Opportunities for Improved Warship Energy Efficiency: A Canadian Patrol Frigate's Operational Energy Use Patterns

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Opportunities for Improved Warship Energy Efficiency:
A Canadian Patrol Frigate's Operational Energy Use Patterns

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Abstract

This project explores a Canadian warship's propulsion and electrical energy use patterns to define energy baselines and determine if the ship would be able to save energy without compromising mission capability. The study also aims to define the key factors preventing more efficient energy use, and suitable technical and behavioral options to reduce overall mission fuel consumption. The author postulates that improved energy efficiency can coincidentally improve mission, cost and environmental performance.

This study defines a Canadian Patrol Frigate's energy baselines for a single warship between July 2015 and March 2016. HMCS VANCOUVER (VAN) machinery control system and bridge logbook data were combined to define the ship's daily trends for both propulsion and electrical energy, and determine what opportunities were available to meet speed demands, using more efficient engine configurations. The ship's new machinery control system also allowed for real-time data capture of the ship's total electrical power demand, and monitoring of the operating trends of electrical motors that drive the ship's array of pumps and fans. These data, coupled with equipment amperage load-checks, provided an estimate of various system's electrical energy use, both at sea and in port.

During approximately 70% of all operations, VAN would have had favorable engineering, operational and weather conditions to assume the most efficient engine configuration, without degrading mission effectiveness. The ship used an average of 40.6 m^3 of fuel, each of the 71 days at sea, spending the majority of her time at speeds between 10 and 15 knots, and demonstrating a strong tendency to utilize a gas turbine for

slower speeds where the propulsion diesel engine (PDE) would have been most efficient. The study shows that if the ship assumed the most efficient, available drive mode, she could have saved 10% of total fuel without compromising mission capability. These results suggest that over a 15-year timeframe, enough fuel could be saved to send the entire fleet to sea for two years. This analysis highlights the criticality of the ship's PDE, due to its fuel economy when compared to the more powerful, but less efficient gas turbines. The reliability and maintenance shortfalls of the PDE may prevent achievable fuel savings unless the PDE's performance can be improved for more frequent use, especially at lower speeds.

The analysis also defines the baseline electrical energy use patterns of the VAN, which used an average of 961 kW per hour at sea, and 620 kW per hour in harbor. The ship used a quarter of its total energy to supply costly onboard electrical power, to feed the high energy demands of key systems, including chilled water, fireman, air compressors, and machinery space ventilation.

This analysis shows that significant energy savings are possible through the implementation of efficient machinery configurations, improved system maintenance, and the isolation of redundant equipment. However in some cases, these savings would require additional investment for more efficient system performance. The information in this study can be used to support additional, detailed energy assessments of individual systems to identify attractive areas for saving energy and costs, with coincidental benefits to capability, and environmental and reputational performance.

Acknowledgements

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Definition of Terms

Alongside: Naval term meaning in port, or harbor.

Canadian Patrol Frigate (CPF): Multi-purpose frigates introduced into the Royal Canadian Navy (RCN) in the early 1990s, with a displacement of approximately 4700 tonnes, a crew of 170+. Twelve CPFs represent the mainstay of the RCN.

Carbon dioxide (CO_2) and CO_2e: CO_2 is main GHG created from the combustion of fossil fuels. CO_2e is the equivalent emissions measure of the global warming potential (GWP) related to the CO_2 base figure.

Combat capability / combat effectiveness: The measure of a platform or group's war-fighting capability, which includes the its resources (materiel, personnel) and its ability to use those to achieve mission objectives.

Diesel Generator (DG): Diesel engine driven generator for ship's electrical power.

Drive Mode (DM): Propulsion engine configuration (i.e. the 'driving' engine) selected for operations by the ship's captain or bridge watch keeper. Energy Efficiency: For the purposes of this study, the term "energy efficiency" can be defined as the minimum primary energy required to provide a desired service, where "primary energy" is the energy embodied in fossil-fuels prior to any conversion activity (i.e. electrical power generation and fuel combustion). The understanding and application of the classical definitions within the 1st and 2nd laws of thermodynamics may still be used throughout discussions, however, the definition proposed here is helpful for discussing the ways in which energy can be more efficiently managed.

Duty cycle: The percentage of time a system or equipment is in operation.

Energy conservation: The avoided use of energy or the reduction in service outputs to reduce the required energy. This term may be confusing, and perhaps best avoided, since many believe it may only suggest that energy conservation leads to "fewer or lower quality energy services" (Lovins, 2004).

Energy use: While energy can neither be created nor destroyed, "energy use" refers to the conversion of energy into a service, desired or otherwise.

Energy intensity: Energy used per unit of delivered service; sometimes referred to as "energy productivity".

Fully Burdened Cost of Fuel (FBCF): The complete set of costs associated to fuels, including their commodity, delivery and direct/indirect support costs.

Gas Turbine (GT): Single Gas Turbine driving the twin propeller shafts (1GT), or Dual Gas Turbine driving the shafts (2GT).

Greenhouse Gases (GHG): Natural or anthropogenic gases that inhibit the escape of radiant heat from the earth's atmosphere. The most prevalent GHG gases are as follows: water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

Integrated Platform Management System (IPMS): The RCN term for platform machinery control system, which is comprised of hardware and software that monitors, controls and logs data for marine systems throughout the ship.

Operational profile: The percentage operational sea time spent at various speeds, for all engine configurations.

Propulsion Diesel Engine (PDE): SEMT Pielstick 18 Cylinder, diesel propulsion engine, with power of 6.47 MW at outlet shaft. Diesel RCN: Royal Canadian Navy; the marine arm of the Canadian Forces (CF), which is part of the Department of National Defense (DND).

Replenishment At Sea (RAS): At sea, ship to ship re-fueling or materiel transfers.

Total Cost of Ownership (TCO): A term to describe the life-cycle costs of materiel, which includes procurement, operating, maintenance, support and disposal costs, which are all important elements to consider when assessing the equipment's financial, environmental and social performance.

Officer of the Watch (OOW): Bridge watch-keeper that directs the safe and effective movements of the ship, as directed by the ship's captain.

Officer of the Day (OOD): The on-duty officer responsible for the ship's safety and routine while alongside (in port).

Operations Room (Ops Room): The headquarters on board that houses the ship's combat planning and action team, which controls the ship's weapons, sensors and communication equipment.

WUPs: An acronym meaning "Work-Ups", which is a period of training led by shore staff to improve the operational competencies of the crew, normally prior to a mission or deployment.

Chapter I

Introduction

Canadian warships have used an average of 3500 m^3 of marine diesel fuel per year since they were first introduced in the early 1990s, which may represent nearly 10% of a ship's total cost of ownership and a significant through-life environmental impact. Although fuel's importance as a capability enabler is well understood, its associated risks have historically been considered a 'cost of doing business', rather than an area of significant opportunity for improved capability, financial and environmental performance. Beyond only a general understanding of ship and fleet fuel use, very little is known about how the Royal Canadian Navy (RCN) uses fuel and electrical energy, and thus, the naval leadership remain uncertain as how to best optimize fleet energy use without impacting war-fighting capability. The International Maritime Organization (IMO) and other global navies are now mobilizing energy management and conservation efforts, while RCN acquisition and equipment teams are only just beginning to consider energy efficiency in their decision making and require a better understanding of its risks and opportunities.

Royal Canadian Navy (RCN) frigates utilize close to 40 m^3 of marine diesel fuel per day to complete military, humanitarian, sovereignty and peacetime operations. Conserving fuel provides the ship with the operational flexibility, range and persistence required to achieve critical mission objectives, and reduces the vulnerability associated with frequent at-sea replenishments. During peacetime operations, increased fuel efficiency delivers savings that stretch fuel budgets and reduce commodity costs, which can be reinvested into operations, training, equipment, and personnel. Reduced energy wastage decreases equipment hours, noise, and waste-heat, thereby reducing system maintenance burdens, decreasing overhaul frequency, reducing cooling load, and overall engine exhaust emissions.

RCN capability and engineering support teams general understanding of ship and fleet fuel use is derived mainly from engine performance data and monthly fuel logistic reports. Very little else is known about how the CPF uses both fuel and electrical energy, and how improvements may lead to coincidental benefits in capability, cost and environmental performance. An in-depth look at how the class of 12 Canadian Patrol Frigates (CPFs) use energy will help inform design guidelines that hope to optimize the next fleet, which is now in a process of detailed design. While some marine system designers focus on increasing system capacity to meet capability targets, it is perhaps critical to highlight the importance of energy efficiency as an alternative route to service delivery, being the “largest, least expensive, most benign, most quickly deployable, least visible, least understood, and most neglected way to provide energy services” (Lovins, 2004). Amory Lovins, global expert on energy and defense, outlines the importance of efficiency as a veritable energy “source” (ibid) to meet increased demand and/or reduce the associated cost and environmental burdens of fossil fuel consumption.

Improving the energy efficiency of a warship may not be an easy task, as ship’s systems have to accommodate a varied set of mission and global environmental conditions, during both peacetime and in conflict. Warships are already starved for space, and systems are often designed to work only optimally in a combat role. Cramped spaces, and high levels of combat redundancy impose many inefficiencies on system performance, configuration and sizing. These ships were also designed when energy was much cheaper and the cost for the inefficiencies was not as significant as it is today (note: oil was near $10 usd per barrel from 1985-1990 (Energy Information Administration [EIA], 2016)). There may be a tendency to assume that unique military capability and designs prevent fuel savings, or only support incremental change, but the US Navy proves otherwise, having realized a 25% reduction in fuel used per hour of sea operations, as compared to 1999 baselines (i-ENCON, 2011). In Amory Lovins' words, the last time industry and the military saved large sums of energy while increasing capability and improving productivity was in 1975-1985, which was "the last time we paid attention" (Lovins, 2013).

Research Significance and Objectives

This study is an analysis of a Canadian warship's energy use patterns and is a first step in gaining a better understanding of propulsion and electrical energy baselines, and opportunities for improvement. Only through more detailed analysis of system energy use, configuration, and limitations, can the RCN hope to implement meaningful improvements that aim to both reduce energy waste, and improve the capability and resilience of operational platforms.

An in-depth look at how the class of 12 Canadian Patrol Frigates (CPFs) use energy will help develop an understanding of the specific RCN technical and behavioural aspects that contribute to inefficiency. This study aims to capture detailed patterns of at-sea and in-port energy-use to identify trends and define the capability/energy relationships needed to make intelligent technical and operational decisions to optimize the efficiency of both current and future platforms. Detailed system-by-system analysis is deemed beyond the scope of this study, and the various assumptions made during this study represent opportunities for future work and further comprehension of CPF energy use patterns.

Improved warship efficiency will deliver a combination of benefits, including increased operational presence, endurance and range, reduced vulnerability (quieter equipment and less frequent / shorter replenishments), and reduced fuel logistic and force-protection requirements. Reduced platform energy intensity will reduce equipment running time its heat and noise signatures, resulting in less cooling demand and reduced system maintenance. Minimizing harmful engine exhaust emissions will reduce environmental and health risks, especially in areas close to populated regions and sensitive ecosystems. Reducing risk in these key areas clearly demonstrates the navy’s commitment to cost and resource conservation and would strengthen the RCN’s institutional credibility as a responsible and ship owner/operator and sustainability leader within the federal government.

Background

The International Energy Agency (IEA) expects energy efficiency to play a central role in global GHG reductions, estimating that 44% of the required reductions in emissions between 2010 and 2035 will come from gains in efficiency (IEA, 2013). Mckinsey & Company estimate that 23% of increased energy demands in the United States will be met by energy efficiency, instead of additional capacity (Keily, 2010). The UN Environmental Protection agency states that “energy efficiency offers perhaps the greatest potential to greatly reduce the amount of polluting energy needed to achieve current and future development targets" (United Nations Environmental Program (UNEP), 2007).

Dow chemical, the world's second largest chemical company, has reduced its energy use by 40% since 1994, saving \$8.4 billion and 86 million tonnes of CO2e, and enough energy to power California's housing for one year (Prindle, 2010). Other industry players are leveraging the advantage of energy efficiency: IBM has set 4% annual energy savings targets since 1996, achieving 6.1% reductions in 2008 with a \$32.3 million savings (ibid); Toyota surpassed its 2011 targets for a 29% energy reduction per US-made vehicle (compared to 2002) (Toyota, 2014). General Electric is a leader in making business from efficiency, having generated over \$10 of revenue for each dollar of their \$12 billion investments in their techno-environmental "Eco-Imagination" campaign, lowering their own energy use by 34% and \$300 million, since 2004 (General Electric, 2014).

The Importance of Energy Efficiency

There are many cases where the economics of energy efficiency offer compelling, cost-negative investments opportunities, which are cheaper than the cost of energy they save. In 2005, McKinsey provided an initial, comprehensive review of technologies that offer cost-negative CO_2 abatement potential, highlighting the economic advantages of supply-side, energy savings (McKinsey, 2007). Yet, in spite of these attractive benefits, many agencies are not yet investing in energy efficiency, likely due to what McKinsey suggests is efficiency's invisible, fragmented and difficult-to-measure characteristics and benefits. An array of technical, informational, organizational and behavioral barriers play key roles in the manner in which energy is managed, consumed and wasted.

Defense Energy Efficiency

Energy use in defense has been on the rise since 1970, steadily climbing 2.6% per year in the US military due to increased mechanization, expeditionary warfare, protracted supply chains and irregular warfare (Deloitte, 2009). The US DoD is a major institutional energy user, consuming 1.8% of total US petroleum, and thus is highly susceptible to price increases, where a $10 rise in barrel costs raises their annual fuel bill by $1.3 billion (Lovins, 2010). In 2008 the United States Under Secretary of Defense published a report identifying opportunities for reducing the fuel demand of deployed armed forces, and also illuminated barriers to adopting transitions towards an energy-efficient and less energy-dependent military. This report followed a popularized quote from General James Mattis, then the Operation Iraqi Freedom US Marine Corps Commanding Officer, requesting the Science & Technology (S&T) community to “unleash us from the tether of fuel” (Lynn, 2011). His request and the Defense Science Board (DSB) recommendations prioritized the implementation of key performance parameters (KPPs) measuring operational fuel demands and the fully-burdened cost to deliver fuel. These metrics are deemed essential to improve future procurement decisions made in upstream acquisition systems (DSB, 2008). Guided by those recommendations, the US DoD has since implemented a number of initiatives to improve platform and system’s efficiency. Their search for technologies that extract more operational capability per unit of energy is of interest to all defense stakeholders.

A department that values the importance of energy as a resource and capability enabler is better positioned for adaptable, agile and sustained operations, more so than a force that treats energy as it perhaps once was perceived – as an inexpensive and inexhaustible commodity. Treating energy as a strategic asset will more appropriately value the total costs associated with mobility, including the cost paid for in lives. A force that values energy alongside capability will be better positioned to achieve the largest possible effect (‘tooth’) with shortest possible logistics burden (‘tail’). Such a force will deliver suitable and capable platforms and equipment to operators without the burden and risks of waste, heat, pollution, maintenance and resources that otherwise would need to be managed.

In 2001, the USN contracted the completion of their first survey of warship energy-use patterns to determine opportunities for fuel savings. That report identified 20-50% in practical shipboard electrical energy savings and possibly up to 75% reductions with intensive efforts (Lovins et al., 2001). These compelling findings have since helped define USN programs for behavioral and technical improvements, and supported investments in efficiency. US government estimates suggest that up to one quarter of future energy demand in the USA will be met by advances in energy efficiency, at a net-cost savings (Grenade et al., 2009). Government and commercial industry programs are recognizing energy efficiency as a key enabler for reducing costs and enhancing competitive advantage. The RCN can learn from these studies and the research and development underway in the US and other navies, to help accelerate programs to drive down the energy required for each unit of capability.

Merchant shipbuilders have begun to invest in improved platform energy efficiency under the UN's International Maritime Organization (IMO) MARPOL legislation (IMO, 2016), and various navies are now actively engaged in similar shipboard energy-reduction programs. The United States Navy (USN) energy programs have set goals, policies and programs to improve ship energy-use since their 2001 Department of Defense (DoD) Science Board report recommended wholesale changes to reduce its dependency on fossil fuels and improve organizational management of energy resources (DSB, 2008).

The USN Maritime Energy Working Group is aggressively developing technologies and investigating in actions to improve energy efficiency. Their 2009 goals set a 15% reduction target for overall fleet energy consumption by 2020, and directed teams to develop energy performance criteria for acquisition (Martin, 2015). Their Naval Sea Systems (NAVSEA) incentivized energy conservation program (i-ENCON) states that operational behavior can deliver fuel savings of 10-15%, within all capability requirements (iENCON, 2010).

Naval and merchant maritime efficiency programs aim to embed efficiency improvements in platform design and operations. These programs define the potential savings of speed reductions, anchoring, drifting operations, idle-time reduction, hull condition optimization, optimized passage planning, weather routing, trim and ballast adjustments, and efficient equipment and system configuration. The United Nations efficiency program suggests that well over 50% energy savings are achievable in future fleets, through both design and operational enhancements to hull and equipment design, speed management, energy demand management and incentivized programs (IMO, 2011).

Energy Full-Cost Accounting

US Navy research shows that a medium surface combatant's lifetime fuel cost is the main platform cost driver, and will equal roughly 10% of its total cost of ownership (Truly & Alm, 2001). Designers armed with accurate through-life energy costs and their impacts will be better positioned to select and integrate the technology options that best balance risk and opportunity. An improved awareness and visibility of total costs of ownership (TCO) is now more easily achieved using more accurate and complete platform performance data that can be combined with naval electronic materiel records, to define through-life running, repair, overhaul and materiel costs.

Historically, fuel commodity prices were used to drive performance and acquisition assessments, which the US DoD Defense Science Board (2001) confirmed was distorting procurement, operational and logistic decisions and masking the potential benefits of improved energy efficiency (Truly & Alm, 2001). Recent models attempt to accurately capture the total costs of fuels, incorporating inter-agency support, stowage and handling costs with commodity prices. This metric, called the Fully Burdened Cost of Fuel (FBCF), accurately depicts the "all-in" costs of naval operations and highlight the true value of efficiency, and how savings can reduce the overall logistic burden required to support and deliver fuel.

The USN suggests that the true cost of delivered fuel may impose three times the cost for fuel from the depot. Their measure of costs combines the direct per barrel costs of fuel with the navy's own downstream costs (e.g.: a barrel of crude oil is refined/processed, which dictates purchase price, and then the USN adds indirect navy-specific handling fees for a truer value of cost per barrel delivered to ship).

Royal Canadian Navy Energy Management

The Canadian Armed Forces is at the early stages of building energy-efficiency targets into policy and programs. Defense Renewal program objectives articulate the general need for improved resource efficiency using technological, operational and cultural measures. The recent Defense Environmental Strategy governs the integration of environmental considerations in operations and acquisition programs, although no formal targets or programs currently exist to support this policy.

Defense Research and Development Canada (DRDC) has recently defined a science and technology (S&T) objective on request from naval requirements teams - to "develop energy initiatives and technologies with the specific goal of increasing the energy efficiency while decreasing the energy intensity of RCN platforms" (Defense Research & Development Canada (DRDC, 2013). Under this S&T objective, the author recently completed an initial study to better understand technologies that could improve the efficiency of existing RCN platforms.

Energy management programs in the RCN are starting to mature in an attempt to drive systematic energy improvements into Canada's current and next-generation fleet vessels. The CPF's new, modern machinery control system is now capable of tracking and reporting fleet equipment and detailed propulsion data, which is deemed critical to defining energy trends and their relationships with capability. This new control system monitors many internal ship's systems such as electrical power, auxiliary, sanitary, fresh water, air conditioning, heating, refrigeration, propulsion, many of which run intensely at sea and alongside. A better understanding CPF energy use patterns represents an important opportunity to affordably optimize the energy intensity of the next generation of Canadian warships, while the designs are still on the table, rather than during costly, future refit programs.

The RCN's engineering branch is developing a suite of environmental management programs, which now include energy efficiency initiatives. The Naval Materiel Environmental Protection (NMEP) program will influence platform and equipment designs for the new classes of ships. Currently, there are no equipment and system efficiency baselines or targets, and additional guidance may be required to deliver meaningful improvements for future platforms. While modern commercial equipment may offer inherent energy improvements over legacy systems, neither RCN requirement drivers, nor naval engineering/shipbuilding practices are challenging teams with ambitious efficiency targets, and thus risk missing significant opportunities to improve the next generation of warships.

Many in the navy's leadership may be hesitant to adopt environmental improvement strategies due to ongoing concerns that energy conservation efforts could have on capability, and uncertain business cases related to affordability and the investment in energy-frugal systems. Uptake of environmental programs may also be hindered by the cultural norms associated with the military's historic exemption from legislated compliance (i.e. GHG and environmental performance for operational units). This study aims to determine if there is significant opportunity to reduce the cost and environmental impacts due to poor energy management, while concurrently strengthening warship mission effectiveness and capability.

Canadian Patrol Frigate (CPF) Energy Usage

Based on naval logistic data, CPFs spend an average of 29% of their service life at sea (105 sea days per year), consuming approximately 3500 m^3 of F76 marine distillate fuel (MARPAC, 2015). Little is known about how the energy is utilized across propulsion and electrical energy systems and equipment. Electrical power trends at sea and alongside are yet defined, and there is no clear understanding of how those compare to overall platform propulsion energy use. This study aims to identify the mix of electrical energy use, as a starting point for detailed analysis.

USN analysis show that once the navy starts accounting for the actual cost of electricity at sea, the financial benefits of saving electricity deliver returns on investment (ROIs) at least one order of magnitude better than typical civilian shore installations. Since at-sea power generation relies on expensive fuel and costly fuel-logistics, a more comprehensive understanding of the full energy costs can provide a better appreciation of the risks and opportunities associated with any strategy to reduce the navy’s energy intensity.

War-fighting capability and survivability priorities can add requirements that may compromise system efficiency by oversizing equipment to meet emergency demands, and forcing systems to run inefficiently during the most frequent peacetime conditions. Introducing energy efficiency as a design requirement will, at least, serve to illuminate the importance of energy as a key enabler and constraint in through-life performance, and allow it to be balanced effectively against other important war-fighting priorities. A better understanding of the total ownership costs of inefficient platform systems will emerge, identifying where extraneous energy-use creates logistics burdens, exacerbates system maintenance, increases noise and promotes subsequent loss of capability and affordability. With uncertain future fuel costs and long service life, risks to total cost of ownership are increasingly severe and important for defense acquisition and support programs.

Canadian Naval Energy Efficiency – Previous Work

Michalchuk's (2013) and Wyand's (2011) studies explore energy reduction design strategies for Canadian Naval Vessels. Their analysis examines the use of a tailored UN efficiency index model for naval applications, in effort to provide a simple, yet broadly applicable energy standard for warship design. This UN's Energy Efficiency Design Index (EEDI) key energy per tonne/mile metric does not easily translate to defense operations, be that maritime interdiction, task group operations, humanitarian aid, combat operations or other domestic sovereignty missions. Finding a single metric to 'roll up' energy performance across multiple ship missions may not be achievable for warships, which questions the suitability of this civilian model for operational warships.

Michalchuk's comparison of warship displacement, installed power and fuel consumption serves to establish a historical average in fuel-economy, which while useful, still requires additional system-level analysis to understand both propulsion and electrical energy savings and their impact on capability. Any naval design standard should help guide equipment selection, system optimization and trade-off analysis, improve designs and promote innovation and ideally enhance all elements of sustainable marine engineering.

In November 2013, the author drafted a briefing note (Work, 2013) to the naval engineering leadership that identified opportunities for fuel savings through economizing main engine operations at sea. This work was based on the analysis of only one platform, with limited sea and harbor data. This analysis of energy savings potential was not discussed in context of operational or capability impact, and was easy to ignore as a theoretical maximum, unachievable in practical terms. Further study as to the capability impacts of energy savings and more actual data samples and steady state energy patterns were required to develop a better understanding of CPF energy use, during normal operations.

Canadian Patrol Frigate (CPF) Historical Operational Profile

The ship's modern machinery control system is called the Integrated Platform Management System (IPMS), which captures propulsion engine and machinery data that can reveal a ship's operational speed versus time, profile. As ships emerge from their recent mid-lifespan refit with the newly fitted IPMS, thousands of real-time machinery parameters, are being logged in onboard servers. Assessing this data can define the ship's operational trends that compare speeds and engine configuration, in what is referred to as an "operational profile".

The data thus far is showing an emerging operational profile that is different than what was estimated during the original shipbuilding program. Understanding the actual operational profile will help identify opportunities for improvements for the remainder of the current fleet's life, and will help inform the design of the new class of warships, and allow engineers to configure machinery to efficiently meet this demand. A recent graphical comparison from a naval engineering assessment shows the legacy, assumed operational profile of the CPF in green (Figure 1), taken from Michalchuk and Snell (2015)), with early 2015 IPMS data (referred to as "CPF Equipment Health Monitoring (EHM) data"), which illustrates CFP operational trends, and tendencies to adopt lower speeds than previously designed or anticipated. Until recently, these same historic and invalidated assumptions were being used to set new shipbuilding baseline standards, which risks adopting inaccurate requirements and imposing sub-optimal designs for machinery performance at various speeds.

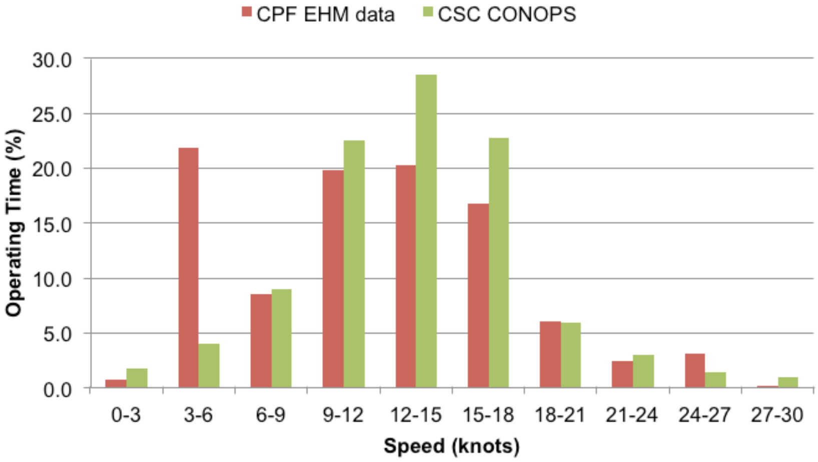


Figure 1. 2015 Operational profile comparison for CPF and future CSC concept. CSC = Canadian Surface Combatant, which is the replacement for the CPF class. (CONOPS = Concepts of Operations). Data source: Michalchuk and Snell (2015).

CPF Machinery Configuration

CPFs are propelled through the water using a combination of their three main engines, coupled to twin shafts through a series of clutches, and steered by a single rudder (Figure 2). CPF Gas Turbines (GTs) are designed for responsive maneuvers and high speed operations. A single GT allows for speeds up to 26 knots, while dual GTs in parallel can achieve speeds above 30 knots (exact top speed is confidential). A propulsion diesel engine (PDE) is used for economical propulsion for speeds below 18 knots, and provides the ship with an economical 'cruise engine', where operations permit. The PDE is used in seas less than approximately 3 meters, since rough seas or heavy maneuvering risks over-speeding the engine.

Each engine is coupled to a transmission system which reduces the engine speeds to appropriate rotational velocities required by the twin shaft propellers. The 'cross connect' gearbox design allows multiple and redundant engine/propeller combinations, coupling the engines to the shaft lines via a series of friction clutches and gearing (Figure 2).

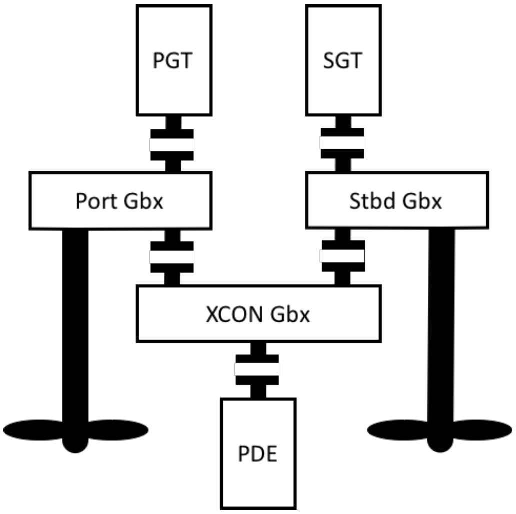


Figure 2. Ship propulsion and gearing configuration. Diagram shows port and starboard gas turbines, (PGT and SGT) and PDE, both attached to port, starboard and cross connect (XCON) gearbox (Gbx).

Several operational restrictions have been imposed on the PDE engine to safeguard against engine carbon accumulation (called ‘coking’) from incomplete combustion at lower powers, and restricted at higher loads in order to reduce the risks due to maximum thermal and mechanical stresses. The engine is restricted to 17 knots maximum for normal operations, and to avoid coking problems, ship’s operators are to ensure at least one hour of operations at or near 17 knots, if speeds in a 24-hour period remained below 10 knots for prolonged periods (DNPS 3, 2014). The engine is also restricted for use during maneuvering and is designed for seas below 3 meters.

The ship generates alternating current, 440 VAC, electrical energy using four diesel generator (DG) sets. All four DGs are identical, producing a maximum, continuous 850 kW of electricity. Normally two DGs share the load at sea, to provide for redundant electrical power generation. The four DGs are split between forward and after sections of the ship, and feed two primary switchboard to distribute and manage electrical energy to all service loads. While alongside, the ship can connect to shore power using one of two upper deck shore power connections, which is common practice when in home port, or when practical connections are available in foreign port.

IPMS provides remote control and monitoring of the engineering machinery on board, and interfaces with operators and maintainers in ship’s control rooms, on the bridge and in remote locations throughout the ship. This system continuously logs nearly 4000 system parameters, which are stored in mainframe servers and uploaded ashore for historical data processing and analysis. The ship’s warfare system is controlled and monitored by a separate system, that manages the ships external communication systems, weapons and sensors. This system was installed at the same time as the IPMS systems, during the most recent mid-lifespan upgrade of the fleet, which commenced in 2012.

Research Questions and Hypotheses

This project combines both operational and energy use information for a single Canadian warship, to gain a better understanding if energy can be used more conservatively, without degrading mission capability. This study addresses four main questions:

- How does a warship use energy at sea and alongside?
- Can a warship decrease energy intensity without compromising mission effectiveness?
- What are the key factors preventing more efficient energy use on board a warship, and
- What are the most suitable technical and behavioral options to reduce overall mission fuel consumption?

Hypotheses

Combining the data from both bridge logbooks the IPMS machinery databases enables an analysis of the energy required to complete a ship's mission. My main hypothesis is that significant energy savings are possible without degrading mission effectiveness. Furthermore, I hope to define the ship's propulsion and electrical energy use baselines, and quantify energy waste, and its implications on operational capability, costs and environmental performance.

Chapter II

Methods

This project examines the current energy consumption patterns on board CPF ships to identify both how energy is used, which systems are the most energy-intensive, and what are the subsequent opportunities for energy savings. In order to answer the above research questions, this study was designed to assess the energy use patterns of a single warship that was sailing frequently during the 2015/2016 timeframe. HMCS VANCOUVER (herein referred to as "VAN") was chosen for analysis due to her operational program and her proximity to the west coast allowing for frequent access to complete the analysis.

This study was completed in three phases: 1) shipboard fuel and electrical energy data capture; 2) examination of operational and technical energy patterns and their relationships with mission capability; and 3) identification of fuel savings opportunities. A fourth step was originally hoped for this study – which was a shipboard trial of energy savings measures, but platform availability and scheduling constraints prevented an in depth energy conservation trial, which would likely be the next step in examination of fleet energy efficiency potential.

At sea and alongside CPF energy use patterns were surveyed across a representative set of operational conditions. Data was gathered from the ship's machinery control system, bridge logbooks and via physical measurements of equipment performance and electrical power demand.

Observation Period

VAN energy use was assessed and monitored between the months of July 2015 and March 2016, where she completed over 70 days at sea, performing various operations in local and foreign waters. Operations included maritime interdiction, local equipment performance trials, training, public relation visits and transits to and from operational areas. The breakdown of sea days, and operations are outlined below, with the corresponding titles used in graphs throughout this report (Table 1). VAN's South American deployment was approximately two months in duration, but a fault in the machinery digital memory storage resulted in only nine sea days of information captured over this period.

Ship's system, equipment, and platform data was compiled to ascertain how the ship used energy during this timeframe. Machinery and electrical equipment information was contextualized by the ship's logs to better understand the relationship between energy and mission objectives. Information was amassed from ship's machinery historic data (via shore-based IPMS digital data storage), ship's bridge log books (Officer of the Watch (OOW) logbooks), manual equipment electrical surveys, publicly available sea temperature and wave height information, naval maintenance system information, and ship's operational deficiency messages and logistics messages (process outlined in Figure 3).

The OOW logs were used to define the times when the ship was performing mission-specific activities, since these notebooks are used to record ship-routine information. This analysis (schematic in

Figure 3) coupled the digital data from

Table 1. VAN operations from July 2015 to March 2016. SWOAD = Ship Without Air Detachment. WUPs is an term for crew team training, meaning "Work-Ups".

Operations	Report Label	Sea Days
Replenishment at Sea Training	RAS Ops RAS Training	15
Flight Crew Training	SWOAD	2
Sensor Trials	SRD 504	4
Submarine Training	Sub	3
Readiness Training	WUPs	21
Interdiction Operations	Op Caribe	10
Return Transit	Transit	4
Public Relations Visit	Vancouver City Visit	2
Foreign Naval Operations	Southploy	9

machinery logs, with written bridge information, inputted manually into a database to be able to assess real-time ship energy use against the ship's operating conditions. This is the first time that hand-written, CPF bridge logbook information has been collated with machinery data to assess energy use. Comparing bridge logs to machinery data is normally only completed to aid formal enquiries related to safety or emergency incidents. Detailed information was compiled only for VAN, and compared to available data for other ships of the same class. The data from this study provides the energy use patterns of a single ship in class, and can be assessed to better understand ship's and fleet energy-use, costs, impacts and opportunities.

The following overall actions (Table 2) were completed to determine how and why VAN uses both propulsion and electrical energy, at sea and alongside (ie. in harbor). The analysis was completed in three main research phases, explained in more detail below.

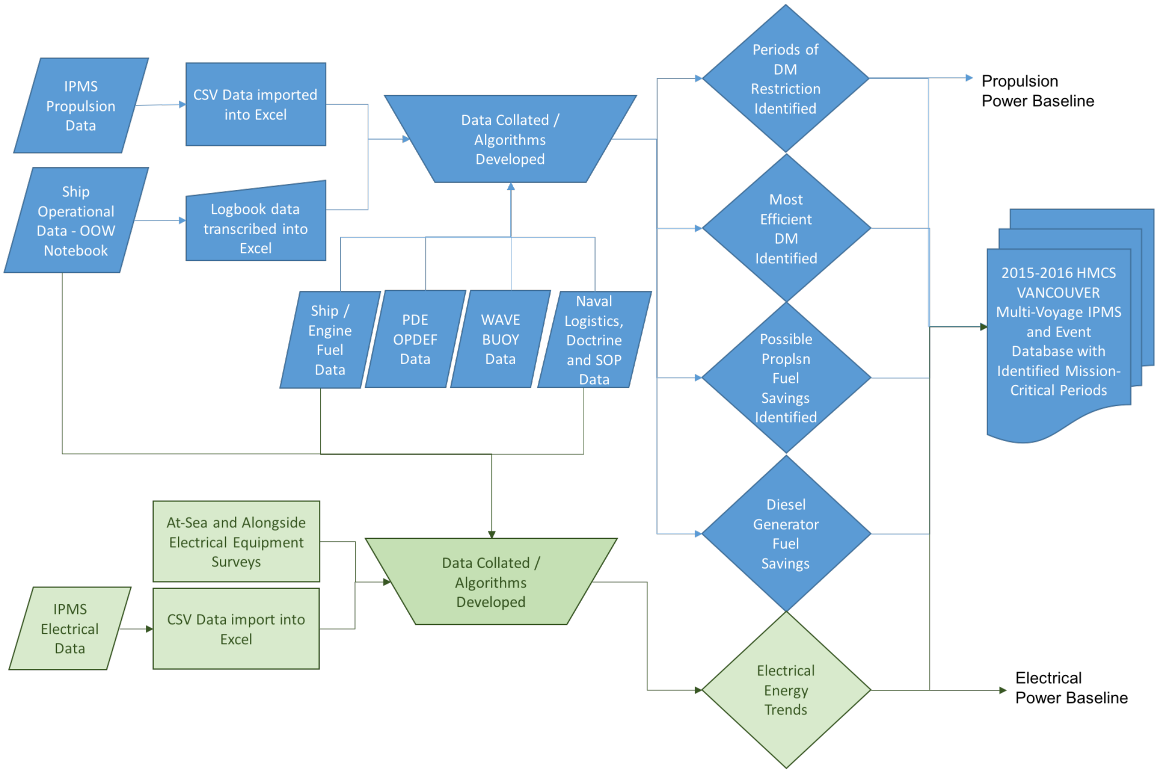


Figure 3. Data analysis process map for ship operational, fuel and electrical assessments. CSV = Comma Separated Variables; DM = engine Drive Mode; PDE = Propulsion Diesel Engine, SOP = Standard Operating Procedures.

Phase 1: Data Capture

The first phase of the analysis was to complete a literature survey and data capture to better understand the current and historical energy-use patterns onboard CPFs. Historical, coastal logistics fuel use data was examined, which defined the fleet’s approximate monthly fuel use and sea-time averages, between 1997-2009. For recent years, monthly IPMS data were downloaded from the ship and from shore data storage units, and organized by time to provide samples of ship’s speed, drive mode (engine configuration), ship’s speed, diesel generator outputs, switchboard total power demand, and the status of various electrical machinery throughout the ship. Digital signals for each of these systems were identified and then amassed for comparison, by date and time.

Those datasets were combined with several hundred manual scans of bridge OOW logs, and the relevant ship data for each sailing was transposed into excel and combined with machinery information from IPMS to compare machinery data with the ship's operational behavior.

Table 2. Research activities. September 2015 - June 2016.

Date	Activity	Explanation
21 – 22 Sep 2015	Initial Sea Checks / Planning	Initial on board energy recce, discussions and equipment and survey planning with ship's staff.
21-27 Nov 2015	Detailed at-sea, electrical energy surveys on running equipment. (San Diego to Victoria)	At sea running equipment load checks and surveys of operational energy behaviors. Completed initial discussions with ship's staff on opportunities associated with on board energy reductions.
Oct 2015–May 2016:	Ship, machinery and operational information gathering.	Reviewed detailed information pertaining to fleet fuel use, engine reliability and availability, detailed equipment logs (electronic), and ship's operational logs.
Jan 2016	Additional at-sea electrical energy surveys (Victoria to Vancouver).	Additional at-sea equipment energy surveys and log book reviews, and installation of diesel and gas turbine engine fuel flow meters, in order to validate OEM fuel consumption rates.
Mar-Jun 2016	Data analysis.	Received additional electronic logs from VAN data server, and completed analysis of energy use patterns against operational requirements.

Phase 2: Definition of Energy Use Patterns

Baselines for both at sea and alongside propulsion and electrical energy use was developed using the IPMS data, providing daily average fuel consumption and electrical load. Machinery status and ship's speed were used to calculate the fuel consumption of the ship, approximated by from the ship's engine and hull fuel consumption data. Ship fuel curves are considered confidential and are not included in this report to meet security classification requirements. These energy profiles were compared to environmental conditions and other pertinent engine status and defect information to determine what engine configurations (called "drive modes") were available for use by ship's captain and OOWs. This analysis was completed for both at sea and alongside, although alongside electrical energy information was only baselined, but not combined with daily shore logbooks, as shore logs may be unsuitable for providing the same level of ship routine data and insights necessary to understand alongside energy use patterns.

Phase 3: Analyzing Energy Patterns, Capability and Opportunities for Improvement

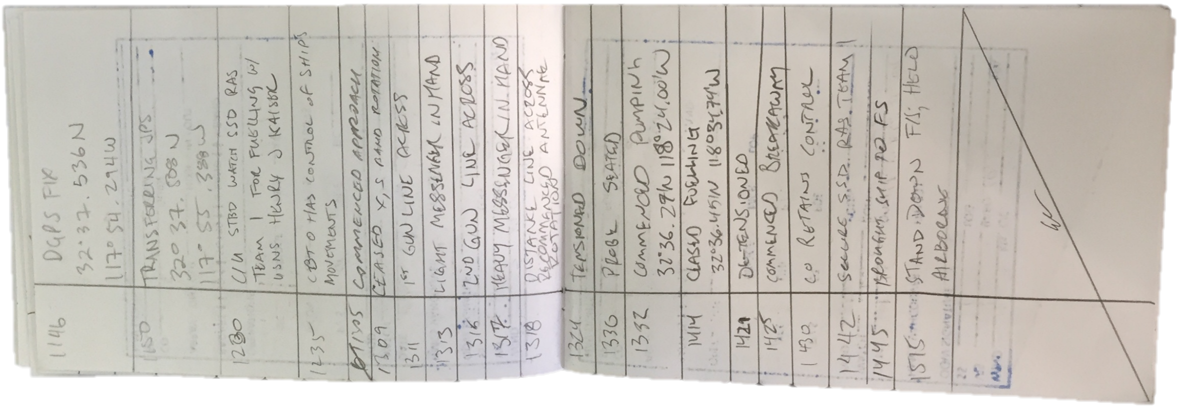
The actual energy used during periods alongside and at sea were then assessed to determine the key influencers of both propulsion and electrical power demand. The data was interrogated to determine what savings may have been possible under those circumstance, if more efficient configurations were chosen in areas that would not impact operational requirements. Initial comparisons were made with other ship's in class, to better understand what patterns may be most important for future analysis.

Based on the information gathered throughout Phase 1 and 2, the reasons why energy is utilized was explored. Periods where discrete operational requirements were dictating ship's movements and speed, were deemed as "restricted" and removed from any assessment of potential energy savings. The windows without restriction were assessed as to the potential for fuel savings. Ship's speed is normally set by the ship's captain, and was taken as a requirement at all times, and not considered as an opportunity for fuel savings. The logical next-step of performing energy savings trials was discussed with ship's staff, but not achievable due to operational and timings constraints.

Combining IPMS Data Logs and Bridge OOW Notebooks

As described, the IPMS data was manually cross-referenced with the ships bridge logbook (Officer of the Watch (OOW) notebook,

Figure 4), which maintains a detailed account of the ships position, operations, and routines at sea. The combination of the IPMS and OOW data was assessed in order to understand the operational or mission capability requirements that influenced the CO's choice for drive-mode.



1146	DGPS FIX 32°37.536N 117°54.294W
1150	TRANSFERRING JPS 32°37.508N 117°55.338W
1230	C/U STBD WATCH SSD RAS TEAM 1 FOR FUELLING W/ USNS HENRY J KAISER
1235	CBT O HAS CONTROL OF SHIPS MOVEMENTS
1305	COMMENCED APPROACH
1309	CEASED X, S BAND ROTATION
1311	1ST GUN LINE ACROSS
1313	LIGHT MESSENGER IN HAND
1316	2ND GUN LINE ACROSS
1317	HEAVY MESSENGER IN HAND
1318	DISTANCE LINE ACROSS RECOMMENCED ANTENNAE ROTATION
1324	TENSIONED DOWN
1330	PROBE SEATED
1332	COMMENCED PUMPING 32°36.27N 118°24.00'W
1414	CEASED PUMPING 32°36.45N 118°34.74W
1429	DE-TENSIONED
1425	COMMENCED BREAKAWAY
1430	CO RETAINS CONTROL
1442	SECURE S.S.D. RAS TEAM 1
1445	BROUGHT SHIP TO FS
1515	STAND DOWN F/S; HELO AIRBORNE

Figure 4. OOW notebook scan, (20 Nov 2015; single page, logbook excerpt).

A small data excerpt from a single voyage is shown in Figure 5, which illustrates the event timeline from the logbooks and how those entries can be aligned with the machinery information. Essentially, this comparison allows the observer to understand the operations of the ship, its relationship with energy, and potentially identify any opportunity for energy savings.

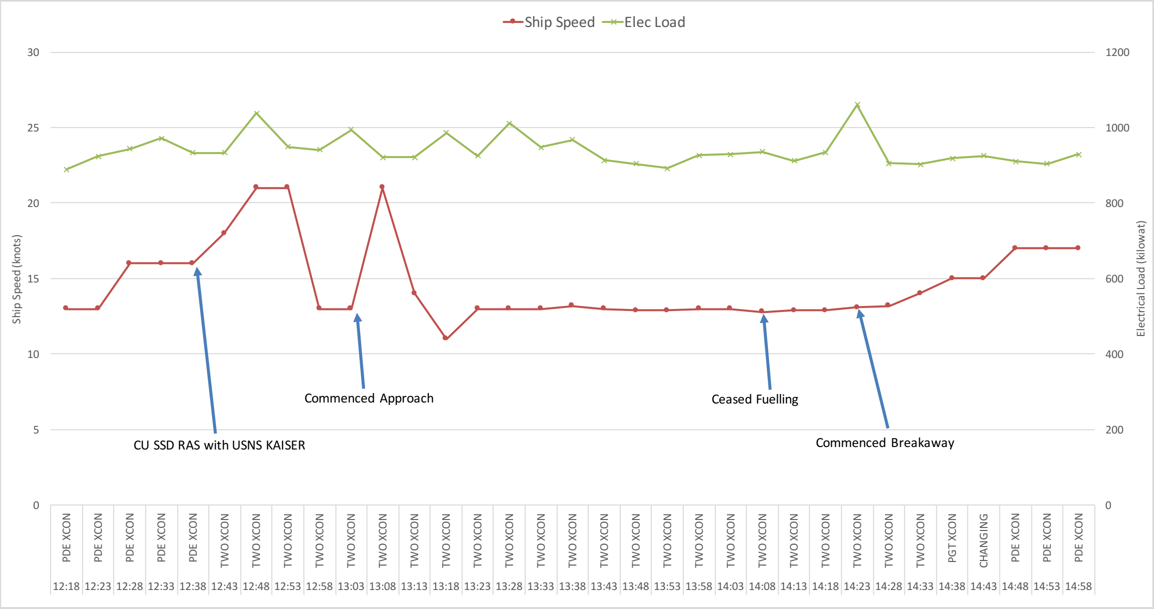
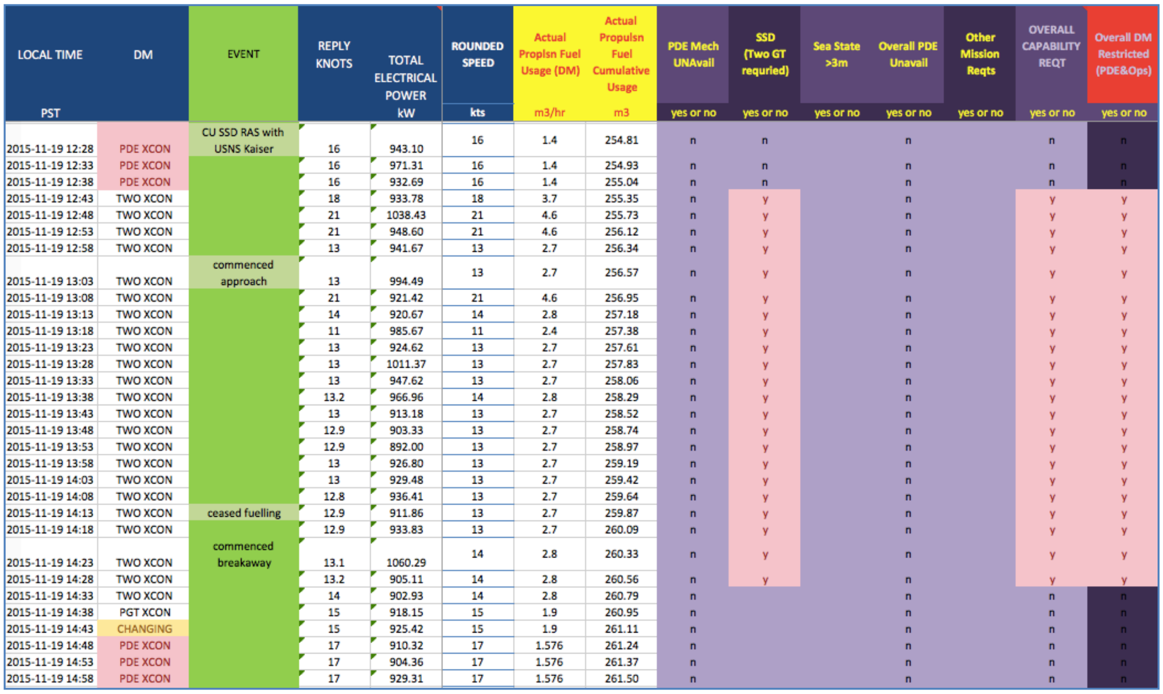


Figure 5. Ship operational data excerpt (20 Nov 2015). This figure shows ship's speed, electrical load and drive mode, with operational event data vs. time.

Pertinent event information was transferred from OOW notebook entries, and graphically represented in Figure 5. The information shows acronyms for ship operations. The drive mode (DM) is shown next to the time and event data, and the IPMS recorded speed and electrical energy demand are also shown along solid graphical lines. Fuel consumption can be calculated from engine/speed curves. The operational event is labelled, as appropriate in the purple section, as to its type and status of operational restriction (y=yes, n or blanks = no).

Figure 5 shows how the ship’s Commanding Officer (CO) selected two gas turbine drive mode upon Closing-Up for Special Sea Dutymen (CU SSD), prior to accelerating for positioning alongside the supply ship (USNS KAISER), to 21 knots, and then settling alongside for re-fueling at 13 knots for approximately one hour, before departing (breakaway). The event text illustrates the ship’s operational events, and drive mode changes in IPMS can be seen to reflect the operations underway, where the ship assumes 2GT XCON (XCON refers to a “cross-connected” gearbox, which allows one engine to drive both shaftlines) in order to provide the most redundant drive mode and reserve of power, possible. The combination of the logbook and IPMS data clearly identifies areas where operational requirements dictate ship speed and engine configuration (Table 3 and Appendix 1 for more information).

Table 3. IPMS and event data excerpt from operational energy model (20 Nov 2015).



LOCAL TIME PST	DM	EVENT	REPLY KNOTS	TOTAL ELECTRICAL POWER kW	ROUNDED SPEED kts	Actual Proplsn Fuel Usage (DM) m3/hr	Actual Propulsn Fuel Cumulative Usage m3	PDE Mech UNAvail yes or no	SSD (Two GT requried) yes or no	Sea State >3m yes or no	Overall PDE Unavail yes or no	Other Mission Reqts yes or no	OVERALL CAPABILITY REQT yes or no	Overall DM Restricted (PDE&Ops) yes or no
2015-11-19 12:28	PDE XCON	CU SSD RAS with USNS Kaiser	16	943.10	16	1.4	254.81	n	n		n		n	n
2015-11-19 12:33	PDE XCON		16	971.31	16	1.4	254.93	n	n		n		n	n
2015-11-19 12:38	PDE XCON		16	932.69	16	1.4	255.04	n	n		n		n	n
2015-11-19 12:43	TWO XCON		18	933.78	18	3.7	255.35	n	y		n		y	y
2015-11-19 12:48	TWO XCON		21	1038.43	21	4.6	255.73	n	y		n		y	y
2015-11-19 12:53	TWO XCON		21	948.60	21	4.6	256.12	n	y		n		y	y
2015-11-19 12:58	TWO XCON		13	941.67	13	2.7	256.34	n	y		n		y	y
2015-11-19 13:03	TWO XCON	commenced approach	13	994.49	13	2.7	256.57	n	y		n		y	y
2015-11-19 13:08	TWO XCON		21	921.42	21	4.6	256.95	n	y		n		y	y
2015-11-19 13:13	TWO XCON		14	920.67	14	2.8	257.18	n	y		n		y	y
2015-11-19 13:18	TWO XCON		11	985.67	11	2.4	257.38	n	y		n		y	y
2015-11-19 13:23	TWO XCON		13	924.62	13	2.7	257.61	n	y		n		y	y
2015-11-19 13:28	TWO XCON		13	1011.37	13	2.7	257.83	n	y		n		y	y
2015-11-19 13:33	TWO XCON		13	947.62	13	2.7	258.06	n	y		n		y	y
2015-11-19 13:38	TWO XCON		13.2	966.96	14	2.8	258.29	n	y		n		y	y
2015-11-19 13:43	TWO XCON		13	913.18	13	2.7	258.52	n	y		n		y	y
2015-11-19 13:48	TWO XCON		12.9	903.33	13	2.7	258.74	n	y		n		y	y
2015-11-19 13:53	TWO XCON		12.9	892.00	13	2.7	258.97	n	y		n		y	y
2015-11-19 13:58	TWO XCON		13	926.80	13	2.7	259.19	n	y		n		y	y
2015-11-19 14:03	TWO XCON		13	929.48	13	2.7	259.42	n	y		n		y	y
2015-11-19 14:08	TWO XCON		12.8	936.41	13	2.7	259.64	n	y		n		y	y
2015-11-19 14:13	TWO XCON	ceased fuelling	12.9	911.86	13	2.7	259.87	n	y		n		y	y
2015-11-19 14:18	TWO XCON		12.9	933.83	13	2.7	260.09	n	y		n		y	y
2015-11-19 14:23	TWO XCON	commenced breakaway	13.1	1060.29	14	2.8	260.33	n	y		n		y	y
2015-11-19 14:28	TWO XCON		13.2	905.11	14	2.8	260.56	n	y		n		y	y
2015-11-19 14:33	TWO XCON		14	902.93	14	2.8	260.79	n			n		n	n
2015-11-19 14:38	PGT XCON		15	918.15	15	1.9	260.95	n			n		n	n
2015-11-19 14:43	CHANGING		15	925.42	15	1.9	261.11	n			n		n	n
2015-11-19 14:48	PDE XCON		17	910.32	17	1.576	261.24	n			n		n	n
2015-11-19 14:53	PDE XCON		17	904.36	17	1.576	261.37	n			n		n	n
2015-11-19 14:58	PDE XCON		17	929.31	17	1.576	261.50	n			n		n	n

At each IPMS data interval, the associated fuel consumption was calculated using the ship’s main engine fuel curves, and an overall fuel consumption was determined for each sailing period. In cases where the ships engine configuration was dictated by operational requirements, those periods were deemed as “drive-mode restricted”, and considered operational imperatives, and represented periods where fuel savings were not practical. The main types of mission requirements which restricted drive-modes and removed opportunities for fuel savings, are identified in the OOW notebooks as follows:

- Special Sea Dutymen (SSD). SSD requires two gas turbines in accordance with Naval doctrine. in restricted waters, entering and leaving harbour, replenishments at sea, and miscellaneous, higher-risk manoeuvres.
- Engineering Drills
- Equipment and Operational Trials
- Training Serials (including maneuvers).
- Action and Emergency Stations (real life or training emergencies)

For each IPMS sampling interval (5 or 10 minute intervals, depending on the data set), the most efficient drive mode (DM) was identified for those periods where operations were not restricting engine choice. An algorithm was created to define the most efficient drive mode for each time interval, and assess the potential fuel savings, which could be summed for each sailing period (all speeds were assumed to be minimum, required). The savings potential was then assessed against the availability of the PDE, to account for times when the PDE was off-line due to mechanical fault or rough weather. Wave buoy data was assessed using the ship's geographic position information, in order to determine if the sea state was too severe for PDE operations. The PDE was deemed as "operationally restricted" during high sea states, and was not considered a viable drive-mode for saving fuel (Appendix 1 for more information).

The summation of all portions of the voyages that were deemed restricted allowed a more accurate estimate of total possible fuel savings available to the ship during those 71 days of actual operations. Note: Additional savings would be possible through slower speeds and higher PDE engine availability, which are commented on in the analysis section.

Research Limitations and Risks

This analysis was based on several key assumptions and limited data, which introduces uncertainty into the study. The fuel consumption for each voyage was estimated using the ship's fuel curves based on engine and hull performance data. Fuel flow meters were not fitted nor available for the duration of this study. The fuel curves were defined for the ship before the recent addition of their "stern-flap" modification at the ship's transom, which was installed to improve efficiency at discrete speeds, and may affect the accuracy of legacy fuel curves. The condition of the main engines was also not assessed, and could reduce actual performance when compared to fuel curves.

The operational energy model has inherent simplifications and errors. Perhaps most significant is that the analysis only accounts for a small portion of operations on a single platform. The detailed assessment of energy use has discrete errors due to the sampling regime (5 or 10 minutes sampling intervals), which prevent capturing all dynamic propulsion movements and data events. Other errors include rounding errors, which were purposefully made conservatively, so that any estimates of possible fuel savings would be under, rather than over-estimated. This study also assumed the actual speed was always the minimum required, and also ignored reverse speeds (0.03% of all samples). Other approximations include midday sea state, which was assessed based on nearest wave buoy, sea condition data (normally within 100 kilometers of the ship's position), and some corrupted IPMS data that was omitted from the analysis. Effects due to acceleration, maneuvering, sea state, wind, currents, hull condition and machinery efficiency performance were not considered as part of this study. Anecdotal discussions with the Diving Officer throughout the sailing program indicated that the hull and propellers remained largely free from excessive growth, and were in "good condition" during the assessment period. Further analysis of these characteristics could add accuracy in the overall energy requirements for various operations and conditions.

The OOW notebook data was the main and only source for ship's operational information, and is not an exhaustive account of ship's operational information, and may include mistakes, illegible notes, and important gaps. Several additional assumptions have been made in the sections of this report and are indicated in footnotes and/or attached sections, and should be the source for further analysis and consideration when interpreting accuracy and uncertainty. The statistical significance of these errors has not been assessed, but may be considered low, when compared to the variability of operations and environmental conditions experienced across the fleet during day-to-day operations.

Chapter III

Results

From July 2015 to March 2016, VAN sailed on several local and foreign operations, and provided over 70 days of information during the 264-day period. IPMS data was collected for all sailings up to the beginning of February 2016, but only partially during the ship's southern deployment, due to data corruption issues. Over 17,000 IPMS samples were examined and compared to the ship's bridge logbooks, which provided an opportunity to assess operational propulsion and electrical energy use patterns at sea and alongside.

VAN averaged 40.6 m^3 fuel per day at sea over the 71 days, with a running electrical power demand of 961 kW, using 16% of overall fuel for electrical power generation. During alongside periods, her average electrical demand was 620 kW; which was either powered by the shore based electrical grid, or by ship's diesel generators, which is common when in foreign port (summarized in Table 4).

Propulsion Energy-Use Patterns at Sea.

Much more data is available in IPMS, but for this study, the ship's speed, drive mode, operational highlights (bridge log), electrical power, and large motor running status, were used to determine how the ship was using fuel to both propel and power the

Table 4. Overall energy use benchmarks. Detailed calculations and assumptions can be found in Appendix 1.

Metric	Benchmark
Daily Fuel Consumption (at sea)	40.6 m^3
Average Electrical Power Demand (at sea)	961 kW
Average Electrical Power Demand (alongside)	620 kW
Propulsion Fuel Usage (at sea)	84%
Electrical Fuel Usage (at sea)	16%
Overall Propulsion Energy Proportion	75 % (MWh)
Overall Electrical Energy Proportion	25 % (MWh)

ship. The speed demand and drive modes were compared to the ship's defined fuel consumption curves, to calculate the fuel use, since fuel flow meters were unavailable and tank level indicators are not accurate enough to provide hourly consumption levels. The approximation of fuel consumption (engine power, specific fuel consumption and ship's speed) was used to define overall fuel usage at sea.

The ship averaged a speed of 11.6 knots over a 71-day period, and consumed approximately 2887 m^3 of F76 fuel, at an average of 34 m^3 per day for propulsion and 6.7 m^3/day for electrical power generation. Table 5 outlines the full suite of operations, used throughout this report, including: Replenishment at Sea (RAS), Ship Without Air Detachment (SWOAD) aircrew training, Sonar Trails (SRD 504), Submarine and local operations (Sub/Local Ops), Work-Ups (WUPs) training, Operation Caribe, City of Vancouver visit and South American Deployment (Southploy).

Over the set of operations between July 2015 and March 2016, the ship's operational speed/time profile was assessed using the control system data. Figure 6 outlines the speed, time and drive-mode over the 71 days at sea. The ship spent 42% of the time on the PDE, 48% on a single GT and the remainder on two GTs. The above graph clearly shows the lack of PDE use at lower speeds, where it is designed to provide economical cruising. The PDE was used infrequently at speeds below 10 knots, and frequently between 12 and 17 knots. The ship spent 64% of her sailings between 10-15 knots, and 11% of at 5 knots, 4% above 20 knots, and only 1% above 26 knots. At speeds below 10 knots, the ship spent the majority of the time on a single GT (73%), and only 11% on the PDE. At mid-speeds between 11-17 knots, the ship sailed on the PDE for 62% of the time, and on a single GT (1GT) for 32% and two GTs (2GT) for 6%.

Table 5. Overall operational data summary. Table entries are ordered from highest to lowest daily fuel consumption.

Operation	Duration (days)	Average Speed (knots)	Average Electrical Load (kW)	Daily Fuel Use (m^3)
Return Transit (San Diego-Esquimalt)	4.1	14.1	954.1	41.0
RAS Training	3.9	11.1	970.0	40.9
RAS OPS	11.3	11.4	965.3	40.6
WUPS Phase IV	4.1	10.0	954.0	38.0
Vancouver City (to)	0.8	10.3	972.4	36.8
Sub / Local Ops	3.1	9.6	925.3	35.8
WUPS	17.1	11.8	955.4	33.7
Vancouver City (return)	0.9	11.6	966.7	33.3
Southploy 2	4.4	13.5	991.9	31.5
OP Caribbe	10.2	12.0	934.5	28.0
Southploy 1	5.0	13.1	1024.5	27.6
SRD 504 Trials	4.1	9.2	961.3	27.0
SWOAD Training	2.3	9.6	957.6	26.4

Overall, the PDE was only used 42% of the time below 18 knots, which represents the vast majority of operations (95%) (note: “shaft stop” is selected 7% of the time, which accounts for the time at zero knots prior to and after arriving in harbor). Overall, the operational profile illuminates not just the time spent at each speed, but the

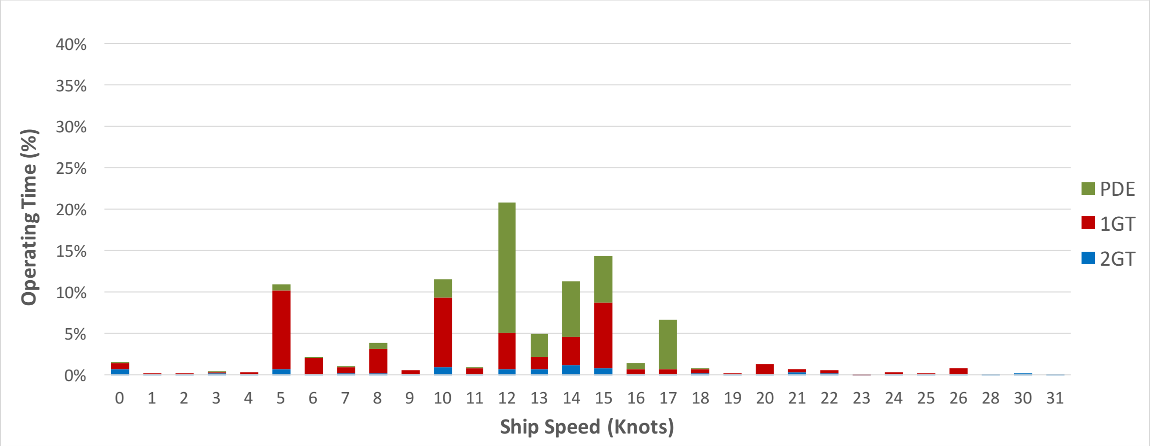


Figure 6. VAN operational speed profile (Jul 2015-Mar 2016). Overall breakdown of drive modes at various speeds. PDE=Propulsion Diesel Engine, TWO GT=Two LM2500 Gas Turbines; ONE GT=One LM2500 Gas Turbine.

drive modes used to achieve those speeds, and the tendency to assume drive modes in many cases, that are oversized, and inefficient in comparison (drive mode breakdowns for various speeds, at Figures 7-10).

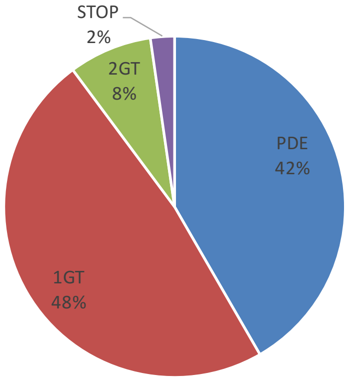


Figure 7. Overall drive mode breakdown (percent of time).

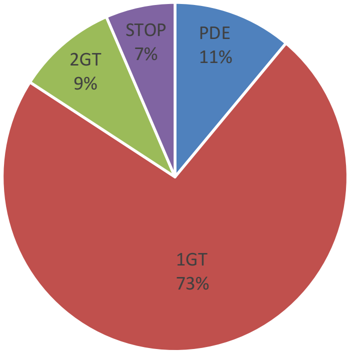


Figure 8. Drive mode breakdown: 0-10 knots.

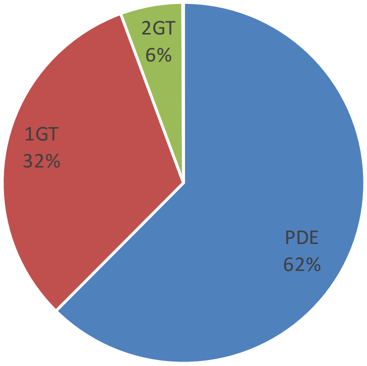


Figure 9. Drive mode breakdown:11-17 knots.

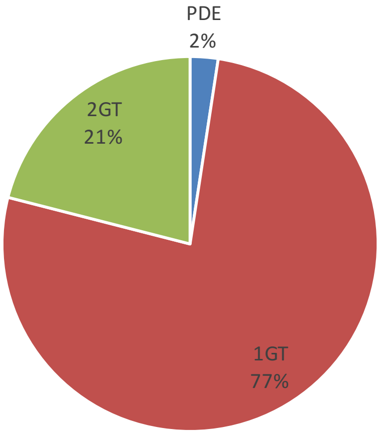


Figure 10. Drive mode breakdown: 18-26 knots.

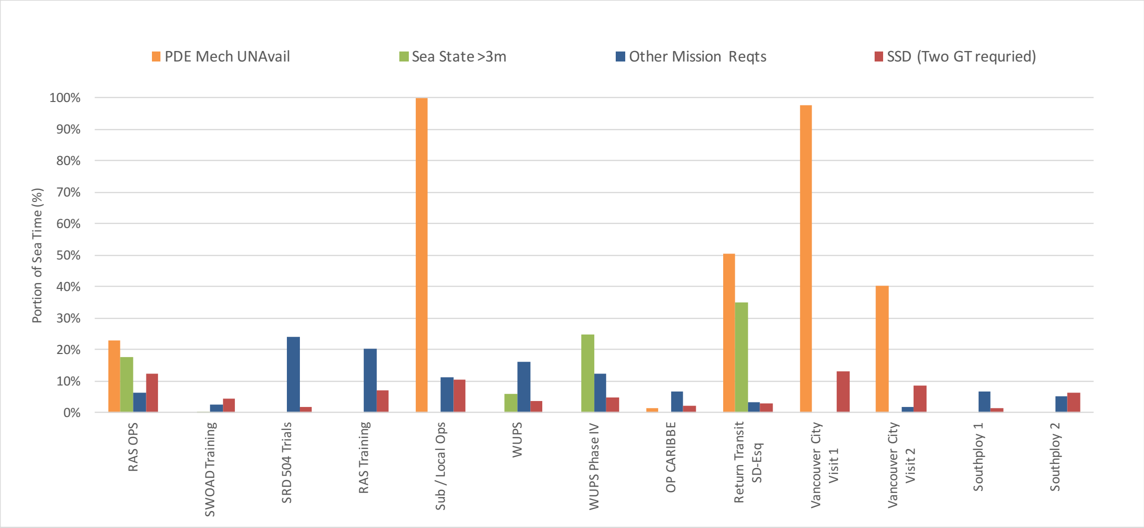


Figure 11. Operational restriction by mission. Portion of each operation where the PDE was unavailable, or where the ship was operating under other mission restrictions.

Table 6. Summary of drive mode restrictions – VAN (July 2015 - March 2016). Note. Individual restriction times overlap; therefore, overall totals are not additive.

Drive Mode Restriction	Portion of Time
PDE Mechanically Unavailable	12.6%
PDE Weather Unavailable (Sea State >3m)	7.6%
SSD (Two GT required)	5.4%
Other Mission Requirements	10.5%
Operationally Restricted	16.0%
Overall Drive Mode Restricted	30.6%

Closer examination of the operational requirements from the OOW notebook, integrated with the associated IPMS data, show opportunities for fuel savings. Overall, VAN was deemed “operationally restricted” 16% of her sailings, meaning she was performing critical operations that required specific drive modes, and speeds. VAN was required to be on 2 GTs during “Special Sea Dutymen” (SSD) for 5% of sailings, and subjected to other mission restrictions 10.5% of the time. This suggests that for 84% of sailings, VAN was free to choose the most efficient drive mode available, without impacting mission objectives. That being said, VANs PDE was mechanically unavailable 13% of the time, and unavailable due to sea state 7.6% of operations. Due to the availability restrictions of the PDE, combined with mission requirements, the ship's overall drive mode was restricted 30.6% of the operations. This result suggests that the ship has flexibility to modify engine configuration just under 70% of operations, to improve efficiency without compromising capability (Figure 11). These results also highlight the PDE's overall benefit as an enabler for economical, fuel-efficient operations.

Table 7. Operational fuel usage and possible savings. Note these savings are possible, without compromising mission capability (WCMC).

Operation	Propulsion Fuel Consumed (m^3)	WCMC Fuel Savings Potential (m^3)	Savings Percent (%)
RAS Training 1	457.0	49.5	11%
SWOAD Training	59.8	11.9	20%
SRD 504 Trials	110.1	16.7	15%
RAS Training 2	161.4	43.6	27%
Sub / Local Ops	110.5	2.0	2%
WUPS	576.3	90.8	16%
WUPS Phase IV	154.1	38.7	25%
OP CARIBBE	284.4	21.4	8%
Return Transit (SD-Esq)	167.6	11.1	7%
Van Day Sail 1	28.7	1.7	6%
Van Day Sail 2	28.8	0.4	1%
Southploy1	136.6	1.8	1%
Southploy2	137.6	4.1	3%
TOTAL	2412.8 m3	293.5 m3	12.2%

Analysis of these periods suggest that the overall fuel savings from switching to a more efficient DM at the chosen speed would save approximately 12% of propulsion fuel, or 10% of overall ship's fuel use. The potential fuel savings from assuming more efficient DM without impacting mission capability is outlined in Table 7, and Figure 12.

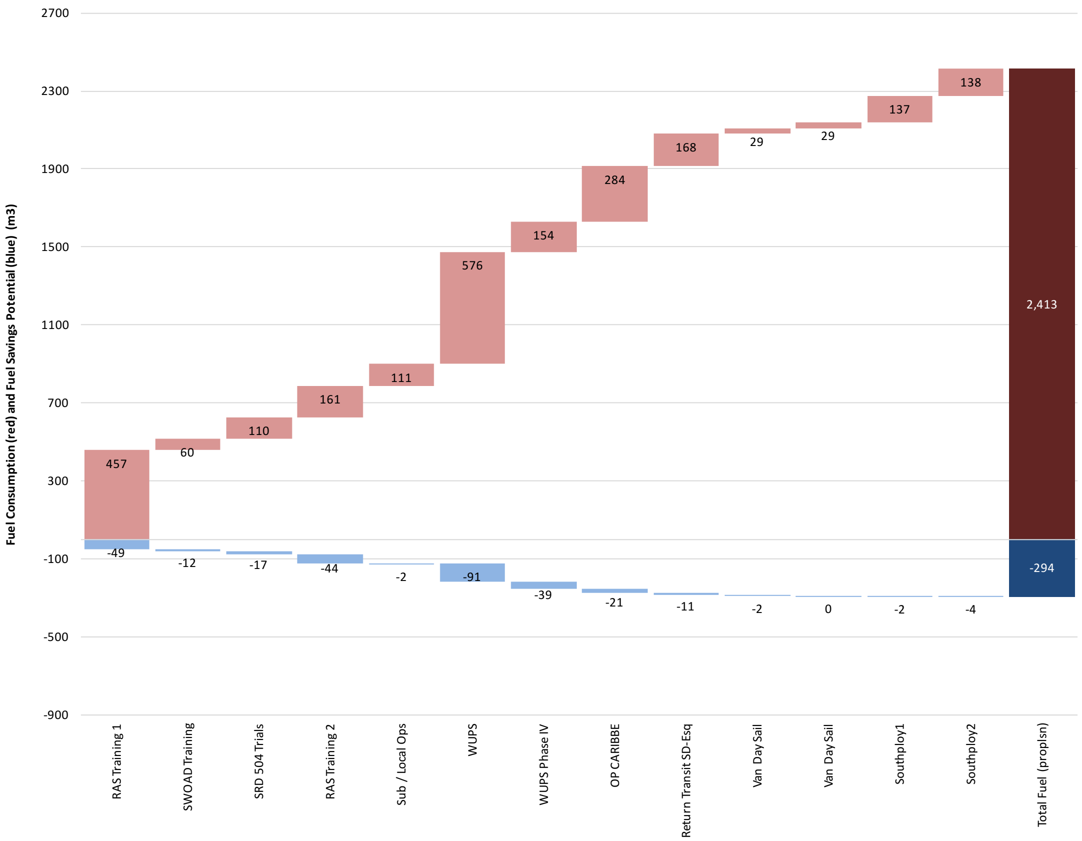


Figure 12. Mission fuel consumption (red) and savings potential (blue). This diagram shows the fuel savings potential for each voyage, without compromising mission capability (WCMC).

At Sea Electrical Energy Use Patterns.

The total electrical load is monitored continuously at sea and alongside. IPMS measures and logs the electrical output from generator sets and the demand power at the switchboards, but does not convey how the energy is divided amongst electrical equipment users. IPMS also monitors the running status for machinery throughout the ship, and manual surveys were completed on this and other equipment to ascertain the individual electrical duty cycle (on/off patterns) and overall energy use. The loads monitored by IPMS constitute approximately 55% of the 961 kW total ship's, at sea, electrical load.

Figure 13 outlines the major system electrical energy breakdown from both surveyed and IPMS running data, across various equipment groups. Ancillary systems (ANC) required to support propulsion, which includes large electrical motor loads (15% of total load) such as lubricating oil pumps for the main gearing, propeller pitch pumps for thrust control, and others, which run continuously at sea. Auxiliary systems (AUX) include steering gear hydraulic pumps for the rudder, air compressors, sea water circulation / cooling pumps and others. Damage Control (DC) system maintains damage and emergency systems, such as firemain seawater pressure, in case of a fire. These pumps run continuously at sea and alongside and constitute 6% of the overall ship's load, due to 100% duty cycles and high individual motor current. Domestic systems (DOM) support the ship's crew, such as food refrigeration, fresh potable water systems, sewages systems, and others, which are on at varying times at sea, consuming approximately 2% of the load. Heating, Ventilation and Air Conditioning (HVAC) systems monitored in IPMS, such as chilled water system, and ventilation systems move and cool air throughout the ship, and improve crew comfort and provide equipment cooling. The HVAC systems monitored by IPMS are numerous and in many cases, require significant power to drive large fans, frequently activated at sea, consuming 25% of the overall power delivered by the diesel generators.

Portions of the electrical system not monitored by IPMS include many variable loads, such as combat weapons, sensors (radars, antennae etc.), warfighting information and control systems, ship's geo-spatial positioning system, hotel services (lighting, multi-purpose outlets, ship's laundry, galley equipment, living and working space heating and

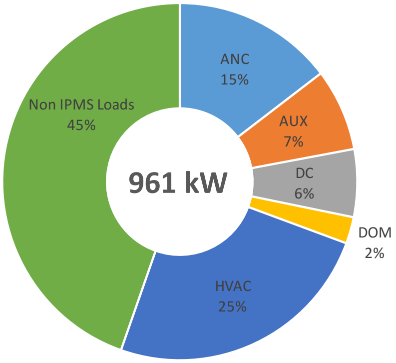


Figure 13. Overview of total at-sea electrical load (961 kW average), with breakdown of monitored IPMS loads.

air conditioning), helicopter support systems, deck equipment and machinery (cranes, boat davits, winches etc.), and others. As lighting, galley services, and space cooling/air conditioning is regularly in use, this equipment was manually surveyed to check running currents and duty-cycles had to be estimated for various systems and equipment not fitted with load-sensing devices or status indicators. These duty-cycles were estimated through discussions with ship's staff, maintainers and users, and from observations at sea and alongside. The only way to capture the actual duty-cycles for loads not monitored by IPMS is to manually monitor or add sensing devices to data-loggers. For the purposes of this study, only estimates have been completed through discussions with ship's staff and any observed patterns while on board the ship.

Approximately 429 kW of loads are demanded from equipment not monitored by IPMS, such as weapons and combat sensors, multi-purpose outlets, ship's lighting, domestic services (laundry, galley) etc. Using manual surveys and duty-cycle estimates, an additional running load of 180 kW was approximated for ship's lighting, galley equipment, laundry, and air conditioning systems. Other loads remain un-estimated, which apply to combat systems and miscellaneous equipment throughout the ship (247 kW, see Appendix 3 for more details).

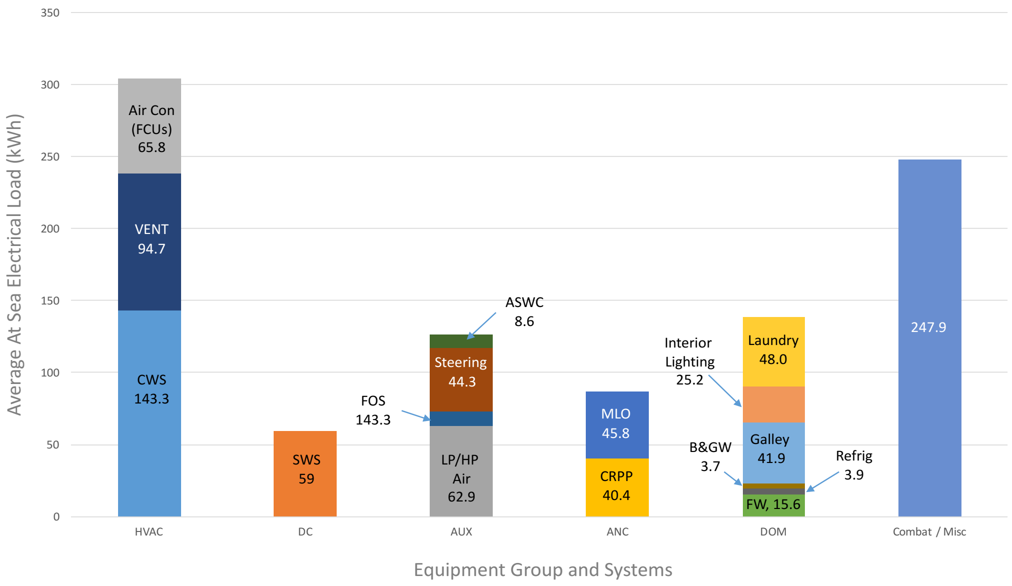


Figure 14. Overall at sea electrical energy breakdown by equipment group including IPMS and estimated loads.

Figure 14 shows the total measured and estimated loads for at-sea electrical power, and the breakdown of relative proportions. The assessment clearly shows the dominance of the HVAC loads, which include both actual (IPMS) and estimated loads (FCUs). More analysis is required to accurately define the estimated portions, but this preliminary analysis shows the significance of cooling demand, and other major electrical users. Figure 18 shows the system energy proportions, including sea water services (SWS), low and high pressure air systems (LP/HP air), machinery space ventilation

(VENT), main lubricating oil (MLO), refrigeration (Refrig), black and grey water (B&GW), auxiliary sea water circulation cooling (ASWC), Controllable Reversible Pitch Propeller (CRPP) pumps, steering motors, fresh water (FW), laundry, and hot fresh water (HFW).

Alongside Electrical Energy Use Patterns

Alongside electrical load data was assessed for the periods between July 2015 and March 2016. For these periods, the average harbor running electrical load for VAN was 620 kW (Figure 15, below). Only days where the ship spent 24 hours alongside on shore-power were assessed in detail to estimate the steady-state power required when the ship was in normal routines. Days that included both at-sea and alongside routines were ignored for the analysis, to avoid any impact posed by higher electrical loads required for operating main machinery and other large equipment prior to proceeding to sea, which is not normally required during alongside periods.

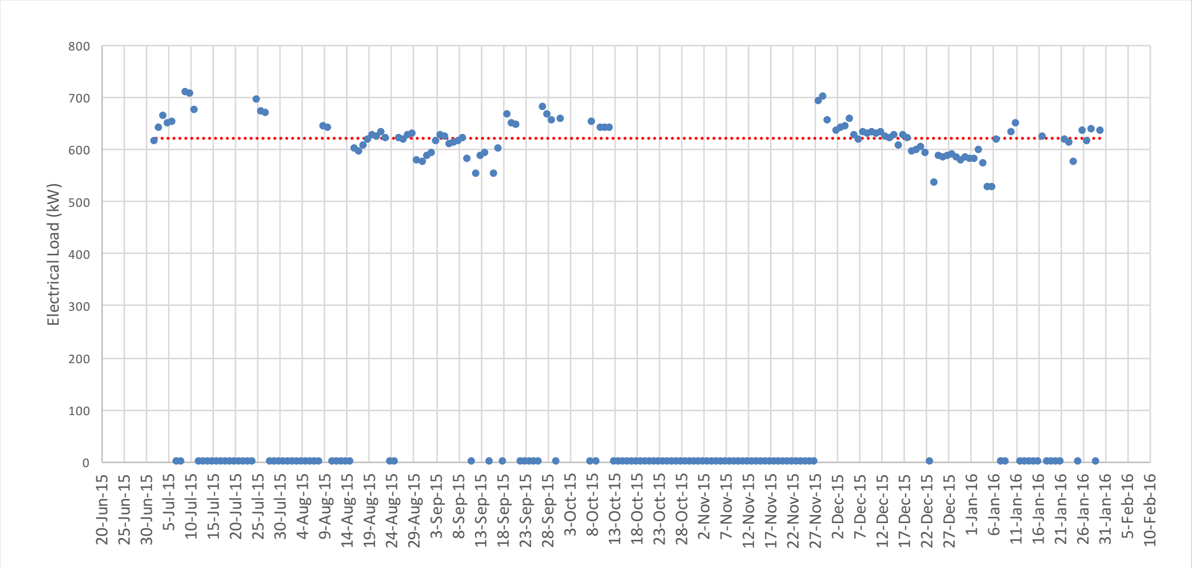


Figure 15. Average daily electrical load alongside (620 kW). This graph shows the ship's electrical load, during 24 hour periods alongside, when connected to shore power, with sampling frequency at 5 minute intervals. 0 kW loads are measured at the shore-

power breakers, during periods at sea or hen using diesel generators within the harbour, and days with partial sea-time have been "zeroed" to avoid skewing averages.

The overall electrical load represents all equipment connected to the ship's power. IPMS monitors approximately 256 kW of the total 620 kW average alongside load, which shows peak and low hourly load averages within 15.2% of the mean (Figure 15). Loads not monitored by IPMS amount to 361 kW, and are from systems such as combat weapons and sensors, multi-purpose outlets and ship's lighting, domestic services (laundry, galley) etc (Figures 16-18).

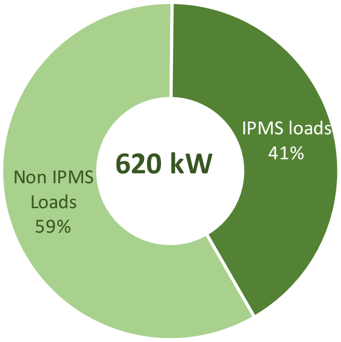


Figure 16. Ratio of alongside IPMS monitored and non-monitored electrical load.

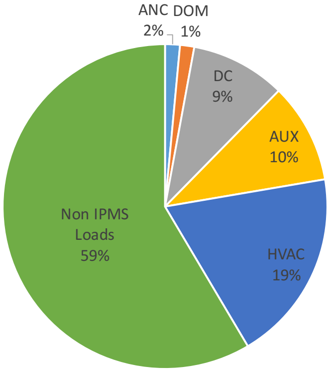


Figure 17. Overview of total alongside electrical energy breakdown by equipment group.

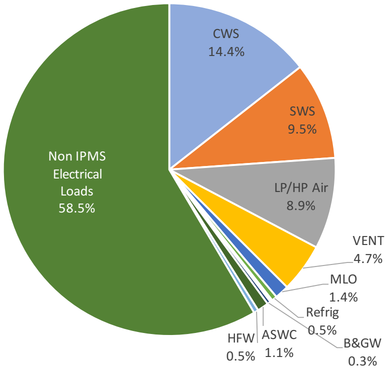


Figure 18. Estimated electrical energy breakdown by system.

Chilled Water System (CWS) poses the largest single electrical burden on the ship, using approximately 90 kW on average, when in port. The Chilled Water System is monitored by IPMS and dedicated, independent controllers not yet completely integrated with the IPMS software. The loading of each chiller is logged via independent controllers and stored in its internal memory. These controller logs were examined during the sailing period between San Diego and Esquimalt, and were assessed to estimate the average chiller loading conditions for at sea periods, during the fall 2015.

The fire pumps, air compressors and ventilation fans also draw significant power, some of which are energized continuously alongside. Four systems constitute 37% of the total ashore electrical load, and represent only a few (four) pieces of machinery (two chillers, one fire pump, and one LP air compressor). See Figures 16-18, and Appendix 4 for more details and breakdown of energy use by systems. These patterns are examined in more detail in the discussion section, which provides an analysis of these results and explores the contributing factors, issues and potential savings opportunities.

Chapter IV

Discussion

The findings from this study have established an initial baselining CPF's energy performance, using VAN as the test-case. The results reflect energy use patterns from a sum of 71 days at sea and 102 days alongside. This analysis defined the fuel and electrical energy usage, operational profile, and electrical energy breakdown, for systems monitored by the new IPMS software. This study represents the first attempt at coupling the relationship of energy with ship's operational requirements, by synthesizing manual bridge logs, with equipment digital logs. Superimposing the ship's speed and engine configuration data with mission objectives, illuminates when the ship was forced to assume less than ideal engine drive mode configurations. The OOW logbook analysis also made it possible to determine the impacts that heavy seas may have on the frequency of PDE use. These types of comparisons have provided the necessary context for CPF operational energy analysis and optimization considerations, and may provide a foundation for further, detailed energy management studies and initiatives.

Overall Propulsion Energy Use

Over the set of operations from July 2015 to March 2016, VAN used an average of 34 m^3 of F76 per day for propulsion, at an average speed of 11.6 knots. She was restricted in her drive mode choices a total of 30.6% of operations, and was otherwise free to adopt the most fuel efficient engine available. Her PDE was available 87.8% of all sailings, when not burdened by mechanical or sea state restrictions. VAN maintained operations within Special Sea Dutymen 5.4% of operations, where she was forced to be on twin gas turbines, as per naval doctrine. Other mission requirements, like trials, training, maneuvers, replenishments, and emergencies comprised 10.6% of all operations.

VANs operational profile for these sailings highlighted the amount of time spent at speed and drive-mode combinations, which illuminated that the ship spent the 72% of sailing between 10-17 knots, and only 4.16% of sea time above 20 knots (refer to Figure 6). Her profile shows significant opportunity to adopt the PDE for speeds below 18 knots, which are dominated by the single gas turbine drive-mode, where the PDE is only used 42.5% of the time. As the major enabler for propulsion fuel efficiency, increasing the time on the PDE where operationally and technically practicable, should be a priority.

Observation Overview

These findings clearly outline the daily fuel requirement of a ship across a variable set of operations, and define the relative speed-time profile, during operations as VAN transitioned from standard to high "readiness" (readiness levels indicate the ship's overall capacity to assume complex operations, where high readiness is the top tier, which VAN assumed in December 2016). While this information could be considered only a starting point for a better understanding of the fleet's steady-state energy use patterns and operational baselines, it is more comprehensive than any other previous study, made possible by the detailed machinery information captured in IPMS databases.

Overall, this study shows that significant energy savings are possible, without detracting from mission capability, but in fact, savings that would support enhanced operations and tactics, with improved endurance, range and persistence. This study also highlights the amount of flexibility a CPF may have to assume more efficient engine configurations, providing an opportunity that may be worth exploring. In many instances, the analysis reveals that an operator's choice to assume an "oversized" drive-mode (i.e., a more powerful engine than was required) played an important role in total fuel consumption. The study shows that assumption of the most fuel efficient drive mode, could deliver up to 25% fuel savings in theory, which is often not achievable, due to mission requirements. Examination of drive mode patterns highlight the criticality of the PDE drive mode across its complete power band, as an enabler for propulsion energy efficiency improvements.

PDE Availability Issues

Unrestricted use of the PDE is challenged by reliability and availability issues. Overall, the PDE was unavailable for a time that totaled 13 of the 71 days at sea (18.2%). In a few instances, the engine was out-of-service during heavy sea states, where it would not have been a practical engine due to risk of damage. Reviewing the periods where drive-modes were not operationally nor PDE-restricted, the potential fuel savings was estimated as if the most fuel efficient drive mode available had been adopted to meet the speed requirements (all speeds assumed to be the minimum required). For the purposes of this study, all ship's speeds were assumed to be required. The loss of the PDE due to both weather and mechanical issues resulted in less than optimum fuel usage during the return transit from San Diego in November 2015, during a period largely free from operational restrictions. During this four-day sailing, the sea state was the main driver for PDE unavailability (35% of duration), which overlapped with the engine's mechanical problems. Overall, the PDE was unavailable for 50% of the transit, resulting in a 41 m^3 daily fuel consumption average (propulsion only, which is 20% more than the 71-day average).

The lack of PDE availability, be that due to sea state or mechanical fault, removed several opportunities for fuel savings. In periods when the PDE was equal or more than 50% unavailable, the daily propulsion fuel consumption was greater than 35 m^3. Conversely, a few periods when the PDE was available and operational restrictions had relatively high daily fuel consumption (~40m^3/day). In this case, the lack of PDE use was primarily due to operator choice, as was the case during RAS operations, where the CO was required to consume more fuel in order to support frequent re-fueling training with a foreign tanker (Butler, personal communication, November 23, 2015). In other instances of high operational restrictions (SRD 504 training window) fuel consumption remained low (27 m^3/day), due mainly to slow speed loitering operations (9 knots average). Overall, daily fuel consumption varied significantly with operational and PDE restrictions, and depended also on the nature of operations and operator choice.

Review of the operational message traffic pertaining to PDE availability (called Operational Deficiency (OPDEF) messages) revealed that the engine was reported as inoperable for 88% of 2015, but in fact was used frequently, albeit with degraded components. Mechanical deficiencies on the PDE during this time included restrictions due to engine trials, cracked exhaust trunking, fuel line failures, oil filter defects, control system faults, and governor faults. In some cases, there was prolonged delays in notification of fault rectification, and even overlapping messages pertaining to the same defect. Examination of the ship IPMS data, clearly shows when the PDE was in operation and allows those time to be compared to deficiency messages. The qualifier on the messages indicating “inoperable” or “degraded” often did not reflect the true status of the engine, which was operated extensively during periods which indicated that the engine was out of service.

For each operational deficiency, a message is released by the ship. The date and time of the defect message did help reveal when the engine failure/defect occurred, and could often be observed in the IPMS data as a cessation of PDE operations several hours before the message was released by ship’s staff. These period gaps where IPMS and OPDEF message timings matched were determined to be when the engine was actually unavailable mechanically at sea, and were often logged in the bridge log books as a failure or engine problem. Overall, these periods represented only 12.8% of total sailings, much less than the periods suggested by the message traffic. This observation clearly shows that the OPDEF messages do not accurately reflect the true nature of the engine availability, nor does IPMS provide a corresponding indicator of engine availability or fault that can be captured in digital logs. IPMS currently only allows for a simple indication of engine status, which allows for operator to input “available” or “offline”, which can be used during oil changes or routine maintenance. More comprehensive IPMS indications could log real-time engine status and help naval equipment managers better understand true engine availability information to help manage through-life performance.

Even if the PDE availability improved, there are still significant issues to overcome in order to realize its fuel economy benefits across its entire speed band. Current policy is to avoid prolonged “low-load” operations on the PDE, where the naval authority has defined “low load” as below 14 knots. The exponential power relationship for ship’s hull and speed, dictates that 50% load is actually just below the top end (14 knots) of the speed range. This same direction from the naval authority stipulates that one hour in 24 should be spent at 17 knots on the PDE to reduce carbon build up in the engine, which may explain the significant time at 17 knots. The PDE is also restricted to a 17 knot maximum speed (vice its 18 knot practical maximum), unless required in an emergency, due to excessive thermal and mechanical stresses at the highest powers. Naval doctrine also stipulates that ships should not perform excessive maneuvering on the PDE, as the engine is designed for “cruise” conditions, with steady speeds and relatively calm seas.

Crews are now forced to complete more frequent oil changes due to excessive carbon accumulation and incomplete combustion at low loads. The VAN reported that prolonged operations below 10 knots required an oil change (1500 liters) every 80 hours of operations, which is both costly and logistically cumbersome. When speeds are maintained above 10 knots, VAN indicates that oil changes may be stretched to an average of 150-200 hour intervals, or even near 240 hours at average speeds above 15 knots (Carter, personal communication, August 23, 2016). These challenges have resulted in the VAN running the GT for extended periods below 10 knots, and sacrificing fuel economy to reduce oil change requirements. These maintenance issues, with their associated financial, logistic and environmental costs, represent difficult compromises to balance against the PDE's offer of improved fuel economy; especially when compared to the maintenance-friendly GTs. The emergence of the PDE as the preferred drive-mode at 12 knots is likely due to informal practice to assume the most economical speed on the PDE per nautical mile, and take advantage of the opportunity to use the PDE for less maintenance prone speeds of 10 and 17 knots.

Overall, the PDE engine availability issues, coupled with actual restrictions (low speed, high speed, maneuvering and sea state) and risks at speeds below 10 knots may even create a cultural reluctance to adopt the PDE, even when conditions are suitable. Improved PDE usage rates could be delivered through superior technical performance, especially at off-design conditions. Consideration of the PDE's energy advantage, off-design technical performance shortfalls, and related health and environmental (i.e., emissions and air quality) concerns, should together inform the best through-life support strategy for the PDE.

Reducing the 'oversized' drive-mode conditions and improving PDE availability could have significant impact on overall CPF fuel economy. Each sailing period was analyzed to better understand the implications of PDE mechanical deficiencies. Considering sea state and operational requirements, further fuel savings of approximately 74 m^3 (2.6%) was possible if the PDE was able to maintain 100% mechanical availability at sea (see Appendix 1 for more detail). This additional savings represents another-opportunity, which may be difficult to realize without promoting lower-load running on the PDE, and being able to overcome its carbon accumulation issues.

Special Sea Dutymen (SSD)

Currently, policy states that during SSD operations, the ship must be on two gas turbines. During VAN's operations, she spent 5.4% of her operations at SSD. If a single gas turbine had been used in place of the two normal engines, the ship would have used much less fuel. For example, on GT at 12 knots consumes approximately 1.5 m^3/hr, while two GTs uses 2.5 m^3/hr (70% more fuel). Overall, operating on two GTs for SSD consumed 80m^3 of fuel. It may not always be practical nor prudent to reduce the level of redundancy offered by two GTs, but it may still be important to note that minimizing the time on two GTs during SSD can save up to 3.3% of overall propulsion fuel. It should also be noted that the bulk of SSDs occur during operations like RAS training, which requires high levels of redundancy to safeguard against collisions when alongside other ships. In VANs case, approximately 38 m^3 of the total 80 m^3 possible SSD savings were during RAS operations. In many instance like this one, SSD is required to maintain adequate levels of safety-redundancy. Minimizing the time on two GTs before and after RAS engagements is likely the only real opportunity for savings, while achieving necessary redundancy margins.

Ship Speed Reductions

Slow speed operations are another very effective way to save fuel. As indicated earlier, the speed set by the Captain and the bridge watch-keepers was never questioned. Reviewing the fuel consumption data, suggests that a 20% speed reduction would provide a 25% or more fuel savings (measured savings could be greater due to the conservative rounding error using speeds to the nearest knot). Further savings would be possible by reducing speed to below thresholds where alternative drive modes could be assumed. Additional investigation with ship's navigator and captain could reveal where actual speed reduction savings would be possible, but were not part of this study. While it is not always practical or appropriate to reduce speeds due to operational restrictions, slower speeds represent a simple pathway for fuel savings.

Fleet Operational Profile Comparison

An initial comparison of the fleet average operational profile and at both sea and shore electrical averages were compiled via IPMS data from central servers. This data for the east and west coast fleets included information up to December 2015, and is missing for portions of various months. Further analysis should continue to determine actual fleet averages, as samples grow with the new IPMS system in operation.

IPMS data for each ship is transferred and manually uploaded in shore servers, and then consolidated into a central data base at the naval engineering headquarters in Gatineau, Quebec. Naval personnel are able to download fleet information and perform a comparison of IPMS speed/time profiles for all ship's fitted with IPMS. When assessing VANs operational profile, it was noted that some of the coastal data had not been uploaded to the central servers, and questions arose as to the completeness of the central data base. The data below provides for initial comparison of ship's operational profiles, but is not considered complete (various ships missing data, and average not yet weighted by sea days), but should be considered a preliminary comparison only, and should be completed once more frequent and complete IPMS data samples is available. As mentioned, VAN is currently operating more frequently than the fleet at speeds between 12 and 15 knots, but less than the fleet at 5 and 10 knots (Figures 19 and 20).

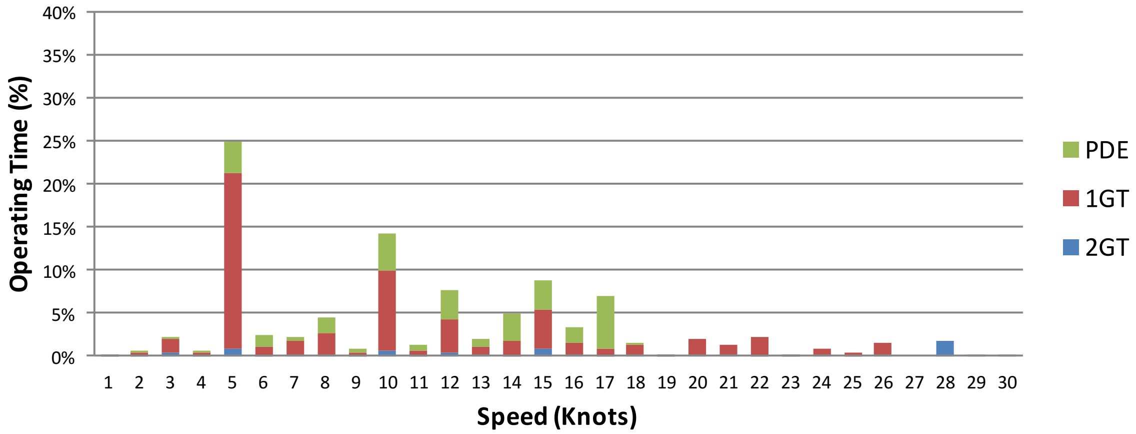


Figure 19. CPF operational profile average. Data source: IPMS central server information - March 2016

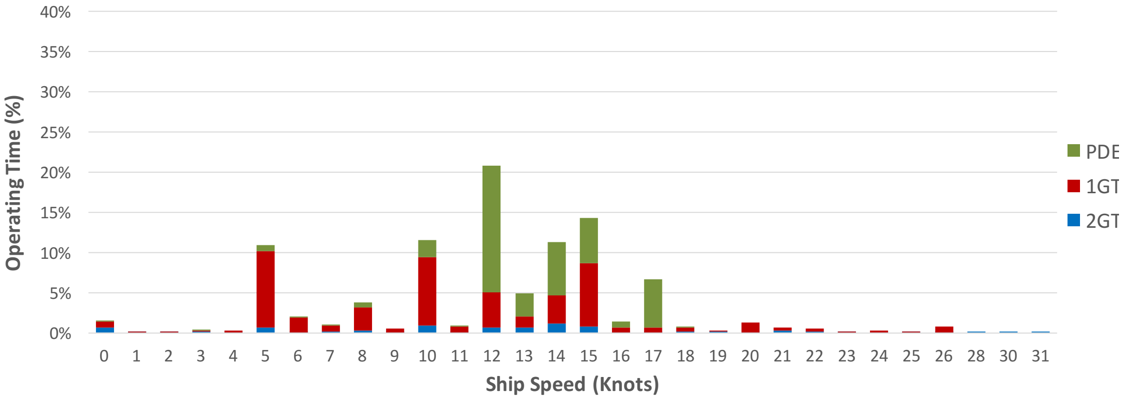


Figure 20. VAN operational profile (July 2015 - March 2016).

Once the operational profile is defined, a detailed understanding of the types of operations at each speed could provide insights and help identify opportunities for fuel savings. Unfortunately, sorting the current model data by speed may hide important operational information that helps define event start and end times. Thus, the current model does not easily show operational patterns at 5, 10, and 12 knots. Future data models should allow for better search-by-speed functionality. Preliminary review suggests the following patterns in speed requirements:

- 5 knots: Entering and leaving harbor, flight operations, gunnery and weapons trials, repositioning, loitering, and boarding party training.
- 10 knots: Entering and leaving harbor, flight operations, transits, repositioning.
- 12 knots: Transit, repositioning.
- 15 knots: Transit, flying operations, repositioning.

Discussions with the ship's staff suggest that 12 knots is often assumed since it is the PDEs most economical speed, and in some cases, more comfortable of a speed, than 10 knots, in rougher seas. Figure 21 and Figure 22 show the more detailed comparison of VAN and the fleet average for discrete speeds and PDE use at certain speeds. This comparison at various speeds illustrates the fleet's tendency at 5 knots, and VAN's tendency at 12 knots. The fleet is also experiencing more time at higher speeds (20-22 knots), which is less prevalent on VAN. More detailed examination of the fleet operational data could help determine what operational factors may be contributing to these differences.

The most significant overall observation from development of modern CPF operational profiles is the difference from the original design profile. As highlighted at Figure 1, the original design intent of the CPF was to spend the majority of time between 12-15 knots, but what was not accounted for in the design, was the strong tendency for the fleet to operate at a significant duration of speed at 5 knots. When designing for the future, careful consideration of the peak at 5 knots should be made by warship designers for both the remainder of CPF life, and for its replacement.

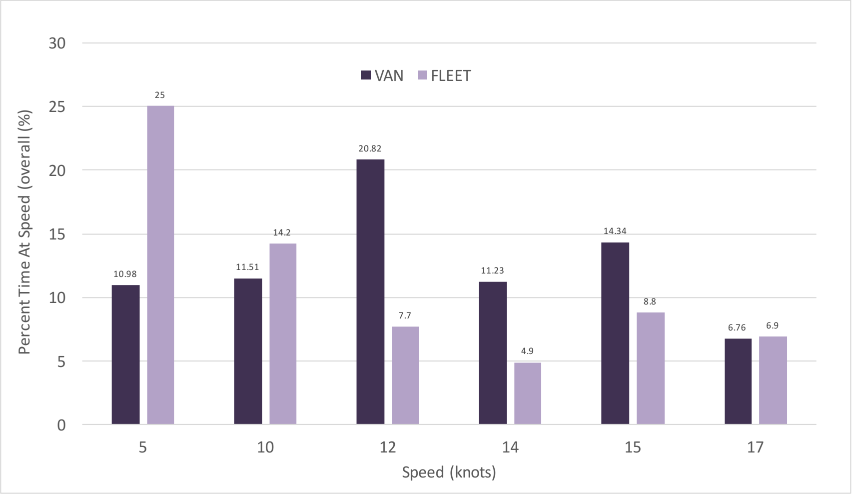


Figure 21. VAN and fleet comparison - time at speeds (overall).

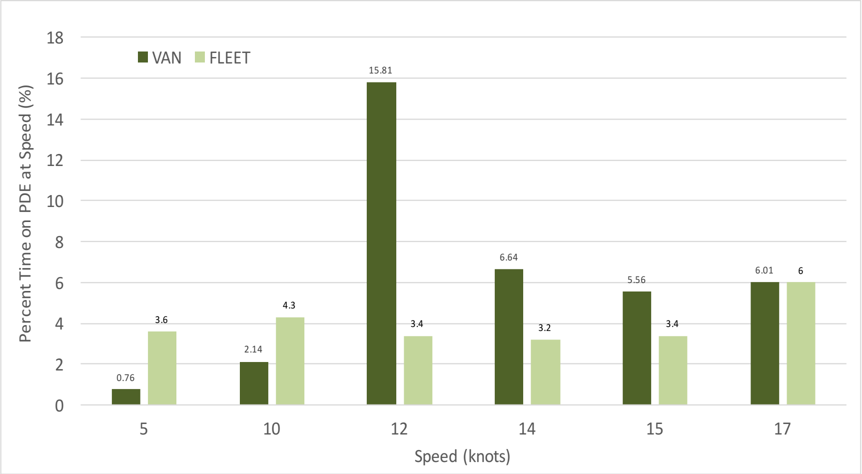


Figure 22. VAN and fleet comparison - PDE drive mode at discrete speeds.

More accurate data from ships operations will help define a steady-state CPF operational profile, and help ascertain how much the 5 knot peak is influenced by the post refit trials program, and how much of the 5 knot peak is due to normal, routine fleet operations, like boat operations, repositioning, flight operations etc. The increased use the PDE at any speed below 18 knots, continues to be challenged by PDE performance shortfalls, and if improved, could deliver significant fleet-wide fuel savings.

Electrical Energy Use - At Sea and Alongside

During her 71 days at sea, the ship had an average electrical load of 961 kW, fed from the ship's diesel generators. Alongside, the ship had an average load of 620 kW, fed from shore power, via the municipal energy grid. Many systems run continuously both at sea and alongside, and pose significant annual power demands.

Surveying the electrical running loads of various motors provided insights into the power demands of individual equipment, and was averaged for units of the same type and application. In very few instances, electric current was approximated using the motor's manufacturer's tally-plate data, in cases where equipment was unavailable during surveys, which makes up less than 1% of the overall demand (see Appendix 3 for more details). More comprehensive surveys in the future would help assess the performance of individual equipment, and provide a more accurate representation of the overall electrical system demands. Continuous duty motors and equipment not monitored by IPMS, such as ship's lighting, galley, space coolers, ship's laundry, and combat systems, also pose large energy demands, and should be measured to define actual duty cycles and total electrical load. For these types of loads, the duty cycles were approximated using at-sea surveys and through estimates derived from discussions with the ship's crew.

Forecasted Annual Electrical Power Demand and Savings Opportunities

IPMS records the status of many individual pieces of electrical equipment, and stores in its digital database. Data captured in IPMS machinery logs indicate if motors are running or stopped, and sometimes, at which speed. Forecasting this data over an annual sea-shore ratio (of 105:260 days) provides an estimate of annual electrical loads by system, shown in Figure 23, below, followed by equipment explanations.

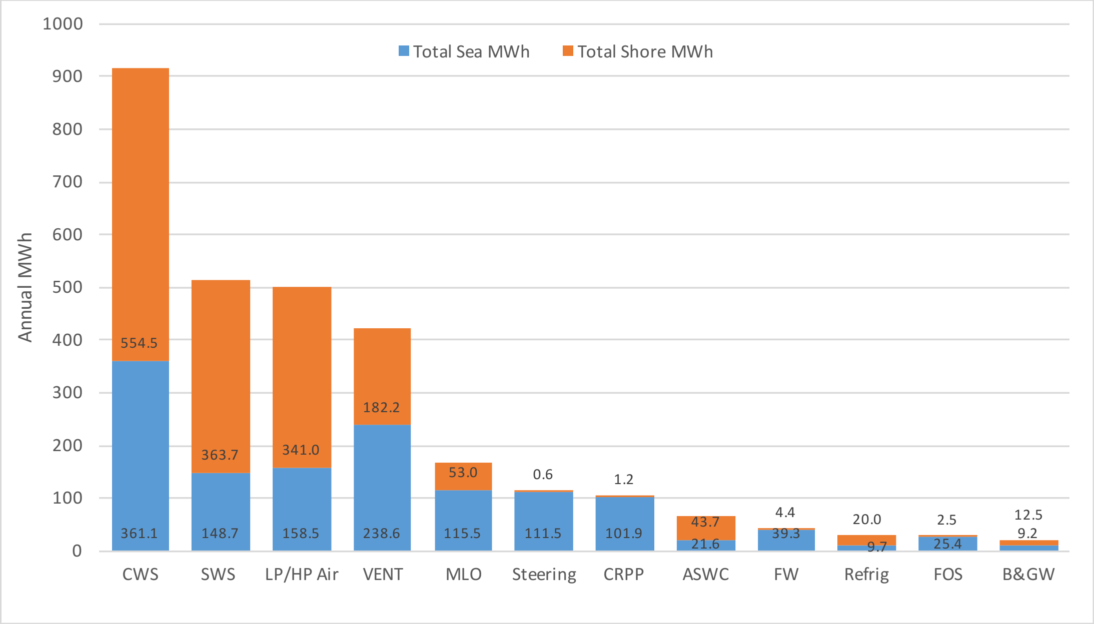


Figure 23. Annual MWh of electrical demand. Diagram shows IPMS monitored loads only, using a sea/shore ratio of 105:260 (the fleet average for west coast CPFs in 2014-2015 was 105 sea days).

Both the chilled water system and ventilation systems are monitored by IPMS, but make up only a portion of the HVAC system. These two systems represent the top two IPMS electrical power demands on board, followed by the compressed air systems and the sea water services. As these systems are largely configurable and include redundant architecture, they likely have large potential opportunities for energy savings.

The four chillers provide cooling water to various equipment and space heat exchangers for temperature control and increased crew comfort. Their refrigerant compressors are powered by large electric motors (~50kW), providing chilled water to various users via 10kW pumps, which run frequently both at sea and alongside. The CWS cooling load is dictated by demand around the ship, due to both automatic and manual temperature controls throughout the ship. Many of these controls are in fault, and poor energy husbandry was noted during rounds of numerous spaces around the ship. Many vacant spaces were being over-cooled (some unmanned spaces had ambient temperatures of 12^{o}C, in outside temperatures above 20^{o}C). Anecdotally, ship's crew were discussing a plan to purchase insulated jackets for on-watch Operations Room staff, who frequently occupy the routinely, overcooled space. The scale of energy wasted by excessive cooling was not quantified by this study, and additional assessment is recommended to determine the scale and frequency of energy savings.

Many navies are focusing significant investment and attention on energy intensity of HVAC and CWS systems, due to high levels of inefficient configuration and in some cases, poor system design and underperforming equipment. The USN has developed a program focused specifically on the future naval HVAC equipment, in order to both reduce cooling load and provide additional electrical load to power more essential services. The USN has also begun to invest in HVAC related technology and system information with a new focus, and are developing Thermal Management Control Systems (TMCS) (McCunney et al., 2012) to provide enhanced levels of system monitoring and control, more appropriate for a system of such importance, and its high through-life cost.

Our navy has recently replaced the controllers on the chillers with more efficient electronic units with improved part-load efficiency. Future chiller units will likely be more efficient than the legacy compressors, but improving overall crew behaviors and reducing system loads can deliver a greater magnitude of savings, than achievable just by introducing new technologies.

Large electric motor driven fans in the machinery spaces exchange air and remove heat from running machinery. Ventilation fans have been identified as the second largest at sea electrical equipment group (monitored by IPMS), and the fourth overall user of electricity on board. Further analysis of configuration and operations of these high energy users will help understand if meaningful energy savings are possible across all ventilation fans. Many options exist to find improved energy efficiencies to move engine room air, such as clean air pathways, optimized fan blade design and cleanliness, and even high efficiency motors with electronic part-load controls. The most effective initial step to improve the energy intensity of this system is to eliminate unnecessary use, and then reducing demand. Since these fans are configured manually, there is a risk that they continue to run even after the requirement has been removed or altered. Comparing fan operations against the ventilation requirements (i.e. outside temperature, running equipment, sea temperature, and operations) could help find ways to reduce unnecessary load.

The ship’s Low Pressure (LP) air compressors were noted to have uncommonly high duty-cycles, somewhat uncharacteristic of system design intent. Discussions with the crew revealed that the system is fraught with leaks, and requires almost continuous compressor operation to maintain system pressure, which is needed to actuate important pneumatic valves throughout the ship.

Fire pumps run continuously at sea and alongside to pressurize the firemain, in case of emergency on board. The smallest fire pump (called the Jockey Driven Fire Pump (JDFP)) has not been in service on VAN due to recent direction from the naval shore authority to reconfigure the system to avoid overpressure and system damage (DNPS 3, 2015). This technical restriction has imposed the use of a single motor drive fire pump (MDFP)) for daily operations, which is 1/3rd more powerful than the JDFP.

Non IPMS Monitored Loads – Estimates and Considerations

The duty cycles of the systems not monitored by IPMS were estimated, and compared to the IPMS monitored loads (Figure 25, below). Ship's lighting, space coolers (FCUs), galley equipment and ship's laundry services were estimated to determine their potential contribution to overall energy use, and illuminate possible areas for further investigation of reduction potential. These systems constitute some of the larger loads on board, and should be examined further to better understand actual power demand patterns, and to identify any areas for possible energy savings. Further estimation data is contained in Appendix 3.

Ship's general lighting is powered through a series of distribution panels and can be measured to determine overall power demand at sea and alongside. The average current draw for each of the eight panels was 27 amps, which, at an estimated 35% duty cycle, requires 361 kW per day. The lighting duty cycles depend on the quality of light services, their required time on, and habits of the users.

Twenty high power (500W) halogen lights are positioned throughout the machinery spaces, which utilize significant amount of power, and are often not configured for effective illumination. The lights were reviewed, and found to be improperly configured (Figure 24), obstructed with debris, and directed away from task areas, providing redundant and/or unrequired lighting of bulkheads or already illuminated passageways. Switching these lights off when not required, and replacing with lower power LEDs would be an effective way to reduce energy and heat loads in the engineering spaces.

Figure 24. 500W halogen light in Forward Engine Room (FER). Figure shows light directed away from crew traffic and task areas to avoid glare and heat when working nearby. Several 500W lights were positioned away from task areas, providing light where services were not required.

The HVAC cooling load on the ship is partially monitored by IPMS, but also includes equipment not fitted with remote monitoring sensors, and remains unavailable for electronic log, data analysis. HVAC equipment in west coast ships is primarily used for cooling in warmer climates. Individual electric heating elements are provided in many unit heat exchangers, but are activated infrequently, and have not been assessed in this study. The ship's four chilled water plants deliver cool water to four main air conditioning (AC) units (two main service units, a galley, and operations room AC plant), and to heat exchangers throughout the ship to maintain room temperature. These heat exchangers are called Fan Coil Units (FCUs) and Booster Cooler Units ("KUs"). Electrical load checks were completed on the AC plants, and taken from the Ops Room unit, due to inaccessibility of motor controller for current checks. The 81 FCUs and 39 KUs use cooling coils and fans to reduce room air temperature, and many units remain on maximum output settings in unmanned spaces, and were found to have faulty controls, during initial surveys at sea. Only a comprehensive analysis of the total system would reveal accurate, full power demand and condition assessments, along with areas for improved configuration, settings, and appropriate demand. This study provides an initial examination of AC unit, FCU, and KU power requirements, estimated in Appendix 2.

The galley is in constant operation at sea, with ovens and convection steamer drawing significant powers, frequently throughout the day. Other equipment, such as the warmer, griddle, kettles, steam line etc., were surveyed to determine current draw, and provided estimated duty cycles, through discussions with cooks on board.

Ship's main and distributed laundry dryers and washing machines are also running frequently at sea and less-so, alongside. The electrical load of these units was surveyed at sea, and duty cycles were estimated through discussions with ship's staff.

IPMS and Non-IPMS Electrical Load Estimates

Based on the estimates and surveys of non-IPMS monitored equipment, additional systems energy use was compared for both at sea and alongside periods, based on an annual 105/260 sea, shore ratio. This comparison is illustrated at Figure 25, below.

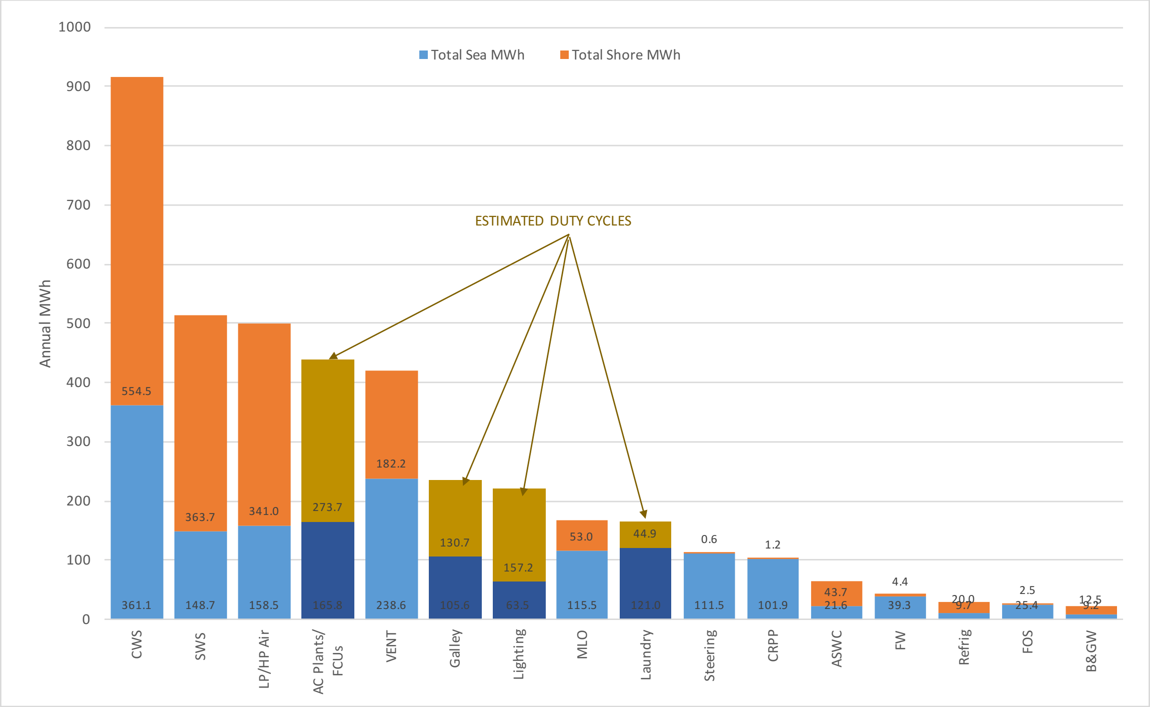


Figure 25. Annual IPMS monitored and non-IPMS estimated electrical load breakdown. This figure represents an assumed sea:shore ratio of 105:260.

Single Diesel Generator Operations

Amalgamation of all electrical power generation to a single DG, was assessed to better understand its potential viability and advantages. Shifting to a single generator would allow one generator to run near maximum capacity, instead of two diesel generators at very low load. Single DG operations could reduce engine hours and maintenance on the remaining DGs and reduce noise signature and decrease engine carbon accumulation and improve emissions. On the other hand, operating a single DG removes additional electrical capacity for equipment that automatically comes on line, and may risk tripping breakers, and interrupting power to sensitive electronic equipment. Overall, combining the load onto a single DG could be viable if the load was reduced by (by 15% or more) to stay within the upper power limits of the generator set and load-tripping settings. Maximum power demand is normally within 15% of the average hotel load demand alongside. The peaks for at-sea electrical load may be much higher due to equipment starting currents, and have been shown to spike up to 30% more than the average at-sea demand.

Fuel savings potential on a single DG may be limited, due to the almost flat specific fuel consumption (SFC) curve of the DGs. While some savings are possible due to the poor low-load fuel economy of the engines, perhaps the most attractive savings are related to reduced maintenance demand achieved by halving the hours of the ship's DGs. And if consolidating power on a single DG can be safely managed (with respect to platform and equipment), the benefits of decreased fuel consumption may be considered trivial (estimated at 0.66 m^3/day), due to the DG fuel curve being relatively flat for higher powers, and a near-linear fuel consumption relationship with kW. SFC at 475 kW is 250 g/kWh, and 225 g/kWh for 950 kW. Single DG operations would likely be most attractive due to benefits of decreased DG hours and maintenance burden, lower lubricating oil consumption, reduced cooling loads (thus further reducing electrical load), reduced noise, reduced emissions, and the third order effects of reducing the support burden on shore agencies that otherwise aim to improve DG low load performance, rather finding clever ways to reduce the likelihood of creating the problematic condition in the first place, which is an operational issue, and one which the engineers are not normally responsible for.

Fleet Electrical Load Comparison – At Sea and Alongside

An initial comparison using available fleet data was completed, to compare the electrical load averages for various CPFs (Figure 25). This comparison used daily power averages in IPMS, to build monthly average load data. IPMS data shows power on DGs, switchboards and shore power breakers. For this comparison, days with less than 50 kW on shore power breakers were considered at-sea days, while days with less than 50 kW on generators were alongside days. Several days were discounted using this filter to avoid days where load was shared between both shore and diesel power. Several other days were discounted due to unknown power conditions, or erroneous data. This assessment therefore ignored days with partial alongside and sea time, and assumed days on DGs were at sea, vice potentially alongside in foreign port, using generators for shore power. A coarse approximation is only possible without more complete or comprehensive IPMS data for each ship in question. This method here is considered only an initial approximation, since a number of days, months or portions had missing data and corrupt information. For example, HMCS CHARLOTTETOWN (CHA) shows months with zero days of data, and others had 2 or 3 days of at-sea power readings (ie. samples) over a month.

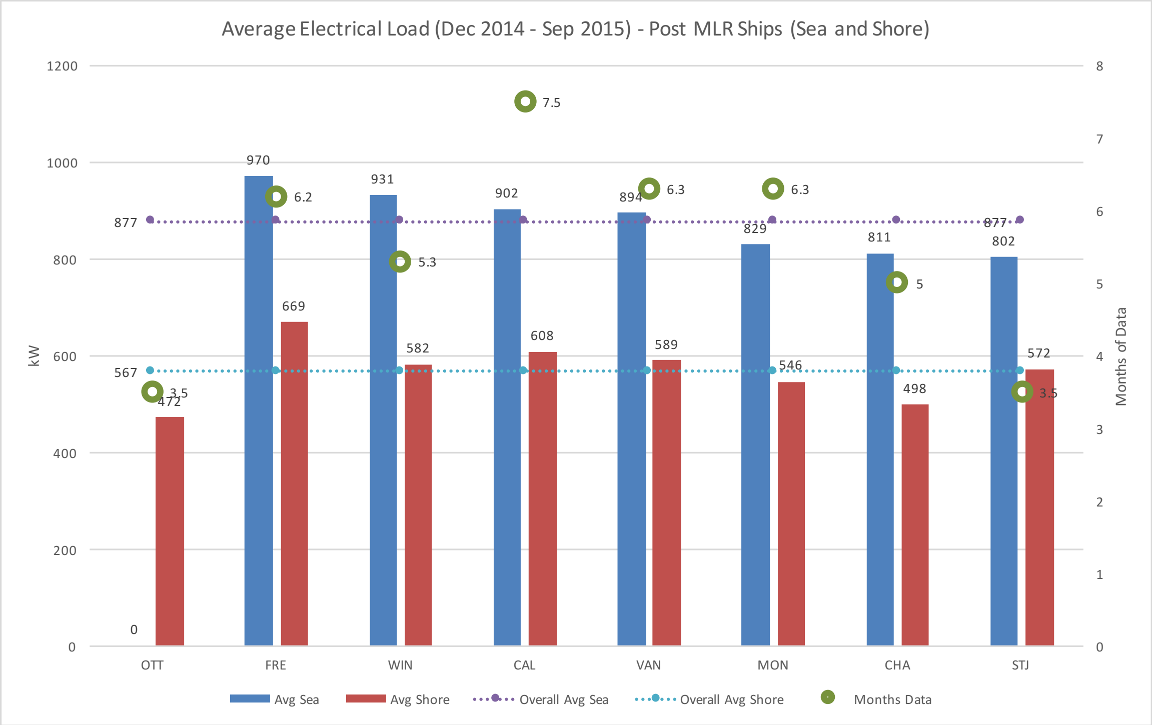


Figure 26. Daily average fleet electrical load - At sea and alongside. This figure represents data for eight of the twelve ships, some of which are operational, completing trials, and or near the end of their mid-life refit (data taken from period between Dec 2014 and Sep 2015). The above IPMS data pertains to ships that have completed, or are emerging out of the refit period, with full, IPMS functionality. Note that Monthly data were not always available for each ship, during this period.

This initial assessment suggests that the overall fleet power average from late 2014 to mid-2015, is 877 kW at sea and 567 kW alongside. Considering that ships with less months of IPMS records may also coincide to ship's in the early reactivation period, and may not have all their machinery installed, as is the trend. IPMS is one of the first systems to be reactivated, prior to many other systems being installed on board. This could suggest that a ship may only be fitted with a full complement of machinery after several months of IPMS data collection. If we assess ship's with more than six months of IPMS information, the average power per ship was 898 kW and 603 kW, for sea and shore, respectively, which closer (7%) to the VAN trends of 961 kW and 620 kW.

VAN's 961 and 620 kW actuals were defined against times at sea and shore, and also clearly showed any anchoring or alongside periods using generators, which removed those periods from energy baseline assessments. Closer analysis of ships with more IPMS samples, organized clearly into actual sea and alongside periods, will help determine the actual, steady-state electrical powers of the fleet. Initial comparison of the fleet electrical data suggests close (within 7%) of the VAN total.

Examination of the WIN loads during her known overseas operations in July 2015 shows an average load of 946 kW during a month of consecutive sea days. This consistent, steady-state comparison potentially provides an equivalent comparison to VAN's average, and is very close to the observed VAN power levels, and may be close to a fleet average power. Analysis of any ship's energy use, once completely reactivated and complete their trials program, could result in more accurate and representative fleet averages that more closely align with actual daily fuel and energy use. Many ships have gaps in their IPMS data saved on shore servers. More investigation regarding data completeness and quality will be required if informed engineering and operational decisions are to be made regarding the equipment and system performance.

USS PRINCETON Electrical Energy Use Study (2001)

Civilian energy experts performed some of the initial USN warship energy studies in 2001, on board USS PRINCETON. Their team completed a detailed analysis of chilled water and both system configuration and settings to ascertain how much energy the ship could save if optimum design and operating parameters were met. They discovered that 20-50% of her electrical load could be saved with moderate retrofitting efforts of the biggest users - chilled water system, pumps, motors, fans and lighting. This study outlined a number of recommendations, including equipment, system and platform operational improvements, and possible areas for future investment in improved design and/or technology. This study highlights their assessed cost of shipboard power, and recommendations that could be as valuable to the RCN, as they have been to the USN and their i-ENCON program. A summary of the key themes from the RMI report offers the following key principles to guide energy savings (Lovins et al., 2001):

- Reduce energy demand by reducing load, removing parasitic loads, and turning off redundant/unnecessary equipment.
- "Right-size" equipment to the load demand (i.e. avoid oversized motors, pumps, piping, etc.).
- Optimize system architecture for multiple load conditions, not a single load point.
- Specify Premium efficiency equipment, and use measured efficiency in calculations/assessments.

- Integrated Analysis: Avoid assessing supply-side efficiency improvements sequentially or in isolation of end-use efficiency improvements, which risks losing three quarters of the potential savings opportunity.

Reducing Energy via End Use Efficiency

The term “end use efficiency” refers to the overall system energy use benefits by reducing demand, and the how energy transmission losses are compounded throughout a system. Figure 27 illustrates the losses across a typical electrical energy system, and how saving a single unit of electricity can save ten units of fuel at the source. Illustrating invisible energy savings may help unlock savings potential, and understanding the upstream benefits of load reduction can provide a much more compelling incentive for behavior change. If helpful, the crew can consider it another way – if the ship is attempting to reduce a system’s fuel consumption by 10%, it may only require a 1% load reduction; which may be much more easily achieved in even optimized systems. Expanding this argument of cascading system losses, to include the upstream logistics system required to deliver that fuel, could also demonstrate a compelling visual picture to understand the total cost of fuel and the potential savings from even a few less units of overall demand. Educating users on the upstream benefits of reducing demand, may remove the tendency to measure the energy savings at the load, rather than the source.

Commodity Costs and the Fully Burdened Cost of Fuel & Energy

The US and other navies are starting to formally account for the upstream costs associated with fuel supply, handling and support. This “fully burdened” cost of fuel, is a more complete assessment of total fuel costs, which are meant to more accurately value assets cost and logistic risks and opportunities.

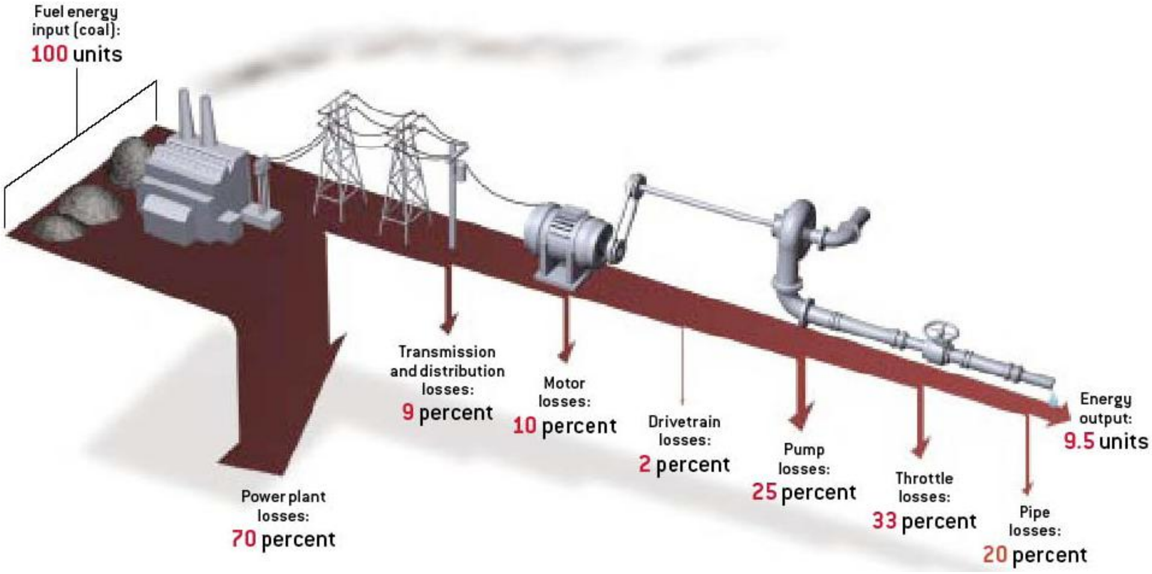


Figure 27. Energy system losses between power generation and delivered services. Figure source: (Lovins, 2004).

The fuel and electrical energy baselines were used to determine the typical fuel and energy costs for VAN, based on an annual average sea:shore ratio of 105:260. Using the 2016 F76 price of \$2.79 USD per gallon, the daily propulsion fuel consumption of 33.9 m^3 would cost just over \$30,000 Canadian (CAD). For 105 sea days per year, the fuel commodity price would be \$3.38M per platform, with \$0.667M used for electricity at sea. For alongside power, the ship uses a mix of both diesel generators (i.e., fuel), and the jetty's connected electrical utility, which is provided by BC Hydro, in home port (low or high rates (0.0536 \$/kWh or 0.1114 \$/kWh, respectively) used here as initial approximations, which depend on the overall military base's power demand). Total, annual ship fuel and energy costs could then be calculated using this sea:shore ratio and the estimated mix of diesel and shore power alongside (using a single DG fuel consumption rate of 0.235 kg/kWh for 620 kW load). Total energy estimates (propulsion and electrical at sea, and shore) are shown below at Figure 28, and would vary depending on how shore power was derived and priced. This estimate suggests that each day, the ship spends $32,200 in propulsion fuel, $6,350 in fuel to power diesel generators, and when alongside, near $2,500 each day in electricity. and This estimate defines that annual electrical energy costs approximately $1.32m per year, which is 28% of the total ship's energy costs.

Calculating power costs using BC Hydro rates shown here ("Large General Service") is considered conservative, since they are some of the lowest rates in North America, and actual shore power in various locations are likely to be higher. This rough analysis shows that electricity commodity costs are roughly a quarter of the annual fuel costs, and slightly more when DGs are used to generate shore power. When applying this model fleet wide, the annual total energy bill ranges from $51 and $63 million, depending on how shore power is generated.

Historically, only the fuel commodity price has been the key financial metric to drive naval acquisition and operational decisions. Recently, the US Department of Defense (DoD) has begun measuring the "all-in" costs of energy to help inform decisions related to military costs and capability. The term "fully burdened cost" of energy or fuel (FBCE and FBCF, respectively) can be used to account for the both the unit price of fuel, and the full spectrum of support costs required to provide that fuel to end-users.

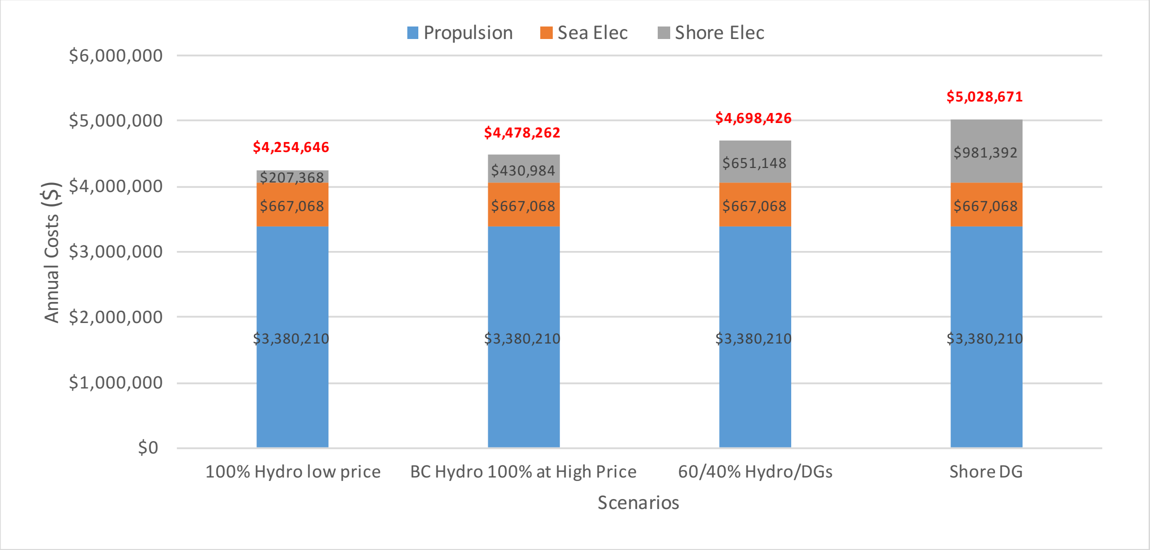


Figure 28. Annual ship propulsion and electrical energy cost mix. This figure shows estimated costs based on shore power scenarios (“Shore Elec” in grey), with overall totals in red.

Using the estimated annual sea and shore electrical power breakdown (at Figure 25) we can also estimate the commodity costs for each system. Using a mix of BC Hydro (at $0.1114 / kWh) and an estimated alongside energy mix of 60% shore power and 40% DG power, the overall system energy costs outlined at Table 8, and show that costs are still driven mainly by fuel use, followed by shore electricity, even with the proportion of some system’s energy use being primarily a function of alongside use.

The annual fuel bill for the fleet could be much less with improvements to only a few systems. A design that would allow for eliminating continuous cycling of the fire pump would save $1.15m over the fleet in a single year, or over $17m for 15 years of service life. It may be reasonable to weigh energy costs against the costs of repairs, use to determine the best strategy for repair, which could save enough electricity and fuel to pay for leak repairs many times over, and deliver the associated benefits of reduced system maintenance, noise, heat and logistic burden - for free.

Table 8. Annual estimated system energy costs per ship. This table illustrates commodity prices for systems above $40,000.

System	Annual Energy Commodity Cost
CWS	$192,795
VENT	$102,174
AC Plants / FCUs	$101,044
SWS	$96,385
LP/HP Air	$91,745
Laundry	$51,087
CRPP	$43,958
Galley	$40,880
Lighting	$40,736

Doerry (2012) illustrates the US Navy's FBCF in 2011 prices, and defines the per-barrel commodity price of $136.72 US, with an additional $46.26 for the handling, storage, asset depreciation, operational and support costs. This additional premium is roughly a third of the commodity price. His analysis would suggest that the FBCF for one barrel of F76 is near $185.98, rather than the purchase price of $139.72. The fully-burdened costs is meant to be a more accurate representation of true fuel costs, and reflect the value of fuel savings. The FBCF can help avoid distortions in acquisition decisions, that historically would have undervalued energy based only on commodity costs. In cases where fuel protection is paid for in human life, the FBCF can be considered immeasurably high. At this stage, it remains unclear whether the US Navy's FBCF/E prices would be greater or lower than the RCN equivalents, since the figures are based on assets, which are unique to each service. Only further analysis could help determine an accurate RCN FBCF equivalent to guide future equipment and energy related decisions.

Considering that today's F76, per-barrel costs are approximately $124.74 (US DoD, 2015), then one could assume that the FBCF may be close to $171 (burden premium of \$46.26). This FBCF would suggest that VAN's fuel usage during the assessment period (2884 m^3, at 6.29 bbl/m^3) equals 18169 barrels of fuel, or \$3,106,963 USD, which totals ~\$4m CAD; and suggests annual fuel savings of 10% may be worth up to \$400k CAD.

Based on the annual fleet fuel use average of 3500 m^3 at today's fuel price (\$0.98 / liter), the forecasted commodity and FCBF costs and potential savings can be assessed. Using the above assumptions, after 15 years of service, 10% fuel savings can deliver over \$81 million in cost avoidance, which is enough money to fuel all 12 ships at sea for 2 years.

Similarly, the costs required to deliver a watt of electricity to the end-user is a function not just of the fuel, but also of the infrastructure costs associated with the power generation and distribution systems. Just as your residential utility power bill includes the appropriate portions of all maintenance and operating costs (associated with power generation and transmission systems, wages, repairs, upgrades, etc.), a full system cost would more accurately reflect the true value of a watt of electricity on ship. To accurately capture the total cost of ownership of electrical energy systems, one would have to account for all system infrastructure, training, operating, maintenance (labor and parts), capital projects, procurement, logistics, etc. These elements, coupled with the inefficient power generation systems of ship's generators, suggest that the price per watt of a warship's power may be up to an order of magnitude more than what one normally pays for conventional electrical power ashore.

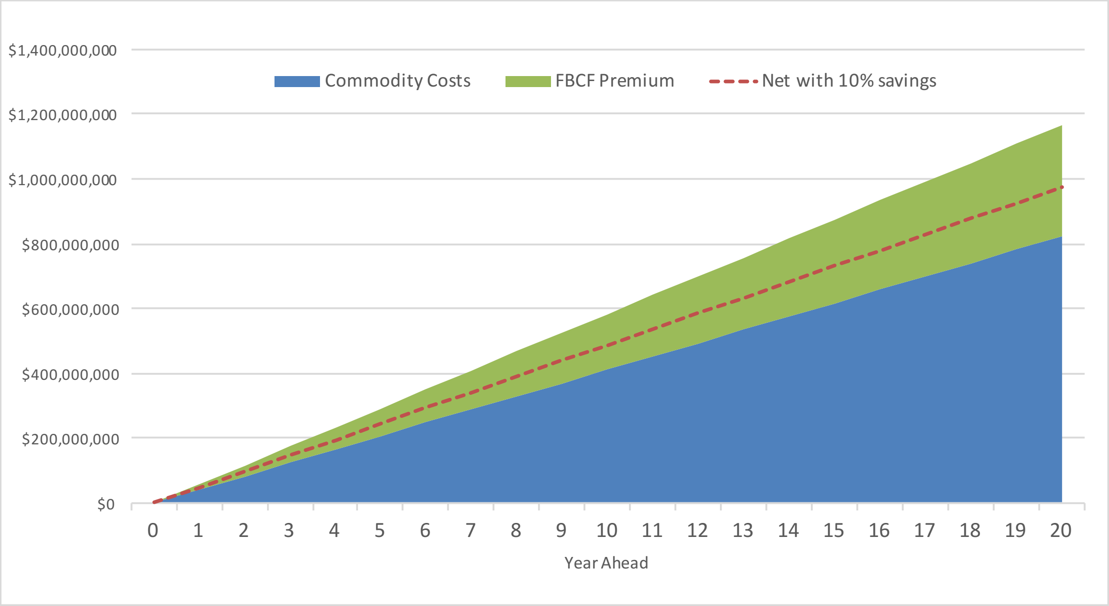


Figure 29. Projected, cumulative fleet fuel costs at current prices.

A USN study of shipboard electrical power concluded that a MWh on ship, was 10 times that of conventional shore power (Lovins et al., 2001), which could be even higher for the RCN, depending on how our maintenance and overhaul trends compare to the USN equivalents. This suggests that a naval watt of electricity is worth much more than a commercial or residential watt, and should be treated accordingly. Defining the RCN true value of a watt could be very important to help inform design and procurement teams in their trade-off and options analysis for both replacement programs and future ship design. Such decisions would rely on complete and accurate financial data for ship's power generation system maintenance, and operating costs, including major projects, upgrades, training, and other related support costs.

The above fuel and energy cost analysis makes it possible to approximate only the commodity cost of a MWh of at sea electricity, which is $0.27/kWh, and does not include the full-cost imposed by power generation and distribution (PG&D) equipment and upkeep. Even though this is more expensive than shore power in home port, it suggests a much lower price than accurately reflects the cost of delivering power to end users, which risks distorting energy related decisions in maintenance, support, and procurement activities.

Initial examination of ship's maintenance records for electrical machinery do not clearly show the total financial investment required to maintain, overhaul and support the PG&D system, as some records only commenced in 2003, several years into the ship's life, they do not include some refit, OEM service, or other overhauls that were completed through contracts at the headquarters. Without this data, a true estimate of through-life costs, and actual price for a MWh of shipboard electricity cannot be made.

Initial Greenhouse Gas (GHG) Assessment – Propulsion and Electrical Energy

Applying the Marine Diesel Oil (MDO) fuel emissions factors from the International Maritime Organization (IMO, 2014) help calculate the greenhouse gas emissions of the ship. Based on the fuel used for ship propulsion and electrical energy generation, the ship produced approximately 8118 tonnes CO2e from the combustion of 2889 m^3 of F76 marine diesel fuel. This fuel was consumed over 71 days at sea, and equates to 114 tonnes per sea day, of which 1/5th is used for electrical power generation (see Figure 30).

GHG emissions are based on combustion of 2413 m^3 of F76 for propulsion and 476 m^3 for electrical power generation. Calculations use Marine Diesel Oil (MDO) emissions factors of 3.206 g CO2/g fuel, 0.00006 gCH4/g fuel, and 0.00015 gN20/g fuel.

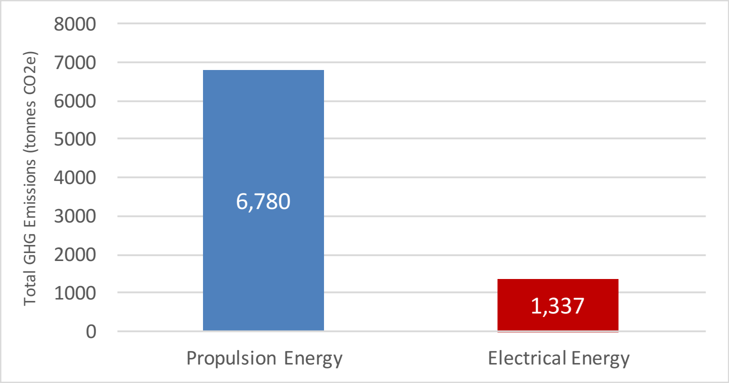


Figure 30. Total at-sea GHG emissions (propulsion and electrical). This figure does not include the ship's embarked vehicle contributions (ie. ship's boats, helicopter).

The total alongside electrical energy GHG emissions will depend on the source of power, and its carbon content. Detailed assessment of the shore power electrical GHG emissions has not yet been completed. At home in Esquimalt harbor, the ship normally uses shore power, which is derived from a mix of approximately 93% hydroelectric power, and 7% LNG (BC Hydro, 2016). While alongside in foreign port, the ship may use shore power and/or diesel generators, which will vary depending on the power availability and ease or viability of connection (ie. some foreign power outlets are difficult to couple with NATO or North American standard physical connections). An ideal scenario would be where all of the ship's alongside power was derived from low-carbon, energy sources, as is the case in home port. If the ship derived all shore power from home port, assuming VAN is operating at a slightly higher than average sea-shore ration of 0.5 during these months (i.e., 71 days at sea, 142 alongside days), the ship would have produced 70.4 tonnes CO2e (see Figure 31), which represents 0.9% of total GHG emissions (8118 tonnes, calculated above).

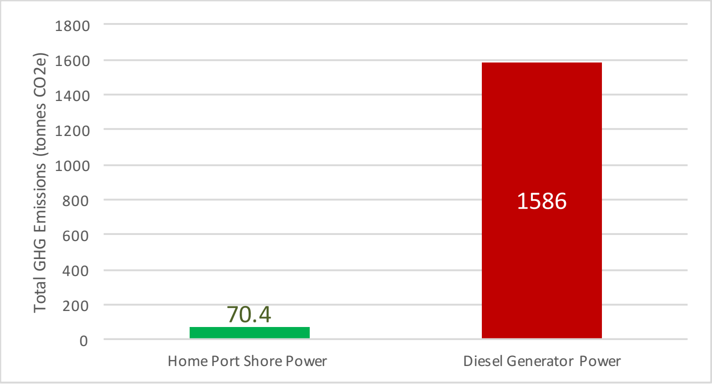


Figure 31. Alongside electrical power GHG emissions (CO2e). Shore power based on 93% hydroelectric/7% LNG, and diesel generator power at 620 kW at 234 g/kWh fuel consumption, for an estimated 142 days alongside.

If the ship had utilized diesel generators for electrical power alongside (~142 days), then the ship would have consumed approximately 564 m^3, or 3.97 m^3/day of F76 (using a DG fuel consumption of 234 g/kWh at 620 kW (assume single engine), with a density of 0.876 kg/litre, at 15°C). Using these approximations, the total GHG emissions for alongside power generation using ship's generators would equal 1586 tonnes, CO2e. Therefore, each day of shore power, reduces the GHG emissions by up to 10.7 tonnes CO2e, depending on the cleanliness of the primary electricity source (11.17 tonnes/day for 142 days). A hydroelectric power mix in home port equals 70.4 tonnes GHG (0.495 tonnes CO2e/day), which gives a savings of 10.67 tonnes CO2e each day using shore power.

Recommendations and Conclusion

This study provides an initial examination of CPF propulsion and electrical energy use patterns. The combination of digital machinery data and bridge logbooks provided the context necessary to understand how and why the ship uses energy to achieve various missions, and to identify possible opportunities for savings. The study suggests that 10% of total fuel could be saved if the ship assumed the most efficient engine configuration, whenever practicable, to achieve the required speeds. Additional savings are possible with improved mechanical availability of the PDE (2.6% additional savings). These potential savings would rely on careful management of the PDE performance and maintenance to reduce risks associated with prolonged low load running. VAN's electrical energy baselines have also been defined, which provide an important first step in understanding CPF electrical energy use, defining how high-energy systems contribute to the overall power demand, due to their duty cycles and current draw, both at sea and alongside.

Summary of Findings

VAN used an average of 40.6 m^3 per day during 71 days at sea, showing dominant trends to spend over 10% at each 5, 10, and 15 knots, and over 20% of operations at 12 knots (Figure 6), with most operations almost equally split between the PDE and a single gas turbine. VAN spent 64% of her time at speeds between 10 and 15 knots, with half of that time on the PDE, with the most significant peak at 12 knots. VAN also demonstrated a strong tendency to utilize a gas turbine mainly for slower speeds.

The ship's electrical load accounts for a sixth of total fuel use at sea, and approximately 25% of total platform energy usage, with an average electrical load of 961 kW at sea, and 620 kW alongside. Of the energy monitored by IPMS, the chillers use approximately 15% of the total electrical power, while the ventilation system for machinery space and funnel cooling uses 10% at sea and 5% alongside power. Much of the HVAC system is not monitored by IPMS, but is estimated at over 30% total electrical power demand at sea (20% alongside), and is required to provide cooling to both crew and equipment. Both firepumps and air compressors together consume a total of 12.6% power at sea, and 18.4% power alongside. Air compressors draw 6.5% of sea and 8.9% of shore power. A number of system air leaks require a constantly running compressor at sea to maintain pressure. The design of the sea water services firemain, which requires a constantly running pump to maintain system pressure and discharge to sea, imposes a heavy burden and significant through life cost on frigate energy use.

High energy systems not monitored by IPMS were surveyed to determine their estimated duty cycles and subsequent power requirements. Ship's galley, laundry, lighting, space cooling and other equipment have been identified as major demand sources, and could be the subject of more in depth analysis, assisted by load-sensing devices to accurately define their energy use, and identify opportunities for improvement.

Fleet IPMS data provided an approximation of the class-average operational profiles and electrical power trends. While there are gaps in the fleet data, the comparison still allows an initial assessment and comparison with VAN. Overall, VAN's operational profile is similar to the fleet average, but where other ships are spending more time at 5 knots, VAN is more frequently operating between 12 and 17 knots. This difference may be due to operational requirements for VAN, or the other ship's tendency to operate at 5 knots early in their reactivation cycle, following refit. During the early part of the ship's post-refit, reactivation period, ship's do not have the full complement of machinery installed, which may be leading to lower daily electrical power demands (7% lower). Only increased sample sizes and further analysis of all ships during other operations may start to reveal the true, steady-state averages for the fleet. Unfortunately, no legacy data exists to compare the new IPMS trends against, so the steady-state operational profile for the CPFs can only be built using IPMS data from the latter half of their service life.

The costs associated with ship's fuel and energy use, likely constitute more than 10% of the vessel's total cost of ownership. When accounting for the full support costs for both fuel logistics and system upkeep, the cost per MWh for both propulsion and electricity may be high enough to warrant targeted attention, especially when designing the next generation of warships. The 10% fuel savings identified in this study would pay for more than a single frigate's operational energy each year, when realized across the fleet of 12 vessels. This improved energy efficiency is likely available at a cost lower than the fuel it saves, and poses the additional and free benefits of increased capability, reduced vulnerability, reduced noise, lower maintenance, reduced cooling load, and lower engine emissions.

A number of barriers prevent more frugal management of ship's energy, such as an absence of timely accurate, and accessible information to inform key decision-makers; a lack of understanding and awareness of energy savings, their benefits and total system cost of ownership; poor performance of legacy equipment and systems; PDE sub-optimal performance and reliability, inefficient system designs, poorly maintained equipment, and lack of priority and incentives.

Recommendations

This analysis has revealed the initial trends for energy use on board a CPF warship, and have helped build a basis for future work. The following recommendations are forwarded for consideration by the naval leadership:

1. Continued analysis and trending of shipboard propulsion and energy use, using combined IPMS and operational data.
2. Continued examination of the assumptions, estimates and omissions in this study, to improve content and accuracy of CPF energy performance and set priority improvements.
3. Detailed system by system energy audit and recommendations for improvement.
4. Life Cycle Costing, including system total cost of ownership (using procurement, maintenance, support, and materiel costs), which includes energy use, to inform future developmental and acquisition programs, and the development of an energy-abatement cost curve for various behaviors, equipment and systems needed to drive high value-for-money energy investments.
5. Development of a real-time energy management dashboard for ships and shore energy monitoring to inform operational and logistic decision making, incorporating a series of metrics that are meaningful to both ship and shore personnel.
6. Development of a coastal and shore energy management program to build capacity for continued improvements in energy management and efficiency improvements across the navy’s operational, training and engineering teams.

7. Establishment of clear goals, objectives, tactics and strategies to achieve enhanced energy efficiency at sea, with the associated accountabilities and capacity building.
8. Examination of the business-case to support PDE design and operational improvements to enable more frequent and acceptable low load / off-design performance. Improvements could be implementation of one or more of the following: modern fuel, air and electronic management systems, oil management programs, education and awareness programs.
9. Examination of SWS / firemain design and operational improvements to reduce energy use, through-life costs, and other impacts.
10. Development of a criteria for planning and prioritizing equipment maintenance routines, that includes energy risks and impacts to capability.
11. Digitizing onboard logbooks to allow for data fusion with IPMS and other synthetic information.
12. Expansion of machinery controls and monitoring software to improve the level of sophistication regarding the management of ship HVAC and thermal load on board.
13. Increasing the electric load-sensing capability within the ship to monitor significant energy users, such as combat systems, HVAC equipment, galley, ship's laundry, lighting, multi-purpose outlets, and others.
14. Development of design for efficiency (DfE) guidelines for current and future ships, based on CPF and other naval / maritime knowledge and experiences, utilizing a 'whole-systems', integrated approach to take advantage of the

cascading savings from efficiency on reduced piping, insulation, electric cabling, ductwork, etc.

15. Consider development of a data-management strategy for energy and other capability improvements, based on the emerging 'big data' sets now available with modern IPMS and other control systems.
16. Consider incentivizing ship's commanders and crews to improve energy management and energy accountabilities.

Conclusion

The examination of VAN's propulsion and electrical energy use patterns have increased the understanding of both how and why Canadian warships use energy to complete missions. This analysis was a first attempt to combine both the new capabilities of the IPMS data monitoring, with the operational footprint of the ship, recorded manually in bridge logbooks. The combination of these two data streams helped reveal how the ship's operations dictated engine and equipment selection, and where and when energy savings. This study has attempted to answer the four main questions posed at the outset of this analysis:

How does a warship use energy at sea and alongside? This analysis captures the propulsion and electrical baseline energy trends of a high-readiness patrol frigate, and defines the energy magnitude and pathways for both propulsion and electrical services.

Can a warship decrease energy intensity without compromising mission effectiveness? This assessment of CPF energy baselines and patterns suggests that the fleet may be able to save at least 10% of fuel through more intelligent management of a ship's engines, while strengthening capability, extending the ship's range, endurance and operational flexibility. Much of VAN's total electrical energy use is a product of inefficient system configuration or degraded equipment status, and therefore poses a strong potential for energy and through life cost savings, improved maintenance profiles, and reduced equipment downtime.

What are the key factors preventing more efficient energy use on board a warship and what are the most suitable technical and behavioral options to reduce overall mission fuel consumption? The study also reveals various pathways to improved energy management, and identifies some of the barriers that may prevent fleet wide energy savings. At first glance, propulsion fuel savings potential may be unlocked by simple behavior modifications, but in fact, the performance shortcomings with the PDE and its degraded maintainability and reliability may prevent an easy or inexpensive pathway to improved drive-mode efficiencies. The importance of the PDE as an enabler for fuel cannot be overstated. The value of the PDE's fuel-saving potential defined in part by this study could help inform future business case decisions related to investments in PDE operational and technical enhancements, especially for off-load performance.

Almost 40% of VAN's electrical energy demand can be saved by proper system maintenance, isolation of redundant equipment, improved system configuration, and improved overall design. Energy conservation efforts targeted at chilled water, ventilation fans, sea water services, and LP air compressors can deliver significant savings, and should be the focus of increased efforts by naval staff.

Potential Benefits

The RCN may be able to invest in energy improvement using the patterns defined in this and future studies. Energy reductions can also unlock much more value at no or low additional cost. Improved energy efficiency has direct financial, operational, environmental, and social benefits. A more efficient ship is cooler, quieter, and more capable, with longer range, greater time on station, less vulnerable, and burdened by less maintenance, less GHGs, and is more comfortable, safer, and reputable.

As the Canadian fleet continues to assemble energy and operational data in the months and years following its mid-lifespan refit, more can be learned about CPF energy use and opportunities for improvement to both enhance capability and performance. The energy data drawn from IPMS can help define the fleet's operational and energy trends, and help inform design and functionality requirements for future ships.

This report's baseline examination is a starting point for improving RCN energy management, while strengthening capability, through life costs, and environmental performance. This analysis may help frame the priorities for action, and build a new discipline for improved fleet energy frugality, that better reflects the true values of the sailors and staff who wish to deliver each unit of mission capability at the lowest possible cost and highest possible benefit to environmental and human health.

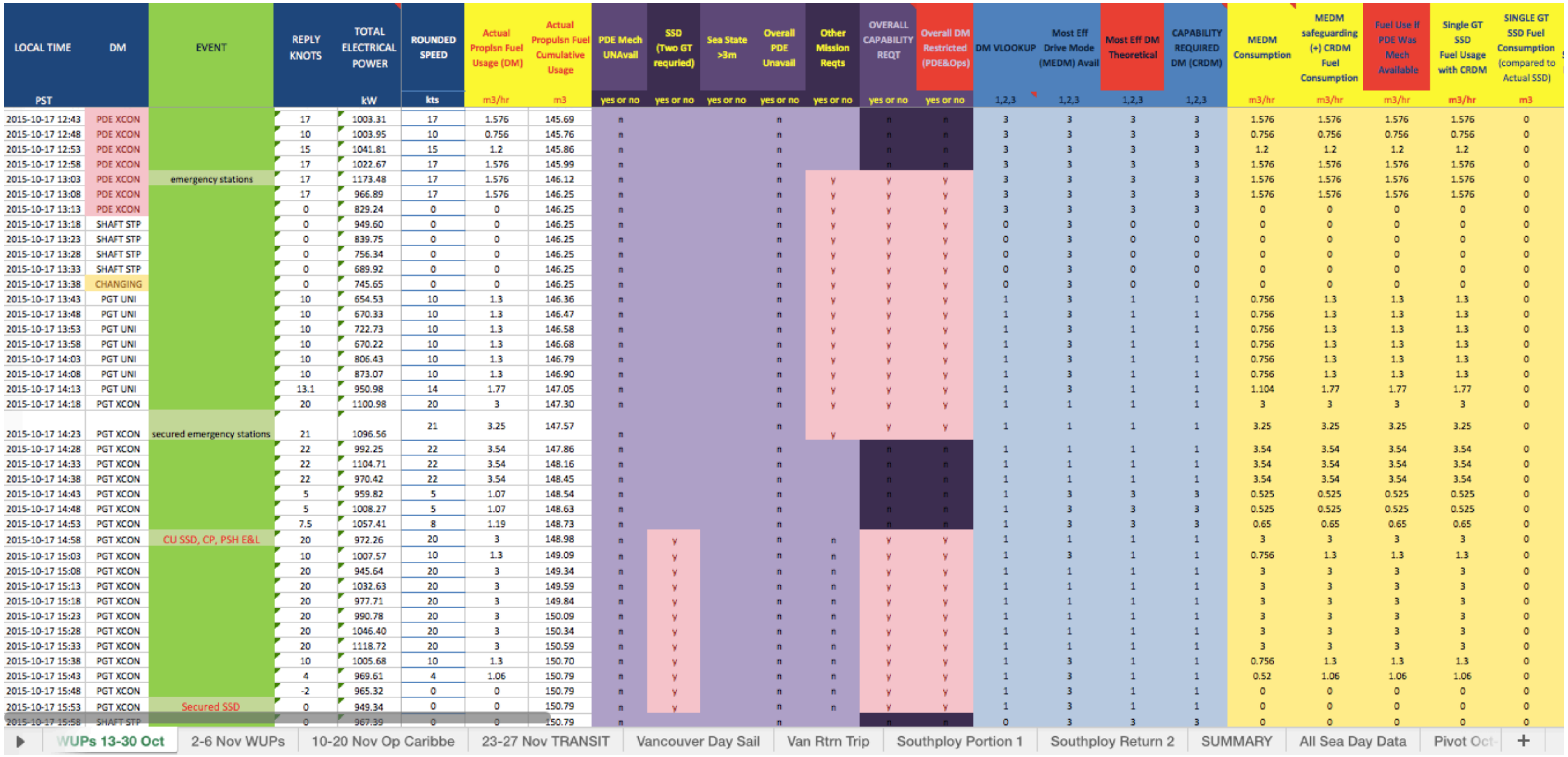
Appendix 1

Operational Energy Model

Table 9. Ship operational energy and voyage data summary.

				SPEED	Electrical Load	Actual Proplsn Fuel Usage (DM)	Operational Daily Fuel Consumptn (m3)	PDE Mech UNAvail	SSD (Two GT requried)	Sea State >3m	Overall PDE Unavail	Other Mission Reqts	OVERALL CAPABILITY REQT	Overall DM Restricted (PDE&Ops)	MEDM Consumption	MEDM safeguarding (+) CRDM Fuel Consumption	PDE Mech Avail 100% savings	Single GT SSD Fuel Usage with CRDM	SINGLE GT SSD Fuel Savings (compared to Actual SSD)
Title	Start	Finish	Days	knots	kW	m3		y	y	y	y	y	y						
RAS OPS	2015-07-12 8:00	2015-07-23 14:03	11.25	11.39	965.32	457.03	40.62	23%	12%	18%	40%	6%	19%	52%	356.61	407.55	24.93	375.81	31.74
SWOAD Training	2015-07-27 8:38	2015-07-29 14:59	2.26	9.59	957.59	59.75	26.38	0%	5%	0%	0%	2%	7%	7%	45.04	47.88	0.00	1.56	1.56
SRD 504 Trials	2015-08-03 13:30	2015-08-07 15:28	4.08	9.20	961.26	110.06	26.96	0%	2%	0%	0%	24%	26%	26%	79.81	93.38	0.53	92.73	0.65
RAS Training	2015-08-10 9:30	2015-08-14 8:07	3.94	11.09	970.02	161.39	40.94	0%	7%	0%	0%	20%	27%	27%	93.24	117.83	1.12	111.98	5.85
Sub / Local Ops	2015-09-21 9:44	2015-09-24 11:46	3.08	9.61	925.27	110.54	35.83	100%	11%	0%	100%	11%	22%	100%	103.95	108.58	28.61	102.81	5.77
WUPS	2015-10-13 9:30	2015-10-30 11:35	17.09	11.82	955.38	576.28	33.73	0%	4%	6%	6%	16%	20%	25%	429.86	485.45	0.00	470.33	15.12
WUPS Phase IV	2015-11-02 9:43	2015-11-06 11:01	4.05	9.99	954.01	154.12	38.02	0%	5%	25%	25%	12%	17%	35%	95.58	115.40	0.00	111.16	4.24
OP CARIBBE	2015-11-10 7:28	2015-11-20 11:35	10.17	12.03	934.49	284.36	27.96	1%	2%	0%	1%	7%	9%	10%	248.48	262.98	0.12	258.07	4.91
Return Transit SD-	2015-11-23 9:30	2015-11-27 11:40	4.09	14.05	954.06	167.63	40.98	50%	3%	35%	50%	3%	6%	55%	151.34	156.50	6.26	154.26	2.24
Vancouver City (to)	2016-01-12 15:00	2016-01-13 9:35	0.78	10.25	972.43	28.66	36.85	98%	13%	0%	98%	0%	13%	13%	25.62	26.96	8.82	25.62	1.34
Vancouver City (return)	2016-01-14 13:30	2016-01-15 10:10	0.86	11.60	966.74	28.81	33.32	40%	8%	0%	40%	2%	10%	46%	26.96	28.40	3.42	27.35	1.05
Southploy 1	2016-03-17 9:18	2016-03-22 10:23	4.95	13.09	1024.45	136.64	27.58	0%	2%	0%	0%	7%	8%	8%	128.04	134.88	0.12	133.56	1.32
Southploy 2	2016-03-26 8:18	2016-03-31 17:00	4.37	13.50	991.87	137.59	31.50	0%	6%	0%	0%	5%	12%	12%	120.98	133.53	0.45	129.06	4.48
			70.99	11.62	961.11	2412.84	33.90	12.6%	5.4%	7.6%	18.2%	10.6%	16.0%	30.6%	1905.49	2119.31	74.38	1994.29	80.27

Table 10. Operational energy voyage excerpt (WUPs, 13-30 October 2015).



LOCAL TIME	DM	EVENT	REPLY KNOTS	TOTAL ELECTRICAL POWER	ROUNDED SPEED	Actual Proplsn Fuel Usage (DM)	Actual Propulsn Fuel Cumulative Usage	PDE Mech UNAvail	SSD (Two GT requried)	Sea State >3m	Overall PDE Unavail	Other Mission Reqts	OVERALL CAPABILITY REQT	Overall DM Restricted (PDE&Ops)	DM VLOOKUP	Most Eff Drive Mode (MEDM) Avail	Most Eff DM Theoretical	CAPABILITY REQUIRED DM (CRDM)	MEDM Consumption	MEDM safeguarding (+) CRDM Fuel Consumption	Fuel Use if PDE Was Mech Available	Single GT SSD Fuel Usage with CRDM	SINGLE GT SSD Fuel Consumption (compared to Actual SSD)
PST				kW	kts	m3/hr	m3	yes or no	yes or no	yes or no	yes or no	yes or no	yes or no	yes or no	1,2,3	1,2,3	1,2,3	1,2,3	m3/hr	m3/hr	m3/hr	m3/hr	m3
2015-10-17 12:43	PDE XCON		17	1003.31	17	1.576	145.69	n			n		n	n	3	3	3	3	1.576	1.576	1.576	1.576	0
2015-10-17 12:48	PDE XCON		10	1003.95	10	0.756	145.76	n			n		n	n	3	3	3	3	0.756	0.756	0.756	0.756	0
2015-10-17 12:53	PDE XCON		15	1041.81	15	1.2	145.86	n			n		n	n	3	3	3	3	1.2	1.2	1.2	1.2	0
2015-10-17 12:58	PDE XCON		17	1022.67	17	1.576	145.99	n			n		n	n	3	3	3	3	1.576	1.576	1.576	1.576	0
2015-10-17 13:03	PDE XCON	emergency stations	17	1173.48	17	1.576	146.12	n			n	y	y	y	3	3	3	3	1.576	1.576	1.576	1.576	0
2015-10-17 13:08	PDE XCON		17	966.89	17	1.576	146.25	n			n	y	y	y	3	3	3	3	1.576	1.576	1.576	1.576	0
2015-10-17 13:13	PDE XCON		0	829.24	0	0	146.25	n			n	y	y	y	3	3	3	3	0	0	0	0	0
2015-10-17 13:18	SHAFT STP		0	949.60	0	0	146.25	n			n	y	y	y	0	3	0	0	0	0	0	0	0
2015-10-17 13:23	SHAFT STP		0	839.75	0	0	146.25	n			n	y	y	y	0	3	0	0	0	0	0	0	0
2015-10-17 13:28	SHAFT STP		0	756.34	0	0	146.25	n			n	y	y	y	0	3	0	0	0	0	0	0	0
2015-10-17 13:33	SHAFT STP		0	689.92	0	0	146.25	n			n	y	y	y	0	3	0	0	0	0	0	0	0
2015-10-17 13:38	CHANGING		0	745.65	0	0	146.25	n			n	y	y	y	0	3	0	0	0	0	0	0	0
2015-10-17 13:43	PGT UNI		10	654.53	10	1.3	146.36	n			n	y	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 13:48	PGT UNI		10	670.33	10	1.3	146.47	n			n	y	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 13:53	PGT UNI		10	722.73	10	1.3	146.58	n			n	y	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 13:58	PGT UNI		10	670.22	10	1.3	146.68	n			n	y	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 14:03	PGT UNI		10	806.43	10	1.3	146.79	n			n	y	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 14:08	PGT UNI		10	873.07	10	1.3	146.90	n			n	y	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 14:13	PGT UNI		13.1	950.98	14	1.77	147.05	n			n	y	y	y	1	3	1	1	1.104	1.77	1.77	1.77	0
2015-10-17 14:18	PGT XCON		20	1100.98	20	3	147.30	n			n	y	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 14:23	PGT XCON	secured emergency stations	21	1096.56	21	3.25	147.57	n			n	y	y	y	1	1	1	1	3.25	3.25	3.25	3.25	0
2015-10-17 14:28	PGT XCON		22	992.25	22	3.54	147.86	n			n		n	n	1	1	1	1	3.54	3.54	3.54	3.54	0
2015-10-17 14:33	PGT XCON		22	1104.71	22	3.54	148.16	n			n		n	n	1	1	1	1	3.54	3.54	3.54	3.54	0
2015-10-17 14:38	PGT XCON		22	970.42	22	3.54	148.45	n			n		n	n	1	1	1	1	3.54	3.54	3.54	3.54	0
2015-10-17 14:43	PGT XCON		5	959.82	5	1.07	148.54	n			n		n	n	1	3	3	3	0.525	0.525	0.525	0.525	0
2015-10-17 14:48	PGT XCON		5	1008.27	5	1.07	148.63	n			n		n	n	1	3	3	3	0.525	0.525	0.525	0.525	0
2015-10-17 14:53	PGT XCON		7.5	1057.41	8	1.19	148.73	n			n		n	n	1	3	3	3	0.65	0.65	0.65	0.65	0
2015-10-17 14:58	PGT XCON	CU SSD, CP, PSH E&L	20	972.26	20	3	148.98	n	y		n	n	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 15:03	PGT XCON		10	1007.57	10	1.3	149.09	n	y		n	n	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 15:08	PGT XCON		20	945.64	20	3	149.34	n	y		n	n	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 15:13	PGT XCON		20	1032.63	20	3	149.59	n	y		n	n	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 15:18	PGT XCON		20	977.71	20	3	149.84	n	y		n	n	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 15:23	PGT XCON		20	990.78	20	3	150.09	n	y		n	n	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 15:28	PGT XCON		20	1046.40	20	3	150.34	n	y		n	n	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 15:33	PGT XCON		20	1118.72	20	3	150.59	n	y		n	n	y	y	1	1	1	1	3	3	3	3	0
2015-10-17 15:38	PGT XCON		10	1005.68	10	1.3	150.70	n	y		n	n	y	y	1	3	1	1	0.756	1.3	1.3	1.3	0
2015-10-17 15:43	PGT XCON		4	969.61	4	1.06	150.79	n	y		n	n	y	y	1	3	1	1	0.52	1.06	1.06	1.06	0
2015-10-17 15:48	PGT XCON		-2	965.32	0	0	150.79	n	y		n	n	y	y	1	3	1	1	0	0	0	0	0
2015-10-17 15:53	PGT XCON	Secured SSD	0	949.34	0	0	150.79	n	y		n	n	y	y	1	3	1	1	0	0	0	0	0
2015-10-17 15:58	SHAFT STP		0	967.39	0	0	150.79	n			n		n	n	0	3	3	3	0	0	0	0	0

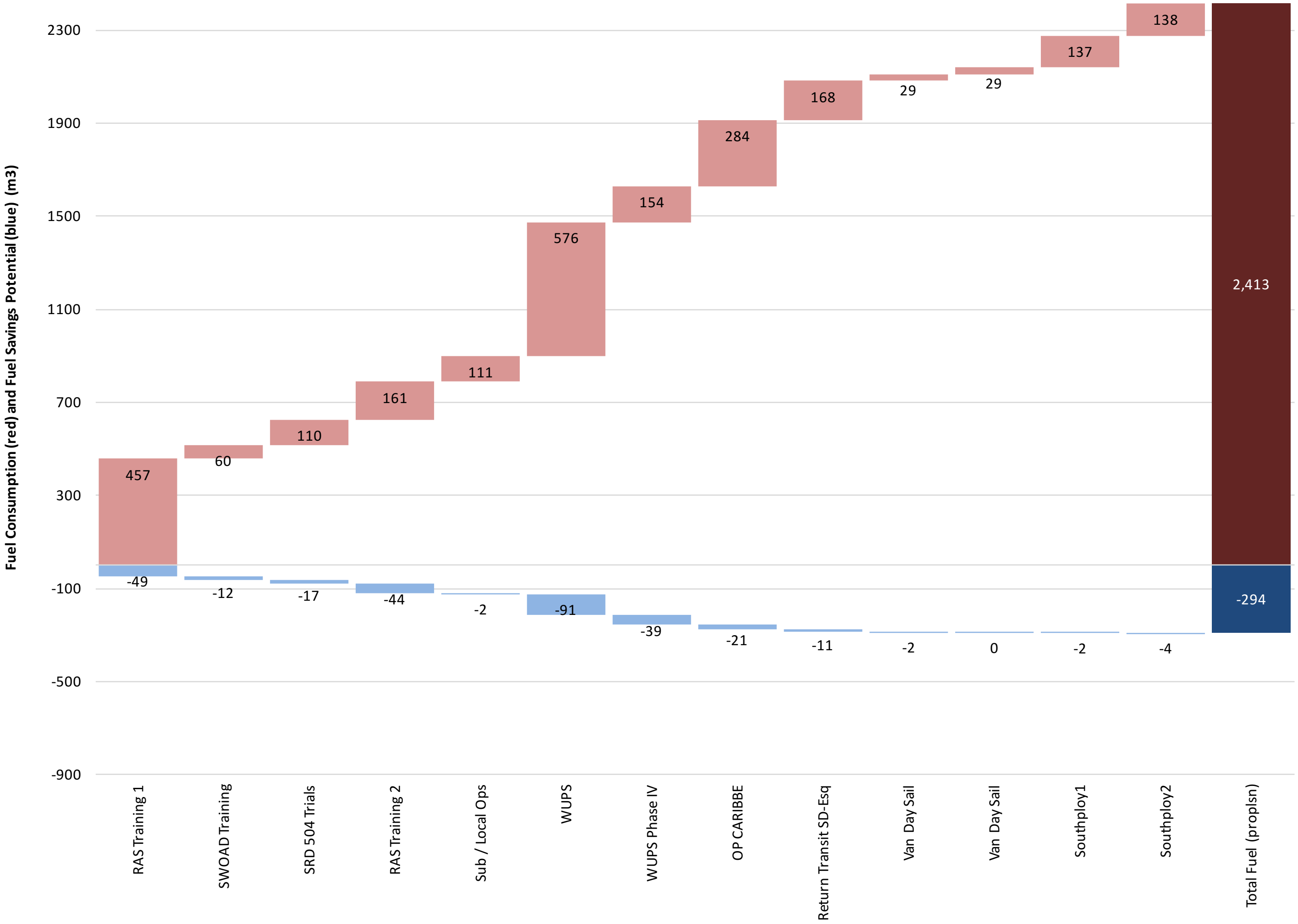


Figure 32. Operational fuel use and savings potential (without compromising mission capability).

Appendix 2

Electrical Duty Cycle Information

The following electrical load information defines VAN's at sea and alongside trends related to the operation duration and times for various electrical equipment. These equipment duty-cycles can help better understand equipment behaviour and assess against required services and overall energy demand, costs, capability, and maintenance implications.

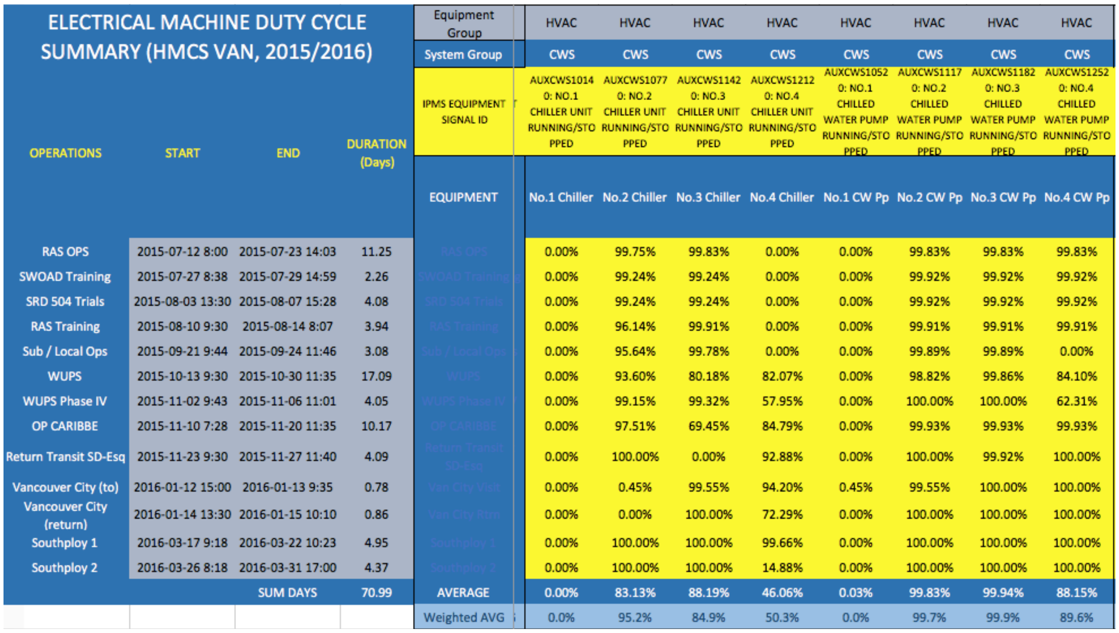
Heating Ventilation and Air Conditioning (HVAC).

The total estimated HVAC electrical load on the ship is 32% and 19%, of at sea and alongside power demand, respectively (at sea data shown at Figure 33). These overall estimates are based on IPMS monitored loads comprising 55% of the total actual load, and 45% of non-IPMS monitored equipment many of which were surveyed manually at sea. The duty cycle summary excerpt is taken from the IPMS data and shown below.

Chiller load fluctuates regularly, and is logged on unit digital controllers that are maintained by shore engineers. Due to the lack of access to VAN during her periods away and system security issues, these logs were only accessed during one complete sailing, from San Diego to Esquimalt. The load average during this time was 60%

The HVAC electrical load depends primarily on the cooling demand, and the technical capabilities of the system – both equipment performance and its configuration.

The supply and demand ‘sides’ of the system provide opportunities for understanding and identifies opportunities for energy intensity improvements.



ELECTRICAL MACHINE DUTY CYCLE SUMMARY (HMCS VAN, 2015/2016)

OPERATIONS	START	END	DURATION (Days)	Equipment Group	HVAC	HVAC	HVAC	HVAC	HVAC	HVAC	HVAC	HVAC
				System Group	CWS	CWS	CWS	CWS	CWS	CWS	CWS	CWS
				IPMS EQUIPMENT SIGNAL ID	AUXCWS10140: NO.1 CHILLER UNIT RUNNING/STOPPED	AUXCWS10770: NO.2 CHILLER UNIT RUNNING/STOPPED	AUXCWS11420: NO.3 CHILLER UNIT RUNNING/STOPPED	AUXCWS12120: NO.4 CHILLER UNIT RUNNING/STOPPED	AUXCWS10520: NO.1 CHILLED WATER PUMP RUNNING/STOPPED	AUXCWS11170: NO.2 CHILLED WATER PUMP RUNNING/STOPPED	AUXCWS11820: NO.3 CHILLED WATER PUMP RUNNING/STOPPED	AUXCWS12520: NO.4 CHILLED WATER PUMP RUNNING/STOPPED
				EQUIPMENT	No.1 Chiller	No.2 Chiller	No.3 Chiller	No.4 Chiller	No.1 CW Pp	No.2 CW Pp	No.3 CW Pp	No.4 CW Pp
RAS OPS	2015-07-12 8:00	2015-07-23 14:03	11.25	RAS OPS	0.00%	99.75%	99.83%	0.00%	0.00%	99.83%	99.83%	99.83%
SWOAD Training	2015-07-27 8:38	2015-07-29 14:59	2.26	SWOAD Training	0.00%	99.24%	99.24%	0.00%	0.00%	99.92%	99.92%	99.92%
SRD 504 Trials	2015-08-03 13:30	2015-08-07 15:28	4.08	SRD 504 Trials	0.00%	99.24%	99.24%	0.00%	0.00%	99.92%	99.92%	99.92%
RAS Training	2015-08-10 9:30	2015-08-14 8:07	3.94	RAS Training	0.00%	96.14%	99.91%	0.00%	0.00%	99.91%	99.91%	99.91%
Sub / Local Ops	2015-09-21 9:44	2015-09-24 11:46	3.08	Sub / Local Ops	0.00%	95.64%	99.78%	0.00%	0.00%	99.89%	99.89%	0.00%
WUPS	2015-10-13 9:30	2015-10-30 11:35	17.09	WUPS	0.00%	93.60%	80.18%	82.07%	0.00%	98.82%	99.86%	84.10%
WUPS Phase IV	2015-11-02 9:43	2015-11-06 11:01	4.05	WUPS Phase IV	0.00%	99.15%	99.32%	57.95%	0.00%	100.00%	100.00%	62.31%
OP CARIBBE	2015-11-10 7:28	2015-11-20 11:35	10.17	OP CARIBBE	0.00%	97.51%	69.45%	84.79%	0.00%	99.93%	99.93%	99.93%
Return Transit SD-Esq	2015-11-23 9:30	2015-11-27 11:40	4.09	Return Transit SD-Esq	0.00%	100.00%	0.00%	92.88%	0.00%	100.00%	99.92%	100.00%
Vancouver City (to)	2016-01-12 15:00	2016-01-13 9:35	0.78	Van City Visit	0.00%	0.45%	99.55%	94.20%	0.45%	99.55%	100.00%	100.00%
Vancouver City (return)	2016-01-14 13:30	2016-01-15 10:10	0.86	Van City Rtrn	0.00%	0.00%	100.00%	72.29%	0.00%	100.00%	100.00%	100.00%
Southploy 1	2016-03-17 9:18	2016-03-22 10:23	4.95	Southploy 1	0.00%	100.00%	100.00%	99.66%	0.00%	100.00%	100.00%	100.00%
Southploy 2	2016-03-26 8:18	2016-03-31 17:00	4.37	Southploy 2	0.00%	100.00%	100.00%	14.88%	0.00%	100.00%	100.00%	100.00%
		SUM DAYS	70.99	AVERAGE	0.00%	83.13%	88.19%	46.06%	0.03%	99.83%	99.94%	88.15%
				Weighted AVG	0.0%	95.2%	84.9%	50.3%	0.0%	99.7%	99.9%	89.6%

Figure 33. Chilled water, at sea duty cycle information.

The actual performance of the units and their set-points was not examined as part of this study, but is an important aspect of overall system performance. System maintenance, temperature settings, valve configuration, insulation condition, was also not assessed, and will likely play critical roles in the equipment’s energy intensity.

During these operations, only three of the four chilled water compressors were in operation, and the three available units were running an average of 65% of the time. Initial load data taken from the chillers dedicated programmable controllers defined the average loading during transit from San Diego to Esquimalt (Figure 34) at approximately 60% on each chiller, with three chilled water pumps running nearly continuously (15 amps each at 96.4% duty cycle). Electrical current surveys on running equipment indicated that the load profile of the running chillers spanned between 74 to 113 amps for 50%-100% load, respectively.

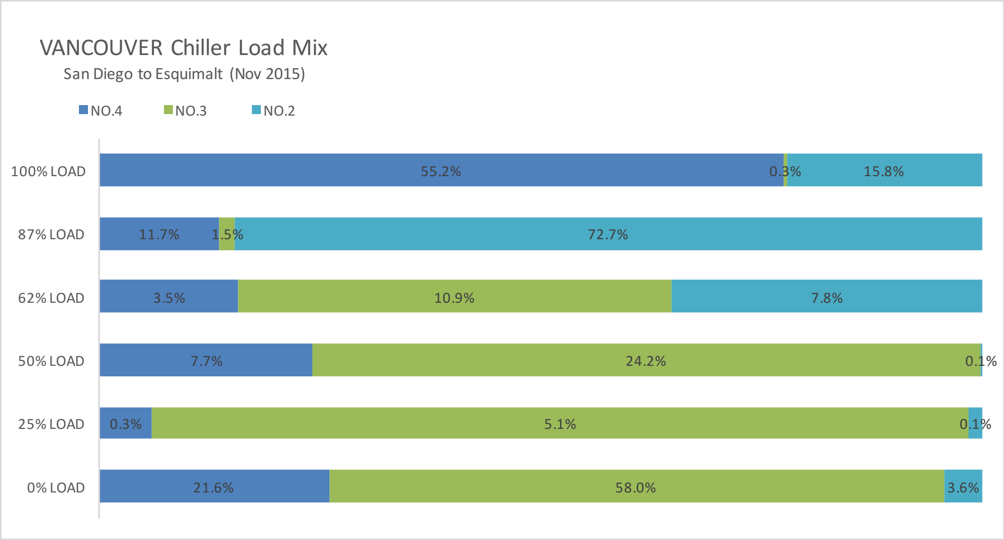


Figure 34. VAN chiller load breakdown during San Diego to Esquimalt Transit (November 2015).

Equipment rounds are completed each hour, and logged in paper logbooks, but detailed trending is now available via the electronic controllers, and collected by shore engineers for filing ashore. It remains unclear if any data analysis is occurring ashore, as my requests to see chiller data represented some of the initial downloads of data by shore support teams. Shipboard operators also admitted that chiller loads weren't monitored automatically, and it was commonplace for multiple chillers to remain running at partial loads, before being noticed, and then consolidated to improve efficiency. A more comprehensive control and monitoring system for thermal management could improve the operation and upkeep of many systems that rely on, or create a need for cooling.

Cooling load mainly depends on the equipment and personnel cooling demands, equipment waste-heat generation, and both the sea and outside air temperature. In a number of instances, redundant cooling configurations were observed, adding unnecessary service load on the system. Numerous air coolers were set on the highest demand (coolest) settings in unmanned spaces, observed during electrical surveys at sea. Experience and discussions with ship's crew illuminated the excessive cooling of the operations room, which is known for its cold temperatures, seemingly to keep electronic equipment cool and fault-free. But, even with the equipment running, the space was well below standard room temperatures (12-14^{o}C), and was being over-cooled, and causing the Ops Room AC plant to run excessively.

Machinery Space Ventilation

Many of the largest motors on board are used to move air in, around and out of the 4 main machinery spaces, as well as the exhaust uptakes. These fans are used to remove waste heat from the machinery, and cool the engine uptakes and exhaust. These fans are monitored by IPMS and provide information as to their duty cycle, and electrical energy surveys were completed on running equipment so that the power requirements of the system can be assessed.

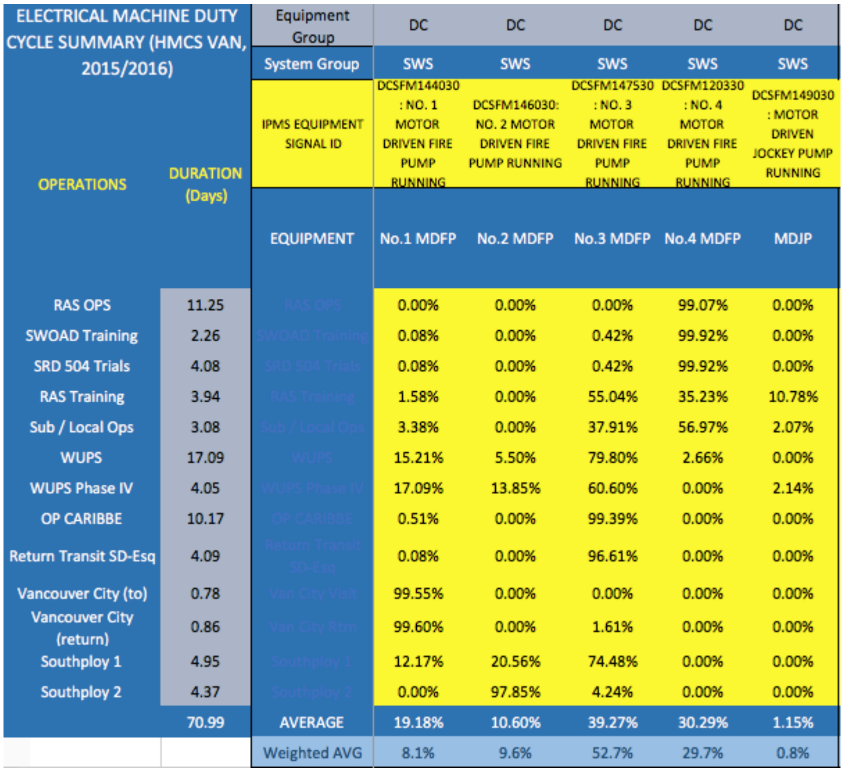
At sea, the average power required to drive the 4 uptake cooling fans, 2 mast fans, 2 filtered air supply fans, and 18 supply / exhaust fans equates to approximately 94.7 kW. Alongside, the fans consume 29.3 kW, on average. These fans are manually operated, and are set to control ambient air temperature to within comfortable limits. The space temperatures are reported via monitoring sensors to the IPMS consoles, but the machinery is nominally setup based on ‘rules of thumb’, and experiential norms. In certain instances, during at sea surveys, some of the largest fans were in operation even when the associated heat source had been isolated. For example, the uptake cooling fans, which draw close to 40 kW may be left running by machinery operators after gas turbines have been shut down, and that level of cooling is no longer required. Detailed examination of these types of system mismatches could be highlighted by examining IPMS data bases and could reveal specific and targeted areas for energy improvement and optimization.

The more equipment that can be isolated, not only reduces maintenance and running hours, but also removes their associated heat signature that otherwise need to be cooled. Conversely, the more equipment that is left running to generate heat needs to be cooled by more equipment, much of which places a heavy burden on power generation equipment and platform fuel usage. Only a more thorough analysis of cooling requirements, heat signatures and equipment operating profiles will reveal the optimum settings for fans ventilation. Increased sensor data and automation will limit the human error associated with leaving equipment running or failing to isolate equipment after the required services have been met.

Sea Water Services System (Firemain)

The ship’s firemain is continuously charged and ready for emergency with pressurized sea water from one of 5 electric motor driven firepumps, or two diesel firepumps in case of power failure. The system is designed to have pressure normally maintained by the Jockey Driven Firepump (JDFP), continuously at sea and alongside.

The JDPF is smaller and less powerful than the Motor Driven Firepumps (MDFPs) that are meant to supply boost pressure in case of ship's damage.



ELECTRICAL MACHINE DUTY CYCLE SUMMARY (HMCS VAN, 2015/2016)		Equipment Group	DC	DC	DC	DC	DC
		System Group	SWS	SWS	SWS	SWS	SWS
		IPMS EQUIPMENT SIGNAL ID	DCSFM144030 : NO. 1 MOTOR DRIVEN FIRE PUMP RUNNING	DCSFM146030: NO. 2 MOTOR DRIVEN FIRE PUMP RUNNING	DCSFM147530 : NO. 3 MOTOR DRIVEN FIRE PUMP RUNNING	DCSFM120330 : NO. 4 MOTOR DRIVEN FIRE PUMP RUNNING	DCSFM149030 : MOTOR DRIVEN JOCKEY PUMP RUNNING
OPERATIONS	DURATION (Days)	EQUIPMENT	No.1 MDFP	No.2 MDFP	No.3 MDFP	No.4 MDFP	MDJP
RAS OPS	11.25	RAS OPS	0.00%	0.00%	0.00%	99.07%	0.00%
SWOAD Training	2.26	SWOAD Training	0.08%	0.00%	0.42%	99.92%	0.00%
SRD 504 Trials	4.08	SRD 504 Trials	0.08%	0.00%	0.42%	99.92%	0.00%
RAS Training	3.94	RAS Training	1.58%	0.00%	55.04%	35.23%	10.78%
Sub / Local Ops	3.08	Sub / Local Ops	3.38%	0.00%	37.91%	56.97%	2.07%
WUPS	17.09	WUPS	15.21%	5.50%	79.80%	2.66%	0.00%
WUPS Phase IV	4.05	WUPS Phase IV	17.09%	13.85%	60.60%	0.00%	2.14%
OP CARIBBE	10.17	OP CARIBBE	0.51%	0.00%	99.39%	0.00%	0.00%
Return Transit SD-Esq	4.09	Return Transit SD-Esq	0.08%	0.00%	96.61%	0.00%	0.00%
Vancouver City (to)	0.78	Van City Visit	99.55%	0.00%	0.00%	0.00%	0.00%
Vancouver City (return)	0.86	Van City Rtrn	99.60%	0.00%	1.61%	0.00%	0.00%
Southploy 1	4.95	Southploy 1	12.17%	20.56%	74.48%	0.00%	0.00%
Southploy 2	4.37	Southploy 2	0.00%	97.85%	4.24%	0.00%	0.00%
	70.99	AVERAGE	19.18%	10.60%	39.27%	30.29%	1.15%
		Weighted AVG	8.1%	9.6%	52.7%	29.7%	0.8%

Figure 35. Firemain duty cycle information (at sea).

Due to recent pressure control and pump failures, the ships have been directed (DNPS3, 2015) to switch primary use to a larger, MDPF. The JDPF runs at a load of 35.6 kW (taken from tally plate reading due to equipment being out of service during survey), while one MDFP was running continuously with a load of approximately 56 kW. Over a year of continuous operation, this 20 kW discrepancy between MDFP and JDFP consumes an additional 175 MW of power per ship per year (based on 8760 hours of use per year), which is generated from both diesel fuel and municipal electricity. Redesigning or solving the pressure control / valve issue on the current JDPF across the fleet would save approximately 2.1 GW of electricity demand per year. Redesigning a firemain that does not require a continuous duty pump could save the fleet 5.8 GW of electrical energy per year.

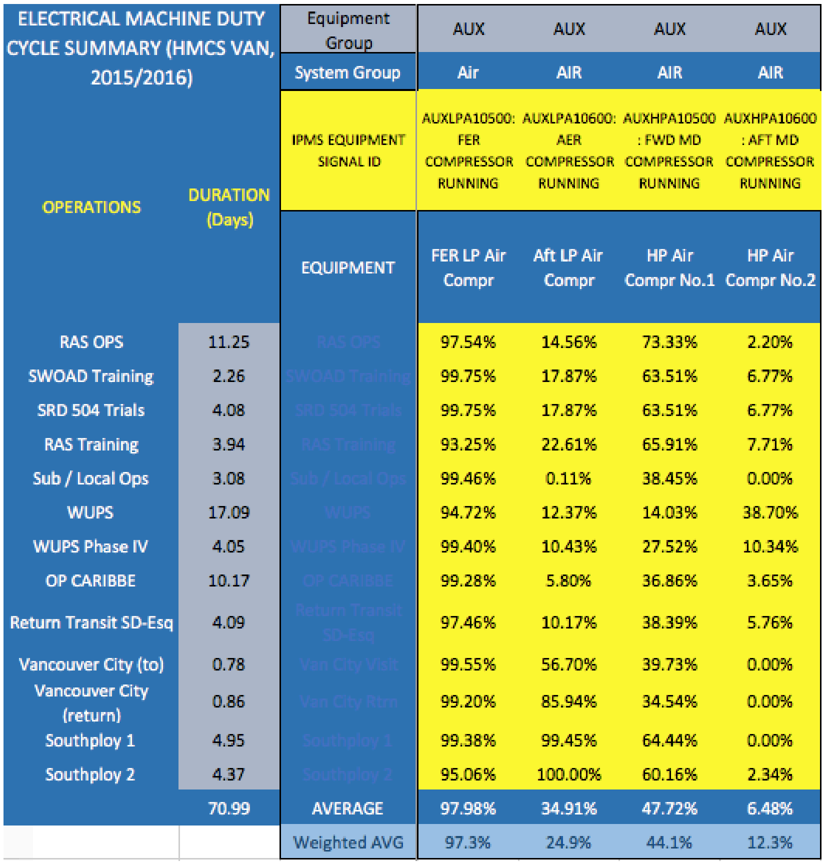
Compressed Air Systems

Twin, distributed low pressure air compressors provide for redundant, compressed air to pneumatic valves and air actuated systems throughout the ship, at low pressure (LP = 14 psi) and high pressure (HP=207 psi). The HP air compressors sustained average duty cycles of 23% each, while the LP air compressors ran at 60% each, at sea and alongside. One compressor per system is designed to meet normal demand, and are set to run when pressure drops below thresholds. The LP air compressors, which feed a large service main, were running near continuously at sea during the observation period. Discussions with ship's staff suggest that numerous air leaks throughout the system prevent reasonable duty cycles, and instead, draw heavily on the machinery. These defects impose a cost of increased compressor and air dryer maintenance, and significant energy burden. The intended energy baseline (i.e., duty cycle times the number of sea days and alongside days) was not able to be identified through this study, but would help define system energy targeted baselines.

A typical duty cycle for a leak-free system has not been defined through this study, but could help define the system's correct energy baseline. For illustrative purposes; if the system leaks were repaired, and the air compressors were able to run at an estimated duty cycle of 33% overall capacity (i.e., 16.5% each compressor), then the system energy would be reduced to almost a third of its current energy use, and save 40 kW per hour, and 68 MWh over the duration of 71 sea days (HP and LP air uses 63 kW average at sea, and if reduced to 33% duty cycle, would yield 23 kW total running load (11.9 kW LP air, 10.9 kW HP air).

Non IPMS Monitored Loads – Duty Cycle Information

Various power estimates were made for loads that were assumed to be significant, but were outside of the monitoring capability of IPMS. Ship's lighting, the individual space coolers, the galley equipment, and the ship laundry have anecdotally high duty cycles. In many cases, the loads of these equipment were surveyed at sea, in order to provide estimates of their possible contribution to the overall electrical power demand. As highlighted in the results section, the non-IPMS loads account for the majority of ship's power demand, and remain largely unmeasured, and therefore difficult to manage and optimize. Based on discussions with the ship's company, the following observations have been made, and estimates on duty cycle were approximated. These preliminary estimates should be validated through additional monitoring and load analysis to better understand where savings are possible and how energy use may help drive more informed decisions for procurement and ongoing life-cycle management.



ELECTRICAL MACHINE DUTY CYCLE SUMMARY (HMCS VAN, 2015/2016)		Equipment Group	AUX	AUX	AUX	AUX
		System Group	Air	AIR	AIR	AIR
		IPMS EQUIPMENT SIGNAL ID	AUXLPA10500: FER COMPRESSOR RUNNING	AUXLPA10600: AER COMPRESSOR RUNNING	AUXHPA10500 : FWD MD COMPRESSOR RUNNING	AUXHPA10600 : AFT MD COMPRESSOR RUNNING
OPERATIONS	DURATION (Days)	EQUIPMENT	FER LP Air Compr	Aft LP Air Compr	HP Air Compr No.1	HP Air Compr No.2
RAS OPS	11.25	RAS OPS	97.54%	14.56%	73.33%	2.20%
SWOAD Training	2.26	SWOAD Training	99.75%	17.87%	63.51%	6.77%
SRD 504 Trials	4.08	SRD 504 Trials	99.75%	17.87%	63.51%	6.77%
RAS Training	3.94	RAS Training	93.25%	22.61%	65.91%	7.71%
Sub / Local Ops	3.08	Sub / Local Ops	99.46%	0.11%	38.45%	0.00%
WUPS	17.09	WUPS	94.72%	12.37%	14.03%	38.70%
WUPS Phase IV	4.05	WUPS Phase IV	99.40%	10.43%	27.52%	10.34%
OP CARIBBE	10.17	OP CARIBBE	99.28%	5.80%	36.86%	3.65%
Return Transit SD-Esq	4.09	Return Transit SD-Esq	97.46%	10.17%	38.39%	5.76%
Vancouver City (to)	0.78	Van City Visit	99.55%	56.70%	39.73%	0.00%
Vancouver City (return)	0.86	Van City Rtrn	99.20%	85.94%	34.54%	0.00%
Southploy 1	4.95	Southploy 1	99.38%	99.45%	64.44%	0.00%
Southploy 2	4.37	Southploy 2	95.06%	100.00%	60.16%	2.34%
	70.99	AVERAGE	97.98%	34.91%	47.72%	6.48%
		Weighted AVG	97.3%	24.9%	44.1%	12.3%

Figure 36. Air compressor duty cycle (at sea).

Adding the sea and shore load totals for the loads not monitored by IPMS provide an initial estimate of their contribution to overall power demand and identify opportunities for future analysis. These estimates were completed using both measured running current readings and estimated time energized per day (see Appendix 3 for more information), while at sea and alongside. While fitting load-sensing equipment to these systems would define actual power demand, these initial estimates still provide useful information to help prioritize future study. These estimates suggest that the FCUs, ship's laundry, galley and ship's lighting may be contributing within the top ten, non-combat system, electric loads on board.

All of these systems are configurable and have potential for energy savings. During electrical inspections, lighting and cooling was observed to be energized in spaces infrequently manned nor required, or improperly confined, or galley equipment left on during periods of inactivity, due to the time required to achieve steady-state temperatures required for meal preparations. Overall at sea and alongside duty cycle summaries are illustrated in the below graphs.

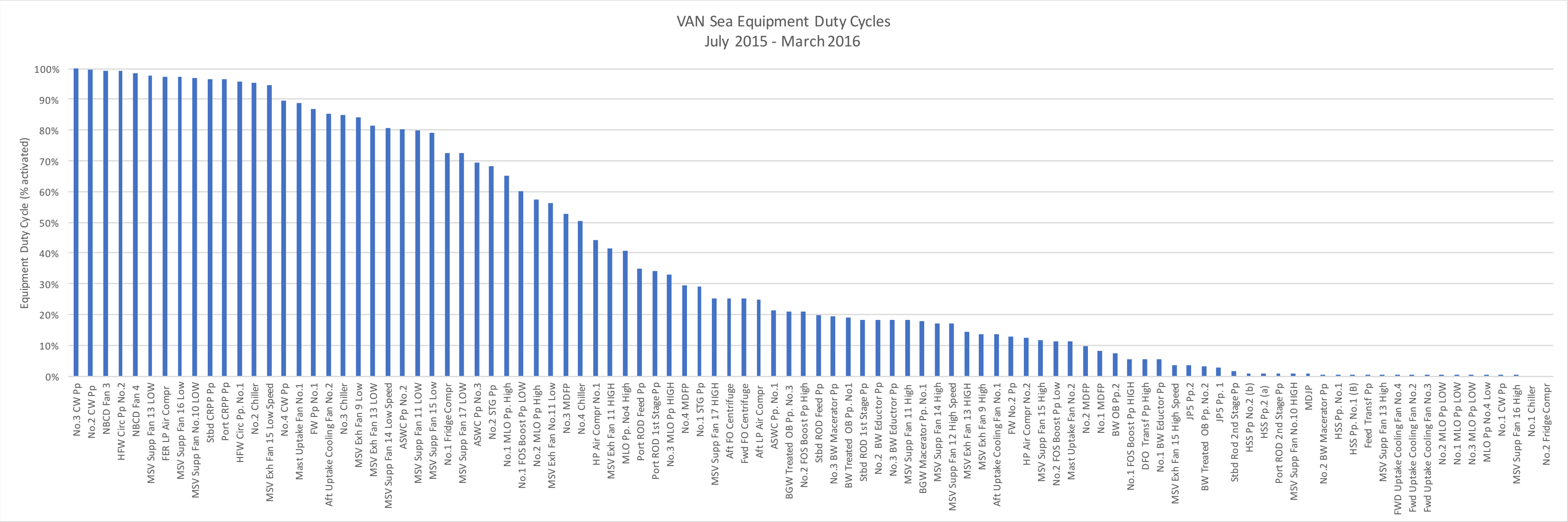


Figure 37. At sea equipment duty cycles

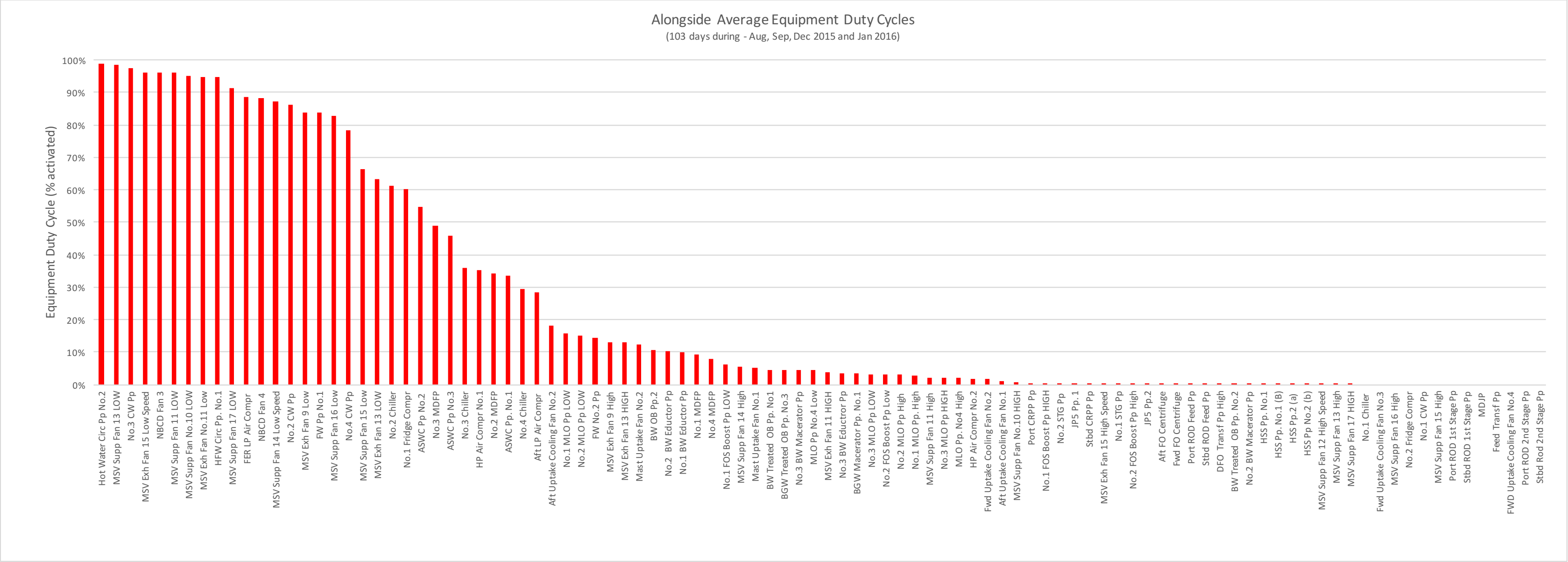


Figure 38. Alongside equipment duty cycles.

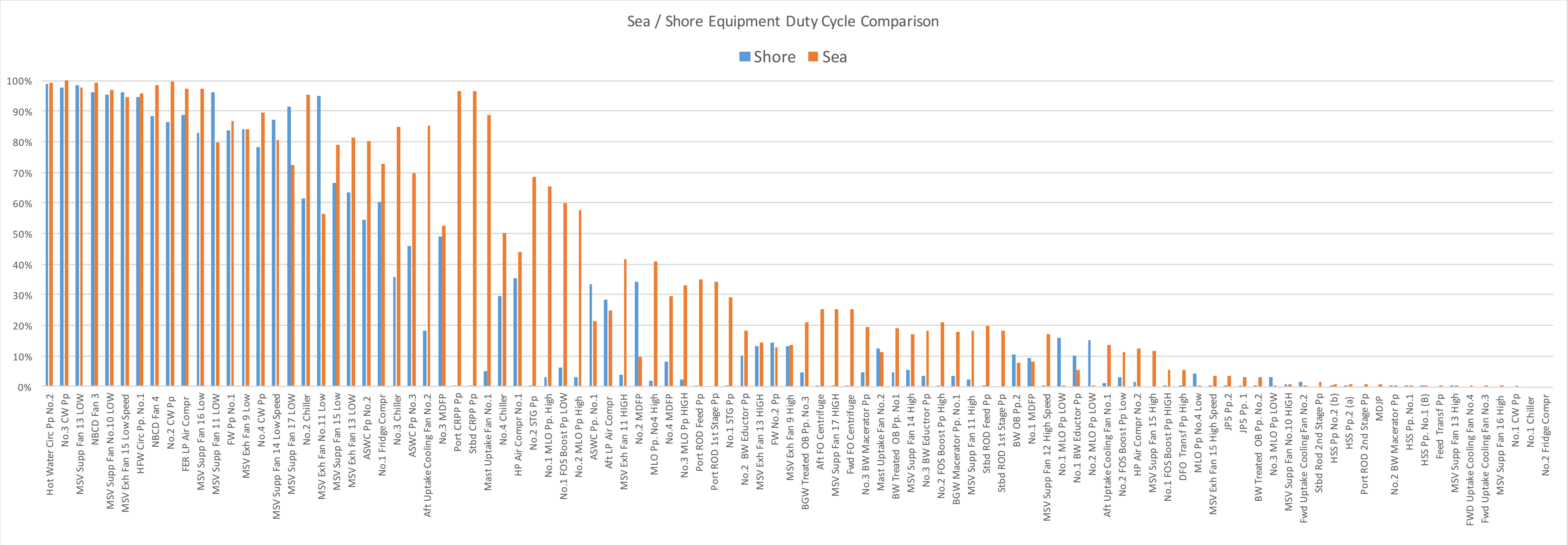


Figure 39. Combined at sea and alongside equipment duty cycles.

Appendix 3

At Sea Electrical Load Data

Table 11. At sea electrical load reference information.

Equipt Group	Equipment	Average Duty Cycle (% on)	Load kW (PF 0.85)	Quality of Measure	Explanation / Comment	Daily Load (kWh)
CWS	No.1 Chiller	0	49.88	60% load average, based on current draw measure	overall average based on SD transit	0.0
CWS	No.2 Chiller	95.2%	49.88	average based on measure	overall average based on SD transit	1140.2
CWS	No.3 CW Pp	99.9%	9.79	average based on measure		234.6
CWS	No.4 CW Pp	89.6%	9.79	measured		210.5
CWS	No.2 CW Pp	99.7%	9.79	average		234.1
CWS	No.1 CW Pp	0.0%	9.79	average		0.0
CWS	No.4 Chiller	50.3%	49.88	average based on measure	overall average based on SD transit	602.7
CWS	No.3 Chiller	84.9%	49.88	average based on measure	overall average based on SD transit	1016.9
SWS	No.2 MDFP	9.6%	57.76	average		132.7
SWS	No.4 MDFP	29.7%	59.72	measured		425.8
SWS	No.1 MDFP	8.1%	54.67	measured		106.4
SWS	No.3 MDFP	52.7%	58.88	measured		744.6
SWS	MDJP	0.8%	35.59	tally plate		6.9
LP/HP Air	FER LP Air Compr	97.3%	36.24	measured		845.9
LP/HP Air	HP Air Compr No.1	44.1%	33.00	measured		349.4
LP/HP Air	HP Air Compr No.2	12.3%	33.00	averaged		97.3
LP/HP Air	Aft LP Air Compr	24.9%	36.24	averaged		216.7
CRPP	Stbd CRPP Pp	96.6%	20.94	measured		485.1
CRPP	Port CRPP Pp	96.5%	20.94	average		485.1
MLO	No.2 MLO Pp LOW	0.1%	15.90	estimated		0.2

MLO	No.2 MLO Pp High	57.4%	23.29	measured		321.0
MLO	MLO Pp No.4 Low	0.0%	15.90	estimated		0.2
MLO	MLO Pp. No4 High	40.9%	23.29			228.4
MLO	No.1 MLO Pp LOW	0.1%	15.90	estimated		0.2
MLO	No.1 MLO Pp. High	65.3%	23.29	average		364.8
MLO	No.3 MLO Pp HIGH	33.1%	23.29	average		184.7
MLO	No.3 MLO Pp LOW	0.0%	15.90	estimated	tally plate	0.2
FW	FW No.2 Pp	12.9%	4.85	measured		15.1
FW	HFW Circ Pp. No.1	95.7%	0.39	measured		9.0
FW	Port ROD Feed Pp	35.1%	4.85	measured		40.9
FW	Stbd ROD Feed Pp	19.8%	4.85	average		23.1
FW	Port ROD 1st Stage Pp	34.1%	13.78	measured		112.7
FW	Stbd ROD 1st Stage Pp	18.3%	13.78	average		60.4
FW	FW Pp No.1	86.9%	4.85	average		101.2
FW	Hot Water Circ Pp No.2	99.2%	0.39	average		9.3
FW	Port ROD 2nd Stage Pp	0.9%	4.73	estimated	tally plate	1.1
FW	Stbd Rod 2nd Stage Pp	1.5%	4.73	estimated	tally plate	1.7
FOS	Fwd FO Centrifuge	25.2%	11.97	measured		72.3
FOS	Aft FO Centrifuge	25.3%	11.97	average		72.6
FOS	No.2 FOS Boost Pp Low	11.4%	3.62	average		9.9
FOS	No.2 FOS Boost Pp High	21.0%	6.04	estimated		30.3
FOS	No.1 FOS Boost Pp LOW	60.0%	3.62	measured		52.2
FOS	No.1 FOS Boost Pp HIGH	5.4%	3.62	average		4.7
STEE	No.1 STG Pp	29.3%	45.29	measured		318.0

RING						
STEERING	No.2 STG Pp	68.5%	45.29	average		744.2
REFRIG	No.1 Fridge Compr	72.7%	5.32	measured		92.8
REFRIG	No.2 Fridge Compr	0.0%	5.32	average		0.0
B&GW	BW OB Pp.2	7.6%	6.54	measured	*confirm from survey data as Grey Water Discharge pump	11.9
B&GW	BW Treated OB Pp. No1	19.0%	1.68	estimated		7.7
B&GW	BW Treated OB Pp. No.2	3.3%	1.68	estimated		1.3
B&GW	BGW Treated OB Pp. No.3	21.2%	1.68	estimated		8.5
B&GW	BGW Macerator Pp. No.1	17.7%	1.68	average		7.2
B&GW	No.1 BW Eductor Pp	5.3%	4.34	measured		5.6
B&GW	No.2 BW Macerator Pp	0.4%	1.68	measured		0.2
B&GW	No.3 BW Macerator Pp	19.4%	1.68	average		7.9
B&GW	No.2 BW Eductor Pp	18.2%	4.34	average		19.0
B&GW	No.3 BW Eductror Pp	18.2%	4.34	average		18.9
VENT	MSV Supp Fan 14 Low Speed	80.6%	1.11	measured		21.4
VENT	MSV Exh Fan 15 Low Speed	94.6%	1.56	estimated		35.4
VENT	MSV Exh Fan 15 High Speed	3.5%	2.26	measured		1.9
VENT	MSV Supp Fan 12 High Speed	17.2%	1.62	measured		6.7
VENT	Mast Uptake Fan No.2	11.4%	2.59	measured		7.1
VENT	Aft Uptake Cooling Fan No.2	85.2%	39.73	average		812.1
VENT	Fwd Uptake	0.1%	39.73	average		0.8

	Cooling Fan No.3					
VENT	Fwd Uptake Cooling Fan No.2	0.1%	39.73	average		0.9
VENT	Aft Uptake Cooling Fan No.1	13.7%	39.40	measured		129.5
VENT	MSV Supp Fan 11 LOW	79.8%	1.11	measured		21.2
VENT	MSV Supp Fan 11 High	18.1%	1.62	measured	IPMS Tech measured	7.0
VENT	MSV Supp Fan 13 LOW	97.6%	1.11	measured	60% of high speed load	25.9
VENT	MSV Supp Fan 14 High	17.3%	1.62	measured		6.7
VENT	MSV Supp Fan 16 Low	97.2%	1.56	measured		36.4
VENT	MSV Supp Fan 16 High	0.0%	1.62	measured		0.0
VENT	NBCD Fan 3	99.2%	2.55	measured	no idea	60.7
VENT	MSV Exh Fan 9 Low	84.1%	1.56	estimated		31.5
VENT	MSV Exh Fan 9 High	13.8%	1.62	measured		5.3
VENT	MSV Supp Fan 13 High	0.1%	1.62	measured		0.0
VENT	MSV Supp Fan 15 Low	79.2%	1.11	measured		21.0
VENT	MSV Supp Fan 15 High	11.7%	1.62	measured		4.5
VENT	FWD Uptake Cooling Fan No.4	0.1%	39.73	measured		1.0
VENT	Mast Uptake Fan No.1	88.7%	39.73	measured		845.7
VENT	MSV Supp Fan No.10 LOW	96.8%	1.11	measured		25.7
VENT	MSV Supp Fan No.10 HIGH	0.9%	1.62	measured		0.4
VENT	MSV Exh Fan No.11 Low	56.3%	1.62	estimated		21.8
VENT	MSV Exh Fan 11 HIGH	41.6%	1.62	measured		16.1
VENT	MSV Exh Fan 13 LOW	81.4%	1.56	estimated		30.5

VENT	MSV Exh Fan 13 HIGH	14.5%	1.62	measured		5.6
VENT	MSV Supp Fan 17 LOW	72.4%	1.11	measured		19.2
VENT	MSV Supp Fan 17 HIGH	25.4%	1.62	measured		9.8
VENT	NBCD Fan 4	98.5%	2.55	measured	no idea	60.3
ASWC	ASWC Pp. No.1	21.3%	5.02	measured		25.7
ASWC	ASWC Pp No.2	80.1%	5.02	average		96.4
ASWC	ASWC Pp No.3	69.5%	5.02	average		83.7
					Sum KWh over day at sea	12772.38
					Average hourly kW load total:	532.18
	ESTIMATED LOADS					
DOM	Galley Equipment		1004.70	estimated	Discussion with ship's staff and surveys	1004.70
DOM	Ships Hotel Lighting		307.17	estimated	ibid	307.17
HOTEL	Engineering Halogen Lighting		297.09	estimated	Ibid	297.09
HVAC	FCUs		328.75	estimated	Ibid	328.75
HVAC	AC Plant 1		370.35	estimated	Ibid	370.35
HVAC	AC Plant 2		425.48	estimated	Ibid	425.48
HVAC	AC Plant 3 (Galley)		307.46	estimated	Ibid	307.46
HVAC	AC Plant Ops		147.52	estimated	Ibid	147.52
DOM	Laundry		1152.96	estimated	Ibid	1152.96
	SUM				Daily Load (kW)	17113.87

Appendix 4

Alongside / Harbor Equipment Electrical Duty Cycles

Table 12. Alongside electrical duty cycle reference data.

Electrical Equipment	System Group	Equipment Group	Aug-Sep 15	Dec, 2015	Jan, 2016	Average (weighted)	kW (PF 0.85)	Average Running Load (kW)
Stbd CRPP Pp	ANC	CRPP	0.26%	0.00%	0.98%	0.37%	20.9355	0.08
No.2 MLO Pp LOW	ANC	MLO	27.92%	0.00%	9.41%	15.00%	15.9035	2.39
No.2 MLO Pp High	ANC	MLO	3.32%	0.00%	5.88%	3.00%	23.29	0.70
BW OB Pp.2	DOM	BGW	23.14%	0.00%	0.28%	10.51%	6.5365	0.69
BW Treated OB Pp. No1	DOM	BGW	0.74%	13.04%	1.74%	4.61%	1.683	0.08
BW Treated OB Pp. No.2	DOM	BGW	0.07%	0.00%	0.00%	0.03%	1.683	0.00
FW No.2 Pp	DOM	FW	26.95%	0.00%	8.75%	14.39%	4.8535	0.70
MSV Supp Fan 14 Low Speed	HVAC	VENT	92.63%	78.63%	87.23%	87.14%	1.11	0.96
MSV Exh Fan 15 Low Speed	HVAC	VENT	95.48%	98.78%	94.51%	96.20%	1.56	1.50
MSV Exh Fan 15 High Speed	HVAC	VENT	0.80%	0.00%	0.01%	0.36%	2.26	0.01
No.2 MDFP	DC	SWS	0.00%	93.41%	27.30%	34.39%	57.7575	19.86
No.4 MDFP	DC	SWS	17.72%	0.00%	0.00%	8.00%	57.7575	4.62
MSV Supp Fan 12 High Speed	HVAC	VENT	0.00%	0.00%	0.01%	0.00%	1.62	0.00

No.1 STG Pp	ANC	STG	0.33%	0.00%	0.62%	0.31%	39.729	0.12
Mast Uptake Fan No.2	HVAC	VENT	18.64%	0.00%	15.92%	12.47%	39.73	4.95
FER LP Air Compr	AUX	LP/HP AIR	89.06%	86.29%	90.80%	88.69%	36.2355	32.14
No.1 Chiller	HVAC	CWS	0.00%	0.00%	0.00%	0.00%	49.8185	0.00
No.2 Chiller	HVAC	CWS	67.53%	86.84%	21.32%	61.42%	49.8185	30.60
No.3 CW Pp	HVAC	CWS	99.77%	95.87%	95.80%	97.61%	9.7665	9.53
No.4 CW Pp	HVAC	CWS	60.29%	98.00%	87.27%	78.24%	9.7665	7.64
Aft Uptake Cooling Fan No.2	HVAC	VENT	17.32%	14.15%	24.56%	18.24%	39.73	7.24
Fwd Uptake Cooling Fan No.3	HVAC	VENT	0.00%	0.00%	0.00%	0.00%	39.73	0.00
MLO Pp No.4 Low	ANC	MLO	3.65%	7.20%	2.66%	4.44%	15.9035	0.71
MLO Pp. No4 High	ANC	MLO	3.16%	0.00%	2.30%	2.01%	23.29	0.47
No.1 MLO Pp LOW	ANC	MLO	30.43%	0.00%	8.45%	15.88%	15.9035	2.53
No.1 MLO Pp. High	ANC	MLO	3.39%	0.00%	5.47%	2.93%	23.29	0.68
BGW Treated OB Pp. No.3	DOM	BGW	0.67%	13.04%	1.74%	4.58%	1.683	0.08
BGW Macerator Pp. No.1	DOM	BGW	0.73%	8.89%	1.64%	3.36%	1.683	0.06
No.2 CW Pp	HVAC	CWS	87.18%	89.01%	81.84%	86.35%	9.7665	8.43
Fwd Uptake Cooling Fan No.2	HVAC	VENT	3.56%	0.00%	0.08%	1.63%	39.73	0.65
Aft Uptake Cooling Fan No.1	HVAC	VENT	2.51%	0.00%	0.00%	1.13%	39.73	0.45
Fwd FO Centrifuge	AUX	FOS	0.01%	0.00%	0.33%	0.09%	11.968	0.01
HFW Circ Pp. No.1	DOM	HFW	99.96%	99.70%	79.89%	94.76%	2.55	2.42

HP Air Compr No.1	AUX	LP/HP AIR	40.49%	36.49%	25.10%	35.39%	32.997	11.68
HP Air Compr No.2	AUX	LP/HP AIR	3.26%	0.00%	0.75%	1.66%	32.997	0.55
Aft LP Air Compr	AUX	LP/HP AIR	12.96%	24.84%	59.70%	28.37%	36.2355	10.28
MSV Supp Fan 11 LOW	HVAC	VENT	97.24%	98.77%	91.38%	96.19%	1.11	1.06
MSV Supp Fan 11 High	HVAC	VENT	2.70%	0.00%	4.02%	2.24%	1.62	0.04
MSV Supp Fan 13 LOW	HVAC	VENT	99.94%	98.78%	95.62%	98.50%	1.11	1.09
MSV Supp Fan 14 High	HVAC	VENT	1.80%	13.60%	3.01%	5.57%	1.62	0.09
MSV Supp Fan 16 Low	HVAC	VENT	68.28%	98.78%	90.23%	82.84%	1.11	0.92
MSV Supp Fan 16 High	HVAC	VENT	0.00%	0.00%	0.00%	0.00%	1.62	0.00
NBCD Fan 3	HVAC	VENT	95.36%	98.77%	94.71%	96.20%	1.62	1.55
No.1 Fridge Compr	DOM	REFRIG	63.84%	57.99%	56.68%	60.30%	5.321	3.21
No.2 Fridge Compr	DOM	REFRIG	0.00%	0.00%	0.00%	0.00%	5.321	0.00
No.2 STG Pp	ANC	STG	0.22%	0.01%	1.27%	0.42%	0	0.00
Port CRPP Pp	ANC	CRPP	0.26%	0.00%	1.32%	0.46%	20.9355	0.10
HSS Pp. No.1	ANC	HSS	0.03%	0.00%	0.01%	0.02%	0	0.00
HSS Pp. No.1 (B)	ANC	HSS	0.03%	0.00%	0.01%	0.02%	0	0.00
HSS Pp.2 (a)	ANC	HSS	0.01%	0.00%	0.03%	0.01%	0	0.00
HSS Pp No.2 (b)	ANC	HSS	0.01%	0.00%	0.03%	0.01%	0	0.00
No.3 MLO Pp HIGH	ANC	MLO	3.38%	0.00%	2.74%	2.23%	23.29	0.52
No.3 MLO Pp	ANC	MLO	0.87%	7.20%	2.60%	3.17%	15.9035	0.50

LOW								
ASWC Pp. No.1	AUX	ASWC	42.32%	29.66%	22.87%	33.64%	5.015	1.69
No.1 BW Eductor Pp	DOM	BGW	5.99%	9.27%	17.74%	9.95%	4.335	0.43
No.2 BW Macerator Pp	DOM	BGW	0.00%	0.00%	0.12%	0.03%	1.683	0.00
No.3 BW Macerator Pp	DOM	BGW	0.75%	13.01%	1.40%	4.51%	1.683	0.08
No.1 CW Pp	HVAC	CWS	0.00%	0.00%	0.00%	0.00%	9.7665	0.00
No.4 Chiller	HVAC	CWS	29.17%	9.09%	53.92%	29.59%	49.8185	14.74
Aft FO Centrifuge	ANC	FOS	0.00%	0.00%	0.71%	0.18%	11.968	0.02
MSV Exh Fan 9 Low	HVAC	VENT	97.27%	74.11%	71.78%	83.97%	1.56	1.31
MSV Exh Fan 9 High	HVAC	VENT	0.19%	24.66%	22.86%	13.16%	1.62	0.21
MSV Supp Fan 13 High	HVAC	VENT	0.00%	0.00%	0.01%	0.00%	1.62	0.00
MSV Supp Fan 15 Low	HVAC	VENT	25.66%	100.00%	100.00%	66.45%	1.11	0.73
MSV Supp Fan 15 High	HVAC	VENT	0.00%	0.00%	0.00%	0.00%	1.62	0.00
Port ROD Feed Pp	DOM	FW	0.13%	0.00%	0.00%	0.06%	4.8535	0.00
Stbd ROD Feed Pp	DOM	FW	0.10%	0.00%	0.00%	0.05%	4.8535	0.00
Port ROD 1st Stage Pp	DOM	FW	0.00%	0.00%	0.00%	0.00%	13.7785	0.00
Stbd ROD 1st Stage Pp	DOM	FW	0.00%	0.00%	0.00%	0.00%	13.7785	0.00
No.1 MDFP	DC	SWS	0.01%	7.50%	28.37%	9.44%	57.7575	5.45
No.3 MDFP	DC	SWS	81.77%	0.44%	47.23%	49.07%	57.7575	28.34
MDJP	DC	SWS	0.00%	0.00%	0.00%	0.00%	35.5895	0.00

DFO Transf Pp High	AUX	FOT	0.01%	0.11%	0.00%	0.04%	6.035	0.00
JP5 Pp. 1	AUX	FOT	0.28%	0.00%	1.06%	0.40%	0	0.00
JP5 Pp.2	AUX	FOT	0.07%	0.00%	0.59%	0.19%	0	0.00
No.2 FOS Boost Pp Low	ANC	FOS	3.49%	0.08%	5.60%	3.03%	3.621	0.11
No.2 FOS Boost Pp High	ANC	FOS	0.40%	0.07%	0.17%	0.24%	6.035	0.01
No.1 FOS Boost Pp LOW	ANC	FOS	2.41%	0.20%	19.88%	6.21%	3.621	0.23
No.1 FOS Boost Pp HIGH	ANC	FOS	0.15%	1.18%	0.12%	0.45%	6.035	0.03
ASWC Pp No.2	AUX	ASWC	43.73%	99.77%	22.10%	54.67%	5.015	2.74
ASWC Pp No.3	AUX	ASWC	56.92%	3.16%	75.62%	45.90%	5.015	2.30
No.2 BW Eductor Pp	DOM	BGW	20.01%	4.12%	0.00%	10.24%	4.335	0.44
No.3 BW Eductror Pp	DOM	BGW	0.62%	8.99%	2.70%	3.61%	4.335	0.16
FW Pp No.1	DOM	FW	73.02%	95.58%	89.15%	83.76%	4.8535	4.07
Feed Transf Pp	AUX	FEED	0.00%	0.00%	0.00%	0.00%	0	0.00
No.3 Chiller	HVAC	CWS	70.77%	0.08%	15.73%	35.97%	49.8185	17.92
FWD Uptake Cooling Fan No.4	HVAC	VENT	0.00%	0.00%	0.00%	0.00%	39.73	0.00
Mast Uptake Fan No.1	HVAC	VENT	6.25%	0.00%	9.13%	5.15%	2.59	0.13
Hot Water Circ Pp No.2	DOM	HFW	99.96%	99.70%	96.43%	98.98%	0.391	0.39
MSV Supp Fan No.10 LOW	HVAC	VENT	97.47%	98.77%	87.03%	95.19%	1.11	1.05
MSV Supp Fan	HVAC	VENT	0.00%	0.00%	3.21%	0.82%	1.62	0.01

No.10 HIGH								
MSV Exh Fan No.11 Low	HVAC	VENT	99.93%	98.78%	81.60%	94.92%	1.56	1.48
MSV Exh Fan 11 HIGH	HVAC	VENT	0.00%	0.00%	14.51%	3.70%	2.26	0.08
MSV Exh Fan 13 LOW	HVAC	VENT	49.11%	56.57%	96.09%	63.28%	1.56	0.99
MSV Exh Fan 13 HIGH	HVAC	VENT	5.80%	35.65%	0.00%	13.09%	2.26	0.30
MSV Supp Fan 17 LOW	HVAC	VENT	97.35%	78.05%	96.11%	91.36%	1.11	1.01
MSV Supp Fan 17 HIGH	HVAC	VENT	0.00%	0.00%	0.01%	0.00%	1.62	0.00
NBCD Fan 4	DC	VENT	80.70%	94.09%	94.78%	88.22%	1.62	1.42
Port ROD 2nd Stage Pp	DOM	FW	0.00%	0.00%	0.00%	0.00%	4.726	0.00
Stbd Rod 2nd Stage Pp	DOM	FW	0.00%	0.00%	0.00%	0.00%	4.726	0.00
						SUM IPMS Monitored Loads (kW)		259.75

Appendix 5

Maritime Efficiency Programs

The US DoD has strong policy implements directing their agencies to improve energy management as a matter of priority. In 2007, the US DoD was directed to improve the efficiency of weapons platforms in order to enhance platform performance and reduce the size of the fuel logistic system, and the burden that high fuel consumption places on agility, operating costs, and price volatility (USC, 2006). Later, orders stipulated that procurement activities would be supported by fuel efficiency Key Performance Parameter (KPP) and life cycle cost analysis for new systems to support evaluation of alternatives in acquisition programs (United States Congress [USC], 2008). In 2012, the Chairman of the Joint Chiefs of Staff set energy as a major capability consideration, and directed acquisition teams across DoD (DoD, 2012) and the Navy (Department of the Navy [DON], 2010) to consider the fully burdened cost of energy and energy efficiency into trade-off analyses and procurement activity (DoD, 2013).

The US Secretary of the Navy has set ambitious and comprehensive energy goals in the Navy's Energy Program. This program has three main strategic goals: increase energy efficiency of sea and shore systems; increase the use of alternative energy; and continual environmental stewardship (DON, 2010). Under this program, the USN incorporates energy conservation initiatives for warships via their incentivized energy conservation project (i-ENCON), priority technology development objectives through the Office of Naval Research (ONR), improved behavioral, communications, education and awareness programs, and strategic partnerships with other defense and government departments, industry, and academia.

USN Maritime Energy Working Group is now aggressively developing technologies and investigating energy and operational actions to improve energy efficiency. Their 2009 goals set a 15% reduction target for overall fleet energy consumption by 2020, and directed teams to develop energy performance criteria for acquisition (Martin, 2015). NAVSEA i-ENCON experience suggests that operational behavior fuel savings of 10-15% have been achievable within all capability requirements (iENCON, 2010). Significant through-life fuel savings are achievable through speed reductions, anchoring, drifting operations, idle-time reduction, hull condition optimization, optimized passage planning, weather routing, trim and ballast adjustments, and efficient equipment and system configuration.

US Navy Warship Electrical Energy Use

The 2001 survey aboard US Navy warship USS PRINCETON (CG59) was the first USN study to take a close look at platform energy use to determine what measures could be taken to improve efficiency. The study was performed by RMI and illuminated the internal ship's systems electrical energy use, which identified priorities for savings and efficiency improvements. The CG59 study found that cooling represents the single largest energy burden, with major electrical energy use in combat systems, auxiliaries, and domestic systems (fresh water, sanitation etc). Much of the combat electrical service load is required for cooling, which can be optimized through improvements to various marine systems. Combat systems energy-use improvements are deemed beyond the scope of this study, but should be integrated into design considerations, especially as to how they relate to HVAC loads.

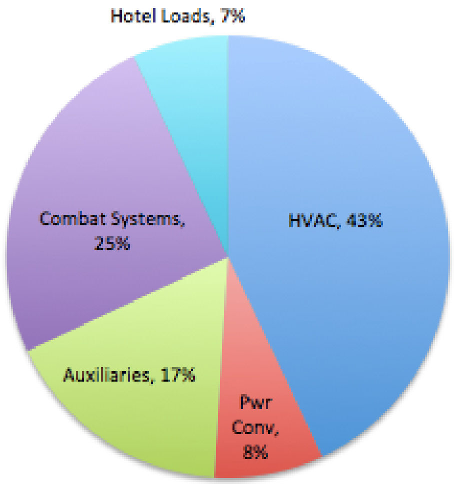


Figure 40. US Navy CG59 estimated service loads. Adapted from Lovins et al. (2001). Hotel Loads = ship electrical loads, Pwr Conv=power conversion, Combat Systems = weapons and sensors, HVAC=heating ventilation and air conditioning.

The RMI study on board CG59 found retro-fittable platform energy savings of 20-50%, with potential for over 50% electrical savings possible across different climate/regional conditions, resulting in fuel savings of 10-25% per year (Lovins et al., 2001**)**. This 2001 study was pivotal in shaping initial USN energy-savings policy measures and activities to reduce overall fleet fuel consumption.

Other Naval Energy Efficiency Efforts

The UK Royal Navy (RN) started its Green Ship program in 2010 to find technical solutions to improve the efficiency, capability and environmental performance of RN platforms. The RN has set an 18% energy reduction target by 2020 (based on 2010 standards) (Bailey & Hardy, 2014), and are now currently assessing promising technological options to reduce energy intensity of future platforms. The RN stresses the importance of energy as an enabler of military capability, and the need for a mix of improved technologies and behaviors to efficiently deliver military effect (ibid). The detailed, current status of their specific developmental and/or trials programs, policy drivers and key achievements are not yet well understood and need to be examined in more rigor. Examination of the other navies' accomplishments in this space can help to identify best practice and potentially leverage ongoing development work and technology programs.

United Nations - Marine Vessel Efficiency

The International Maritime Organization (IMO) aims to improve civilian vessel fuel conservation through a design standard for cargo-carrying ships, which sets metrics for overall platform energy use. The IMOs Energy Efficiency Design Index (EEDI) provides ship builders, operators and regulators the management framework to drive technical (systems and structure) and operational improvements and reduced platform energy intensity. The EEDI approach focuses efforts on recovering the most significant savings related to civilian hull and propulsion designs as well as operational measures / behaviors. The IMO's 2009 2nd study on Green House Gas (GHG) reductions revealed potential civilian shipping benefits, as highlighted later in the report, which provides potential savings estimates, although not always directly translatable to warship applications.

Table 13. CO$_2$ Emissions Reduction Potential - Existing Technologies. Source: 2009 IMO 2nd GHG Study (International Maritime Organization [IMO], (2011)).

DESIGN (New ships)	**Saving of CO$_2$/tonne-mile**	**Combined**	**Combined**
Concept, speed and capability	2% to 50%[+]	10% to 50%[+]	25% to 75%[+]
Hull and superstructure	2% to 20%		
Power and propulsion systems	5% to 15%		
Low-carbon fuels	5% to 15%[*]		
Renewable energy	1% to 10%		
Exhaust gas CO$_2$ reduction	0%		
OPERATION (All ships)			
Fleet management, logistics and incentives	5% to 50%[+]	10% to 50%[+]	
Voyage optimization	1% to 10%		
Energy management	1% to 10%		

[+] Reductions at this level would require reductions of operational speed.

[*] CO$_2$ equivalent, based on the use of Liquefied Natural Gas (LNG).

The EEDI IMO policy and bulk of industry focus is applicable to civilian platforms, and only addresses new-build ships. Warships are not intended to be regulated by this international legislation, but may still target emerging performance standards, and could capitalize on the benefits from civilian maritime R&D to improve system architecture, total ownership costs and environmental impacts.

Merchant navy shipping improvements in ‘power and propulsion’ efficiency are mainly focused on prime mover efficiency upgrades and propulsor / underwater appendage design. Although smaller in magnitude, other machinery improvements pose significant energy savings potential, especially when considered over a 20 to 40-year life. In some cases, it is likely that developments in the civilian maritime domain will be suitable for adoption in military platforms. Primary focus areas for civilian energy savings are operational measures (i.e., speed reduction), Waste Heat Recovery (WHR), improvements to Heating, Ventilation and Air Conditioning (HVAC), increased controls with automation and intelligent system software, and the use of shore power when in port.

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