Green Energy Study for British Columbia
Phase 2: Mainland

Tidal Current Energy

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Prepared for:

BC Hydro, Engineering

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Vancouver BC

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Executive Summary

BC Hydro is investigating the application of Green Energy technologies to electrical power generation in British Columbia. As part of this large study, Triton Consultants Ltd. has completed an initial evaluation of the feasibility of exploiting tidal current energy as one source of Green Energy. This study included five principal elements;

- a detailed assessment of the tidal current resource available in BC,
- preliminary tidal modeling studies,
- case studies of one large (800 MW rated capacity) and one small (43 MW rated capacity) potential tidal current power site, including indicative energy costs,
- an initial evaluation of environmental issues and
- a review of selected tidal current technologies which are in various stages of development.

The results of this study suggest the following key conclusions, which are useful when tidal current power is compared to other Green Energy alternatives:

Pros

- Tidal current energy is **predictable** – tides can be predicted centuries into the future
- Tidal current energy is **regular** - tidal currents follow a daily cycle
- Tidal current energy peaks at different times at different sites – power can be **phased** into the electricity grid.
- Tidal current energy will not be effected by **global climate change**
- Based on tidal modeling studies, **environmental** and **physical** impacts of tidal current power generation are expected to be small.
- Tidal current resources in British Columbia are considerable – the mean annual exploitable power ranges from about **2,700 GWh/annum** for large scale installations with existing technology to approximately **20,000 GWh/annum** with realistic assumptions on near future technology. Note that 2,700 GWh and 20,000 GWh represent 5.6% and 40% respectively of BC Hydro's power generation in the year spanning 2001 to 2002.
- Present tidal current energy generation costs, using currently demonstrated technology, appear to be competitive with other Green Energy sources, at **11¢ / kWh** for a large site (800 MW rated capacity and 1400 GWh/annum) and **25¢ / kWh** for a small site (43 MW rated capacity and 76 GWh/annum). These costs assume a conservative capacity factor (mean power/rated power) of 20% and a maximum current speed of 3.5 m/s.
- Future energy costs are expected to reduce considerably as both existing and new technologies are developed over the next few years. Assuming that maximum currents larger than 3.5 m/s can be exploited and present design

developments continue, it is estimated that future tidal current energy costs between **5¢** / kWh and **7¢** / kWh are achievable.

Cons

- Tidal current technology development is in its **infancy**. There are no commercial tidal current installations presently operating in the world. Tidal current power development is estimated to be one to three years behind ocean wave and five to eight years behind wind power.
- Tidal current power generation at a specific site **varies significantly** during a typical day. This creates problems for power distribution but suggests the application to hydrogen generation or pumped storage.
- There is presently no significant **Government funding in Canada** directed at tidal current power generation. The recent rapid development of wind power turbines was as a direct result of the Danish government's direct investment in wind technology research.

Future Considerations

Following a review of this report and integration with the goals of BC Hydro Green Energy Phase 2 Study, BC Hydro Engineering has outlined a series of next steps which include:

a) Maintain a technology watch on tidal current technologies,

b) Improve knowledge of the tidal current resource in British Columbia,

c) Expand the scope to study the in-stream flow resources in British Columbia rivers,

d) Consider ways to "enable" development of tidal current energy in BC as it progresses to a near commercial energy resource.

These activities would include the following recommendations of Triton Consultants Ltd, specifically:

1. Improve the detail in the tidal model grid, specifically at narrow high current areas. Calibrate the new model grid with measured tidal data and perform additional simulations of proposed tidal power sites (e.g., Race Passage (Victoria) and Weynton Passage (Alert Bay).
2. Undertake a resource assessment for the Queen Charlotte Islands. Tidal current power potential in these islands could be significant.
3. Revise this report as new technologies become known, present technologies proceed through their development phases and more information is made available.
4. Consider collaboration with ongoing and planned pilot/demonstration installations.
5. Investigate the application of hydrogen generation to remote tidal current sites.

1. INTRODUCTION

This report on Tidal Current Energy was prepared for BC Hydro Engineering by Triton Consultants Ltd. in association with Mr. Walt van Walsum, P.Eng. The information presented will be included in the Phase 2 portion of BC Hydro's Green Energy Study.

The report describes the work completed to meet the terms of reference described in a request for proposals from BC Hydro received September 7th, 2001, and Triton's proposal dated September 25, 2001.

The study approach is outlined in the following bullets:

- Review theoretical considerations related to tidal energy extraction
- Identify sites within BC (excluding the Queen Charlottes) that have a high tidal energy potential
- Undertake a scoping level assessment of the potentially available energy at each of these sites
- Select a subset of preferred sites that meet additional development criteria such as developable area, proximity to developed areas and distribution network, etc.
- Undertake a conceptual level design and cost estimate for several sites
- Assess the hydraulic implications of a tidal energy development on the existing tidal regime
- Assess the implications of a tidal energy development on the environment
- Review available technology from global proponents of tidal energy

2. *BC RESOURCE ASSESSMENT*

A detailed tidal current resource inventory of British Columbia waters (excluding the Queen Charlotte Islands) has been completed for this study. This chapter describes the general nature of tides in British Columbia, the theoretical basis of the resource assessment and provides estimates of the tidal current power potential in the Province.

2.1 TIDES AND TIDAL CURRENTS IN BRITISH COLUMBIA

2.1.1 An Introduction to Tides

Tidal current energy is derived from the flow of coastal ocean waters in response to the tides. A background understanding of tides is helpful in understanding this report, therefore a brief description is included below. A more detailed explanation of tides can be found in "Canadian Tidal Manual" (Publication P252–Canadian Hydrographic Service website www.chs-shc.dfo-mpo.gc.ca/chs/en/products/publications.htm#pubs or on US NOAA website http://co-ops.nos.noaa.gov/restles1.html.

Tides and tidal currents are generated by gravitational forces of the sun and moon on the ocean waters of the rotating earth. Because of its proximity to the earth, the moon exerts roughly twice the tide raising force of the sun. Tides repeat themselves once every 24 hrs and 50 minutes or the lunar day, which is the time it takes a point on the earth to rotate back to the same position relative to the moon during each daily revolution.

The sun's and moon's gravitational forces creates two "bulges" in the earth's ocean waters: one directly under or closest to the moon and other on the opposite side of the earth. These "bulges" are the two tides a day observed in many places in the world. Unfortunately, this simple concept is complicated by the fact that the earth's axis is tilted at 23.5 degrees to the moon's orbit – the two bulges in the ocean are not equal unless the moon is over the equator. This difference in tide height between the two daily tides is called the diurnal inequality or declinational tides and they repeat on a 14 day cycle as the moon rotates around the earth.

Spring and neap tides have been known for many centuries. Spring tides occur at the time of new or full moon when the sun and moon's gravitational pull is aligned. These tides occur at a 15 day cycle and the combination of this cycle and that of the 14 day declinational tidal cycle explains some of the variability of the tides through the months of the year. There are more than a hundred harmonic constituents or cyclic components of the tide each with a different cycle time. These constituents combine so that tides completely repeat themselves every 18.6 years.

Tides move as shallow water waves in ocean and coastal waters. Despite its name a shallow water wave can exist in any depth of water. Their main characteristic is that the whole depth of water moves as the wave passes. This is unlike wind waves which, except in very shallow water near shore, only move the top few tens of metres of the water column. Shallow water waves move at a celerity related to the square root of the water depth which in the open sea can be several hundred kilometres per hour. In the open ocean tides are small, rarely exceeding 0.5 m. However, as the tidal wave enters coastal waters it slows down, shoals (increases in height) and is reflected in coastal basins. This explains how a small deep ocean tide can result in 15 m tides in the Bay of Fundy or the 8 m tides at Prince Rupert.

As discussed above the total tidal wave is made up of components (constituents) with different harmonic periods and wave lengths. The principal semi-diurnal or twice daily components are M2 (moon, twice daily) and S2 (sun, twice daily) and the principal diurnal or once daily components are K1 and O1 (moon+sun and moon declinational constituents respectively). Like all diurnal components the KI and O1 result from the declination of the moon and sun relative to the earth during the monthly tidal cycle. In coastal waters these different components may resonate in the bays and straits along the coast depending on their wavelength determined by water depth and the size and shape of the basin. This process is much like the slopping of water in a bathtub. For example, the Bay of Fundy is perfectly “tuned” in terms of water depth and shape to the semi-diurnal tide entering at its mouth. In BC, the small diurnal tides at Victoria and the increasing tide range as one moves north in Strait of Georgia result from the “tuning out” of the M2 tide in Juan de Fuca Strait and the resonance or tuning of the M2 tide in Strait of Georgia respectively.

Tidal currents result from the passage of the tidal wave. Contrary to popular belief large tidal currents do not necessarily require a large tidal range. Some of the largest tidal flows in the world occur between the islands on the east side of the Philippines where the tidal range is small but the tide is high in the Pacific at the same time that the tide is low within the Philippine Islands. In technical terms, this is described as the two tides being 180 degrees (or half a cycle) out of phase. The result is very large tidal currents.

Another factor that impacts the magnitude of tidal currents is the presence of narrow passages. These passages result in a narrowing and concentration of tidal flow. However the flow through a passage is constrained by the loss of energy due to friction. If this loss exceeds a certain value the flow will start to reduce and in the case of a tidal inlet (e.g., Sechelt Inlet), the tidal range and resulting flows are reduced. There is clearly a limit to the energy that can be extracted, either by nature (in friction) or with a tidal power plant, from such tidal current flows.

In BC, some of the highest velocity tidal current flows occur through the passages between Strait of Georgia and Johnstone Strait. The tidal range is moderate (5 m), but the tides from the Pacific through Johnstone Strait are roughly 180 degrees out of phase with the tides in Strait of Georgia entering south of Vancouver Island.

From a tidal current perspective, it is also important to understand that semi-diurnal tides produce twice the current of the diurnal tide of the same height. This is because the semi-diurnal tide rises in half the time of the equivalent diurnal tide. This is particularly important in British Columbia where many of the potential tidal current power sites are located in areas where the diurnal tide component is strong.

2.1.2 Tides in British Columbia

Tides in British Columbia coastal waters are complex and their characteristics change from place to place. Figure 1 shows typical monthly tide height curves for January 2002 for Victoria, Vancouver, Campbell River and Prince Rupert along with current velocity curves for Race Passage, First Narrows, Seymour Narrows and Tuck Narrows respectively.

For reference, we have included the tidal curves and currents for the North Devon Coast (UK) where Marine Current Turbines (see section 6.1) propose their first prototype tidal current power unit. The tide heights shown for that location correspond to the Port of Ifracombe, and the current velocities are based on those assumed by Binnie, Black and Veatch (2001) in “The Commercial Prospects for Tidal Stream Power“ (the UK Department of Trade and Industry, New and Renewable Energy Program) for the same location as described in BBV (2001).

The following notes are useful in reviewing the tide and current data shown in Figure 1.

Victoria/ Race Passage

The tides at Victoria are principally diurnal or once per day. There exists near Victoria an amphidromic (near zero tide height) point in M2 where semi-diurnal tides are extremely small. Although the Race Passage currents look very attractive for power generation, it is important to understand that extensive energy extraction may move the location of the amphidromic point and seriously alter the tidal current energy available at this site.

Note that despite the very small semi-diurnal tide height component at this site, the large tidal currents in Race Passage are dominated by the semi-diurnal component rather than the diurnal component.

Vancouver/ First Narrows

Vancouver shows the transition from the diurnal tides at Victoria to the more typical mixed or diurnal/semi-diurnal tides in the Strait of Georgia. Note the significant diurnal inequality for both tide height and current or the difference between the height and current from the higher high tide and the lower high tide each day.

Campbell River/Seymour Narrows

Campbell River/Seymour Narrows show the gradual increase in the importance of the semi-diurnal tide as one moves north in the Strait of Georgia. In particular, the diurnal inequality in currents has reduced significantly from Vancouver. However, it is important to remember that tidal current power is proportional to the cube of current speed. The inequality is still very important.

Prince Rupert/Tuck Narrows

The tides at Prince Rupert are classified as mixed mainly semi-diurnal. This can be seen on the tide height curve where the diurnal inequality is much reduced from Campbell River and Vancouver. Because the semi-diurnal tide tends to dominate currents the diurnal inequality in current is quite small at Tuck Narrows.

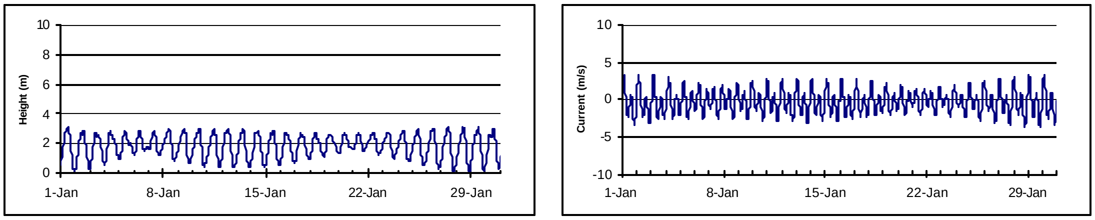
North Devon Coast – Marine Current Turbines Prototype Installation Site

This tidal station is included for comparison of BC tides with those in the UK where tidal current energy resources are closer to being developed commercially. Tides in North Western Europe are basically semi-diurnal, that is to say that the height of the two daily high waters are very similar. For tidal current, the maximum speeds of the two tides are almost identical. Note that the tidal range in North Devon approaches 10 m which is more than double the typical range in British Columbia. Although this flow is not constrained by narrows, as in BC, it nevertheless produces moderate but usable currents for tidal power over large areas. This characteristic makes these NW European tidal flows very suitable for tidal farm exploitation, where large areas of seabed with moderate current are required.

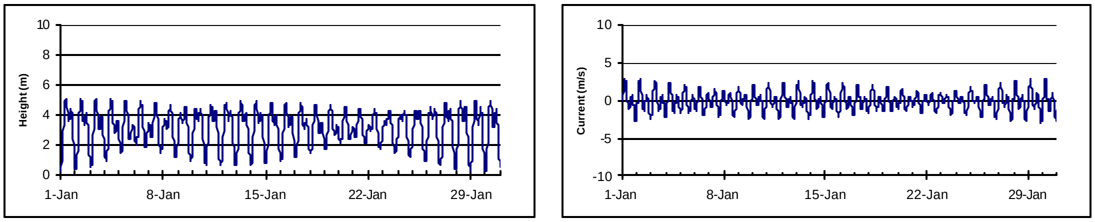
An important conclusion from this comparison of tidal curves in BC and NW Europe is that because of the diurnal inequality in BC and the dependence of tidal current power on the cube of current speed, the same daily maximum current will produce less power in BC than in the fully semidiurnal tidal regime in Europe.

Figure 1: Representative BC Tidal Curves

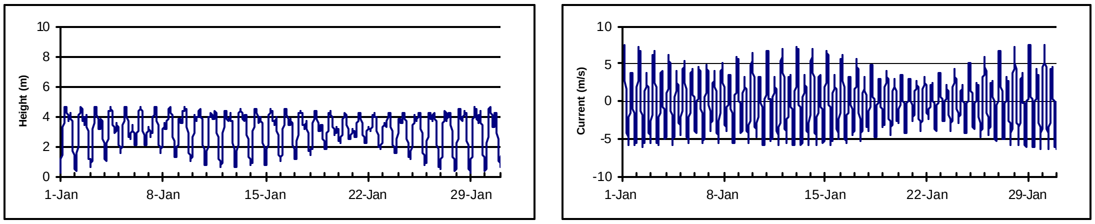
VICTORIA



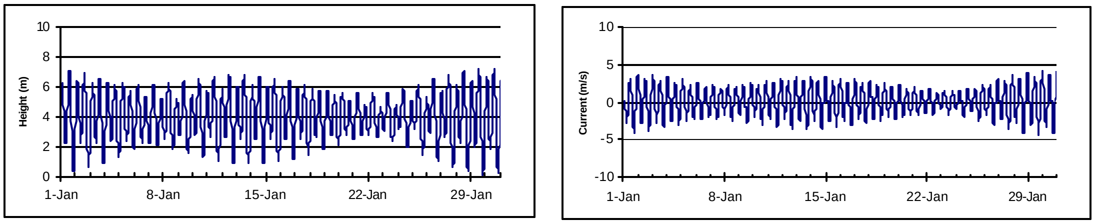
VANCOUVER



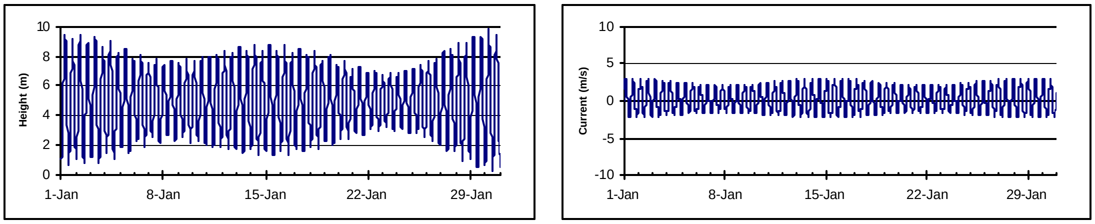
CAMPBELL RIVER



PRINCE RUPERT



NORTH DEVON, ENGLAND

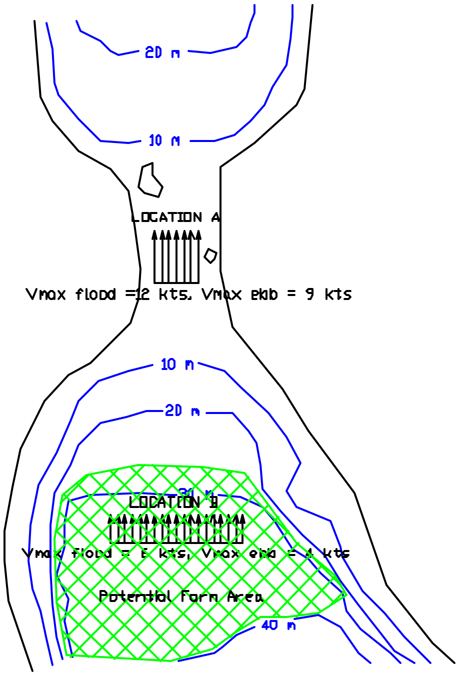


2.2 THEORETICAL BASIS

In concept, tidal energy may be viewed as being extracted directly from the kinetic energy of a tidal stream, or as being extracted from the potential energy of impounded tidal water. In reality, the two are closely related since the extraction of kinetic energy from a tidal stream increases the slope of the hydraulic grade line yielding “partially impounded” water on alternating ends of the tidal channel[1]. Nevertheless, the two approaches are described separately in the following sections.

Figure 2 shows a hypothetical tidal site that will be used to describe the approach followed in the assessment of tidal stream energy.

Figure 2: Hypothetical Tidal Current Site - Definition Sketch



Location A is representative of those locations typically described by the Canadian Hydrographic Service as “narrows” or “tidal rapids” which are critical to marine navigation. For this reason, information pertaining to these areas was used as the primary basis of the overall assessment of provincial tidal resources.

For the example shown, the flood/ebb maximum currents in the narrows peak at 12 knots/9 knots a few times per year. Although these currents carry enormous quantities of energy, marine construction in such conditions would be extremely difficult and the cost and feasibility of constructing/maintaining infrastructure in these currents may be prohibitive. For this reason, Triton has taken the conservative assumption that

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[1] Theoretical considerations (Garrett, unpublished) demonstrate that the maximum power that can be extracted from a series of tidal stream turbines across the entrance of an embayment will result in a situation in which the tidal amplitude inside the bay is reduced to 71% of that outside the bay.

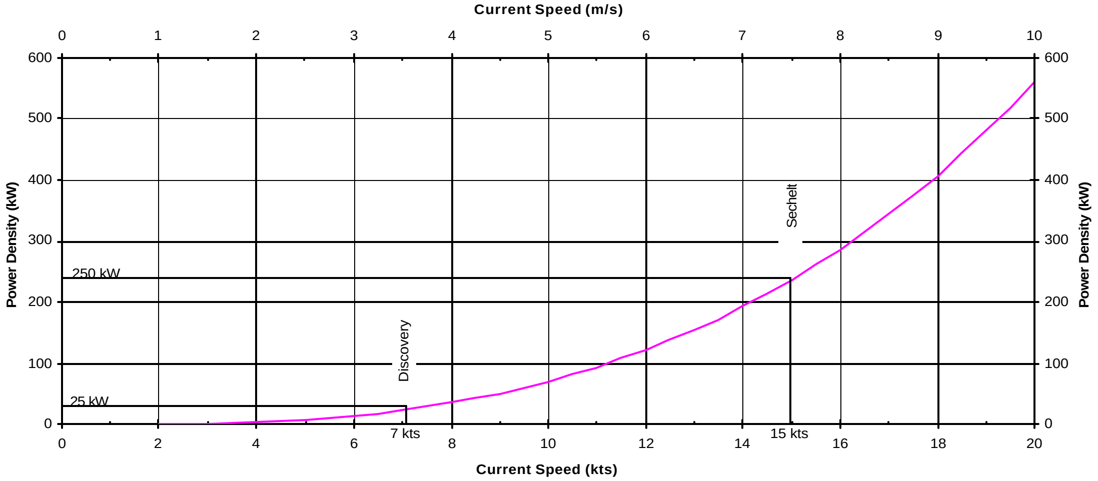
infrastructure would be installed somewhere near but outside of the region of maximum currents.

One well-documented example (by Binnie, Black and Veatch, 2001) of tidal current energy technology is that developed by Marine Current Turbines Ltd. (MCT) which is described in detail in Section 6.1. BBV (2001) indicate that an optimal maximum design current for their present design is of the order of 6 knots, which is consistent with Triton's experience. Because of flow continuity, there exists a wider and/or deeper cross section outside the narrows that will exhibit maximum currents of this magnitude (e.g., Location B). It is at this location that the theoretical power (energy flux) across the channel cross section is computed and tabulated for potential sites throughout the province. The theoretical instantaneous power $P_{cross\text{-}section}$ (W) in a flow cross-section is given by:

$$P_{cross-section} = \frac{1}{2} r A_{cross-section} U^3$$

where ? is the density of water (kg/m^3), $A_{cross\text{-}section}$ is the cross-sectional area (m^2), and U is the instantaneous current velocity (m/s). The average value of this parameter throughout the year yields the mean theoretical power at each site considered. Figure 3 shows the sensitivity of the power calculation to the current speed selected.

Figure 3: Sensitivity of Power to Current Speed



The 6 knot assumption is extremely sensitive to advances in technology as it is quite likely that a more advanced method of anchoring the turbines[2] could emerge that would allow deployment of the turbines within the areas of maximum current velocity. Given the U^3 power relationship, such a technological advance might provide a significant leap in available power.

We believe that the theoretical mean power is a reasonable benchmark to gauge the relative tidal current potential of various sites. It must be noted, however, that this

---

[2] Perhaps a variation of UEK's (see Section 6.5) approach

parameter is only loosely related to the extractable power since extractable power is highly dependant on the physical characteristics of the site and the technology applied.

For MCT technology, the instantaneous extractable power $P_{extractable}$ is given by:

$$P_{extractable} = N_{units} h \frac{1}{2} r A_{turbine} U^{3}$$

where N_{units} is the number of installed units, ? is the turbine/mechanical/electrical efficiency, and $A_{turbine}$ is the turbine rotor area in each unit. The number of units that can be installed in a MCT farm is primarily limited by construction issues related to water depth (18 m to 40 m) and inter-unit wake considerations. The turbine area is defined by rotor diameter which is limited by water depth/clearance draft above and manufacturing consideration (10 m to 16 m). A final overriding consideration is the feedback of this energy extraction on the driving marine hydraulic conditions; i.e., are the post-project flow conditions significantly lower than pre-project therefore resulting in less available energy than anticipated in the first design iteration. This consideration is described in detail in Chapter 3.

For the example shown in Figure 2, there is a finite farm area that can be used that dictates the maximum number of units that can be installed. Note that, in theory, the “total extractable power” could be greater than the “theoretical power” described above if the number of units installed is so large that the value of ? x $A_{turbine}$ exceeds $A_{cross\ section}$ provided that the driving hydraulic conditions have not been significantly reduced.

2.3 POTENTIAL TIDAL CURRENT POWER SITES

The area considered in this assessment includes the BC mainland, Vancouver Island, but excludes the Queen Charlotte Islands. This inventory was based on a variety of available data sources including:

- existing Triton numerical model results and previous Triton project experience within BC,
- published Canadian Hydrographic Service (CHS) tide books, charts and the BC Coast Pilot,
- discussions with key oceanographic experts within the province including Dr. Falconer Henry (Triton Consultants), Institute of Ocean Sciences (IOS) scientist Dr. Michael Foreman, CHS representative Mr. Fred Stephenson, and local pilots.

This information was used to create a resource database that summarizes the key physical parameters for a long-list of potential sites. This database was used to identify the most promising sites in the province.

A total of 100 sites were selected for initial consideration (see Appendix A). Only sites with maximum recorded large tide flood or ebb current speeds over 3 knots (1.55 m/s) were included in the initial site listing. This current speed is equivalent to about a 1.24 m/s depth/cross-sectional average current speed or about 80% of the recorded maximum current. Portions of the relevant nautical chart were compiled for each site and converted to Adobe PDF format.

The mean annual potential (or theoretical) cross-sectional power for all these sites was estimated to be 3020 MW. As described in Section 2.2, we believe that potential mean cross-sectional power is a reasonable benchmark to gauge the relative tidal potential of different sites. However, it must again be noted that this parameter is only loosely related to extractable power since extractable power is highly dependant on the physical characteristics of the site and the technology used.

Figure 4 to Figure 9 show the potential sites considered. The plotted red circles are scaled to represent the theoretical mean annual cross-sectional potential power at each site. Sites with maximum depth and cross-sectional current speed greater than 2.0 m/s are shown with a central black dot. Note that the Ripple Rock site shown on Figure 8 is the same as Seymour Narrows shown in Appendix A and Table 1.

Figure 4: Potential Tidal Sites - Overview

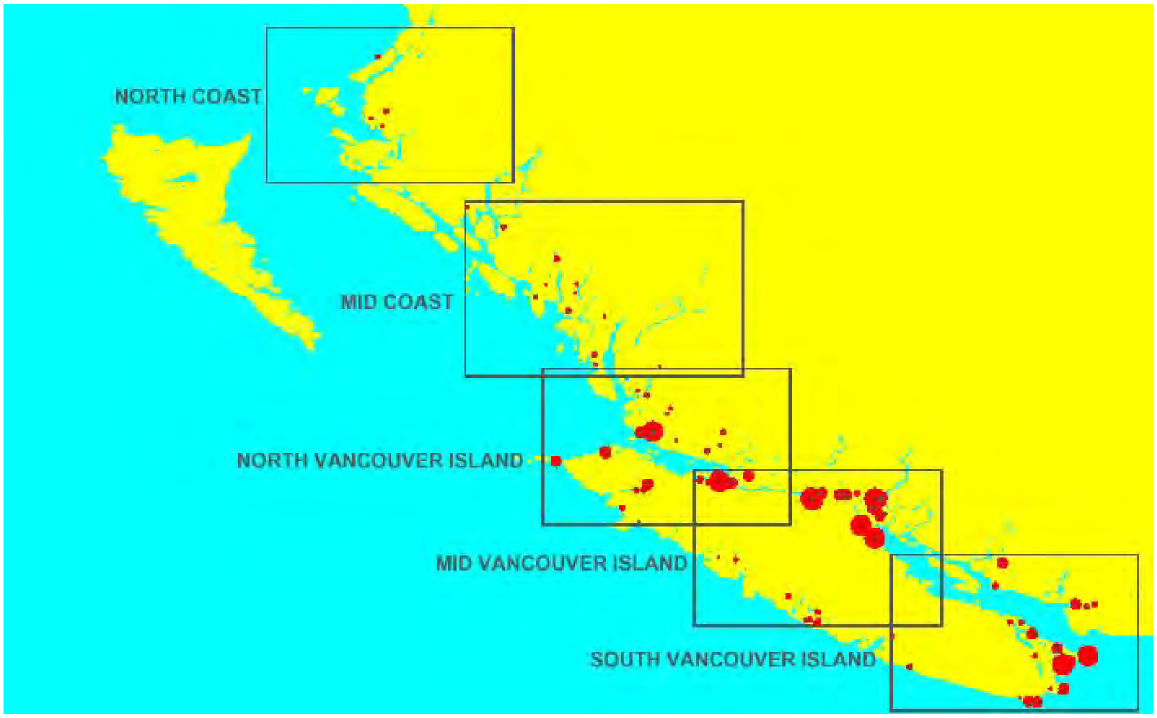


Figure 5: Potential Sites - North Coast

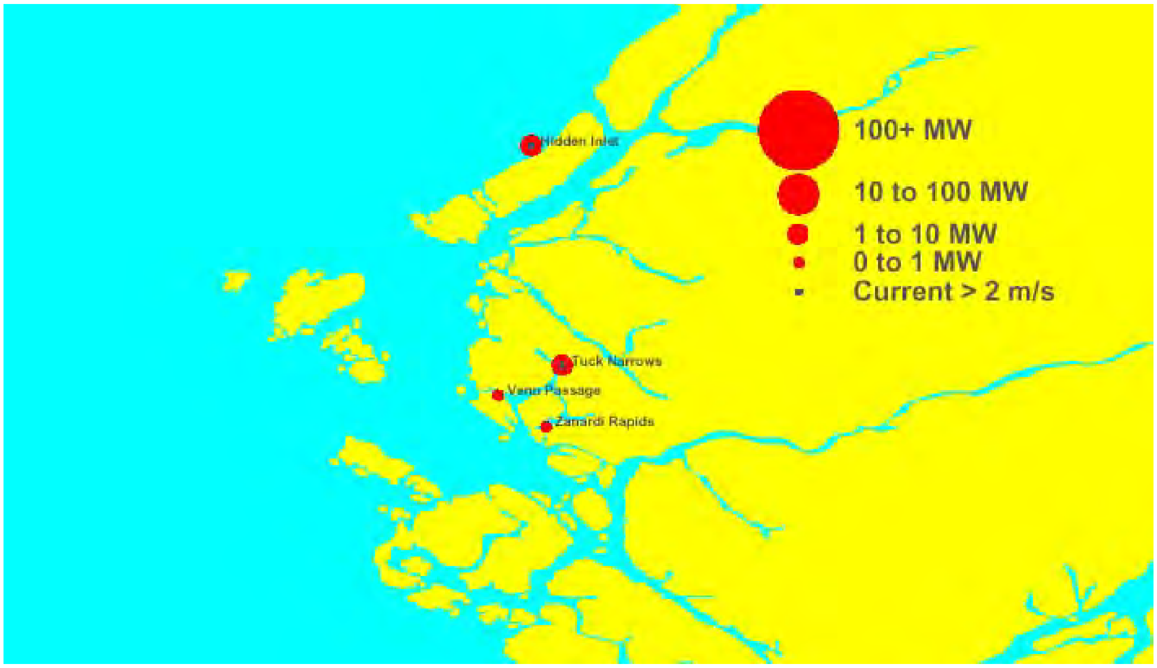


Figure 6: Potential Sites - Central Coast

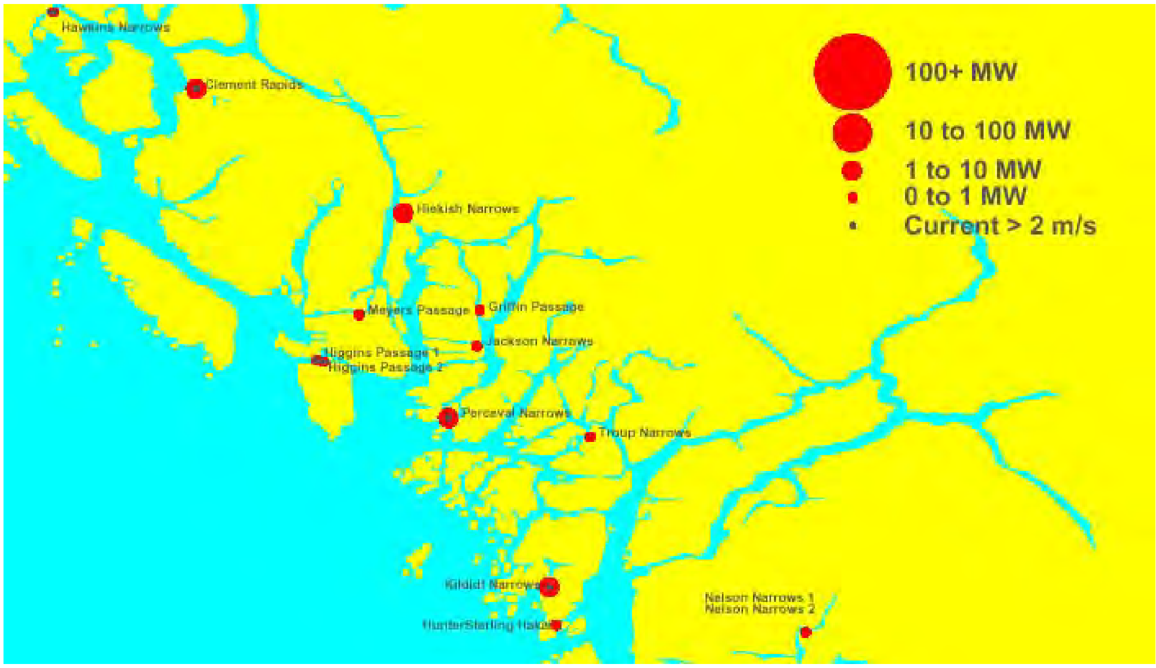


Figure 7: Potential Sites – North Vancouver Island

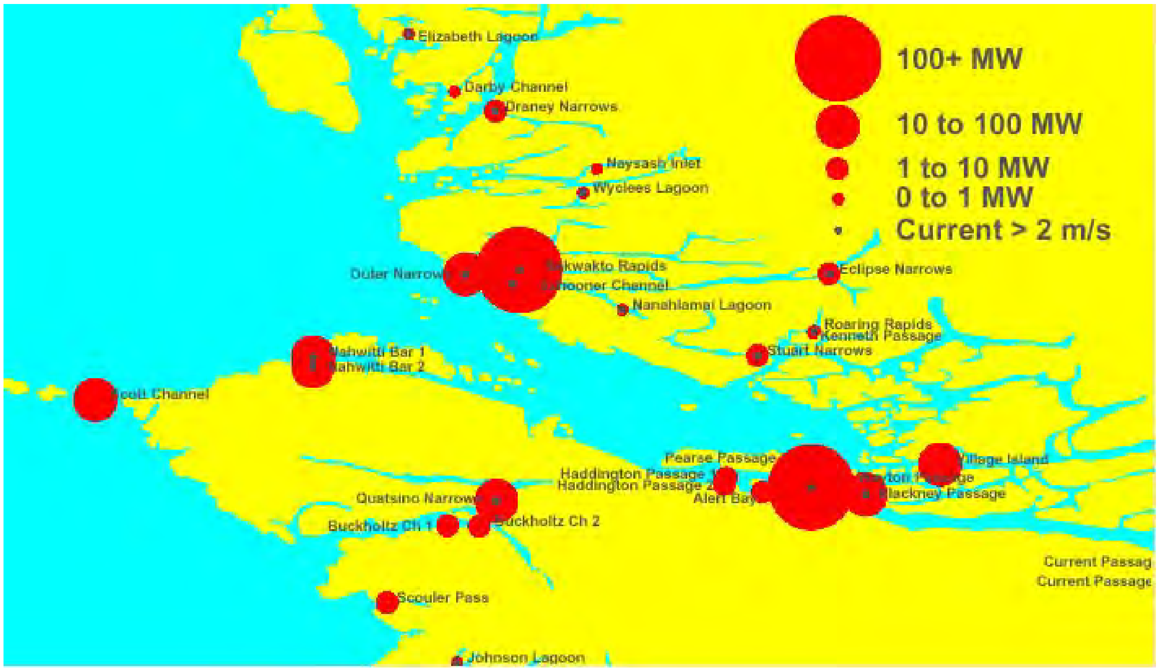


Figure 8: Potential Sites – Central Vancouver Island

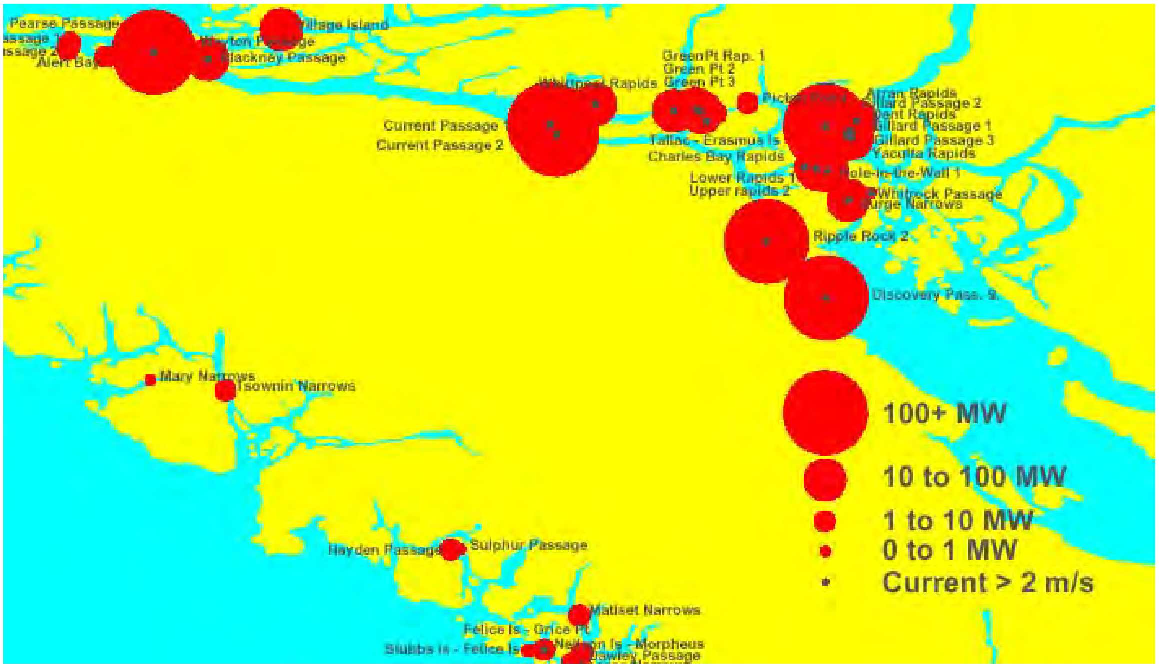
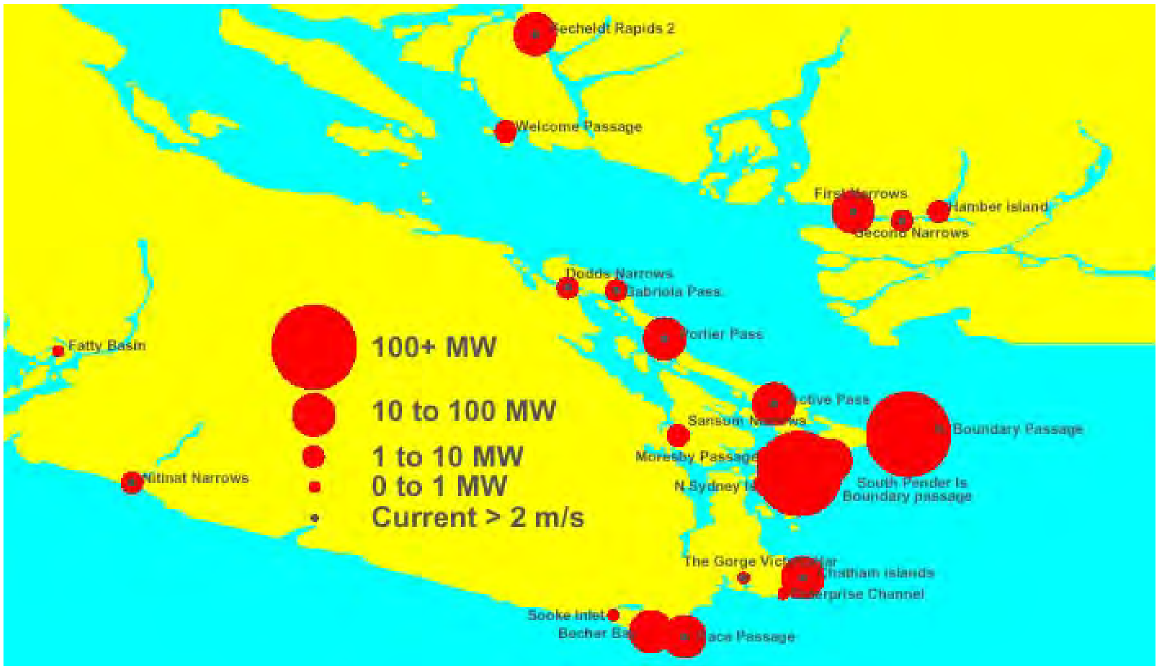


Figure 9: Potential Sites – Southern Vancouver Island and Lower Mainland



Following review of Figure 4 to Figure 9, in conjunction with the initial site resource data base (see Appendix A), a selected list of potential tidal current sites with a maximum (depth-averaged) current greater than 2.0 m/s has been developed. This data is shown on Table 1 below. Based on the present and probable future technology available for tidal current extraction, it is believed that 2.0 m/s is the smallest maximum current that should be seriously considered for power generation.

The total provincial potential tidal current energy for all sites with maximum currents greater than 2.0 m/s, based on cross-section current or energy flux, is **2,224 MW (19,482 GWh/annum)**. This is the average power generated by tidal currents and not the rated capacity of the turbines. Potential power sites range in size from over 600 MW for Seymour Narrows near Campbell River to very small sites such as the Gorge in Victoria (potential about 0.1 MW). At some of these sites, such as Seymour Narrows, the current is too strong for a tidal current power installation using present techniques. However there is good reason to believe that advances in technology and construction techniques will make high current sites exploitable in the future.

Note: Annual mean power density and the resulting mean potential power is based on the expression ½ x ? x $^{4}/(3\pi)$ x U^3, where U is the annual mean peak flood and ebb current velocity equal to 0.9 and 0.5 times their large tide mean depth and cross-section average values respectively. Currents are assumed to vary sinusoidally. A more detailed description of the power calculation for mean power density and mean potential power is shown on Table 2 and Table 3 in the following section.

Table 1: Potential Tidal Current Power Sites – Maximum Current > 2.0 m/s

				Maximum Current Speed		Mean Maximum Depth Average Current Speed	Mean Power Density	Width of Passage	Average Depth of Passage	Flow Cross-sectional Area	Mean Potential Power
Site Name	Chart	Latitude	Longitude	Flood knots	Ebb Knots	Umax m/s	kW/m2	m	m	m2	MW
Seymour Narrows	353902	50.13195	125.3532	16	14	6.18	21.896	765	35.0	28689	628.2
Discovery Pass. S.	353901	49.99732	125.21074	7	7	2.88	2.225	1866	35.0	69993	155.8
Current Passage 2	354401	50.38846	125.85515	6	6	2.47	1.401	1502	80.0	123931	173.7
Weyton Passage	354601	50.58507	126.81597	6	6	2.47	1.401	1535	75.0	118985	166.7
Nakwakto Rapids	355001	51.09701	127.50349	14	16	6.18	21.896	434	10.0	5426	118.8
Current Passage 1	354401	50.41137	125.87088	5	5	2.06	0.811	1398	100.0	143331	116.2
Dent Rapids	354301	50.4081	125.21222	11	8	3.91	5.562	420	45.0	19955	111.0
Yaculta Rapids	354301	50.37895	125.14969	10	10	4.12	6.488	539	20.0	12135	78.7
Arran Rapids	354301	50.42057	125.13931	14	10	4.94	11.211	271	22.0	6629	74.3
Secheldt Rapids 2	351403	49.7378	123.89563	14.5	16	6.28	23.009	261	8.0	2739	63.0
Gillard Passage 1	354301	50.39297	125.15883	13	10	4.74	9.867	237	16.0	4393	43.3
Active Pass	344201	48.85934	123.32864	8	8	3.29	3.322	561	20.0	12628	41.9
Nahwitti Bar 1	354901	50.89223	127.99033	5.5	5.5	2.27	1.079	2993	9.0	34417	37.1
Race Passage	344001	48.30701	123.54017	6	7	2.68	1.782	884	20.0	19885	35.4
Green Pt 2	354301	50.44883	125.52102	6	6	2.47	1.401	538	35.0	20157	28.2
Blackney Passage	354601	50.56755	126.68757	5	5	2.06	0.811	814	40.0	34598	28.1
GreenPt Rap. 1	354301	50.44127	125.50964	7	7	2.88	2.225	440	25.0	12093	26.9
Porlier Pass	347303	49.01427	123.58759	9	8	3.50	3.984	339	15.0	5926	23.6
Gillard Passage 2	354301	50.39559	125.15103	10	8	3.71	4.730	393	10.0	4916	23.2
Upper rapids 2	353701	50.30565	125.23395	9	9	3.71	4.730	242	18.0	4955	23.4
Whirlpool Rapids	354401	50.45994	125.76201	7	7	2.88	2.225	321	28.0	9804	21.8
Surge Narrows	353701	50.2307	125.15816	6	6	2.47	1.401	413	30.0	13432	18.8
Chatham Islands	344001	48.44708	123.25929	6	6	2.47	1.401	903	12.0	13099	18.4
Quatsino Narrows	368106	50.55297	127.55808	9	8	3.50	3.984	207	18.0	4240	16.9
Hole-in-the-Wall 1	353901	50.30068	125.20804	12	9.5	4.43	8.060	189	8.0	1985	16.0
Outer Narrows	355001	51.0874	127.63174	7	10	3.50	3.984	210	17.0	4101	16.3
Green Pt 3	354301	50.44464	125.57464	5	5	2.06	0.811	673	25.0	18498	15.0
Nahwitti Bar 2	354901	50.87027	127.99101	5.5	5.5	2.27	1.079	2012	4.0	13078	14.1
First Narrows	349301	49.31557	123.13949	6	6	2.47	1.401	418	16.0	7734	10.8
Lower Rapids 1	353701	50.30959	125.26255	7	7	2.88	2.225	371	8.0	3891	8.7
Perceval Narrows	371004	52.33428	128.37644	5	5	2.06	0.811	382	25.0	10518	8.5
Charles Bay Rapids	354301	50.41842	125.49489	5	5	2.06	0.811	664	12.0	9631	7.8
Draney Narrows`	393102	51.47226	127.56075	9	9	3.71	4.730	139	7.5	1394	6.6
Gabriola Pass.	347501	49.12907	123.70216	8.5	9	3.60	4.346	137	8.0	1435	6.2
Second Narrows	349402	49.29472	123.02383	6	6	2.47	1.401	254	13.9	4159	5.8
Nitinat Narrows	364703	48.67282	124.85237	8	8	3.29	3.322	61	20.0	1376	4.6
Stuart Narrows	354701	50.89622	126.943	6	7	2.68	1.782	261	7.0	2478	4.4
Dodds Narrows	347501	49.13552	123.81752	9	8	3.50	3.984	91	9.0	1047	4.2
Kildidt Narrows	393701	51.88615	128.10968	12	12	4.94	11.211	75	2.0	338	3.8
Hidden Inlet	399401	54.94961	130.33449	9	9	3.71	4.730	142	2.5	710	3.4
Gillard Passage 3	354301	50.3877	125.16275	10	8	3.71	4.730	92	5.0	686	3.2
Tuck Narrows	396402	52.39984	130.25672	6	6	2.47	1.401	138	7.0	1310	1.8
Eclipse Narrows	355201	51.0886	126.77381	6	5	2.27	1.079	141	6.0	1199	1.3
Neilson Is - Morpheus	368501	49.15596	125.88366	5	5	2.06	0.811	202	4.0	1311	1.1
Clement Rapids	374001	53.20422	129.04198	6	6	2.47	1.401	80	7.0	760	1.1
Schooner Channel	355201	51.06466	127.52058	6	6.5	2.57	1.584	72	6.0	612	1.0
Hawkins Narrows	372201	53.40701	129.41822	8	8	3.29	3.322	55	2.5	273	0.9
Higgins Passage 2	371005	52.48271	128.70529	5	5	2.06	0.811	173	3.0	952	0.8
Whitrock Passage	353701	50.24827	125.10346	7	7	2.88	2.225	68	2.0	304	0.7
Nanahlamai Lagoon	355201	51.00323	127.26068	8	9	3.50	3.984	46	1.0	161	0.6
Higgins Passage 1	371005	52.48653	128.72405	5	5	2.06	0.811	110	1.0	384	0.3
Roaring Rapids	354701	50.95378	126.80936	6	6	2.47	1.401	60	1.0	212	0.3
Wyclees Lagoon	393101	51.27947	127.35355	7	7	2.88	2.225	30	1.0	105	0.2
Johnson Lagoon	368301	50.17105	127.65066	5	5	2.06	0.811	47	3.0	261	0.2
The Gorge VictoriaHar	341501	48.44637	123.39983	6	6	2.47	1.401	20	2.0	90	0.1
Elizabeth Lagoon	392101	51.65427	127.76427	5	5	2.06	0.811	38	1.0	134	0.1

Total Mean Potential Power Umax>2.0m/s **2224 MW**

2.4 UTILITY SCALE TIDAL CURRENT POWER SITES

One of the principal objectives of this study was to evaluate the potential for “Utility Scale” tidal current power sites in British Columbia using available or soon to be available technologies. We have assumed that utility scale implies sites with a potential power greater than 10 MW.

At the present time, there is no significant tidal current power site operating anywhere in the World. As will be discussed in Section 6, only Marine Current Turbines (UK) is close to installing a large scale test unit in the ocean this year (2002). Except for UEK (USA) which has actually tested small scale units, all the other companies promoting large scale tidal current power are at the very early research and development stage.

Despite this lack of real installation data, Marine Current Turbines (MCT) have published a number of excellent research and development reports which can be used to evaluate the potential and costs for tidal current power in BC. The most useful of these reports is that produced by Binnie, Black and Veatch (BBV) in April 2001 for the UK Department of Trade and Industry, New and Renewable Energy Program, European Commission 1996. These reports are considered to be the best reviews of tidal current power technology and costs available at this time. They have therefore have been used as the basis for estimating utility scale power developments in the present report.

A description of MCT’s technology can be found in Section 6.1.

Table 2 shows a list of utility scale tidal current site in British Columbia selected from the potential sites identified in Section 2.3 and is based on the following assumptions:

- Marine Current Turbines technology
- Seymour Narrows was not included due to the fact that currents are too high
- Active Pass was not included due to the fact that the passage is too shallow and is a ferry route
- First Narrows was not included due to the fact that it is too shallow and is subject to intensive marine traffic
- Maximum flood and ebb currents reduced by a factor of 0.8 to represent mean max cross-sectional and depth averaged current speed - U max
- Power Density = 0.5 x 1.025 x U^3 KW/m^2
- Turbine Mean Power 200 kW
- Turbine density approximately 0.5 units (2 rotors) per hectare (1 unit/20,000 m^2)
- Sites with a potential cross-sectional power greater than 10 MW
- Sites with a mean maximum cross-sectional current speed greater than 2.4 m/s
- Sites with currents in excess of 3.5 m/s have been down rated to 3.5 m/s (as described in Section 3.2)

Table 2: Selected List of Utility Scale Tidal Current Power Sites

Turbine Technology Assumption - Marine Current Turbines (UK)

Sites with Potential Cross-sectional Power > 10 MW
Sites with Mean Maximum Cross-section Current Speed > 2.4 m/s or 4.7 knots
Sites with a Cross-section Mean Water Depth >= 18 m

(1) Site Name	(2) Chart	(3) Latitude	(4) Longitude	(5) Maximum Current Speed Flood	(6) Maximum Current Speed Ebb	(7) Mean Maximum Depth Average Current Speed	(8) Mean Power Density	(9) Width of Passage	(10) Average Depth of Passage	(11) Flow Cross-sectional Area	(12) Mean Potential Cross-Sectional Power	(13) Mean Potential Power Max Velocity 3.5 m/s	(14) Passage Length	(15) Potential Area of Turbine Farm	(16) No of Turbines "Marine Current Turbines"	(17) Mean Power	(18) Annual Power	(19) Realistic Farm Area Factor	(20) Realistic Mean Power
				knots	Knots	m/s	kW/m2	m	m	m2	MW	MW	m	ha		MW	GWhr		MW
Discovery Pass. S.	353901	49.99732	125.21074	7	7	2.88	2.225	1866.49	35	69993	155.76	155.757	17000	3173	1587	317.30	2780	0.50	158.7
Current Passage 2	354401	50.38846	125.85515	6	6	2.47	1.401	1502.19	80	123931	173.67	173.672	5000	751	376	75.11	658	0.75	56.3
Weyton Passage	354601	50.58507	126.81597	6	6	2.47	1.401	1535.29	75	118985	166.74	166.741	5000	768	384	76.76	672	0.80	61.4
Dent Rapids	354301	50.4081	125.21222	11	8	3.91	5.562	420.1	45	19955	111.00	88.827	1200	50	25	5.04	44	0.90	4.5
Yaculta Rapids	354301	50.37895	125.14969	10	10	4.12	6.488	539.33	20	12135	78.73	56.861	2400	129	65	12.94	113	0.60	7.8
Arran Rapids	354301	50.42057	125.13931	14	10	4.94	11.211	270.58	22	6629	74.32	37.275	700	19	9	1.89	17	0.60	1.1
Race Passage	344001	48.30701	123.54017	6	7	2.68	1.782	883.78	20	19885	35.43	35.429	1400	124	62	12.37	108	0.70	8.7
GreenPt Rap. 1	354301	50.44127	125.50964	7	7	2.88	2.225	439.73	25	12093	26.91	26.910	1675	74	37	7.37	65	0.80	5.9
Upper rapids 2	353701	50.30565	125.23395	9	9	3.71	4.730	241.72	18	4955	23.44	20.897	527	13	6	1.27	11	0.70	0.9
Whirlpool Rapids	354401	50.45994	125.76201	7	7	2.88	2.225	321.45	28	9804	21.82	21.817	600	19	10	1.93	17	0.90	1.7
Surge Narrows	353701	50.2307	125.15816	6	6	2.47	1.401	413.28	30	13432	18.82	18.823	800	33	17	3.31	29	0.90	3.0
Quatsino Narrows	368106	50.55297	127.55808	9	8	3.50	3.984	206.85	18	4240	16.90	16.889	450	9	5	0.93	8	0.90	0.8
											903.53	819.90			2581.17	516.23	4522.21		310.83 MW

Annual Power GWhrs 2722.867

Notes:

1. Seymour Narrows not included - currents too high
2. Active Pass not included - too shallow with Ferry Traffic
3. First Narrows not included - to shallow with intensive marine traffic

Assumptions

1. Maximum flood and ebb currents reduced by a factor of 0.8 to represent mean max crossectional and depth averaged current speed - U max
2. Mean Power Density based on Umax(spring tide)=Umax * 0.9 and Umax(neap tide)=Umax * 0.5
3. Mean Power Density = 0.5 * 4/3/pi*(Umax(spring tide)**3 + Umax(neap tide)**3)/2* 1.025 KW/m2
4. Turbine Mean Power 200 KW
5. Turbines approx 0.5 unit (2 rotors) per hectare (1 unit/20,000 m2)

The values in the columns of Table 2 are described in Table 3

Table 3: Description of Columns in Table 2

Column	Description
1	Site name
2	CHS Nautical Chart
3	Latitude of site
4	Longitude of site
5	Maximum large tide flood current speed at location critical to navigation
6	Maximum large tide ebb current speed at location critical to navigation
7	Mean depth- and cross-section averaged speed during large tides (80% of average maximum large tide flood and ebb values)
8	Annual <u>mean</u> power density based on the expression ½ x ? x $^{4}/(3\pi)$ x U^3, where U is the annual mean peak flood and ebb current velocity equal to 0.9 and 0.5 times their large tide mean depth and cross-section averaged values respectively. Currents are assumed to vary sinusoidally.
9	Representative channel width at location of maximum currents
10	Representative channel depth at location of maximum currents
11	Representative channel area at mean tide at location of maximum currents
12	Mean cross sectional potential power at location of maximum currents computed from the product of the annual mean power density and the mean channel area.
13	As Column 13 except that the power is now calculated at a location in which maximum currents are limited to 3.5 m/s.
14	Potential length of channel in which MCT turbines could be installed
15	Potential area of channel in which MCT turbines could potentially be installed
16	Potential number of MCT turbines that could be installed
17	Potential mean extractable power assuming each turbine generates 200 kW
18	Potential annual extractable energy
19	Fraction of potential farm area that would realistically be utilized
20	Mean power that would realistically be extracted

As shown in Table 2, the mean total provincial (excluding Queen Charlotte Islands) realistic tidal current resource potential for sites with greater than 10 MW potential is about 300 MW (or 2700 GWh/year) assuming MCT technology is applied. The most energy rich site based on the above assumptions appears to be Discovery Passage with almost one half of the provincial total.

Other evolving tidal current technologies, for example Clean Current (Section 6.3) and RVco (Section 6.4), may yield a potential resource that is significantly larger than this value, possibly by a factor of two to as much as five times. However, at this time, we do not feel we have sufficient information on these advancing technologies, to provide a valid estimate.

Three factors will determine whether the tidal current potential will exceed the 300 MW calculated for a MCT “Farm”, these are:

- the future ability to install turbine units at a greater density than 1 unit per 2 ha
- the future ability to install fully submerged turbine units thus avoiding the navigation constraints on deployment and
- the future ability to install units in very fast tidal currents i.e., currents that exceed the assumed upper limit of 3.5 m/s.

2.5 MEAN VS RATED SITE AND TURBINE CAPACITY

There is some potential for confusion when comparing the power values referenced in this study, with those of conventional thermal or hydroelectric generating facilities with which the public is most familiar. With conventional power generation, reference is usually made to the rated power of the facility which is the value stamped on the manufacturer’s nameplate. It is generally the goal of conventional facility owners to operate the facility near its rated capacity. Moreover, the day-to-day variability of conventional energy resources is relatively minor which allows these facilities to operate near their rated capacity for relatively continuous periods of time. This means that rated capacity is generally a good first approximation to the actual power production of a conventional power plant.

In the case of tidal current energy extraction, the resource potential goes to zero two to four times per day and reaches its peak annual value only a few hours per year. For this reason, it is much more informative to speak of mean power in the context of tidal power, as such a definition integrates the effect of the highly variable daily and annual variation of the resource (see Figure 1 which shows representative BC tidal curves). The choice of turbine design rated capacity is therefore much more closely related to the optimization of the turbine efficiency curve with typical prevailing conditions, than the power available in maximum extreme flow conditions. Indeed, for some BC sites the maximum currents may be too high for unit operation and the facilities may need to be partially shutdown in these conditions to avoid self-damage. For these reasons, mean power is used as the baseline parameter throughout the present study.

For estimating purposes, mean power should be multiplied by a factor of between approximately 2.5 and 5.0 to yield rated capacity (equivalent to a Capacity Factor of 40%-20%). The factor is 5.0 for a MCT installation in Discovery Passage, although detailed design studies would likely reduce this factor considerably.

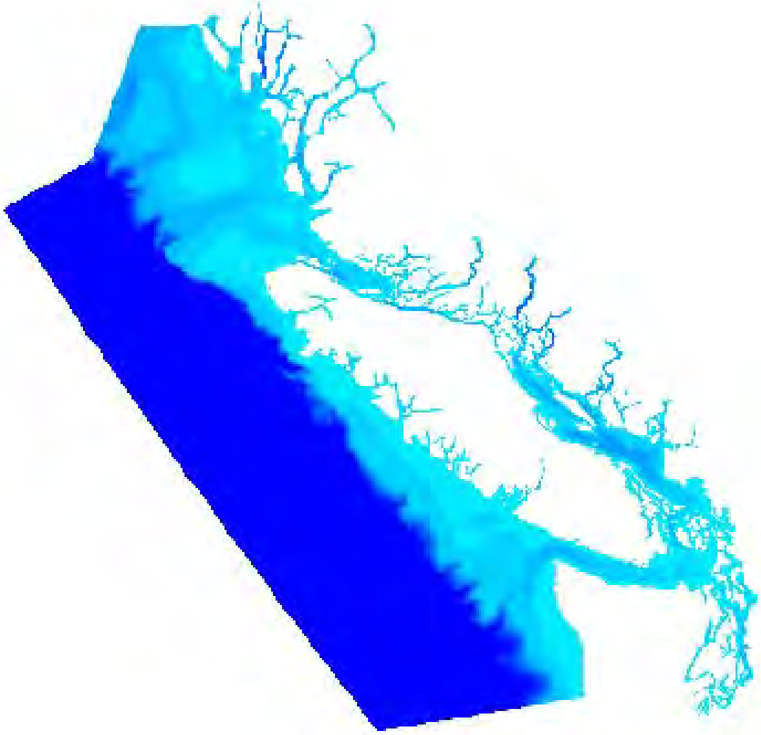
3. TIDAL MODELLING STUDIES

This section describes the approach followed to investigate the likely effect of extracting tidal stream energy from BC coastal waters. These effects must be understood since a change in existing conditions could result in less extractable energy than anticipated, or a change in environmental conditions that could be detrimental to some species.

3.1 TWO-DIMENSIONAL FINITE ELEMENT TIDAL MODEL –TIDE2D

A finite element tidal model of the BC coast was implemented for this study. The model grid was developed over many years by the Institute of Ocean Sciences (Dr. Michael Foreman) with the assistance of Triton Consultants. The model computational grid is considered to be the best available discretisation of the BC coastal waters (see Figure 10).

Figure 10: Computational Tidal Model Domain



The hydrodynamic engine used to compute tides on this grid was Tide2D. Tide2D is a harmonic (frequency domain) program that solves the non-linear, shallow water equations for sea level and depth averaged velocity using a finite element discretisation in space and harmonic expansion in time (Walters, 1987). Because the governing equations are elliptic, there are no stability criteria such as associated with hyperbolic time-stepping methods.

Continuity

$$\frac{\partial ?}{\partial t} + \nabla \cdot (H + h)\overline{U} = 0$$

Momentum

$$\frac{\partial u}{\partial \mathrm{t}} + (u \cdot \nabla)u + f \times u + \mathrm{g}\nabla h - \frac{\partial}{\partial \mathrm{z}}\left(N \frac{\partial u}{\partial \mathrm{z}}\right) = -\frac{\mathrm{g}}{?_0}\int_{\mathrm{z}}^{0} \nabla r \, \mathrm{dz}$$

where

$$\boldsymbol{N}\frac{\partial \boldsymbol{u}}{\partial \mathrm{z}} = \Psi \quad (\boldsymbol{z} = 0)$$

$$\mathrm{N}\frac{\partial \mathrm{u}}{\partial z} = \tau |\mathrm{u}| \mathrm{u} \quad (\mathrm{z} = -H)$$

The numerical solution applies harmonic decomposition of the governing shallow water equations and solves the equations in the frequency domain rather than using time-stepping procedures. This technique is exceptionally computationally efficient and is particularly well suited to modelling tidal motions where the number of frequencies is small in number or for modeling steady state forcing mechanisms such as quasi-stationary wind/pressure systems or river flow. This model has been used successfully for modeling tides, currents and surges in many places in the world including the English Channel, Delaware Bay, Kingston Harbour (Jamaica), Fraser River, Chukchi Sea, Beaufort Sea and the North East Pacific.

3.2 SIMULATION OF TIDAL POWER EXTRACTION

To assess the effect of tidal energy extraction on existing tidal conditions, an analogy was drawn between the energy lost from the tidal system due to friction and that extracted by any proposed turbines. The principal two dimensional equations solved in Tide2D are analogous to the following one dimensional, depth-integrated equation for **conservation of mass** and **conservation of momentum** per unit width:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0$$

Continuity

and

$$\frac{\partial q}{\partial t}+\frac{\partial M_x}{\partial x}=-gH\frac{\partial h}{\partial x}-K\frac{q|q|}{H^2}$$ Momentum

where

$q=\int_{z=-d}^{z=h} udz=UH$ = unit discharge or volume transport per unit width [m^2/s]

x, z, t = horizontal and vertical coordinates [m] and time coordinate [s]

H = instantaneous depth [m]

g = acceleration due to gravity [m/s^2]

h = water surface elevation [m]

d = water depth below datum [m]

r = water density [kg/m^3]

u, U = instantaneous and depth-averaged water velocity [m/s]

$M_x=\int_{z=-d}^{z=h} u^2 dz$ = momentum transport in x direction [m^3/s^2]

$K=\frac{g}{C^2}$ = dimensionless bottom friction coefficient [-]

C = Chezy coefficient [$\sqrt{m}/s$]

The last term in the conservation of momentum equation presented above represents the fluid acceleration (deceleration) due to friction. Since force is the product of mass and acceleration, the frictional force per unit channel width F_f is given by:

$$F_f=-r\frac{Kq|q|}{H^2}$$

or

$$F_f=-rKU^2$$

Since power or energy flux is the product of force and velocity, the vertically-integrated power (loss) P_f per unit width due to friction is given by:

$$P_f=-rKU^3$$

Integrating this frictional power loss across an area of channel seabed A_{seabed} yields:

$$P_f = -rKA_{seabed}U^3$$

This relationship provides a means for computing the energy lost within a region as a function of friction factor. By varying friction between model runs, the difference in power within a potential tidal energy farm area can be computed and viewed as an equivalent number of turbines.

3.3 TIDAL MODELLING RESULTS

The tidal model was operated for six tidal constituents, namely: M2, N2, S2, K1, P1, and Q1. Figure 11 shows typical output of the model, namely the computed current amplitude and phase of M2 throughout the model domain. Note the regions of high current speed in the vicinity of Cape Scott, Campbell River, and Victoria. Figure 12 to Figure 14 show close-up views of the model near Discovery Passage, Johnstone Strait and Victoria.

Figure 11: M2 Tidal Currents – Model Domain

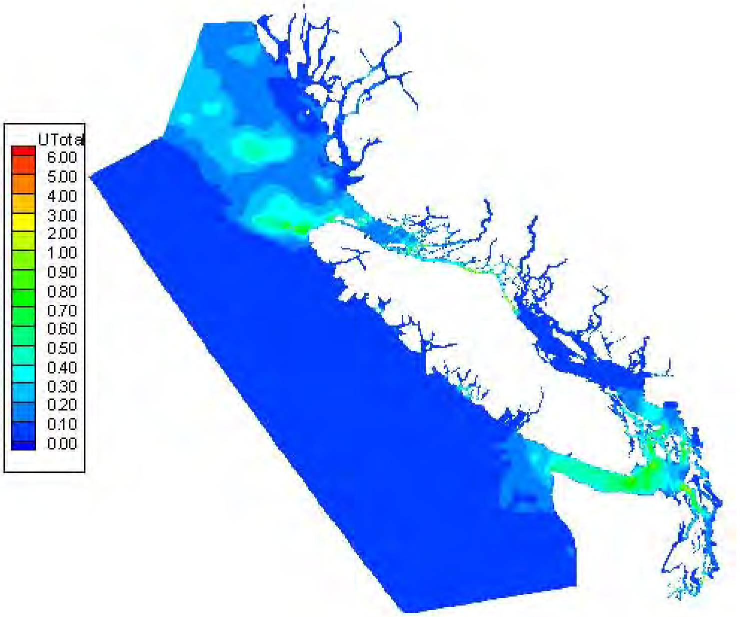


Figure 12: M2 Tidal Currents – Discovery Passage

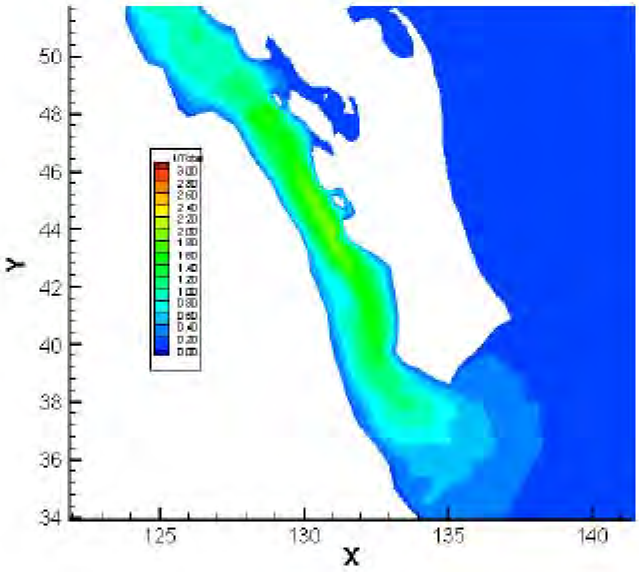


Figure 13: M2 Tidal Currents - Johnstone Strait

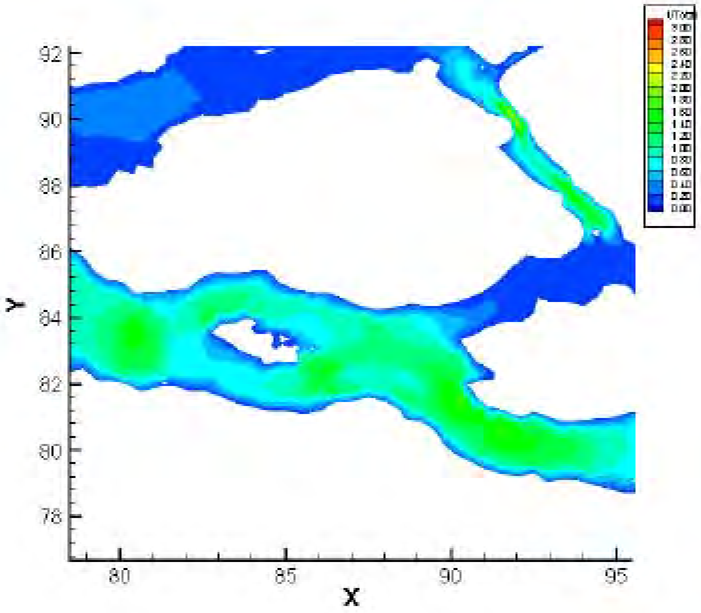
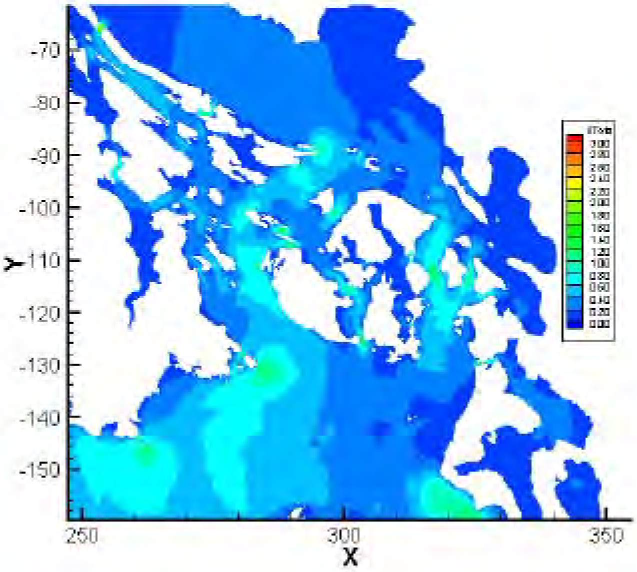


Figure 14: M2 Tidal Currents – Victoria Region



The model was run initially with the friction factors that represent the best representation of existing conditions, namely a global Chezy coefficient of 63 $m^{1/2}/s$ with increased values of 36 $m^{1/2}/s$ and 31 $m^{1/2}/s$ in southern Strait of Georgia and southern Johnstone Strait respectively. The model was run again with friction in Johnstone Strait and Discovery Passage increased to 22.1 $m^{1/2}/s$ which corresponds to the removal of approximately 600 MW of tidal power.

Figure 15 shows Discovery Passage, Johnstone Strait and Point Atkinson before and after implementation of a tidal current project. The diagonal line on the figure represents a “no change” condition. The figure indicates that there is not expected to be a significant change in existing tide height as the result of extracting 600 MW of tidal current power. Similarly, Figure 16 shows that there is not expected to be any significant change in the timing or phase of the tide.

Figure 15: Model Results – Tidal Heights Amplitude

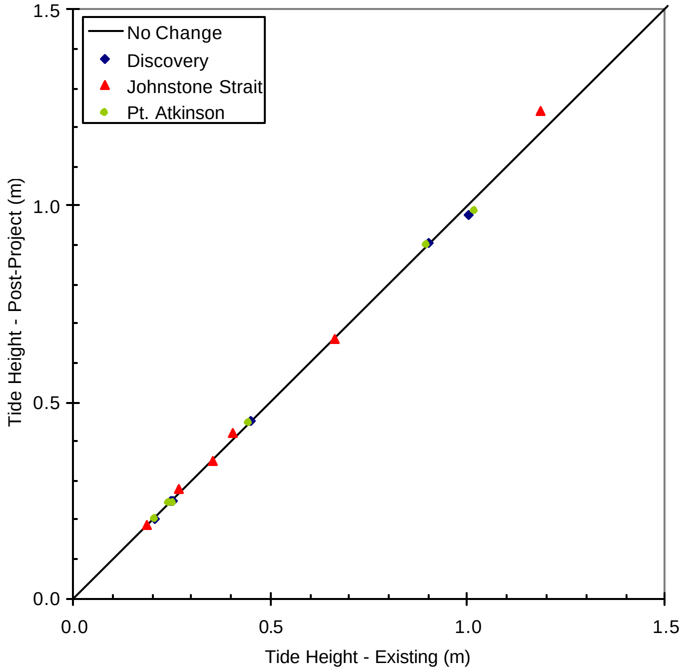


Figure 16: Model Results - Tide Heights Phase

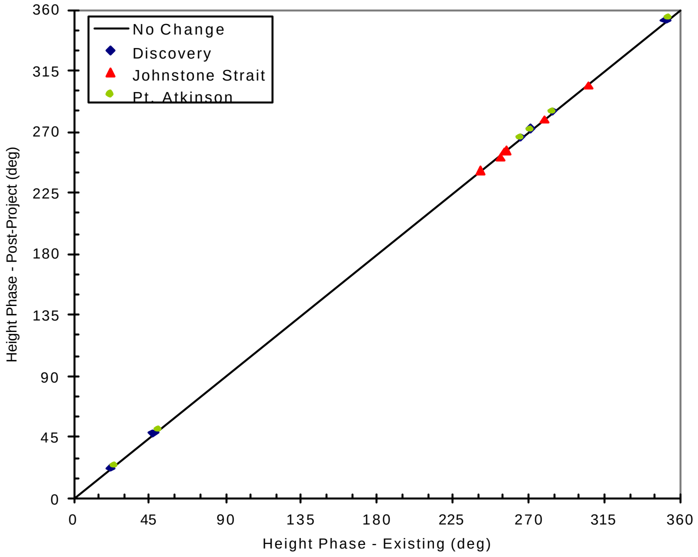


Figure 17 shows there is a noticeable change in the current speed in Discovery Passage (about a 10% reduction) as a result of power extraction in both Discovery Passage and

Johnstone Strait. The reduction in current in Johnstone Strait is measurable but small in magnitude. The larger reduction in Discovery Passage is thought to be the result of currents diverting to channels on the East side of Quadra Island such as Okisollo Channel. As shown on Figure 18, the changes in current phase are very small.

Figure 17: Model Results - Current Amplitude

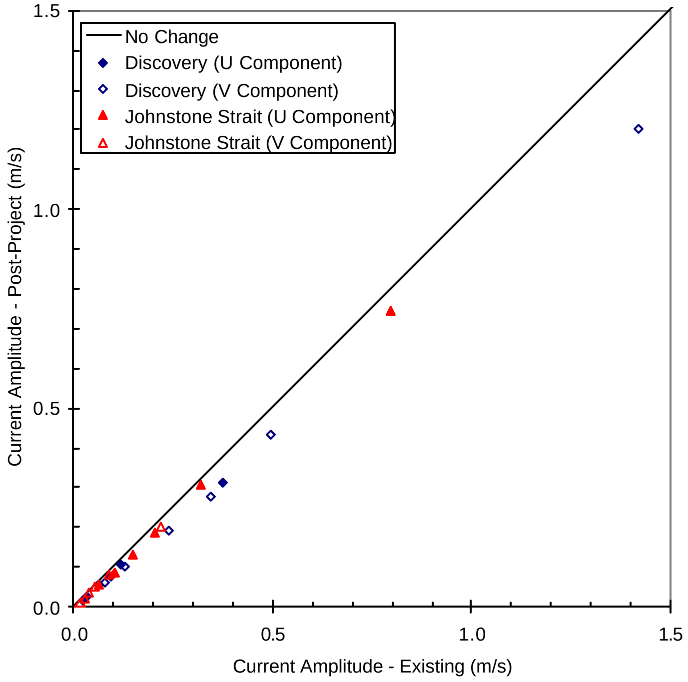
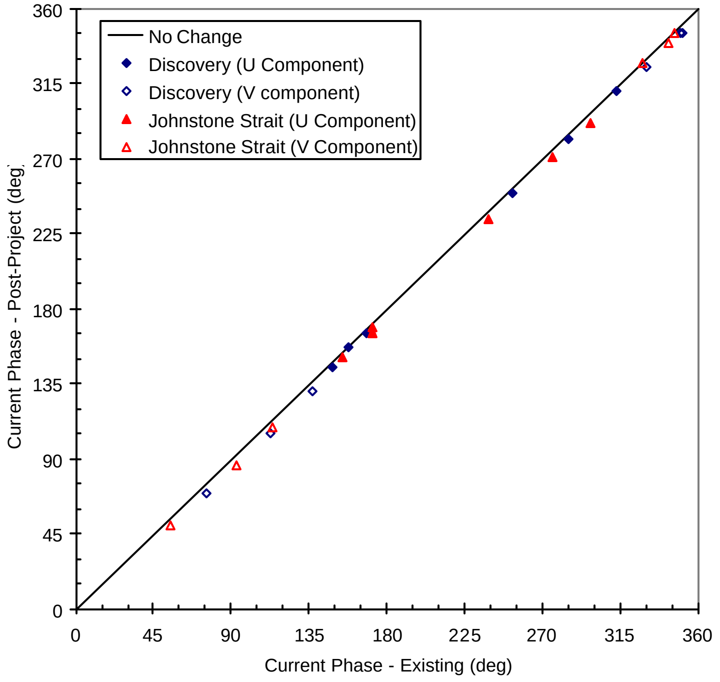


Figure 18: Model Results – Current Phase



The tidal modelling described above show that the physical impacts of extracting approximately 600 MW of tidal power from the Discovery Passage/Johnstone Strait region of British Columbia, will be small. There will, however, be a local reduction in current velocities in Discovery Passage in the order of 10%. In view of the U^3 current power law, this reduction must be considered in future more detailed assessments of tidal power potential.

Note that these modelling studies have only been applied to the Discovery Passage/Johnstone Strait region of the Province. If other sites such as Race Passage (Victoria) are considered in the future, we recommend that further tidal modelling studies should be undertaken.

4. CASE STUDIES

4.1 DISCOVERY PASSAGE SITE

4.1.1 Extractable Power

A potential tidal energy installation based on Marine Current Technology was considered for the Discovery Passage site described in the Utility Scale Resource evaluation spreadsheet (Table 2). The key parameters for that site are summarized in Table 4. Note that the numbers shown have not been rounded so that they may be compared directly with the computed values shown in the resource summary where applicable.

Table 4: Key Parameters - Discovery Passage Installation

Parameter	Value
Potential Farm Area	3173 ha
Potential No of Turbines	1587
Developed Farm Area	1587 ha
Actual No of Turbines	794
Realistic Mean Power	158.7 MW[1]
Mean Annual Energy	1390 GWh

[1] Note: This value, computed from gross flow properties, is of a similar order of magnitude to detailed, hour-by-hour calculations for a location in Discovery Passage for which the mean power was estimated to be 209 MW (263 kW/unit x 794 units; see Table 5).

Table 5 shows that the mean annual power output of each 1 MW rated unit is 263 kW, and the monthly average fluctuates between 75 and 110 % of this value. A more detailed description of how this energy is delivered throughout the day and throughout the year is shown in Figure 19 and Figure 20. It can be seen that the instantaneous power varies significantly throughout the day, and even the daily average power fluctuates between about 30% and 175% of the average annual output. This clearly demonstrates the need for an associated power distribution/storage system that is sufficiently flexible to accommodate this degree of variation.

Table 5: Detailed Extractable Power Summary

Hour	Total	Calendar Month (-)											
		1	2	3	4	5	6	7	8	9	10	11	12
(-)							(kW)						
0													
	253.94	251.22	259.20	296.30	302.15	231.84	249.45	279.10	227.00	196.97	211.10	271.69	271.87
1													
	275.36	267.33	287.62	280.13	332.64	294.62	308.82	277.89	205.88	216.30	265.22	283.90	286.42
2													
	287.09	292.46	304.28	288.95	325.12	336.58	307.28	249.80	230.77	282.72	274.78	273.44	281.80
3													
	288.71	332.25	294.34	317.86	323.14	305.22	276.82	254.36	279.54	284.41	268.24	269.70	259.19
4													
	291.95	341.65	285.62	352.63	323.42	281.76	267.32	276.17	285.46	281.97	265.20	266.94	273.78
5													
	293.56	337.88	315.97	355.21	324.15	274.28	264.82	284.00	273.32	269.48	252.45	265.70	305.99
6													
	281.06	324.27	320.87	315.64	312.62	268.90	254.67	273.98	252.50	244.21	229.62	262.26	315.45
7													
	255.18	247.79	257.93	270.50	292.06	246.12	232.65	252.34	235.64	227.97	221.14	261.46	316.60
8													
	238.14	203.30	212.22	262.94	269.31	211.19	213.34	236.08	226.22	219.96	233.87	291.44	276.67
9													
	229.99	201.43	185.91	301.69	244.88	184.29	204.14	221.21	224.56	232.92	282.87	257.64	214.75
10													
	227.56	176.28	235.54	307.50	214.42	182.18	209.39	219.45	227.54	267.94	292.56	219.76	178.98
11													
	235.97	202.69	272.08	266.03	207.42	205.62	227.07	232.52	239.10	293.15	288.38	217.39	183.65
12													
	253.95	279.50	225.75	259.24	236.97	229.11	244.77	256.75	259.82	306.06	286.75	238.23	222.04
13													
	275.36	271.83	268.05	251.43	248.23	247.40	268.14	283.38	283.92	314.47	298.25	276.63	292.10
14													
	287.21	263.34	292.72	256.59	265.39	262.44	276.55	297.41	302.37	320.23	312.75	309.51	288.50
15													
	285.27	287.18	262.72	278.82	274.41	263.03	278.42	299.52	306.04	323.05	319.80	289.23	239.65
16													
	285.81	303.70	247.99	286.02	285.94	273.68	297.17	286.97	301.40	320.13	327.62	264.95	231.26
17													
	286.99	299.94	274.39	266.90	291.57	310.28	284.63	270.95	293.57	320.59	329.27	259.53	241.26
18													
	279.61	296.43	239.66	280.42	283.23	296.54	265.55	263.84	285.29	317.66	315.71	256.62	250.67
19													
	261.87	252.79	241.23	259.17	277.58	281.36	262.02	256.23	249.27	286.44	282.05	247.45	245.71
20													
	241.44	221.58	255.94	251.12	272.15	256.85	250.45	207.05	204.17	264.14	253.01	234.86	229.20
21													
	229.92	220.94	258.68	262.25	250.99	248.14	205.42	175.38	196.61	266.82	238.81	223.21	215.42
22													
	230.11	238.75	247.86	277.62	267.07	220.54	183.72	179.55	223.64	251.31	234.15	219.70	219.17
23													
	239.68	257.78	237.08	288.74	276.52	232.05	195.30	202.94	250.99	228.36	222.84	237.38	245.29
24													
Total	263.16	265.51	261.82	284.74	279.22	256.00	251.16	251.54	252.69	272.39	271.10	258.28	253.57

Figure 19: Daily Power Variation

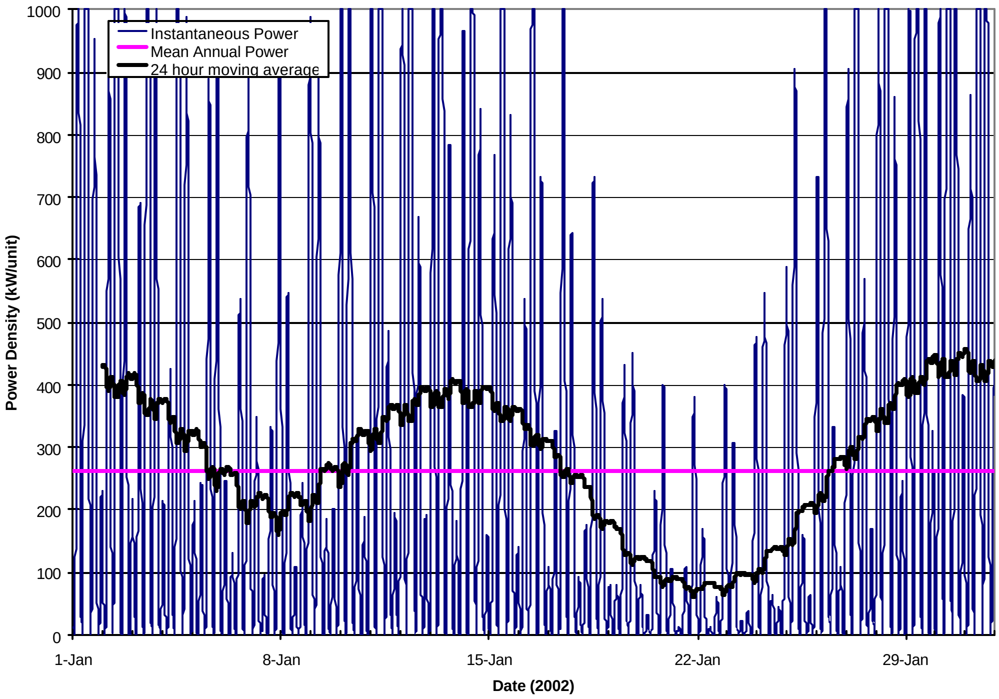
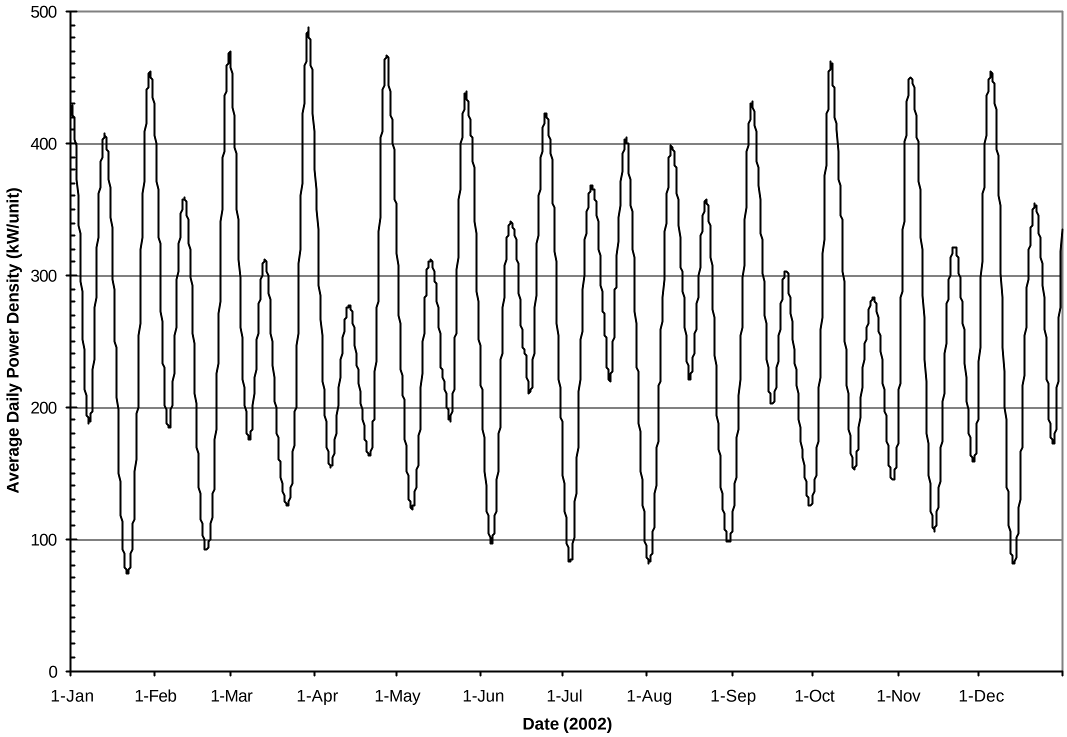


Figure 20: Annual Power Variation

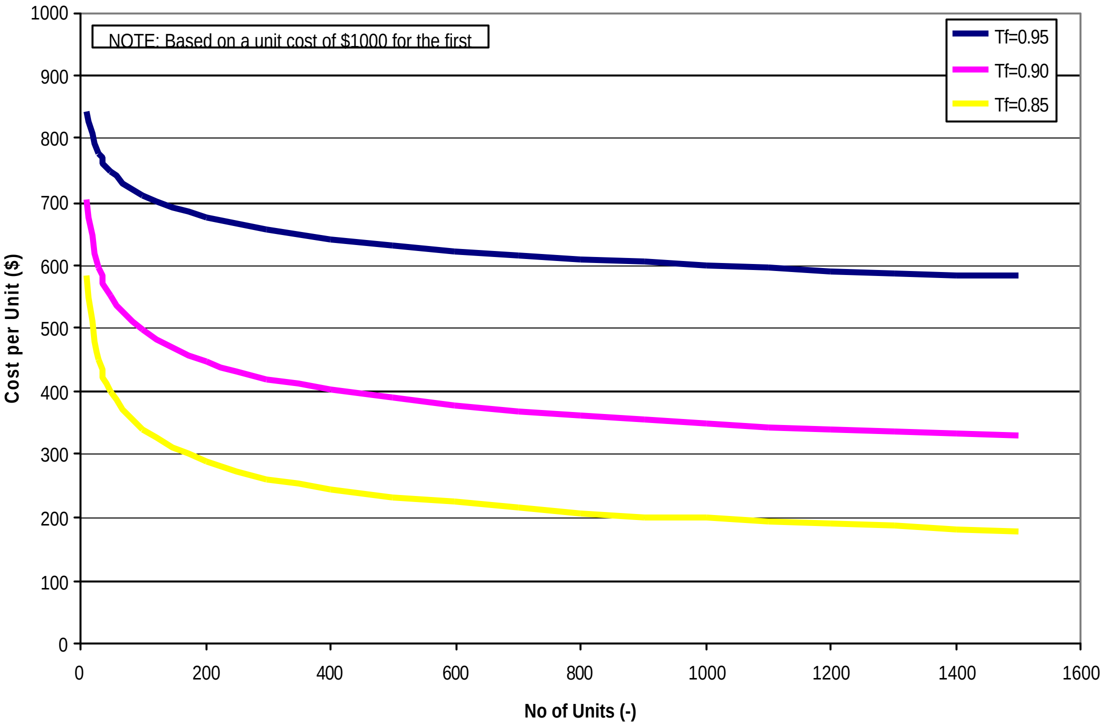


4.1.2 Cost of Energy

The parameters described above were used to construct an indicative estimate of the unit cost of energy based on the assumptions that are described below. The cost estimate was scaled from BBV (2001), therefore the assumptions made in that study are implicit in this one. These, and additional assumptions made for the present study, are listed in the following bullets:

- Each “unit” consists of two 15.9 m diameter variable-pitch rotors with a combined power output of 1 MW at a rated velocity of 2.3 m/s
- Initial capital, maintenance and salvage costs were scaled linearly from the BBV proposed baseline installation of 30 MCT 1 MW units. These costs were adjusted using factors of 0.5 for capital, 0.7 for decommissioning, and 0.7 for annual maintenance cost. These cost factors are indicative of the mean unit cost following application of a technology factor of between 0.9 and 0.95 (Figure 21)

Figure 21: Technology Factor



- Various aspects of the design require considerable development, including field tests, to produce a scheme that will operate in the conditions encountered with the reliability assumed. These development costs were not included in the BBV estimates.
- The BBV baseline scheme corresponds to a site where the water depth is 30 m, mean tidal range 5 m and peak stream velocity on a mean spring tide 3.0 m/s.

- Rotor and power train - The comments about development costs apply particularly to the mechanical and electrical elements of the rotor and power train, which are assumed to include a variable pitch mechanism and to operate with an overall 95% reliability in difficult environmental conditions.
- Mono-pile design - The cost of the mono-pile has been increased by 5% to allow for use of standard thickness steel plate and dynamic effects.
- Electrical system (including cabling) - The cost estimates for electrical plant have been based on conventional, existing equipment with limited assessment of the advantages to be obtained by reducing the size and using modular construction, or of the extra costs this will incur. Allowances for offshore and onshore sub-stations have been included.
- Grid system strengthening – BC Hydro have made a budget estimate of $40 million for the power transmission interconnection costs for the Discovery Passage Site.
- Installation - Installation costs have been based on the costs of hiring a jack-up barge that can operate in the required depth of water and modifying it to carry the drilling equipment, with a waiting on weather allowance of 10%.
- Design and management - Allowances for the design of the mechanical and electrical plant and for managing the construction of the scheme have been included.
- Maintenance - An average of one visit a year to each mono-pile unit has been allowed for inspection, maintenance and repairs, with an allowance of 5% of the cost of electrical and mechanical plant for spares and an additional 4% per year for maintenance.
- Rated velocity - The rated velocity of each scheme (the current velocity at which the power train produces its rated output) has been optimised by minimising the unit cost of energy as calculated by the MCT spreadsheet using the MCT site characteristics.
- Energy output - The energy output has been estimated as described in the resource summary listing, assuming a rotor efficiency of 45% (based on wind power experience), gearbox and generator (including transmission) efficiencies of 94% and 92% respectively, and reliability of 95%.
- Unit cost of energy - The unit cost of energy has been determined for a discount rate of 8% over 29 years with the scheme being de-commissioned after 25 years of production (beginning in Year 4).

Table 6 shows that the capital cost for developing the Discovery Passage site with an MCT type installation using existing technology, would be of the order of $1,040 million including an interconnection cost of $40 million. Annual power generation from this site would be 1,390 GWh/annum at a cost of 11¢/kWh.

Table 6: Indicative Unit Energy Cost Estimate – Discovery Passage Site

Discovery Passage - Cost Estimate for 800 MW Rated Capacity (reworked from Table 3.6 (BBV, 2001))

$CDN/£UK	$2.27	Future Cost Factor	
capital cost (1000's)	1,037,951	0.5	Interconnection cost of $40 million included
decommissioning cost (1000's)	$189,222	0.7	
annual cost (1000's)	$51,831	0.7	
annual energy output (MWh)	1,390,212		

	Year	**1**	**2**	**3**	**4**	**5**	**…**	**25**	**26**	**27**	**28**	**29**
Capital Expenditure		5%	29%	66%	0%	0%	…	0%	0%	0%	0%	18%
Annual Expenditure		0%	0%	0%	100%	100%	…	100%	100%	100%	100%	0%
Energy Expenditure		0%	0%	0%	100%	100%	…	100%	100%	100%	100%	0%
Discount Rate		8%	8%	8%	8%	8%	…	8%	8%	8%	8%	8%
ANNUAL COSTS	**Totals**											
Capital cost	$1,227,173	$49,898	$299,385	$688,668	$0	$0	…	$0	$0	$0	$0	$189,222
Annual cost	$1,295,779	$0	$0	$0	$51,831	$51,831	…	$51,831	$51,831	$51,831	$51,831	$0
Total	$2,522,952	$49,898	$299,385	$688,668	$51,831	$51,831	…	$51,831	$51,831	$51,831	$51,831	$189,222
ANNUAL OUTPUT												
Energy Output (MWh)	34755300	0	0	0	1390212	1390212	…	1390212	1390212	1390212	1390212	0
DISCOUNT RATE												
Discounted Cost	$1,413,815	$49,898	$277,208	$590,422	$41,145	$38,097	…	$8,174	$7,568	$7,008	$6,489	$21,933
Discounted Energy (MWh)	12723081	0	0	0	1103595	1021847	…	219236	202996	187959	174036	0
Unit Cost of Energy (¢/kWh)	**11.11**											

4.2 RACE PASSAGE SITE

To contrast the large Discovery Passage installation with a much smaller scale approach, a second site was considered at Race Passage at the south end of Vancouver Island. This site was selected from the short list of potential sites shown in Table 2 for the following reasons:

- The mean available power at that site is much smaller than that at Discovery Passage (approximately 5%) and hence represents the opposite end of the potential range
- It is located in a region that is clearly geographically distinct from the Discovery Passage site
- It is near a major demand centre (Victoria) in a region that is known to require supplementary power
- It is an easily visualized location since it is well known to most British Columbians.

Based on the utility scale tidal current power sites shown in Table 2, a total of 43 (i.e., 62 units x 0.7 farm area factor) MCT 1 MW units could be deployed at Race Passage to harness an annual mean power of approximately 8.7 MW. Table 7 shows a projected cash flow summary for an installation at this site. The same analysis method that was followed for the Discovery Passage installation was adopted for this site except that somewhat higher technology factors were assumed to reflect the relatively fewer number of turbine units that would be deployed at this location (namely 0.9 for capital cost and 1.0 for decommissioning and annual cost).

It can be seen that the capital cost for this project is of the order of $140 million, including an interconnection cost estimated by BC Hydro at $41.7 million, yielding approximately 76,000 MWh annually. The estimated unit cost for this energy is just over 25¢/kWh.

Table 7: Indicative Unit Energy Cost Estimate – Race Passage Site

Race Passage - Cost Estimate for 43 @ 1 MW Rated Capacity (reworked from Table 3.6 (BBV, 2001))

$CDN/£UK	$2.27	Future Cost Factor	
capital cost (1000's)	$139,104	0.9	Interconnection cost of $41.7 million included
decommissioning cost (1000's)	$21,134	1.0	
annual cost (1000's)	$5,789	1.0	
annual energy output (MWh)	76,212		

	Year	**1**	**2**	**3**	**4**	**5**	**…**	**25**	**26**	**27**	**28**	**29**
Capital Expenditure		4%	21%	75%	0%	0%	…	0%	0%	0%	0%	15%
Annual Expenditure		0%	0%	0%	100%	100%	…	100%	100%	100%	100%	0%
Energy Expenditure		0%	0%	0%	100%	100%	…	100%	100%	100%	100%	0%
Discount Rate		8%	8%	8%	8%	8%	…	8%	8%	8%	8%	8%
ANNUAL COSTS	**Totals**											
Capital cost	$160,238	$4,870	$29,221	$105,013	$0	$0	…	$0	$0	$0	$0	$21,134
Annual cost	$144,728	$0	$0	$0	$5,789	$5,789	…	$5,789	$5,789	$5,789	$5,789	$0
Total	$304,966	$4,870	$29,221	$105,013	$5,789	$5,789	…	$5,789	$5,789	$5,789	$5,789	$21,134
ANNUAL OUTPUT												
Energy Output (MWh)	1905300	0	0	0	76212	76212	…	76212	76212	76212	76212	0
DISCOUNT RATE												
Discounted Cost	$177,389	$4,870	$27,057	$90,032	$4,596	$4,255	…	$913	$845	$783	$725	$2,450
Discounted Energy (MWh)	697485	0	0	0	60500	56018	…	12019	11128	10304	9541	0
Unit Cost of Energy (¢/kWh)	**25.43**											

5. *ENVIRONMENTAL CONSIDERATIONS*

Environmental considerations play an important part in the siting, design, construction, operation and public acceptability of all major energy developments. The installation of one or more tidal current electric generating plants onto the BC coastal environment would be no different. At the present time, since this is still new technology and no comparable facilities are in place anywhere, there is no directly applicable, practical experience upon which to base an assessment of the environmental and socioeconomic impacts. The following review therefore, is based on reasoned and informed judgment which, as more information comes to light, may well require changed or new conclusions and perspectives to be drawn. It is presented with the intent of identifying the sort of concerns which emerge and which should be considered when preparing the terms of reference for full scale environmental assessment studies and research. The discussion is presented at three levels of potential effects, namely global, regional and local or direct effects. While several types of plant design are under consideration this review does not attempt to differentiate between them.

5.1 GLOBAL ISSUES

Electricity generation using tidal currents would use some very small (minuscule?) fraction of the energy input to the oceans from the gravitational interplay between the Earth and the Moon. Without attempting to compute the energy withdrawal in terms of the total available, it is clearly implausible that the installation of a small, in global tidal energy terms, tidal current power plant would have any effect on the macro tidal energy balance.

This method of electricity generation does not result in any discharges or emissions and would therefore make no contribution to the problems of air pollution or global climate change. This together with the fact that it is renewable and diurnally reliable makes it, at the macro level, most attractive.

5.2 REGIONAL EFFECTS

Regional effects refer to those impacts which are likely to be felt within the same or adjacent coastal inlets, foreshores and passages. Given the locations of interest and their proximity to a complex array of nearby islands and waterways, this area is unlikely to extend beyond a hundred or so kilometres from the generation site.

To assess what changes would be brought about by a tidal power farm; estimates of the changes in tidal velocity, tide height and its timing have been made. The results show that there is unlikely to be any meaningful change in tidal height or timing. However, immediately downstream of the generation farm there would be a decrease of about 10% in the current velocity. It is uncertain what biological effects may result from this change. At first sight, it would seem reasonable that changes, of the magnitude suggested, would be unlikely to affect physical processes such as sediment suspension and deposition. On the one hand, it may be argued that tidal currents are naturally and continually changing and that the change predicted here falls within that range of normal variation. If this were so then we would not expect to see any adverse effects. On the other hand, effects on biological processes may be subtle and telling on some species.

Once a firm proposal based on a specific location and configuration is advanced, this issue of indirect effects due to changes in current velocity, tidal height and timing should be re-examined. It should include an assessment of the biological implication of those changes.

5.3 DIRECT EFFECTS

The following discussion deals separately with Plant Design/Construction and Plant Operation since the effects and precautions will in most cases be quite different. It is recognized that for some matters an understanding of the impacts in the operation phase of the plant would be most helpful to the design/construct phase particularly in designing out problems. A well-defined and comprehensive monitoring of the environmental effects of even the most modest initial installation would potentially pay substantial dividends. It is strongly recommended that development(s) of tidal current power plants be actively monitored, world wide, and in particular, attention be paid to following their environmental effects.

5.3.1 Plant Design/Construction

Site selection

In any major industrial development the question of where the best site would be needs detailed consideration. In natural resource exploitation, this is always constrained by the location of that natural resource. However, within that larger site where tidal currents are sufficient to warrant harnessing, it may be possible to optimize the specific location for other competing values and interests. Some of the factors that would need to be considered include:

- Proximity of marine traffic
- Recreational and commercial fishing
- Expandability of the farm
- Biological resources in and passing through the area

A similar process to select optimal sites for inter tidal and land based facilities should be undertaken.

Facility layout

Two of the major decisions that need to be made relate to the nature of the turbine and how far up the water column it and its associated structural components would extend. The following factors would be advantageous to environmental interests:

Regarding the turbine: a means of preventing fish and marine mammals from swimming into and being adversely affected by the turbine blades. In this respect, the ducted designs are appealing and would probably lend themselves to the addition of screens or other behavioural devices effective in diverting fish and marine mammals around the plant.

Regarding the position in the water column: an arrangement that positioned the entire facility sufficiently below the surface that it would be out of reach of even large marine traffic. It is well understood that there are a number of practical implications here and that it is no simple decision; nevertheless the point is not lost.

__Construction__

All arrangements would require some form of anchoring to keep the turbines in place and, in inter tidal zones, to secure electric transmission cables. Setting these anchors would result in temporary impacts associated with excavation, including possibly blasting, material deposition, and grouting. Species at risk would be those least likely to be able to move out of the way quickly, that is, most benthic fauna and flora. In the case of blasting, fish near the blast zone would be vulnerable to the effects of the blast shock waves. It would be necessary to assess these effects and where possible select areas where impacts may be avoided and, in others, establish procedures whereby the adverse effects of these activities may be minimized. With prudent planning and execution these impacts would be temporary in nature.

The timing of work needs to be considered in light of seasonal use of the site by, for example, migrating salmon. Along salmon migrating routes, the June to September period should be avoided for underwater work that includes blasting and indeed, in some locations, work during this period may need to be avoided entirely.

Oil and fuel storage and use on barges, in inter tidal zones and at port facilities will need to be well managed. Standard practices, already developed and in use elsewhere should be effective.

5.3.2 Plant Operation

__Marine Traffic__

The presence of a tidal current power plant in narrow and well-used waterways would be a concern for all marine traffic. This includes barges, cruise liners and recreational and commercial fishing boats. Much of this concern, but not all of it, would be allayed if the entire structure could be below the water line at levels in the water column that would not interfere with the largest vessels using these water ways. For configurations where support structures are above the ocean surface, it would be necessary to deny access to all vessels over the full extent of the power farm. Given that ships/boats do from time to time lose power and are vulnerable to storm conditions, which blow them off course, the fully submerged option clearly has some advantages. Both commercial and recreational fishing would probably be impossible over the area of the power farm. As noted above, these factors would need to be taken into account in the technology selection/design stage of any proposed project.

__Fish and Marine Mammals__

The matter of how these types of facilities would affect and be affected by fish and marine mammals is the overriding environmental issue to be resolved. As noted at the outset, there is also a dearth of actual experience based information on the subject. Examination of the most favourable sites, Table 1 and Table 2 indicate that two thirds are located in the area of Johnstone Strait/Discovery Channel. This is also a major migration route for salmon and is home to resident marine mammals notably killer whales. It is uncertain if salmon, which will generally seek out advantageous currents during their migration, would "see", react and avoid large rotating turbine blades. There is not any particular elevation in the water column which the fish favour over others and which could be used to locate turbines to avoid collisions. The blades themselves rotate quite slowly relative to hydroelectric and wind turbines, namely a few revolutions per minute depending on current speed, blade curvature and size but always to maintain a blade tip speed of less than 7m/s (when cavitation is likely to occur). Those configurations which either use a ducted turbine or a venturi and which could be fitted with a screen to keep fish from entering the machine would be advantageous. It may also be worth testing other, behavioural means of keeping fish and mammals away, e.g., tickle voltages, strobe lights.

As noted this is a major issue for tidal current power facilities. It is doubtful that it can be fully resolved prior to installing a demonstration unit. However, such a demonstration unit would provide a much-needed opportunity to assess this technology and its environmental effects especially those related to fish and marine mammal impacts.

Marine Pollution

Since there are no emissions or discharges from these units, marine pollution would be restricted to matters related to leakage of lubricants and the type of paint or coating that the subsurface structures would use to prevent excessive growth of marine organisms. Some of these materials are extremely toxic. They would need to be carefully selected with the implications of their use fully considered.

5.4 PUBLIC CONSULTATION AND RELATED ISSUES

British Columbia’s coastal waters are used by a wide range of interests, commercial and recreational. If/when such a development is considered, care will need to be exercised to ensure that those with either direct or indirect interests in location(s) where it is intended to place the unit(s) are consulted and their concerns considered.

5.5 REGULATORY MATTERS

In reviewing this proposed technology and its attendant environmental factors, a number of factors came to light concerning licensing of a tidal current plant. These are noted below:

- The primary Acts that would apply to the in water and inter tidal components of such a development are the Federal Fisheries Act and The Navigable Waters Protection Act.
- There would almost certainly be a need for an authorization from either or both of the agencies that administer these Acts and that would trigger the Canadian Environmental Assessment Act. If the project were larger than 200MW in size the CEAA would be triggered automatically
- A project screening would be needed which may be sufficient for the purpose of regulatory approval.
- However, if the effects of the proposal were particularly uncertain, and/or there was substantial public concern, then the matter could be referred to a panel who would rule on it from a broader public policy perspective (as opposed to single agency authorizations which take account only of the interests of that agency).

- Provincial government processes would apply to the land based components, namely transmission lines and substations. The triggers for consideration by the BC Environmental Assessment Act are greater than 40 km of new transmission line and/or 500 kV lines or stations. If these were not exceeded then individual acts would apply e.g. Water Act, Land Act etc.

6. TECHNOLOGY REVIEW

A review of commercial organizations offering tidal current technology was made including the following:

BLUE ENERGY CANADA INC.
Box 29005, 1950 West Broadway
Vancouver, British Columbia V6J 5C2
Contact: Martin Burger, Blue Energy President and CEO
Phone: 1-604-682-BLUE (2583)
Fax: 1-604-682-8683
Email: mjburger@istar.ca
URL: www.bluenergy.com

CLEAN CURRENT
1025 Belmont Avenue
North Vancouver, British Columbia V7R 1K3
Contact: Dr. Stephen Allison, President
Phone: (604) 924 9749
Email: sva@aquaconsult.org
URL: www.cleancurrent.com (authorization required)

MARINE CURRENT TURBINES LTD
The Manor House
Chineham Court, Lutyens Close, Chineham, Basingstoke, Hants. RG24 8AG
UK Contact: Peter Fraenkel, Director
Phone: (+44 or 0) 1256 470149
Fax: (+44 or 0) 1256403129
Email: PeterFraenkel@compuserve.com
URL: http://www.marineturbines.com

RVco Ltd. (Now renamed **Hydro Venturi**)
Blackett Laboratory, Prince Consort Road,
London SW7 2BW, UK.
UK Contact: Dr John Hassard.
Email: john@rvcogen.com
US Contact: Joseph Wilson Neil
Email: joseph@rvcogen.com
URL: www.rvcogen.com

UNDERWATER ELECTRIC KITE CORPORATION - UEK® Corporation
PO Box 3124
Annapolis, MD 21403 USA
Contact: Philippe Vauthier, President and CEO
Phone: 410-267-6507
Email: ph.vauthier@uekus.com

There were two major difficulties encountered during our review of tidal current technologies, specifically:

- most technologies are in the early stages of development, often laboratory or small scale prototype installations and,
- all technologies appear to be being developed as “commercial” ventures. Proponents are reluctant to divulge any information because of the fear that competing systems may “get an edge”.

The technologies come from principally two geographic regions, Europe (Marine Current Turbines and Rochester Venturi) or North America (Blue Energy, Clean Current and UEK Inc).

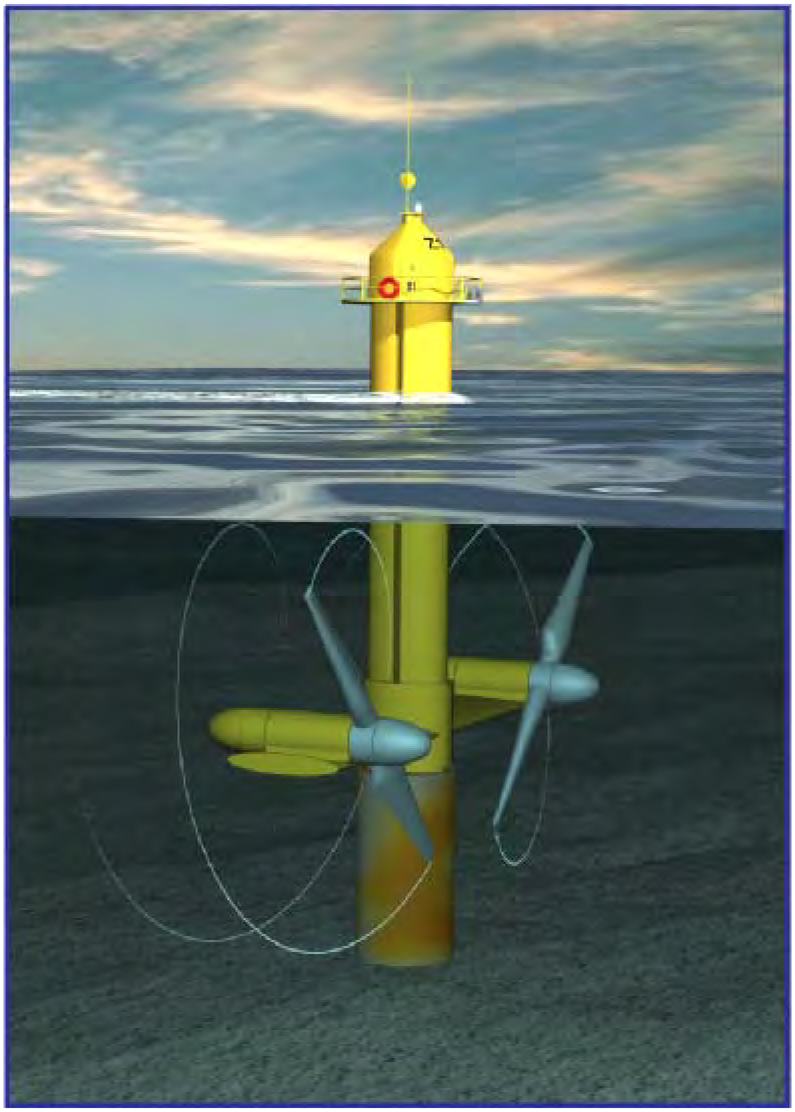
A number of other small scale tidal current power systems such as the Tyson Turbine (Australia) were encountered during the literature review but were not considered in detail as they were deemed inappropriate for commercial scale energy production. In addition, information on two interesting European developments became available after this report had been completed. A) The Engineering Business Limited, Riding Hill, Northumberland, UK – the Stingray oscillating underwater aerofoil (www.engb.com) and B) Hammerfest Strom (Norway). Both these two latter developments are being substantially supported by UK and Norwegian Government funds.

The systems proposed by Blue Energy Canada Inc, Clean Current, Marine Current Turbines Ltd., RVco Ltd. and UEK Corporation are described in the following sections.

6.1 MARINE CURRENT TURBINES

Marine Current Turbines Ltd. (MCT) technology is similar to a submarine windmill Figure 22).

Figure 22: Marine Current Turbines



The technology consists of a pair of axial flow rotors 15 m to 20 m in diameter that each drive a generator via a gearbox, much like a hydro-electric turbine or a wind turbine.

The power unit is mounted on a tubular steel monopile that is 2 to 3 m in diameter which is set into a hole drilled into the seabed from a jack-up barge. The technology for placing these monopiles was developed by Seacore Ltd., a specialist offshore engineering company and MCT's largest shareholder.

The patented design of MCT's turbine is able to be installed and maintained without underwater operations. The turbine is connected to the shore by a marine cable lying on the seabed which emerges from the base of the pile. The submerged turbines are generally rated individually from 500 to 1000 kW. The turbines are grouped in arrays similar to wind turbines in a wind farm.

Tidal turbine technology is modular, so small batches of machines can be installed with only a short elapse time between investment in the technology and the time when revenue starts to flow. This is in contrast to large hydro-electric schemes, tidal barrages or other projects involving major civil engineering works, where the lead time between investment and gaining a financial return can be many years.

Marine Current Turbines have very solid UK Government support and a serious prototype installation in 2002. The company states that it will design, build and install a single 300 kW-rated prototype turbine, which will start operation in 2002 in South West England. MCT intend to develop a commercial twin-rotor prototype rated at about 650 kW to be installed by 2003, and a 3 MW array of turbines (4 @ 750 kW) to be installed by 2004.

Marine Current Turbines have provided us with a pre-publication copy of an independent review of their technology by consultants Binnie, Black and Veatch (BBV) for the UK Department of Trade and Industry, New and Renewable Energy Program (BBV, April 2001). This report is the best review of tidal current power technology and costs available at this time. (as discussed in Section 2.4)

The major innovation of the MCT design is the use of a single vertical monopile to carry the twin rotor generator units. This design allows installation and maintenance of the units from a large jack-up barge. The rotors can be readily raised to the surface for maintenance either from a jack-up or directly from the monopile. MCT have designed variable pitch blades for their system and they will be used on their 300kW experimental project. Variable pitch blades will provide an increase in the turbine rotor hydraulic efficiency over that possible with fixed blades.

Tidal Current turbine farms of the type proposed by MCT appear to be feasible for some locations in British Columbia. However two factors may limit their application on a large scale: a) turbine farms require very large areas of moderately shallow water (30 to 100m say) essentially free of major ship traffic – most of BC's energetic current sites are in relatively narrow channels which are often major navigation routes and; b) impact from deadheads and semi-submerged debris could be a major rotor design problem.

6.2 BLUE ENERGY APPROACH

Blue Energy Canada was established by Barry Davis[3] and Martin Burger about eight years ago. Barry Davis, under his former company Nova Energy, had undertaken extensive laboratory and field trials on Darrieus type underwater vertical axis turbines. This detailed research work was funded by the Canadian Government (1980-1984) through the National Research Council and laboratory testing was conducted at the NRC in Ottawa.

A report commissioned by the British Columbia government (Ministry of Employment and Investment) and completed in 1994 by Dr. Harold Halvorson entitled 'Evaluation of Nova Energy Ltd's Hydro Turbine' can be downloaded from the Blue Energy website, www.bluenergy.com .

Darrieus Turbines (or what are now often known as Davis Turbines) are ultra-low head underwater devices that are capable of efficiently extracting energy from high currents

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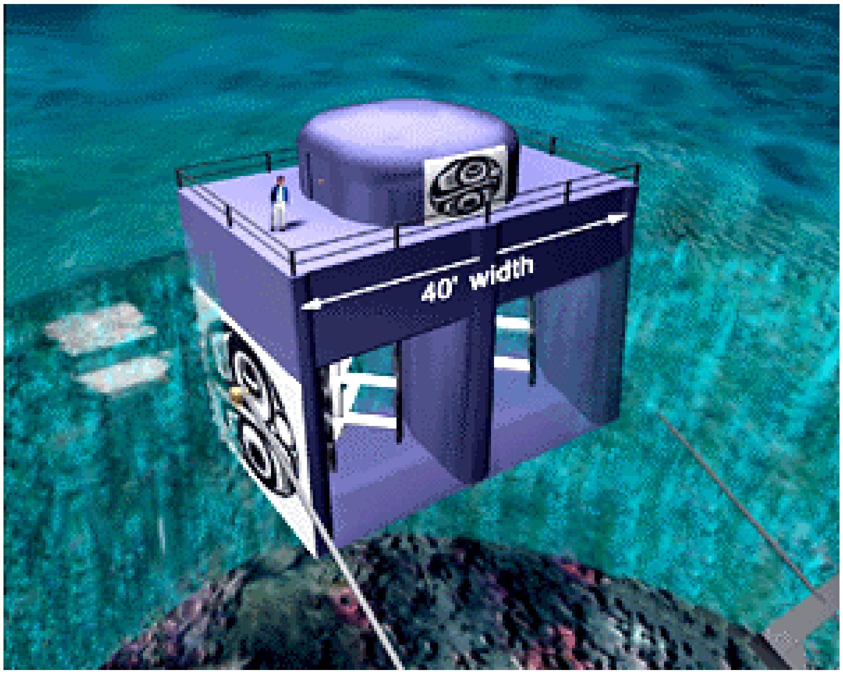
[3] no longer part of Blue Energy Canada

rather than the more traditional high head regimes used in conventional tidal power systems (e.g., Bay of Fundy). The turbines can be used as individual units in a "free stream" mode (Figure 23) or banked into a Tidal Fence (Figure 24) where flow acceleration from ducting and head capture provide a significant improvement in efficiency and energy extraction.

Figure 23: Blue Energy rendering of 250 kW Midrange Unit

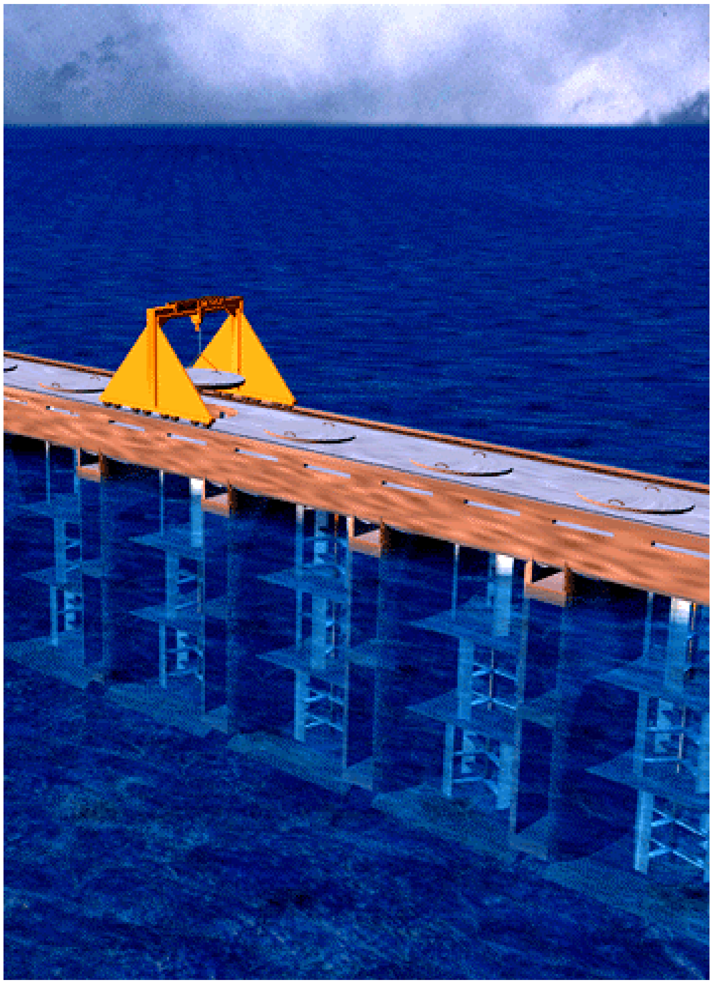


Vertical axis turbines used in a tidal fence arrangement have the added advantage of keeping the gear box and electrical system above water level rather than submerged.

Blue Energy, and Nova Energy before it has, in the past, suffered from a Canadian technical emphasis on tidal head systems exemplified by the Bay of Fundy Tidal Projects. Tidal currents have been dismissed by many experts in tidal power as inherently uneconomic relative to projects in the Bay of Fundy where the tidal range is the largest in the world. However, this report shows that tidal current energy presents a major resource in British Columbia and based on our preliminary studies it may indeed become economic.

Discussions with Blue Energy suggest that they continue to be very serious about using the Davis Turbine in a tidal fence application. They firmly believe that the tidal fence or array is the way to proceed in tidal energy exploitation. Our present analysis shows that the physical differences between a fence/array and a tidal current farm are small. Both systems require head to drive the turbines. The main difference between the two concepts is the issue of marine transportation through a fence. Generally the environmental impact of both the fence and the farm are equally small although local impacts may be larger for the fence.

Figure 24: Blue Energy Tidal Fence



Blue Energy are aggressively soliciting financing for their Tidal Fence ideas and have very near term plans for a prototype scale demonstration project, supported by research, laboratory testing and design development; probably located near Seymour Narrows. Blue Energy see their future product marketing moving in two directions: 1) Local installations for small communities of 500 to 1000 kW, either free stream or small tidal fences, and 2) very large tidal fence projects in the 500 to 1000 MW range. Both these directions, they believe, will allow them to position their company for exploitation of both the BC, North American and large scale overseas markets.

Blue Energy has proposed the potential combination of tidal fence power generation with transportation links (bridges). This concept is interesting and involves possible cost sharing, and cross-discipline synergies. However, the limited information available regarding the energy conversion technology and the lack of information around bridge impacts prevent evaluation of this concept as part of this study.

6.3 CLEAN CURRENT APPROACH

Clean Current (Power Systems) was established in British Columbia in 2001 by Dr. Stephen Allison, Barry Davis and others. To date, Clean Current have undertaken numerical hydrodynamic design studies on the ducted horizontal axis turbine and have developed two very innovative ideas related to electrical generation and turbine design. No detailed information about Clean Current's technology can be described here due to their patent application process.

It is understood that Clean Current will be testing a large-scale, 1 m diameter model of their turbine in the towing tank at BC Research (on the UBC Campus) later this year. The results from this tank testing will be used to finalise the design for a twin 3 m diameter unit to be installed at Race Rocks near Victoria later in 2002. This latter prototype installation is designed to form an integral part of the University of Victoria (IESVic Integrated Energy Systems) research program.

As presently envisioned the Clean Current tidal current power generator will be anchored in the water column, below navigation depth, with sufficient buoyancy to allow de-ballasting and maintenance above water. The details of the anchoring and maintenance equipment requirements have not yet been determined. It is understood that a twin 8 m diameter turbine unit would have a rated power capacity of about 2 MW. It is also possible to mount such a unit on the seabed (dimensions 25 m wide, 15 m long, 12 m high using Triton Consultant concept numbers) with sufficient buoyancy to allow maintenance at the water surface.

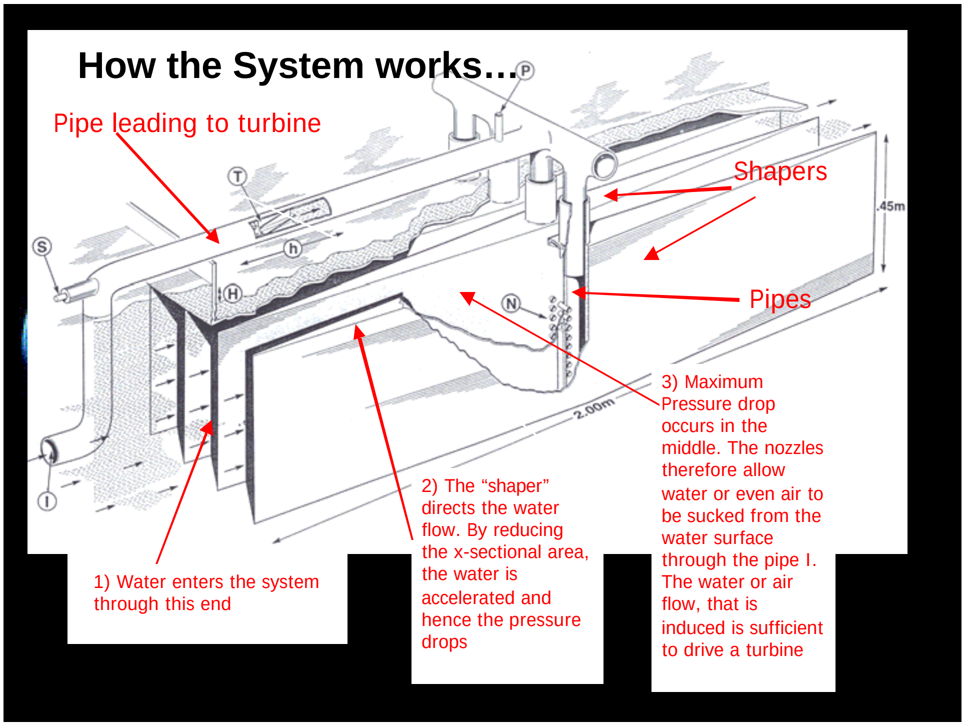
Although Clean Current is at a very early stage of the development of their technology, the design concepts appear to have real potential for tidal current extraction in British Columbia. The ducted turbine has the added advantage that it can be protected from impact by deadheads and debris and also provides protection for large marine mammals.

6.4 RVCO APPROACH

RVco Ltd was formed in 2000 and is a spinout company from Imperial College, London, and IC Innovations Ltd. RV stands for Rochester Venturi which reflects the Imperial College founder of the company (Dr. Rochester), and the fundamental physics of the approach. By accelerating tidal water flow through a choke (venturi), Bernoulli's principle dictates that the water pressure within the venturi becomes lower than ambient. The resulting pressure gradient is then harnessed to drive a conventional pipeline turbine.

Figure 25 demonstrates the key features of the concept. The technique concentrates the low density energy in ocean currents into a more rapid flow of a smaller quantity of water in a pipe to the shore. The efficiency of the RV approach can be tuned and RVco claim to have attained 24% efficiency in one design. The primary advantage of the approach is the lack of moving parts below water and the opportunities for modular installation.

Figure 25: RVco System



How the System works…

1) Water enters the system through this end

2) The "shaper" directs the water flow. By reducing the x-sectional area, the water is accelerated and hence the pressure drops

3) Maximum Pressure drop occurs in the middle. The nozzles therefore allow water or even air to be sucked from the water surface through the pipe I. The water or air flow, that is induced is sufficient to drive a turbine

Presently, RVco have built, tested and modeled a 0.6 m aperture system and claim to have proven the scheme. RVco claim cost estimates range from 2.5¢/kWh up to 5¢/kWh, although this power cost is highly site specific.

In principle, the Rochester Venturi concept is extremely attractive for tidal current power extraction in British Columbia. It may be the best method for extracting energy from very high velocity tidal streams where the current speed is too high to deploy or maintain other turbine systems. At this stage, insufficient manufacturer information is available to allow a defendable technical evaluation of this technology. However, this approach has the potential to revolutionise tidal current power extraction and it is recommended that BC Hydro continue to track the developments of this technology.

6.5 UNDERWATER ELECTRIC KITE

The Underwater Electric Kite (UEK) turbine concept is a hydrokinetic energy conversion system that is installed in a free stream river or tidal current with a minimum of infrastructure. It consists of a self-contained moderately-buoyant turbine/generator that is suspended like a kite within the tidal stream (see Figure 26). Significant power can be generated when multiple turbines are clustered together into a "farm", forming a group of generating units. For a typical project, each of the UEK turbines is anchored to the seabed, on a bottom plate from which they can easily be removed for periodic maintenance. Besides being installed on bottom plates or attached to existing structures such as a bridge or on a floating platform such as a barge, the UEK turbine, in a twin rotor design configuration, can be self-positioning in the fastest core of an ocean or river current on an electro-anchorage cable where the depth of the water is substantial or the current flow is not confined. The system is operational in both directions of the tidal flow at the same efficiency. The electronic controlling modules are located on shore and are designed to match the UEK's electrical output to the utility grid. The turbines can be vertically positioned to avoid being a hazard to navigation.

UEK turbines are available in either a shrouded single-stage or double-stage models. With the single-stage turbine, the mechanical power is applied directly through a speed increaser to a generator. With the double-stage design, the large turbine's hollow blades act as penstocks that channel water through the hub and discharge it in the low pressure region behind the shroud. In the second-stage of the double-stage turbine, a small power turbine is located in the accelerated flow of the large first-stage turbine which drives an electrical generator.

Figure 26: Underwater Electric Kite

At the present time, the standard UEK machine is the 3.0 m twin turbine which delivers 90 kW in 5 knot currents. The system weighs approximately 5,720 lbs without anchorage harness and the shore equipment designed for indoor service (additional weight ~3,000 lbs.) With additional electrical control devices, the turbine unit can be synchronized with the grid and supply power to utilities. UEK state that they will have a 6.7 m twin turbine system available in the near future. This larger machine is presently being developed to be deployed off the coast of Florida for the US Department of Energy and Small Business Innovative Research.

UEK state that they can “definitely build 0.5 MW to 1 MW and more” subject to some non-recurring engineering and comprehensive site survey, interconnection and distribution planning. Table 8 shows how the units might be configured for a 500 kW and 1 MW installation in a range of current velocities.

UEK appear to be presently promoting their technology into a small niche market. Interestingly, UEK Inc. has the most developed system of all the proponents that were identified. UEK have taken a very measured and professional approach to current power development over a period of ten years and have recently been awarded a major research and development project for the US government.

Table 8: UEK Unit Configurations

Speed	500 kW Nominal	1 MW Nominal
5 knots	4 Twin 141 kW Units	8 Twin 141 kW Units
6 knots	3 Twin 244 kW Units	5 Twin 244 kW Units
7 knots	2 Twin 389 kW Units	3 Twin 389 kW Units
8 knots	1 Twin 577 kW Units	2 Twin 577 kW Units
9 knots	1 Twin 822 kW Unit	2 Twin 822 kW Units
10 knots	1 Twin 1128 kW Unit	1 Twin 1128 kW Unit

UEK state that an extreme site with 17 knot currents would generate a maximum of 5.5 MW with one twin 5540 kW unit. Such a machine would have 3.0 m diameter augmenter rings, 5-blade 2.4 m diameter runners at 130 rpm. UEK calculate that the maximum thrust on the anchorage system would be 145 tonnes in this case. We note that the buoyancy of the system is insufficient to support simple bottom-anchoring in such high flows due to the high downward component of the anchor loads with this geometry. The units would likely require either additional vertical load support from above (e.g., floating barge) or a change in anchoring method to a horizontally tethered system (e.g. to a pile) that remove the downward component of anchor loads without interfering with the ability of the turbine to orient itself with changing current direction.

7. CONCLUSIONS

7.1 RESOURCE EVALUATION

7.1.1 Potential Tidal Current Power Sites

A total of 100 energetic BC tidal current sites (excluding Queen Charlotte Islands) were selected for initial consideration (see Appendix A) following review of nautical charts, navigational pilots, discussions with the Canadian Hydrographic Service (CHS) personnel and numerical modelling. These sites generally correspond to locations where peak annual flood or ebb current speeds exceed about 3 knots (1.55 m/s). Based on this long list, the mean annual **potential or theoretical cross-sectional power** for all sites was estimated to be over **3000 MW or approximately 26,000 GWh/year**. Given the U^3 power relationship, consideration of a larger number of milder sites would not change this value significantly. As described in Section 2.2, we believe that this measure is a reasonable benchmark to gauge the relative tidal potential of different sites. However, it must be noted that this parameter is only loosely related to extractable power since extractable power is highly dependant on the physical characteristics of the site and the technology used. Interestingly, this does not mean that extractable power is less than potential cross-sectional power since at certain sites the extractable power may exceed the theoretical cross-sectional power.

Based on the present and probable future technology available for tidal current extraction, it is believed that 2.0 m/s is the smallest maximum current that can be seriously considered for power generation. Given this assumption, the number of potential sites is reduced from 100 to about 55 and the mean annual **potential or theoretical cross-sectional** power is reduced to just over **2200 MW or approximately 20,000 GWh/year**. This is the average power generated by tidal currents not the rated capacity of the turbines. Potential power sites range in size from over 600 MW for Seymour Narrows near Campbell River to very small sites such as the Gorge in Victoria (potential about 0.1MW). At some of these sites such as Seymour Narrows the current is too strong for a tidal current power installation using present techniques. However there is good reason to believe that advances in technology and construction techniques will make these very high current sites exploitable in the future.

7.1.2 Utility Scale Tidal Current Power Sites (existing demonstrated technology)

For arguments presented throughout this report, Marine Current Turbines technology was used as the basis for identifying the mean total provincial **realistic** annual tidal current resource potential for utility scale sites with greater than 10 MW annual mean power potential. For this technology, a minimum mean current velocity of 2.4 m/s is required, as well as a minimum depth of about 18 m; these criteria reduce the number of provincial potential sites to twelve. It is estimated that over **300 MW or approximately 2700 GWh/year** is available province wide assuming MCT technology is applied. We caution that this value is specific to MCT and that application of other technologies may yield significantly different results.

The most energy rich site based on the above assumptions appears to be **Discovery Passage** with almost one half of the provincial total (see Section 7.2 Indicative Energy Costs below)

7.1.3 Utility Scale Tidal Current Power Sites (future technology)

Other evolving tidal current technologies (e.g., Clean Current and RVco) may yield a potential utility scale energy resource that is significantly larger than the 2700 GWh/year noted in Section 7.1.2, possibly by a factor of two to as much as five times. However, at this time, we do not feel we have sufficient information on these advancing technologies, to provide a valid estimate.

Three factors will determine whether the tidal current potential will exceed the 300 MW calculated for a Marine Current Turbines “Farm”, these are:

- the future ability to install turbine units at a greater density than 1 unit per 2 ha
- the future ability to install fully submerged turbine units thus avoiding the navigation constraints on deployment and
- the future ability to install units in very fast tidal currents i.e., currents that exceed the assumed upper limit of 3.5 m/s.

Tidal modelling suggests that changes in tidal range caused by current power extraction will be relatively small (except in tidal inlets). However, tidal currents at the extraction site are reduced which has a significant impact on exploitable power. This is principally because the magnitude of tidal current power is extremely sensitive to current speed (U) since power is a function of U^3. Detailed tidal modelling will therefore be an essential design requirement at any proposed tidal current power site.

7.2 INDICATIVE ENERGY COSTS

7.2.1 Discovery Passage Site

Capital, operating and decommissioning costs have been estimated for a tidal current power installation located in Discovery Passage in British Columbia. An installation of almost 800 1 MW rated turbines would yield a mean annual power of about 160 MW (1400 GWh/year). The calculations were based on an extension of the Binnie, Black and Veatch (2001) detailed cost analysis for a 30 MW rated Marine Current Turbines farm. A discount rate of 8% has been used combined with a facility life of 30 years and technology factors of 0.5 for capital and 0.7 for other costs.

The technology factor recognises the cost reductions that occur, as design and manufacturing improvements are spread over a large number of units (in this case, from 30 to 800 units).

Based on these assumptions, we estimate that a tidal installation with a mean capacity of 160 MW (1,400 GWh/year) could be built, operated and decommissioned at an energy cost of about **11¢/kW hour** ($CDN).

7.2.2 Race Passage Site

A similar analysis was undertaken for a much smaller installation at Race Passage near Victoria. A total of 43 1 MW rated MCT units could be deployed to harness an annual mean power of almost 10 MW. The same analysis method that was followed for the Discovery Passage installation was adopted for this site except that somewhat higher technology factors were assumed to reflect the relatively fewer number of turbine units that would be deployed at this location (namely 0.9 for capital cost and 1.0 for decommissioning and annual cost).

The capital cost for this project is of the order of $140 million, yielding approximately 76 GWh/year. The estimated unit cost for this energy is just over **25¢/kWh**.

7.2.3 Future Tidal Energy Costs

As summarized in Section 7.2.1 and 7.2.2 above, present tidal current energy generation costs using existing technology appear to be competitive with other Green Energy sources, at **11¢/kWh** for a large site (800 MW rated capacity and 1400 GWh/annum) and **25¢/kWh** for a small site (43 MW rated capacity and 76 GWh/annum). These costs assume a conservative capacity factor (mean power/rated power) of 20% and a maximum current speed of 3.5 m/s.

Future power generation costs are expected to reduce considerably as both existing and new technologies are developed over the next few years. Assuming that maximum currents larger than 3.5 m/s can be exploited and present design developments continue, it is estimated that future tidal current energy costs between **5¢/**kWh and **7¢**/kWh are achievable.

7.3 TIDAL CURRENT TECHNOLOGIES

Tidal current technologies proposed by five companies have been reviewed;

Blue Energy Canada	Vancouver, British Columbia
Clean Current	Vancouver, British Columbia
Marine Current Turbines	London, UK
UEK Corp.	Annapolis, MD, USA
RVco Ltd	London, UK and CA, USA

The technologies come from principally two geographic regions: Europe (Marine Current Turbines and Rochester Venturi) and North America (Blue Energy, Clean Current and UEK Inc).

There were two major difficulties encountered during our review of tidal current technologies, specifically:

- all technologies are in the early stages of development, often laboratory or small scale prototype installations and,
- all technologies appear to be being developed as “commercial” ventures, therefore proponents are reluctant to divulge any information because of the fear that competing systems may “get an edge”.

Table 9 illustrates the overall characteristics of the technologies examined including information on financing, the type of technology, type and location of the power generation system, maintenance considerations and probable major type of application.

Based on the Technology Review, detailed in Section 6 of this report, the available tidal current technologies can also be compared on the following general criteria.

- Present Technological Development
- Future Potential (technological) Development
- Cost Efficiency
- Environmental and Navigational Acceptability
- Applicability to British Columbia (projects >10 MW)

Table 9: Technology Comparison Summary

Company	Financing	Type of Technology	Generation System	Location of Generation System	Maintenance	Major Application
Blue Energy Canada (BC)	Private	Vertical Axis Darrius Turbine	Conventional Gearbox and generator	Above Water	Well thought out	Tidal Fence
Clean Current (BC)	Private	Horizontal Axis Wells Turbine	Rim Generator (no gearbox)	Submerged	Yet to be detailed	Free Stream or farm
Marine Current Turbines (UK)	Govt + Private	Horizontal Axis Variable Pitch Conventional Turbine (wind type)	Conventional Gearbox and generator	Submerged	Well thought out	Farm
UEK Corp (USA)	Private+ Govt	Horizontal Axis Single or Double Acting Turbine Rotors	Conventional Gearbox and generator	Submerged	Well thought out (for small units)	Individual free stream units
RVco Ltd (UK)	Private	Venturi	Onshore (gas type) turbine and generator	Onland or Above Water	Uncertain but probably easy	Uncertain

7.3.1 Present Technological Development

At the time of writing, UEK Corp. was the only firm that has had an actual generating unit in the water. They are judged to be the most technically advanced at this date. On the other hand, RVco Ltd. has recently installed a test installation at Grimsby, UK although detailed test results are not presently available. Blue Energy Canada base their system on extensive tests done at the National Research Council (NRC Ottawa) in the 1980s. As far as can be determined, design improvements in the Davis Turbine made during the last 15 years have not been tested in the laboratory, although Blue Energy has done studies on tidal fence applications. Marine Current Turbines have completed the most advanced design studies of all the proponents examined, although the extent of laboratory testing is not known. Clean Current is at the initial design studies stage of their development.

7.3.2 Future Technological Development

Future development of tidal current technologies is extremely difficult to evaluate. To a large degree the advancement of each of the systems reviewed depends on three factors:

a) the potential efficiency and applicability of the underlying design concept,

b) the present level of technological development, and

c) the availability of funds (either Government or Private) to finance research, design development and prototype testing.

In theory, the least developed systems are likely to provide the best potential for future technological developments. However, many excellent technical developments have failed because of lack of development funding. In addition, detailed research and development may show that there are hidden flaws in the underlying concepts.

Therefore, based on the limited technical information available at this time, it is our opinion that no definitive conclusions can be reached regarding the future development of the tidal current technologies proposed by specific companies.

However, our review has shown that tidal current power technology is rapidly developing and there are very strong indications that future design, research and testing will result in considerable improvements in the efficiency and costs of extracting power from tidal currents.

7.3.3 Cost Efficiency

As discussed in Section 4.1.2, the only credible cost data for tidal current power installations have been prepared by Marine Current Turbines and UEK. MCT cost data for a 30 MW tidal current farm were published in an independent report by consultants Binnie, Black and Veatch (2001). UEK costs are only available for small turbine units which cannot, at this time, be realistically scaled up for a “Utility Scale” tidal current installation.

The lack of detailed cost data from other tidal current companies makes it impossible to compare the proposed technologies on the basis of cost efficiency. Hopefully, this situation will improve as companies undertake detailed design studies.

7.3.4 Environmental and Navigational Acceptability

The tidal modelling analysis and environmental review undertaken for this study indicated that the physical and environmental impact of tidal current extraction is expected to be relatively small; although technologies which use ducted turbines as a opposed to open blades, are believed to be better able to include protection for fish, large marine mammals, and floating debris such as deadheads.

A review of the environmental impact of tidal fences was not part of this report. Nevertheless, it is clear that the impacts of such designs are extremely site specific and can be either positive or negative depending on the particular application and location.

Marine navigation will have to be given serious consideration when siting future tidal current power installations. Surface piercing technologies such as the tidal fence (Blue Energy) and MCT will have to be specifically designed to accommodate vessel and small boat traffic.

7.3.5 Applicability to British Columbia (Projects >10 MW)

Although UEK Inc has the most developed and tested tidal current power system on the market, in its present form the technology would appear to be unsuitable for large scale developments. However, we would need much more detail information on the turbine units before we can confirm this initial impression. UEK units would seem to be directed at the niche market of power generation 1 to 10 MW.

All the remaining tidal current technologies appear to be potentially suitable to large scale power generation or utility scale projects >10 MW.

8. FUTURE CONSIDERATIONS

Following a review of this report and integration with the goals of BC Hydro Green Energy Phase 2 Study, BC Hydro Engineering has outlined a series of next steps which would include:

a) Maintain a technology watch on tidal current technologies,

b) Improve knowledge of the tidal current resource in British Columbia,

c) Expand the scope to study the in-stream flow resources in British Columbia rivers,

d) Consider ways to “enable” development of tidal current energy in BC as it progresses to a near commercial energy resource.

These activities would include the following recommendations of Triton Consultants Ltd, specifically:

1. Improve the detail in the tidal model grid, specifically at narrow high current areas. Calibrate the new model grid with measured tidal data and perform additional simulations of proposed tidal power sites (e.g., Race Passage (Victoria) and Weynton Passage (Alert Bay),
2. Undertake a resource assessment for the Queen Charlotte Islands. Tidal current power potential in these islands could be significant,
3. Revise this report as new technologies become known, present technologies proceed through their development phases and more information is made available,
4. Consider collaboration with ongoing and planned pilot/demonstration installations,
5. Investigate the application of hydrogen generation to remote tidal current sites.

9. REFERENCES

Binnie, Black and Veatch, 2001. The Commercial Prospects for Tidal Stream Power. Final report to DTI New and Renewable Energy Programme, April. 67p.

European Commission, 1996. Non-Nuclear Energy – JOULE II, Wave Energy Project Results – The Exploitation of Tidal and Marine Currents. Luxembourg: Office for Official Publications of the European Communities. ISBN 92-827-5658-0. 67p.

Faure, T.D., Ploeg, J. and Dudgeon, E.H., 1984. Experimental results of a Darrieus type vertical axis rotor in a water current, NRC Canada.

Forrester, W.D, 1983. Canadian Tidal Manual. Department of Fisheries and Oceans, Canadian Hydrographic Services Ottawa, Ontario 138p.

Garrett, Chris, 2001 unpublished. Tidal Power Generation by Continuous Flow. University of Victoria. 12 p.

Simons, H.A. (International) Ltd., Keefer, B. and Associates and Nova Energy Limited, 1984. An Ultra-Low Head Approach to Tidal Energy, Preliminary Appraisal, for NRC Canada, March.

UK House of Commons, 2001.

Walters, R.A. “The frontal method in hydrodynamics simulations”, *Computers and Fluids*, **8**, (1980) 265-272.

Appendix A

Potential Tidal Current Sites in BC

Potential Tidal Current Power Sites in BC (excluding Queen Charlotte Islands)

Site Name	Chart	Latitude deg N	Longitude deg W	Maximum Current Speed Flood knots	Maximum Current Speed Ebb knots	Mean Maximum Depth Averaged Current Speed m/s	Mean Power Density kW/m^2	Width of Passage m	Average Depth of Passage m	Flow Cross-sectional Area m^2	Mean Potential Power MW
Seymour Narrows	353902	50.1320	125.3532	16.0	14.0	6.2	21.9	765	35	28689	628.17
N. Boundary Passage	346201	48.7875	123.0085	4.0	4.0	1.6	0.4	5158	140	734949	305.16
Discovery Pass. S.	353901	49.9973	125.2107	7.0	7.0	2.9	2.2	1866	35	69993	155.76
Boundary passage	344101	48.6944	123.2680	3.5	3.5	1.4	0.3	4472	175	793760	220.80
Current Passage 2	354401	50.3885	125.8552	6.0	6.0	2.5	1.4	1502	80	123931	173.67
Weyton Passage	354601	50.5851	126.8160	6.0	6.0	2.5	1.4	1535	75	118985	166.74
Nakwakto Rapids	355001	51.0970	127.5035	14.0	16.0	6.2	21.9	434	10	5426	118.81
Current Passage 1	354401	50.4114	125.8709	5.0	5.0	2.1	0.8	1398	100	143331	116.24
Dent Rapids	354301	50.4081	125.2122	11.0	8.0	3.9	5.6	420	45	19955	111.00
South Pender Is	344101	48.7248	123.1929	4.0	4.0	1.6	0.4	1985	100	203416	84.46
Yaculta Rapids	354301	50.3790	125.1497	10.0	10.0	4.1	6.5	539	20	12135	78.73
Arran Rapids	354301	50.4206	125.1393	14.0	10.0	4.9	11.2	271	22	6629	74.32
Secheldt Rapids 2	351403	49.7378	123.8956	14.5	16.0	6.3	23.0	261	8	2739	63.03
Gillard Passage 1	354301	50.3930	125.1588	13.0	10.0	4.7	9.9	237	16	4393	43.34
Scott Channel	362501	50.7912	128.5049	3.0	3.0	1.2	0.2	9970	22	244256	42.79
Active Pass	344201	48.8593	123.3286	8.0	8.0	3.3	3.3	561	20	12628	41.95
Nahwitti Bar 1	354901	50.8922	127.9903	5.5	5.5	2.3	1.1	2993	9	34417	37.15
Race Passage	344001	48.3070	123.5402	6.0	7.0	2.7	1.8	884	20	19885	35.43
Green Pt 2	354301	50.4488	125.5210	6.0	6.0	2.5	1.4	538	35	20157	28.25
Blackney Passage	354601	50.5676	126.6876	5.0	5.0	2.1	0.8	814	40	34598	28.06
GreenPt Rap. 1	354301	50.4413	125.5096	7.0	7.0	2.9	2.2	440	25	12093	26.91
Porlier Pass	347303	49.0143	123.5876	9.0	8.0	3.5	4.0	339	15	5926	23.61
Gillard Passage 2	354301	50.3956	125.1510	10.0	8.0	3.7	4.7	393	10	4916	23.25
Upper rapids 2	353701	50.3057	125.2340	9.0	9.0	3.7	4.7	242	18	4955	23.44
Becher Bay	341001	48.3190	123.6205	3.0	3.0	1.2	0.2	2148	60	134263	23.52
Whirlpool Rapids	354401	50.4599	125.7620	7.0	7.0	2.9	2.2	321	28	9804	21.82
Surge Narrows	353701	50.2307	125.1582	6.0	6.0	2.5	1.4	413	30	13432	18.82
Chatham Islands	344001	48.4471	123.2593	6.0	6.0	2.5	1.4	903	12	13099	18.36
Quatsino Narrows	368106	50.5530	127.5581	9.0	8.0	3.5	4.0	207	18	4240	16.90
Hole-in-the-Wall 1	353901	50.3007	125.2080	12.0	9.5	4.4	8.1	189	8	1985	16.00
Outer Narrows	355001	51.0874	127.6317	7.0	10.0	3.5	4.0	210	17	4101	16.34
Village Island	351501	50.6389	126.5119	3.0	3.0	1.2	0.2	1234	70	89461	15.67
Green Pt 3	354301	50.4446	125.5746	5.0	5.0	2.1	0.8	673	25	18498	15.00
Nahwitti Bar 2	354901	50.8703	127.9910	5.5	5.5	2.3	1.1	2012	4	13078	14.12
First Narrows	349301	49.3156	123.1395	6.0	6.0	2.5	1.4	418	16	7734	10.84
Buckholtz Ch 2	367901	50.4932	127.5988	3.0	3.0	1.2	0.2	1073	50	56329	9.87
Buckholtz Ch 1	367901	50.4946	127.6737	3.0	3.0	1.2	0.2	997	50	52357	9.17
Tallac - Erasmus Is	354301	50.4391	125.4746	3.0	3.0	1.2	0.2	665	75	51522	9.03
Lower Rapids 1	353701	50.3096	125.2626	7.0	7.0	2.9	2.2	371	8	3891	8.66
Perceval Narrows	371004	52.3343	128.3764	5.0	5.0	2.1	0.8	382	25	10518	8.53
Picton Point	354301	50.4633	125.3980	3.0	3.0	1.2	0.2	881	50	46235	8.10

Potential Tidal Current Power Sites in BC (excluding Queen Charlotte Islands)

Site Name	Chart	Latitude	Longitude	Maximum Current Speed Flood	Maximum Current Speed Ebb	Mean Maximum Depth Averaged Current Speed	Mean Power Density	Width of Passage	Average Depth of Passage	Flow Cross-sectional Area	Mean Potential Power
		deg N	deg W	knots	knots	m/s	kW/m^2	m	m	m^2	MW
Charles Bay Rapids	354301	50.4184	125.4949	5.0	5.0	2.1	0.8	664	12	9631	7.81
Hiekish Narrows	373802	52.8757	128.4949	4.0	4.5	1.8	0.5	571	25	15715	7.83
Pearse Passage	354601	50.5786	126.8952	4.0	4.0	1.6	0.4	1168	13	18104	7.52
Welcome Passage	351201	49.5063	123.9652	3.0	3.0	1.2	0.2	746	50	39189	6.86
Draney Narrows`	393102	51.4723	127.5608	9.0	9.0	3.7	4.7	139	7.5	1394	6.59
Gabriola Pass.	347501	49.1291	123.7022	8.5	9.0	3.6	4.3	137	8	1435	6.24
Alert Bay	354601	50.5740	126.9308	3.0	3.0	1.2	0.2	1771	18	36311	6.36
Second Narrows	349402	49.2947	123.0238	6.0	6.0	2.5	1.4	254	13.88	4159	5.83
Haddington Passage 2	354601	50.5918	127.0215	3.0	3.0	1.2	0.2	1311	20	29492	5.17
Moresby Passage	344101	48.7313	123.3434	3.0	3.0	1.2	0.2	1191	20	26793	4.69
Nitinat Narrows	364703	48.6728	124.8524	8.0	8.0	3.3	3.3	61	20	1376	4.57
Stuart Narrows	354701	50.8962	126.9430	6.0	7.0	2.7	1.8	261	7	2478	4.42
Hamber Island	349501	49.3164	122.9373	4.0	4.0	1.6	0.4	414	22.5	10362	4.30
Dodds Narrows	347501	49.1355	123.8175	9.0	8.0	3.5	4.0	91	9	1047	4.17
Kildidt Narrows	393701	51.8862	128.1097	12.0	12.0	4.9	11.2	75	2	338	3.79
Sansum Narrows	344101	48.7846	123.5551	3.0	3.0	1.2	0.2	553	40	23509	4.12
Hidden Inlet	399401	54.9496	130.3345	9.0	9.0	3.7	4.7	142	2.5	710	3.36
Gillard Passage 3	354301	50.3877	125.1628	10.0	8.0	3.7	4.7	92	5	686	3.25
Haddington Passage 1	354601	50.6069	127.0164	3.0	3.0	1.2	0.2	570	25	15684	2.75
Matlset Narrowsq	367301	49.2380	125.7999	4.0	4.0	1.6	0.4	464	10	5799	2.41
Tsownin Narrows	367601	49.7754	126.6452	3.0	3.0	1.2	0.2	283	45	13460	2.36
Hayden Passage	367403	49.3954	126.1069	4.0	4.0	1.6	0.4	312	15	5457	2.27
N Sydney Is	344101	48.6684	123.3489	3.0	3.0	1.2	0.2	1029	9	11833	2.07
Tuck Narrows	396402	54.3998	130.2567	6.0	6.0	2.5	1.4	138	7	1310	1.84
Scouler Pass	365101	50.3127	127.8158	4.0	4.0	1.6	0.4	512	4	3327	1.38
Eclipse Narrows	355201	51.0886	126.7738	6.0	5.0	2.3	1.1	141	6	1199	1.29
Dawley Passage	368501	49.1480	125.7935	3.0	3.0	1.2	0.2	289	20	6509	1.14
Neilson Is - Morpheus	368501	49.1560	125.8837	5.0	5.0	2.1	0.8	202	4	1311	1.06
Clement Rapids	374001	53.2042	129.0420	6.0	6.0	2.5	1.4	80	7	760	1.07
Tsapee Narrows	368501	49.1231	125.8173	4.0	4.0	1.6	0.4	280	6.5	2517	1.05
Schooner Channel	355201	51.0647	127.5206	6.0	6.5	2.6	1.6	72	6	612	0.97
Hawkins Narrows	372201	53.4070	129.4182	8.0	8.0	3.3	3.3	55	2.5	273	0.91
Felice Is - Grice Pt	368501	49.1539	125.9147	3.0	3.0	1.2	0.2	339	12	4915	0.86
Higgins Passage 2	371005	52.4827	128.7053	5.0	5.0	2.1	0.8	173	3	952	0.77
Nelson Narrows 1	393302	51.7682	127.4316	3.5	3.5	1.4	0.3	313	6	2660	0.74
Sooke Inlet	341001	48.3579	123.7097	4.0	4.0	1.6	0.4	267	4	1735	0.72
Whitrock Passage	353701	50.2483	125.1035	7.0	7.0	2.9	2.2	68	2	304	0.68
Nanahlamai Lagoon	355201	51.0032	127.2607	8.0	9.0	3.5	4.0	46	1	161	0.64
Kenneth Passage	354701	50.9486	126.8126	4.0	4.0	1.6	0.4	177	6	1509	0.63
Nelson Narrows 2	393202	51.7665	127.4336	3.0	3.0	1.2	0.2	95	35	3554	0.62
Zanardi Rapids	395502	54.2455	130.2971	4.5	4.5	1.9	0.6	185	2.5	925	0.55
Sulphur Passage	367401	49.3963	126.0836	4.0	4.0	1.6	0.4	133	7	1263	0.52
Darby Channel	393402	51.5187	127.6566	3.0	3.0	1.2	0.2	122	22	2995	0.52

Potential Tidal Current Power Sites in BC (excluding Queen Charlotte Islands)

Site Name	Chart	Latitude deg N	Longitude deg W	Maximum Current Speed Flood knots	Maximum Current Speed Ebb knots	Mean Maximum Depth Averaged Current Speed m/s	Mean Power Density kW/m^2	Width of Passage m	Average Depth of Passage m	Flow Cross-sectional Area m^2	Mean Potential Power MW
Stubbs Is - Felice Is	368501	49.1539	125.9254	3.0	3.0	1.2	0.2	262	8	2748	0.48
Naysash Inlet	393101	51.3367	127.3219	4.0	4.0	1.6	0.4	147	5	1100	0.46
HunterSterling Hakai	393501	51.7864	128.0911	3.0	3.0	1.2	0.2	164	12	2375	0.42
Enterprise Channel	344001	48.4085	123.3054	3.0	3.0	1.2	0.2	241	7	2287	0.40
Higgins Passage 1	371005	52.4865	128.7241	5.0	5.0	2.1	0.8	110	1	384	0.31
Roaring Rapids	354701	50.9538	126.8094	6.0	6.0	2.5	1.4	60	1	212	0.30
Wyclees Lagoon	393101	51.2795	127.3536	7.0	7.0	2.9	2.2	30	1	105	0.23
Johnson Lagoon	368301	50.1711	127.6507	5.0	5.0	2.1	0.8	47	3	261	0.21
Venn Passage	395503	54.3250	130.4166	3.0	3.0	1.2	0.2	148	4.5	1035	0.18
Griffin Passage	396201	52.6180	128.2933	4.5	4.5	1.9	0.6	93	0.5	278	0.16
The Gorge VictoriaHar	341501	48.4464	123.3998	6.0	6.0	2.5	1.4	20	2	90	0.13
Elizabeth Lagoon	392101	51.6543	127.7643	5.0	5.0	2.1	0.8	38	1	134	0.11
Jackson Narrows	373402	52.5242	128.3006	3.0	3.0	1.2	0.2	119	2	535	0.09
Meyers Passage	371001	52.6070	128.6110	3.0	3.0	1.2	0.2	141	1	494	0.09
Mary Narrows	367601	49.8005	126.8245	3.0	3.0	1.2	0.2	93	0.5	280	0.05
Troup Narrows	372002	52.2840	128.0022	2.0	2.0	0.8	0.1	106	6	903	0.05
Fatty Basin	364602	48.9850	125.0271	4.0	4.0	1.6	0.4	27	0.5	81	0.03
										MW Average	3022
										GWh/annum	26474