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REDUCING NAVAL FOSSIL FUEL CONSUMPTION AT SEA IN THE 21ST CENTURY

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Climate change negatively impacts the Navy's ability to conduct its missions and represents a serious threat to the safety, sovereignty, and future prosperity of the United States. In his Executive Order 14008 dated 27 January 2021, President Joe Biden remarked that current climate considerations are essential to U.S. foreign policy and national security. The Department of Defense is one of the largest single consumers of fossil fuel in the United States. For example, in 2020 the Defense Logistics Agency (DLA) procured over $3.3 billion in fuel for the Navy. It will be the view in this thesis that the motivation and the means exist today, more so than any other point in the Navy's history, to decrease fossil fuel use while increasing operational readiness, and that Navy surface small-combatant ships currently consume more fossil fuel in their daily operations than would otherwise be permitted through the implementation of certain fuel conservation technologies. That is, by updating the fleet the Navy can reduce fossil fuel use and carbon emissions.

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REDUCING NAVAL FOSSIL FUEL CONSUMPTION AT SEA IN THE 21ST CENTURY

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ABSTRACT

Climate change negatively impacts the Navy's ability to conduct its missions and represents a serious threat to the safety, sovereignty, and future prosperity of the United States. In his Executive Order 14008 dated 27 January 2021, President Joe Biden remarked that current climate considerations are essential to U.S. foreign policy and national security. The Department of Defense is one of the largest single consumers of fossil fuel in the United States. For example, in 2020 the Defense Logistics Agency (DLA) procured over $3.3 billion in fuel for the Navy. It will be the view in this thesis that the motivation and the means exist today, more so than any other point in the Navy's history, to decrease fossil fuel use while increasing operational readiness, and that Navy surface small-combatant ships currently consume more fossil fuel in their daily operations than would otherwise be permitted through the implementation of certain fuel conservation technologies. That is, by updating the fleet the Navy can reduce fossil fuel use and carbon emissions.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	alternating current
AEM	advanced energy and materials
AI	artificial intelligence
AoA	angle of attack
AoR	area of responsibility
ARPA-E	advanced research projects agency-energy
BAA	broad agency announcement
BBL	one barrel
CA	heavy cruiser
CFD	computational fluid dynamics
CG	guided missile cruiser
CGN	guided missile cruiser nuclear
CoP	conference of parties
COVID	coronavirus disease
DARPA	defense advanced research projects agency
DC	direct current
DDG	guided missile destroyer
DIU	defense innovation unit
DLA	Defense Logistics Agency
DoE	department of energy
DOD	department of defense
EO	executive order
EERE	energy efficiency and renewable energy
ESM	energy storage module
FT	Fischer-Tropsch
GAO	Government Accountability Office
GGF	great green fleet
GPH	gallons per hour
GPS	global positional system
HED	hybrid electric drive

HEFA	hydro-processed esters and fatty acids
Hr	hour
Hz	hertz
kW	kilowatt
Lb	pound
LCS	littoral combat ship
LORAN	long range navigation
LRU	line replaceable unit
MARPOL	international convention for the prevention of pollution from ships
MILSPEC	military specification
MOVREP	movement report
MW	megawatt
NAVSTAR	national satellite timing and ranging
NFMS	Navy fuel management system
NM	nautical mile
NREL	national renewable energy laboratory
ONR	office of Naval research
OPNAV	office of the chief of Naval operations
OPTEMPO	operational tempo
OTTER	optimized transit tool and easy reference
PBCF	propellor boss cap fin
PIM	position of intended movement
PNT	position navigation and timing
RADAR	radio detection and ranging
RASP	replenishment at sea planner
RIMPAC	rim of the Pacific
ROI	return on investment
SFC	specific fuel consumption
SONAR	sound navigation and ranging
SSTG	ship service turbine generator
TACAN	tactical air navigation
TFE	task force energy

UPS	uninterruptible power supply
USS	United States ship

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I. INTRODUCTION

A. MOTIVATION

Much of the motivation for this work comes from an understating that fossil fuels are a finite resource, and the burning of fossil fuels has a negative impact on the environment and imposes limitations on Naval operational capabilities. The Navy as a consumer of large quantities of fossil fuels has a responsibility to act wherever possible to reduce its fossil fuel consumption, consistent with mission requirements. One key point of this motivation is the common conception the Navy takes long periods of time to seemingly catch up to the innovation and technological advances adopted by commercial industry.

Climate change represents a serious threat to the safety, sovereignty, and future prosperity of the United States President Joe Biden stated in his executive order (EO) 14008 dated 27 January 2021 that current climate considerations are essential to U.S. foreign policy and national security.

B. PROBLEM

Operational units within the Navy, such as surface ships and aircraft, consume vast amounts of fossil fuel in their daily operations. In 2020 Defense Logistics Agency (DLA) Energy reported over 9.5 billion dollars in fuel sales to the Department of Defense with over 3.3 billion dollars to the Navy (Defense Logistics Agency, 2020, p. 23). Although numerous systems and methods exist such as the Hybrid Electric Drive (HED), Optimized Transit Tool and Easy Reference (OTTER), Navy Fuel Management System (NFMS), and Replenishment at Sea Planner (RASP) have been identified to reduce consumption and increase operational capability and efficiency, the acquisition and implementation of these ideas fleetwide often takes decades. Whether its cost, resistance by leadership, or acquisition challenges, these failures of the Navy result in hundreds of millions of dollars in avoidable fuel costs.

C. SCOPE AND LIMITATIONS

The scope of this thesis is limited to technologies and methodologies which are applicable to U.S. Navy surface combatants, specifically guided missile Cruisers (CG) and Destroyers (DDG). Further research could determine if the ideas discussed are applicable to other fossil fuel burning surface vessels in the U.S. Navy fleet.

All the technologies considered in this thesis are commercially available. However, purchase costs cannot be accurately estimated as all of these engineering modifications are custom designed to fit specific applications. Additionally, testing and installation are required, and costs will vary based on both of these factors. The hardware modifications are ship specific and have not been acquired or tested by the U.S. Navy, therefore complete and accurate acquisition data for Navy ships cannot be estimated at this time.

Estimations of improvements in efficiency are based on the reported observations of real world, model, and computer testing results and compared to current fuel prices and estimated usage.

D. ORGANIZATION

The remainder of this thesis is broken into four chapters. Chapter II will discuss the relevant background information and provide insight into specific examples of the Navy's resistance to adopting new and innovative technologies. Chapter III will discuss engineering modifications currently used in the commercial industry specifically targeted towards increasing the overall efficiency of surface ships including testing and relative cost savings. Chapter IV compares the Navy's current alignment with industry best practices related to improving fuel efficiency and decreasing fuel consumption. Chapter V is the concluding chapter summarizing research findings, recommendations, and follow-on research.

II. BACKGROUND

A. SMALL SURFACE COMBATANTS

The U.S. Navy is often thought to be reluctant to adapt to new technologies. One example is a long-standing reluctance to develop or adapt to more fuel-efficient and operationally capable propulsion systems for small surface combatants over the last century and into the 21st century. During the middle of the 20th century, the U.S. Navy had almost shifted entirely to sophisticated external combustion steam turbine engines. Steam turbines have several advantages. They require less space in the engine room than previous systems, less maintenance, and allow a ship to attain relatively high speeds. Steam turbines work under a straightforward principle called the Rankine Cycle. In the Rankine Cycle, fuel burns in a boiler, which in turn heats water to produce steam. This high-pressure, high-temperature steam travels through multi-stage turbines. After passing through the turbine, the water condenses and is pumped back into the cycle.

The high-speed and low torque of the turbine is reduced through the main reduction gear to provide the high torque and low-speed power needed to propel the ship through the water. Although advanced for its time, the steam turbine does have several drawbacks. The boiler must heat the water in the steam plant, and sufficient steam head pressure must build for a period before setting sail. If the heating cycle is disrupted, the cycle must begin again. A steam turbine system takes to significant time to become operational. Moving forward, the Navy would need a more reliable propulsion plant. Finally, in the mid-1970s, the Navy began experimenting with placing aviation gas turbine engines on ships.

Today the Navy's surface combatant fleet is comprised mainly of CG's and DDG's designed in the 1980s. Each ship uses four large gas turbines for propulsion and three smaller gas turbines to generate power (Anderson, 2013, p. 18). When fully fueled these ships carry approximately 500,000 gallons of diesel fuel.

Modern day CG's and DDG's use efficient gas turbine engines A gas turbine uses the Brayton Cycle, in which air is pulled in through the compressor, forced into the combustion chamber, and ignited. The pressurized gas is passed through and spins a power turbine which is coupled to the compressor. As in the example of the steam turbine, high-speed, low torque gets converted to high torque low speed. A significant advantage to the gas turbine is the speed at which it can be employed. The start-up time of the engine is essentially only limited to the alignment of the fuel system and any required regular maintenance. A much shorter time when compared to the length of time to bring a steam plant online. Additionally, gas turbine engines operate most efficiently at or near their max horsepower output.

B. SPEED AND FUEL CONSUMPTION

The most effective way to reduce a ship's fuel consumption, other than by reducing OPTEMPO, is to implement technology which operates efficiently at the most - operated speeds. To determine which technology is the most fitting for this task we must first determine what is the most common speed requirement. A small surface combatant with all four engines online can burn through their fuel supply in a matter of days. CG's and DDG's and their crews are effectively creatures of habit. In 2013 Travis J. Anderson wrote his thesis examining the operating profiles of the Arleigh Burke-Class Destroyer (Anderson 2013). In his thesis he discusses the most common engineering plant configurations, DDG' use while operating. He also compares the time spent at different engineering configurations, the speed of the ship, against habits of the crew to operate at standard bell or set measurements of engine speed. Understanding a ships engineering configuration is paramount to understanding why ships consume great quantities of fuel with relatively small increases in speed.

CG's and DDG's operate in three different engineering configurations: Full power consumes the most fuel but allows the ship to achieve the highest speed approximately 30 knots. All four engines, two per shaft are producing thrust at once. Split plant is more efficient than full power however, this efficiency comes with a decrease in top speed. Two engines one per shaft is producing thrust. In this configuration the maximum speed is approximately 27 knots. The final and most speed limiting but most efficient configuration is the trailing shaft configuration. In this configuration one engine on one shaft is producing thrust and the pitch of the no thrust producing propellor is set nearly 100 percent ahead to reduce the drag of the blade through the water. In this configuration the ship can reach a maximum speed of approximately 15 knots.

In 2013 Anderson’s data revealed the least common speeds were those requiring full power. He determined DDG’s spent less than 1 percent of their time operating at speeds of 30 knots (Anderson, 2013, p. 25). This finding is especially relevant because it illustrates DDG’s seldomly have a need to operate at any time at full power. At full power a DDG will consume approximately 6,400 gallons per hour (GPH) (Crawford, 2014, p. 2).

By a substantial margin, nearly 70 percent of the time, DDG’s operated in the trail shaft configuration (Anderson 2013, p. 25). Traveling at 10 knots a DDG will burn approximately 730 GPH (Crawford, 2014, p. 2, making trail shaft the most fuel-efficient engineering configuration. There is another component to the application of speed we must consider when discussing habits and traditions of ship driving, that is the use of standardized bell orders. A bell order corresponds to a specific state of engine performance. The commanding officer, officer of the deck could give an order, all engines ahead full for 10 knots. This would relay to engineering, to bring all engines online, to maintain the ship speed of 10 knots. This is relevant because Anderson found in his research over 40 percent of the time DDG’s were operating at standard bell orders at 0, 5, 10, and 15 knots (Anderson, 2013, p. 24).

Examining this data leads us to conclude the Navy should focus its efforts on finding a suitable fuel-efficient propulsion technology that allows ships to operate efficiently up to speeds of at least 15 knots.

1. Hardware

Ships do receive modest upgrades over time to increase performance and reduce fuel consumption. For instance, the Navy installed stern flaps to help increase the hydrodynamic efficiency of the vessels (Crawford, 2014, p. 9). The greatest leaps in naval innovation historically take deceases to become standardized in the fleet.

Nearly ten years ago, the USS Zumwalt (DDG 1000) launched with an advanced hybrid drive system that uses the ship’s power turbine to drive electric motors for propulsion. This hybrid drive paired with a unique hull design enables the ship to burn less fuel and achieve higher speeds than its CG and DDG counterparts. Testing a similar drive system with a conventional CG design yielded an annual fuel savings of nearly 24 percent or 3 million dollars per ship (Alexander et al., 2010, p. 69). Hybrid drive technology represents the cutting edge of naval technology with regards to the main propulsion of a ship. Current CG's and DDG's main propulsion as discussed are still comprised of four large gas turbines.

2. Software

In addition to technological advances in hardware, the Navy has access to several other fuel conservation methodologies, which the Navy has thus far been reluctant to adopt fleet-wide. Once implemented, these methodologies will effectively reduce fuel consumption and cost while increasing operational range and effectiveness. Fuel management computer programs such as the Optimized Transit Tool and Easy Reference (OTTER) and Replenishment at Sea Planner (RASP) are comparatively inexpensive compared to significant ship engineering upgrades and likely could be integrated fleet-wide within a realistic timeframe. Regrettably, RASP met with significant resistance from intended users. During the program's presentation to the 5th fleet area of operations (AOR), fuel schedulers, leadership, and the planners pushed back on using the program. Users stated it was another form of data entry they didn't have time for (Brown et al., 2017, p. 695). Eventually, RASP personnel and 5th Fleet planners reached a compromise, and programmers modified the program to decrease data entry, making the program more user-friendly.

a. Effectiveness

The OTTER program calculates the fuel burn rates of various engineering pant configurations and makes configuration recommendations. In one study of the Littoral Combat Ship Freedom (LCS1), the program recommendations resulted in a fuel burn rate decrease of nearly 10 percent and an increase of on-station time of almost 200 hours (Blackburn, 2016, p. xvi).

Similarly, the RASP program calculates the most efficient refueling routes for Combat Logistics Ships in a theatre of operations. Traditionally these plans are calculated by hand; however, the RASP program can accomplish in minutes what otherwise would have taken hours. In some instances, RASP calculated that by decreasing the required fuel safety stock from 60 percent to 50 of capacity for a given surface combatant, one could yield a decrease in fuel consumption of the combat logistics ship by 20 percent (Brown et al., 2017, p. 691).

The Navy could make changes today to decrease its consumption of fossil fuels and increase its operational capability. Research into these areas will provide insight into what individual methods and combinations of efforts yield the most fuel savings and reduce excess fuel consumption.

C. MOVEREP: PLAN OF INTENDED MOVEMENT

The mission was to deliver an atomic bomb to the tiny Pacific Island of Tinian. After successfully delivering the bomb, 29 July 1945 would be the last time the USS Indianapolis (CA-35) was ever heard from. The ship, a Portland Class Cruiser, and her crew were assigned to a top-secret mission to help facilitate the end of World War II.[30] July 2945. The Indianapolis was sunk by a Japanese submarine (Naval History and Heritage Command, 2020). Of the nearly 1200-member crew, 316 sailors would survive floating nearly five days in the open ocean ("Story," n.d.). Although the mission was successful, the loss of the Indianapolis and the ship's crew brought about a new methodology for maintaining a ship's position at sea, the movement report or (MOVREP).

The MOVREP system is a simple concept. It is an operational report designed to provide a constant operational picture to theatre commanders. A ship submits a MOVREP when it leaves or enters a port. Especially relevant to fuel consumption is the requirement for ships to submit a MOVREP and include a plan of intended movement (PIM). The PIM is the plotted ship's course or track with a box or window on the map around the ship. If the ship deviates from its PIM by exceeding a speed of 15 knots, reaches 100 nautical miles (NM) on either side of its PIM course, falls behind by or exceeds its PIM by four hours, the ship must submit a new MOVREP to correspond to its new position (Crawford, 2014, p. 26).

There is any number of legitimate reasons a ship could deviate significantly from its PIM track. The ship could have a severe casualty, fire, flooding, or personnel casualty. Engineering and damage control practice drills can also require the ship to slow or even stop at times (Crawford, 2014, p. 26). Shipping, biologic interference, and weather can also cause a deviation from PIM.

The current MOVREP system and the PIM requirements force unnecessary constraints on surface combatants, which in some cases lead ships to burn excess fuel to maintain their PIM track. We believe a culture of resistance to adapt to and rely on new technology, particularly a global positioning system (GPS), and the intentional or unintentional manipulation of the PIM window by the ship are significant contributors to the reluctance to drop the PIM window requirement.

1. Positioning, Navigation, and Timing

In 1979 the Government Accountability Office (GAO) issued a report outlining a new cutting-edge system that would cost approximately 1.7 to 2.5 billion dollars. The system would provide space-based radio navigation to over 27,000 users, including the U.S. military. The National Satellite Timing and Ranging (NAVSTAR) GPS provides users with three-dimensional (longitude, latitude, and altitude) position and navigation information. The system consists of 24 satellites in geo-synchronous orbit, providing real-time, precise location information (General Accounting Office, 1979, p. i-ii).

A section in the report for potential cost savings calls out specific Navy systems to be phased out and eventually replaced by GPS. There are four navigational systems: tactical air navigation (TACAN), long-range navigation (LORAN), Transit, and Omega. Two of the four systems, TACAN and LORAN, exist today in a modernized form. The report also details reasons such as reluctance to accept a new system and reliance on external systems as potential barriers to adapting to the NAVSTAR GPS (General Accounting Office, 1979, p. 10).

Fast forward to September 30th, 2019, the Office of the Chief of Naval Operations (OPNAV) issues instruction 9420.1C regarding positioning, navigation, and timing (PNT) policy. The policy applies to all U.S. vessels, regardless of size. It states every user with a valid PNT requirement must have a primary and alternate means of determining precise position and time. The only DOD and U.S. Navy–approved primary source is the NAVSTAR GPS. There are several alternated sources for determining position, celestial navigation, radio detection and ranging (RADAR), and inertial navigation systems (Office of the Chief of Naval Operations, 2019, p. 4). These are back-ups to GPS; however, as they are not as accurate, NAVSTAR GPS remains the primary means of determining position.

D. SUMMARY

The above examples highlight a period of over 40 years of technological innovation and slow adaption by the Navy. The remarkably slow transition from steam turbines to gas turbines illustrates that despite having a reliable alternative the Navy is resistant to change. This notion of resistance is further reinforced by with the reluctance to update and use new hardware, and software designed to reduce fuel consumption such as the HED, OTTER, and RASP. Finally, the PIM window is an antiquated methodology that served its purpose in the past; however, modern technology has replaced it. It was not until the highest levels of leadership made GPS a requirement did the Navy accept GPS as a standard for navigation.

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III. ENGINEERING IMPROVEMENTS

A. ENERGY STORAGE MODULE SYSTEM

As a simple rule regarding a combustion engine, one way to reduce fuel consumption is to burn less. One method of burning less fuel for Navy CG's and DDG's is to reduce the number of gas turbines in operation at a given time to the minimum required to support current operations. Research conducted in 2014 by then Naval Postgraduate Student Dustin Crawford highlighted the reluctance of CG and DDG commanding officers to operate on a single ship's service turbine generator (SSTG) for ships' power at a time. His research explained that single generator operations burned 95–120 gallons per hour (GPH) less fuel two generator operations, but that ships avoided this practice because a loss of one generator could cause the whole ship to lose power (Crawford, 2014, pp. 21–22). This statement is partially true. A more detailed explanation of the importance of consistent power will provide context to the risks of losing all power. It will also explain how an Advanced Shipboard Energy Storage System (Mahoney et al., 2012, p. 1) could lessen the likelihood of a complete power loss and make single generator operations a more acceptable option for operations at sea. In addition, as more advanced systems with more significant power requirements emerge, Energy Storage Module (ESM) technology has the potential to serve as a bridge for closing the gaps between increasing operational capabilities, current single generator limitations, and reducing fuel consumption.

1. Risks of Traditional Single Generator Operations

Crawford's thesis does point out some of the risks associated with a ship losing power at sea. The loss of navigation lights and Radio Detection and Ranging (RADAR), are dangerous and do greatly contribute to the risk of collision (Crawford, 2014, pp. 21). However, damage to sensitive equipment is a more likely outcome of power loss than those mentioned by Crawford. Many of the ship's more complicated displays, weapons, and fire control systems rely on a consistent 400 Hertz (Hz) power supply, and these systems are typically more sensitive than those which operate on 120 Hz power. In particular, losses of power, inconsistent voltage, or frequency variations can damage this sensitive equipment

(Naval Sea Systems Command, 1998, pp. 320–37). Unfortunately, comparing potential equipment casualties and equipment repair costs against potential fuel consumption savings while operating on a single SSTG is virtually impossible because of the infinite possibilities of what could fail. A more realistic solution to this challenge would be a solution that prevents damage due to loss, interruption, or power fluctuations. A solution that implements this kind of technology would allow CG's and DDG's to operate safely and reliably on a single SSTG.

DDG's have three Allison 501-K34 SSTG's and CG's have 3 501-K17's to generate power. When examining single SSTG operations onboard a ship, an important factor is understanding why a single SSTG is more efficient than two. Although two SSTG's can more consistently carry the dynamic electrical load of the ship, one SSTG can handle a constant load more efficiently when at or near its maximum power rating. At the point near its maximum power output, the SSTG is most efficient and is producing the most horsepower per pound of fuel burned (Mahoney et al., 2012, p. 3). However, a 2500 kW load is also near the high end of the 501 K34 and the 501 K17 generator ratings. As such, this load level increases the generator's sensitivity to changes in load demand.

2. Staged Load Shedding

The next step in understanding the potential for an ESM system is defining what happens within a ship's electrical system when the load becomes too great for a single generator to support. As the load on a generator increases, the speed of the generator's gas turbine engine increases to match the demand. The increase in turbine speed increases inlet air temperature, and it is known that gas turbine engines are susceptible to fluctuations of inlet temperatures (Naval Sea Systems Command, 1998, p. 320). The load shedding system uses sensors within the generator switchboards, which measure power output in real-time. The load shed system has pre-established limits. For example, if the load limit were set at 95 percent of the generator rating of 2500 kW or 2,375 kW when the generator reaches that limit, the system would shed different portions of the load in stages to rebalance the load. Although no two ships engineering systems are the same, all load shed system have two categories: nonvital and vital systems.

a. Stage One

During the first stage of load shedding, the system opens connections between nonvital loads and the switchboard. Nonvital systems are not required for the ship to maintain safe operations, do not impact survivability, or risk harm to personal if shut down for a short interval. Examples of nonvital systems would be laundry equipment, galley equipment, heating, and some cooling systems. The load shed process will intentionally secure power to these systems in an overload scenario (Naval Sea Systems Command, 1998, p. 320–20).

In contrast, vital systems are those required for the safe operation of the ship. Examples are fire pumps, navigational systems, and primary air search RADAR systems. Power to these systems is never intentionally interrupted during a load shed (Naval Sea Systems Command, 1998, p. 320–21).

b. Stage Two

If the stage one load shed does not reduce the load on the overloaded generator, the system will split the load to the paralleled generator (during two generator operations). In this situation, the shift can take less than a second for the paralleled generator to pick up the load.

c. Stage Three

The last option, should stage one and two not shed enough load on the overloaded generator, is for the system to try for an automatic startup of the standby generator. Suppose the system cannot rebalance the load by reducing the load in stage one, splitting the load to the paralleled generator in stage two. In that case, the system's last effort is to bring an additional generator online. If the standby generator does not activate and the overload remains, the ship will lose all power as the generator shuts down. This kind of shut down can cause loss of navigation, propulsion, and damage to equipment.

The load shed process generally takes a few seconds. This short time between an overload condition and a shutdown is a likely culprit for not wanting to operate a warship on a single generator. On the other hand, an energy storage system could provide a ship's engineering team several minutes to assess the overload condition and manually start a generator, if necessary, without losing power.

3. Advanced Shipboard Energy Storage System

The concept of energy storage systems is not new. In many office buildings, homes, and board ships, the same technology is in use. Colloquially the technology is referred to as UPS or Uninterruptible Power Supply. A UPS is a series of batteries wired in parallel, creating a direct current (DC) power bank. The DC power is converted to alternating current (AC), which allows a user a short time to safely shut down or run their equipment before a complete power loss.

4. Demonstration

In 2010 a company called RCT Systems, in conjunction with Creative Energy Solutions and NDI engineering, demonstrated a 600 kW Advanced ESM unit developed in response to a Broad Agency Announcement (BAA) (Office of Naval Research Science and Technology, 2007, p. 2) by the Office of Naval Research (ONR) (Mahoney et al., 2012, p. 1). If implemented, the system could potentially allow a CG or DDG to operate for approximately 10 minutes on battery backup power alone if necessary. This kind of technology could bridge the gap between the ship’s dynamic electrical load and the loss and subsequent recovery of the ship’s gas turbine electrical plant. An ESM system is a practical and available technology for conserving fuel and potentially opens a path for other advancements in high powered lasers and microwave emitter weapon technologies.

5. ESM System Overview

An ESM system is a simple concept, and in relative terms, it is an equally simple design, and is based upon familiar and proven battery technologies. The system employs several battery banks, which depending on the power requirements and ship configuration, would be placed strategically around a ship. Using a DDG as an example, for 10 minutes of backup power with no generator online, the system could support a load of 3 Megawatts (MW). The design in this discussion consists of four modules containing four battery packs.

These battery packs are the line replaceable units (LRU) designed to use lithium-ion batteries. Each LRU has a capacity of 200 kW (Mahoney et al., 2012, p. 4).

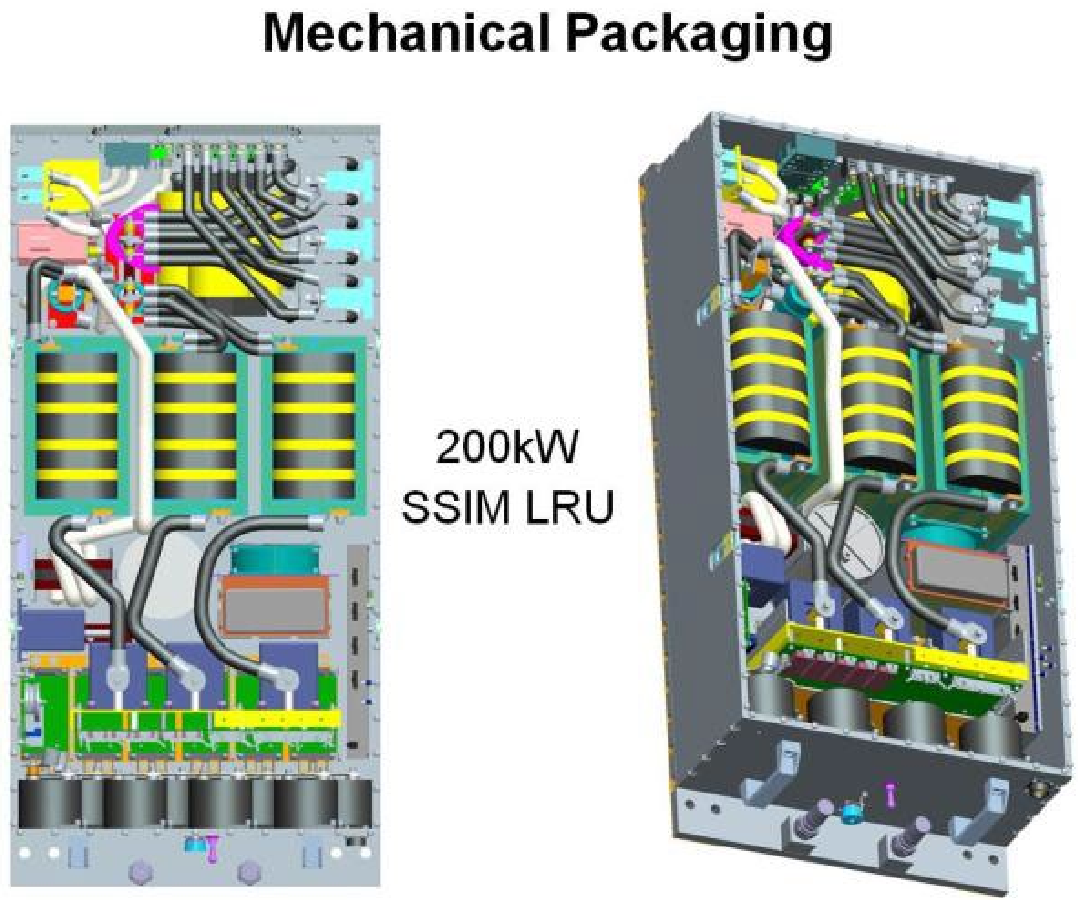

Figure 1. Individual LRU isometric basic design.
Source: Mahoney et al. (2012).

The four LRU's are contained within an electronics cabinet and will supply 600 kW. A system with five cabinets supports a load of 3MW.

Figure 2. LRU cabinet with four LRU’s, 150 kW each, total power 600 kW.
Source: Mahoney et al. (2012).

The system is modular and easily integrates with the existing ship’s power grid. One of the significant advantages of this type of system is its near-instantaneous response to power fluctuations. If the online generator becomes overloaded, this system will respond quickly enough to either prevent the generator from overloading or accept the entire load of the generator in case of a total shut down. Figure 3 illustrates RCT testing of a single 200 kW unit which showed a 100 percent load acceptance and rejection rate of .2 seconds (Mahoney et al., 2012, p. 6).

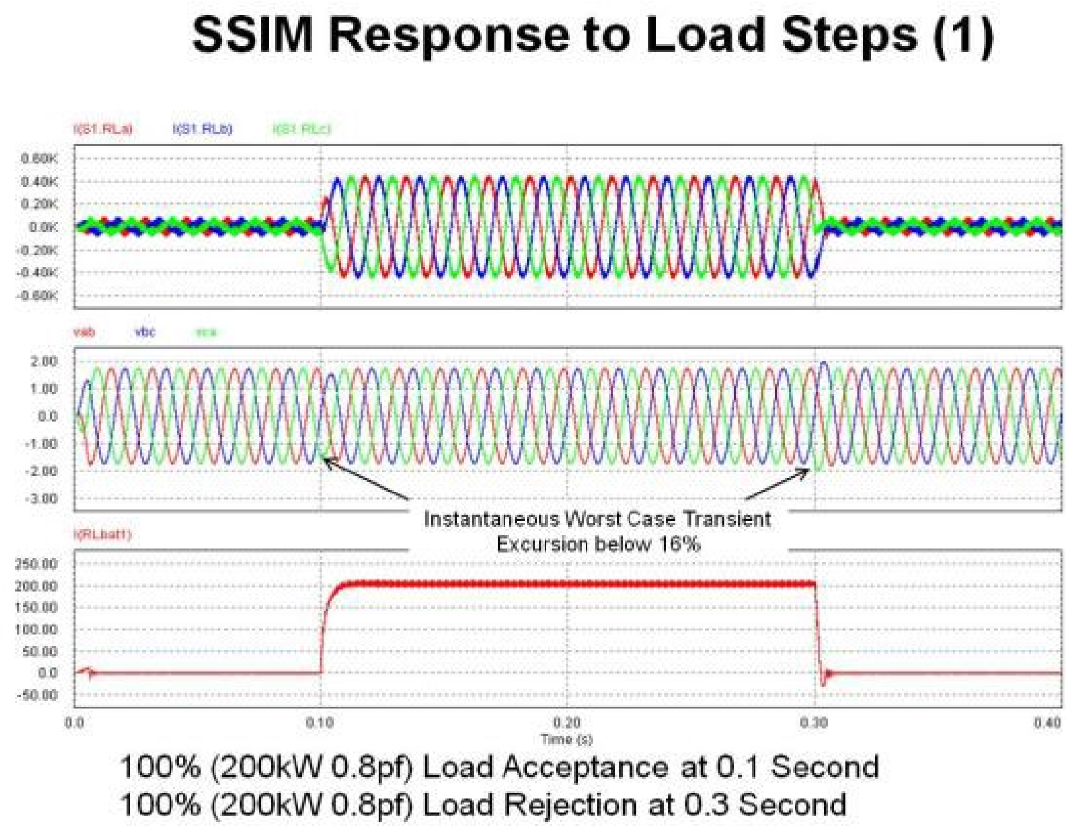

Figure 3. ESM response to 100 percent step load increase.
Source: Mahoney et al. (2012).

In comparison, current automatic power transfer systems in DDG's, when shifting power sources in response to fluctuations, take between .3 and .5 seconds to respond (Naval Sea Systems Command, 1998, p. 320–17).

6. Fuel Savings

Crawford's thesis calculated fuel savings of 27.4 million dollars in 2014 for 62 DDG's based on an average of 127 underway days and single generator operations 25 percent of the time (Crawford, 2014, pp. 23). Rather than use the number of days underway, a calculation using the average number of hours a generator runs in a year would represent more accurate fuel consumption. The generator set for CG's Allison 501-K17 is very similar to the DDG Allison 501-K34. For calculating savings, analyzing the operating profiles, and fuel consumption, the generators are comparable. An additional consideration is the use of bleed air from the turbine. Bleed air usage does decrease efficiency; however, the use of the bleed air for operations like sound masking and anti-icing is inconsistent and likely does significantly impact fuel consumption in everyday operations. Figure 4 illustrates the difference between one and two Allison 501-K34 gas turbines operating at 2525 kW loads. Two gas turbines splitting a 2525 kW load operating at approximately half their maximum shaft horsepower have a specific fuel consumption (SFC) of .68 pounds per brake horsepower (lb/hp-hr). In contrast one engine operating near its maximum horsepower has an SFC of .50 lb/hp-hr. Clearly single generator operations are more efficient, as the generator can meet the same electrical load demand while burning .18 lb/hp-hr less fuel.

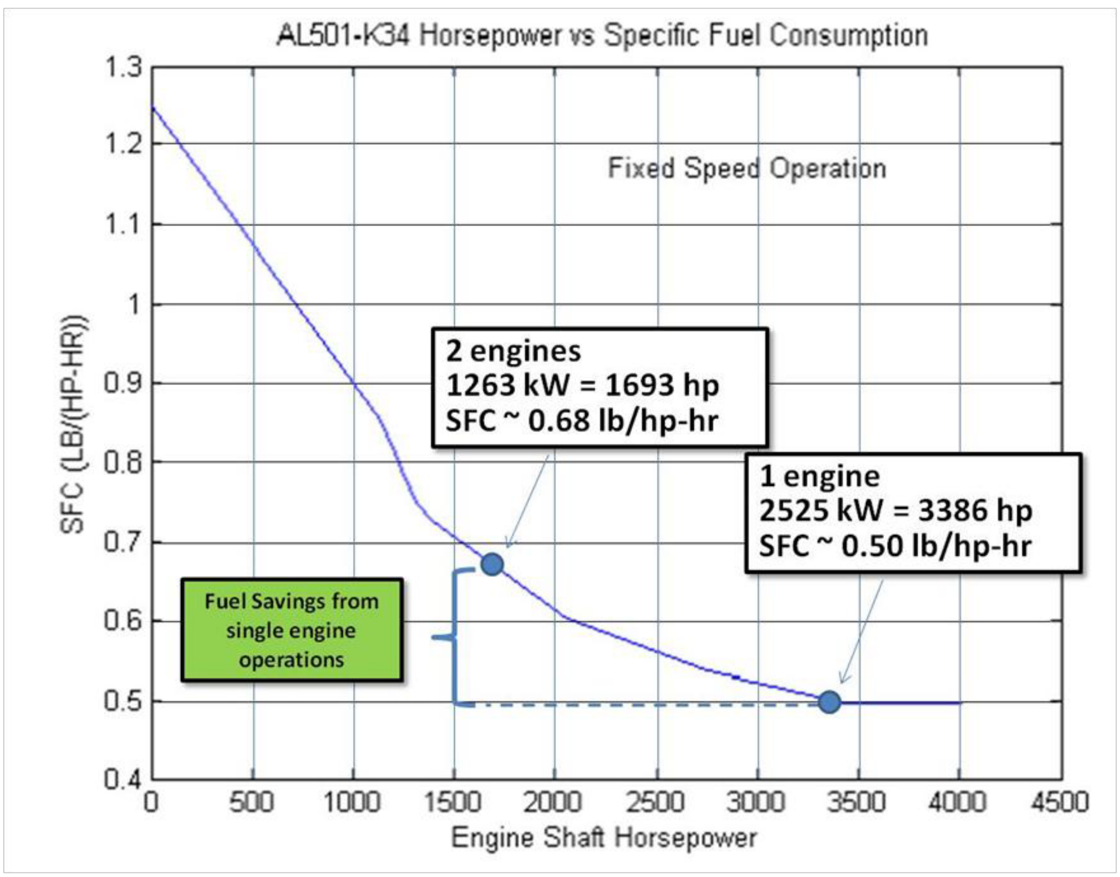

Figure 4. Fuel savings from single vs. two generator operations.
Source: Mahoney et al. (2012).

As per the ONR's BAA, calculations are based on a DDG typically consuming 24,000 Bbl's of fuel per day. Operating on a single SSTG at 4000 hours per year constitutes a fuel savings of around 8,000 Barrels (BBL) or an efficiency increase of approximately 30 percent. In 2021 DLA prices of 100.38 U.S. dollars per BBL (Office of the Under Secretary of Defense, 2020, p. 2) would yield an approximate savings of 800,000 dollars per ship per year (Mahoney et al., 2012, p. 3). The current Navy has a current inventory of 69 DDG's and 22 CG's. Adding this technology to existing platforms could yield a yearly savings of nearly 72.8 million dollars. Throughout its recently recalculated 35-year lifespan (Larter, 2020), a single DDG at today's oil prices could realistically save nearly 28 million dollars in fuel costs.

B. PROPELLOR MODIFICATION

With a growing fleet of 69 DDG's and 22 CG's one area of design has received little attention over the lifespan of these ships, the design characteristics of the exterior design characteristics of the ship. While the Navy has no plans to build more CG's, it is incrementally modernizing its CG fleet. This modernization could represent an opportunity to install the fuel-saving improvements discussed in this section to CG's. Unlike engineering upgrades to equipment like electrical plants and gas turbines or changes to operating procedures such as single generator operations. Exterior hull modifications are generally cheaper than complex engineering upgrades and are designed to survive the rigors of being submerged; because of this design, they require little or no maintenance after installation. Additionally, the modifications to the hull are permanent, so fuel-saving estimates apply to the ship's lifespan.

This section will discuss two exterior modifications to the hull and one modification to the propellor. These modifications are in use commercially and by foreign militaries; however, testing, measurements, calculations, and estimates are based on these results as currently no existing data specific to CG's and DDG's is available.

1. Propellor Hub

CG and DDG propeller designs are very similar, if not identical. The propellor and hub design is a system that has changed very little in terms of its exterior design over the last several decades. Functionally, propellor design has changed very little over the last century. As a propellor rotates in the water, the pitch of the propellor blade creates an area of high pressure that flows over the hub or boss of the propellor and generates lateral thrust. This thrust is what propels the ship through the water. CG and DDG propellors are approximately 17 feet in diameter, and each ship has two. They are controllable pitch propellors which means the propellor shaft only rotates in one direction, and the propellor blades rotate independently to lessen, increase, or change the direction of thrust. This section will discuss the effects of water moving down around the propellor boss and the low-pressure hub vortex created by this action. This hub vortex effect is common to every propellor system, and its effect is the scattering of a portion of the forces created by the propellor resulting in a loss of thrust. The hub vortex causes an increase in propellor torque and a decrease in propellor efficiency. Figure 5 is an example of the low-pressure scattering effects indicated in blue of a hub vortex.

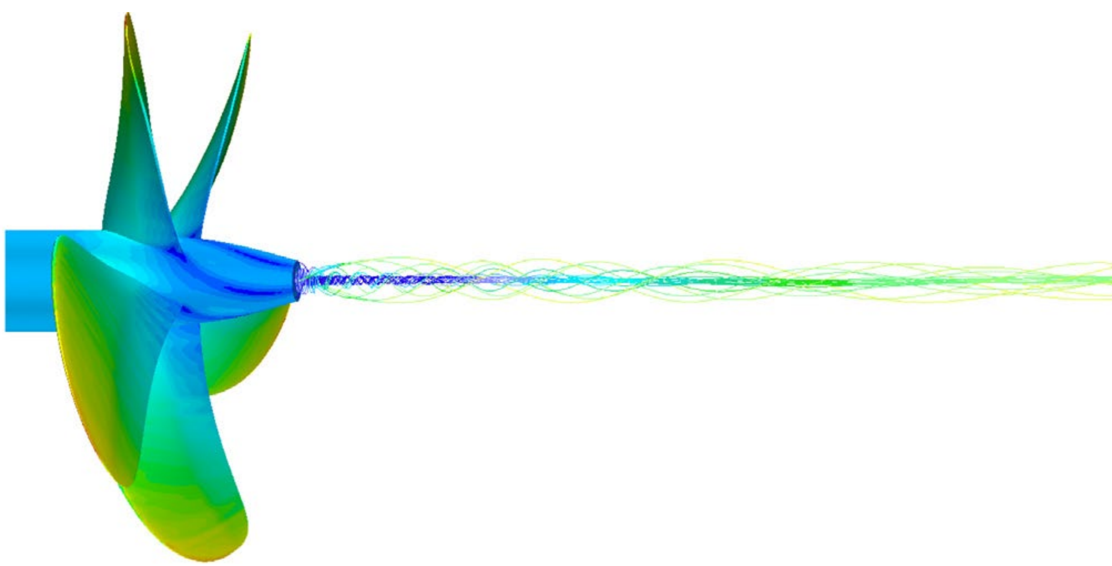

Figure 5. CFD model hub vortex no PBCF installed.
Source: Mizzi et al. (2017).

2. Propellor Boss Cap Fin

To lessen the effects of the hub vortex, a Japan-based company has developed a proprietary technology designed to disrupt the low-pressure flow around the propellor hub, which creates the propellor vortex. MOL Techno-Trade, Ltd. A Japanese company designed a bolt-on propellor hub fin system called the Propellor Boss Cap Fins (PBCF), which to date is installed on 3,553 ships worldwide (MOL Techno-Trade Ltd., n.d.). The PBCF replaces the traditional propellor hub seen in Figure 6.

Figure 6. Current DDG propellor hub and rudder configuration.
Source: O’Rourke (2006, p. 7).

The fins of the PBCF seen in Figure 7 are stationary. As the water flows around the hub, the fins disrupt the concentrated low-pressure stream and prevent it from forming a significant hub vortex.

Figure 7. PBCF divergent design mounted on ship's propellor hub.
Source: Kimura et al. (2018).

Mol Techno-Trade company states their PBCF can improve a ship’s fuel efficiency by 5 percent (MOL Techno-Trade Ltd., n.d.).

3. ECO-Cap

Another study in 2015 aimed at decreasing the effects of the hub vortex and damage it causes to the rudder of a ship was conducted using a similar propellor hub cap called the ECO-Cap. Although similar in design, the research led to slightly different features. The research acknowledged the advantages of the PBCF technologies and intended to refine the overall design of the fins by using Computational Fluid Dynamics analysis (CFD) (Katayama et al., 2015).

4. Testing

To design, study, and refine the PBCF and the ECO-Cap, three primary forms of testing were used: CFD, scale models, and full-scale testing. CFD analysis in this discussion focuses on the results surrounding the interaction of solid bodies and fluids

(Blazek, 2051, p. 4) and the display of these results by graphical representation. Scale model testing is in controlled water tanks under specific conditions. Full-scale or open ocean testing is unique in that the environment, water conditions, and currents offer the potential for unpredictable results.

a. CFD Analysis

CFD analysis was conducted using multiple open-source computer-based modeling systems to investigate the PBCF and ECO-Cap design and compare the computed efficiency to real-world observations. An advantage of CFD testing is the variations of propeller design and hub cap combinations which can be programmed and simulated. In multiple observations, CFD modeling revealed maximum increases of efficiency between 2 percent (Lim et al., 2014, p. 200) and 1.28 percent (Katayama et al., 2015, p. 3), a substantial difference in the reported 5 percent increase reported by the manufacturer. CFD analysis concluded that the current divergent design seen in Figure 9 of the PBCF did not reduce the hub vortex as significantly as intended.

A 2015 follow-up investigation into the design of the PBCF used CFD modeling to explore a more efficient alternative to the divergent design. The ECO-Cap hub design explored ways to improve on the PBCF design. Figure 8 shows the ECO-Cap design with the fins converging at the end of the cap.

Figure 8. ECO-Cap fins converging at the center of the propellor hub.
Source: Katayama et al. (2015).

Despite this change in design, the ECO-Cap design CFD analysis still resulted in a maximum efficiency increase of 1.28 percent (Katayama et al., 2015, p. 4).

b. Scale Modeling

Scale model testing confirmed CFD results and anticipated efficiency results. Scaled testing also used air injection, which visually represents the hub vortex using a conventional hub cap, PBCF, and the ECO-Cap designs.

Figure 9. Scale PBCF design, hub vortex cavitation with divergent cap.
Source: Lim et al. (2014).

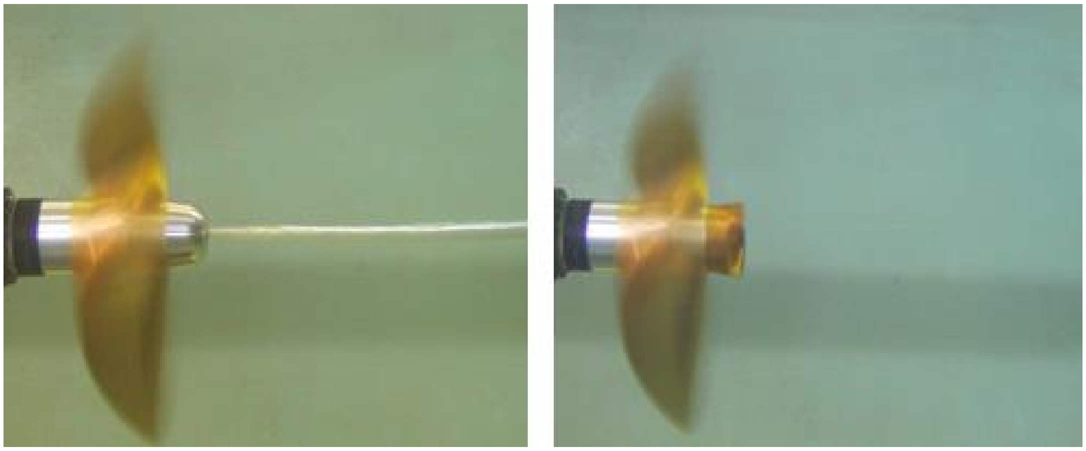

Figure 10. Rounded hub design and ECO-Cap cavitation.
Source: Katayama et al. (2015)

c. *Full-Scale Testing*

In 2011 the full-scale test results conducted on the Aframax tanker, the Kilimanjaro Spirit, were presented at the Second International Symposium on Marine Propulsors in Hamburg, Germany. The test conducted in the Adriatic Sea consisted of two runs of the vessel. One with the unmodified traditional propellor hub and one with the PBCF. Results were calculated with readings at speeds ranging from eight to sixteen knots. On average, they measured a 3.7 percent power requirement reduction across all speeds, which translates into an approximately average 3.5 percent reduction in fuel consumption (Hansen et al., 2011, p. 10). Figure 11 illustrates the relationship between speed and the required power reduction observed between run one without the PBCF and run two with the PBCF.

Summary of Corrected Trial Results

Trial 1 - No PBCF			Trial 2 - With PBCF		
Mean Ship speed through Water	Mean Corrected Shaft Power	Mean Corrected Revs	Mean Ship speed through Water	Mean Corrected Shaft Power	Mean Corrected Revs
Vs	Ps	Ns	Vs	Ps	Ns
Kts	kW	kW	Kts	kW	kW
14.300	8740.1	92.08	14.385	8612.3	92.15
14.882	10261.9	97.07	15.054	10354.2	97.59
15.406	11706.3	101.25	15.647	11831.1	101.96
15.588	12131.7	102.22	15.728	12077.8	102.42
15.619	12165.4	102.47	15.889	12477.4	104.00

Faired Results at Even Speeds

Trial 1 - No PBCF			Trial 2 - With PBCF			Change in Power and Revs	
Vs	Ps	Ns	Vs	Ps	Ns	% Ps	% Ns
(knots)	(kW)	(RPM)	(knots)	(kW)	(RPM)		
14.4	9003.4	92.99	14.4	8653.5	92.30	-3.89%	-0.74%
14.6	9541.1	94.79	14.6	9173.0	93.90	-3.86%	-0.93%
14.8	10073.8	96.49	14.8	9690.5	95.49	-3.80%	-1.04%
15.0	10601.6	98.10	15.0	10205.9	97.06	-3.73%	-1.06%
15.2	11124.4	99.62	15.2	10719.4	98.61	-3.64%	-1.01%
15.4	11642.3	101.04	15.4	11230.8	100.15	-3.53%	-0.89%
15.6	12155.2	102.38	15.6	11740.2	101.67	-3.41%	-0.69%

Figure 11. Testing without and with PBCF installed for Kilimanjaro Spirit. Source: Hansen et al. (2011)

The study's authors acknowledge hull fouling, and weather conditions likely did impact the results. However, the impacts are negligible as the conditions were similar for both runs.

Similarly, in 2015 at the Fourth International Symposium on Marine Propulsors in Austin, Texas, results were published of the ECO-Cap design fitted to a car ferry. The vessel in this scenario was significantly smaller and had a two-propellor system. This real-world test indicated an average drop in fuel oil consumption of 2.8 percent over six months.

5. Economy

As each PBCF and ECO-Cap is engineered to fit the specification of the customer's individual requirements, cost and pricing data to calculate a return on investment (ROI) is not available. By applying the estimation previously mentioned of a single DDG consuming 24,000 bbl's per day at sea (OFFICE OF NAVAL RESEARCH, 2007, p. 3). A 2.8 to 3.5 percent reduction would constitute savings of 672 to 840 bbl's per day, respectively. Current DLA prices set at 100.38 dollars this technology could potentially save 67,455 to 84,319 dollars per underway day.

C. STERN FOIL

1. Background

The stern flap for Navy ships is perhaps the most significant fuel-saving add-on component to existing ships in the last 35 years. The design is simple, permanent, and effective. The stern flap works well, especially for DDG's and CG's because they are non-planing hull vessels.

a. Stern Flap

The stern flap extends out from the bottom edge of the ship's transom angled slightly downward as the ship increases speed, the water pressure against the hull increases. The water flows along the ship's hull and contacts the stern flap, which creates an upward force on the stern. This upward force at the ship's stern forces the bow down, assisting the ship in leveling its trim. All of this works to correct the ship's trim by reducing drag and increasing efficiency. The Navy estimated in 2006 stern flaps would increase ship's fuel efficiency by approximately 7.5 percent and potentially save around 195,000 dollars per ship, per year (O'Rourke, 2006, p. 6).

b. Foils

In the past few years, there has been research into an addition or alternative to the stern flap for non-planing hull vessels, the stern foil. The stern foil is also a permanent no-maintenance addition that works similarly like the stern flap but is more refined in design and offers the potential for more significant increases in efficiency. The stern foil is similar in design to the modern-day wing of an aircraft. It has a teardrop shape that tapers towards the aft end. In its most basic form, a foil shape consists of a leading-edge, trailing edge, and upper and lower surfaces. The lower surface is relatively flat in comparison to the upper surface. The increased camber or rounded shape of the upper surface allows for an increase in speed and decrease in pressure of the media the foil is in as it travels over the foil, as displayed in Figure 12. At the same time, the contour of the bottom edge of the foil generates a positive pressure or lift. For the proposes of this discussion, the media is water, and although this is often associated with aircraft in flight, similar principles apply in water.

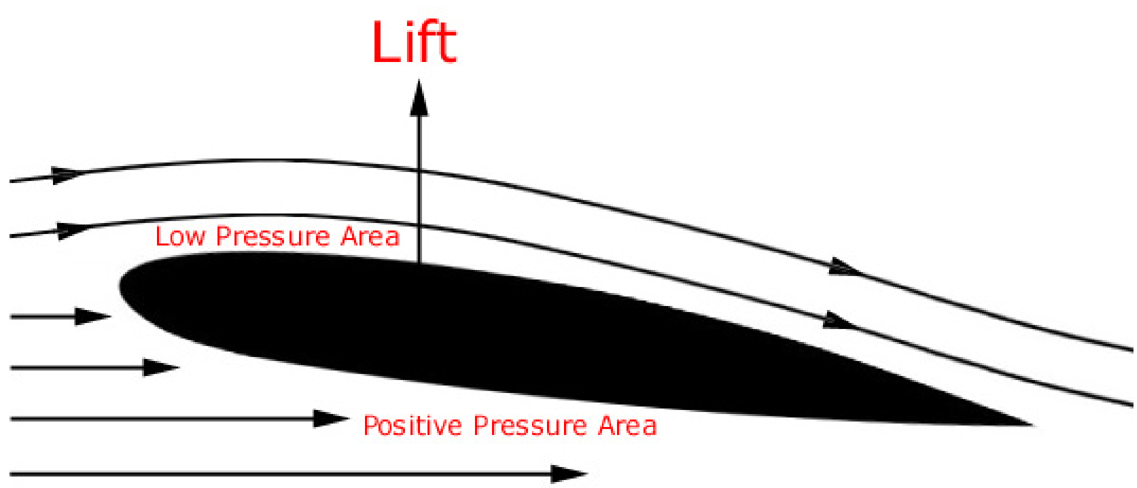

Figure 12. Foil design illustrating low-pressure, high-pressure areas lift.
Source: "Airfoils and lift" (n.d.).

2. Hull Vane

In 1992 a Dutch hydrodynamicist, Dr. Pieter Oossanen, designed the Hull Vane. The Hull Vane was patented in 2002 (Suastika et al., 2017, p. 1266). The idea and application of hydrofoils are not new to the Navy. The Navy operated hydrofoil vessels up until the latter half of the twentieth century. Those vessels were much smaller, and the foil design lifted the vessel out of the water onto a plane, allowing it to travel very fast. Less water in contact with the hull reduces friction and allows the vessel to operate at high speeds effectively.

The Hull Vane operates on the same principle as this earlier vessel; however, today's application is intended to be used on much larger ships to create lift and reduce overall ship resistance, thereby increasing efficiency. The Hull Vane is essentially a large wing mounted to the bottom of the transom running parallel along the ship's stern. Refer to Figure 13, for example.

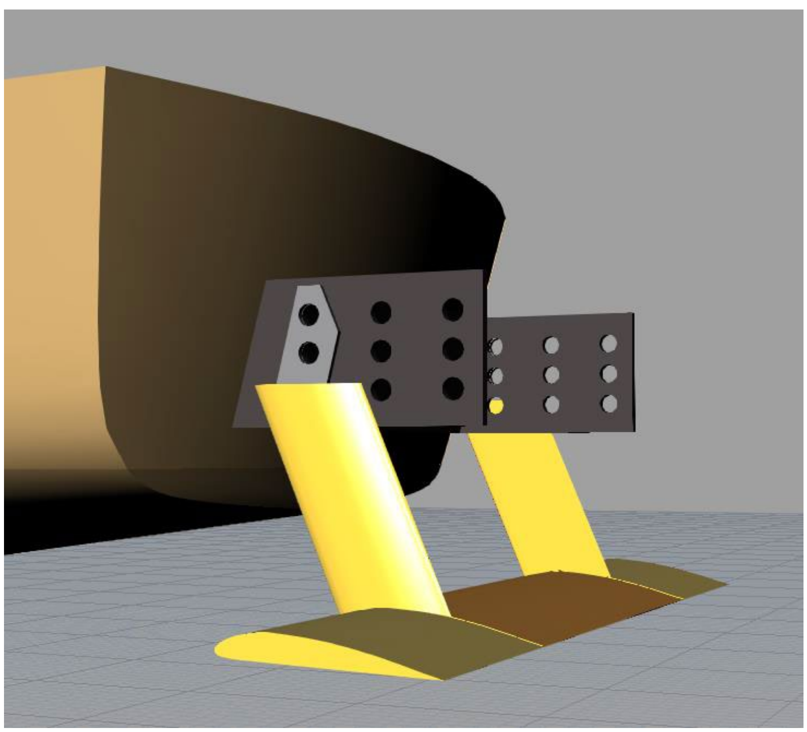

Figure 13. Hull vane installation and setup example.
Source: Hou et al. (2020).

The manufactures of the Hull Vane claim with the correct design and installation the Hull Vane can reduce a ships fuel consumption by 29 percent (Hou et al., 2020, p. 2).

3. Sinkage

A contributor to loss of fuel efficiency is sinkage or squat associated with the stern of a ship at speed. Squat affects a ship's trim, and the less balanced a ship's trim, the less efficient the ship travels through the water. As a ship increases speed, the stern tends to squat into the water. The stern flap and Hull Vane are designed to lessen the impact of a ship's squat by increasing pressure upward to the ship's stern, forcing the ship's bow down and leveling the trim.

4. Testing

The Hull vane has been tested using a variety of methods. The three discussed in this section relate to CFD testing, scale model testing, and real-world observation. As with the ECO-cap and the PBCF, there are significant differences in performance between CFD testing and real-world measurements.

a. CFD analysis

One of the key outcomes in CFD modeling is determining the optimal size of the foil and the angle of attack of the leading edge. If the foil's angle of attack (AoA) is too steep, it creates significant resistance at all speeds. If the angle of attack is not steep enough, the foil will not have the desired effects. CFD modeling also revealed other potential benefits. With the Hull Vane installed, there is a decreasing intensity of the ship's wake. It also reduced the pitching motion of the ship at the bow and stern. A study in 2020 revealed the application of a stern foil reduced the ships overall resistance by 3.6 percent at normal speed; however, the pitch, heave, and heave speed of a 1200 gross ton passenger ship was reduced by 10.75 percent, 6.96 percent, and 7.32 percent respectively (S Asmara et al., 2020, p. 10). While this increase in efficiency of 3.6 percent is nowhere close to the manufacturer's claim, the reduction of the pitch of the ship speaks to the increased stability of the ship's trim with the stern foil application.

b. Scale Model Testing

In 2017 a scale model test confirmed that drag was significantly increased at slower speeds with the application of a stern foil. The test was conducted in a 50-meter water tank using a model meant to simulate the performance of a 40-meter planing hull vessel with a top speed of 28 knots (Suastika et al., 2017, p. 1266). The model was towed through the water at various speeds. The foil had a set AoA of two degrees. Table 1 illustrates the increases and decreases in resistance compared to the vessel with Hull Vane installed.

Table 1. Resistance comparison to speed and AoA; relative change in speed of planning hull vessel. Source: Suastika et al. (2017).

Foil AoA	Speed	Overall resistance
2 degrees	14 knots	+ 13.9 percent
2 degrees	16 knots	+11.8 percent
2 degrees	22 knots	-8.4 percent
2 degrees	24 knots	-7.1 percent
2 degrees	28 knots	-10 percent

An additional scale model test was conducted in 2020 to determine Hull Vane's performance with large displacement ships. The chosen hull form was a publicly available model of an Arleigh Burke Class destroyer, including the SONAR dome but without the stern flap as seen in Figure 14.

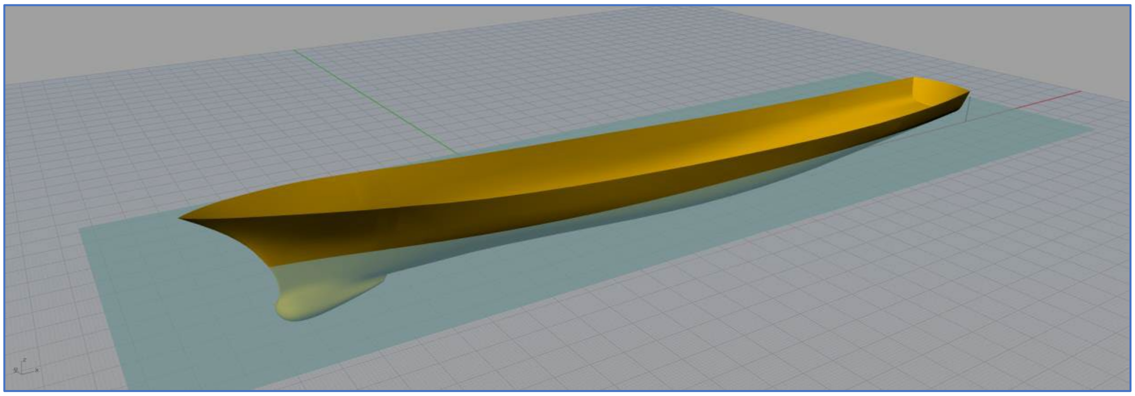

Figure 14. Computer-aided design model of Arleigh Burke Class DDG. Source: Hou et al. (2020)

The AoA for this test was also set at two degrees; however, adjustments to the AoA ranging from -17 to 30 degrees were made to determine the most effective combination of speed and AoA. The testing was conducted in simulated calm seas and in waves of a simulated height of one to two meters with speeds ranging from 18 to 30 knots (Hou et al., 2020, p. 11).

c. Extreme AoA

Regardless of speed, any extreme AoA led to significant resistance increases and changes in vessel trim. As anticipated by CFD modeling, a reduction in the size of the ship's wake was also observed. Additionally, depending on the AoA, the pitch of the ship could be reduced anywhere between 20 to 30 percent (Hou et al., 2020, p. 14). The test concluded that with the optimum combination of the AoA and speed, a realistic expectation for resistance reduction is approximately 10 percent (Hou et al., 2020, p. 19).

5. CG and DDG Application

For the Hull Vane to be most effective as a permanently mounted energy-saving device, the most effective AoA and speed combination must be determined. In 2013 Travis J. Anderson determined in his thesis that DDG's spend most of their time below eight knots (Anderson, 2010). As highlighted in Table 1, the Hull Vane at low speeds increases the resistance of a vessel in the water dramatically. As DDG's and CG's spend most of their time at lower speeds, the Hull Vane does not represent a practical approach to increasing the ship's overall efficiency within its typical operating profile.

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IV. GREEN INITIATIVE

This section will not attempt to make a climate change argument in favor of the Navy reverting to wind power from fossil fuels to prevent future greenhouse gas emissions. The scientific establishment has already come to a strong consensus regarding climate change. This point is most clearly demonstrated in the significant investment and expansion of alternative energy projects in the past several decades, primarily in wind and solar power (Gates, 2021). Fuel is an essential to every operational mission that the Navy performs. Without a secure and robust source of fuel, the Navy would be unable to fly its jets, operate its ships, or maintain its installations. For these reasons, that is why alternative fuel is the answer to how the Navy increases its sustainability at sea, gains strategic independence from foreign supplies, and increase its warfighting capabilities (Mabus, 2020).

A. LEADING BY EXAMPLE

Like any other large and complex organization, the Navy can be reluctant to change its established ways and embrace new technology. There is too much inertia with existing technology and practices to shift to an unproven and uncertain path. The introduction of new technology into operational use is also a very long and time-consuming process, often spanning decades. It is challenging to invest limited money and resources in research that may never show results, and if it does, the results are distant years away in the future. The only way that the Navy will achieve energy breakthroughs in the future is serious investments in research and innovation are made now. The Navy has the unique opportunity and financial resources to lead the charge in this new energy frontier. The environmental reasons for embracing energy-efficient technologies are abundantly clear. Less discussed, though just as relevant, is how lucrative the economic opportunity is for advancing green technology. Suppose the U.S. can demonstrate the operational viability of green technology and expand its implementation to its foreign partners and the commercial industry. In that case, this technology will become the standard across the world. Furthermore, when the military pursues new innovative technologies, there tends to a spillover effect in the civilian sector. Critics may argue that in a fiscally constrained environment, unproven technology is the last place the Navy should invest its money, especially when sufficient capabilities are already in place with conventional fuel. History has shown, however, that the military has always been on the cutting edge of technology and must remain so to maintain its competitive advantage over foreign forces. If the military leads the way in alternative energy, the rest of society will follow.

B. TASK FORCE ENERGY

The Navy established Task Force Energy (TFE) in 2008 to develop metrics, processes, and tools to support the Navy's energy strategy. TFE paved the way for the Great Green Fleet (GGF), announced by Secretary of the Navy Ray Mabus in 2011 (King, 2019). The GGF was just one aspect of a broader national energy strategy to help combat climate change. GGF made its grand debut at the 2012 Rim of the Pacific (RIMPAC) Exercise, the world's largest international maritime warfare exercise. For the first time in history, the U.S. Navy's carrier strike group operated on a unique blend of biofuel and conventional fuel. The U.S. had exhibited on a global stage that its commitment to battling climate change was more than just a talking point in Washington. This demonstration validated years of research and proved that advanced biofuel could be effectively integrated into operational units with zero degradation to mission or equipment. The Navy reaffirmed this capability during the subsequent RIMPAC exercise in 2016 by incorporating biofuel into a broader array of vessels and aircraft. Moving forward, the Navy intends to operate a permanent green strike force at sea. "The Great Green Fleet will signal to the world America's continued naval supremacy, unleashed from the tether of foreign oil" (Mabus, 2012).

The two main priorities of the GGF and the Navy's broader energy policy are to enhance energy security through sustainable supply sources and increase energy independence by severing the Navy's reliance on disruptive foreign energy production and supply chains (Andrews, 2012). These priorities were directly in line with President Obama's energy goals to reduce the nation's dependence on fossil fuels, respond to the global climate change crisis, and create new green energy jobs (Chambers, 2011).

C. ADVANTAGES OF BIOFUEL

Biofuel is an appealing alternative to conventional fuel because it has all the benefits of petroleum minus the negative externality of increasing greenhouse gases and degrading the ozone. Biofuel is also carbon neutral because the plants used to produce it absorb carbon dioxide from the environment, making it a sustainable alternative to petroleum which is a finite resource. To widen biofuels' marketization and lower its cost, the GGF subsidized the production of advanced biofuels. By creating a demand for biofuel, suppliers were motivated to innovate and lower their costs to offer a competitively priced product to the marketplace. Lower prices for the military also equated with lower prices for the average American consumer at the gas pump. Finally, buying local had the added benefit of creating new jobs for farmers in rural America (Chambers, 2011).

The Navy must be strategic in identifying which varieties of biofuel best meet its unique operational needs. To be a viable option for the Navy, the biofuel must be a "drop-in" replacement for current petroleum-based fuel, meaning it can effectively drop into the existing fuel system without any costly modifications or changes. Biofuel must meet certain performance and chemical criteria before it can be used by the Navy. The ideal biofuel must maintain high performance at low temperatures and not clog the system or experience any water separation issues. Unlike its commercial counterpart which is available in vast supply and commonly used in vehicles worldwide, the Navy's subset of biofuels that meet military specification (MILSPEC) standards are in a much shorter supply and are therefore much more expensive. In the past, the Navy used biofuels derived from cooking oil and algae. During RIMPAC 2016, for instance, the GGF used more than 48 million gallons of F-76 blended with 10 percent alternative fuels made from beef tallow (King, 2019). These fuels were not ideal matches for the Navy as only a low percentage could be blended in with the existing fuel to maintain the required fuel specifications. In recent years, the Navy began testing biofuels derived from hydro-processed esters and fatty acids (HEFA) and Fischer-Tropsch (FT) liquids (Radich, 2014). These varieties of biofuels were an enormous improvement of the previous generation of biofuels, as they were nearly identical to their petroleum counterparts regarding their chemical composition and could be dropped into existing fuel tanks without any blending or alterations.

D. DRAWBACKS OF BIOFUEL

Despite the promising benefits of biofuel, its use remains a contentious issue for multiple reasons. Environmentalists argue that the cure for climate change may be worse than the disease. First-generation biofuels, which are derived from food crops, have the negative externality of impacting food security. Diverting arable land customarily used for food production towards fuel decreases food stores and raises food prices for the public. Additionally, slashing down forests to grow crops for biofuel decreases biodiversity in essential ecosystems. Another disadvantage of biofuel is the potential net energy loss or unsustainable nature of its production. In other words, when all the transportation and production costs are added together, producers may be pouring more energy in than they are taking out. For these reasons and more, environmentalists argue that there should be a complete ban on all food-based biofuels, and the world should focus instead on other alternative energy sources such as wind and solar power (Debnath, 2019). Second-generation biofuels, such as cellulosic ethanol, maybe the answer moving forward. This fuel derives from wood, grass, or other nonedible plants unsuitable for human consumption. Unlike first-generation biofuels, cellulosic ethanol utilizes low-quality peripheral lands, so there is no conflict with food crops for available land (Debnath, 2019).

The military may be the largest single consumer of petroleum in the nation. Even with its substantial buying power, however, the military is not strong enough to drive down the price of biofuel singlehandedly. To increase its leverage, the Navy partnered with industry players to attract new investors and grow the fledgling alternative fuel market together as a united force. The major challenge with the biofuel industry is its high cost of production. To limit overspending in this emerging market, the 2014 National Defense Authorization Act was enacted to prohibit DOD from purchasing alternative fuels at a higher cost than traditional fossil fuels (Radich, 2014). In anticipation of this challenge, the Navy collaborated with the Department of Agriculture to create the Farm-to-Fleet program in December 2013. The program was established to expand the range of possible feedstocks available to produce biofuel for the Navy (Debnath, 2019).

E. GREAT GREEN FLEET DEBATE

Critics of the GGF argue that the rationale and logic behind the project were flawed and poorly conceived. When compared to existing energy sources like petroleum, biofuel was significantly more expensive and in shorter supply. Furthermore, it can be argued that the motivation behind purchasing biofuel was based on the false premise that the world had reached peak oil production. Peak oil is the point where global oil production has reached its maximum point of production. Everything after this point will show a decline in production, until there is eventually no fuel remaining to produce. This argument is a highly contentious and much-debated point, especially considering that in the years since 2011, the U.S. has dramatically expanded its oil reserves and energy independence through fracking and other emerging technologies (Yergin, 2021).

The GGF was merely a jumping-off point for future discussions regarding renewable energy options for the Navy. More than just a Navy policy or mission, it was a new ethos and attitude regarding how the nation treats it limited natural resources. While biofuels may have their disadvantages, the goal behind energy efficiency is still valid and worth pursuing. Rather than abandoning the concept altogether, the Navy needs to find a better mechanism or path to reach energy efficiency and zero emissions. These goals not only help our planet but improve the Navy's warfighting ability. The Navy has a challenging road ahead to fulfill Secretary Mabus' vision of operating a permanent green strike force at sea. Significant progress is still needed in biofuel technology development. Energy priorities vary widely based on who is occupying the White House at the time. When President Obama's second term concluded, the subsequent Republican administration was less interested in responding to climate change, and the GGF was largely forgotten by Washington. With President Biden now in command, however, renewed interest in battling climate change has emerged. There are several key actions and policy changes that government can take to support alternative energy.

F. BUILDING ACQUISITION PARTNERSHIPS

To foster innovation, Navy acquisition should establish long-term partnerships with industry. Partnering with industry will increase the Navy's ability to overcome technological barriers that have impeded previous efforts at progress. The pace of innovation will also increase through greater collaboration with industry. By investing in products together, the risks inherent in developing new and unproven technology will be shared equally. There is no perfect solution yet, so the Navy must push forward in all promising directions. Breakthroughs in the future will only be possible through heavy investments now. If new alternative energy products are ever going to compete with the existing status quo, the rules need to be adapted through subsidies and other measures to level the playing field and give emerging technologies an opportunity to expand.

There are many changes that the Navy should make to support the acquisition and growth of green technology. First, energy policy should focus on targeted incremental energy goals to ensure long-lasting success that can survive political shifts in Washington. To realize the full potential of the GGF, TFE should expand its scope into a fleet-wide operational energy program. "Realizing the potential of the GGF will pave the way for a DOD energy program that garners precious energy resources in peacetime and saves lives in war" (King, 2019). The Navy should use GGF as a model to incorporate emerging technologies into operational forces, so the merits and lessons learned from the GGF are not lost. Furthermore, the Navy is a massive consumer of goods. If the Navy prioritizes buying green products and investing in green technologies, this takes significant risk and pressure off new developers and innovators who now know that they have a dedicated customer base who will purchase their products and invest in their services. To understand the true cost of buying petroleum, the Navy should project out the true cost of buying fossil fuel. Alternative fuels immediately become much more appealing when you weigh them against fossil fuel's numerous externality costs (Gates, 2021).

G. SUMMARY

To create the right conditions for alternative to grow, three different levers must be activated simultaneously. These levers are technology, the market, and policy. Like the combustion or fire triangle where all three elements (heat, fuel and oxygen) need to be present in order to ignite a fire, all three levers must be working together in order for alternative energy to succeed. Simply adopting a policy of zero emissions will be ineffective if the technology and market cannot support this plan. Likewise, technology and the market can be making enormous strides, but if an unsupportive government does not support their growth through policy, this new tech and emerging market will likely die (Gates, 2021).

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V. ALIGNMENT WITH INDUSTRY

A. INTRODUCTION

Aside from nuclear power, the bulk of the Navy surface fleet has proven that accepting and implementing new fuel efficiency technologies is a slow and painstaking process compared to its commercial counterparts. This divide will continue to grow as the commercial shipping industry constantly pursues multiple energy efficiency strategies and Navy will likely continue its more conservative ways. These commercial advances include increased energy efficiency standards for new construction vessels, new energy-saving technologies such as real-time monitoring and analysis, more intelligent software, speed-reduction measures, a phase-out of older inefficient units, and increased use of advanced biofuel (Gilbert, 2021). These measures directly support the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), which was initially signed in 1973 and impacted 99.42 percent of the global shipping tonnage across 158 partner states. However, the regulations outlined in ANNEX IV specifically target the reduction of nitrogen and sulfur oxides from merchant ships ("MARPOL annex VI and the act to prevent pollution from ships (APPS)," 2020), therefore, the U.S. Navy is less motivated to improve their energy efficiency standards (Folorunsho, 2020).

Inherently the motivation for the commercial industry and the U.S. Navy to develop and adopt to changes in technology are different. For the commercial sector, reducing fossil fuel consumption and greenhouse gas emissions means reduced operating costs and greater profits, and in some cases, companies can earn tax subsidies from the federal government for reducing their carbon output. This motivation generally leads to a more streamlined and responsive decision-making process. In contrast, the government has a complex system of research and development, testing requirements, and a robust bureaucracy which new systems must weave their way through. As a result, most technological innovation occurs in private industry rather than the government.

Additionally, engineers and researchers with a postgraduate degree or higher likely gravitate towards the private industry as wage compensation is typically greater

(Congressional Budget Office, 2017, p. 10). Rather than compete with private industry, the defense industry should form strategic partnerships with private industry to innovate green technology together. This chapter will explore established and emerging technologies and practices within the commercial industry that may have crossover potential for Navy applications. This chapter will also highlight current partnerships with industry that may be expanded through additional funding and cooperation.

B. DEFENSE INNOVATION UNIT (DIU)

To mitigate risk with new, unproven technologies, a proven method of past success is for the military to partner with industry leaders and fashion a process that results in sharing the risk. One such example of this military-industry partnership is the Defense Innovation Unit (DIU). Secretary of Defense Ash Carter founded DIU in 2015 to align the Department of Defense (DOD) with the commercial technology industry in Silicon Valley. DIU's operating strategy is to locate emerging technologies in the commercial industry and leverage them for military application. The Artificial Intelligence (A.I.) task force, for instance, has advanced numerous A.I. technologies in recent years for the military.

Appreciating the need for greater energy efficiency in the military, DIU formed an Advanced Energy and Materials (AE&M) portfolio in 2020 to pursue advanced power and energy storage, following general fuels and mobility and materials and sustainment. According to DIU's recent press statement, this sector focuses on "leveraging proven advancements in energy and materials technology to enhance capabilities and strengthen resilience across installations and distributed operations" (Richardson, 2020). To expedite the development and production of new technologies, DIU streamlines arduous Federal Acquisition Regulation guidelines and milestones to make it easier and simpler for commercial innovators to move at a faster speed. A standard caveat amongst technology developers is that innovation needs to move rapidly to overcome internal obstacles common in federal acquisitions (Gholz, 2021). DIU partners with the Department of Energy via the National Renewable Energy Laboratory (NREL) to further improve coordination amongst strategic partners and expedite the commercialization of its technologies. This partnership has already advanced the development of advanced battery technology for the military and has assessed numerous other emerging renewable energy technologies for military application (Glickson, 2021).

C. ADVANCED RESEARCH PROJECTS AGENCY-ENERGY (ARPA-E)

Advanced Research Projects Agency-Energy (ARPA-E) was established by the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) in 2009. Based on the Defense Advanced Research Projects Agency (DARPA) model, ARPA-E focuses exclusively on advanced clean energy innovation. Promising energy startups are evaluated and awarded government grants to advance their respective clean energy projects within this construct. While some projects have shown incredible promise, none to date have achieved the level of success of the original DARPA. Breakthroughs, however, have the potential to transform the energy industry. The major hurdle with these investments is overcoming the "valley of death" that most startups encounter at the 10–15-year mark when they attempt to transition from the development phase to full-scale commercialization. To date, despite its numerous failures, ARPA-E-funded projects have a 19 percent annual return on taxpayer investment based on the valuation of its most successful startups valued at 8.5 billion dollars, 2.5 times greater than their 3.3 billion dollars in funding (Kramer, 2020).

D. BREAKTHROUGH ENERGY VENTURES

Bill Gates, Microsoft founder, and technology entrepreneur, highlights several emerging green technologies within his climate investment fund, Breakthrough Energy Ventures, that he believes hold the most potential for future development and commercialization. These technologies include hydrogen fuels, sustainable fuels, energy storage, and technology that removes carbon from the air. All four of these technologies have potential applications for naval vessels. To qualify for this investment fund, technologies must demonstrate they can remove at least 500 million tons of emissions per year when fully executed (Gates, 2021). Anything less than this threshold would not be enough to combat climate change significantly.

In a nod to the Navy, Gates notes that the Navy's nuclear fleet of aircraft carriers and submarines may be a model for the commercial shipping industry to follow.

The Navy has already solved the bulk of the technical issues associated with nuclear-powered vessels, so commercial shipping would need to figure out how to mitigate the apparent risks associated with this technology.

E. NUCLEAR ENERGY

The Australian Navy expected upgrade to nuclear-powered submarines offers a helpful illustration of how the U.S. Navy is collaborating with partner navies to expand the adoption of nuclear-powered vessels. This historic trilateral arrangement between the United Kingdom, the U.S., and Australia will provide a roadmap for future creative partnerships with other navies and industry leaders. This sharing of nuclear technology is an ambitious plan expected to span decades before it is fully implemented. Australia must make significant investments to expand its industrial shipbuilding base and vastly increase its number of educated nuclear engineers to achieve this visionary plan. The Australian Navy is not alone in this pursuit, the Brazilian Navy is also building its fleet of nuclear-powered attack submarines, and South Korea is exploring nuclear-powered submarines to counter the threat of North Korea (Buckley, 2021)

There are many negative connotations attached to nuclear energy. The fear of nuclear weapons looms large and creates an irrational fear of nuclear energy. Of the 37 countries that possess nuclear weapon technology, only nine have constructed weapons. This figure demonstrates how nuclear energy is the predominant choice over weapons (Jayarajan, 2021). Nuclear energy is the safest and most efficient form of energy with the smallest amount of emissions. “More people die from coal pollution in a single year than have died in all nuclear accidents combined” (Gates, 2021). Unlike carbon emissions from fossil fuels which contribute to global warming and millions of deaths, no deaths have ever been reported from nuclear waste. In response to the storage concerns, “all of the used nuclear fuel ever generated in the U.S. can fit on a single football field stacked less than seventy feet high” (Shellenberger, 2020). Lastly, concerning deaths from nuclear accidents, the media has vastly inflated these numbers when the reality is, slightly over one hundred people have died from nuclear accidents. Meanwhile, 1.35 million people die from air pollution caused by fossil fuel emissions every year (Shellenberger, 2020). To summarize the importance of nuclear power, “It is the only carbon-free energy source that can reliably deliver power day and night, through every season, almost anywhere on earth, that has been proven to work on a large scale” (Gates, 2020).

There are more significant national security implications regarding the use of nuclear power. To advance the commercial application of nuclear energy, countries often seek assistance from more advanced nuclear states. This assistance corresponds with more significant influence over another country. The U.S. forfeits this influence when it neglects to assist partner nations in developing their nuclear power. Within this gap, China can insert itself and gain power and influence. China does not share the same values as much of the Western world, such as respect for human rights, democracy, freedom, and the rule of law. Considering how nuclear power will inevitably expand into these emerging energy markets regardless of how the U.S. responds, the world will be much a safer place if the U.S. takes the lead as opposed to China (Strobel, 2020).

The energy decisions of France and Germany offer a helpful case study on the importance of maintaining a balanced energy portfolio. Both are highly developed, France drawing 70 percent of its electricity from nuclear energy (World Nuclear Association, 2021) and Germany starting from 2011 to present has decreased from 25 percent to 10 percent reliance on nuclear energy ((World Nuclear Association, 2021). countries with similar populations. France invests in a broad range of energy sources, including nuclear power, while Germany has divested away from nuclear towards renewables like wind and solar, and has a robust Hydrogen program France, however, spends roughly half as much money on electricity that produces 10 percent of the carbon emissions per unit of electricity as Germany. These figures are tied directly to the individual power plants each country employs. By retiring its nuclear power plants and relying exclusively on renewable energy, Germany was forced to turn many carbon-rich coal factories back online to compensate for the intermittent and unstable nature of solar and wind power. “Had Germany invested 580 billion dollars into new nuclear plants instead of renewables like solar and wind farms, it would be generating 100 percent of its electricity from zero-emission sources and have sufficient zero-carbon electricity to power all of its cars and light trucks” (Shellenberger, 2020). France demonstrated that countries do not need to choose between the environment and the economy. By choosing nuclear power, the world can have both.

Rather than subsidize energy sources that have been proven detrimental for the economy and/or environment, an alternative would be to leverage nuclear power, which has a proven record of success in both categories. Despite the benefits of nuclear energy, its future use remains a contentious issue throughout much of the world. As recently as the 26th United Nations Climate Change Conference of the Parties (COP26) in Glasgow, Scotland, in November 2021, negotiators on both sides argued for and against its increased utilization. The European Union (E.U.) has yet to decide whether to designate nuclear power as "green officially." Billions of dollars in future investment rest on this designation (Charlton, 2021). COVID-19 demonstrated how national solutions to global issues are not effective. The same rationale is valid for global warming. Over 100 countries at COP26 made pledges to save the environment. All pledges, unfortunately, are voluntary, which means they are often not followed.

In summation, a way forward is for the U.S. to maximize its nuclear energy usage whenever possible over other forms of energy. The Navy can contribute to this national goal by maximizing its nuclear energy in its fleet operations. During the Cold War, the Navy briefly experimented with applying nuclear power to its surface combatants. Commissioned in 1961, the USS Long Beach Guided Missile Cruiser Nuclear Nine (GCN-9) was the Navy's first of nine nuclear-powered surface combatant ships. USS Arkansas (GCN-41) was the last, commissioned in 1980. Since then, the Navy has elected not to build additional nuclear-powered surface combatants due to their high construction and operational costs. Nuclear technology has made significant strides in the past 40 years, and it may be time for the Navy to revisit its stance on nuclear-powered surface combatants. The Cold War may be over, but with the rising threat of China and Russia, greater longevity at sea for our surface combatants may give the U.S. Navy a greater competitive advantage over its adversaries. After back-to-back misfires of the DDG-1000 and Littoral Combat Ship (LCS) programs, a detailed cost-benefit analysis would be necessary to determine the warfighting potential of nuclear-powered surface combatants (Hooper, 2020).

IV. CONCLUSIONS, RECOMMENDATION, AND FOLLOW-ON RESEARCH

The Navy spent approximately 3.3 billion dollars for fuel in support of operations in 2020 (Defense Logistics Agency, 2020, p. 23). This research has examined several methods currently available through commercial resources which could lessen the Navy's fuel consumption and increase the operational effectiveness of surface combatants.

In January of 1975, the price of crude oil was 6.75 dollars per bbl. In August 2021, the price of crude oil is 65.67 dollars per bbl. During that timeframe, there were price spikes in 2008, 2011, 2012, 2013 when the price of crude was over 100 dollars per bbl for several months of the year. ("U.S. crude oil first purchase price (Dollars per barrel)," 2021). Today the price of a bbl of diesel hovers around 100 dollars or 2.30 per gallon. During the summer of 2008, the price of diesel per gallon reached 4.70 dollars per gallon or 197 dollars per bbl ("U.S. no 2 diesel retail prices (Dollars per gallon)," 2021).

The price spikes over 100 dollars per bbl lasted only a few months. However, the tendency for volatility in crude oil prices remains constant. Compounding the issue of cost is the issue of future availability. As discussed in this research, crude oil is a finite natural resource. As the supply perceivably decreases, the volatility in the oil market will likely remain or become more drastic. The variability of price increases is possibly the most significant driver for the Navy to act now to reduce its consumption as practically and quickly as possible. Table 2 provides a quick reference go-no-go assessment of the technologies reviewed in this thesis. The technology is evaluated based on five elements, listed below.

(1) Practicality

This aspect is judged by the extent to which the technology can be utilized by the ship. The combination of the ship's mission and technology complement one another. Does the technology increase current capabilities? Does it require minor or significant ship modifications for installation?

(2) Ease of Acquisition

This aspect considers the technology's maturation and the system's availability to be implemented into existing C.G.'s and DDG's. Is the technology proven? Is it available for purchase as commercial of the shelf?

(3) Value to the Navy

Value is judged by the monetary savings in fuel costs, increases in maintenance, and other future requirements such as training or repairs. What percentage of increase in efficiency does it provide? What are the annual savings of savings over the life of the ship?

(4) Acceptability

As discussed in this thesis, several methods of conserving fuel have met resistance by either the individual command or the Navy as a whole. Acceptability is considered based on what extent by the nature of the technology its likely to meet with resistance.

Table 2. Go-no go quick reference guide. Red and green reflect go-no go determination

Technology	Practicality	Ease of Acquisition	Value	Acceptability
ESM				
PBCF/ECO-Cap				
Stern Foil				
Bio-fuel				
Nuclear				

1. ESM

ESM technology is currently used in the commercial industry and has been tested to meet the specific requirements of U.S. Navy C.G.'s and DDG's electrical systems. The size and performance are directly engineered to meet the expectations outlined in the BAA 07–029 released by the ONR in 2007. Its design orientation makes the ESM a mature technology, and its acquisition a straightforward process. ESM offers the highest potential value of all the systems researched in this paper, including the most significant potential increase in operational range. As discussed over a 35-year lifespan (Larter, 2020), a single DDG could save nearly 28 million dollars in fuel costs at today's oil prices. Unfortunately, this system is also likely to meet with significant leadership pushback due to the previously discussed risks associated with operating on a single generator.

2. PBCF/ECO-Cap

Propellor cap systems offer a unique capability in terms of ease of use. The PBCF is currently available commercially by custom order which makes it a practical addition to any ship. ECO-cap is still in the development phase, and no production date is available. While PBCF and ECO-Cap do not offer the most significant savings potential, 2.8 to 3.5 or 67,455 to 84,319 dollars per underway day. Average underway days for C.G.'s and DDG's are approximately 120 per year (Crawford, 2014, p. 45). With current fleet strength at 91 C.G.'s and DDG's, this technology would save between 8 and 10.1 million dollars per year. PBCF and ECO-Cap are passive systems that require no maintenance. They also do not alter the ship's handling characteristics or require the leadership to accept any additional risk.

3. Stern Foil

The stern foil is another unique addition to surface ships. The technology is mature, proven, and represents significant savings; however, its application does not compliment C.G. and DDG operating profiles. The significant increase in drag at the most common operating speed makes the stern foil impractical for C.G.'s and DDG's.

4. Bio-fuel

Bio-fuel is a proven technology that has been tested and operationally used. The overwhelming advantage of bio-fuel is the decrease in greenhouse gases caused by the combustion of traditional fossil fuels. Bio-fuels are also publicly favorable and could decrease our reliance on fossil fuels; however, they have several current disadvantages. It is expensive to produce and relies on successful and high-volume production of its agricultural sources. Bio-fuel is cheaper than F-76, 114.66 dollars a bbl versus 119.28

(Office of the Under Secretary of Defense, 2020, p. 2) dollars a bbl. However, it is limited in its availability, making it currently impractical for operational use.

5. Nuclear

In summation, the U.S. should maximize its nuclear energy usage whenever possible over other forms of energy. The Navy can contribute to this national goal by maximizing its nuclear energy in its fleet operations. During the Cold War, the Navy briefly experimented with applying nuclear power to its surface combatants. Commissioned in 1961, the USS Long Beach (CGN-9) was the Navy's first of nine nuclear-powered surface combatant ships. USS Arkansas (CGN-41) was the last, commissioned in 1980. Since then, the Navy has elected not to build additional nuclear-powered surface combatants due to their high construction and operational costs. Nuclear technology has made significant strides in the past 40 years, and it may be time for the Navy to revisit its stance on nuclear-powered surface combatants. The Cold War may be over, but with the rising threat of China and Russia, greater longevity at sea for our surface combatants may give the U.S. Navy a greater competitive advantage over its adversaries. After back-to-back misfires of the DDG-1000 and Littoral Combat Ship programs, a detailed cost-benefit analysis would be necessary to determine the warfighting potential of nuclear-powered surface combatants (Hooper, 2020).

A. RECOMMENDATION

The Navy should align with commercial industries and acquire technology that is already being used to reduce fuel consumption. The PBCF represents the best possible combination of practicality, ease of acquisition, value, and acceptability. As a passive, no maintenance system that requires no consideration by the ship's leadership or crew, acquisition of the PBCF should be a top priority for the U.S. Navy.

F. FOLLOW-ON RESEARCH

This thesis is focused on determining what the Navy can do to reduce its fossil fuel consumption. Follow-up research should focus on determining what barriers the Navy has preventing the acquisition of commercially available fuel-efficient technology for surface ships. Once these barriers are defined, research efforts should again focus on determining what technology offers the greatest potential decreases in fuel consumption and increases in operational capability.

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APPENDIX

A. CRUDE OIL PRICES

U.S. Crude Oil First Purchase Price (Dollars per Barrel)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1974	6.95	6.87	6.77	6.77	6.87	6.85	6.80	6.71	6.70	6.97	6.97	7.09
1975	7.61	7.47	7.57	7.55	7.52	7.49	7.75	7.73	7.75	7.83	7.80	7.93
1976	8.63	7.91	7.78	7.86	7.89	8.00	8.04	8.03	8.39	8.46	8.61	8.62
1977	8.50	8.56	8.45	8.41	8.49	8.44	8.47	8.45	8.43	8.72	8.69	8.81
1978	8.71	8.86	8.80	8.82	8.81	9.05	8.96	9.05	9.15	9.17	9.20	9.47
1979	9.46	9.69	9.83	10.33	10.71	11.70	13.39	14.00	14.57	15.06	15.52	17.00
1980	17.86	18.86	19.33	20.28	21.05	21.52	22.31	22.62	22.59	23.23	23.99	25.83
1981	28.81	34.30	34.59	33.92	32.73	31.68	31.10	31.10	31.10	30.98	30.97	30.80
1982	30.80	29.73	28.31	27.64	27.66	28.12	28.09	27.99	27.99	28.76	28.74	28.02
1983	27.22	26.41	26.08	25.85	26.08	25.98	25.86	26.03	26.08	26.04	26.09	25.88
1984	25.93	26.06	26.05	25.93	26.00	26.09	26.11	26.02	25.97	25.92	25.44	25.05
1985	24.26	23.64	23.89	24.19	24.18	24.07	24.04	23.99	23.96	24.10	24.27	24.51
1986	23.12	17.65	12.62	10.68	10.75	10.68	9.25	9.77	11.09	11.00	11.05	11.73
1987	13.79	14.51	14.54	14.95	15.29	15.95	16.88	17.06	16.25	15.95	15.46	14.27
1988	13.64	13.43	12.96	13.92	14.12	13.59	12.38	12.22	11.63	10.62	10.31	11.99
1989	13.80	14.24	15.65	17.04	16.76	16.42	16.32	15.01	15.58	16.25	16.30	17.01
1990	18.49	18.16	16.57	14.52	13.82	12.79	14.03	21.87	28.46	30.86	27.53	22.63
1991	19.60	16.28	15.13	16.16	16.44	15.58	16.36	16.60	16.71	17.72	17.12	14.68
1992	13.99	14.04	14.12	15.36	16.38	17.96	17.80	17.07	17.20	17.16	16.00	14.94
1993	14.70	15.53	15.94	16.15	16.03	15.06	13.83	13.75	13.39	16.27	15.21	12.95
1994	10.49	10.71	10.94	12.31	14.02	14.93	15.34	14.50	13.62	13.84	14.14	13.43
1995	14.00	14.71	14.68	15.84	15.85	15.02	14.01	14.13	14.49	13.68	14.03	15.02
1996	15.43	15.54	17.63	19.58	17.94	16.94	17.63	18.29	19.93	21.09	20.20	21.34
1997	21.76	19.38	17.83	16.63	17.23	15.88	15.89	16.19	16.41	17.66	16.83	15.04
1998	13.45	12.17	11.15	11.28	11.13	10.00	10.44	10.20	11.29	11.32	9.64	8.03
1999	8.57	8.60	10.76	12.82	13.92	14.39	16.12	17.58	20.03	19.71	21.35	22.55
2000	23.53	25.48	26.19	23.20	25.58	27.62	26.81	27.91	29.72	29.65	30.36	24.46
2001	24.64	25.27	22.98	23.39	24.06	23.43	22.82	23.08	22.37	18.73	16.40	15.54
2002	15.89	16.93	20.28	22.52	23.51	22.59	23.51	24.76	26.08	25.29	23.38	25.29
2003	28.42	31.85	30.10	25.45	24.95	26.84	27.52	27.94	25.23	26.53	27.21	28.53
2004	30.35	31.21	32.86	33.20	35.73	34.53	36.54	40.10	40.56	46.14	42.85	38.22
2005	40.18	42.19	47.56	47.26	44.03	49.83	53.35	58.90	59.64	56.99	53.20	53.24
2006	57.85	55.69	55.64	62.52	64.40	64.65	67.71	67.21	59.37	53.26	52.42	55.03
2007	49.32	52.94	54.95	58.20	58.90	62.35	69.23	67.77	73.27	79.32	87.16	85.28
2008	87.06	89.41	98.44	106.64	118.55	127.47	128.08	112.83	98.50	73.18	53.67	36.80
2009	35.00	34.14	42.45	45.19	52.67	63.09	60.44	65.28	65.28	69.82	71.99	70.42
2010	72.87	72.74	75.77	78.80	70.91	70.77	71.37	72.07	71.23	76.02	79.20	83.98
2011	85.66	86.69	99.19	108.80	102.46	97.30	97.82	89.00	90.22	92.28	100.18	98.71
2012	98.99	102.04	105.42	103.62	95.57	83.59	86.10	92.53	95.98	92.24	89.64	89.81
2013	95.00	95.01	95.54	94.41	94.75	93.82	101.41	102.96	102.32	96.18	88.70	91.85
2014	89.57	96.86	96.17	96.49	95.74	98.68	96.70	90.72	86.87	78.84	71.07	54.86
2015	43.06	44.35	42.66	49.30	54.38	55.88	47.70	39.98	41.60	42.34	38.19	32.26
2016	27.02	25.52	31.87	35.59	41.02	43.96	40.71	40.46	40.55	45.00	41.65	47.12
2017	48.19	49.41	46.39	47.23	45.19	42.17	43.42	44.96	47.17	49.12	55.19	56.98
2018	62.25	61.18	60.68	63.50	66.16	62.80	67.00	62.64	63.54	65.18	55.65	47.63
2019	48.00	52.60	57.46	63.00	59.73	54.34	56.47	53.63	55.14	53.14	54.96	58.41
2020	56.55	49.66	31.01	15.18	18.02	33.81	37.44	39.37	36.82	36.39	38.25	43.92
2021	49.73	56.72	60.67	59.87	62.80	68.57	70.12	65.67				

Figure 15. Price of crude oil from 1974 to 2021. Source: "U.S. crude oil first purchase price (Dollars per barrel)," 2021

B. DIESEL FUEL PRICES

U.S. No 2 Diesel Retail Prices (Dollars per Gallon)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1994			NA	1.107	1.100	1.103	1.110	1.123	1.125	1.122	1.131	1.113
1995	1.098	1.088	1.088	1.104	1.126	1.120	1.100	1.105	1.119	1.115	1.120	1.130
1996	1.145	1.145	1.183	1.275	1.273	1.201	1.176	1.201	1.265	1.323	1.323	1.309
1997	1.291	1.280	1.229	1.212	1.196	1.173	1.151	1.165	1.160	1.183	1.192	1.166
1998	1.120	1.084	1.063	1.067	1.069	1.041	1.029	1.007	1.024	1.039	1.022	0.973
1999	0.967	0.959	0.997	1.079	1.073	1.074	1.122	1.172	1.215	1.228	1.263	1.292
2000	1.356	1.461	1.479	1.422	1.420	1.421	1.434	1.466	1.637	1.637	1.621	1.565
2001	1.524	1.492	1.399	1.422	1.496	1.482	1.375	1.390	1.495	1.348	1.259	1.167
2002	1.153	1.152	1.230	1.309	1.305	1.286	1.299	1.328	1.411	1.462	1.420	1.429
2003	1.488	1.654	1.708	1.533	1.451	1.424	1.435	1.487	1.467	1.481	1.482	1.490
2004	1.551	1.582	1.629	1.692	1.746	1.711	1.739	1.833	1.917	2.134	2.147	2.009
2005	1.959	2.027	2.214	2.292	2.199	2.290	2.373	2.500	2.819	3.095	2.573	2.443
2006	2.467	2.475	2.559	2.728	2.897	2.898	2.934	3.045	2.783	2.519	2.545	2.610
2007	2.485	2.488	2.667	2.834	2.796	2.808	2.868	2.869	2.953	3.075	3.396	3.341
2008	3.308	3.377	3.881	4.084	4.425	4.677	4.703	4.302	4.024	3.576	2.876	2.449
2009	2.292	2.195	2.092	2.220	2.227	2.529	2.540	2.634	2.626	2.672	2.792	2.745
2010	2.845	2.785	2.915	3.059	3.069	2.948	2.911	2.959	2.946	3.052	3.140	3.243
2011	3.388	3.584	3.905	4.064	4.047	3.933	3.905	3.860	3.837	3.798	3.962	3.861
2012	3.833	3.953	4.127	4.115	3.979	3.759	3.721	3.983	4.120	4.094	4.000	3.961
2013	3.909	4.111	4.068	3.930	3.870	3.849	3.866	3.905	3.961	3.885	3.839	3.882
2014	3.893	3.984	4.001	3.964	3.943	3.906	3.884	3.838	3.792	3.681	3.647	3.411
2015	2.997	2.858	2.897	2.782	2.888	2.873	2.788	2.595	2.505	2.519	2.467	2.310
2016	2.143	1.998	2.090	2.152	2.315	2.423	2.405	2.351	2.394	2.454	2.439	2.510
2017	2.580	2.568	2.554	2.583	2.560	2.511	2.496	2.595	2.785	2.794	2.909	2.909
2018	3.018	3.046	2.988	3.096	3.244	3.253	3.233	3.218	3.262	3.365	3.300	3.123
2019	2.980	2.997	3.076	3.121	3.161	3.089	3.045	3.005	3.016	3.053	3.069	3.055
2020	3.048	2.910	2.729	2.493	2.392	2.408	2.434	2.429	2.414	2.389	2.432	2.585
2021	2.681	2.847	3.152	3.130	3.217	3.287	3.339	3.350	3.384	3.612		

Figure 16. Price of diesel fuel from 1994 to 2021.
Source: "U.S. no 2 diesel retail prices (Dollars per gallon)," 2021

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