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ELECTRICAL PROPULSION: THE FUTURE IN WARSHIP PROPULSION

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ELECTRICAL PROPULSION: THE FUTURE IN WARSHIP PROPULSION

AIM

1. This service paper is presented as an information piece for consideration by Commodore Wood, the Project Manager of the Canadian Surface Combatant project. The aim of this paper is to advise on the latest marine propulsion topologies that could be designed into the Royal Canadian Navy's future surface combatant. The paper recommends that the Canadian Surface Combatant (CSC) project's contractual documents clearly specify a need for this next generation of Royal Canadian Navy's warships to be designed with a Hybrid Electric Propulsion system.

INTRODUCTION

2. The Government has initiated an extensive $32B ship renewal program for the Royal Canadian Navy. The program includes the Canadian Surface Combatant (CSC) project that will "replace the Royal Canadian Navy's Iroquois-class destroyers and the Halifax-class frigates."[1] The project must select the best solution to meet the specified operational requirements, be procured within a determined funding ($26.2B), while minimizing the new fleet's Through Life Cost (TLC).

3. The cost of operating a ship through life can be broken into four cost categories (ignoring research & development as well as disposal): procurement, personnel, fuel, and operation and support (O&S). D.W. Elmendorf produced an analysis of the TLC of four classes of US Navy ships in order to provide the US Senate with a context to assess the cost of the new Littoral Combat Ships. [2] Similar data was extracted from various Canadian Naval analyses and used to

[1] Public Works and Government Services Canada, "National Shipbuilding Procurement Strategy," last accessed on 02 February 2016, http://www.tpsgc-pwgsc.gc.ca/app-acq/amd-dp/mer-sea/snac-nsps/index-eng.html.

[2] Douglas Elmendorf,. *"Life-Cycle Costs of Selected Navy Ships*", Congressional Budget Office Cost Analysis. Washington, Congressional Budget Office, www.cbo.gov, April 28, 2010.

plot Figure 1. This service paper will highlight the inefficiencies of conventional marine propulsion topologies, present the benefits and challenges of an electric propulsion system, and finally offer that a Hybrid Electric Propulsion System would be the perfect balance to achieve an efficient and cost effective propulsion system.

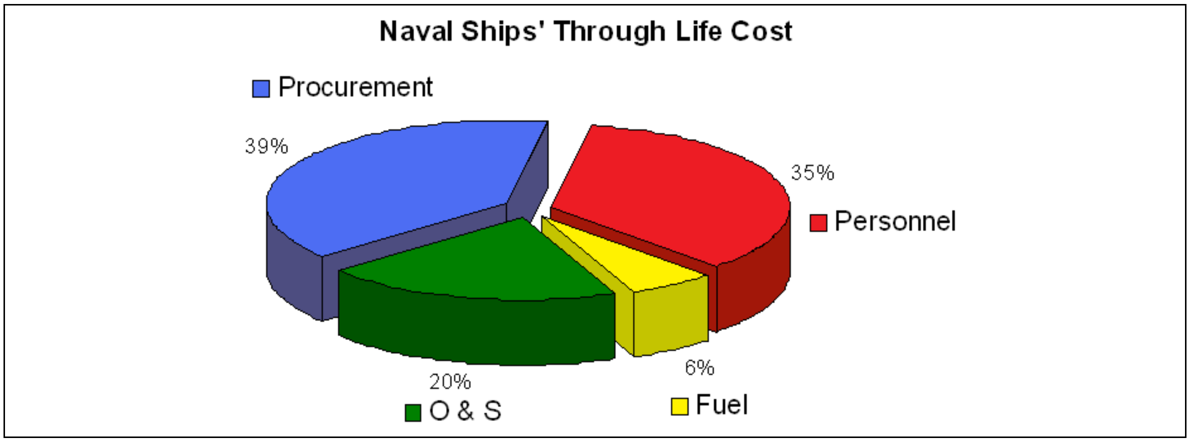

Figure 1 -- Cost of warship ownership, based on US and Canadian Navy Data

DISCUSSION

Conventional Marine Propulsion

4. The majority of current and planned "warships use mechanical transmission where the prime movers drive a gearbox, which in turn powers the shaft and propeller"[3].They are so prevalent that seven of eleven potential Design Reference Points identified for the CSC project use a conventional propulsion system[4]. These systems offer great flexibility and practicality, but navies have observed significant opportunities for improvements, notably:

a. Efficiency: Conventional propulsion systems are "95% efficient at full power"[5], but warships are rarely operated in a manner maximising fuel efficiencies. Conventional

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[3] C. Hodge and D. Mattick, "*The Electric Warship*", Trans IMarE, Vol 108, Part 2, 1995, 109.
[4] A.J. Snell and Brian Michalchuk "Analysis of contemporary warship operating profiles against Canadian Surface Combatant statement of requirements", 2015, 10.
[5] Hodge, "*The Electric Warship"*, 109

propulsion systems would typically be designed for two specific speeds (cruising and full power), but the nature of naval operations demands frequent manoeuvring and results in operations at various speeds. Furthermore, research has demonstrated that warships operate a significant portion of their missions loitering at very low speeds: see Figure 2 for the German Navy's analysis of its speed profiles as an example.[6] Conventional propulsion systems are not able to sustain efficient operations in such wide ranges of speed. Improving the ability for the engines to use a greater amount of the fuel's energy, through the entire range of speeds, would significantly improve ship efficiencies and reduce cost of operations.

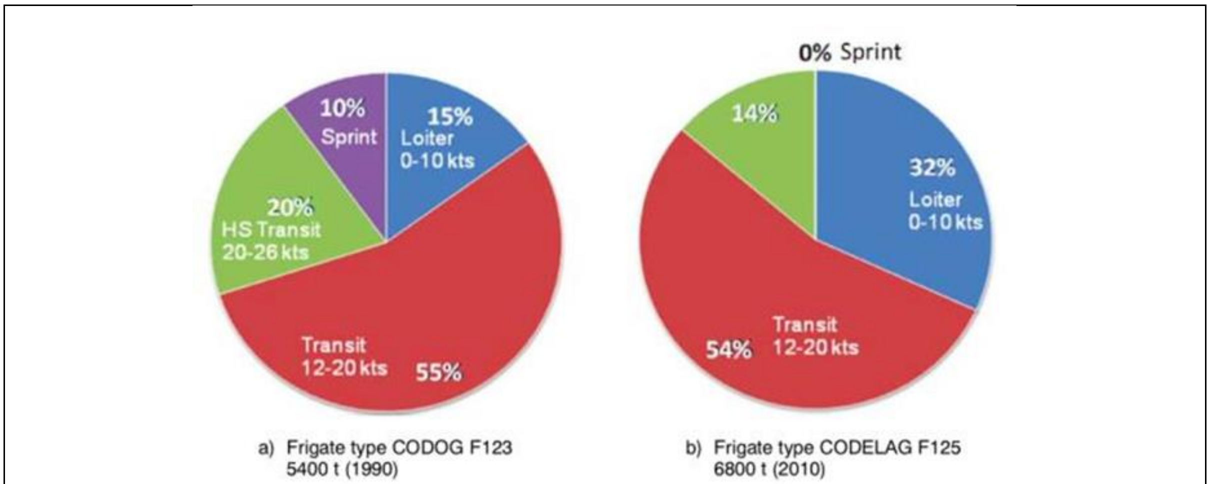

Figure 2 -- German Warship Speed Profiles

Source: B. Pinnekamp, F. Hoppe, M. Heger, "*Combined Marine Propulsion Systems: Optimization and Validation by Simulation*", American Gear Manufacturers Association, Alexandria, ISBN 978-1-61481-039-1

b. <u>Maintenance</u>: The cost of maintaining the Canadian frigates is obviously significant and is closely monitored by the Naval Administration. The Department of National Defence evaluates the Halifax Class Frigates maintenance cost to be $150 million

[6] B. Pinnekamp, F. Hoppe, M. Heger, "*Combined Marine Propulsion Systems: Optimization and Validation by Simulation"*, American Gear Manufacturers Association, Alexandria, ISBN 978-1-61481-039-1, 2012, 5. Canada and the US have conducted similar analysis resulting in congruent results.

per year, excluding the additional $360[7] million Mid-Life Refit per ship required to keep them relevant for the next 15 years. The inefficient operation of the propulsion engines outside of their designed speeds significantly contributes to the maintenance issues: "the typical [naval] ship spends more than 90% of its life below 60% load."[8] The partial and low loading of the propulsion engines causes premature degradation and breakdown, resulting in losses of operational time as well as repair costs.

5. Conventional propulsion topologies have been the preferred solution for warships of the past generation. These systems proved effective and flexible, but navies around the world have experienced significant financial and operational costs as their propulsion systems are not able to efficiently suit their missions' operating profile. The United States and United Kingdom, amongst others, have identified the electric propulsion as the solution to these important inadequacies.

Integrated Full Electric Propulsion

6. The most significant propulsion system innovations revolve around the Integrated Fully Electric Propulsion (IFEP) concept. It is widely accepted, as noted by Casson, that electric propulsion brings together efficiency, flexibility, survivability and reduction in cost of ownership.[9] These advantages are the results of two major improvements compared to a conventional propulsion system: efficient ship layout and efficient engine loading.

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[7] National Defence and the Canadian Armed Forces, "Halifax-Class Modernization (HCM) / Frigate Life Extension (FELEX)," last accessed 06 February 2016, http://www.forces.gc.ca/en/news/article.page?doc=halifax-class-modernization-hcm-frigate-life-extension-felex/hkm9beb0.

[8] Gene Castles et al., "*Economic Benefits of Hybrid Propulsion for Naval Ships",* IEEE, 2009, 516.

[9] P. Casson, "*Power and Propulsion for the New Global Combatant*", Royal Institution of Naval Architects, 2006.

7. The naval architect of an electric propulsion ship is freed of the *tyranny of the shaftline*[10]. The machinery can be effectively distributed through the ship to improve redundancy, weight distribution, intake and exhaust routing, as well as maintenance and access routes. These improvements also benefit stability, survivability, habitability, damage control, and overall crew effectiveness. These advantages to the ship layout are worthy, especially in consideration with the significantly improved efficiency of the propulsion system.

8. An IFEP system allows for the entire ship's electrical load (ancillary and auxiliary equipment, hotel services, as well as combat, command, communication and aviation systems) to come from the same source as that of the propulsion system,[11] see Figure 3. The elimination of the requirement for a separate power generation capability provides saving in both preventive and corrective maintenance efforts as well as procurement and support cost.

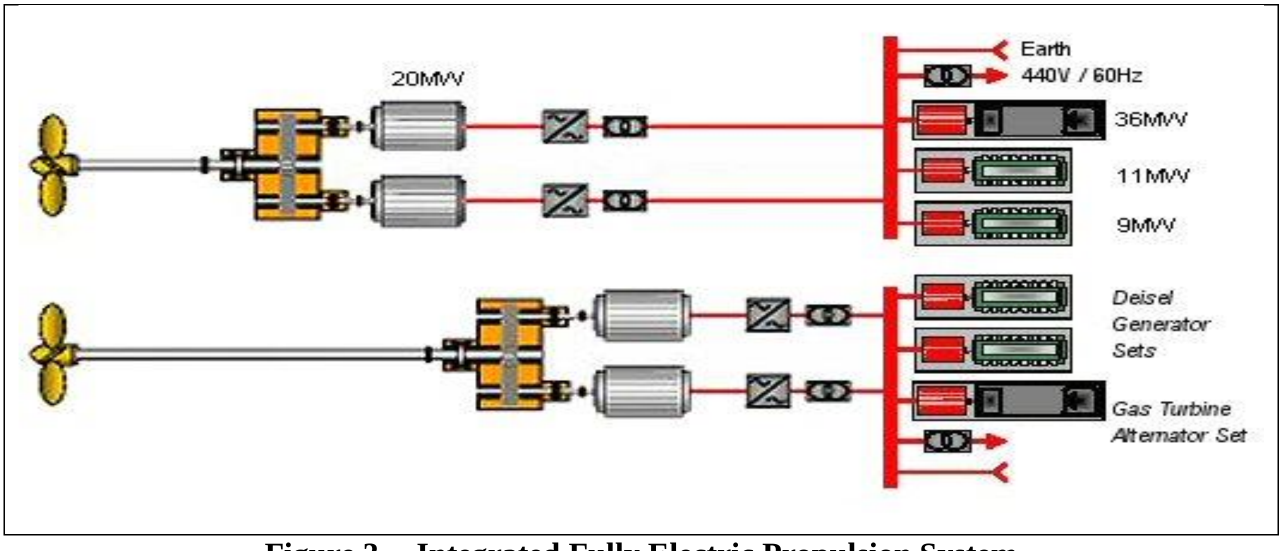

Figure 3 -- Integrated Fully Electric Propulsion System
Source: http://navy-matters.beedall.com/cvf6.htm. last accessed via archives on 02 Feb 2016

[10] Tyranny of the shaftline is the curse of the Naval Architect. Conventional Propulsion Topology requires the placement of the main engines in the middle of the ship in order to accommodate their size and weight. This results in a cumbersome shaftline that must traverse many compartments in order to join the engine to the propeller.

[11] Edward Lundquist, "*Navy and Industry Pursuing New Power and Propulsion Methods",* s.l. : The WSTIAC Quarterly. Vol. 9, 1.

9. The combination of the entire power demands of the ship (electrical and propulsive) into one system allows for a far more efficient management of prime movers. The ship will be able to select an efficient combination of generators for a given operational scenario: ie selecting a minimum amount of engine being operated as close as possible to their designed nominal power. This will result in increases to system efficiency and reduced maintenance requirements[12], which could translate into reduced manning requirements. Analyses have shown that using the engines closer to their design power output could result in fuel savings of 15 to 19% for a surface combatant.[13]

10. IFEP ships possess an enormous additional amount of power, which would otherwise only be available for propulsion. This provides two important advantages: no more need for growth margin on the electrical system, and the opportunity for more powerful weapons and sensors to be implemented. Furthermore, because IFEP ships will be more efficient, they will require fewer sailors to crew them. For example, the new US Navy DD(X) will require fewer than 100 people, while other destroyers are normally manned by 300 sailors.[14]

11. Unfortunately, the IFEP system may not suit every application, which is partly due to the immaturity of the technology: motors have poor power densities and have significantly reduced efficiencies at lower speeds, which negate their fuel consumption advantage when compared to partially loaded diesel engines.[15] Consequently, IFEP ships currently in operations are not indicating the expected fuel efficiency improvements. Finally, it has been reported that

[12] Stuart C. Karon, "*Optimal Electrical Ship Propulsion Solution*", s.l. : Marine Reporter. 2002.
[13] Ronald O'Rouke, "*Navy Ship Propulsion Technologies: Options for Reducing Oil Use - Options for Congress*", Congress Research Service, December 11, 2006.
[14] Sharon Berry, "*Electricity work to unlock power shipwide*", AFCEA, 2002.
[15] Stuart C. Karon, "*Optimal Electrical Ship Propulsion Solution*", s.l. : Marine Reporter. 2002.

shipbuilder's flexibility in locating the IFEP equipment is very limited and counters the "flexibility in ship layout" argument.[16] Casson concluded that due to the IFEP equipment volume requirements, it was impossible to fit electric propulsion, and achieve a maximum speed of 26 knots, into a surface combatant of less than 6000 tonnes[17]; this would mean an exponentially bigger ship to provide a maximum speed of 30knots.

12. The IFEP ship is evidently the future of warship propulsion. An integrated fully electric propulsion ship will provide such improvements as greater flexibility in ship layout, increased available electrical power, increased prime mover efficiency, improved fuel consumption, improved system reliability, and reduced manning. These benefits will further translate in increased time on station. Unfortunately, the poor power density of current high power motors and very high procurement costs are significant factors preventing new ship design to adopt an IFEP system. The solution is however, not to remain with the archaic conventional propulsion topology but to elect a Hybrid Electric Propulsion system.

Hybrid Electric Propulsion

13. The hybrid electric drive topology provides the ability of using smaller engines to generate power for the electrical motors to propel the ship at loitering and cruising speeds, while only engaging the larger propulsion engines in direct drive mode to operate at the higher speeds. "The use of hybrid electric drive systems for naval vessels is an appealing concept for the fuel savings at low ship speeds, and has been implemented and demonstrated on [various warships]."[18] These

[16] *Ibid.*
[17] *Ibid.*
[18] James Langston et al., "*System Studies for a Bi-Directional Advanced Hybrid Drive System (AHDS) for application on a Future Surface Combatant"*, IEEE, 2013. 509

topologies offer considerable fuel savings when compared to a conventional topology.[19] The concept also allows for the option for the main propulsion engine(s) to generate electrical power as well as to propel the ship. This provides additional power that can be used for advanced weapon systems and sensors requiring large amount of electrical power (Figure 4).

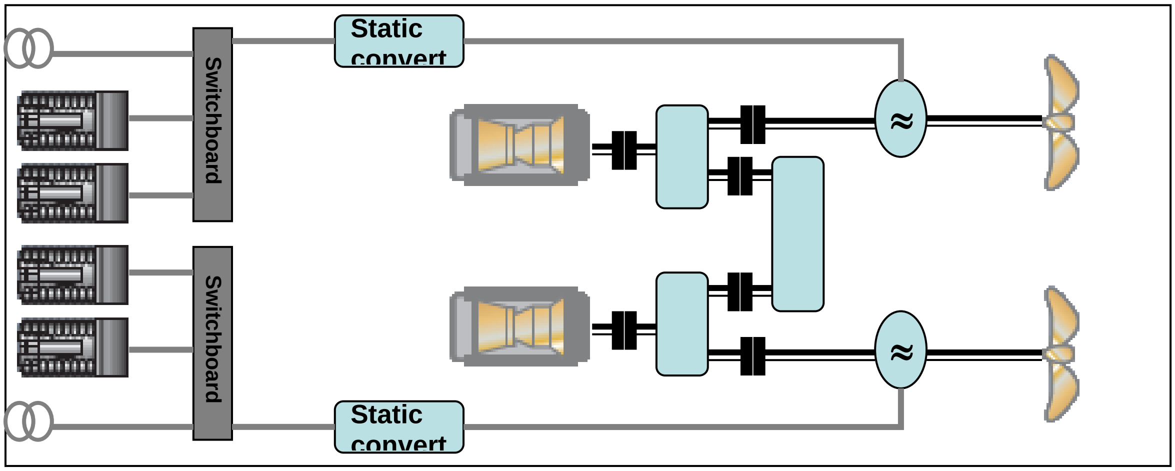

Figure 4 -- Hybrid Electric Propulsion System Configuration

14. The hybrid propulsion topology doesn't offer the reduced manning, stability, survivability advantages of a fully electric ship, but it does provides an improved efficiency through a full warship operating profile. This provides significant cost savings in both fuel and maintenance, while the increased available power offers opportunities for technology insertions/upgrades through the life of the vessel. Consequently, the hybrid system has long been the preferred solution for the future Canadian Surface Combatant project.[20]

15. For Canada, the current CSC procurement strategy may result in the selection of a ship design that includes a conventional propulsion system: most of the identified potential Design Reference Points have a mechanical direct drive propulsion system. The cost effective option,

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[19] *Ibid.*

[20] R. McCallum and L. Mischke, "*Canadian Surface Combatant Power and Propulsion System Option Analysis Paper*", 2009.

from a procurement and design perspective, will be to maintain the ship propulsion as is instead of redesigning the ship to a hybrid electric system. This decision, to accept a conventional propulsion system, would have significant negative implications on the TLC of this future fleet: high fuel cost, excessive maintenance costs, operational availability limitations. The advantages of a hybrid system are so significant that the US Navy is investigating the feasibility of retrofitting the DDG-51 Arleigh-Burke class' conventional propulsion to a hybrid system. This initiative could be leveraged by Canada to investigate the feasibility of redesigning the selected Design Reference Point to a hybrid electric propulsion system.

Retrofitting

16. The US Navy would like to lower the DDG-51's operating costs, "especially fuel use."[21] It is also concerned with the fact that the "destroyers are having trouble generating enough power [to be able] to receive new radars."[22] The solution would be a new version of the DDG-51 with an IFEP systems, but "previous studies have shown that installation of an [IFEP system] in an existing ship is cost prohibitive due to the very large installation costs. The hybrid electrical systems would be far less intrusive than an IFEP system, and could therefore be a viable solution to improve the efficiency of an existing ship.[23]

17. Doyle and Clayton[24] have proposed the option of adding an electric motor to the DDG-51 main reduction gearbox, while McCoy[25] examined the option of "direct drive low speed and

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[21] Defense Industry Daily staff, "*US Destroyers Get a HED: More Power to Them!",* 2012, last accessed 02 February 2016, www.defenseindustrydaily.com.

[22] *Ibid.*

[23] Timothy McCoy et al., "*Hybrid Electric Drive for DDG-51 Class Destroyers",* American Society of Naval Engineers, Vol 2, 2007, 83

[24] T Dalton and D. Clayton, "*Propulsion cross-connect on DDG-51",* ASNE Advanced Naval Propulsion Symposium, Oct 2006

[25] Timothy McCoy et al., "*Hybrid Electric Drive for DDG-51 Class Destroyers",* 83

geared motors attached to the main propulsion shafts."[26] Both of these modifications would offer significant fuel savings as well as long term reduction in maintenance efforts. They would however, be challenging to implement due to various constraints. Doyle's option of installing a motor to the existing gearbox may not be cost effective as it would require requalification of the gearbox "to various military specifications if it is modified in any way."[27] The most significant challenge for McCoy's option would be the available space as the retrofitting is restricted by the current ship configuration and equipment layout. McCoy however, investigated his option of a shaft-mounted-motor and was able to find reasonable space to accommodate a workable solution. [28] There is also the fact that "refits dealing with propulsion systems tend to be expensive, because the builder usually has to cut into the hull to move engines around, etc…"[29] These concerns are not as applicable to a ship in design and not yet built: "for new ships, like the notional DDG-51 Flight III, a [hybrid] approach could be [incorporated into a revised design and] installed during construction."[30]

18. The challenges being faced in modifying an existing variant of the DDG-51 to hybrid electric propulsion are significantly more difficult than those of a Warship Designer altering its Design Reference Point. Canada will not be purchasing an existing ship; it will be evolving a design to address various requirements specific to the Royal Canadian Navy. It will include newer systems and different standards that will require significant design efforts and result in notable changes to the ship design. There would not be significant increase in complexity in the design effort in including a propulsion conversion to a hybrid electric system. The option to

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[26] *Ibid.*
[27] *Ibid.*
[28] *Ibid.*
[29] Defense Industry Daily staff, "*US Destroyers Get a HED: More Power to Them!"* 2012, last accessed 02 February 2016, www.defenseindustrydaily.com..
[30] *Ibid.*

convert the propulsion system should at the very least be subject to a thorough feasibility study and a Through Life Cost analysis.

CONCLUSION

19. Conventional propulsion topologies have been the preferred solution for warships of the past generation. These systems proved effective and flexible, but navies around the world have experienced significant financial and operational costs as their platforms are not able to efficiently suit their missions' operating profile. The United States and United Kingdom, amongst others, have identified the electric propulsion as the solution to these important inadequacies.

20. An Integrated Fully Electric Propulsion ship would provide improvements such as greater flexibility in ship layout, increased available electrical power, increased prime mover efficiency, improved fuel consumption, improved system reliability, and reduced manning. These benefits will further translate in increased time on station. Unfortunately, the technology has not yet matured enough to make the IFEP ship a truly viable and cost effective solution.

21. The values and advantages of a hybrid system are well understood and it has long been the preferred solution for the future Canadian Surface Combatant project.[31] The hybrid propulsion topology doesn't offer the reduced manning, stability, survivability advantages of a fully electric ship, but it does provide an improved efficiency through a full warship operating profile; this offers significant cost savings in both fuel and maintenance. The hybrid system also increases the available power to afford opportunities for technology insertions/upgrades of energy demanding systems through the life of the vessel.

[31] R. McCallum and L. Mischke, "*Canadian Surface Combatant Power and Propulsion System Option Analysis Paper*", 2009.

22. Canada may find itself designing its future warships from a Design Reference Point that unfortunately includes a conventional propulsion topology. The procurement strategy however, includes a design phase to ensure that the CSC solution will meet specific requirements of the Royal Canadian Navy. The project can therefore revise the design and conduct a propulsion conversion to a hybrid electric system, thereby providing the RCN with future warships fitted with a significantly more efficient propulsion system. The CSC project's objective must be to procure hybrid electric warships; otherwise, the RCN will be plagued by another 40 years of inefficient and needlessly costly naval operation.

RECOMMENDATION

23. It is recommended that the CSC project's contractual documents clearly specify a requirement for the next generation of Royal Canadian Navy's warships to be designed with a Hybrid Electric Propulsion system. The Statement of Work should include a requirement for a feasibility study and Through Life Cost analysis for the conversion, if required, of the Design Reference Point mechanical propulsion to a hybrid electric system.

BIBLIOGRAPHY

Berry, Sharon. "*Electricity work to unlock power shipwide*", AFCEA, 2002.

Casson, P. "*Power and Propulsion for the New Global Combatant*", Royal Institution of Naval Architects, 2006.

Castles, Gene, G. Reed, A. Bendre and R. Pitsch, "*Economic Benefits of Hybrid Propulsion for Naval Ships",* IEEE, 2009.

Dalton T and D. Clayton. "*Propulsion cross-connect on DDG-51",* ASNE Advanced Naval Propulsion Symposium, Oct 2006

Defense Industry Daily staff, "*US Destroyers Get a HED: More Power to Them!",* 2012, last accessed 02 February 2016, www.defenseindustrydaily.com.

Elmendorf, Douglas W, *"Life-Cycle Costs of Selected Navy Ships*", Congressional Budget Office Cost Analysis. Washington, Congressional Budget Office, www.cbo.gov, April 28, 2010.

Herbst, J.D., S.P. Pish, J.R. Jackson, B. Gully, and A.L. Gottozi. "*Electric Power System Concepts and Pulsed Loads in the DDG-51 Class Ships".* ASNE Day 2013: Engineering America's Maritime Dominance, Arlington, VA, Feb 21-22, 2013.

Hodge, C and D. Mattick, "*The Electric Warship*", Trans IMarE, Vol 108, Part 2, 1995.

Karon, Stuart, C. "*Optimal Electrical Ship Propulsion Solution*", s.l. : Marine Reporter. 2002.

Langston, James, Micheal Andrus, Micheal Steurer, George Robinson, Dwight Alexander, Jeffrey Buck, and Don Wieczenski. "*System Studies for a Bi-Directional Advanced Hybrid Drive System (AHDS) for application on a Future Surface Combatant"*, IEEE, 2013.

Lundquist, Edward. "*Navy and Industry Pursuing New Power and Propulsion Methods",*The WSTIAC Quarterly. Vol. 9.

McCallum, R. and L. Mischke. "*Canadian Surface Combatant Power and Propulsion System Option Analysis Paper*", 2009.

McCoy, Tymothy, Jim Zgluczynski, Niles Johnason, Frederick Puhn and Thomas Martin. "*Hybrid Electric Drive for DDG-51 Class Destroyers"*, American Society of Naval Engineers, Vol 2, 2007.

McCoy, Tymothy. "*Electric Ships: Past, Present and Future".* IEEE Electrification Magazine, June 2015.

Michalopoulos, P., J.M. Prousalidis, G.J. Tsekouras and F.D. Kanellos. "*Comparison of Ship Power Systems from an Optimal Economic Operation Point of View."* IEEE, 2015.

National Defence and the Canadian Armed Forces, "Halifax-Class Modernization (HCM) / Frigate Life Extension (FELEX)." Last accessed 06 February 2016, http://www.forces.gc.ca/en/news/article.page?doc=halifax-class-modernization-hcm-frigate-life-extension-felex/hkm9beb0.

O'Rouke, Ronald. "*Navy Ship Propulsion Technologies: Options for Reducing Oil Use - Options for Congress*", Congress Research Service, December 11, 2006.

Petersen, Lynn, Donald Hoffman, Joseph Borraccini and Steven Swindler. "*Next-Generation Power and Energy: Maybe Not So Next Generation"*, American Society of Naval Engineers, Vol 4, 2010.

Pinnekamp, B., F. Hoppe and M. Heger, "*Combined Marine Propulsion Systems: Optimization and Validation by Simulation"*, American Gear Manufacturers Association, Alexandria, ISBN 978-1-61481-039-1, 2012.

Public Works and Government Services Canada, "National Shipbuilding Procurement Strategy." Last accessed on 02 February 2016, http://www.tpsgc-pwgsc.gc.ca/app-acq/amd-dp/mer-sea/snac-nsps/index-eng.html.

Snell, A.J. and Brian Michalchuk, "Analysis of contemporary warship operating profiles against Canadian Surface Combatant statement of requirements", 2015.