The Economics of Tidal Stream Power

Boronowski S.[1], Monahan K.[2] and van Kooten G.C.[3]

[1]University of Victoria, Department of Mechanical Engineering, Victoria, Canada
[2] University of Victoria, Department of Economics, Victoria, Canada
[3] University of Victoria, Department of Economics, Victoria, Canada

Abstract— **Renewable solar, tidal and wind energy have the potential of reducing dependency on fossil fuels and their environmentally negative impacts. Because of their variability, wind and solar energy in particular impose added costs on electrical grids as system operators attempt to balance operation of existing thermal power plants. In this regard, tidal stream power has an advantage over solar and wind energy as tides are predictable and comparatively regular; yet, tides remain intermittent and thereby still may create inefficiencies to the grid.**

In this paper, we develop a dynamic optimization framework for analyzing the allocation of power output across generating sources when tidal and wind power are added to the system. In particular, we minimize the cost of satisfying the 2006 British Columbia electricity demand. We use tidal current and wind data from sites around Vancouver Island to estimate the effects of an increase in renewable energy penetration into grids consisting of three typical generating mixes – the British Columbia generation mix that has a significant hydro-power component, the Alberta generating mix with a coal-fired power dominance, and the Ontario generation mix which includes significant nuclear and coal-fired generation.

Simulation results over an entire year (hourly time step) indicate that the cost of electricity will increase from its current levels by between 73% and 150% at renewable penetration rates of 30% depending on the assumed generating mix. The cost of reducing CO_2 emissions ranges from \$97.47 to \$1674.79 per tonne of CO_2, making this an expensive way of mitigating emissions. The reasons for these high costs are increased inefficiencies from standby spinning reserves and operation of plants at less than optimal levels (so that more fuel is burned per unit of electricity). Further, it is impossible to determine the displacement of emissions by renewable energy without considering the complete operating system.

Keywords— **renewable energy; electrical grids; mathematical programming models**

I. INTRODUCTION

Adequate investment in renewable energy assets in the electricity sector is a pressing concern for policy makers due to the growing sense of unease about the environmental damage and CO_2 emissions from traditional thermal generating sources. Currently in British Columbia, about 90 per cent of electricity is generated by large-scale hydro or other clean or renewable resources and, under the 2007 BC Energy Plan, the Government commits to maintain this high standard. However, energy demand in the province is expected to increase by 45 per cent over the next 20 years and the heritage capacity of the existing dams has already been exhausted [1]. Without further investment in renewable energy, British Columbia's generating mixture is predicted to include an increasingly larger percentage of "dirtier" fuels.

In theory, tapping local renewable energy resources such as hydro, wind or solar could provide a solution to these issues, but studies have found that their benefits in terms of displaced emissions, effective capacity and fuel costs decrease as their penetration into the electricity grid increases [2]. This is because these types of renewable power are only available at intermittent intervals (e.g., when the wind is blowing) and there is currently no practical way to store the power to be dispatched when it is needed. Therefore, efficiency losses or 'wasted' energy arises when the system operator cannot ramp-down the thermal sources instantaneously when the renewable resource becomes available.

There has recently been a surge of enthusiasm into a relatively new form of renewable energy: tidal stream power. Tidal stream power works in a similar fashion to wind power, using large turbines installed underwater to harness the kinetic energy supplied by tidal currents rather than the wind. It has the advantage over other forms of renewable energy of being regular and mostly predictable and therefore may be more appealing to system operators as they attempt to balance supply with demand in any given period. Recently, it has gained international recognition and utility-scale turbines have now been approved for installation in Nova Scotia and British Columbia. British Columbia has been identified as an ideal location for resource extraction with potential power capacity in the range of 3000MW, equivalent to 21.8% of BC's 2007 generating capacity [3].

The costs and benefits of incorporating tidal power into an electricity grid depend not only on the costs of installing, operating and maintaining the individual turbines, but also on how the entire generating system is affected by the tidal generated power penetration (tidal capacity as a percent of peak system load). Following a similar methodology as studies of wind power [4], we use a mathematical linear programming model to determine the impacts of integrating tidal power along with wind power into electricity grids. Potentially available tidal and wind power is determined using data from sites around Vancouver Island, British Columbia (BC). The model minimizes system costs of meeting the 2006 BC electricity load by optimally choosing the power-makeup between the available sources. The model results provide the megawatt hour costs of tidal and wind integration; the amount of carbon dioxide (CO_2) that can be displaced by these renewable energies; and the unit cost of CO_2 mitigation. These costs and benefits will depend on the pre-existing mix of power sources. Therefore, we examine scenarios using generating mixes that represent those currently found in BC, Alberta and Ontario. Although tidal power is obviously not suited for land locked provinces such as Alberta, the use of these three mixes enables us to use real data for the actual provincial generating mixes that could be typical of usage elsewhere. This will quantify which pre-existing generating mix benefits most from the inclusion of tidal and wind power.

In the first several sections, we discuss the technological development of tidal stream power, how it works, and what the scientific methods are for establishing the energy potential from a specific site. We then consider the model under various scenarios and draw conclusions about system costs and displaced emissions depending on the generating mix. We conclude by outlining some possible non-marketed values of tidal stream power and encourage subjective discussion into why these types of renewable energies are being promoted.

II. TECHNOLOGY

There is no doubt that wind power is much more established than tidal power in terms of technological progress. For instance, the first megawatt sized windmill was constructed in 1941 [5], while the first megawatt size tidal-turbine has only been ready for installation since August 2007. However, extraction and conversion of tidal energy is not a new concept. Tide mills have been used for grinding grains for nearly a thousand years and Barrage Tidal Power Systems have been around since the 1960s. Barrage systems use the potential energy from the difference in height between high and low tides by capturing the waters brought in by high tides in a holding area (similar to a hydro dam) before releasing them through a generator once the tide has receded. The largest barrage station is La Rance in St. Malo, France, with an installed capacity of 240 MW. Canada had been one of the pioneers of this technology with the Annapolis Royal Generating Station in operation since 1984 in the Bay of Fundy, Nova Scotia, with an installed capacity of 20 MW [6]. It is worth noting that this project was largely unpopular due to high costs and negative environmental impacts such as upstream/downstream soil erosion and injury to marine life and it is now the only tidal generating station of any type in North America besides model prototypes.

Tidal stream systems use kinetic energy from the moving water to power turbines in the same fashion that wind turbines gather energy from the moving air. Ideally, the turbines are anchored to the sea floor at least 15 meters below low tide so as not to interfere with shipping. There are many potential designs but the self-claimed world's most advanced utility size unit "The SeaGen", was developed by the British company Marine Current Turbines. The Nova Scotia Department of Energy plans to have SeaGen tidal turbines operating in the Bay of Fundy by 2009 and a cooperation agreement was signed on November 8th 2007 with BC Tidal Energy Corporation to install at least three 1MW turbines off Vancouver Island near Campbell River [7].

The first "SeaGen" project was a 1.2 MW turbine that was ready to be installed in Northern Ireland in August 2007. Marine Current Turbines had previously spent over two years testing a 300 KW Horizontal-Axis turbine named "SeaFlow" off the coast of Devon in England. The SeaGen twin rotor turbine incorporates a patented system for raising the rotors and power train above the surface of the water, eliminating the problem of using divers or submarines for maintenance in high tidal velocities.

We use the Marine Current Turbine design to calculate the extractable power from the tidal stream velocities for our modeling scenarios. The technological assumptions are summarized below:

Rotor diameter of 15 m,
Turbine efficiency of 20%
Nameplate capacity of 500 kW per rotor (1 MW per unit)
Generator efficiency of 30%
A "cut in" velocity of 1 m/s.
A "cut out" velocity of 3.6 m/s.

Over the last four years, various other prototypes have been tested. Generally, the four types of designs are: "The Horizontal Axis Turbine" which is similar to wind turbines where rotor blades are spun by the tidal currents; "The Vertical Axis Turbine" which has a short blades axis that lies horizontal to the ocean floor; the "Oscillating Hydrofoil" creates electricity from the lift and drag to the hydrofoil system; and the "Venturi System" where water is accelerated through a 'choke system', creating a pressure drop in the device that can be used to drive turbines located above the water or even on shore [5].

All these designs have emerged with varying degrees of success. Noteworthy commercial prototypes include the 2001 trials of the Vertical-Axis systems in the Strait of Messina in Italy, as well as the 2002 Oscillating Hydrofoil turbine assembled along the Gold Coast of Australia. In 2005-2006, Quantum Hydro Power tested the Gorlov Helical Turbine (Horizontal-Axis) on the Canadian West Coast, and the 2006 Vancouver Island Race Rocks project captured the attention of the entire province. Two Canadian companies: Blue Energy and Clean Current Power Systems Incorporated have prototypes of utility scale turbines ready after Blue Energy announced it had completed testing a turbine prototype at the University of British Columbia on September 26, 2006.

In 2002-2003, a 150-kilowatt oscillating hydroplane device, "The stingray", was installed in 37 meters of water at Yell Sound in Scotland's Shetland Islands. The $2.8 million project marked the world's first offshore installation of a full-scale tidal stream power plant. The world's first grid-connected tidal stream turbine was successfully constructed in Hammerfest, Norway on the 13th of November 2003. The prototype was responsible for 240kW of capacity but, contrary to expectations, no new further turbines have been developed by the firm, although the technology was sold to Murmansk in Russia for their prototype plant due for construction in January of 2008. It is worth noting, however, that many of these trials have not led to any successive attempts to integrate the power into the nation's power portfolio. Possible reasons involve faulty designs that involve excessive maintenance and high costs.

It is important to recognize that since the technology for tidal turbines is still in its infancy, Canada has the potential of benefiting financially as a leader in this emerging market.

III. POWER AVAILABILITY

Tides are caused by the gravitational attraction between the moon, and to a lesser extent the sun, and the oceans' waters. As the ocean is pulled primarily towards the moon, movement of the water in areas where it is concentrated or focused by the shape of the seafloor creates tidal currents. Tidal heights vary between limits, depending on a combination of cycles of approximately 12 and 24 hours, 14 and 28 days, half year and year, culminating in an 18.6 year cycle. Generally, tidal currents vary with tidal heights so that, at any location, there will be periods when the water is still, and times when it reaches its highest velocities. The tides vertical rise and fall of water is related to the horizontal flow known as tidal currents [8]. The velocity of the currents can be forecast with a high degree of accuracy based on over a hundred harmonic constituents and the area of the restricting channel (Blanchfield, 2007, unpublished thesis, Department of Mechanical Engineering, University of Victoria). The velocity of the moving water is the dominating factor determining how much power an underwater turbine can generate and thus locations known for their strong currents should be the focus of resource exploitation.

Although tidal movements are predictable, the currents are intermittent and therefore the power that is actually generated at any one location and supplied to the grid can range between zero and the maximum rated capacity of the turbine – assuming that the currents are strong enough to allow the turbine to reach its maximum capacity (Figure 1). The percentage of this rated capacity that would be available over the year (the capacity factor) can range from 8% to 30% depending on the site [7].

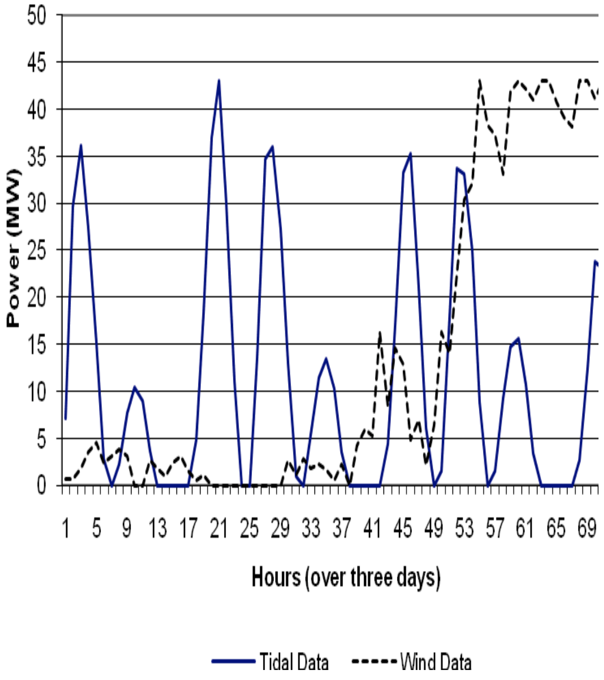

Fig. 1 Tidal Power Output vs. Wind Power Output

Due to this intermittency of power, a storage device would be desirable to smooth-out dispatch or make the power available when it is needed. Potential storage technologies involve traditional batteries, fuel cell systems, compressed air energy storage plants, and pumped-hydro (pumping water into a reservoir). Unfortunately, the land requirements for the huge batteries, dual reservoir requirements for hydro storage, and low efficiency of fuel cells make these aspiring technologies financially too expensive at this time.

One alternative to this dilemma involves tapping more than one location for tidal power exploitation since the currents in one place may be flowing when the water is slack in a nearby location, and vice versa. The 'front' of the tide advances up a bay so high tide at the head of the bay can be hours after high tide near the mouth. Therefore, if you have two generators, one can run while the other is in still water and, theoretically, a network of turbines could be planned to ensure that there is always one turbine spinning. This type of strategic planning has not been examined in detail to date. We address this issue to some extent by using data from two very different locations with different tidal movements.

IV. RESOURCE POTENTIAL AND EXTRACTABLE POWER

Calculating the potential extractable power from ocean currents is subject to large uncertainty. There is controversy over conflicting estimation techniques at specific sites due to the mathematical formula's inclusion or exclusion of site characteristics such as bottom composition, the size of the channel, and the different possibilities of turbine spacing patterns. In 2004, the UK consulting firm *Black and Veatch* performed an extensive literary review on the potential tidal-stream resources in the UK and elsewhere [5]. The review used several references from the *2000 Blue Energy* study which estimated a total global energy resource of ~450 GW. Blue Energy is a Canadian-based tidal stream/marine current energy development team whose most recent report estimates total Canadian potential at 42 GW [9] which represents 36% of Canada's 2007 total generating capacity from all power sources. However, Blue Energy states that their estimate is an absolute upper bound and is subject to extraction technology, environment, climate and the characteristics of individual sites.

The government of British Columbia had been relatively slow to recognize the large potential resource of its underwater tidal streams, which is estimated at 3000MW or equivalent to 21.8% of BC's 2007 overall generating capacity [5, 9]. Nevertheless, the 2006 report "Renewable Energy Option for British Columbia" used case studies by Triton Consulting to estimate the costs and extraction possibilities of two sites: Discovery Passage and Race Passage off Vancouver Island. The study estimated the extraction possibilities at Discovery Passage to be 800MW (1400 GWh per year) yielding a cost of 11 cents per kWh, while the possibilities at the smaller Race Passage was 43 MW (76 GWh per year) yielding a cost of 25 cents per kWh. For the purpose of our model's validity, as well as general study consistency, we use current velocity data from these two sites for the modeling section of this paper. Thus, since the rated capacity of our turbines is 1 MW, we assume that 100 turbines are to be installed at Discovery Passage and 43 turbines at Race Passage, which is less than or equal to the maximum extractable energy for the sites as estimated by the Triton study [10].

Although ignored here, environmental impacts should be considered when determining extractable energy from specific sites. For example, a case study performed for Haida Gwaii, revealed that the maximum extractable power from Masset Sound is approximately 54 MW (Blanchfield, 2007). The study results suggested that extracting 54 MW from Masset Sound would decrease the maximum flow rate through the channel by approximately 40% from its undisturbed regime. The consequences of altering the natural patterns of the currents are unknown but would most likely effect the spawning and migratory patterns of aquatic life. The study determined that the tidal regime could be kept to within 90% of the undisturbed state by limiting the average extracted power to approximately 12 MW.

For our modeling scenarios, we use recorded current velocities to derive the extractable power. The basic estimation technique is the same as that used for wind turbines, which uses the basic law of thermodynamics to derive the theoretical maximum energy that can be created from a rotor when a fluid moves through it at a certain speed. The formula can be expressed as:

$$E = \tfrac{1}{2} \times \rho \times S \times v^3 \qquad (1)$$

where E is the power delivered to the turbine, ρ is the fluid's density, S is the total swept area of the rotor blades, and υ is the velocity of the fluid. To determine the actual power P at the specific sites, we extract only a fraction of the available kinetic energy in the same way as the 'Betz limit' only allows for a maximum of 59.3% of wind's kinetic energy potential to be extracted. This limit accounts for the fact that we need to keep the tidal currents moving past the rotor after each stage of energy extraction to allow the incoming water to enter the rotor at an acceptable speed which ensures the greatest overall extraction over the time frame. Based on previous work done on tidal power conversion (Blanchfield, 2007), we use:

$$P = N \times \eta \times \mu \times \tfrac{1}{2} \times \rho \times S \times v^3 \qquad (2)$$

where N is the number of turbines at the site (100 at Discovery Passage and 43 at Race Passage), η is the turbine efficiency (20%), and μ is the theoretical extractable power affected by the bottom drag and the ability of the water to 'stream around the turbine' (30%). The density of water is assumed to be 1030 kg/m^3 and the rotor diameter is 15m based on Marine Current design.

V. A MODEL OF THE ELECTRICITY GRID WITH TIDAL POWER INTEGRATION

We use a linear mathematical programming model to determine the optimal economic dispatch of power output from several different sources. This allows us to examine the impacts of tidal and wind power integration into an electricity grid consisting of different mixes of traditional fuels. In our model, we assume that the grid will take all of the available electricity produced by the renewable energy sources. The model optimizes over the full year of 2006 using an hourly time step. The system operator chooses the output allocations from all the remaining sources to minimize the overall cost in every hour over the year allowing for a 5% "safety allowance". Included in the objective function are fuel costs, variable O&M costs and fixed O&M costs. The model is constrained by the individual plant's capacity, ramping up and down speeds, and the necessity of meeting the load demand in every given hour of the year. We assume rational expectations in the sense that the system operator has full knowledge of demand and power availability within the 5% safety allowance. The model is solved using MATLAB with calls to GAMS to solve the linear programming problem. Data are drawn from a table constructed in Microsoft Excel.

VI. MODEL PARAMETERS

A. Tidal Data

We use tidal current speed data from Discovery Passage and Race Passage on Vancouver Island. The data was obtained from the Institute of Ocean Sciences at the federal Department of Fisheries and Oceans. They calculated the current velocities by utilizing past observations and generating 'hindcast' predictions for 2006 using harmonic constants that are used by the Canadian Hydrographic Service to produce its Tide Tables. The velocity profiles of the two sites vary considerably. The maximum speed for Race Passage is 3.59m/s, while it is 7.527m/s at the Discovery Passage site. Considering that extractable energy is directly related to the cube of the velocities, this difference implies that potential extraction varies radically with site location. However, the generators in the current technological designs are not able to capture the kinetic energy of current speeds greater than 3.6m/s. We therefore do not allow any data to exceed the cap of 3.6m/s during our modeling scenarios. Other considerations are that the model cannot exceed the rated capacity of the site (100MW for Discovery Passage and 43MW for Race Passage), and we assume that the generator will switch on (the "cut-in rate") when the current speed exceeds 1m/s. We then apply the constrained data to the Betz Limit formula for extractable power. We assume that the power is non-dispatchable and thus the system operator is required to accept all the tidal power provided to the grid at the time it is provided.

B. Wind Data

Wind power is now a recognized and utilized form of energy generation. We include wind data in our model in addition to tidal stream power to make the scenarios more realistic. This is to say, that the province will most likely have wind power in place before large scale tidal stream power is introduced. The addition of wind power into the model demonstrates how these types of renewable energy will affect the grid. Wind data are gathered from four sites in the Peace River Region of BC as well as one site at Pulteney Point on Vancouver Island. The total installed capacity is assumed to be 218 MW, which is consistent with previous modeling scenarios [4]. We assume that wind is perfectly predictable within the scope of our model which is not completely unreasonable since forecasting methods are now becoming increasingly accurate.

C. Load Data

Historical demand for electricity in British Columbia was obtained from the BC Transmission Corporation which plans, operates and maintains the province's publicly-owned electrical system. Hourly load data (MWh) were calculated using a sample that was drawn every five minutes for the year of 2006. The wind and tidal name plate capacities are normalized to the maximum load of 11039MW (minus the safety allowance) to represent different penetration rates throughout the scenarios. The renewable penetration refers to the ratio of the wind and tidal installed capacity divided by the peak system load. We chose penetration rates of 10%, 20% and 30%. This will quantify the effects of increased renewable penetration into the gird. Figures 2 and 3 depict the pattern of energy demand versus the pattern of tidal and wind energy availability.

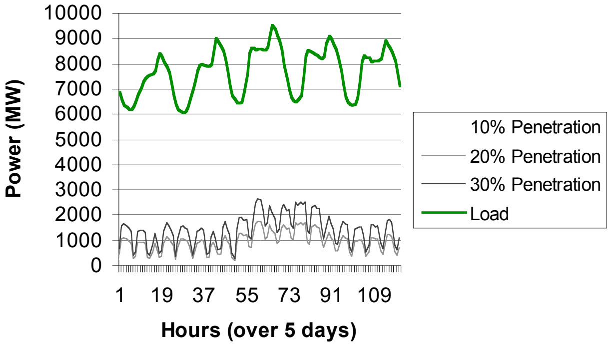

Fig. 2 Extractable Tidal and Wind Power vs. BC Electricity Demand

This chart displays the cyclical demand for electrical power in British Columbia and the cyclical movements of the tidal power availability. Notice how the cycles are completely unrelated meaning that the electrical demand curve may peak while the tidal power availability curve may trough or vice versa.

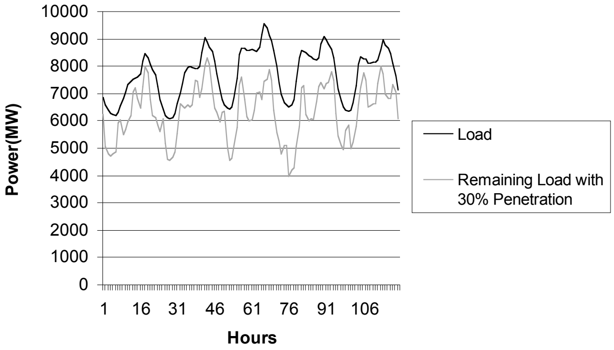

Fig. 3 Remaining Load to be met by Traditional Power Sources

The graph depicts the remaining load that must be met by traditional sources- such as hydro or thermal- once the renewable power is introduced to the grid at a 30% penetration rate. Notice how the original load is smooth and cyclical thereby allowing the thermal power sources to vary their generator ramping actions in a similar fashion. Once the tidal and wind energy are introduced to the grid, the remaining demand for energy creates a higher degree of fluctuation in amplitude in the graphical representation. The load that must be met by the traditional sources becomes much more erratic and thus may cause strains or inefficiencies by causing much more varied ramping up and down of traditional generating sources.

D. Generation Mixes

We investigate the impacts of increasing renewable energy penetration into various generating mixes, which we normalize to meet the 2006 load data for British Columbia. This allows us to see the differences in costs and emission reductions that arise depending on the overall portfolio of energy sources. We choose to use the present-day thermal source capacities from BC, Ontario and Alberta, which consist of five traditional generation technologies: natural gas combined cycle (NG CC), petroleum combined cycle (P CC), pulverized coal steam cycle, large-scale hydroelectric, and nuclear power. We also introduce biomass into all the mixes at a modest rate of 0.5%, which is consistent with near-future expectations for all provinces.

British Columbia generated 90% of its power from hydro sources in 2006, while the remaining 10% was a mixture of natural gas, diesel and biomass. British Columbia has a transmission interconnection with Alberta whose generation mix consists of large amount of coal (64%) and gas (21.5%), with the remainder mixture consisting of hydro, wind and biomass. Considering that electricity trade among the provinces is expected to expand, the model results for Alberta's generating mixture will be significant to British Columbians. Finally, we investigate Ontario's mixture that includes less coal but more nuclear. The exact generating mix makeup is summarized in Table 1. It is taken from actual data of capacity portfolios for the three provinces in 2006 and is provided by Environment Canada's statistics [11].

Table 1 Energy Source Portfolios by Province 2006
Notes : BC=British Columbia ; AB=Alberta ; ON=Ontario;
Source: [11]

Source	BC	AB	ON
Hydro	89.5%	9.7%	20%
Nuclear	0	0%	44%
Coal	0	63.8%	19%
Gas	10%	21.5%	11.5%
Petroleum	0	4.5%	5%
Biomass	0.5%	0.5%	0.5%

E. Hydro Considerations

Due to fluctuating water levels in hydro reservoirs as well as low prices in the U.S. and Alberta energy markets, British Columbia is sometimes a net importer of electricity. However, when reservoirs are full, the generating capacity of British Columbia exceeds peak demand. The actual generating capacity in 2006 was 13749.5 MW which equates to a 13.451% reserve margin for the peak load of 12119.33 MW [11]. Our peak load for the control area data provided by the ITC is 11039 MW, but since we assume that hydro capacity is constant throughout the year, we model the overall generating capacity at 15% less than actual capacity. We carry this assumption over into all three generating mixes.

F. Ramping Constraints

Thermal generators take time to "ramp-up" to their full capacities or "ramp-down" to a lesser power output when they are not needed. This is in fact the reason that efficiency losses arise when renewable tidal and wind power are introduced because the ramping limits may lead to excess generation in some periods when there is more than sufficient wind and tidal power available but some traditional capacity needs to remain on line as spinning reserve for a following period when wind and tidal are not available. The thermal sources are modeled with ramp rate constraints that represent the time it takes for the generators to increase or decrease their power output to the desired levels for production. The coal and nuclear power plants are the slowest and are assumed to take three hours for full ramping times, while the natural gas, biomass and petroleum generators are faster and thus are assumed to take only two hours.

G. Costs

Costs for wind, combined cycle gas and coal are taken from a report prepared by Americas Limited for the Alberta Electric System Operator (AMEC) in October 2006 [12]. The costs for Hydro power and the thermal sources are summarized in Table 2. The fuel price is calculated using the ratio of the cost of the fuel in \$/MWh to the maximum efficiency of the generating station.

Table 2 Electrical Generation Costs and Efficiencies by Source

Source	Variable O&M Cost (\$/MWh)	Fixed O&M Cost (\$/KW)	Max Efficiency	Fuel Price (\$/MWh)
Hydro	0	14.5	100%	1.1
Nuclear	12.0	35.0	40%	2.3
Pulverized Coal	6.0	39.9	38%	4.5
Natural Gas cc	5.0	10.9	49%	16.9
Petroleum cc	6.0	12.9	40%	27.0
Biomass	2.8	10.0	35%	14.7

H. $C0_2$ Emissions

Carbon dioxide emissions are a direct function of the type of fuel burned and the generating plant's efficiency. Mathematically this can be expressed as:

$$\text{tCO2} = \text{Emission Factor/Average Plant Efficiency} \qquad (3)$$

where the emission factor is equal to 0.346 tCO_2 per MWh for sub-bituminous coal and 0.202 tCO_2 per MWh for natural gas [13]. The emission factor for oil is estimated to be 0.28 tCO_2 per MWh based on Environment Canada data. The plant efficiencies vary depending on generator make-up and age of the facility; thus, we assume the following based on aggregation averages: 0.38 for coal, 0.49 for gas and 0.4 for oil.

VII. MODEL RESULTS

We begin the model scenarios by examining how demand is satisfied without the inclusion of wind and tidal power into the grid. A total of 64.63 TWh (64.63 million MWh) are generated from all sources in the model, thus satisfying the British Columbia demand in 2006. This is comparable with the actual recorded generation for the year (with a reliability factor of 5%) of 64.09 TWh. To minimize the cost of generating this electricity, the model chooses different allocations of dispatch across all sources. For example, using the BC installed capacity mix, the model chooses to satisfy demand using 97.4% hydro with the remaining generation covered by gas and biomass. This is almost exactly the same as Environment Canada data for 2006 which shows that 96.6% of BC's demand is satisfied using hydro generation.

The traditional sources of fuel must supply the power in a fashion that follows the cycle of demand over the day. Figures 4 and 6 show how load is met using the traditional generation sources that are found in the BC and Alberta generating mixes, respectively. The traditional sources mirror the two peak patterns of demand. Figures 5 and 6 illustrate how demand is satisfied by the variety of sources once wind and tidal power are added to the mixture. The traditional sources are now forced to follow a much more irregular pattern of power generation. It becomes apparent that having to ramp the generators up and down more frequently may lead to inefficiencies in the overall generating system.

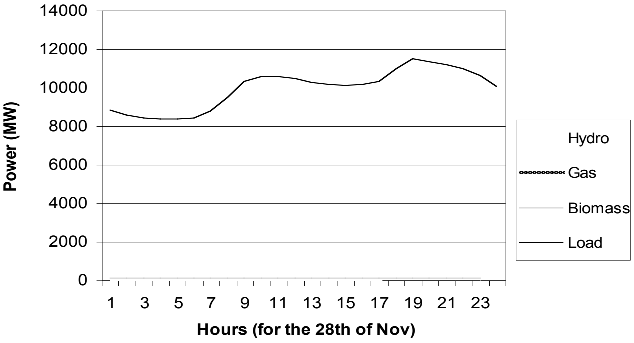

Fig. 4 Load met through Traditional Sources for the BC Generating Mix

The chart illustrates how the load demand is satisfied using the traditional generating sources in the British Columbia portfolio. Hydro power satisfies almost the entire load but gas must be used in periods of peak demand when hydro capacity is exceeded.

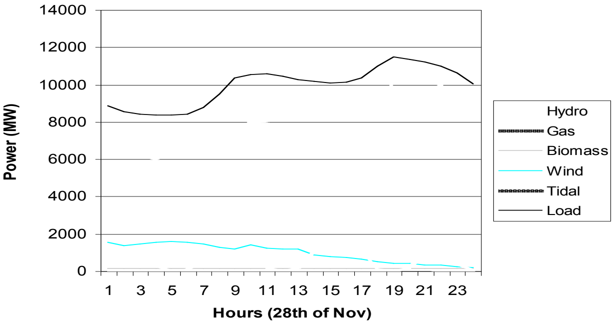

Fig. 5 Load met through all Sources for the BC Generating Mix

The chart illustrates how the load demand is satisfied by different power sources once tidal and wind power are added to the British Columbia generating mix. Notice how the wind and tidal power have mostly displaced hydro power, and there still remains the necessity for gas generation at the period of peak demand.

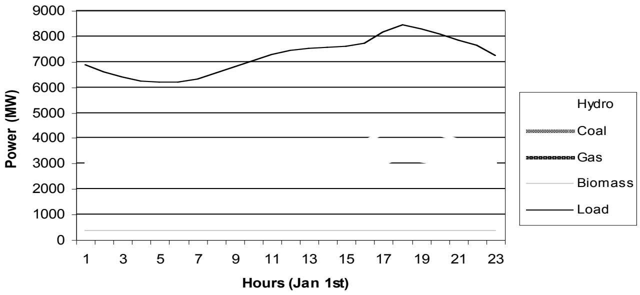

Fig. 6 Load met through Traditional Sources for the Alberta Generating Mix

The chart illustrates how load electricity demand is satisfied using the traditional sources of electricity found in the Alberta generating mix. Gas mirrors the pattern of demand and it is necessary to ramp up the coal fired generators during the period of peak demand.

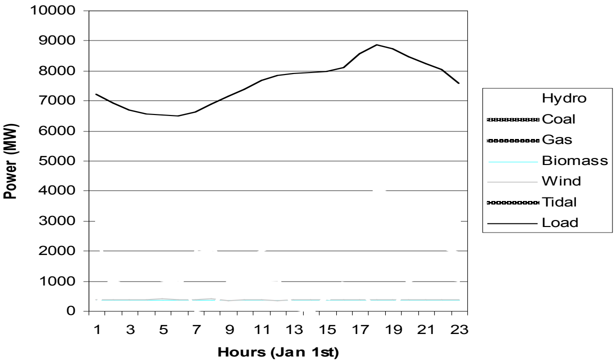

Fig. 7 Load met through all Sources for the Alberta Generating Mix

The chart illustrates how the model satisfies electricity demand using the Alberta generating mix once tidal and wind power are added to the grid at a rate of 30% of peak demand. Gas generation no longer mirrors the load and becomes more sporadic. It is no longer necessary to ramp-up the coal generator during peak demand since the tidal and wind power is able to cover the excess generation needed in this period.

A. Cost Results

Capital costs of wind farms are assumed to be $600 000 per MW for wind, and $1800 000 per MW for tidal. The reader should be aware that these costs are very modest (roughly half of what the market value is at present) because we allow for expectations of a significant decrease in costs as technology becomes more efficient or as economies of scale are developed. The capital costs are amortized over 25 years at an interest rate of 6%. The fixed O&M costs are assumed to be $45320/MW for wind and $61714/MW for tidal based on the UK tidal resource study figures [5]. Although the 'fuel' for the wind and tidal power generation is free, the capital cost will grow as renewable penetration increases. Capital costs for generators other than the wind farm are not included because new wind capacity is introduced at varying levels into a pre-existing mixture.

Electricity costs per megawatt hour are calculated by summing all the fuel, variable and fixed O&M costs of the thermal sources individually for each hour and adding them to the O&M costs and amortized capital costs of the wind and tidal farms. This in then divided by the sum of all electricity produced over the year. Since capital costs for the traditional thermal sources are ignored, the resulting $/MWh will be biased downward; therefore, we record the *change* in cost as penetration increases. This will allow us to conclude which generating mixes experience the sharpest change in electricity costs when tidal and wind power are added to the portfolios.

The change in the cost of electricity is provided in Table 3 for each generating mix. The British Columbia mix exhibited the largest increase in cost ($/MWh) as tidal and wind energy are added to the portfolio. At a penetration rate of 10%, the cost increased from its original amount by 48%. This grows to 150% of original cost when penetration reaches 30% of load. This is the expected result since tidal and wind generation simply replace cheap hydro; therefore, fuel costs are not displaced and the capital cost of the renewable installation increases with penetration.

For the Alberta mix, costs increase by 32% over the original level with a 10% penetration and then double from the original level at 30% penetration. Tidal and wind generation are able to displace some of the fuel costs of traditional fuels such as coal, but the capital costs outweigh the reductions in fuel costs at all levels of penetration investigated here. The Ontario generation mix showed the least increase in costs as penetration increases. Costs rose by only 23% from their original levels with a 10% renewable penetration, while they continued to increase to 73% when renewable penetration increased to 30%. This demonstrates that renewables manage to displace some of thermal sources, such as gas and nuclear, but the necessity for high expenditure during initial installation results in an overall increase in costs of generating electricity for the system. Table 3 demonstrates the degree to which costs rise for all scenarios and generating mixtures when the renewable tidal and wind power is added to the portfolio.

Table 3 Cost of Electricity for three Generating Mixes with Wind and Tidal Penetration

Tidal/Wind Penetration	Electricity Cost ($/MWh) by Generating Mix			Cost Ratio by Generating Mix		
	BC	AB	ON	BC	AB	ON
0%	4.22	6.12	8.27			
10%	6.25	8.06	10.21	1.48	1.32	1.23
20%	8.35	10.10	12.10	1.98	1.65	1.46
30%	10.54	12.25	14.27	2.50	2.00	1.73

Table 3 gives the cost of generating electricity in dollars per megawatt hour with and without tidal and wind power penetration. Since the amortized capital costs of the wind and tidal farms outweigh the saved fuel cost in every generating mix, we observe an increase in costs with penetration for all three generating mixtures.

B. Reduction in CO_2 Emissions

Policy makers will be primarily concerned with the amount of CO_2 emissions that renewable energy is able to displace. We use our model to determine the extent to which wind and tidal power can offset CO_2 emissions. This is done by calculating the sum of all electricity produced by the various generating types multiplied by their corresponding emission factors for various *ex ante* and *ex post* tidal and wind penetration rates. Specifically, the function is:

$$\text{CO}_2\text{ Reduction} = \sum_{i=1}^{N} GS_i \times EF_i - \sum_{j=1}^{N+\text{Winf}+\text{Tidal}} GS_j \times EF_j \quad (4)$$

where GS_k is the sum of all electricity generated by source k and EF_k is the emission factor for that type of generation. The results are provided in Table 4 for varying renewable penetration rates.

Table 4 Reductions in CO_2 Emissions by using Tidal and Wind Power

Tidal/Wind Penetration	Carbon Dioxide Emissions (Megatonnes)			Incremental Percentage Change		
	BC	AB	ON	BC	AB	ON
0%	0.92	42.30	18.51			
10%	0.72	40.44	17.30	-21.6%	-4.4%	-6.5%
20%	0.68	38.66	16.48	-26.1%	-8.6%	-11.0%
30%	0.68	36.97	15.51	-26.1%	-12.6%	-16.2%

Table 4 displays the CO_2 emissions that arise from satisfying the British Columbia 2006 electricity demand. As tidal and wind power are added to the portfolio of our three different generating mixes the emissions are reduced as some of the dirtier fuels are displaced by the clean renewable power. However, the rate of this reduction varies with the original generating portfolio and the penetration of the renewable power.

Carbon Dioxide emissions are produced as a byproduct of generating electricity through thermal sources such as gas, oil and coal. Depending on the original generating mix, the amount of emissions produced will vary considerably when generating the 64.63 TWh of electricity that is needed to satisfy the British Columbia 2006 demand. Prior to the model's inclusion of tidal and wind energy, the BC mix only generates 0.9 Mt of CO_2 while the Ontario mixture generates 18.5 Mt and the Alberta mixture generates 42.3 Mt. This is what we would expect to find considering the generating mixes. Since BC produces most of its energy with hydro its generating mix would produce much less CO_2 than the Alberta coal dominated mix, or the Ontario mix that incorporates a range of sources. According to Environment Canada Statistics, British Columbia produced 1.2 Mt of CO_2 during 2006 while Alberta and Ontario produced 115 Mt and 72 Mt respectively [14]. Therefore, our model results are comparable to the statistical amount of emissions produced in each province during 2006 once demand is factored down to the BC load.

For British Columbia's generating mix the amount of displaced CO_2 decreases substantially as the penetration rate of the renewable power increases. That is, the results display diminishing returns for abated emissions as the renewable penetration rate increases. Thus, adding a small amount of tidal power to the BC portfolio (such as 10% penetration) displaces a large percentage of CO_2 (21.6%), but adding larger amounts of the renewable power will provide much fewer benefits in terms of abated emissions (less than 1%). However, in comparison to the other generating mixes, the initial introduction of a 10% renewable penetration rate leads to the sharpest fall in emissions in relative terms in the BC mix. Before the introduction of renewable energy, the model chooses hydro to its maximum capacity to cover demand, but is forced to use gas to cover peak demand in periods when demand exceeds what can be supplied with the hydro capacity. Throughout the entire year, about 3% of the total electricity that is generated comes from gas. Note that this is consistent with actual British Columbia data for 2006. Once renewable power is introduced, we see that gas is replaced or reduced by the clean renewable power in many of the peak demand hours.

Unfortunately, the renewable power is not always available when it is needed; therefore available wind and tidal power are not completely able to replace gas in periods of high demand. During non-peak hours, the renewable energy simply replaces inexpensive and clean hydro thereby providing no improvement in terms of emissions reductions. There exist some periods when the renewable energy is able to replace gas, but only at the same rate that hydro generation is also reduced. That is, renewables are only able to reduce the overall amount of electricity that must be generated by the other sources, but they are not able to decrease the relative relationship of gas and hydro. Gas remains almost constant as a percentage of overall generation – between 2.50% and 2.98%. Due to the intermittency of the renewable power, there are still periods where no or little power is produced and gas must be used to cover the excess of demand over hydro supply. However, we must keep in mind that the penetration rate is artificially created by factoring up the power that is available. As mentioned earlier, increasing penetration by exploiting a variety of sites would reduce periods of non-availability since currents will be strong at one point when non-existent elsewhere. However, exploiting a multitude of sites is probably unrealistic and would increase O&M costs as well as the costs associated with transmission lines.

For the Ontario generating mix, renewable tidal and wind energy are able to decrease CO_2 emissions by roughly 5% as the renewable penetration is increased by 10%. Thus emissions will fall as renewable penetration increases in this type of generating mix. For the Alberta generating mix there is no change in the extent of CO_2 that is displaced as tidal and wind power penetration increases. Nonetheless, the absolute fall in emissions is the greatest in comparison to the other generating mixes since a large amount of coal is displaced by the clean renewable power. Although the benefits display constant returns to scale in our scenarios, they are most likely to begin to fall at greater renewable penetration rates as increased ramping up and down pressure is put on the system. Yet model results indicate that renewable tidal and wind power are able to mitigate substantial amounts of CO_2 emissions for this type of generating portfolio.

C. Costs of Reducing CO_2 Emissions

We calculate the cost of reducing one tonne of CO_2 (tCO_2) as the difference in our objective function (plus the capital costs of the tidal and wind farms) with and without renewable penetration, divided by the displaced CO_2 emissions when the renewable is introduced. Specifically, the function is the same as (3) and repeated here:

$$CO_2 \text{ Reduction} = \sum_{i=1}^{N} GS_i \times EF_i - \sum_{j=1}^{N+\text{Winf}+\text{Tidal}} GS_j \times EF_j \quad (5)$$

The results are provided in Table 5. The July 4, 2008 price of carbon on the European market is €27.65 (http://www.pointcarbon.com/), or about \$41 per tCO_2. On July 1, 2008, government of British Columbia began to phase in a carbon tax that will start at a rate of \$10/tCO_2 and rise by \$5 a year for the next four years to reach \$30 per tonne by 2012 [15]. Compared to these benchmarks, the model's predictions of the costs of mitigating CO_2 by introducing tidal power are high. From a purely financial prospective it would be more efficient to buy carbon credits or pay the tax.

Table 5 The Cost of Reducing CO2 Emissions through Tidal/Wind Power

Renewable penetration rate	BC	AB	ON
	\$/tonne of Carbon dioxide		
10%	659.71	133.88	103.67
20%	1112.56	104.53	121.89
30%	1674.79	97.47	129.01

As expected, the cost of reducing one tonne of CO_2 by installing tidal and wind power in the British Columbia generating mix is the highest since the renewable power mostly displaces hydro power which is considered emissions free. Only 0.92Mt of CO_2 are produced over the year because of the small amount of gas power generation that is found in the BC mix. At low penetration levels, renewable power is able to replace some of this gas, but it becomes increasingly more difficult to do so at higher penetration rates since the peaks of electrical demand occur at moments of slack water or calm winds. Therefore, the cost of displacing emissions rise sharply to \$1674.79 at penetration rates of 30%.

For the Alberta and Ontario generating mixes, the emission abatement costs are more reasonable with the highest price of \$133.88 tonne/tCO_2 and the lowest price of \$97.47 t/CO_2. Although these costs are still higher than the benchmark of \$30/tCO_2, it is encouraging to see that the costs are more moderate. If energy production can become more environmentally friendly by utilizing renewable power, society will benefit without having to change their electricity consumption behaviour. This may be the only way that climate change can realistically be fought.

D. Nonlinear Relationship between Tidal Power Capacity and Emission Abatement

Usually when policy makers consider adopting renewable energy they perform a cost benefit analysis in terms of capital cost versus displaced emissions. Often they will take the capacity factor of the renewable source and assume that it will displace a proportional amount of existing generating capacity on a one-to-one basis. They may even assume that the renewable power will displace generation from the dirtiest source one-for-one. The results of this model clearly show the error in this way of thinking. Not only can we not be sure of which traditional sources will be displaced, but the displacement is non-linear because of the efficiency losses to the entire system.

VIII. OTHER COSTS AND BENEFITS

Politically the province of British Columbia has established a climate change mitigation strategy that includes an overall target of GHG reductions of 33% below 2007 levels by 2020. Actions to achieve this objective include policies requiring all new natural gas, coal and oil fired electricity generation projects developed in BC and connected to the integrated grid to have zero net GHG emissions [16]. This will drive up the prices of thermal forms of electricity generation making renewables more cost competitive. Moreover, according to the 2008 budget announced on July 1, 2008, the province will begin phasing in a carbon tax on gasoline, diesel, natural gas, coal, propane, and home heating fuel. The starting rate will be based on $10/tCO$_2$, and rise $5/tCO$_2$ a year to $30/tCO$_2$ by 2012 [15]. These types of policies are designed to shift the market structure away from carbon based power. Thus thermal power demand will decrease since there will be economic pressure to conserve electricity and use it more efficiently, or to switch to cleaner power options.

There are many other negative environmental impacts that result from the use of traditional fuels such as air pollutants that cause health problems and damage to physical capital. There are also considerations for thermal mining practices that pollute lakes and rivers and destroy the natural landscape. Even large-scale hydro dams can cause ecological damage as the geological state of the water system is significantly altered. British Columbia has the opportunity to act as a steward to the rest of the world in demonstrating that options exist for cleaner energy generation to encourage innovation.

IX. CONCLUSION

In this paper, we used a dynamic optimization model to determine the effects of tidal and wind power integration into grids powered by different mixtures of traditional fuel. Although the pattern of available tidal stream power is more cyclical and predictable than wind power, attempting to harness power from only one location leads to irregular intervals of power supplied to the grid. Since these intervals often fail to coincide with the pattern of rising and falling electricity demand, electricity will be wasted within the generating system due to the inability of the thermal sources to adjust their power output instantaneously when the renewable power becomes available. This inefficiency leads to an added cost of tidal and wind power that must be considered in renewable project analysis.

Results indicate that wind and tidal power do have the ability to displace a percent of dirtier fuels and their corresponding emissions, but that their ability to do so depends heavily on the original portfolio of generating sources. Generating systems supplied by mixes consisting of a large percent of hydro benefit least from renewable adaptation since the tidal or wind energy mostly replaces hydro power that is already clean and cheap, while, at the same time, fails to eliminate the need for additional gas back-up power to cover periods of high demand when reservoirs are low. Areas supplied by generating mixes with a higher percent of coal in their portfolios will benefit more from the inclusion of tidal power as long as there is enough gas capacity to cover the interlude between renewable power availability and the coal plant ramping up to reach its full generating capacity.

The emission abatement cost results indicate that attempting to use tidal stream power as a means of mitigating CO_2 is an expensive alternative compared to the current price of carbon on the European market. Therefore, any recommendation to policy makers about investing in tidal stream power at this time, would be based on non-marketed values such as technological environmental stewardship or experimenting with alternatives to harmful mining practices.

REFERENCES

1. **Murphy** R, Jaccard M (2003) The voluntary approach to GHG reduction: a case study of BC Hydro. Energy Studies Review 11(2): 131-151

2. **Pitt** L, van Kooten GC, Love M, Djihali N (2005) Utility-scale wind power: impacts of increased penetration. REPA Working Paper 2005-01. University of Victoria, Victoria, British Columbia, Canada
3. **BC Hydro Green and Alternative Energy Division** (2002) Green energy study for British Columbia phase 2: mainland. Report No. E44. British Columbia, Canada
4. **Maddaloni** JD, Rowe AM, van Kooten GC (2007) Wind integration into various generation mixtures. REPA Working Paper 2007-05. University of Victoria, Victoria, British Columbia, Canada
5. **Black and Veatch** Holding Co (2006) UK tidal stream energy resource assessment. Report No. II. Carbon Trust, United Kingdom
6. **Dadswell** MJ, Rulifson RA, Daborn GR (1986) Potential impact of large-scale tidal power developments in the Upper Bay of Fundy on fisheries resources of the Northwest Atlantic. The American Fisheries Society 11(4):26-35
7. **Fraenkel** P (2006) Tidal current energy technologies. International J for Avian Science 148(1):68-70
8. **Bowditch** N (1977) American practical navigator. Washington, DC, United States, Defense Mapping Agency Hydrographic Office
9. **Blue Energy** Canada Inc (2000) Blue Energy resource study at http://www.treesearch.fs.fed.us/pubs/20572 http://www.bluenergy.com/renewable-energy.html
10. **Triton** Consultants Ltd (2002) Green energy study for British Columbia phase 2: mainland. Prepared for BC Hydro, Vancouver, British Columbia, Canada
11. **Environment Canada** (2006) Appendix A - data and inputs; key data required by the model for existing units at the unit level at http://72.14.253.104/search?q=cache:ri61M_c7lKwJ:www.ec.gc.ca/pdb/ghg/guidance/protocols/Electric2003/p7_e.cfm+typical+%22heat+rate%22+canada&hl=en&ct=clnk&cd=8&gl=ca
12. **AMEC Americas Limited** (2006) Alberta 10 year generation outlook. Calgary, Alberta, Canada
13. **International Energy Association** (2007) Statistics for western Canada 2006 at http://www.iea.org/
14. **Environment Canada** (2007) Information on greenhouse gas sources and sinks at http://www.ec.gc.ca/pdb/ghg/onlineData/kdt_t2_e.cfm?year=2006
15. **British Columbia Ministry of Finance** (2008) B.C.'s revenue-neutral carbon tax at http://www.bcbudget.gov.bc.ca/2008/backgrounders/backgrounder_carbon_tax.htm
16. **Legislative Assembly of British Columbia** (2008) Speech from the Throne 2008 at http://www.leg.bc.ca/38th3rd/4-8-38-3.htm

Enter address of the corresponding author:

- Author: G. Cornelis van Kooten
- Institute: Department of Economics, University of Victoria
- Street: PO Box 1700, Stn CSC
- City: Victoria, BC V8W 2Y2
- Country: Canada
- Email: kooten@uvic.ca