Abstract—Canada possesses both a viable resource and technology development capacity for helping to lead the emerging marine energy sector. In order to remain at the forefront of technological innovation, Canadian companies require intensive research efforts to reduce development costs and commercial uncertainty. The programs of research detailed in this article are aimed at fulfilling this requirement in three main type of marine energy: wave, tidal and river kinetic. Key contributions of these research programs are detailed, including modeling developments to enable a streamlined design process with increased confidence in performance predictions, and experimental testing to obtain practical experience and real-world testing results.

I. INTRODUCTION

MARINE energy represents a viable source of alternative energy for Canada, accessible in three forms: ocean waves and tides, and kinetic hydropower. Ocean waves ultimately derive from solar power, through the chain of solar heating of earth, through wind generation, and final creation of ocean waves. Tidal power results from earth-moon-sun system gravitational interactions. Kinetic hydropower for river applications uses submerged turbines to produce power from water currents present in the hydrological cycle, and is therefore applicable to river and channel flows in a diversity of installation sites. Each variant is heavily influenced by the geographic location of installation, in terms of energy capture, economic costs and environmental impact. With proper site selection, each technology offers the possibility of delivering electricity with minimal Greenhouse Gases (GHG) impact. The size of the devices (10’s kW – MW) allow the resources to be incrementally developed, enabling application to remote locations where energy costs are higher and hence benefits maximized. All three technologies are nascent, allowing technical maturation to occur with initial machine deployments.

Excellent review articles are available on the world development status of these technologies [1], [2]. Canadian industry is represented in all three areas, although given the competitive marketplace and early stage of the technologies, fast-paced research is required in support of commercial demonstration projects. Both technology ‘push’ and ‘pull’ forces are at work to develop the technology, the former including advanced analysis tools and power electronics, and the latter created by increasing energy costs and government/consumer commitment to reduce GHG emissions. Domestic government commitment is illustrated by the 2004 BC Energy Plan which called on Independent Power Producers (IPPs) to champion new alternative generating technologies, including Renewable Ocean Energy (ROE), that would decentralize energy generation in BC.

The Canadian ROE technology industry is comprised of small to medium sized enterprises and a number of IPPs and coastal utilities working to develop an ocean energy marketplace. Commercialization of innovative Canadian ROE concepts will require comprehensive justification of performance specifications, survivability and environmental impact. This process must culminate with full-scale demonstration projects supported by extensive physical model testing programs executed at Canada’s world class tank testing facilities at the NRC Institute for Ocean Technology (IOT). However, the disproportionate cost of initial small scale or demonstration deployments strains the limited resources of the typical Canadian ROE developer. Canadian marine energy start-up companies lack funding to access the iterative, systematic performance evaluation, applied research and development process that sensible technology development requires.

The current article presents research that is occurring in Canadian universities, in concert with commercial ventures, to develop wave, tidal and hydrokinetic devices. The work is focused on streamlining the applied research stage to bring Canadian developers from early concept to demonstration readiness. To accomplish this task, an array of inexpensive design tools for rapid iteration of early stage concepts is being developed, in addition to accurate estimation of performance data for selected concepts in a variety of deployment circumstances, high-fidelity structural and dynamic analyses of refined designs, and experimental work where facilities allow.

II. WAVE ENERGY

At the University of Victoria (UVic), expertise in dynamics modeling, design and renewable energy integration is contributing heavily to industrial research and development of wave energy converter technology. The objective of this collaborative research is the commercialization of technology that can play a part in servicing small, remote, and off grid Pacific coastal communities (50–200 kW loads) which rely solely on expensive diesel generation systems.

Since 2006, researchers at UVic have partnered with Syncwave Energy Inc. in development of Syncwave’s floating point wave energy point absorber. The immediate goal of the UVic wave energy research team is to build numerical modeling expertise to refine Wave Energy Converter (WEC) designs, and ultimately to streamline subsequent IOT testing.
programs and accelerate the progression from the IOT tests to the demonstration phase. Accurate high-fidelity numerical models, validated by IOT test data, can serve to bridge the gap between small-scale model and ocean-scale device dynamics by improving the success rate of companies that transition from early stage industrial funding, like NRC-IRAP, to large scale demonstration funds, such as Canada’s SDTC program.

Towards the development of a comprehensive suite of numerical tools, the UVic team is active in resource characterization, conventional frequency domain modeling and active control, computer aided design and integration analysis and high-fidelity converter simulations.

A. Resource Characterization

UVic researchers, in collaboration with Syncwave and BC Hydro, have begun a detailed characterization of the wave energy flux off of the West Coast of Vancouver Island. At the core of this study is an in-house capability to model the propagation of high energy off-shore waves to the near-shore. The dominant processes occurring during wave transportation are refraction, diffraction, reflection, shoaling, bottom friction, breaking energy dissipation and resonance [4]. Based on propagation model comparison studies completed to date [5]–[7], Dalrymple’s REF/DIF-1 (v2.6) was implemented with an aim to evaluating the operating environment of wave energy converters located off of SW Vancouver Island. The REF/DIF-1 code captures the dominant transport phenomena, except wind, and a spectral analysis is completed through repeated runs of REF/DIF-1 applying individual components of the offshore spectra along the outer boundary of the modeled domain. The UVic REF/DIF-1 studies draw upon digital bathymetry files from the Canadian Hydrographic Service (CHS).

To date, the offshore spectra used to drive the propagation studies are drawn from the nearest WaveWatch III grid point. However, UVic and Syncwave have initiated a field monitoring program using a TriAXYS directional wave buoy donated by BC Hydro in 2006, as shown in Fig. 1. The buoy site is 17 km off of Lennard Island near Tofino BC and the program is conducted with participation of the Canadian DFO. As discussed in the CHC Wave and Tidal assessment [8], several Canadian Marine Environmental Data Service (MEDS) buoys are located on the Pacific Coast, but many are in sheltered coastal regions and can’t be directly used to guide the search for energetic near shore locations. Furthermore, offshore buoys, other than a Directional Wave Rider Buoy (DWR) deployed near Tofino (49.03N 125.8W) between Sept. 1998 and May 1999, did not record directional spectra. Recent research has shown that in order to obtain realistic estimates of wave power capture from a wave energy converter a detailed characterization of the wave climate including spectrum shape and direction is necessary [9], [10].

B. WEC Frequency Domain Modeling

Early device design and optimization research conducted at UVic in 2006–2007 was focused on the use of conventional frequency domain models to justify and optimize the Syncwave SWELS tuning system. The modeling work was based on the “small-body approximation” which affords simple parametric representation of the wave excitation force [11]. The SWELS equipped Syncwave WEC is a variation on the classic resonating point absorber introduced by Budal and Falnes [12] that relies on out of phase motion of two heaving surface piercing floats, the primary and secondary bodies, to drive a generator.

The Syncwave concept departs from the use of a relatively stationary, possibly submerged, secondary body that acts as a reference for the primary float [13], [14]. Using two streamlined floating bodies, the SPR concept exploits powerful buoyant forces on both floating components to drive the generator. A prime advantage is the ability to minimize drag on both bodies and thus ease the mooring loads in storm conditions. However, to ensure out-of-phase motion, a tuning system is required to adjust the heave response of at least one of the bodies – hence the UVic led development of SWELS. The tuning system uses an internal reaction mass to generate the frequency response adjustments similar to the suggestions of Gerber [15], Bracewell [16] and Korde [17]. In contrast to these existing concepts, the UVic prototype complements variable spring stiffness with inertial adjustments to affect changes in the frequency response of the spar. The
SWELS system is seen in Fig. 2c; the reaction mass motions drive rotation of a ballscrew assembly. Continuous changes in the rotational inertia of the ballscrew assembly, achieved by positioning flyball masses, results in continuous changes in the natural frequency of the reaction mass and changes in the heave response of the WEC hull.

The SWELS control variables, rotational inertia and generator damping, are varied rapidly to capitalize on the predominant wave components and no energy is consumed between adjustments. The simplified wave-body dynamics model was used to explore the potential benefits from, and justification of, this type of tuning system in a wave tank specific design scenario. The frequency response predicted by the simplified models was applied to generate objective function values and optimization algorithms available in Matlab were used to search for optimal WEC geometries and the associated SWELS control settings across the frequency domain. The UVic team showed that the presence of the reaction mass plus the SWELS behavior produced significant power production improvements for the test tank prototype [18]. Figure 3 shows some results of that work.

In 2006 a small proof of concept prototype was constructed and was tested in a small wave channel at the University of British Columbia [19] - a tank facility that unfortunately was decommissioned in 2007. The primary function of this prototype was to act as an experimental platform for the continued testing and revision of the SWELS mechanism. The 2006 tests were used to extract estimates of the small body wave excitation coefficients and to validate the reduction of the simple model to a heave only analysis. The prototype employed a fixed, and non-optimal, generator and produced an average of 5.5 W from .2 m waves and frequencies of 0.35–0.65 Hz.

C. Demonstration Unit Design and Integration Analysis

The parametric design principles and SWELS sizing procedure developed for the prototype design are now being applied by UVic researchers in the design of a 20 kW/180 kW
(a) Suggested deployment location and Hs-Tp probability distribution

(b) WEC hull

Fig. 4: Syncwave demonstration WEC for St. George project

In collaboration with Engineers from Marinus Power in Houston TX. Figure 4 shows images of the demonstration unit.

In collaboration with Triton Consulting of Vancouver BC, the frequency domain model of a preliminary Syncwave demonstration device was used in an integration study [20] conducted for the island community of St. George, AK. A summary of seasonal and directionally screened WWIII Hs-Tp data provided by triton was used to synthesize hourly spectra at the WWIII grid point nearest the deployment location 6km SW of the St. George Island coastline, shown in Fig. 4a. The integration study showed that the average wave energy flux at the deployment site was 34 kW/m after accounting for the sheltering effect of the island. The joint Hs-Tp probability is shown in Fig. 4a. The WEC provided a 16 kW average and could provide 10% of the island electrical energy demand. The hourly analysis showed that this integration scenario, drawing on the standards of wind-diesel hybrid systems, can be classified as medium penetration. A simplified economic analysis, based on revenues due to fuel savings, suggests a break even cost of electricity of 0.50 $US/kWh using realistic diesel price forecasting and a typical discount rate. A sample of the weekly WEC power supply in comparison to the Island energy demand is shown in Fig. 5.

D. High Fidelity Simulation of WEC Dynamics

UVic researchers are collaborating with engineers at Dynamic Systems Analysis (DSA) in the creation of a comprehensive suite of dynamics modeling codes that can be assembled to form high fidelity simulations of articulated wave or tidal energy converters. At the core of the simulations is a cable dynamics model developed over the past decade at UVic for use in the simulation of tethered underwater vehicles. The cable model is capable of capturing classic low tension effects such as bending and torsional contributions to cable motion (an example being hockling), as well as cable to cable contact, cable self contact and the payout or retrieval of cable (as during deployment or recovery operations). DSA has also applied articulated body algorithms (ABA) to the dynamics of the multi-body SyncWave WEC and also recently applied the technique to the simulation of a moored turbine being developed at the Florida Centre for Excellence in Ocean Energy. The ABA method is ideal for jointed bodies moving in fluid; it is a recursive approach that accounts for the joints between the WEC components and also allows the added mass forces to be included directly without approximation, as is the case when applying Newton-Euler dynamics formulations. The hydrodynamic forces are evaluated over the WEC hull using a strip theory approach with a Morrison-type approximation applied on each strip. Buoyant effects are calculated by discretizing the surface of the hull and integrating the pressure field at each time step.

Figure 6 shows two views of the SyncWave WEC during simulations. UVic researchers are currently engaged in aspects of cable dynamics and numerical hydrodynamics in order to improve the utility of the simulations and make a move away from the use of conventional frequency domain models for performance estimation.
III. Tidal Energy

Tidal energy may be harnessed either indirectly from hydraulic head converted to kinetic energy (barrages), or directly from free current flows. Relative to most other renewable energy sources, the power density is high and tidal cycles can be predicted with certainty. A few barrages have been installed to impound and harness tidal flows in basins, but direct kinetic energy technologies have only recently received interest. Barrages can theoretically extract all available power from a tidal range (as would a complete “tidal fence” of kinetic machines), but cannot be installed incrementally (to ease capital cost financing) and have a significant environmental impact. For any means of harness tidal power, fundamental hydrodynamics constraints dictate maximal power extraction fractions owing to flow blockage effects [21].

Successful concepts have generally been of a rotating turbine design, along the lines of conventional wind turbines. However, the underwater environment is unique (inflow turbulence, fluid density, cavitation, marine growth [22] and corrosion, etc.). Precise economic estimates of energy cost from marine turbines are unavailable at the present state of development. UVic researchers are currently working with Clean Current Power Systems (CCPS) to develop their ducted bi-directional design, targeting machines from 100’s kW–MW’s. While ducted turbines were a failure in large-scale wind turbines, the reason for the failures, namely storm loads, are not present underwater. Ducted tidal turbines have an advantage in decreasing the size of the rotor and operating at higher rotation speeds (to facilitate direct-drive electrical generator operation) for the same output power. The extra drag on the duct must be borne by the tower, and further study is required to quantify the optimal duct for a farm of turbines attempting to extract maximum aggregate energy.

A. Inflow Characteristics

The underwater environment contains significant turbulent velocity fluctuations. The characterization of the turbulence is however not well quantified. To that end, Acoustic Doppler Current Profiler (ADCP) data provided by CCPS, such as that shown in Fig. 7, is being analyzed to extract the characteristics of the flow turbulence. The boundary layer underwater is frequently strongly stratified, but success in modeling the flow has been had by departing from atmospheric models [23], outside of the near-surface region where coupled surface gravity waves/turbulence effects occur (e.g. Langmuir circulation).

An additional effect that must be considered are internal waves. These originate from perturbations to the hydrostatic equilibrium (density variations) driven by gravity and buoyant restoring forces. The susceptibility of a water body to these effects may be quantified by the Richardson (Ri) number. Long time-series of test data may be required to detect these waves, as they are non-periodic and highly site specific. While the frequencies are low compared to surface waves, the amplitudes of motion are larger, with important consequences for the flow ingested by the machine’s rotor.

The distinction between near-surface and deep concepts should be appreciated. Some machines, such as Marine Current Turbines (MCT), position the rotor near the free-surface,
whereas the CCPS machines are closer to the bottom of the water column in deep water. Water particle velocities due to surface waves are characterized as shallow, intermediate and deep. The former sees significant flow velocities from free-surface to bottom, whereas deep water conditions show an exponential decay in velocities becoming negligible below one-half wavelength. Based on site analysis of CCPS potential sites using wave data, the machines will operate in deep water, only entering intermediate-depth conditions at extreme tide conditions, thereby avoiding wave-induced loads that competitors machines will experience.

B. Device Modeling

Modeling tools for the analysis of tidal turbines has to date utilized the methods of the wind turbine community, namely the Blade Element Momentum (BEM) theory. The codes are similar those for wind and in some cases include unsteady formulations [24]. Differing Reynolds number regime and cavitation effects require new experimental validation data and sectional input data [25]. At UVic, an existing time-dependent wind turbine code is being extended to include these effects, as well as modifications for ducted rotors by extending generalized BEM theory [26] and including the turbulent inflow discussed above. Vortex-filament based methods and full-field CFD methods with rotors modeled as porous discs [27] are also being explored for validation and tuning or lower order models. Preliminary studies indicate that fatigue loading must be taken into account in the structural analysis of submerged turbines [28], given the waves (both surface and internal) and turbulence encountered underwater.

During start-up, the turbine blade sections will experience very high Angle of Attack (AOA) (up to 90°) at high Reynolds numbers. Virtually no experimental data is available for this flow regime. Consequently a coupled effort is underway to identify proper turbulence models for Computation Fluid Dynamics (CFD) simulations (including Large Eddy Simulation (LES)) of the foils, supported by model-scale testing in the water tunnel, and full-scale of models towed by boat (to avoid blockage effects at high AOA).

C. Composite Blade Design

The blades of the CCPS prototype machine are machined steel; in the future, composite blades will be required for production machines to reduce manufacturing costs and lower machine weight (for barge-based installation). In support of that activity, a comprehensive review of composite materials for the underwater environment has been conducted [29]. The primary areas of uncertainty identified include biofouling, impact characteristics and appropriate strength allowables. Biofouling may be mitigated by traditional means (antifouling paint), however more benign methods may work such as pulse-power or extremely smooth and slippery materials (e.g. thermoplastics to replace the conventional epoxy/vinyl ester matrix). Impact damage must be avoided, as some detritus is likely to be ingested by the rotor. Key concerns are proper core selection, in initial damage resistance and post-damage water absorption, as well as energy absorbing skin materials, such as Aramid fibres used in key locations.

Marine and civil design standards suitable for marine design include large safety factors, while those from the wind turbine community are more precise but require a better understanding of material degradation from continuous submersion. The literature suggests strength losses due to immersion up to 30% have been observed (even larger stiffness reductions), and are highly laminate dependent. The matrix may leach away, making post-cure critical. Vinyl ester performance is superior to epoxy, in turn superior to polyester resins. The reinforcement itself, be it water absorption preferentially along the matrix-fibre interface, or degradation of glass and Aramid fibres, is also of concern.

A custom program developed for the structural analysis of wind turbines blades has been extended for modeling the CCPS rotor blades. The program builds up Euler-Bernoulli beam properties from the skin/web/core layup definitions of each section and hydrofoil shapes. Hydrodynamics loads from the BEM simulations are applied to the beam, and the statically indeterminate system is solved with an Finite Element Method (FEM) formulation. Various boundary conditions for the blades have been studied, corresponding to support by both inner and outer rings of the rotor/generator. The stresses and then compared to allowables to enable preliminary blade designs for costing and weight estimates. In order to reduce the safety factors applied to the design, a material characterization program will carried out on candidate layups which have been subjected to accelerated immersion testing.

IV. River Kinetic Energy Extraction

River kinetic turbines operate in less than ideal conditions, including extreme turbulence and ice/debris-laden flows, in-
Fig. 8: River shapes favoring high velocity flows

(a) Point du Bois

(b) Seven Sisters

(c) Whitemud Cut

Fig. 9: Kinetic turbine sites on the Winnipeg River showing winter conditions with summer aerial photographs. Areas with high flow velocity do not freeze during winter.
including fallen trees during spring run-off that can damage or destroy a turbine. Installation of a trash rack is possible but poses operational and maintenance problems. The surrounding boundary geometry, including the riverbed, is not a readily controllable parameter, and therefore kinetic turbines must accept adverse effects. Conducting research in this area is multidisciplinary, necessitating the close collaboration of institutions because of the wide range of expertise required.

Operation of river kinetic turbines in cold Canadian weather has been experimentally proven to be possible at the Pointe du Bois test site on the Winnipeg River. A consortium of researchers and stakeholders are focusing on the design and development of kinetic turbines for applications under cold climatic conditions and are currently testing 5 kW and 25 kW Darrieus turbines from New Energy and a 60 kW horizontal turbine from UEK. The key research objectives for Canadian river applications remain the reliability, survivability, safety of personnel and costs of delivered grid power. Of key interest is to assess device performance, develop an approach to optimize array layout, and mitigate the impact of turbulence, ice, and debris. Key research areas include: turbine sitting; foundation and retrievals; survivability and reliability improvement; ascertain the impact of environmental factors on performance; reduce costs of installation, deployment and retrieval.

A. Turbine Sittings

The method for kinetic turbine sitting and resource assessment for river applications remains in its infancy. Figure 8 shows a part of the Winnipeg River showing the Pointe du Bois test site. It is important to pick locations where the river banks increase the flow velocity sufficiently to create an opportunity to commercially extract kinetic energy. Figure 9 shows three sites on the Winnipeg River showing winter conditions where kinetic river potential sites where freezing does not occur due to large flow velocities. Aerial views taken during the summer show some of the turbulent eddies on the river surface.

B. Foundations, Deployment and Retrieval

These are critical to the application of this technology in Canadian rivers. The scientific issues relate to the application of novel methods, materials, and system configurations to
ensure that the deployment and retrieval of systems is cost effective and safe, as the flow does not slacken during deployment and retrieval, as for tidal applications. Development of foundations for unstable river beds that can withstand settling of sediments in the periphery of the turbine is an important issue to address. Ways to safely and cost effectively deploy kinetic turbines is an important factor that needs to improve for river applications. For example, the Pointe du Bois test site anchoring system was installed from a floating barge to simulate remote conditions, where marine equipment normally available in cities with ports cannot be brought to site due to excessive costs. This is similar to large crane unavailability in remote areas for wind applications.

C. Survivability, Reliability and Environmental Factors

Kinetic turbine devices need to be able to withstand ongoing disturbances from rotor dynamics, ice, cold weather and debris. Moreover, turbulence in river applications impact the ability to produce maximum power from the available kinetic resource. Methods to modify blade design for higher turbulence applications and quantify the dynamics loads on the turbines need to be investigated. Figure 10 shows winter conditions where ice had an adverse impact on the turbine supporting structure. Floating logs caught in horizontal turbines are shown in Fig. 11. Experiments so far have shown that logs do not damage the turbine or the support structure but can cause the turbine to stall requiring an operator intervention.

V. Conclusions

Marine energy devices, while promising, present a host of interesting and challenging research questions. The Canadian efforts detailed in this paper are aimed at reducing uncertainty in the operational and economic case for wave, tidal and kinetic turbine technologies. The relevance of the work is illustrated by the industrial collaborations undertaken as part of the detailed research.

ACKNOWLEDGMENTS

The authors would like to acknowledge the following sources of funding: MITACS BC, BC Innovation Council, NSERC, Manitoba Hydro, Western Economic Diversification, CEATI and industrial partners.

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