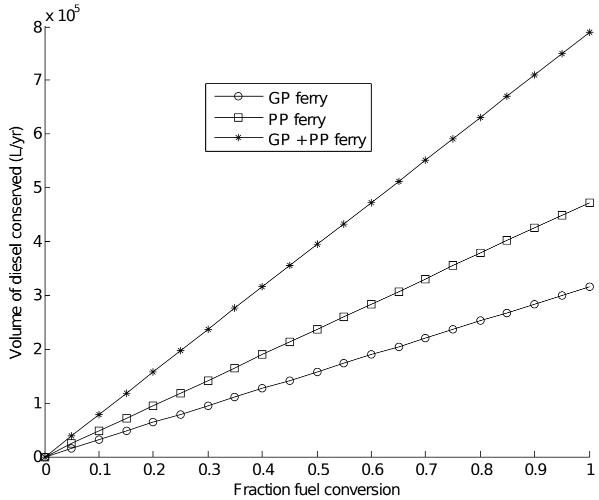

Fig. 5: Volume of diesel conserved over a one-year duration (L/yr)

Estimates of the associated reductions in carbon dioxide (CO_2) emissions using an emission factor for diesel combustion of 2.663 kg CO_2 / L [15] are shown in Fig 6.

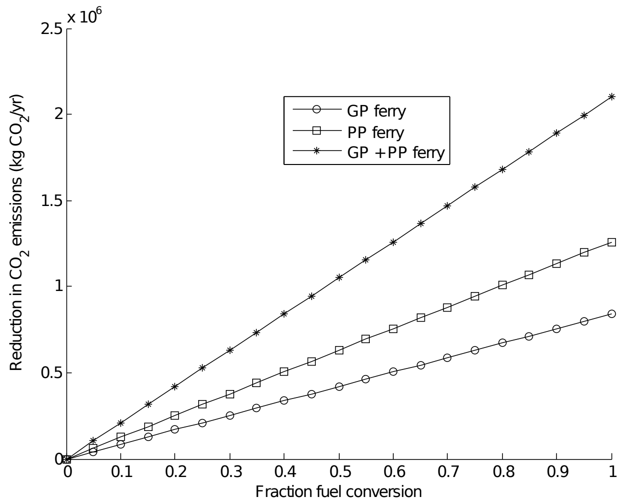

Fig. 6: Reduction in carbon dioxide emissions over a one-year duration (kg CO_2/yr)

The annual diesel fuel cost savings based on a market price of $1.30/L is shown in comparison to the cost of power drawn from the grid to supply electric and ammonia hybrid ferries at the residential and Small-Scale Tidal COMFIT power rates in Figs. 7 and 8, respectively.

As shown in Fig. 7, running an electric hybrid ferry with energy purchased at the residential rate may be an economically viable alternative based on the assumptions used for battery storage and electrical machine efficiencies in this assessment. This finding is in line with a general assessment for electric hybrid harbor tugs by B. Perry et *al.* (2010).

All other scenarios result in increased cost compared to diesel fuel purchased at $1.30/L. A useful metric is conversion of diesel cost to $0.0338/MJ or $121.6/MWh using an energy density of $\varepsilon_{f,d}$ = 38.5 MJ/L.

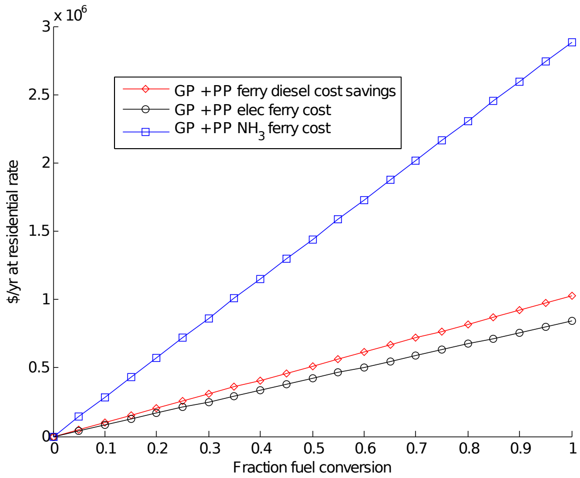

Fig. 7: Comparison of diesel fuel cost savings to cost of power to supply electric and ammonia hybrid ferries at the residential rate of $133.36/MWh

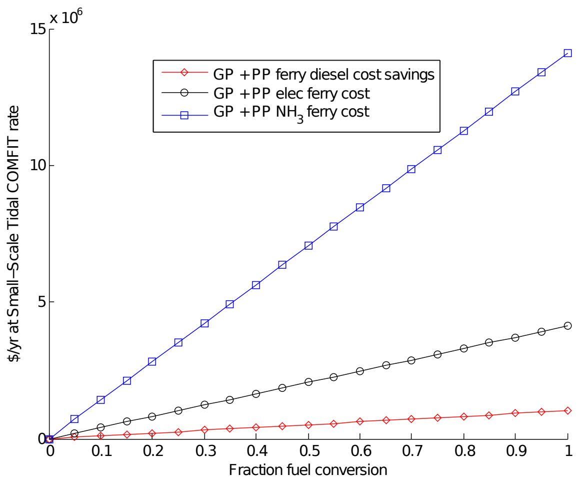

Fig. 8: Comparison of diesel fuel cost savings to cost of power to supply electric and ammonia hybrid ferries at the Small-Scale Tidal COMFIT rate of $652/MWh

Breakeven points for the cost of diesel and cost of power to equate the diesel fuel cost savings to the cost of power drawn from the grid to supply electric and ammonia hybrid ferries are shown in Fig. 9. The diesel cost intersection points with the residential and Small-Scale Tidal COMFIT power rates are shown in Table 1.

The region below the line plotted in Fig. 9 for each hybrid ferry system is representative of power and diesel cost scenarios where it is economically viable to run the hybrid system (i.e. diesel cost savings are greater than the cost of power from grid). As such, a significant reduction in the cost of alternative energy or increase in the cost of diesel is required for the ammonia hybrid system to become economically viable based on this initial assessment. However, while the ammonia system is more expensive on a cost of fuel basis, combustion occurs in a modified diesel engine and capital costs associated with replacement of the existing ferries may not be required.

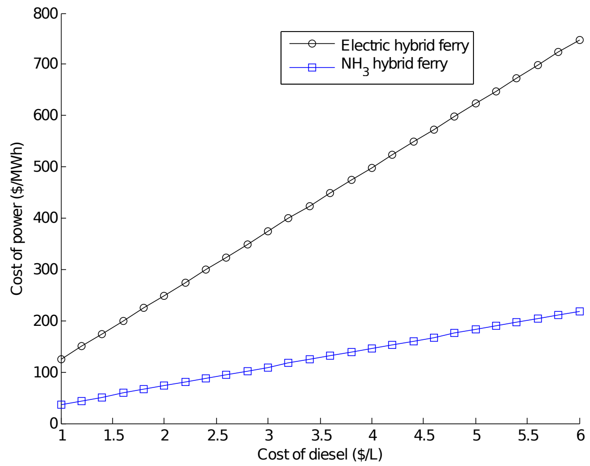

Fig. 9: Breakeven points for cost of diesel and cost of power supply to electric and ammonia hybrid ferries

Energy rate	Residential $133.36/MWh	COMFIT $652/MWh
Battery storage	$1.1/L	$5.2/L
Ammonia storage	$3.6/L	$17.9/L

Table 1: Break even cost of diesel fuel ($/L)

4. Conclusion and Recommendations

The role of energy developers extends well beyond the direct challenges of harnessing marine energy to supporting local economies, balancing regrowth and energy extraction for a sustainable future. The focus must be on innovative solutions that reduce reliance on imported energy, while reshaping community load and establishing energy security.

This paper presents a numerical model that can be used to predict the electrical power supply required to meet demand arising from reducing existing fossil fuel combustion. The model was applied to a case study of passenger ferries that cross Grand Passage and Petit Passage.

The case study shows that the average power drawn from the grid would increase by ¼ of the existing estimated annual minimum load (900 kW /4 = 225 kW) by converting approximately 32% or 10% diesel combustion to power supplied by electric or ammonia hybrid ferries, respectively. Using C_p = 0.33, the associated rated capacity of a tidal turbine installation required to supply the power to battery or ammonia storage is approximately 675 kW. The additional capacity could be made available to future distribution connected community energy projects.

An initial economic analysis suggests that electric hybrid ferries may be commercially viable at current residential power and diesel cost rates. However capital and operation costs have not been included in this initial assessment. Additionally, reduction in energy requirement due to conservation from the lack of idling with an electric motor has not been included, which will further decrease the annual cost of electrical energy.

A detailed analysis of commercially available hybrid ferry systems should be conducted including refinement of the energy transfer, storage, and machine efficiencies and forecasting future diesel and electrical costs. Reductions in emissions should be considered, as well as a power systems analysis regarding the ability of different hybrid systems to charge and deliver the variable power required by the ferries. Additionally, a site-specific analysis should be conducted using a tidal turbine power curve and time-series of flow velocities to accurately predict annual tidal energy production using Eqs. (10) and (11).

Consideration should also be given to further development of hybrid ferries using emerging energy storage technologies and extending this initial assessment to evaluate the feasibility of hybrid marine propulsion and additional efficiency improvements for fishing and other marine vessels.

Studies are also recommended to expand upon this work, evaluating the feasibility of additional approaches for adding sustainable energy to the grid in rural maritime communities, including those listed in the introduction of this paper, some of which the authors of this paper intend to address in future works.

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