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Energy storage requirements for in-stream tidal generation on a limited capacity electricity grid

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ABSTRACT

This study presents the modeling and analysis of an ESS (energy storage system) for a TEC (tidal energy converter) to be installed in the Bay of Fundy, Canada. The electricity distribution grid that services the region has a minimum annual electricity demand of 0.9 MW. Policy limits the installation of renewable electricity generators to 0.9 MW at this site. An existing 0.9 MW WEC (wind energy converter) occupies this capacity, inhibiting further installations. The use of an ESS enables the installation of a 0.5 MW TEC by ensuring the combined electricity output from WEC and TEC does not exceed 0.9 MW. The objective of this study is to model the system and determine the characteristics of the ESS capacity, power, and cyclic nature.

The WEC and TEC are modeled based on measured and simulated wind and tidal speed data respectively. An ESS is modeled to de-couple the TEC output from the grid demand. A curtailment analysis is conducted for various ESS capacity and power sizes to determine the economic benefit. Avoidance of all curtailment requires nearly 7 MWh of storage. Significant economic benefit may be found by reducing the ESS to less than 3 MWh, resulting in minor curtailment.

1. Introduction

In-stream TEC (tidal energy converter) systems have undergone significant development in the last decade with emphasis placed on converter technologies [1], resource assessment [2,3], and installation/interconnection [4]. The vast tidal resources found throughout the world present an opportunity to offset fossil-fuel consumption and reduce greenhouse gas emissions. The well-understood gravitational interactions between the earth, moon, and sun that cause tides, make it a predictable and reliable renewable energy resource. The unique ability to forecast tidal power production allows electricity system managers to prepare for this non-dispatchable electricity. However, many promising tidal resources are located in rural areas that are interconnected with the electricity grid through weak and aging distribution circuits that have limited capacity.

The Bay of Fundy located in NS (Nova Scotia), Canada has one of the best tidal energy resources worldwide [5]. In NS, small-scale (up to 0.5 MW) medium-voltage TEC distribution-interconnected sites are accessible through the COMFIT (Community Feed-in Tariff) program [6]. These small projects may be implemented throughout NS but are limited by program policy such that the combined renewable energy generator capacity (MW) on a distribution circuit is not larger than the minimum annual demand (MW) at the supplying substation. This study focuses on a proposed TEC development project on the Digby Neck which separates the St. Mary's Bay from the outer Bay of Fundy. The minimum annual demand of the distribution circuit is estimated to be 0.9 MW [7]. There exists a 0.9 MW WEC (wind energy converter) located on the circuit, effectively rendering this circuit unavailable for further renewable energy project development. However, an allowance has been given by policy makers to accommodate a 0.5 MW TEC, contingent upon inclusion of an ESS (energy storage system).

The ESS should have sufficient capacity and power to ensure that the combined WEC and TEC output (1.4 MW total capacity) does not exceed 0.9 MW as seen by the distribution circuit. It accomplishes this by charging when the combined output of the WEC and TEC is greater than 0.9 MW. When the combined output of the WEC and TEC falls below 0.9 MW, the ESS will discharge in preparation for future charging, while continuing to respect the 0.9 MW distribution circuit limit.

The objective of this study is to define suitable ESS requirements of capacity, power, and cyclic nature in order for the TEC project to proceed. This article presents in the following sections: Section (2) a brief ESS literature review for TEC systems, Section (3) a summary

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List of nomenclature and symbols

Acronyms

COMFIT	Community Feed-in Tariff
ESS	energy storage system
NS	Nova Scotia
REG	renewable energy generation
TEC	tidal energy converter
WEC	wind energy converter

Symbols

A	swept rotor area (m^2)
C	power coefficient (−)
E	energy (MWh)
P	power (electrical) (MW)
U	fluid flow speed (m/s)
ρ	fluid density (kg/m^3)
η	efficiency (−)

of the renewable resources, Section (4) the new modeling method, and Section (5) the results of simulation of the tidal and wind energy resources, their respective converter systems, and the ESS operation.

2. Review of energy storage for tidal generating systems

Energy storage is a research topic garnering significant interest because the penetration rate of non-dispatchable renewable electricity converters has become, or is poised to become, significant in many jurisdictions (i.e. greater than 30% by capacity) [8]. Recent reviews of storage discuss the several technologies and compare their characteristics. These include: pumped hydro, CAES (compressed air), batteries, flywheels, hydrogen, and capacitors [9,10]. A comprehensive comparison of storage technology characteristics includes values of: energy capacity; peak and average power; cycle efficiency and self-discharge; cycle and calendar life; capital and operating costs; technological maturity and availability of supply; as well as direct and life cycle environmental impact assessment [11]. In addition, the performance of a storage technology to suit a specific project is based upon the effectiveness of the services it provides, and the effect it has on the project from a technical, economic, and/or greenhouse gas emissions perspective [12], as well as local community perspectives [13]. At present, the majority of research effort is focused on storage for WEC because this technology is experiencing unprecedented growth rates and has the greatest installed generating capacity amongst non-dispatchable renewable energy converters worldwide [14,15].

Because of the immaturity of tidal electricity generation, minimal investigation of storage systems has been completed. In fact, less than a dozen research articles have been published since year 2000, and prior to that only a half-dozen articles were published in the late 1970's and early 1980's. These older articles all focused on the use of pumped hydro storage methods for the UK. Following is a review of recent literature.

Bryden and Macfarlane conducted a numerical investigation of the use of flywheel and battery ESS with TEC [16]. A simple mathematical model was used to simulate the tidal generated electricity based on the cyclical and elliptical nature of the tides. By comparing the generated power (700 kW maximum) to the electricity demand of consumers (average 100 kW), a storage capacity of 500 kWh of storage is required. 3D surface plots are used to compare average power, storage time, and storage capacity, the latter ranging up to 6 MWh.

Clarke et al. examined the fluctuations in tidal generation in an attempt to provide firm electricity [17]. They combined the power output of three separate tidal streams and applied selective curtailment, which smoothed certain peaks and valleys in power, but could not entirely filter out the twice-daily cycle. They suggest the use of pumped hydro ESS for the twice-daily tidal cycle, but consider the lunar cycle fluctuations "intractable".

Testa et al. simulated the impact of using a vanadium redox flow battery with a prototype standalone tidal turbine [18]. The 18 kW TEC that supplied three residences was evaluated on a basis of *loss of power supply probability*. They selected an ESS rated 10 kW and 75 kWh that operates over 60% of the capacity range and achieves 12 h autonomy.

Barbour and Bryden conducted a study of ESS efficiency required to produce firm or load following output during a one month period [19]. They modeled a 1.2 MW turbine with a grid export limitation of 0.5 MW. They found that only during neap tide would the turbine remain within the grid limit. By applying a 1 MWh and 0.7 MW ESS the turbine was no longer curtailed. 3D surface plots comparing the ESS capacity as a function of round trip efficiency indicate a 15% gain in energy production using 1 MWh storage, but diminishing returns beyond that point.

Recently, researchers have examined combinations of off-shore WEC and TEC fields. Wang et al. examined a flywheel ESS applied to an 80 MW offshore WEC and 40 MW TEC field [20,21]. They found a 30 MW flywheel suppressed voltage and speed variations of the TEC. Mousavi examined the performance of 1.4 MWh battery ESS integrated with a 315 kW offshore WEC, 175 kW TEC, and 290 kW gas turbine [22]. They limited the battery power to ±100 kW, which indicates that it only acted as a minor power quality participant.

Zhou et al. investigated a 24 h ESS for a 500 kW TEC in France [23]. They conclude that energy shifting requires an 800 kWh and 500 kW ESS to be suitable for 3–6 h operation, whereas ESS for power quality purposes requires only 2 kWh but 700 kW for 5–20 s of operation.

The novelty of this research lies in the model, which describes a unique renewable energy integration issue. The capacity of a distribution circuit is extended by using an ESS to de-couple the power output of a TEC from the grid. The unique control strategy of the ESS (which seeks to discharge as quickly as possible) requires communication with the WEC located on the same distribution circuit. An energy curtailment analysis is used to perform an economic analysis used to optimize the power and energy capacity of the ESS.

3. Renewable energy resource assessment

The renewable energy resources considered for this study are wind and in-stream tidal flow. Fig. 1 shows the general Digby Neck area and Petit Passage, along with sites of interest such as meteorological stations and existing electrical infrastructure. Measured data from the existing WEC and the in-stream tidal location of Petit Passage is desired, but unfortunately, is unavailable. As an alternative, nearby measured values and modeled values were employed.

3.1. Wind resource

Measured wind speed data was acquired from a nearby metrological tower (#2 in Fig. 1) located outside of Digby NS, approximately 30 km northeast of the existing WEC (#3 in Fig. 1). This data was measured at 50 m a.g.l. (above ground level), and is a 10 min timestep data series of wind speed (m/s) that spans from

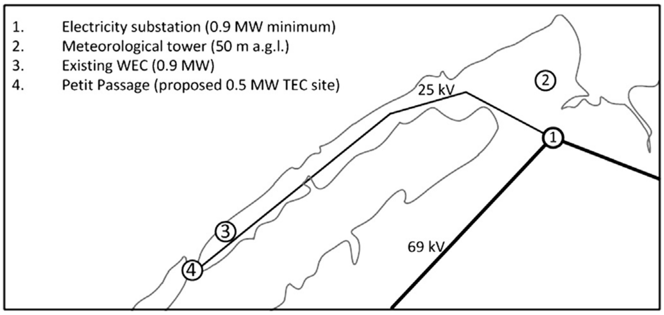

Fig. 1. Digby Neck region sites of interest.

January through December, 2010. Data quality control was performed to remove icing events and ensure a complete annual dataset. The annual average wind speed is 6.67 m/s. Because there is a distance of 30 km between the WEC and meteorological measurement site, a comparative analysis using two additional nearby measured data sets was performed. Data from #2 was trimmed to match the temporal resolution (1 h) and adjusted to match the measurement altitude (10 m a.g.l.) of another meteorological tower at the southern tip of the peninsula on Brier Island. Comparing the two data sets against each other, as shown in Fig. 2, shows consistency in the wind regime across the entire Digby peninsula, passages, and islands, thereby giving confidence in the use of the meteorological data to represent the WEC site.

3.2. Tidal resource

A two dimensional time series data set of in-stream tidal flow velocity for the TEC site of interest in Petit Passage was generated using a finite volume coastal ocean model [24]. The model includes the Bay of Fundy, the Gulf of Maine, and extends out to the continental shelf. It produces one month of high resolution (10 m block) two dimensional velocity data (range 0–7 m/s) that is depth averaged for a specific location. The month of data is extrapolated to a full year using a classical harmonic analysis in which the tides are modeled as the sum of a finite set of sinusoids whose frequencies are based on astronomical parameters [25]. The model predicts that the annual average in-stream tidal flow speed is 2.49 m/s, with a maximum of 6.15 m/s at the Petit Passage site. It exhibits a four-times-lunar-daily speed magnitude cycle (tides are semi-diurnal).

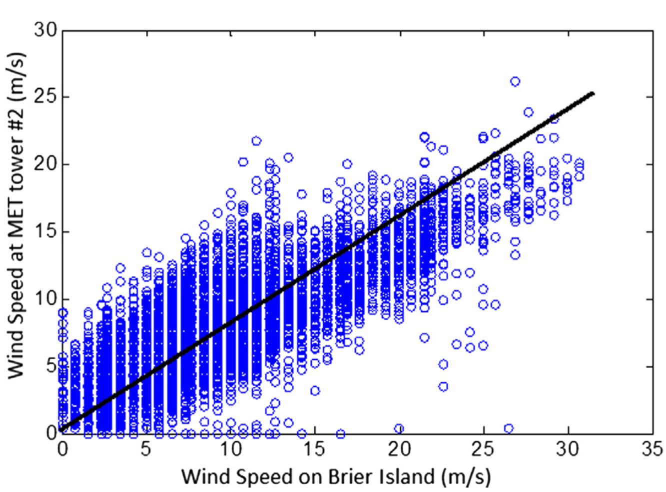

Fig. 2. Relationship of wind speeds across the Digby Neck.

4. Modeling methodology

The WEC and TEC are modeled in MATLAB by applying turbine power coefficient curves to the resource data given in Section (3). The ESS is modeled in MATLAB based on the power outputs of the WEC and TEC and the electrical interconnection limitations. A simplified system one line diagram is shown in Fig. 3, which shows the WEC, TEC, and ESS interconnection to the distribution grid. A unique aspect to this system is the ESS control strategy. The objective is to limit the combined output of the WEC and TEC to 0.9 MW, as seen by the distribution circuit. Thus, the ESS control strategy seeks to discharge all accumulated energy as soon as possible in preparation for the next charge cycle. This differs considerably from control strategies that provide backup power, energy time-shifting, or power ramp-rate compensation. The following subsections describe the modeling methodology for each component in detail. Results and discussion of the model are given in Section 5.

4.1. Wind energy converter

A simulation of the existing WEC is necessary as it has priority access to the distribution circuit. The WEC electrical power output, P, is a function of its power coefficient, C, and swept rotor area A, along with the air density, ρ, and wind speed, U.

$$P_{\mathrm{WEC}} = \frac{1}{2} C_{\mathrm{WEC}} A_{\mathrm{WEC}} \rho_{\mathrm{air}} U_{\mathrm{air}^3} \tag{1}$$

The C_{WEC} is the ratio of P_{WEC} to the flow power available over the swept rotor area. It is strongly related to wind speed and aerodynamic characteristics of the WEC. The existing WEC is an EWT 52-900, rated maximum 0.9 MW, with a rotor diameter of 52 m, rotor swept area of 2123 m^2, and mounted on a tower with a 50 m hub height. It has cut-in and cut-out wind speeds of 3 and 25 m/s, respectively, and P_{WEC} was assumed to be zero outside these limits. The power coefficient curve of the WEC indicates a C_{WEC} ranging up to 0.48 [26]. Because the WEC has pitch control, variations in ρ_{air} (1.225 kg/m^3) due to air temperature has a minimal impact upon P_{WEC} [27] and this effect will be neglected. Throughout the annual simulation, the 10 min average wind speeds are used to calculate P_{WEC}.

4.2. Tidal energy converter

The electrical power produced by a TEC from the in-stream tidal water flow is similar to wind (Eq. (1)) with the exception that there is no cut-out speed. The in-stream tidal flow speed is taken as the magnitude of the velocity vector from the tidal resource model. This implies that the TEC is capable of yawing such that the rotor swept area is always perpendicular to the direction of flow. Examination of the in-stream tidal resource data indicates that ebb and flood flows are nearly 180 ° apart and that there is only minor variation in heading for a particular flow direction.

Several TEC technologies are under consideration for this development, and consequently the TEC power output was modeled using a constant power coefficient and a maximum electrical power capability according to the following equations:

$$\text{If } U_{\mathrm{water}} < U_{\mathrm{TEC,cut-in}} \text{ Then } P_{\mathrm{TEC}} = 0 \tag{2}$$

$$\text{Else } P_{\mathrm{TEC}} = \frac{1}{2} C_{\mathrm{TEC}} A_{\mathrm{TEC}} \rho_{\mathrm{water}} U_{\mathrm{water}^3} \tag{3}$$

$$\text{If } P_{\mathrm{TEC}} > P_{\mathrm{TEC,max}} \text{ Then } P_{\mathrm{TEC}} = P_{\mathrm{TEC,max}} \tag{4}$$

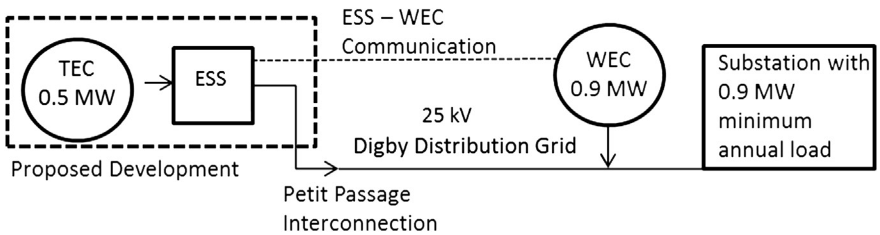

Fig. 3. One line diagram of the electrical infrastructure, WEC, TEC, and ESS.

The TEC was defined to have a $P_{TEC,max}$ of 0.5 MW, rotor diameter of 8 m, and swept rotor area of 50 m^2. The constant C_{TEC} is 0.40 with a cut-in tidal flow speed of 1 m/s. The density of seawater, ρ_{water}, is considered to be constant at 1025 kg/m^3. Throughout the annual simulation, the 10 min average in-stream tidal flow speeds are used to calculate P_{TEC}.

4.3. Energy storage system

The ESS model for this simulation is technology unspecific. Instead, it defines the capacity, power, and cycle life characteristics required of the storage, and these can later be used to assess the appropriateness of a particular storage technology. Initially, the model assumes an infinite energy sink that is able to accommodate all the excess energy generated when the combined WEC and TEC power is beyond the 0.9 MW limit. It should be noted that this requirement necessitates communication between the ESS and the WEC, as shown in Fig. 3. This ESS charge power would reach a maximum of 0.5 MW when the WEC and TEC are both operating at maximum power. The discharging power varies by the available capacity on the distribution circuit, up to a maximum of 0.9 MW. This would occur when both the WEC and TEC power output is zero.

The ESS control strategy seeks to discharge all stored energy as soon as possible by discharging at the fastest rate up to the limitations. This is done to prepare for the next charging period which helps to avoid curtailment. This is substantially different from most storage systems (e.g. wind/diesel, uninterruptable power supply, solar storage) which seek to charge as soon as possible to insure energy is available when needed. By placing priority on discharge the system ensures that there is available storage capacity for upcoming charge requirements, and that the required storage capacity of the system is minimized. It should be noted that this control strategy will result in the ESS primarily being in a discharged state, a condition that is not desirable for certain storage technologies.

4.3.1. Energy storage control strategy definition

The following steps detail the ESS control strategy. For each time step in the simulation, the total electrical power from renewable energy generators, P_{REG}, is the sum of the power from the WEC and TEC.

$$P_{REG} = P_{WEC} + P_{TEC} \tag{5}$$

P_{net} is the difference between P_{REG} and the export limitation of the distribution circuit, $P_{export,\ limit}$, which set by policy to the minimum annual load.

$$P_{net} = P_{REG} - P_{export,\ limit} \tag{6}$$

If P_{net} is greater than zero, then P_{REG} up to the $P_{export,\ limit}$ is fed directly into the distribution circuit, with the balance, P_{net}, being used to charge the ESS from the TEC at a rate of $P_{charge} = P_{net}$. The energy input to the ESS during this charge step is the product of charge rate and the time-step (in this case 1/6 of an hour), $E_{charge} = P_{charge} \times \Delta t$. This is then added to the stored energy in the ESS, E_{ESS}, inclusive of charge efficiency, η_{charge}.

$$E_{ESS,\ i+1} = E_{ESS,\ i} + E_{charge} \times \eta_{charge} \tag{7}$$

If P_{net} is less than or equal to zero, both the WEC and TEC electrical power is fed directly into the distribution circuit, bypassing the ESS. Furthermore, when the ESS contains stored energy and P_{net} is less than zero, the ESS discharges at the highest rate possible without exceeding $P_{export,limit}$, thus, $P_{discharge} = -P_{net}$. The discharge energy is $E_{discharge} = P_{discharge} \times \Delta t$. This is then subtracted from the stored energy in the ESS, inclusive of discharge efficiency, $\eta_{discharge}$.

$$E_{ESS,\ i+1} = E_{ESS,\ i} - \frac{E_{discharge}}{\eta_{discharge}} \tag{8}$$

Discharge terminates when E_{ESS} equals zero. The ESS is then prepared to undergo another charge. For this research the discharge and charge efficiency were assumed to be 80% each, resulting in a conservative 64% round trip efficiency that adequately represents many storage technologies.

As the annual simulation runs, a time series of values is created for each of the above variables, enabling the study of charge and discharge power, and the stored energy profiles of the ESS. The data set is then analyzed by identifying each *energy storage event*. This refers to the period from when E_{ESS} increases from zero and then returns to zero. Within each energy storage event, the duration, maximum energy level, and total stored energy are calculated. These metrics are used to identify the ESS characteristics required for the WEC and TEC to operate within $P_{export,\ limit}$ as seen by the distribution circuit.

4.3.2. Curtailment analysis

The preceding ESS control strategy has no upper limit on stored energy capacity. As such, the storage could accommodate the worst case scenario that occurs when the WEC operates at full power for several days. It is unlikely that such an ESS is economical. A curtailment investigation is conducted to determine the impact of choosing an ESS with limited storage capacity or power. This "undersized" system requires that the TEC be curtailed or have its production diverted to another application (e.g. desalination [28]) during the worst case scenario. The curtailment analysis uses the same control strategy outlined in Eqs. (5)–(8), but imposes maximum values of $E_{ESS,\ max}$, $P_{charge,\ max}$, and $P_{discharge,\ max}$.

Because the P_{REG} has a maximum of 1.4 MW, and $P_{export,\ limit}$ is 0.9 MW, there is no advantage to increasing $P_{charge,\ max}$ beyond 0.5 MW, and this value was used in all cases. The maximum value of $P_{discharge,\ max}$ is 0.9 MW to remain within $P_{export,\ limit}$ while the TEC and WEC are at zero production. It should be noted that $P_{charge,\ max}$ does not necessarily need to equal $P_{discharge,\ max}$, as this may save cost on chargers or inverters. For the curtailment analysis, $P_{discharge,\ max}$ is varied from 0.1 to 0.9 MW by intervals of 0.05 MW to determine its effect on required ESS capacity, as a faster discharge rate is advantageous in preparing for the next charge. Meanwhile,

$E_{ESS,\ max}$ is varied from zero to the maximum stored energy level observed in the initial simulation, in intervals of 0.25 MWh. A matrix is then created to assess the shortfalls of each ESS power and capacity combination.

The energy storage system is analyzed on a *failure to absorb* basis, a condition that occurs if the ESS is fully charged and P_{net} is positive. During simulation, each 10 min time-step would count as one failure. Zero failures means the ESS is able to absorb all excess energy generated from the TEC without having to curtail. Because a TEC without an ESS would be forced to curtail significantly, the amount of energy that is discharged from the ESS to distribution circuit is considered as additional saleable energy. By analyzing the different combinations of ESS power and energy capacities on the basis of enhanced saleable energy, the value proposition of different capacity and power characteristics of the ESS can be quantified in terms of energy and economics.

5. Results and discussion

The simulation results are presented in the following subsections. The results of the WEC and TEC model components are presented first to introduce the generating characteristics. The ESS results are then presented.

5.1. WEC and TEC energy converter results

The monthly aggregate WEC and TEC electricity production is shown in Fig. 4. Annually, the WEC is estimated to produce 2104 MWh and achieves a capacity factor of 27%. The WEC production profile throughout the year is consistent with wind speed patterns found throughout Nova Scotia, with a high production in the fall and winter followed by lower production in the spring and summer. In contrast, the TEC experiences monthly variations representative of the harmonic analysis extrapolation described in Section 3.2. Annually, the TEC is estimated to produce 1345 MWh, achieving a capacity factor of 31%. As an example of the TEC revenue, the annual electricity production at the COMFIT price of \$652/MWh [6] would total \$876,940 per year. Detailed descriptions of the WEC and TEC power output variations as a function of time are given in the next section.

5.2. Energy storage performance results

To demonstrate the ESS control strategy functionality, a series of charts for the same 12 day period (Feb 24 to Mar 06) that requires the highest level of ESS capacity found throughout the year are given in Fig. 5.

Fig. 5(A) shows the WEC, TEC, and combined REG power profile. It is apparent that the WEC goes through sustained periods of high power (0.9 MW) for days at a time. Meanwhile, the TEC reaches maximum power of 0.5 MW during each tidal cycle (four times a day) for nearly a week. The combination of these generator outputs have periods above and below the distribution limit of 0.9 MW, achieving peak values of 1.4 MW and minimum values of less than 0.1 MW.

Fig. 5(B) shows the corresponding charge (positive) and discharge (negative) power profile of the ESS during the same period. The charging power profile tracks P_{REG} whenever it is above the 0.9 MW grid limit given in Fig. 5(A). The ESS is able to take advantage of fluctuations in the WEC power while slack tide occurs by discharging at rates up to −0.8 MW. By discharging as soon as possible and at the largest rate, the required ESS capacity is minimized. When the WEC power output decreases on Feb 26, the ESS discharges most of the stored energy in less than a day, and then remains idle until Feb 28.

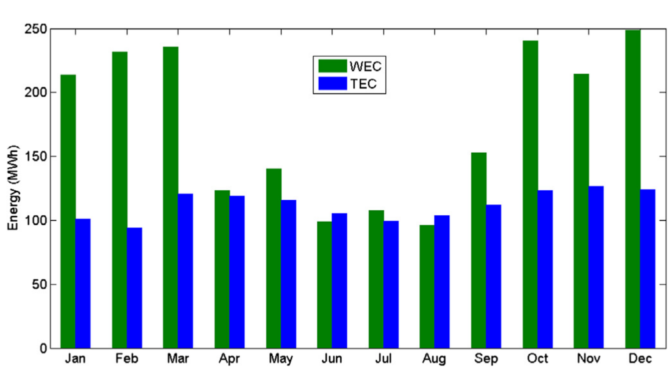

Fig. 4. Monthly electricity production from the WEC and TEC.

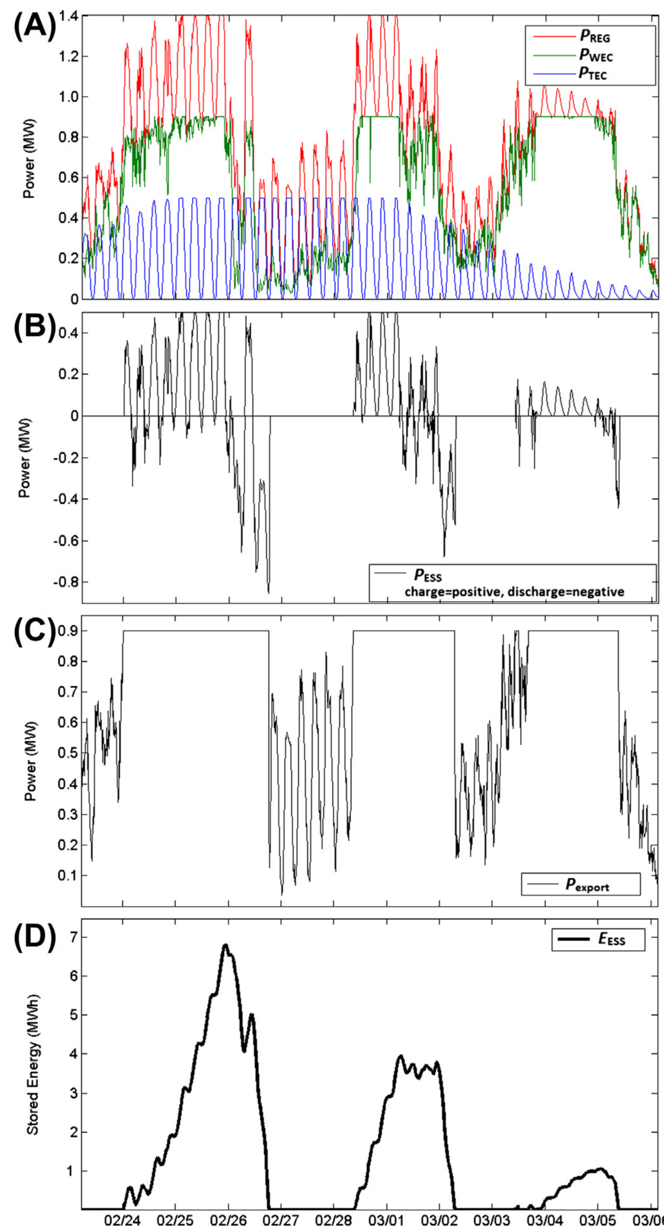

Fig. 5. Example performance period of 10 February days: (A) WEC, TEC, and REG electrical power; (B) ESS charging (positive) and discharging (negative) power; (C) Combined power output to the distribution circuit due to the WEC, TEC, and ESS; (D) Stored energy in the ESS.

Fig. 5(C) shows the combined power exported from WEC, TEC, and ESS, as seen by the distribution circuit. The ESS is successful in limiting the maximum renewable generated electricity exporting to the distribution grid to 0.9 MW. During the periods where this combined power value is exactly 0.9 MW, the ESS is actively participating by charging or discharging. In all other cases where the combined power is less than 0.9 MW the ESS is sitting idle. This may be verified by comparing Fig. 5(C) with Fig. 5(B).

The corresponding profile of stored energy in the ESS, due to the charging and discharging shown in Fig. 5(B), is given in Fig. 5(D). It can be seen that three storage events occur. During the first period of high WEC power, the ESS stored energy rapidly increases corresponding with TEC production, up to a maximum of nearly 7 MWh. Eventually the WEC power reduces and the ESS stored energy decreases as it discharges according to the available power within the 0.9 MW distribution circuit export limit. This process is repeated twice more throughout the 12 day period, although to a lesser stored energy extent. Based on Fig. 5(D) the required ESS capacity is nearly 7 MWh, however, the full storage capacity would only be utilized only once throughout the year. Fig. 5(D) also demonstrates how an ESS of particular size can store more energy than its rating during one storage event, so long as it does not discharge completely. For example, the first storage event of Fig. 5(D) shows a brief discharge on Feb 26, followed by more charging; so an ESS rated 7 MWh is required, but it stores nearly 8 MWh over the entire duration of the storage event.

A summary of the annual simulation results is given in Table 1, where the ESS is characterized by storage capacity and the energy turn-around. The storage capacity (#1) of 6.8 MWh ensures that all electricity generated by the TEC can be sent to the distribution circuit (i.e. no curtailment). This value is representative of a single event during the simulation that requires the most energy to be stored. Row #2 shows that throughout the year, only 74.2 MWh of saleable energy is fed from the ESS into the distribution circuit. The TEC directly sends 1228.6 MWh of electricity to the distribution circuit when storage is not required (#3). However, the TEC generates 1344.6 MWh (#4), which is larger than the sum of #2 and #3 because of losses due to efficiency in the ESS. Subtracting #2 and #3 from #4 equals 41.8 MWh lost. From this it may be determined that the ESS has an efficiency of 64% (74.2/(74.2 + 41.8)). Finally, #5 shows that approximately 5.5% of TEC generated electricity is stored for a period of time so as to keep within renewable energy export limitations of the distribution circuit on the Digby Neck.

Table 1 may also be used to investigate the contributions of each specific component of a TEC and ESS project. As an exercise of energy and economics using the COMFIT price of $652/MWh, envision the project first without any export limitations. The TEC could theoretically produce 1344.6 MWh and have revenue of $876,679 annually. The distribution circuit export limitation of 0.9 MW is then imposed, causing the TEC to be curtailed by 116.0 MWh, a reduction in revenue of $75,632. This is 91.3% of the original value, indicating that the maximum TEC and WEC production are infrequently coincident in time. This curtailed case represents the minimum energy production and revenue case for the TEC. If an ESS with storage capacity of 6.8 MWh is then implemented at a cost of $250,000/MWh,[1] this will incur additional capital cost of $1,700,000. The annual total charge energy to the ESS is 116.0 MWh and its discharge, because of inefficiencies, is only 74.2 MWh. This 74.2 MWh is an additional amount of saleable energy, enhancing revenue by $48,378 per year. It is immediately apparent that the simple payback of the ESS is 35 years, a significant economic disadvantage.

There are two perspectives from which to view the economic feasibility of the ESS: (1) that while an economic disadvantage on its own merits, it complies with the allowance made by policy makers, thus enabling the TEC project as a whole which may remain economically feasible; or (2) that a smaller ESS combined with some minor amount of curtailment may be economically advantageous on its own merits. The following sub-sections address these two ESS variants. Specifically, Section 5.3 deals with an ESS that avoids all curtailment and describes characteristics suitable for use in selecting a storage technology (perspective 1), and Section 5.4 conducts a curtailment analysis for use in selecting optimal storage power and capacity to maximize revenue enhancement while minimizing ESS capital cost (perspective 2).

Table 1
Comparative annual values of TEC and ESS.

#1. ESS capacity rating	6.8 MWh
#2. Cumulative electricity discharged from the ESS	74.2 MWh
#3. TEC generated electricity that is exported directly to the distribution circuit	1228.6 MWh
#4. Total TEC generated electricity	1344.6 MWh
#5. Portion of TEC generated electricity that is discharged through the ESS	5.5%

5.3. Energy storage capacity and power characteristics

The ESS performance profile was analyzed throughout the year by various measures. The first measure is storage event duration, the length of time for the ESS to complete a charge and discharge cycle. If this time is large then the self-discharge rate of a storage technology is of concern. It was determined from the data that 87% of the energy storage events last under 5 h, indicating that the combined output of the WEC and TEC is rarely sustained above 0.9 MW. Rather, it is typically brief peaks when high winds correspond to peak tidal production. In most of these cases, the combined output drops below 0.9 MW within approximately 3 h (the length of time between mid-tide, when the TEC is at peak production, to slack tide, when the TEC is idle). The longest amount of time that the ESS maintains a charge is 60 h (2.5 days). The short term nature of this application means that self-discharge will likely not have a significant impact on efficiency of the ESS.

The second performance measure is the frequency of occurrence of storage events requiring different levels of energy storage capacities as shown in Fig. 6(A). This information enables analysis of the cycle life characteristics required at each capacity level. The typical utilized storage capacity is less than 0.25 MWh, although a value of nearly 7 MWh is required to entirely avoid curtailment. In this application an ESS would experience hundreds of shallow cycles and perhaps up to 25 deep cycles per year. However, the utility of allowing for these deep cycles should not be underestimated from an energy perspective. Fig. 6(B) shows the total energy stored throughout the year at each level of ESS capacity. While it is rare that several MWh of capacity is required, the amount of energy cycled through a single one of these *high stored energy level* events is comparable to the stored energy of many occurrences at lower ESS capacities. For example, the few storage events at 5 MWh store approximately the same amount of energy as the hundreds of storage events at 0.5 MWh.

[1] This value is the representative cost of large-scale lead-acid battery storage based on consultation with industry. To account for variations in supply price or technologies, a range of one-half to twice this value should be considered (i.e. $125,000 to $500,000 per MWh of storage).

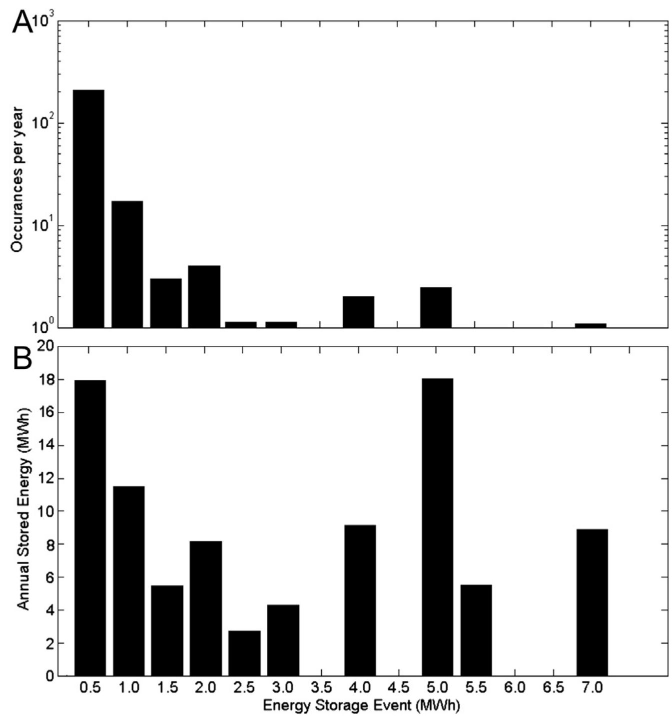

Fig. 6. ESS values as a function of storage capacity (A) Occurrences of energy storage events; (B) Quantity of stored energy at each energy storage event.

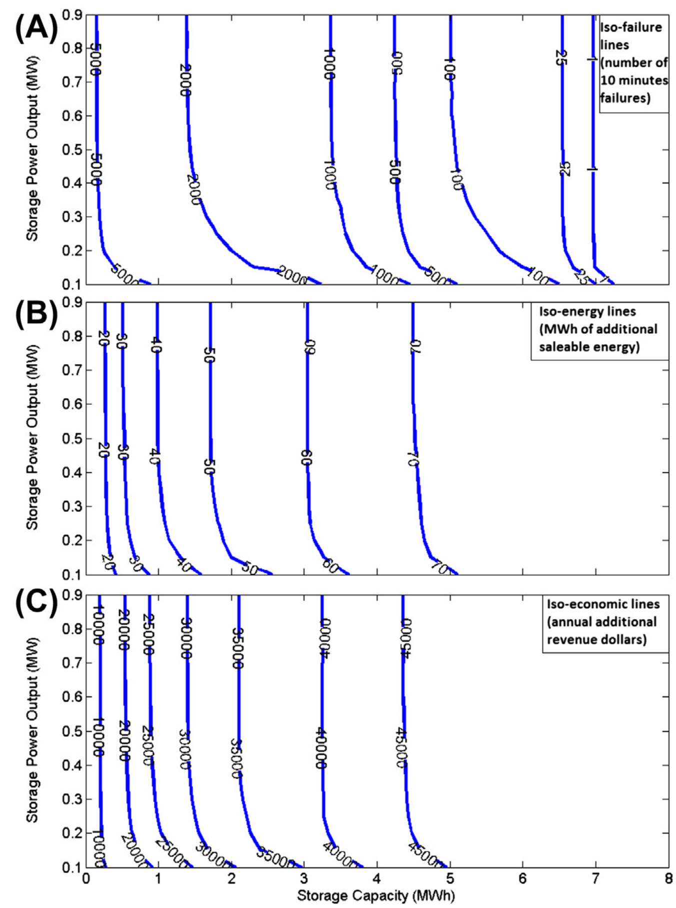

Fig. 7. Iso-lines as a function of ESS power and capacity: (A) Failure; (B) Energy; (C) Economic.

5.4. Curtailment and storage sizing analysis

An analysis was performed to determine the extent of curtailment when the ESS is reduced below the power or capacity values described in Section 5.2. Fig. 7(A) shows a map of ESS *iso-failures* as a function of storage power and capacity. This is the number of 10 min failures that occur annually where the ESS is fully charged and TEC and WEC production continues to exceed 0.9 MW, resulting in curtailment of the TEC. The ESS discharge power values range from 0.1 to 0.9 MW and the storage capacity ranges from 0 to 7 MWh. This indicates a relatively low discharge rate compared to energy storage capacity; industry would term this 1/10 C-rate. Such a rate is feasible over a wide range of storage technologies.

Fig. 7(A) shows that there are diminishing returns with respect to both ESS power and capacity. This is most evident for storage power, where vertical lines indicate that increasing the capabilities for discharge power does not impact number of failures. For example, a system capable of discharging at 0.5 MW is just as effective as a 0.9 MW system for any storage capacity. This is because there are typically long periods between storage events, allowing for slow discharge. The discharge power capability should be selected as the minimum value along the vertical portion of an iso-failure line. In contrast to power, Fig. 7(A) shows that reducing the storage capacity of the ESS has greater consequences, with failure rate increasing dramatically as storage capacity is reduced. For example, reducing from 7 MWh to 5 MWh would cause 100 failures (16 h/year), whereas reducing to 1.5 MWh would cause 2000 failures (333 h/year).

In Fig. 7(B) the iso-failure lines are translated into *iso-energy* lines corresponding with the annual quantity of energy discharged from the ESS. These are units of additional saleable energy that have been produced because the ESS was implemented into a TEC system that would otherwise need to be curtailed. Fig. 7(B) shows that there are diseconomies-of-scale in sizing storage capacity to achieve additional saleable energy. This is evident because the consistent 10 MWh increments of iso-energy lines are separating as ESS capacity is increased. For example, a 1 MWh ESS results in additional saleable energy of 40 MWh; this ESS is only 15% of the capacity of the no-curtailment ESS (6.8 MWh), but results in 54% of the saleable energy.

5.5. Simple economic impact analysis

A simple economic analysis determines the value proposition of adding ESS to the TEC project. This is achieved in Fig. 7(C) by translating the iso-energy lines into *iso-economic* lines by multiplying the additional annual saleable energy by the COMFIT price of $652/MWh. By using the largest capacity ESS described in Table 1 the revenue can be increased by $48,378. However, smaller ESS can achieve increased revenue with significantly less capital cost. Using the capital cost of the ESS, the project lifetime, and Fig. 7(C) the optimal economic ESS capacity can be determined through simple payback analysis. Section 5.2 gave the example that a 6.8 MWh ESS implemented at a cost of $250,000/MWh would have an economically disadvantageous simple payback of 35 years. However, Fig. 7(C) shows a 1 MWh ESS costing $250,000 would increase revenue by $27,000 per year, achieving a simple payback of 9.3 years.

It is important to note that such a simple economic analysis does not take into account operating/maintenance costs and assumes the following for an ESS: (i) capital cost of $250,000/MWh, (ii) efficiency of 64%, and (iii) sufficient cycle and calendar life to reach the simple payback duration. Obviously, a detailed study to parametrically investigate the nominal variation amongst these values is warranted and desirable; however, it is beyond the scope of this study. Additionally, the economic value of the ESS providing enhanced services to the electricity grid utility operator should be considered. These support services could address: voltage sag, flicker, reactive power, ramp-rate compensation, and black start.

6. Conclusion

In this work, tidal and wind resource data was used with turbine power coefficient curves to create a renewable energy generation model of Digby Neck, NS. The 0.9 MW WEC produces 2104 MWh annually and has a stochastic power output profile with respect to time. The 0.5 MW TEC, with an assumed coefficient of performance of 0.40, produces approximately 1345 MWh annually and has a four-times-daily cyclic profile. These generator profiles were combined to determine when their output exceeds the 0.9 MW export limitation to the distribution circuit of the local electricity grid. A new model of energy storage with constant 64% efficiency was created with a control strategy that seeks to discharge in preparation for the next charge cycle. In this fashion the ESS is optimized to avoid curtailment of the TEC. It was determined that an ESS rated approximately 7 MWh and 0.5 MW is sufficient to avoid all curtailment and will deliver 74 MWh of additional saleable energy annually. Throughout the year, several hundred shallow cycles and several tens of deep cycles will occur.

Such an ESS was determined to be uneconomic on its own merits. However, the ESS is required by policy and may allow the project to be profitable as a whole. Alternatively, the model was exercised by limiting the ESS size to investigate the impact it has on curtailment, enhanced saleable energy, and economic value. Values ranging from 0 to 7 MWh were investigated and it was found that *diseconomies* of scale are present.

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