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How the Royal Canadian Navy Could Leverage Innovations in the Energy Sector in Pursuit of Green Propulsion Solutions

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ABSTRACT

Canada's energy sector is developing many promising technologies in the pursuit of climate change targets. Among these innovative technologies, Small Modular Reactors (SMR) are emerging as viable contenders to produce safe, reliable, and scalable carbon-free thermal or electrical energy and to provide new economically viable ways of producing clean hydrogen and ammonia for energy storage or transport. Canada's SMR Action Plan aims to position Canada as a key contributor in providing viable solutions to combat climate change. Currently, the marine sector across the world is lagging in pursuit of carbon-free technologies. There are many ways that Canada could leverage the innovations occurring in its energy sector to address similar challenges in the marine sector. By doing so, Canada can further position itself as a global leader who utilizes innovation to combat climate change. The most promising technologies to decarbonize naval propulsion systems are nuclear reactors, hydrogen fuel cells, and ammonia-based gas turbines and fuel cells. These technologies are in perfect alignment with the types of energies expected to be generated as outputs of Canada's SMR action plan and mirror many of the proposed solutions in the long-range transport sector. However, to date, there are no clear partnerships between the energy and marine sectors. If the Royal Canadian Navy (RCN) seeks to be compliant with the International Maritime Organization's (IMO) environmental targets as envisioned within the Departmental Environmental Strategy, investing in the development of these carbon-free propulsion technologies must start with its next capital acquisition projects.

HOW THE ROYAL CANADIAN NAVY COULD LEVERAGE INNOVATIONS IN THE ENERGY SECTOR IN PURSUIT OF GREEN PROPULSION SOLUTIONS

INTRODUCTION

The Defence Environmental Strategy (DES) expresses a vision for the Canadian Armed Forces (CAF) that "moves beyond compliance" to be recognized as a leader through innovative integration of environmental considerations.[1] Yet, for the Royal Canadian Navy (RCN), the stated strategy continues to look to the Safety and Environmental Management System (SEMS), a bottom-up efficiency-based approach, to seek improvements. As the International Maritime Organization (IMO) sets goals to reduce greenhouse gas emissions in half (compared to a 2008 baseline) by 2050 and the world's largest cargo ship company aims to introduce carbon-neutral ships as early as 2030 aiming to have a carbon-free fleet by 2050, the RCN already trails behind rather than assuming a leadership position.[2] Indeed, the Canadian Surface Combatant (CSC), currently predicted to start service life in 2031, will barely meet 2013 environmental standards with its combined diesel electric or gas (CODLOG) propulsion plant and is making no headway towards future IMO targets.[3] Leaning on SEMS alone is unlikely to enable the requisite design changes to achieve the DES vision. The only way to make headway towards the IMO environmental targets is to start pursuing viable green propulsion solutions today for the future fleets.

Meanwhile, in the energy sector, as the world pursues green energy to combat climate change, it has become increasingly apparent that reliance solely on low density, intermittent energy sources such as wind and solar will have many limitations and challenges if used solely

[1] National Defence. "Defence Environmental Strategy" 2021, p. 7
[2] Johnson, T. "Towards a zero-carbon future" 2019.
[3] Brewster, M. "at least a decade before new frigates" 2021.

on their own, to provide dependable, sustainable, and safe energy across the grid.[4] Other viable carbon-free energy sources such as hydro and geo-thermal are somewhat limited in growth by geographical and physical factors.[5] The *Breakthrough Institute* anticipates that "there is no credible path to climate stabilization that does not include a substantial role for nuclear power".[6] According to the IEA, achieving net zero emission targets set in the 2015 Paris Agreement shall take longer with higher risk for failure and cost $1.6 trillion (USD) more if it was done without the use of nuclear energy.[7] Canadian political leaders at both national and provincial levels have therefore announced significant investments in development of Small Modular Reactors (SMR) which offer promising solutions to complement other green energy technologies.[8] A pan-Canadian SMR action plan has been put in place by the Ministry of Natural Resources to complement other renewables in the development of Canada's green energy future.[9] Among its many stakeholders and potential partners, the SMR action plan currently includes neither the Department of National Defense (DND) nor the CAF.

Historically, large navies (notably the United States, the United Kingdom, France, Russia, and China) mastered modular nuclear reactors.[10] Due to existing reactor sizes, nuclear reactors have traditionally been limited to larger ships such as aircraft carriers and large submarines. Given that the Royal Canadian Navy (RCN) has not operated any class of ship large enough to wield a traditional nuclear reactor in decades, it is unsurprising that nuclear propulsion and the RCN have historically been mutually exclusive. The last time the RCN proposed the

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[4] Shellenberger, M. "Had They Bet On Nuclear" 2018.
[5] Gioquito, R. "Hydroelectric Energy", 2020. and Hyder, Z. "Geothermal energy" 2020.
[6] Pethokoukis, J. "Climate scientists" 2013.
[7] IEA. "Nuclear Power in a Clean Energy System" 2019.
[8] Perkel, C. "Federal government backs development of mini nuclear reactors" 2020.
and Scheel, E. "Group of premiers band together to develop nuclear reactor technology" 2019.
[9] Ministry of Natural Resources. "SMR Action Plan" 2021.
[10] Conca, J. "U.S. Navy Remains Masters of Modular Nuclear Reactors" 2019.

acquisition of a nuclear asset was in a 1987 white paper which called for a Canada-class submarine.[11] That proposal was met with tremendous opposition and outrage, likely due to the recency of the Chernobyl incident which occurred the preceding year. In the thirty-four years that followed, nuclear propulsion for an RCN asset was never overtly revisited.

Much has changed in the past three decades. Although another nuclear disaster occurred in Fukishima in 2011, significant technological progress has been made to greatly improve nuclear safety. The requirement to develop technologies that reduce reliance on fossil fuels is also becoming paramount. It is timely for the RCN to start looking at innovative solutions to address its own contributions to the environment and climate change. The RCN's strategic document, Leadmark 2050, calls for "technological innovation, founded in effective relationships with the Department of National Defence's research and development and materiel arms".[12] The emergence of SMR technology as a candidate for producing safe and reliable energy independent of fossil fuels presents significant opportunities for both the RCN and Canadian industry writ large.

Can mutual benefits be leveraged between the significant innovations in the Canadian energy sector and the Canadian Armed Forces (CAF)'s inevitable pursuit of green propulsion solutions?[13] Tackling this question requires a threefold approach. The first step is to explore the characteristics of the Canadian nuclear industry within the energy sector to see how its promising approach to posture Canada as a global leader to combat climate change could be leveraged. The second step is to gain a better understanding of existing and emerging maritime and naval green propulsion technologies. The final step will be to evaluate the RCN's Force Development plan

[11] Ferguson, J.H. "Through a Canadian Periscope: Canadian Submarine Service" 1995.
[12] RCN. "Leadmark 2050" 2016.
[13] The term green propulsion is being used to describe carbon free solutions that do not depend on fossil fuels.

to determine the windows of opportunity to introduce these technologies to the future fleet.

Literature Survey

Determining how aggressively the RCN should pursue green propulsion technologies for its future fleets requires an understanding of Climate Change science and how it is being interpreted by global leaders. An overwhelming consensus has been formed that anthropogenic climate change is real and has already started to impact the terrestrial biosphere and human health.[14] Anthropogenic climate change is considered one of the defining challenges of the 21st century.[15] Key themes surrounding climate change are that the climate is changing, that the change is due to human activities, and that greenhouse gases constitute the largest contributor to these changes.

The science behind greenhouse gases and their correlations with the earth's surface temperature was first discovered by Arrhenius in 1896.[16] The debate of whether the effects of a rising surface temperature would be good or bad for human civilisation has persisted ever since. Carbon dioxide recording started in 1958 by Charles David Keeling which led to the Keeling curve that shows a cumulative increase of 30% in carbon dioxide levels from 1960 to 2020.[17] A scientific consensus states that rising carbon dioxide levels are leading to increased average global surface temperature, increased melting rates of polar ice sheets, and rise in sea level.[18] Most areas of contention surrounding the climate change debate involve the rates of change and future projections. Despite a general agreement on the core principles and systems impacting climate change, according to Lawrence Krauss, a theoretical physicist, the problems surrounding

[14] Maslin, M.A. "Climate change" 2019.
[15] Ibid.
[16] Krauss, L. "The Physics of Climate Change" 2021.
[17] US San Diego. "The Keeling Curve" 2021
[18] Krauss, L. "The Physics of Climate Change" 2021.

addressing climate change arise when politics enter the debate.[19]

One side of the polarized political isle is often labelled as climate change deniers. This position likes to quote science research that demonstrates the potential positive benefits of carbon dioxide such as increased growth rate, potential size, and new growth areas for trees such as the current observable greening of parts of the Sahara Desert.[20] They like to point at older predictive models and how they have consistently overestimated the future impacts as a means to question the validity of current models. This approach to addressing climate change is problematic because it promotes inaction by encouraging people to ignore refined models that account for more factors. Although many effects of climate change have been slower than some older models, it does not mean that the effects are not happening or prevent them from getting worse over time. A climate change denier approach to this paper would lead to recommendations that delay development of solutions and prolong dependence on fossil fuels. Focus areas for innovation would be to focus on carbon capture mechanisms. Alternate fuels to fossil-fuels would only be considered after tangible evidence exists that they can be economically viable. This approach would most definitely lead to undershooting the IMO environmental targets by a large margin.

The opposite side of the political isle is sometimes characterized as climate change alarmists. A study by James Risbey claims that many alarmists like to use key phrases such as 'catastrophic', 'rapid', 'urgent', 'irreversible', 'chaotic' and 'worse that previously thought' to compel action.[21] This approach tends to stifle important scientific discourse over aspects of climate change that are still being studied by scientists such as exact rate of ice sheet breakdown

[19] Krauss, L. "The Physics of Climate Change" 2021.
[20] Worstall, T. "Global warming" 2012. and Pausata, S.R. et Al. "The Greening of the Sahara" 2020.
[21] Risbey, J. "The new climate discourse: Alarmist or alarming?" 2008.

and potential impacts of sustained warming. Another trait of climate change alarmism is the exclusion of some viable technological solutions, such as nuclear energy, on an ideological basis. Michael Shellenberger, an environmentalist, makes a case that climate change alarmism is counterproductive to finding impactful solutions.[22] The climate change alarmist approach is problematic in the domain of finding green propulsion solutions because it systematically rules out many of the top contending solutions. Data and facts are important when seeking the most technically and economically viable solutions. Although existing wind and solar technologies could reduce the carbon footprint of warships, these solutions are too intermittent and do not have sufficient power density to be competitive contenders for long-term naval applications. Therefore, the climate change alarmist approach, much like the climate change denier approach, is not productive to advance key discussions towards solutions.

The aim of this paper is neither to fuel nor to solve a century old political debate. Although literature can be found that supports dissenting opinions on either side of the political isle, for the purpose of leading the discussions to a technically and economically viable solution, an apolitical position will be taken. The majority consensus in environmental literature acknowledges that increased carbon dioxide emissions are likely to continue to influence observable climate change phenomena such as increased global surface temperature, increased rate of melting of polar ice sheets and increased sea level. Also, it is important to recognize that cumulative addition of carbon dioxide into the atmosphere has a long-lasting latent effect and any delays in reducing human generated carbon dioxide emissions is only exacerbating the problem.[23] To remain focused on the key issue to determine viable green propulsion solutions for the RCN, this paper uses recommendations put forth by recognized international bodies such

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[22] Shellenberger, M. "Apocalypse Never" 2020.
[23] Krauss, L. "The Physics of Climate Change" 2021.

as the IMO, the United Nations (UN), and Lloyds Register (LR) as well as Canada's own authorities such as the Canadian Nuclear Safety Commission (CNSC) and the Canadian Nuclear Association (CNA).

Literature focused on maritime applications is significantly dwarfed by those with land applications. Energy generation and transport industries are the primary focus of climate change technology research. Although many aspects of these research fields are directly applicable, it must be acknowledged that the maritime environment comes with many unique challenges. International environmental targets in the maritime sector are currently lagging by 20 years when compared to energy and land transport sectors. There are many potential explanations for this lag. One is that shipping by sea is already less emission intensive than alternatives.[24] Another is that many of the front runners in land application technologies are not directly transferable to sea. Much of the literary research done in the maritime sector has focused on maritime shipping because it is the largest contributor to maritime emissions. NYK Line and Maersk are currently leading research in low-carbon transition in the sea shipping sector.[25] Many initial recommendations to lower emissions in the maritime sector, such as slowing down ships and increasing implementation of renewables, are incompatible with naval applications. This means that research directly focusing on naval propulsion applications is rather scarce in the public domain, potentially because it is being protected for national security reasons.

Literature surrounding nuclear energy typically takes one of two forms. Analysis focusing on data reveals that nuclear energy is safe, reliable, and economically justifiable in many markets. Dissenting opinions regarding nuclear energy bring forth four main arguments. The first argument against nuclear energy is that its pursuit has the potential to lead to nuclear

[24] CDP. "Shipping heavyweights at risk of missing climate targets" 2019.
[25] Ibid.

weapons. The second argument is that nuclear waste is toxic and lasts forever. The third argument is that nuclear energy is too expensive and takes too long to build. The final argument is that the impacts of nuclear disasters are too catastrophic. It must be acknowledged that each of these arguments has at least one aspect that is based in ideology and are not actually supported by evidence. Michael Shellenberger assesses that most anti-nuclear positions are grounded in fear rather than reason.[26] Since the proliferation of nuclear energy, weapons and wars have reduced in size and scope, not the other way around. On the topic of waste, nuclear generates less waste per unit of energy than even solar and wind.[27] Furthermore, technological advances are making the use of the nuclear fuel more efficient which not only creates less new waste but also provides new opportunities to reduce existing waste. The ability to capture all the waste in solid form and not release any pollutants into the atmosphere is one of the key reasons why nuclear energy is a solution to the environmental crisis.[28] On the topic of costs and building times, nuclear power infrastructure costs are entirely front-loaded. The through life costs are extremely competitive even with the most recent technologies. Construction overruns are typically due to a combination of anti-nuclear lobby efforts and due to skill fade due to a period of drought in building new nuclear power plants. The United Kingdom has determined in their energy plan that the most cost-effective way to build safe and reliable energy will be by building a series of nuclear reactors with the same specifications and the same crew.[29] Overall, a general literary consensus is that a rational analysis of 6 decades of data concludes that nuclear power is safe and reliable when done competently with adequate regulatory oversight.[30]

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[26] Shellenberger, Michael. "Apocalypse Never" 2020.
[27] Rhodes, R. "Why Nuclear Power Must Be Part of the Energy Solution" 2018.
[28] Ibid.
[29] World Nuclear Association. "Nuclear Power in the United Kingdom" 2021.
[30] World Nuclear Association. "Safety of Nuclear Power Reactors" 2021.

No existing literature was found that attempts to draw parallels and links between the pursuit of green technologies in the Canadian energy sector and propulsion systems for the Royal Canadian navy.

CHAPTER 1: STATE OF THE CANADIAN NUCLEAR INDUSTRY

Viable solutions for green propulsion systems become palatable to the Canadian government and the public if industrial and economic benefits accrue, quality and sustainable jobs result, and value proposition is possible. To date, the Canadian nuclear sector has contributed to providing customers a safe, dependable energy baseload for 70 years. It has provided quality jobs at its power plants, within academia, at mine sites, and in the medical radioisotope field.

Current nuclear energy landscape – the aging nuclear reactor fleet

Canada's nuclear energy is currently produced by 19 reactors spread across 6 nuclear power stations located in Ontario (Bruce, Darlington, and Pickering), and Point Lepreau (New Brunswick).[31] Together, these power stations produce 13.5 GWe of electric power capacity which accounts for 15% of Canada's total electricity consumption.[32] All these reactors are Pressurized Heavy-Water Reactors (PHWR) which use a CANDU design that operate using unenriched uranium.[33] These reactors entered service between 1971 and 1993 with a designed service life of 50 years.[34] Although the life of a nuclear power plant can be extended by decades through proper refurbishment, to date, only 5 of these nuclear reactors have been refurbished.[35]

CANDU reactors were originally designed for a 30-year service life but have received life extensions mostly due to research that demonstrated that safe continued operation was possible for longer than originally anticipated.[36] Constructing a new Advanced CANDU Reactor (ACR) would take several years upon project approval. Although a nuclear reactors' through life

[31] GoC. "Uranium and nuclear power facts" 2021.
[32] World Nuclear Association. "Nuclear Power in Canada" 2020.
[33] Ibid.
[34] Ibid.
[35] CSNC. "Refurbishment and life extension" 2015.
[36] Nuclear Engineering International. "Candu reactors: ageing well" 2017.

cost produces viable price points for energy production, the fact that most of the costs are front loaded, the time required to get a return on investment, and the significant governmental regulations make it prohibitive for the private sector to invest in an undertaking of this type. The time required to plan and build a nuclear reactor has also been prohibitive from a political perspective given that any elected official proposing this solution space is not likely to reap the benefits or the credit for the initiative by the time it would be put in place. These challenges are not exclusive to nuclear energy. Big hydro-electric projects in Newfoundland and British Columbia face similar circumstances.

Although construction time and costs remain a major hurdle, several provinces including Ontario, New Brunswick, and Alberta have proposed building new reactors.[37] Most recently, Ontario has applied for a construction license to decommission old reactors and to build four new reactors at their Darlington site.[38] However, due to a combination of factors mentioned above, these net new builds of legacy reactor designs have been deferred in favour of refurbishment projects of existing reactors and research into emerging designs such as SMRs.

Links with Academia and Research Laboratories

Since the early onset of the nuclear industry in Canada, academia has played a vital role to develop, implement, and improve nuclear reactors. The CANDU designs have been extremely successful from many perspectives. Not only does this reactor type have a flawless safety record, but the CANDU 6 technology has also been successfully sold and utilized by India, Pakistan, Argentina, South Korea, Romania, and China.[39]

[37] World Nuclear Association. "Nuclear Power in Canada" 2020.
[38] CNSC. "Nuclear facility – Darlington" 2020.
[39] GoC. "Uranium and nuclear power facts" 2021.

One of the most useful aspects of the CANDU reactor is that it can run on fuel cycles that can utilize either slightly enriched Uranium or even unenriched Uranium.[40] This capability means that the CANDU reactors can produce clean and abundant energy while destroying long-lived nuclear waste or surplus plutonium.[41] Unfortunately, most research from the past twenty years has not resulted in any practical implementation of new plants. The CANDU 9 model as well as the more recent Advanced CANDU Reactor (ACR) design did not attract buyers.

Canada's current Federal Nuclear Science and Technology Work Plan invests $76 million annually towards research in health, nuclear safety and security, energy, and the environment.[42] This nuclear energy research investigates improving existing technologies as well as next-generation energy systems. Canada has been a leader in nuclear research and development in nuclear medicine, pharmacology, environmental protection, and wastewater treatment.[43] The recent shut-down of the Chalk River reactor in 2018 marks the end of an era given that it was Canada's largest producer of several key medical isotopes such as Cobalt-60, Palladium-103, and Iodine-125.[44] However, the Canadian Nuclear Isotope Council continues to monitor 25 cyclotrons across the country and many of the SMR technologies in development also have promising uses for radioisotopes. In addition to exporting CANDU Reactors and medicinal radioisotopes, 75% of Canada's uranium production was exported for use in nuclear power throughout the world.[45] This figure demonstrates the extent to which Canada has been involved in development of safe nuclear energy on the world stage. Despite the shut-down of Chalk River, Canada continues to produce 40% of the world's medicinal radioisotopes.[46]

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[40] CANDU Owners Group. "CANDU Reactors" 2012.
[41] Whitlock, J. "The evolution of Candu fuel cycles" 2001.
[42] AECL. "Federal Nuclear Science & Technology Work Plan" 2018.
[43] GoC. "Uranium and nuclear power facts" 2021.
[44] Canadian Nuclear Isotope Council. "Canadian Isotope Landscape" 2019.
[45] GoC. "Uranium and nuclear power facts" 2021.
[46] Canadian Nuclear Isotope Council. "Canadian Isotope Landscape" 2019.

Emerging SMR Technologies

In the energy sector, design efforts in Ontario have converged towards a CANDU SMR (CSMR).[47] This design, led by SNC-Lavalin, is the only all-Canadian design and is the most mature towards implementation. The CSMR avoids the long construction costs and time of a traditional reactor by being built into a single container that can be shipped, in one whole unit, to its destination. The CSMR resulted from a Public-Private Enterprise that combines Canadian scientists, universities, laboratories, utilities, engineering firms, manufacturers, and construction companies.[48] CSMRs are expected to play a significant role in Canada's green energy future and help off-grid northern and remote communities reduce their reliance on diesel generators.[49] The CSMR is designed to produce 300 MWe of energy and operates on natural uranium which does not need to cross borders for enrichment purposes. Among other stated advantages are compatibility with an existing mature Canadian supply chain and nuclear waste program, additional capability for medical isotope production, and readiness to start construction as early as 2023.[50]

While this reactor design is too large to be applied directly to a naval environment, it illustrates the competencies and partnerships that exist within the Canadian nuclear sector. It is noteworthy that SNC-Lavalin has significant experience in the maritime sector as a long-standing In-Service Support Contractor (ISSC) for the RCN managing maintenance programs for Minor Warships and Auxiliary Vessels (MWAV). Furthermore, in a domain that is characterized by its construction delays and cost overruns, SNC-Lavalin has completed its last 7

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[47] SNC-Lavalin. "Candu SMR" 2020.
[48] Ibid.
[49] GoC. "Reducing energy in rural and remote communities" 2020.
[50] SNC-Lavalin. "Candu SMR" 2020.

CANDU reactors on budget and ahead of schedule.[51] This track record demonstrates competency compared to other firms throughout the world. Although SNC-Lavalin is lacking current large reactor build experience, their combined work on reactor In-Service Support, the Darlington refurbishment project and the CSMR prototype keeps skillsets relevant and up to date.

While the CSMR is the prime candidate to replace Ontario's nuclear energy capability, New Brunswick has invested in a smaller 100 MWe reactor by ARC Nuclear in collaboration with GE Hitachi (GEH). The ARC-100 is a sodium-cooled fast reactor with a metallic uranium alloy core.[52] It is based on an Experimental Breeder Reactor-II (EBR-II) prototype that operated for over 30 years from 1961 onward in Argonne National Laboratory in the United States.[53] This reactor has already passed Canadian pre-licensing milestones and is being considered by other provinces. Among this design's stated advantages are its ability to consume its own waste, operate for 20 years between refueling cycles, and create clean power for the grid while simultaneously producing hydrogen to support modern transportation systems.[54] Although the power output of this reactor exceeds the typical power output of a typical RCN blue water warship, the time between refueling cycles invites naval application. The most interesting aspect of this reactor, however, is not whether it could be utilized directly for naval propulsion, but rather due to its stated hydrogen production.

In the past, hydrogen was not considered a green technology because the most cost-efficient way to produce hydrogen is through natural gas reforming which emits significant

[51] SNC-Lavalin. "CANDU SMR – The Original Canadian Solution" N.D.
[52] WNN. "ARC-100 passes Canadian pre-licensing milestone" 2019.
[53] Ibid.
[54] ARC Energy. "Becoming a clean energy reality in Canada." 2021.

quantities of greenhouse gas.[55] A significant feature of future SMR technologies is their operation at higher temperatures and lower pressures compared to traditional nuclear reactors which in turn provides new efficient ways of producing clean hydrogen.[56] This feature of many emerging SMR models introduces a new contender for green propulsion options in the form of hydrogen fuel cells. If the Canadian Nuclear Industry, through the SMR Action Plan, becomes a major producer of clean hydrogen, it opens more options for green propulsion.

Molten Salt Reactors

While the CSMR and the ARC-100 are the current short-term nuclear solutions for the Canadian energy sector, a small handful of other Canadian partnerships are involved in developing the next generation of nuclear reactors, notably Molten Salt Reactors (MSR). The history of MSRs dates to the dawn of the nuclear age. Oak Ridge National Laboratory (ORNL) in Tennessee built the first MSR in tandem with their fast breeder reactor as a component of the infamous Manhattan Project.[57] The MSR program ran from 1957 to 1976. Although an 8MWe prototype operating with Thorium-based fuel was successfully operated over 4 years, the decision to pursue the Uranium-based fast breeder was preferred at the time due to its ability to provide weapons grade plutonium.[58] Ironically, the main reason that the MSR was not chosen as the technology of choice at the time (the ability to produce weapons grade isotopes) is one of the reasons it is so attractive today, especially for a nation such as Canada that is aiming for safe and peaceful nuclear power.[59] Additionally, the MSR design possesses several innate and passive safety features that significantly reduce safety risks compared to other reactor models.

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[55] U.S. Department of Energy. "Hydrogen Production and Distribution" 2021.
[56] Delbert, C. "Tiny Nuclear Reactors Yield a Huge Amount of Clean Hydrogen" 2020.
[57] World Nuclear Association. "Molten Salt Reactors" 2020.
[58] Ibid.
[59] Hadhazy, A. "Why aren't we using Thorium in Nuclear Reactors" 2014.

One of the Canadian contributions to developing MSR technology is in a partnership with the United States and the United Kingdom by a company named Terrestrial Energy. Their Integral Molten Salt Reactor (IMSR) produces 195MWe using a thermal-spectrum, graphite-moderated, molten-fluoride-salt reactor system that uses low-enriched uranium (less than 5% Uranium-235).[60] This reactor uses the same proven concept as the ORNL. The limiting factor of such a reactor is the lifespan of the graphite moderators. To counter this, Terrestrial Energy created a sealed and replaceable reactor core that has an operational life cycle of 7 years and is simple and safe to replace.[61] This reactor design is also able to produce carbon-free hydrogen and ammonia while simultaneously desalinating water as it produces its electric power. Green ammonia is interesting because it is currently recognized as the highest carbon-free method to store hydrogen for usage in hydrogen fuel-cells.[62] It is considered by Maersk to be one of the most promising carbon-free fuels for long range maritime shipping.[63] Although this reactor model remains too large for shipboard use, the ability to desalinate water as a biproduct of the operational cycle is not to be underestimated for applications in a naval setting. This company, although founded in 2013, is filled with global experts in the nuclear industry and is setting extremely high aspirational goals for itself. While this company is multinational, much of its SMR innovation efforts are being focused on Canada as the United States becomes significantly more focused on solar and wind as part of their Green New Deal and the United Kingdom is currently invested in building large traditional reactors.

Another upcoming MSR design is coming from Moltex Energy. Selected by NB Power from over 90 applications, the Moltex Stable Salt Reactor – Wasteburner (SSR-W) will be built

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[60] Terrestrial Energy. "How It Works" 2021.
[61] Ibid.
[62] The term green is being used to describe a carbon-free manufacturing process that does not depend on fossil fuels.
[63] EURACTIV. "Ammonia: The missing link in the hydrogen story?" 2020.

alongside the ARC-100 reactor at the Point Lepreau site.[64] Showing clear collaboration among stakeholders, Moltex Energy, NB Power and ARC Canada signed a Memorandum of Understanding (MOU) on 17 November 2020 formalizing and strengthening existing relationships in their commitment to develop solutions to fight climate change.[65] What makes the SSR-W interesting is that it is designed to be fueled by recycled nuclear waste including those from the CANDU reactors. It will be a 300MWe reactor that is developing energy storage technology to enable its reactor to be used as a 900MWe peaking plant to complement intermittent renewable energy sources.[66] The ability to store energy to surge on demand makes this technology a direct replacement to natural gas. Traditionally, nuclear energy was relied upon only as baseload power source due to its slow ramp up time. To this point, few energy sources have been as reliable as natural gas to provide surge energy on demand to the grid. As the energy sector increases dependence on intermittent renewable sources of energy such as wind and solar, the ability to provide reliable on-demand energy surges to the grid is only increasing. Therefore, energy storage and supply to the grid capability are extremely important in the energy sector. This reactor is much too large for shipboard use, but, like other MSRs, the SSR-W can produce clean hydrogen.

Smaller SMRs

To this point, all discussed SMRs have exceeded the size requirements for shipboard application. Among the companies building smaller reactors as part of the SMR Action Plan is the Montreal-based StarCore Nuclear with High Temperature Gas Reactors (HTGR) ranging from 20 to 100 MWe. This reactor design is considered “inherently safe” due to a steep negative

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[64] Moltex Energy Ltd. “Our first reactor” 2021.
[65] Moltex Energy Ltd. “Moltex, NB Power and ARC Canada sign MOU” 2020.
[66] Ibid.

thermal coefficient which eliminates the possibility of a core meltdown and its usage of helium, which does not become radioactive, as a coolant medium.[67] It uses spherical particles of uranium fuel coated by carbon which effectively gives each particle its own containment system.[68] This reactor was designed for use in remote sites in Northern Canada. Its biggest downside if being utilized in a naval setting is the designed 5 year refueling cycle. All things considered, its size makes it the first viable Canadian candidate for naval applications. However, the technology is yet to be proven and is only starting its initial design reviews with the CNSC. This project is proof that the concept of an SMR that would fit within a sea container and would provide sufficient power to fuel a Canadian sized frigate is on the brink of becoming a reality. Although the concept of a reactor of this size will take several years to prove for usage in the energy sector, it should remain as a future contender for applications in the maritime sector.[69]

Canadian Nuclear Industry Characteristics

The deep 75-year Canadian nuclear energy heritage as well as its promising road ahead does not capture the true scale and magnitude of Canada's SMR Action Plan. Contributing partners to the national plan include 5 federal regulation bodies, 6 provinces and 1 territory, 6 indigenous group authorities, 5 municipalities, 6 power utilities companies, 17 civil societies, 10 academic institutions, 45 industrial partners, and 11 SMR Vendors.[70] This is clear indication that the Canadian nuclear sector inherently possesses deep competencies, significant knowledge, and key partnerships. All these efforts are currently focused on the energy sector and do not show any linkages to the transport industry which is one of the largest energy consumers.

It is important to note that the existing government agencies that would play a regulatory

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[67] WNN. "Canadian design review for StarCore HTGR" 2016.
[68] Ibid.
[69] Hirdaris, S.E. "Considerations of Nuclear SMR technology for merchant marine propulsion" 2014.
[70] GoC. "SMR Action Plan" 2021.

role in developing the Canadian nuclear sector, including Atomic Energy of Canada Limited (AECL), the bank for Canadian entrepreneurs (BDC), the Canadian Commercial Corporation (CCC), and the Canadian Nuclear Safety Commission (CNSC), do not currently have any existing regulations for utilizing nuclear energy in the transport sector. This would likely be one of the most significant inhibiting factors to pursuing nuclear propulsion in a naval setting. In the United States, the regulatory bodies for nuclear energy and for nuclear propulsion are completely dissociated from one another. Whether considering the likelihood of creating a completely new regulatory body or extending current organizations to a naval setting, either case would be accompanied with significant challenges and would require its own pan-Canadian effort. Thus, in pursuit of green propulsion solutions, the two most apparent solutions would be to either leverage our allies' naval nuclear reactor capabilities or to seek indirect ways of leveraging the SMR action plan by considering clean fuel types that will be produced in Canada. Should the SMR action plan come to fruition, top candidates would include either hydrogen or ammonia fuel cells.

The Canadian nuclear industry has a long-standing tradition of building functional partnerships among government, academia, and industry to develop, implement, improve, and sustain industry leading technologies. To this point, the Canadian nuclear industry has been focused on producing power for the energy grid and to explore multiple ways to utilize products of nuclear reactors in multiple domains. Canadian participants in the nuclear industry are highly skilled and knowledgeable and have shown an uncanny ability to conform and adapt to strict regulations. Current investments in CSMR, ARC-100, and Wasteburner reactor designs are early indicators of the resurgence of nuclear energy sector. Furthermore, Canada's role in development of promising SMR designs also confirm the competence and skillsets that lie within our borders. Canadian nuclear technologies are already strategically anchored on Canada's Energy Innovation roadmap. There are two potential ways that the maritime sector could leverage these competencies, partnerships, and industrial capabilities. The first would be to find ways to directly convert small reactors for naval applications and the second, would be to utilize technologies that rely on clean fuels that can be produced by off peak energy produced by nuclear reactors, such as hydrogen or ammonia.

CHAPTER 2: EXISTING AND EMERGING GREEN PROPULSION SYSTEMS IN NAVAL AND MARITIME SETTINGS

The international landscape of stakeholders seeking ways to achieve IMO environmental targets is extremely diverse. The requirements of a cargo ship operating on an international trade route is quite different from those of a local ferry. Similarly, the requirements of a blue navy warship operating in an international task group are also incongruent with those of a littoral ship operating within its national waters. Yet, the list of viable technologies that can realistically help the industry achieve net-zero greenhouse gas emission targets in the maritime and naval sectors is not as deep as it is in the energy sector. Many renewable green technologies are too intermittent and do not have the requisite power density to meet naval requirements.[71] Instead, some current and emerging technologies offer the most viable way of moving forward.

In their 2020 Flagship report, the International Energy Agency (IEA) evaluated over 800 technologies to determine what a viable path to net-zero emissions could look like. In their assessment, they determined that the bulk of the maritime transport sector is likely to operate on a combination of Nuclear, Hydrogen, and Ammonia.[72] Each of these fuel sources comes with different advantages and disadvantages that can be leveraged by different stakeholders for various maritime and naval applications. Each of these technologies has the potential to be leveraged by the RCN based on their current state of development and utilization.

History of naval nuclear applications

The concept of harnessing nuclear energy to produce a self-sustaining release of energy was originally conceived by Francis Perrin in 1939.[73] Prior to this point, almost all nuclear research was dedicated towards weaponizing nuclear energy in the form of an atomic bomb.

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[71] Bard, F. "Emerging Propulsion System Technologies for a Greener Fleet" 2021.
[72] IEA. "Energy Technology Perspectives" 2020.
[73] World Nuclear Organization. "Outline History of Nuclear Energy" 2020.

Researching nuclear energy in parallel to the infamous Manhattan Project, it was Enrico Fermi who successfully built the first controlled nuclear chain reaction in December 1942.[74] Although the Second World War caused a pause in the development of non-weaponized nuclear applications, by 1951, the first nuclear reactor to produce electricity was created in the form of a small experimental breeder reactor.

It did not take long to find naval applications of a nuclear reactor once a proven prototype had been built. In fact, utilizing a nuclear reactor as an energy source to propel a vessel was one of the first applications of nuclear energy. It was Admiral Hyman Rickover who developed the pressurized water reactor (PWR) for naval use.[75] *USS Nautilus*, named after the vessel in Jules Vernes' *2000 Leagues Under the Sea* fictional novel was launched in 1954 and successfully completed its sea trials in 1955.[76] Implementing nuclear reactors to naval ships was not a daunting task. Steam-powered vessels had already been utilized for more than a century. The nuclear reactor only needed to provide the energy to convert water to steam and the steam could be fed to time-tested and proven technologies to turn steam turbines to activate the vessel's shaftlines and propellers.

The first naval nuclear core revolutionized maritime warfare. In its two years of operation, *USS Nautilus* was able to sail 62,560 Nautical Miles without refueling.[77] Today, typical nuclear cores can easily exceed 40 years of consistent operation. In naval settings, however, they are typically changed-out after 20 years as a safety precaution.[78] The first surface vessel to operate with nuclear reactors is also well known. The *USS Enterprise*, the first nuclear

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[74] World Nuclear Organization. "Outline History of Nuclear Energy" 2020.
[75] Ibid.
[76] Largest Submarines. "The First Nuclear Submarine" 2016.
[77] Ibid.
[78] EPA. "Nuclear Submarines and Aircraft Carriers" N.D.

powered aircraft carrier, was built in 1961.

In 67 years of naval vessels operating with nuclear reactors, only 6 assets have been lost due to accidents.[79] In every incident, the maritime environment is being monitored to assess the levels of radionucleotides and thus far, the design of these reactors has successfully contained the radioactive substances despite the sinking of the vessels to large depths. Essentially, since their conception, naval applications of nuclear propulsion technologies have enjoyed a phenomenal safety record to date. This is extremely impressive considering that early versions of the technology did not have the same level of designed safety features of current reactors and required significant manual operator calibrations in real-time to prevent potential runaway effects. Current technologies benefit from even greater safety designs.

Current use of Naval Nuclear Technologies across the world

According to the World Nuclear Association (WNA), as of 2020, over 160 nuclear powered vessels operated across the world which are being powered by more than 200 small nuclear reactors.[80] This is significantly lower than the reported number of 400 submarines toward the end of the Cold War. Almost all nuclear-powered vessels are either submarines, aircraft carriers, large cruisers, or icebreakers. Different nuclear technologies continue to be utilized, developed, and pursued by large navies across the world showing that nuclear propulsion continues to have many operational advantages.

Russia has been a significant investor in nuclear-powered vessels (mostly submarines) with a total of 468 nuclear reactors powering half as many units.[81] Russia has used four generations of PWRs in their fleet. Cruisers have used twin 300MW KN-3 reactors. Successful

[79] IAEA. “Inventory of accidents and losses at sea involving radioactive material” 2001.
[80] World Nuclear Association. “Nuclear-Powered Ships” 2021.
[81] Ibid.

submarines used 155MW PWRs with highly enriched uranium that delivered 30 shaft MW. Recent Alfa-class submarines used a single Liquid Metal Cooled (LMC) 155MW VM-40 fast neutron reactor. This model design was not optimal for a stealthy submarine due to its noise generation but provided significant shaft power enabling submarines to surpass 40 knots in speed. However, due to numerous technical challenges including corrosion particles from the liquid metal coolant, the Alfa-class reactor design proved to be unsuccessful and was retired early.[82]

France provides an interesting comparison for naval ships using nuclear propulsion because they have produced some smaller nuclear ships in a naval setting. The Rubis-class, in service since 1983, is the smallest nuclear submarine ever built. It uses a 48MW PWR reactor by Areva RA. France also has experience with larger ships such as the aircraft carrier Charles de Gaulle that uses twin K15 150MW PWR reactors which can drive 61MW Alstom turbines. The Triomphant class of ballistic missile submarines, launched in 2008, uses the same reactor (although only one) as Charles de Gaulle, and can achieve 32MW of shaft power. The Barracuda/Suffren class attack submarines, that are currently under construction, will use hybrid electric or pump-jet propulsion for higher speeds. These attack submarines will use a 150MW reactor by Areva TA which resembles the K15 that can deliver 21.5MW shaft power.[83]

The United Kingdom has employed three generations of Rolls-Royce PWRs combined with 6 generations of internal cores. Rolls-Royce claims that the Core H PWR2 has six times the power of its original design and runs four times longer yet exact parameters remain undisclosed.[84] The Astute class attack submarines, commissioned in 2010, have small PWR

[82] Rawool-Sullivan, M. et al. "Technical and Proliferation-Related Aspects of the Dismantlement of Russian Alfa-Class Nuclear Submarines" 2002.
[83] World Nuclear Association. "Nuclear-Powered Ships" 2021.
[84] Ibid.

reactors that drive two steam turbines and a single pump jet which are reported to produce 11.5MW of shaft power. The Vanguard replacement Dreadnought class SSBN will use the latest generation of reactor which is reported to be more expensive to build but cheaper to maintain.

The United States is not only the first country to utilize nuclear propulsion, but it also produced the most reactors at 526.[85] Although the United States has not had as many total nuclear-powered vessels as Russia, the most significant difference is that their nuclear program has, to this point, been completely radiological incident free.[86] Key reactor designs include the Virginia-class SSN S9G 150MW reactor that drives a 30MW pump-jet propulsion system by BAE Systems and does not need refueling throughout its designed service life of 33 years. Also, the Ohio-class submarines use single 220MW S8G reactors that produce 45MW shaft power and only require refueling after 25 years of service. Currently in construction is the Columbia-class submarines which will use S1B nuclear reactors with electric drive without reduction gears and pump jet propulsion. The reactor in the Columbia-class submarine will also not require mid-life refueling.

Characteristics of naval nuclear reactors

There are several commonalities among the nuclear reactor technologies used among the world's most advanced navies. Firstly, their power density in terms of both weight and volume are significantly higher. This has traditionally only been achieved with the most highly enriched levels of uranium. Most reactors listed above contain between 20 and 45% of the 235 atomic weight version of the Uranium isotope (U-235). Anything above 5% of U-235 is considered weapons grade. Only the newer French reactors run on low-enriched Uranium fuel (7% of U-235) which is still above the weapons-grade marker of 5%. In contrast to the Canadian nuclear

[85] World Nuclear Association. "Nuclear-Powered Ships" 2021.
[86] Ibid.

industry, Canada does not currently have any remaining nuclear reactors that operate on fuels above the weapons-grade threshold. Furthermore, the current government's position is clear that the Canadian nuclear mandate is that of peace and safety for energy generation, not weapons.[87] This essentially means that utilization of any technology that operates on a weapons-grade fuel would likely be a non-starter.

Another key characteristic of the naval nuclear reactors is the long service life of the nuclear cores. In most cases, the designed service life of the core is aligned with that of the ship. While some reactors are designed to have one refuelling at mid-life, this is considered the exception and not the norm. It is also noteworthy that the thermal efficiency of naval nuclear reactors cannot compete with that of civilian nuclear power plants given that there is a requirement for flexible power output on a ship. Additionally, there are space constraints for the steam system on a ship that do not exist in a shore establishment. As a result, the shaft power output of the ship is typically between one fifth and one third that of the nuclear reactor output.

Potential downsides of pursuing nuclear propulsion are the significant infrastructure requirements and commensurate building times. For example, it took France 11 years to build Charles de Gaulle mostly due to nuclear reactor requirements.[88] Considering that France was already among the world's experts in nuclear energy when they initiated that project, it certainly raises concerns on the potential learning curve if Canada decided to develop this niche expertise. Indeed, if Canada were to consider nuclear propulsion to decarbonize its navy, it would entail significant investments in infrastructure and regulatory bodies. However, given that nuclear propulsion is currently the only existing carbon-free marine propulsion technology with a proven track record, it is still worth considering if the potential benefits are worthy of investment.

[87] RAND Corporation. "Issues of Aircraft Carrier Production in France" N.D.
[88] Chapter S. "Why Aircraft Carriers and Submarines are Nuclear Powered" 2019.

Lloyds Register, a long-standing classification society interested in naval and maritime safety standards, did an extensive study on the viability of nuclear propulsion as a commercial solution in the shipping sector. They determined that although the capital costs associated with supporting a nuclear fleet are enormous, that the low operational costs are such that when considering total cost of ownership, that nuclear could be overall cost effective.[89]

Other than costs, safety is extremely high on the list of considerations that must be addressed. There would not be any point in adopting technologies in the name of saving the environment if they were to endanger people's lives. The naval nuclear safety record speaks for itself. Oxford University found nuclear energy to be the safest major energy source in a 2017 study.[90] What about the radiation doses for sailors working on nuclear vessels? According to the World Nuclear Association, the average annual occupational exposure was 0.06mSv per person in 2013.[91] To set comparable benchmarks, the Canadian Nuclear Safety Commission (CNSC) states that the worldwide average for natural background radiation is 2.40mSv and sets a maximum annual dose limit for nuclear workers at 50mSv per year and 100mSv in 5 consecutive years.[92] Designed internal neutron and gamma shields used in naval applications are extremely effective. The militarized specifications for these self-contained PWR modular units have an impeccable track record in 65 years of operation.

Potential to expand nuclear propulsion in new marine markets

Existing regulations for nuclear power at sea stated in Chapter VIII of the International Convention for the Safety of Life at Sea (SOLAS) were written in 1974. These regulations,

[89] Lloyd's Register. "How can nuclear support shipping's route to zero-carbon" 2021.
[90] Ritchie, H. "Safest and cleanest sources of energy" 2020.
[91] World Nuclear Association. "Nuclear-Powered Ships" 2021.
[92] CNSC. "Radiation doses" 2020.

centered around PWR technology, have not significantly evolved since their inception.[93] With fourth generation nuclear reactors becoming operational across the world that will utilize a wide range of different technologies, it is important to ensure the long-standing safety standards of the naval nuclear sector remain intact. To account for safety considerations of emerging nuclear technologies, Lloyds Registry produced a high-level framework of rules for nuclear propulsion in 2010 which currently sets a baseline for the industry.[94] Within this framework, a roadmap to safely license a self-contained military nuclear reactor to a commercial ship was established.

The Lloyds Registry nuclear safety baseline for commercial ships led to studies that assessed the viability of nuclear-powered tankers on international trade routes. These studies, led by the IMO and supported by the IAEA, determined that while the concept was feasible, "further maturity of nuclear technology and the development of harmonization of the regulatory framework would be necessary".[95] Although nuclear propulsion is a proven technology with an exemplary safety record, the largest obstacle if a new consumer, such as the RCN, were to consider adopting it is for the requisite regulatory bodies in both nuclear and maritime sectors to create room for it.

Emergence of hydrogen and ammonia as contenders

The Organisation for Economic Co-operation and Development (OECD) estimates that by 2070, 12% of marine transport will be fuelled by hydrogen and 55% by ammonia.[96] These fuels can be used either in internal combustion engines or in fuel cells. The Canadian National Laboratory (CNL) has been contracted by Transport Canada to use its Marine-Zero Fuel (MaZeF) Assessment Tool to help Canada assess and pursue the use of these technologies in

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[93] Lloyd's Register. "How can nuclear support shipping's route to zero-carbon" 2021.
[94] Ibid.
[95] Hirdaris, S. et Al. "Concept Design for a Suezmax Tanker Powered by a 70MW Small Modular Reactor" 2014.
[96] IEA. "Energy Technology Perspectives" 2020.

marine vessels.[97]

Although Ammonia and Hydrogen technologies have existed for decades, they have not yet achieved the same commercial viability as other technologies. The road vehicle industry can be used as a point of comparison because both hydrogen fuel cells and Lithium-Ion batteries have been competing for market space for several years. When comparing these technologies applied to electric road vehicles, the Lithium-Ion Battery cars currently have significantly higher market penetration than Hydrogen Fuel Cell equivalents due mostly to their comparatively low cost but also due, in part, to lack of current availability of clean and affordable clean hydrogen.[98] However, Lithium-Ion Batteries have one significant flaw which is their range. As long as a Lithium-Ion vehicle operates for shorter distance in proximity to the power grid, this does not become a limiting factor for consistent operation. However, larger vehicles that travel longer distances, such as transport trucks, favour hydrogen fuel cells because their range and refuel times are significantly better.[99] The same logic applies to ships. Short-range ferries that have sufficient docking time to plug into the grid between transits can operate on Lithium-Ion Batteries. However, as soon as the size and range of the ship exceeds a certain tipping point, alternate fuels such as Hydrogen and Ammonia emerge as better contenders. It is also important to note that electric vehicles can easily operate with both hydrogen fuel cells and lithium-ion batteries working in tandem. Both technologies produce electricity which can then be utilized for propulsion and hotel loads.

Although the most recent proton exchange membrane fuel cells (PEMFC) are a relatively new concept (developed in the late 1980s), the initial concept for the hydrogen fuel cell is not

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[97] Green Car Congress. "CNL to research clean energy technologies to decarbonize marine sector. 2020.
[98] Euronews. "Hydrogen Fuel Cell vs Electric Cars" 2020.
[99] Muller, J. "Trucking into the hydrogen era" 2020.

new. It was originally invented in 1839 by a scientist named William Grove.[100] One may easily be tempted to ask how this technology could possibly be commercially viable if it has been around for almost two full centuries without finding its niche. However, to understand why this technology is becoming increasingly viable, one must understand its limitations and how they are progressively being mitigated.

Hydrogen production

The first limitation of the hydrogen fuel cell is the natural properties of hydrogen itself. Although hydrogen is the most abundant element in the universe, it is not typically found in nature bonded to itself. Its most typical natural forms are found in water and in innumerable carbon compounds.[101] Currently, the most economic method to produce hydrogen in its isolated form remains through methane steam reforming which emits significant quantities of greenhouse gases.[102] For this reason, using hydrogen as a fuel is only considered environmentally friendly when it is produced in a process that does not produce greenhouse gas emissions. The emergence of high temperature nuclear reactors is a key factor that is changing the landscape of hydrogen because it would provide a carbon-free way to produce hydrogen fuel in bulk.[103] However, it is not the only emerging method to produce hydrogen. One company has discovered a way to use methane steam reforming principles within existing oil sands to liberate hydrogen gas from molecules within the ground without emitting greenhouse gases in the atmosphere.[104] Another way to produce clean hydrogen is through the hydrolysis of water. This is far from being the most cost-effective way; however, with an increasing tendency to rely on more

[100] FuelCellsWorks. "History" N.D.
[101] Jolly, W.L. "Hydrogen chemical element" 2020.
[102] Ayodele, F.O. et al. "Impacts of Natural Gas Conversion Technologies" 2020.
[103] Office of Nuclear Energy. "Could Hydrogen Help Save Nuclear?" 2020.
[104] CGTN America. "Cheap and clean Hydrogen fuel" 2020.

intermittent renewable energy sources, there are times where more power is produced than the demand on the power grid. One way to store excess energy in these situations is production of hydrogen via electrolysis of water.

Hydrogen storage

If efficiently creating clean hydrogen was the first hurdle, storing it is the second. The images of the Hindenburg dirigible disaster in 1937 or the Challenger Shuttle explosion in 1986 are often what come to mind when one thinks of the pitfalls of hydrogen as a fuel source.[105] Luckily, significant advances have been made to hydrogen storage in the past decades. There are several ways to store hydrogen. The most typical is in gaseous form. Current reservoirs are designed to safely store Hydrogen at high pressure (700 Bar) in containers that are designed to withstand shock, vibrations, temperature gradients and even damage from bullets and mortars.[106] While storing hydrogen in this manner provides an excellent power density per unit of mass, it is not considered efficient from the perspective of power density per unit of volume. Furthermore, in the marine industry, any fuels with a flashpoint higher than 60 degrees Celsius are typically stored on the upper decks. While it is possible to safely store hydrogen in such reservoirs inside the ship in well ventilated compartments, this would not be considered the ideal solution for safe hydrogen storage.

Another promising form to safely store Hydrogen is through Liquid Organic Hydrogen Carriers (LOHC). Using this approach, hydrogen in stored in a porous carbon molecule so that it can be safely stored and transported.[107] To hydrogenate or dehydrogenate the porous molecule can be as simple as controlling the ambient temperatures and pressures. One promising example

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[105] Szalay, J. "Hindenburg Crash" 2017. and Think Reliably. "Challenger Explosion" 2021.
[106] Weisberg, A.H. et al. "Hydrogen Storage Using Lightweight Tanks" 2002.
[107] Xia, Y. et al. "Porous carbon-based materials for hydrogen storage" 2013.

of LOHC is achieved through the hydrogenation of dibenzyl toluene (DBT) which, when saturated with hydrogen (9 hydrogen atoms per molecule), acts as an inert oil that can be carried and stored like any diesel oil.[108] Because LOHC is only a carrier and not actually a fuel, the energy requirements to hydrogenate and dehydrogenate the fuel must be factored into the efficiency value chain. On one side, the utilization of this type of hydrogen carrier would increase the onboard safety of manipulating the fuel. On the other side, it would adversely impact the overall range of the vessel with regards to its fuel carrying capacity. If a ship were to have onboard electrolysing capability to extract hydrogen from sea water, this form of storage would suddenly become significantly attractive.

Characteristics of Hydrogen

The following table compares volumetric and weight power densities of various forms of hydrogen storage to those of Distillate Fuel Oil (DFO) and Lithium-Ion batteries. It is possible to deduce from this data that the energy density properties in terms of volume and weight are significantly different in from one storage medium to another. The properties of DFO are provided as an indicator of the type of energy densities that hydrogen must compete with to be a viable replacement. The data for lithium-ion batteries are provided to show how uncompetitive this technology is in terms of power density in a context that is distant from a power grid.

Table I: Power Densities of various fuels[109]

Fuel Type	**DFO**	**H gas**	**H liquid**	**Metal Hydride**	**NH3**	**Li-ion**
Efficiency (%) - min	20	40	40	40	30	70
Efficiency (%) - max	40	60	60	60	60	95
Energy density per volume (MWh/m3)	9.7	1.4	2.36	3.18	4.82	0.30

[108] Hydrogenious. "LOHC Research" 2021.
[109] Royal Institution of Naval Architects. "A comparison of Hydrogen and Ammonia for Future Long Distance Shipping Fuels" 2020.

Energy density per mass (MWh/kg)	0.0116	0.0333	0.0333	0.0006	0.0052	0.0002

Based on this data, it is not surprising that Metal Hydrides and Ammonia are considered by many to be the primary candidates for safe hydrogen storage onboard naval ships. The limiting factor on most ships is volume rather than weight. In fact, marine vessels typically store fuels as close to the keel as possible to lower centre of gravity and therefore increase the strength of righting moment of inertia and thus general stability. Metal hydrides provide a safe and efficient method of storing hydrogen if there is sufficient reserve buoyancy to add additional ballast. Theoretically, if a hydrogen fuel cell was incorporated with metal hydride storage and an electrolyser, a ship would be able to sail indefinitely if the electrolyser could keep up with the overall hydrogen demand.[110] This is a technology that is more likely to be researched for naval application given that naval ships tend to have more room for ballast weight, especially in submarines which try to be as close to neutrally buoyant as possible prior to filling any ballast tanks.

Ammonia

Many marine sector experts do not consider ammonia and hydrogen to be in competition with one another.[111] In fact, it can be argued that both technologies can operate within the same value chain. Ammonia can be used directly within an internal combustion engine or as a hydrogen delivery vehicle for a proton fuel cell. Maersk, the world's largest cargo ship company sees ammonia as the top candidate for fossil fuel replacement carbon-free propulsion.[112] They are currently the company in the maritime sector that has set the most aggressive self-imposed targets to achieve net-zero. Their plan is to start commissioning carbon-free propulsion systems on ships as early as 2030 to ensure that their fleet is as close to zero emissions by 2050. If the

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110 Han, G.K. et al. "High-energy-density portable/mobile hydrogen energy storage system" 2020.
111 EURACTIV. "Ammonia: The missing link in the hydrogen story?" 2020.
112 Ibid.

RCN wishes to be recognized as a world leader for innovative environmental solutions moving forward, then Maersk is the one setting the bar that must be beat.

Among the reasons ammonia is considered to be a front runner as a potential maritime fuel of the future is because it is considered to be the technology with the lowest overall risks and the easiest to implement on a large scale. Ammonia is the most energy efficient liquid that can meet the IMO criteria to be considered a sustainable fuel.[113] Although ammonia is a hazardous material that comes with its own rulesets and regulations, this technology already exists in the marine sector. The existing practices and know-how are already present to ensure safe production, transport, and storage for this fuel.[114] Taldor Torpsoe, the world's current largest producer of ammonia states that this fuel type is available and scalable to meet future marine sector needs.

Ammonia can be used directly in an internal combustion engine or as a delivery mechanism for hydrogen in a fuel cell. When used for combustion, it can produce various nitrous oxides which are toxic to the environment. This can be somewhat mitigated by scrubbers. However, if used in a fuel cell, free nitrogen atoms typically bond together and are released as nitrogen molecules which are completely safe for the atmosphere (70% of the atmosphere is already nitrogen).

The three prime movers that the IEA considers to be the most viable paths to the net-zero emissions target set by the IMO are nuclear, hydrogen, and ammonia. Currently, the most proven technology is the traditional PWR nuclear reactor. This technology has a stellar safety track record, especially among allied nations. Limiting factors for RCN usage are mostly political and would require the development of necessary regulatory bodies. While it is unlikely

[113] Haldor Topsoe. "Green ammonia as marine fuel" 2020.
[114] Ibid.

that the RCN will ever move towards developing requisite infrastructure to support usage of a traditional PWR, it is important to consider that fourth generation nuclear reactors, including MSRs, have significant long-term potential for marine applications. Although these technologies require the greater part of a decade to achieve regulatory permissions to test commercial viability for shore usage, if expected outcomes are achieved, it does not require a far stretch of the imagination to find viable utility for either direct marine propulsion or power generation using an electric drive train.

The second technology is the hydrogen fuel cell. Although this technology has historically suffered from many challenges and constraints, the world seems to be converging on a heading that will see this technology shine in the transport sector in applications that involve large vehicles that operate off the power grid. The hydrogen fuel cell can efficiently complement and leverage electric technology that came before it and offer an alternate way to provide electricity to end users. Although previously impeded by production costs and safe storage technologies, hydrogen is quickly becoming a contender to fuel electric ships of the future.

Between the tried and tested nuclear reactors and the yet unrealized potential of the hydrogen fuel cell lies the low-risk option of ammonia. Ammonia can be used directly to power internal combustion engines or to deliver hydrogen to fuel cells. Although it has not been widely adopted in the marine sector to this date, the technology already exists and is considered a safe intermediate solution moving forward. Ultimately, the concept of greening the entire fleet likely requires a combination of these technologies rather than a focused or targeted investment in just one.

Canada's Hydrogen Industry

Canada is currently ranked 10th in total hydrogen production and 3rd for clean hydrogen production.[115] However, most of Canada's hydrogen and ammonia are currently produced through steam methane reformation.[116] Although this is currently the most economical method to synthesize these fuels, it is not environmentally friendly due to carbon dioxide emissions. The high operating temperatures and high-quality steam generated in fourth generation SMRs have the potential to make the nuclear energy sector a meaningful producer of clean hydrogen and ammonia.

In January 2021, the federal government published a Hydrogen Strategy which states a vision to have 30% of Canada's energy delivered in the form of hydrogen by 2050.[117] Canada is not a new player in the Hydrogen industry. It was the first country to patent electrolysis technology in 1915 and made a significant breakthrough in proton exchange membrane (PEM) fuel cell power density in the 1990s.[118] Much like the Canadian nuclear industry, the Canadian hydrogen landscape has been blessed with a long history of partnerships among academia, government, and industry. These partnerships are still relatively new compared to those in the Canadian nuclear industry. However, publication of Canada's hydrogen strategy is a meaningful sign that these bonds will grow and strengthen in time. Significant investments in infrastructure to support growth in this industry is required. Canada's Hydrogen Strategy is in line with this requisite growth.

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[115] Olexiuk, P. et al. "Federal government announces Canada's hydrogen strategy" 2020.
[116] Olexiuk, P. et al. "hydrogen strategy". 2020. and Karaca, A.E. et al. "Ammonia-based energy solutions" 2020.
[117] GoC. "The Hydrogen Strategy" 2021.
[118] Ibid.

CHAPTER 3: INNOVATION ROADMAP FOR RCN'S FUTURE FLEET

While the IMO's emission reduction targets may seem far away, it is important to recognize that in terms of realistic timelines associated with force development and force employment, most ships being designed today are likely to form a significant portion of the RCN fleet in 2050. Recently decommissioned classes, the Iroquois Class destroyers, and the Protecteur Class auxiliaries, had service lives exceeding 40 and 50 years, respectively. The Kingston Class vessel, originally designed as a mine countermeasure vessel but currently employed as a multi-role coastal surveillance and patrol platform, remains in service beyond its designed service life of 25 years. The trend to utilize warships well beyond their designed service life is likely to continue in the near term given expected delivery timelines of vessels under the National Shipbuilding Strategy (NSS).[119] Ultimately, if the NSS reaches a steady state, the long-term aim is to have each new ship being commissioned as its predecessor is decommissioned thus keeping the total cost of ownership down by avoiding escalating maintenance costs typical of aging ships.

Decarbonizing the RCN's propulsion systems will require significant innovation. New infrastructure and competencies shall need to be developed. Technologies forecasted to be implemented in the near-term, including the AOPS diesel electric CODLAG propulsion system, are not steering the RCN towards achieving IMO environmental targets. However, important aspects of the RCN adopting these new technologies are extremely important for the future roadmap. AOPS will be the first high-voltage ship utilized by the RCN. The willingness to incorporate this higher risk technology demonstrates that the RCN is not afraid to lean on its sailors' competency to achieve its operational capability. High voltage is significantly more

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[119] GoC. "National Shipbuilding Strategy" 2020.

dangerous than traditional NATO standard power. Significant additional training and safety procedures and equipment are required to ensure safe and efficient operation of such a platform. With the RCN gaining experience with high voltage equipment, it opens new doors for many green propulsion options in development.

History of innovation in the RCN

Other than updating its weapons and sensors as part of the Halifax Class Modernization Frigate Life Extension (HCM FELEX) program, high-voltage diesel electric power plant is undoubtedly the most specialized capability introduced to the RCN in decades. The drought of new marine system capabilities, especially at the platform level, may be partly attributed to defence cutbacks tied to the end of the Cold War and lack of acquisition of major warships in over 20 years. Nonetheless, it is important to remember that the RCN has a long-standing history of significant innovation, some of which have revolutionized the way naval allies and even every maritime vessel operate.

The most impressive example of sheer innovation by the RCN was the creation of the hydrofoils for HMCS Bras d'Or between 1968 and 1971. This ship, during its trials, was able to achieve speeds exceeding 63 knots (116 km/h), making it the fastest unarmed warship in the world at the time.[120] It must be noted that this level of innovation was not cost effective in the short term, which was ultimately the reason the project was discontinued. Spending government funds on innovation can easily be perceived by the average taxpayer as wasteful or frivolous spending. However, many benefits of such programs manifest themselves as social or economic benefits realized afterwards for years or even decades after the programs themselves. The Space program is likely the best example of social benefits realized in the long term despite significant

[120] Adams, S. "The winged ship: HMCS Bras d'Or" 2020.

incurred costs during the program itself.[121]

Unfortunately, the HMCS Bras d'Or was the last time the RCN dedicated significant effort to innovate at the platform level. The focus of most innovation since then has been at the system level. Two of the most significant system-level innovations realized in support of Canada's navy were the Canadian Towed Array Sonar System (CANTASS) and the Integrated Machinery Control System (IMCS). Both technologies were developed in the Cold War era. The former was designed to improve submarine detection capability and the latter was used to increase remote control and operation capabilities of ship machinery. In the case of CANTASS, every blue water navy that wants to dedicate assets to submarine detection now has naval assets fitted with a descendant of this technology. IMCS has evolved from simply monitoring and controlling machinery to being a fully Integrated Platform Management System (IPMS). The Montreal-based company (CAE) that created IMCS for the Halifax Class Frigates eventually sold the intellectual property to L-3 MAPPS which is now the global leader in IPMS systems for both naval and maritime applications.[122] These clear examples demonstrate how becoming an early contributor in an emerging market can yield long term strategic benefits for defence and the Crown as a whole.

Today, the RCN recognizes the key role that innovation must play in achieving its mandate. The RCN has created an Innovation Program to promote a culture of innovation within its ranks.[123] Collaboration with industry, academia and other government agencies are cited as being the key to success in supporting agile solutions in pursuit of positive change.[124] Other government solutions supported by the RCN Innovation Program include Innovation for Defence

[121] Sachdev, N. "The human side of space exploration" 2019.
[122] L-3 MAPPS. "Integrated platform management systems" N.D.
[123] RCN. "RCN Innovation Program" 2020.
[124] Ibid.

Excellence and Security (IDEaS), the Build in Canada Innovation Program, and Innovative Solutions Canada.[125] All these programs encourage a bottom-up approach to innovation which solicits ideas from RCN members, industry partners, and any other potential stakeholder that wants to contribute. Although these innovation programs are an excellent starting point to re-introduce a culture of innovation, it has two significant shortfalls. Firstly, it places a ceiling on the scope of innovation that can occur by placing a cap on individual submissions.[126] Secondly, the bottom-up approach does not interact well with the CAF's Capital Investment Plan (CIP) which operates in a top-down manner. The scale of investments required to innovate within the green propulsion system environment does not fit anywhere within any of the programs cited by the RCN Innovation Program.

RCN Force Development Plan

Naval strategists recognize that building a navy requires a series of substantial government investments spanned over multiple decades.[127] The projected requirements for the 2050 RCN fleet were defined in 2016 in a strategic document named LEADMARK 2050 - Canada in a New Maritime World.[128] This document forms a baseline for projected RCN requirements. In terms of Force Development (FD), the strategy specifies a "nearer-term" window as pre-2035 and "longer-term" window as post-2035.[129]

According to Leadmark 2050, the nearer-term period will deliver the Arctic and Offshore Patrol Ship (AOPS), CSC, and the new Joint Support Ship (JSS).[130] In this FD window, the stated environmental objectives in terms of either propulsion and electrical systems is to

[125] RCN. "RCN Innovation Program" 2020.
[126] GoC. "Innovation for Defence Excellence and Security" 2021.
[127] RCN. "Leadmark 2050" 2016.
[128] Ibid.
[129] Ibid.
[130] Ibid.

introduce "green fleet" technologies to improve fuel consumption, optimize shipboard electrical power, reduce emission of engine exhaust, and improve sustainable environmental practices.[131] In other words, during this FD window, there is no stated intention to replace carbon emitting engines but rather to rely on increased efficiency and carbon capture mechanisms. This is problematic if any attempt is to be made at reaching 2050 IMO environmental targets given no "green fleet" technology can reduce carbon emissions anywhere near the 50% mark. Assuming a shipbuilding capacity of one combat ship per year with delivery starting in 2031, the last ships designed in this window may not be commissioned until 2046. NSS was created in 2012 with an initial contracting period of up to 30 years which means that NSS capacity is essentially already overbooked beyond its current contract time.[132] Although NSS was created as a strategic means to break the "boom and bust cycles" of government shipbuilding contracts, increased media scrutiny following the first batch of ships is calling for Canadians to scrutinize the shipbuilding policy altogether.[133] While the policy requirements to build ships in Canada lies beyond the scope of this research project, one could infer that if Canada is unable to build its own ships, any thought of expanding Canadian industry to incorporate infrastructure to support and sustain green propulsion initiatives would be unfathomable.

It is difficult to see a path to reaching 2050 IMO environmental targets based on the strategic approach detailed in Landmark 2050's pre-2035 FD period. This period places too much emphasis on improving efficiency of existing technologies which prevents exploration of new innovative strategies that could make the requisite leaps to carbon free propulsion systems. According to the *Harvard Business Review*, placing too much emphasis on increasing efficiency

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[131] RCN. "Leadmark 2050" 2016.
[132] PSPC. "Phases of the National Shipbuilding Strategy" 2019.
[133] Gilmore, S. "It's time to ban the buying of made-in-Canada warships" 2021.

is extremely inhibitive to innovation.[134] Landmark 2050 seems to recognize this and attempts to create room for technical innovations by citing a plan to dedicate an entire frigate to experimenting with new technologies. This healthy approach to experiment with different plug and play sensors and weapon systems can come with significant constraints when considering detailed requirements in hull design and fuel storage that come with the contending propulsion systems. Assuming the first ship designated as the experimental innovation ship is a CSC, it is easy to see that any innovation regarding propulsion systems would be extremely constrained by the CODLAG ship design choices. On one hand, it might be possible to attempt to swap out diesel generators for hydrogen fuel cells relatively easily with little impact to most of the ship's machinery. On the other hand, if the intent is to maintain the hybrid Gas Turbine capability, fuel storage would be extremely problematic. If ammonia were chosen as the experimental fuel type, it would be relatively simple to swap out diesel generators for ammonia fuel cells and to replace gas turbines that run with DFO with ones that run on ammonia. However, in this case, the challenge becomes the design of the fuel storage tanks as well as the auxiliary equipment to safely handle and transfer this fuel. In the case of a nuclear reactor, the concept of plug and play does not work. A complete redesign of the ship would be required. Reading between the lines of Landmark 2050, it does not seem as though any innovation was anticipated regarding propulsion systems in any of the ships currently being designed to be built under NSS.

It is in the longer-term period (after 2035) that the naval strategy calls for new propulsion and power technologies to be examined as possible candidates to succeed the CSC.[135] The naval strategy specifically favours "all-electric propulsion" as the primary candidate for green

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[134] Martin, R.L. "The High Price of Efficiency" 2019.
[135] RCN. "Leadmark 2050" 2016.

propulsion without providing any specificity or definitions.[136] There are many ways to build an all-electric ship. One could argue that a ship that produces electricity via a diesel engine is all electric. However, in the context of environmental compliance, it should be inferred that the all-electric solution proposed in the strategy would be a combination of carbon-neutral electricity generation combined with an electric drive train. This would mean that the all-electric option would likely be comprised of a combination of lithium-ion batteries and fuel cells (hydrogen and/or ammonia) but a small modular nuclear generator should not be ruled out. At the time this strategic document was developed (2016), it may not have been known that ammonia-fuelled gas turbines were in development.[137] However, given how reliable gas turbines have been for naval applications for both their power output and their responsiveness, the option of an ammonia gas turbine and fuel cell hybrid configuration should not be ruled out. Another longer-term requirement specified in Leadmark 2050 is that air-independent propulsion would be a key capability to consider for submarines.[138] Out of the three top contenders for green propulsion named by the IEA, only nuclear reactors or fuel cells would meet this criterion given that ammonia combustion is air dependent.

If by the end of delivery of CSC, NSS manages to prove its worth and gain favour with Canadians, it can be assumed that from 2040 onward, combat ships would continue to be built at a rate of one per year and the ships would be effectively retired after a service life of 30 years. In terms of the IMO 2070 net-zero target, any RCN ship built from 2040 onward must absolutely operate using a carbon free propulsion system if its designed service life is projected to reach 2070 and beyond. This means that of the "up to 15" CSC ships that are being planned, any ship

[136] RCN. "Leadmark 2050" 2016.
[137] Argus. "Mitsubishi developing ammonia-fired gas turbine" 2021.
[138] Ibid.

built from 2040 onward must be fitted with a green propulsion system. Therefore, either a compatible green propulsion system would have to be developed for the last batch of CSC platforms or that the total number of CSC ships would have to be capped to allow the introduction of a new green surface combatant design from 2040 onward. This constraint is the minimum requirement to achieve compliance with stated IMO climate targets. This is without even considering the strategic vision to move "beyond compliance" and be recognized as a global leader as stated in the Defence Environmental Strategy.[139]

While achieving 2050 IMO targets are extremely unlikely based on the RCN force development plan and the capital acquisitions currently being pursued, the 2070 IMO targets remain within reach. Slippage in the delivery timelines of the assets factored in the pre-2035 FD window introduces additional risks to achieve sufficient progress towards environmental compliance. It is of outmost importance that the stated plan to introduce new propulsion and power technologies from 2035 onward is not delayed because if even a single asset remaining in service in 2070 generates greenhouse gases, then achieving net-zero becomes impossible.

Innovation Opportunities

While a roadmap to replace major surface combatants over the next 20 years is well developed, the exact mix of vessels to support domestic operations, forward-deployed continental and international operations, and any contingencies such as task groups remains largely undefined.[140] Operational research assesses that the RCN requires a mix of at least 25 total combatants supplemented by 3 auxiliary support ships and an unspecified number of submarines to fulfill its mandate.[141] Given that 12 to 15 CSCs, 6 AOPS, and 2 JSS are expected

[139] National Defense. "Defense Environmental Strategy" 2021
[140] RCN. "Leadmark 2050" 2016.
[141] Ibid.

to come from the current NSS contract, it can be deduced that the next capital acquisition projects to be initiated by the RCN will be for a submarine capability to replace the Victoria Class and for additional minor warships to replace the Kingston Class. These potential future projects represent the perfect opportunity to experiment with promising carbon-free propulsion technologies.

In the case of a future submarine, several possibilities exist. To date, every Canadian submarine was acquired from one of our allies. Submarines are not considered part of the NSS, therefore this acquisition strategy remains viable. Canada's first submarine, HMCS Grilse, was supplied by the US Navy in 1961 and both the Oberon and Victoria Class submarines were supplied by the Royal Navy in 1962 and 1998, respectively. All these submarines have been diesel electric. Given that most of our allies have mostly invested in nuclear submarines, Canada's contribution of smaller electric submarines to naval operations is welcomed by allies given the complementary capability of these assets, especially in littoral environments.

One of the most logical leaps to transition from current capabilities to green propulsion systems would be to simply introduce a hydrogen fuel cell in lieu of most batteries into a diesel electric submarine.[142] In this design, the submarine runs on an electric drive that is powered either by a diesel generator or by a hydrogen fuel cell. One of the key advantages of this design concept is that it can operate in ultra-quiet mode for 14 consecutive days.[143] This is a significant endurance gain compared to any battery option. The downside of this concept is that the maximum speed based on a 600kW fuel cell is limited to 8 knots.[144]

If speed is considered an important factor, another interesting design concept is a Royal

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[142] Brighton, D.R. et al. "Fuel cells to enhance underwater performance of diesel electric submarines" 1994.
[143] Ibid.
[144] Ibid.

Navy hybrid nuclear/fuel-cell submarine that can operate extremely quietly for 7 consecutive days at an average speed of 6 knots on fuel cells yet retains the capability to conduct high-speed transits with the nuclear reactor when called upon.[145] Study of this design concept makes a strong case that the next generation of naval nuclear power plants are heading in the direction of low shut down power and increased passive safety which makes it ideal for an operational scenario when quickly alternating between speed and stealth modes is appealing.[146] Also, given current speed limitations of fuel cell technology, acquiring such a capability from an ally allows the RCN to test and assess sustainment requirements of naval nuclear capability to position itself to be a more informed customer during future procurements if such a capability were to be sought. No other green propulsion technology offers the same power output or power density as nuclear, by a significant margin. If transit speed is a capability that the RCN considers important, taking a first step towards this type of technology would strategically position the CAF to have more confidence in subsequent acquisitions.

There is no shortage of other potential configurations that could be utilized to create a submarine with the desired attributes. If the aim is to stay within the confines of an all-electric submarine, the use of hydrolysis of coarse-dispersed aluminum powder to enable continuous production of hydrogen via hydrolysis is interesting.[147] Given that hydrogen has a better specific density by weight than by volume, a submarine is somewhat limited in range by how much fuel it can carry. Technologies that enable hydrogen production from sea water hold the potential to increase the range of a boat to the point that fuel is no longer the limiting factor.

Other than submarines, the RCN will require coastal defense vessels with mine

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145 Goodenough, R.H. and Greig, A. "Hybrid Nuclear/Fuel-Cell Submarine" 2008.
146 Ibid.
147 Nikiforov, B.V. and Chigarev, A.V. "Problems of designing fuel cell power plants for submarines" 2011.

countermeasure capabilities to replace the Kingston Class. These vessels would become excellent test platforms for hydrogen or ammonia powered technologies because they are significantly smaller in scale than a major surface combatant which make them an excellent candidate for proof of concept during a stage in which the supply and fuelling infrastructure are still in development. As coastal defense vessels operate in littoral waters, these platforms would be able to test core components of these technologies such as storage, transport, and usage while some more ambitious aspects of these emerging technologies such as production, replenishment, and range are still being developed. Additionally, given that minor warships' employment profiles are often single ship operations, green propulsion systems could be tested independently of what standards are being developed by NATO allies.

The topic of NATO is of great significance in discussion of green propulsion technologies. Any vessel operating in a task group environment must be compatible with replenishment vessels from allied nations. Unfortunately, NATO's stance on environmental compliance is not as ambitious as Canada's stated Defence Environmental Strategy. NATO's policy states that forces "must strive to respect environmental principles and policies under all conditions".[148] There is a significant gap between striving to respect principles and attempting to be recognized as a leader that moves beyond mere compliance. This gap can either be considered a challenge or an opportunity. Within NATO, no country has overtly committed itself to meeting any of IMO environmental targets. Much like it set itself as a leader in anti-submarine warfare and in platform control systems, Canada would have an opportunity to position itself as a leader in environmentally compliant propulsion systems. That said, Canada would do well to actively participate in NATO environmental committees to ensure that

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[148] NATO. "Environment – NATO's stake" 2020.

whatever answer remains compatible with its multiple allies.

Investing in green propulsion technologies cannot be an isolated RCN endeavor. With an aimed fleet size of two dozen major warships, a few submarines and a handful of minor warships, the total investment in these technologies is not self-justified. Any investment by Canadian taxpayers into the development of these technologies and infrastructure to support them must also provide benefits and opportunities for the Canadian marine industry and complement other government departments. Canada is not the only nation aiming to reduce greenhouse gas emissions and fossil fuel dependency. If investments lead to innovations that provide competitive solutions on the global scale, export opportunities and value proposition shall abound. Likewise, if other nations are willing to cooperate in pursuit of these technologies, mutually beneficial opportunities should be leveraged to maximum effect.

The IEA sees hydrogen as playing a key role in a clean, secure, and affordable energy future.[149] It forecasts that industrial port cities will be the nerve centres for scaling up the use of clean hydrogen.[150] Port cities are hubs not only for ships but also for long range ground transport. DND is a significant stakeholder in areas in which it operates a port such as Halifax, Esquimalt, and Nanisivik. Establishing infrastructure to produce, transport, and store hydrogen in these areas would provide potential benefits to several stakeholders beyond just the navy. DND could take a lesson from the example provided by the Ministry of Natural Resources in establishing its SMR action plan to bring together various stakeholders from academia, industry, government, and community groups. Pursuit of green propulsion solutions is bigger than the RCN and likely requires a commensurate pan-Canadian strategy with multiple stakeholders to realize maximal benefits.

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[149] IEA. "The Future of Hydrogen" 2019.
[150] Ibid.

What is not yet clear is whether one green propulsion technology will dominate the future market or whether different technologies will each find their niche. Much like the energy sector is diversifying its portfolio among nuclear, hydro, geothermal, wind, solar, and natural gas, it would also make sense to pursue multiple green propulsion options. Fuel cell technology provides significant advantages for quiet operation but are currently limited by how much power output they can generate. Ammonia presents itself as a versatile DFO replacement that can be used either in fuel cells or gas turbines but storage and handling standards, although existent in industry, remain completely foreign to the RCN. Finally, nuclear reactors remain a heavily tested and proven technology that offers significant power with limitless range but comes with multiple regulatory requirements and has no Canadian naval precedent to use as a starting point.

Ultimately, there is no actual requirement for Canada to invest in building its own industry for any of these technologies. None of the propulsion technologies used in any RCN warship today comes from a Canadian company. General Electric is American, MAN Diesel is German, and Wartsila is Finnish. This said, the opportunity to create the requisite infrastructure to produce a capability that is likely to be used by stakeholders around the world should not be easily dismissed. Much like the SMR action plan attracted international industrial partners to set footholds in Canada, investments in green propulsion technologies could easily do the same.

CONCLUSION

Whether the RCN could leverage innovations in the Canadian energy sector in pursuit of green propulsion solutions depends upon the Canadian nuclear industry. While Canada has a long and rich history of developing and utilizing non-weapon applications for nuclear energy, the past few decades have experienced a bit of a lull. Canadians can be extremely proud of the development and utilization of its CANDU reactor technology that has operated safely and reliably for many decades in multiple reactors located across the world. However, Canada's energy future is currently focused on development of small modular fourth generation reactors to provide a baseload as well as energy storage to complement the increasing number of intermittent renewables forming the total energy blend. The first Canadian SMRs are expected to be functional within the next 5 years and could potentially start feeding the power grid as early as 2028. Although the first models in development remain too large for naval applications, several innovative concepts on the horizon could be suitable for shipboard use. Independently from direct usage of nuclear reactors, among the most appealing features of Canada's SMR Action plan is additional capability to effectively produce clean hydrogen and ammonia through the high-quality steam and high temperatures of these fourth-generation nuclear reactors.

The direct and indirect outputs of Canada's SMR Action Plan are in perfect alignment with the OECD predictions of what maritime propulsion will look like in 2070 if the IMO environmental targets are to be reached. Amongst existing and emerging maritime and naval green propulsion technologies, the top contenders are nuclear, hydrogen, and ammonia. The nuclear reactor option has two avenues. The first is the traditional, proven, and tested use of highly enriched uranium to fuel PWRs. Every navy using a nuclear-powered vessel today deploys this technology. Such technology would be prohibitive for use in the RCN because of smaller size ships and because Canada's present nuclear policy eschews weapon grade enrichment of uranium. Emerging technology that has potential to revolutionize both power and propulsion plants in the navy is the development of cargo container sized SMR reactors. Although theoretically promising, proof of concept remains at least several years away which eliminates it as an immediate option for the next acquisition projects but remains interesting for later long-term projects.

The most easily implementable green propulsion technologies for future vessels after CSC is a combination of either hydrogen or ammonia fuel cells and ammonia-fired gas turbines. Given recent trends towards either all-electric ships or electric and gas turbine hybrids, these technologies provide the easiest institutional transitions because they are compatible with all other shipboard equipment in a CODLAG ship. A hydrogen ship would be all-electric and ultra-quiet. A small vessel is currently limited to transit speeds of approximately 8 knots with fuel cell technology. However, companies such as Ballard are already developing fuel cell stacks that produce 10 times more power, which would translate to faster cruise speeds. Until fuel cell technologies increase total capacity, this technology would be limited to slow moving silent vessels such as mine countermeasure vessels and small submarines.

An ammonia ship would have similar operating parameters as a hybrid diesel-electric or gas turbine vessel. Ammonia is a transitory fuel that could be most easily implemented in the near term with the smallest overall impact to current operations. Safe ammonia storage is more complex than DFO. However, industry standards and procedures already exist to mitigate these additional risks. Until SMRs produce a viable system that can provide power to vessels used by the RCN (frigates, submarines and patrol vessels), Ammonia remains the top contender to produce green propulsion for warships used by the RCN with higher speed demands such as frigates. Ultimately, there is no reason for the RCN to go all-in on any one of these green propulsion systems given that they each have their own complementary niche.

Contrasting availability of emerging technologies with the RCN's Force Development plan reveals that the next opportunities to acquire a green propulsion solution will be for either the next submarine to replace the Victoria Class or for a minor warship to replace the Kingston Class. In any case, given that they are each a smaller platform, the option to go either towards an all-electric solution or an ammonia electric/gas turbine hybrid solution are both relatively simple to implement compared to alternative solutions. Considering that it takes at least 15 years to acquire a vessel from initial concept to commissioning and that these warships can reasonably be expected to operate for at least 30 years, the RCN must immediately recognize that choices made in the imminent future significantly impact the institution's ability to make any progress towards the IMO's 2050 and 2070 environmental targets.

While DND's capital budgets play an important role in creating room for innovation and creating industrial benefits and value proposition, it should be recognized that the effort is but a small part to combat climate change. Canada's energy sector's SMR Action Plan is an excellent example of how government, academia, industry, and social groups can work together toward a common goal. Furthermore, the more recent Hydrogen Strategy creates links between the energy and transport sectors. The time has come for DND to work with other government departments to align its capital acquisition plans with other pan-Canadian efforts. Infrastructure required to support any green propulsion initiative should parallel other efforts in the energy and transport sectors. Whether by creating a new pan-Canadian maritime sector action plan or by adding DND as a stakeholder in the existing SMR Action Plan and Hydrogen Strategy is less significant than the acknowledgement that under the current environmental strategy, the RCN will likely not realize its stated vision.

The RCN should decide whether to be a world leader going beyond compliance in the environmental domain. On one hand, it can stand up as a potential key stakeholder and find ways that current and future projects could complement those in the energy and transport sectors to make actual progress toward decarbonizing the RCN and the maritime industry. On the other hand, incremental efficiencies generated through SEMS combined with minor innovations projects will likely neither reduce nor eliminate carbon emissions to a sufficient degree. Perhaps waiting for others to find technological solutions to decarbonize propulsion systems is a viable strategy. Whatever the chosen course of action, the RCN must remain cognizant of the vision statement in the Defence Environmental Strategy as it moves forward on a greener path.

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