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Riding the wave: Challenges and opportunities for marine renewable energies in Canada's energy transition

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Executive Summary

Canada has committed to reaching net-zero greenhouse gas emissions by 2050. Achieving this objective will require a rapid transition to renewable energy sources to decarbonize existing electricity supply and power new end uses. The roles that different renewable technologies will play in a future energy mix is up for debate; we must decide where and to what extent renewable power sources will be developed and scale them up quickly to enable a transition away from emitting sources. While Canada has over 2300 gigawatts (GW) of potential marine renewable energy (MRE), over 20 times its existing hydroelectric capacity, no utility scale MRE developments exist in Canada at present.

In this report, we assess the opportunities for MRE and the barriers to its development in Canada. Specifically, we assess 1) the status of the major MRE technologies: offshore wind, tidal, and wave; 2) the total potential MRE capacity across the country; 3) the current economic landscape for MRE; 4) the ecological and other environmental risks of MRE technologies; 5) the public perception of MRE, and 6) some potential roles for and advantages of MRE over other renewable sources. We conclude by pointing out some relative advantages of marine renewable power as compared to other renewables, some key impediments to MREs growth, and some key questions that remain for the future of these technologies.

We find that, on average, MREs are more predictable and consistent than terrestrial renewables in providing power. They are also abundant in coastal and island regions, where they are not bound by the spatial constraints of terrestrial renewables. We also find that most forms of MRE are unlikely to significantly affect ecosystems based on currently available research. Marine renewable technologies can provide energy security to remote coastal communities that currently rely on diesel and have the potential to support a just transition by providing jobs to workers in dying coastal and offshore industries such as oil and natural gas extraction. However, several factors have prevented Canada from capitalizing on its wealth of MRE resources and expanding the sector: namely 1) an often-convoluted regulatory environment; 2) a history of poor public perception and engagement; 3) a lack of available capital investment; 4) a need for additional evidence to support the viability of novel MRE technologies; and 5) economic competition from terrestrial wind and solar. Moving forward, we propose that an expansion of the MRE sector will require continued capital investment in research and deployment of test arrays, changes to the regulatory landscape to streamline development and responsible project planning with community engagement and support.

1. Introduction

The Government of Canada has committed to reaching net-zero greenhouse gas emissions by 2050, as outlined in the 2021 Canadian Net-Zero Emissions Accountability Act[1,2]. Achieving the net-zero emissions target will require both the decarbonization of electricity generation, as well as rapid electrification of sectors that currently rely on fossil fuels, particularly the heating of buildings and transportation[3]. The *Canadian Energy Outlook* projects that this rapid transition would require a two-fold increase in electricity generation by 2050[4], which must be met by renewable generation sources if Canada is to meet its legislated climate commitments[1].

While terrestrial renewables, like wind and solar, are rapidly expanding in Canada[5], the role of marine renewable energy (MRE) technologies in decarbonization is still unclear. MRE technologies are designed to harness the power of the ocean by leveraging the flow of offshore winds, waves, and tides to generate electricity[6,7]. Canada's tidal and wave energies alone have a potential of at least 340 gigawatts (GW), while offshore wind capacity has been estimated at over 2000 GW, over twenty times larger than our current hydroelectric capacity[8].

Canada has been building a MRE industry for the past two decades, motivated by the huge potential for electricity generation and higher predictability of MRE technologies compared to terrestrial renewables[9]. Because of these characteristics, MRE could provide a stable supply of energy to the grid and reduce the need for excess energy storage[10]. These technologies could also aid in the decarbonization of remote, coastal, and Indigenous communities that largely rely on burning diesel to generate electricity[11]. Additionally, marine renewables have been deployed successfully in Europe and Asia, where their contribution to the share of power generation is growing[12–14]. Thus, MRE has the potential to facilitate Canada's energy transition by complementing terrestrial renewables. However, questions about the maturity of the technologies, as well as cost-efficiency, public acceptance, and environmental impacts have historically limited the development of marine renewables in Canada.

In this context, the following report aims to comprehensively assess the barriers and opportunities associated with scaling up the development of offshore wind, tidal and wave energies in order to facilitate Canada's transition to net-zero by 2050. Moreover, we aim to assess the potential role of MRE in Canada's transition to a carbon-neutral energy system by midcentury. The report draws on a thorough overview of available academic and grey literatures, as well as technical interviews with experts from research institutes (Interviewees 1 and 8), academic institutions (Interviewees 4 and 8), utility companies (Interviewee 3), non-profit organization (Interviewee 5), industry associations (Interviewee 6), and the federal (Interviewee 7) and provincial (Interviewee 2) governments.

2. Marine Renewable Technologies

2.1 Offshore winds

Of the existing methods of harnessing renewable marine energy, offshore wind turbines are the cheapest and most developed[7,9,11]. Wind forces turn the rotor blades of offshore turbines, which are driven into the seabed or fixed to a floating foundation in the high seas[15]. Many turbines, which can be switched on and off, are installed in an array that feeds power to the mainland through a seabed cable.

Offshore wind arrays are deployed at large scales across the globe[7,11], especially in Europe, which had 16.3 GW of installed offshore wind capacity in 2018, accounting for 90.5% of a worldwide market which has only grown since then[16]. By contrast, and despite having some of the world's best wind resources on its east and west coasts[8], Canada has no utility-scale offshore wind farms at all[17]. This lack of development is related to the higher cost of offshore wind power production compared to its inland counterpart[18] as well as political and regulatory factors discussed in further sections. Though offshore winds are generally more predictable and powerful than those on land, the harsh marine environment introduces design and cost hurdles to all phases of development[18] (Interviewee 4, 6). Despite this, offshore wind projects are becoming cost-competitive with other renewables particularly in Europe, as the number and size of developments increase and costs associated with installation and maintenance are reduced[8,19].

2.2 Tidal stream and barrage

There are two main classes of tidal energy technology, tidal stream and tidal barrage. In tidal stream generation, flowing water spins stationary, underwater turbines attached to a generator as the tide comes in or goes out, converting the kinetic energy of moving water into electricity that can be fed by cable to a mainland substation[20]. There is significant variation in turbine design, and some tidal stream technologies are bi-directional[11] (Interviewee 8). Most turbines are anchored or driven into the seafloor[11]. Tidal barrage generation traps water as the tide comes in, either in a lagoon or behind a set of sluice gates at the mouth of an estuary[21].

As the tide goes out, trapped water is released through a series of turbines, and its flow generates energy, which is fed to a nearby substation[11,21].

There is no commercial tidal stream capacity currently connected to the grid in Canada, although the Bay of Fundy has experimental projects[22] and some coastal communities in B.C. have projects in the proposal and planning stages of development (Interviewee 8). For their part, tidal barrage systems produce a significant amount of power globally, especially those across the Rance river in France[23] and Lake Shiwa in South Korea[24]. Canada's only tidal barrage plant, the Annapolis Generating Station, was decommissioned in 2019[25] due to its detrimental effects on fish populations and recurrent technological breakdowns[26]. Internationally, tidal power is not developed to the extent of offshore wind; there are projects running in Europe and Asia with capacities ranging from 1 MW to 250 MW[21]. Looking across the Atlantic, the United Kingdom is at the forefront of wave and tidal energy development. Like the Canadian government, the British government has invested millions into the development of tidal and wave technologies, which one review estimated could generate 34 TWh/year, or 11% of its total electricity demand by 2050[13]. Canada has an enormous potential for tidal energy generation at an estimated 35700 MW; the Bay of Fundy boasts the largest tidal resource in the world, and B.C. has numerous fjords that could also prove suitable for tidal energy generation[11] (Interviewees 1, 8).

Tides are highly predictable, which means the contribution of tidal energy to the grid is more easily modelled than for some other renewables[21] (Interviewees 1, 2, 8). As a result, tidal does not suffer from the 'energy storage problem' to the same degree as other renewables, which often require extra infrastructure to handle excess loads on the grid when the electricity is not needed. This makes tidal power well-positioned to help meet the steady baseline demand on the grid, while other renewables do the bulk of power generation (Interviewees 1, 4 and 8). Additionally, remote communities and island nations with a lack of suitable land may prefer tidal due to both how predictable it is but also the relative lack of 'space' it takes up, since tidal turbines are usually deployed on the seabed. Funding tidal projects in remote communities may be preferrable to building long-distance cables to connect them to the grid, as local power is less prone to transmission issues and will make communities more self-sufficient (Interviewees 3 and 8). Tidal power is also reliable through the winter, when solar and onshore wind may not be as productive (Interviewee 1).

2.3 Wave

Methods for wave energy generation are varied, many different designs have been tested with varying degrees of success (Interviewee 8). All of these operate on the principle of trapping the energy of waves to spin a turbine or move a fixed piston. While wave technology is still in the early stages of development, promising designs include pitching devices and point absorbing buoys where waves move pistons inside a central shaft and overtopping devices where waves spin turbines[27] (Interviewee 8).

Surveys of Canada's wave energy resources vary widely between reports, largely depending on which sites are included and which model is used[27,28] (Interviewee 8). What is clear is that Canada has a massive wave resource[27] which remains unexploited (Interviewee 8). British Columbia has a great deal of potential, with some estimates exceeding 100 GW[28], or over half of Canada's projected electricity use for 2035. While technological development is ongoing and no commercial capacity is connected, there has been recent progress in the design space and costs are coming down (Interviewees 1 and 8). As with tidal, wave inputs are often predictable and are much higher in the winter[27] when other renewables are less reliable and energy use is more intense (Interviewee 8).

2.4 Technological Barriers

The construction of wind, wave and tidal arrays in the ocean requires specialized equipment and professional divers, and becomes challenging in bad weather, making the installation and maintenance of devices in the sea more expensive and time-consuming than on land[16] (Interviewees 2,4). One expert we interviewed (Interviewee 6) also pointed out that a lack of sufficient construction infrastructure and an inexperienced workforce limit the expansion of MRE development in Nova Scotia compared to the northeast coast of the U.S.[29]. Site investigation and evaluation of seabed conditions (e.g., depth, width, slope and composition) are also essential to the viability and safety of wind farms[30], and other considerations such as ice cover and nearby shipping lines must be accounted for[16,31]. Additionally, the use of traditional ocean-monitoring equipment is not always possible in regions with strong tides, such as the Bay of Fundy which hosts Canada's largest tidal resource (Interviewee 2). As the amount of work to characterize and install generating devices and underwater cables increases, projects may become economically impractical; fixed-foundation wind turbines become uneconomical when installed in water deeper than 50 meters for instance[16,31]. Saltwater also corrodes generating devices and cables, which necessitates a more costly, resilient design and reduces the overall lifetime of devices[32]. For tidal, the intense flow of water, which is much denser than air, also strains turbine components and necessitates both robust design and careful placement (Interviewees 1, 2, 3, 8). Developers also have yet to converge on an optimal turbine design for tidal stream, and tidal stream and barrage are in relatively early phases of development in comparison to offshore wind and land-based renewables (Interviewees 1, 8). For its part, wave energy is still in the technology-development phase, where costs are high and no one design has been optimized (Interviewee 8). As a result, it will likely be some time before wave energy technology is efficient and cost-effective enough for large-scale deployment.

The lack of sufficient infrastructure for energy storage and transmission is another critical factor that currently limits the development of MRE in Canada (Interviewees 6, 8). The electricity generated by wind, tidal or wave is fed by seabed cable to onshore substations and then transmitted to the main utility grid or stored in a local battery system[15]. While transmission infrastructure is currently lacking or needs upgrading in many places, building and upgrading these cables is inevitable regardless of what the future mix of renewables looks like in Canada (Interviewees 3, 5, 6).

3. Economy

Canada's marine renewable energy (MRE) has the potential to contribute to the electrification necessary to achieve net-zero emissions by 2050 along with other renewable sources. However, the sector faces two significant barriers on the financial side, a high cost per unit of energy and low access to capital (Interviewees 1-6). In general, MRE projects are costly, large investments are required for materials, the construction and installation of arrays in the ocean, the maintenance and monitoring of the technology, and if necessary, the withdrawal of devices[33,34]. Project permitting also requires investment and can be a confusing process under the current provincial regulatory frameworks[35]. Taken together with the relative economic attractiveness of onshore renewables, private investment in MRE is generally lacking (Interviewee 2).

In this section, we report the cost of tidal and offshore wind energies in Canada, as examples. We also detail the difficulties in obtaining capital to fund marine renewable projects. Lastly, we summarize the benefits marine renewables could bring to communities and propose possible solutions to the cost of MRE implementation. Wave energy is very expensive per unit of energy generated, and too early in the development phase for realistic cost estimates, especially given the wide range of different wave technologies being explored.

Table 1. Estimated costs of marine and terrestrial renewable energies.

Technologies	Offshore wind power	Wave power	Tidal power	Solar	Inland wind power	Nuclear
Electricity unit price (CAD$/kWh)	0.09-0.11[36]	0.10-1.90[37,38]	0.40-0.66[37]	0.18-0.28[17]	0.07-0.22[17]	0.14-0.28[17]

3.1 Tidal power

Tidal energy has been around for many years; however, it still requires a very high initial investment, has long construction times, and the future of the technology is uncertain[35] (Interviewee 8). The United Kingdom has developed tidal energy to a much larger degree than Canada has, and though the economic and environmental conditions of the two countries are quite different, tidal is not yet cost-competitive in either one. However, when factoring in subsidies, the scaled-up construction of tidal arrays and cost benefits to the grid from the predictable nature of tidal power, costs are much lower than they may appear at first glance and on a steep downward trajectory[13] (Interviewees 4, 8). The U.K. and Canada have also built a huge number of test sites, an expensive but necessary step in bringing costs down and refining technology which can then be deployed or sold to other countries[13] (Interviewee 2).

Nova Scotia has made significant capital investments in developing tidal technologies in collaboration with industry, first nations groups and academic institutions (Interviewee 2). Currently, these projects are subsidized almost entirely by the federal and provincial governments. Last year, provincial investment in Nova Scotia tidal energy research was 28.5 million dollars, but more still is needed to achieve the objective of cost-effective technology[39] (Interviewee 2). One solution for more rapid development might be to seek private investment, but some of these investors are reticent to invest in tidal energy due to the high uncertainty on their return (Interviewee 8). The most common concern is whether the benefits of tidal will ever outweigh the cost, and if so, when will this become a reality (Interviewees 1, 8). Public investment in renewables in general, on the other hand, is likely necessary to develop efficient technologies that will help Canada to achieve its 2050 carbon goals, the question is how much of that money should go to which technology to maximize return and shield ratepayers from high electricity costs (Interviewees 1, 2). Some argue that the development of technology alone will pay dividends, even if it is never connected to the grid. Furthermore, how much costs will be reduced is a matter of disagreement; while some say that we are in a similar place with tidal as we once were with offshore wind and that costs will inevitably come down (Interviewees 4, 8), others see the increased cost of operating in a turbulent marine environment as inherent to the technology (Interviewees 1, 2, 5).

3.2 Offshore wind

Currently, there are no operational offshore wind farms in Canada, but many other nations have significant capacity installed[33]. However, the costs associated with the construction of turbines, underwater cabling, maintenance of offshore arrays, and the transmission of the electricity generated are considerably higher than onshore wind power[33]. For example, offshore maintenance and cabling can be up to ten times more expensive than onshore cabling[14]. The overall energy cost of offshore (USD $0.115/kWh) wind in the US was up to three times higher than onshore wind (USD $0.03kWh/ - $0.053/kWh) as recently as 2019[40]. However, the cost of onshore has declined in recent years. Since 2012, offshore wind power has reduced its cost by around 67%, and it is expected to continue falling, from its current price of $84000/KWh to $58000/KWh by 2025[41]. Increased scale of arrays and a growing number of investors in this field are cited as the main reasons for this reduction, due mostly to the recent advancements in technology and deployment making offshore wind projects more economical[33]. In 2021, offshore wind projects are considered cost-competitive with other renewables in some environments when built at scale[42].

Despite the rapid decline in the cost of offshore wind and the increase in the potential of energy generation[43], private investors and the government in Canada (federal and provincial) are still reluctant to invest in offshore wind energy. This lack of investment is partly due to competition with the generally cheaper onshore wind power, which is already well developed, easier to install, is not as constrained by land space in Canada as in other nations. Furthermore, there are a limited number of offshore wind projects in North America, which limits confidence[33] (Interviewee 4).

3.3 Potential cost reductions

The following are proposed cost-reduction strategies for marine renewables (Interviewees 1-8):

- Public or private utilities could build the transmission cables required to connect devices to the main grid to reduce the cost for developers.
- Private and public organizations could clarify and streamline the regulatory and environmental assessment processes to reduce the cost for developers.
- Exporting energy to other countries as demand increases will yield a better return on investment in these projects. For example, the export of electricity generated by offshore winds to the U.S.
- Most importantly: global collaboration and technology sharing would speed up technological development, increase the supply of materials and reduce their cost.

3.4 Socio-economic benefits of marine renewables

Marine renewable energies could have localized benefits if developed with the wellbeing of these communities in mind. Renewable energy projects provide numerous jobs in the construction, installation, maintenance and monitoring of generating infrastructure. In the case of marine renewables, these opportunities are often in rural and remote parts of the country[44]. For example, across the U.K., offshore wind currently employs 26,000 people, projected to rise to over 69,000 by 2026[45]. In Canada, a study in Nova Scotia found that by 2040 tidal energy could employ up to 20,000 people full-time and generate $815 million in income for those workers[46]. In remote communities especially, generating and selling power back to the grid is an attractive option, and local ownership over MRE projects could also create wealth and stability in these towns. It should be noted that these benefits depend on the degree to which public and private investment is used to develop the various marine resources in a responsible manner, and how ownership of those projects is allocated. Ultimately, local ownership and control may help to bring communities onside with renewable projects and speed up development.

Box 1. Orkney Islands Case Study

Figure 1. The most powerful tidal turbine in the world, Orbital 02, being towed to Orkney. Photo by Orbital Marine Power project.

The Orkney Islands is an archipelago of 70 islands, located off the north coast of mainland Scotland[47]. Since 2016, Orkney has been producing over 120% of its total electricity needs through renewable energy sources, mainly wind, but also solar, wave, and tidal power. These islands are one of the only jurisdictions in the world that produces an excess of renewable energy[48]. Their investment in renewable energies started in the 1950s when Orkney suffered from fuel poverty due to the high cost of imported fossil fuels and the impoverished economic state of the island, a result of its rough climate, few industries, and poorly built housing. In 1950, Orkney built the first wind turbine in the U.K., but a massive hurricane destroyed the project. In the late 70s, Orkney resumed its efforts to grow local renewable energy generation, and over the past two decades its renewable energy production has grown rapidly, from 17 GWh in 2003 to 140 GWh in 2014; most of this growth is from onshore wind power[48–50].

Yet, wind intensity varies seasonally (higher in winter and lower in summer) and diurnally, meaning that generation patterns do not always align with the demand[51,52]. Thus, the intermittent nature of wind energy generation did not allow Orkney to rely solely on this energy source for its power supply. Rather, to achieve energy independence, Orkney also needed to develop more predictable tidal and wave energy[49].

Another key development came in 2003 when the island established the European Marine Energy Centre (EMEC), which is now the leading centre for the testing and accreditation of marine energy devices. The centre gives developers the opportunity to test their prototypes with a set-up grid connector [53]. Some of the devices have shown promising results: for example, in 2021, the O2 tidal turbine was launched, and it is expected to operate in Orkney waters for the next 14 years and meet the demand of around 2000 U.K. homes (Figure 1)[54]. The energetic results for this device are not yet available, but it can already be appreciated that MRE is having a beneficial economic footprint on the islands. Moreover, since EMEC was established, the population of the Orkney Islands has grown, and younger people are returning to settle with the prospect of new jobs and a blossoming MRE industry (Interviewee 2).

Orkney is a global leader in MRE development, demonstrating the economic value of marine renewable energy to local communities as well as to the broader energy industry and other nations. They have also shown that it is possible to power entire islands and cities entirely with renewable energy. Most importantly, their example indicates that marine renewable energy can play a complementary role in achieving net-zero carbon emissions without the need for massive storage infrastructure since wind and solar power are somewhat intermittent and tidal and wave energy can help fill in supply gaps.

4. Environment

All Marine Renewable Energy Technologies have the potential to positively *and* negatively impact wildlife and the abiotic environment. However, the type and degree of impact and the specific taxonomic groups impacted varies significantly with the type of technology deployed. In this section, we discuss the concerns and potential impacts of each MRE technology on the environment, detail the level of support for or against these impacts in the literature, and highlight the need for additional research where evidence is scarce. We draw significantly upon one key publication, a report written by members of the Pacific Northwest National Laboratory, "Risk Retirement for Environmental Effects of Marine Renewable Energy", supplemented by additional scientific articles, reports, and interviews. While we will not systematically compare MREs to other forms of energy generation, we stress that any technology to generate electricity will have some degree of environmental impact and involve various trade-offs[55]. We must consider whether the immediate risks posed by MRE technologies outweigh the risks posed by other energy generation technologies. For example, terrestrial wind and solar arrays require land use changes for resource extraction and deployment, and the excessive burning of fossil fuels has caused the climate crisis, land use change, and other detrimental effects on the environment[55].

Table 2. Environmental impacts of marine renewable energy technologies at small scales (one to a few deployed devices).

Risk/Impact Type	**Technology**	
	Offshore Wind	**Tidal, Wave & Current**
Collision	Low to no impact[56]	High potential and uncertainty for collision risk to marine life[57,58]
Noise	Low to no impact[59–63]	Low to no impact[59–63]
EMF	Low to no impact[64–68]	Low to no impact[64–68]
Change to Habitat	Low risk; potential for positive impacts[69,70]	Low risk; potential for positive impacts[69,70]
Displacement	High potential for displacement of marine life during installation, decommissioning; low-medium potential during operation[71,72]	High potential for displacement of marine life during installation, decommissioning; low-medium potential during operation[71,72]
Hydrodynamics	Low to no impact[73]	Low to no impact[73]

4.1 Retiring Risks

Small-scale deployment of MRE technologies (one to a few devices) has been well studied and environmental risks have been assessed at this scale. Copping et al. (2020) review and summarize numerous studies on impacts from deployments at small scales and use a circular "risk retirement" system to determine if risks should be dismissed, properly mitigated, or deemed unacceptable. The publication has become the field standard for assessing the environmental impacts of MRE (Interviewee 8). The risks identified by Copping et al. are: 1) animal collision with turbines and other equipment, 2) the effect of noise from installation and operation of MRE deployments (MREDs) on animal behavior, 3) the effect of electromagnetic fields (EMF) from power cables on marine life navigation, 4) changes to the seabed or water column habitats during installation, operation, and removal of deployments, 5) displacement or barrier effects of arrays on wildlife, and 6) changes in circulation and sediment transport due to device operation. Based on the "risk retirement" system and existing evidence and engagement from the MRE community, including developers, regulators, researchers, and consultants, four of the six risks were deemed suitable for retirement at small scale: the effects of underwater noise; EMF; changes to habitat; and changes in oceanographic systems. We will provide an explanation for their dismissal for small-scale MREDs below.

4.1.1 Noise

All MRE technologies produce sound above and below the surface, which may impact marine animals' behavior, causing avoidance or attraction to an area, and/or interrupting communication and navigation ability[59,61]. Moreover, device construction and removal have the potential to produce enough noise to cause temporary or permanent tissue damage and hearing loss in marine mammals[60,62]. However, most MRE devices are installed/decommissioned using low noise technologies[63]. Additionally, several studies have demonstrated that operational noise from MREs is undetectable at decibel levels above ambient noise and other anthropogenic sources, such as container ships. The risk of marine noise pollution will, however, need to be reassessed for behavioral impacts resulting from MRED arrays as MREs are deployed at scale.

4.1.2 Electromagnetic fields (EMF)

EMFs produced by undersea cables and other elements of MREs have the potential to interfere with certain organisms' ability to navigate their environment or migrate, as they may interfere with the detection of Earth's natural geomagnetic field. However, all subsea cables and many bridges and tunnels deployed in the ocean already produce EMFs. Additionally, oil and gas facilities emit EMFs[74,75] at levels equal to or greater than MREs produce, even at large scales[76,77]. Laboratory and field studies show that electro- and magneto-sensitive species, including marine invertebrates and fish, are sensitive to EMFs but show no significant changes in behavior as a result, even at high energy[64–68]. The impacts of EMFs on the migration and behavior of sensitive species, though unlikely to change at large scales based on current evidence, should still be reassessed as MRE are deployed at scale.

4.1.3 Changes in Benthic and Pelagic Habitats

All MREDs, from offshore wind turbines driven into the seabed to tidal barrages floating near the surface, have a footprint, as do all maritime activities. An oil platform, for example, alters the seabed by providing a hard surface structure and shelter for organisms in areas with naturally soft substrates. This typically leads to an increase in the diversity and abundance of invertebrate species like barnacles, as the newly-introduced hard surface provides the structure they need to filter-feed on suspended food particles in the water column[70]. This changes the energetics of the ecosystem, as other organisms colonize the area to feed on the invertebrates[69]. MREDs also typically function as *de facto* marine protected areas (MPAs), preventing fisheries activities in the immediate area[69]. While this is unlikely to significantly impact marine populations at small scales, this may result in significant changes to fishing pressures at large scales and may lead to conflicts between fishers and MRE developers. Thus, these changes to system energetics and community structure will need to be modelled and tested at large scales to see if they result in different, unforeseen impacts on far-field habitats.

4.1.4 Changes in Oceanographic Systems

MREDs will disturb the natural water flow and remove kinetic energy from the system. This has the potential to change sediment transport and water quality and could cause downstream effects on other habitats. At small scales, however, the effects from devices will be lost in the natural variability and stochasticity of the system[73]. At larger scales, further studies employing numerical models are required to test the potential effects of MRED arrays on oceanography.

4.2 Remaining Risks

Two risks have yet to be considered for retirement at small scales: collision of marine organisms with devices and displacement of marine life due to deployment. Below, we describe their potential impacts and what further evidence is needed to determine the degree of risk.

4.2.1 Collision

The risk of collision is considered a serious threat to marine life and seabirds posed by MREDs. The blades of submerged turbines, such as those used in tidal technology, pose a serious risk of injury or death to animals. The level of risk is entirely dependent on context, including the type of device deployed and the ecology of the area. At present, behavioral studies suggest that most marine mammals and seabirds simply avoid turbine structures, causing displacement risk, as discussed below[56–58,78]. However, there are several challenges in assessing this risk for other taxonomic groups; firstly, detection of animals can be extraordinarily difficult in high-energy environments underwater, as turbidity and entrained air can obscure video footage and make observation difficult (Interviewee 1). Secondly, monitoring equipment is not typically built for the high-energy environments where MREDs are deployed, leading to a lack of reliable measurement, damage to devices, and/or irretrievability (Interviewee 1). For these reasons, computer models are often employed; however, these models over-simplify the risk of collision by using variables like blade sweep, population size, and range estimates to estimate encounter rates and impact (Interviewee 2). Ultimately, understanding the risk of collision posed by MREDs will require improvements in monitoring devices, an increase in the scale of deployment to allow for more widespread data collection, and context-specific analyses[56,58,73,78].

4.2.2 Displacement

MREDs occupy space, pose a physical threat, make noise, emit EMFs, and change habitats. While any one of these factors may be unlikely to dramatically impact a population in the long term, their cumulative effects may cause marine life to avoid areas they once inhabited[73]. For example, during MRED construction, harbour porpoises will often vacate the area they formerly inhabited and will only return once conditions have stabilized[71,72] (Interviewee 6). The degree to which MREDs will permanently displace organisms and the downstream impacts of these displacements on marine communities is still largely unknown.

4.3 Environmental Risk Summary

The evidence to date suggests that, at small scales, MREDs pose minimal risk to marine life, or, at most, risks comparable to those of existing maritime activities. However, a much greater degree of uncertainty exists around large-scale deployments. Efforts to minimize these risks include selecting sites with low abundance, those outside of key feeding grounds or migratory routes, and design modifications to physically reduce collision risk[73]. However, the overlap of ideal locations for MREDs and those important to marine life is extensive, and sometimes collisions cannot be entirely avoided. Additionally, not all environmental impact studies produce transferrable results and conclusions, as many risks are context dependent. Therefore, additional studies on the environmental impacts of MREDs at large scales are needed. Before large-scale MREDs exist in Canada, modeling and simulation studies should be used to produce estimates of risk. Ultimately, however, understanding their impact will require the development of large-scale MREDs and subsequent *in situ* studies. Yet, environmental assessments to meet rules and regulations are often one of the key inhibitors of developments (Interviewee 6). Canada therefore needs to create a regulatory process catered to MRE, which permits low-risk MREDs, as ultimately, MREs diffuse benefits (countering the climate and ecological crises) will likely outweigh their acute environmental risks.

Box 2. Trillium Power Case Study

[*Disclaimer*: *much of the following information was gathered from news articles and a statement of claim from Trillium Power Wind Corporation against the Government of Ontario. The order and content of events detailed here may reflect the biases of the claimant and/or news outlets, as these sources are the only publicly available records of events on the topic.]*

Figure 2. An offshore wind development. Photo by Masha Basova (Shutterstock.com)

In 2011, Trillium Power Wind Corporation, a private, Canadian-owned company was set to build a 500 MW far-offshore wind farm, “TPW1”, on Lake Ontario near Kingston. They completed 105 studies, reports, and regulatory actions including studies on environmental impacts and found low overall risk. Trillium was initially permitted to proceed with development, but the project was cancelled by the Ontario government on February 11, 2011. The company had already invested over 5 million dollars in the project. The project not only could have powered at least 130,000 homes in Ontario, but Trillium estimated that it would have offset 2.57 million tonnes of carbon emissions, 7,500 tonnes of nitrous oxide emissions, and 15,500 tonnes of sulfur oxide emissions, and reduced water use in coal and natural gas generation by 14.1 billion liters per year[79]. TPW1 would have created roughly 2,100 jobs, generated $1.16 billion in tax revenue for the province, and initiated a new era for the offshore wind industry on the Great Lakes and Canada[79]. **So why did the Ontario government cancel the project and impose a moratorium on all offshore wind energy developments that is still in place today?**

The cancellation in February 2011 did not occur without warning. Some Ontarians with property near the Great Lakes had expressed their opposition, citing changes to the view from shore and negative impacts on their property values. Trillium later alleged in a lawsuit that this political pressure is what led Ontario’s government to impose a unilateral moratorium on all offshore wind developments in November 2006, in the run up to the October 2007 election[80]. In late 2006, Trillium urged the OMNR to reconsider the moratorium, citing the distinction between near-shore and far-offshore power generation and that Trillium’s proposed development raised none of the objections being advanced against near-shore locations. In 2008, following the elections, the moratorium for offshore wind development on Ontario’s Great Lakes was lifted. Trillium resumed permitting and engaged with St. Lawrence College to initiate an offshore wind technician training program, expecting to manufacture turbines in Ontario. In May 2009, the Ontario Government passed the *Green Energy Act* (GEA), with support and an endorsement from Trillium Power. The GEA created a feed-in tariff (FIT) to support commercial renewable energy generation, and a “made in Ontario” clause which required that a large percentage of the labor and production be sourced in Ontario. In August 2010, the Ministry of Environment (MoE) notified Trillium that the updated TPW1 project proposal had been reviewed and accepted by MoE and would be a high priority for processing by the Ontario Government. In January 2011, Trillium made all legal and financial arrangements in preparation for construction. A month later, in February 2011, the Government of Ontario imposed another moratorium on offshore wind, catching Trillium off guard. The company was set to finalize their financial agreements with an investor, Dundee Incorporated, but the moratorium ended this agreement, effectively terminating TPW1.

[Continued on p. 16]

Lessons Learned: Barriers and Opportunities

Several pitfalls along TPW1's development route led to the cancellation of the project: principally, 1) multiple offshore wind moratoriums, 2) the prolonged time to project approval due to the cumbersome project review and approval process, and 3) complex and time-sensitive financing arrangements. Yet, these pitfalls have underlying socio-economic and political drivers. The offshore wind moratoriums imposed by the Ontario Government were the result of political pressure from constituents, implying at least some degree of local opposition to the "aesthetic burden" of turbines. The prolonged time to project approval resulted from regulatory bodies that were ill-equipped to handle a novel renewable energy project like TPW1. Lastly, funding a project as novel as TPW1 comes with inherent risks to which investors are acutely attuned. Each delay and obstruction gave TPW1's investors more reason to worry, and the second offshore wind moratorium was the final straw. The failure of this project to proceed not only directly affected all those involved and its potential beneficiaries, but also had rippling effects across Ontario and Canada's nascent renewable energy industries, and the story likely plays a major role in the state of Canada's renewable energy sector (or lack thereof) today.

5. Public Perception

The degree of public acceptance of marine renewable energy technologies is a significant factor in determining their success in Canada's electricity generation market, as opposition can lead to projects cancellations, delays and increased costs[81,82]. Multiple renewable energy project proposals in Canada have faced significant opposition from local communities for various complex reasons, including the Site C dam in British Columbia, the Muskrat Falls hydroelectric facility in Newfoundland and Labrador, and multiple proposed on-shore wind turbine projects in Ontario[83–85]. In light of this, the following section will discuss (1) the public perception of MRE in Canada, (2) the factors that may contribute to the acceptance of, or opposition to, MRE projects, and (3) potential strategies for increasing public support for MRE in Canada.

Concerning the general public's perception of MRE, interviews with the experts suggest the existence of a diverse pool of opinions on MRE technologies in Canada. Interviewee 6 recalled mixed perceptions of MRE following community outreach, with some participants expressing eagerness to bring clean technologies into the community, and others having a more critical stance. In line with this, Interviewee 1 noted that in coastal fishing communities, tidal energy development faces opposition amongst some fishermen due to concerns regarding the impact of devices on already-dwindling stocks and preferred fishing sites, the latter being closely guarded and passed down the generations in fishing families. While lack of support for MRE development from local communities may arise from concerns around property values or environmental impacts, it can also be the result of a general lack of trust in industry and government (Interviewees 4, 6, 8).

The perception of tidal, wave and offshore wind technologies in remote, off-grid coastal communities has been an important theme explored in interviews with those working in the marine renewables space. This is because these projects have been proposed as an alternative to the diesel generation currently powering these communities. Canada has over 280 communities that are not connected to the North American electrical grid or to a natural gas pipeline, representing about 200 000 people in total[86]. The majority of these off-grid, and often Indigenous, communities rely on diesel-fired electric generators[86,87], which are associated with significant economic and environmental challenges[88–90]. These concerns often translate into positive attitudes towards switching to alternative clean energy sources, especially MRE projects which are locally owned and community-led[91](Interviewees 3, 6). A study by Mercer et al. (2020) suggests that communities' judgment of different renewable energy technologies is shaped by many factors, such as community perception of the abundance of the resource (e.g., observations of the strong wind, waves, or tides), the familiarity with the technology, successes or failures of previous projects, implications for cultural activities, associated environmental effects, affordability, reliability, and health implications. For emerging marine renewables, the findings of the study suggest that the lack of familiarity with a particular technology may be the most significant barrier to widespread community acceptance of energy proposals[89].

5.1 Fostering support for MRE

Fostering community support for MRE is crucial for ensuring the successful growth of the offshore wind, tidal and wave industries in Canada. Public opposition may translate into extended project development times and increased projects costs or even lead to cancellations[81,82]. In Ontario for example – where on-shore wind development drew significant and, at times, organized public opposition resulting in project cancellations and delays (Box 2) – community resistance to energy projects poses significant barriers for obtaining necessary road use, entry, and building permits and agreements, hence potentially decreasing the likelihood of successful siting[82,92].

In this context, multiple experts stressed that **the ongoing and thoughtful engagement of local communities** affected by MRE project development is critical for fostering greater support for MRE (Interviewees 4, 6). Interviewee 6 suggests that companies interested in MRE development should set local community engagement and building social license as their primary focuses, especially in the early stages. This might entail organizing education campaigns or community outreach events to provide community members with a better understanding of the risks and benefits associated with a particular MRE technology, and how they compare to those of the current energy source. Additionally, it is crucial to ensure ongoing communication that extends beyond isolated events, to establish meaningful relationships with stakeholders. Interviewees 6 and 8 noted that overcoming the critical perception of the MRE technologies may require providing concerned community members with additional resources, credible academic studies, or an opportunity to meet one-on-one with company representatives or experts. The study by Jami & Walsh[82] provides similar insights into the factors necessary for successful public engagement and fostering community support for energy projects. The study finds that Ontario citizens usually criticized the governmentally mandated consultation process due to a perceived lack of genuine effort for two-way communication and consideration on the government's part[82]. Similar citizen concerns could arise in the context of MRE development, especially as the number of proposed MRE projects in Canada increases. Academic studies suggest that these challenges may be addressed through early involvement, meaningful public participation rather than consultation, collaborative consensus building and decision making, relationship and trust-building, and the proactive presence of developers within the community[82,93].

Besides the meaningful involvement of local communities, sharing the benefits of the project with stakeholders or community ownership may aid in speeding up development of MRE and fostering support for projects. This may be achieved, for example, by relying on local suppliers and providing employment opportunities during project development and operation. Another possibility is having locals maintain part or total ownership of power projects, which could provide additional sources of revenue for the community and compensate for potential losses of fishing sites (Interviewees 4, 6). Interviewee 4 also suggested that public support for the project may be strengthened by compensating the affected population for any impacts associated with MRE development, such as landscape view impacts from offshore wind turbines.

5.2 Partnership with Indigenous communities and reconciliation

In addition to climate change mitigation benefits, supporting clean energy development in Indigenous communities is often seen as a pathway to the reconciliation of the relationship between Indigenous and non-Indigenous peoples in Canada[90]. Nearly 85% of Canada's remote Indigenous communities rely on their own diesel generation, which is associated with significant economic, environmental, and social tolls[88–90]. Many Indigenous communities are interested in transitioning towards clean energy sources to meet their energy needs, increase sovereignty, enhance environmental sustainability, decrease energy expenditures, and even generate sustainable incomes by selling power to the main grid[90].

As part of the Pan-Canadian Framework (PCF) on Clean Growth and Climate Change, the federal government has committed to reducing greenhouse gas emissions in rural and remote communities in general by aiding in their transition towards clean energy sources[94]. Prime Minister Justin Trudeau has also promised to ensure that diesel is eliminated from Indigenous communities by 2030[95]. Moreover, the federal government provides funding for Indigenous communities to develop their own community-led clean energy projects, including MRE[96,97]. Public and private utility companies could also aid in the communities' transition towards clean energy sources as part of their reconciliation mandate by providing technical and financial support in the development of community energy plans, resources assessment, planning and construction of clean energy projects and training locals in device operation (Interviewee 3).

However, it is important to acknowledge that clean energy initiatives do not always contribute to reconciliation, but may also perpetuate colonial structures[90], for example, in the case of hydropower projects in northern Manitoba in 1970s that resulted in the relocation of an Indigenous population against their wishes[98]. While Canada does mandate consultations with Indigenous communities, a lack of open-mindedness and genuine effort to seek compromise among government actors and proponents may undermine relationship-building and reconciliation objectives[99]. This may be of particular concern when proponents are international companies, which may not fully understand the historical context surrounding Indigenous-crown relationships (Interviewee 4). Moreover, Stefanelli et al. (2019) note that while meaningful participation, collaboration, and engagement are crucial for project support and approval, Indigenous communities often strive to achieve energy sovereignty through community-driven renewable energy projects. Indigenous, community-driven clean energy projects done right ultimately result in decreased energy costs, contribute to communities' economic prosperity and independence and create an opportunity to direct more funds into community-development initiatives, such as education, job training and social supports[90]. This suggests that supporting Indigenous community-driven projects that may foster their energy sovereignty could constitute one of the pathways towards reconciliation. Marine renewable energy may also be well-positioned to provide power to a remote island or coastal communities, due to the abundance of these resources along Canada's coast as well as the lack of vast land availability in island communities for installation of onshore renewables (Interviewee 2).

6. Future electricity demand and potential roles for MRE

Achieving an economy-wide net-zero emissions objective will require the electrification of transportation, buildings, and industrial sectors, leading to an increased demand for non-emitting electricity. In light of this, Canada's renewable electricity capacity must expand rapidly[3,100,101]. Simultaneously, existing electricity production must be decarbonized or offset by carbon capture and storage technologies if cannot be decarbonized fully[100]. *Canada's Energy Outlook 2021* projects that to meet the rising electricity demand the generation could increase two-fold by 2050 if Canada reaches its net-zero objective[4]. If net-zero is achieved earlier – which aligns more closely with the equitable effort sharing principle prescribed by the Paris Agreement[102–104] – the electricity demand in 2050 could be even higher, as evident from net-zero 2045 scenario projected by Canada's Energy Outlook[4]. However, the projected role of electricity in the decarbonization of Canada's economy varies depending on model assumptions: projected share of electricity in final energy consumption in 2050 ranges between 28% and 66%[100], representing significant uncertainty in future demand.

As for trends in the sources of electricity generation, Canadian Energy Outlook predicts a tremendous increase in wind and solar capacity, with wind production expected to increase by a factor of 15 by mid-century compared to 2016 levels[4]. These projections, however, do not differentiate between onshore and offshore wind resources. The report also projects that other renewables - which, among others, include tidal stream and wave energy - will increase slightly, but will not contribute significantly to electricity generation by mid-century[105]. The limited projected development of these resources could be explained by the decline in price for wind and solar energy technologies that are currently projected to dominate the market[4,105]. It is important to note, however, that these projections are based on assumptions regarding market development and future technology price and are hence subject to uncertainties and limitations.

In line with the Canadian Energy Outlook reports, the results of our interviews with industry groups, academics and government officials generally suggest that while offshore wind may be developed to a larger degree, tidal and wave may contribute to the decarbonization of Canada’s economy through niche uses (Box 3) and are unlikely to account for a significant share of the overall electricity production in Canada (Interviewees 2, 4). Experts note that the relatively low costs of onshore wind and solar energy make the wider implementation of these resources favorable as compared to tidal and wave energy (Interviewees 4, 6). Lack of large-scale implementation of tidal and wave, in turn, may preclude the technologies from decreasing in price sufficiently to compete with more mature renewables unless the wider implementation is achieved outside of Canada. Moreover, the installation and maintenance of the devices in the sea is intrinsically more challenging and expensive, contributing to higher costs for tidal and wave and suggesting that these technologies are unlikely to match the price of onshore wind and solar energy production anytime soon (Interviewee 1).

Unlike tidal and wave technologies, the offshore wind industry may have a better chance for large-scale commercial growth in Canada, as multiple large-scale offshore wind farms are already operational in Europe and the technology is already cost-competitive outside of Canada due to high capacity factors (Interviewee 4). Moreover, fewer components of offshore wind turbines come into contact with salt water than do those of wave and tidal devices, which results in less challenging design and better longevity of parts (Interviewee 4).

Box 3: Niche markets for MRE

1. **Decarbonizing remote off-grid communities.** Canada’s off-grid communities – or non-integrated areas – currently rely on diesel, which is costly, dangerous to transport, and associated with environmental hazards (Interviewee 3). Connecting some of these communities to the main grid is impractical or very expensive in many cases, which makes generating local power with marine renewables a desirable substitute; several tidal, run of river, and wave projects are already in development, funded by the federal and provincial governments (Interviewees 1, 2, 3, 6, 8). MRE projects also provide local employment and skills training and allow remote communities to develop and own their own power sources, building resiliency into the community and directly benefitting its citizens (Interviewees 3, 4, 8).

2. **Complimenting other renewables.** Increasing the rates of deployment of intermittent renewable energy sources, such as onshore wind and solar, requires the presence of more consistent and predictable energy sources to supply power when sun and wind are weak or absent [101]. Tidal and offshore wind energy could be used to complement intermittent renewables, as energy from tides is predictable and forecastable (Interviewees 1, 2, 6) and offshore winds are usually stronger and more consistent than onshore winds (Interviewee 6). As a result, future deployment of MREs could reduce reliance on hydroelectric dams as means of energy storage and compensate for the intermittence of onshore renewables (Interviewees 6, 8).
3. **Powering island communities.** MREs could be particularly useful in powering island communities that have limited available space to construct onshore installations (Interviewees 1, 2).
4. **Ensuring a just transition for workers in coastal regions.** The decline in offshore oil and gas production is associated with negative outcomes for the workers of these industries in coastal regions such as Newfoundland and Nova Scotia (Interviewee 6). MRE projects in these regions could benefit from the existing supply chain, as well as provide new job opportunities for those previously employed in the offshore gas and oil industry (Interviewee 6). Hence, while MRE may be more expensive than onshore renewables at present, they may serve an important role in ensuring just energy transition for the workers of coastal regions affected by the decline in off-shore fossil-fuel production (Interviewee 6).
5. **Decarbonizing marine industries.** MRE could also be used to power marine industries, such as oil and gas production, aquaculture, or mining in coastal regions (Interviewee 6). As has been mentioned previously, MRE deployment in the regions that have offshore oil and gas industry could benefit from the existing supply chain (Interviewee 6). The use of MRE to decarbonize oil and gas may, however, create opposition from local communities. For example, Interviewee 3 noted that the Haida had expressed their opposition to a large offshore wind project in their territories because the produced electricity was designated for LNG liquefaction.
6. **Producing cleaner fuels for transport.** MRE could also be used to produce hydrogen or ammonia (Interviewees 4, 8), which are emerging fuel sources for transport generally, especially for ships on long-term voyages which cannot be powered by electricity alone. The energy produced from offshore wind, for example, can be used to desalinate water and produce hydrogen[106] (Interviewee 8).

7. Conclusions

An unprepared regulatory environment, several failed deployments, the need for additional evidence to support the viability of novel marine renewable energy (MRE) technologies, and economic competition from terrestrial wind and solar have prevented Canada from capitalizing on its wealth of MRE resources and expanding the sector. Despite these challenges, offshore wind has potential as a large-scale development option, and tidal and wave will likely serve an important niche role in contributing to Canada’s energy decarbonization while simultaneously, fostering the development of Canada’s blue economy. This is due to several strengths of MRE:

1. The predictability of MRE supply can support a more efficient power storage and transmission system by flattening out grid loads to complement other, more intermittent renewable energy sources such as solar and onshore winds[7].
2. Installing MRE devices could avoid the spatial limitations and costs of building terrestrial power plants close to metropolitan areas, where energy demand is highest[9,31].
3. The evidence to date suggests that marine renewable energy developments (MREDs) have less of an ecological impact than terrestrial renewables and fossil fuel energy[55,73], though continued research and monitoring are needed to assess the impacts of MREDs at large scales.
4. MRE can play a unique role in providing power to island nations, coastal communities, or remote off-grid Indigenous communities that have access to substantial offshore wind, river current, wave, or tidal resources. This is particularly important as many of these communities currently rely on expensive and highly polluting diesel power generation[11]. Community-led and community-owned MRE projects could provide economic benefits to local stakeholders and lessen environmental pollution associated with diesel generation.
5. MRE could help to decarbonize other carbon-intensive industries, such as offshore mining, aquaculture, and transportation by providing clean energy for their operations (Interviewees 6, 7).
6. MRE could create job opportunities for coastal communities currently reliant on employment from carbon-intensive industries (e.g., natural gas and petroleum). These new jobs could contribute to a post-pandemic economic recovery and ensure a just energy transition. This is especially true for areas where fossil fuel industries are declining, and mass layoffs are common (Interviewees 2, 6).

Despite these strengths, our findings show that there is uncertainty around the future development of marine renewable technologies in Canada. While offshore wind, tidal and wave might not be likely to make up the lion's share of Canada’s overall electricity production on their own, they may compliment other renewables and fill important niches by providing energy where other methods of generation are ill-suited, all while having a low environmental impact and reducing greenhouse gas emissions.

During our interviews, policy, and regulatory barriers to the expansion of MRE emerged as a common theme; however, a systematic analysis of existing policies and regulations preventing MRE’s growth in Canada was beyond the scope of this report. Future research should focus on assessing policy and regulatory barriers impeding the growth of the MRE industry, as well as the potential approaches that can be taken by provincial and federal government to overcome these barriers. Given the high uncertainty in the environmental impacts of MRE deployments at large scales, great efforts should also put on environmental monitoring and research to better understand and manage these impacts. Furthermore, we have identified that while public acceptance of MRE may determine the success of MRE deployments, studies exploring public perception of these technologies in Canada are limited. Thus, more research is needed on exploring the public perception of MRE in Canada’s coastal communities, including communities around the Great Lakes.

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