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Analysis of Pathways to Reach Net Zero Naval Operations by 2050

by

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January 2023

Prepared for: N9 – Warfare Systems

REPORT DOCUMENTATION PAGE

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1. REPORT DATE 22 October 2022	**2. REPORT TYPE** NRP Technical Report	**3. DATES COVERED** **START DATE** 10/22/2021	**END DATE** 10/22/2022

4. TITLE AND SUBTITLE
Analysis of Pathways to Reach Net Zero Naval Operations by 2050

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER**
5d. PROJECT NUMBER NPS-22-N258-A	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Energy Academic Group Systems Engineering Naval Postgraduate School	**8. PERFORMING ORGANIZATION REPORT NUMBER**

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Cayle Bradley N9 – Warfare Systems Arlington, Virginia	**10. SPONSOR/MONITOR'S ACRONYM(S)**	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

With the backdrop of net-zero emissions as an essential element of national security, this study undertook an analytical approach to evaluate current Department of the Navy (DON) emissions and understand energy needs to support mission readiness while reducing emissions over time. In this report, researchers present current and proposed low-carbon energy sources as possible pathways for shifting DON to net zero by 2050 with models showing four pathway options. Strategies toward net-zero emissions for the DON include alternative fuels, hydrogen, unmanned systems, batteries, improved operational efficiencies, nuclear energy, renewable energy, and carbon capture and sequestration. The research identifies challenges and gaps to advance future research and analysis to further emissions reduction by the DON.

15. SUBJECT TERMS
Net Zero Emissions, carbon emissions, climate change, energy security

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**C. THIS PAGE** Unclassified		

19a. NAME OF RESPONSIBLE PERSON Kristen Fletcher	**19b. PHONE NUMBER** *(Include area code)* 831.920-1090

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

ACKNOWLEDGEMENTS

The research team extends its gratitude to Cayle Bradley, Bill Muras, and David Hume for their significant assistance in the research and preparation of this report. Their time, expertise and patience helped make this report possible. The research team also thanks the Naval Research Program for its financial and technical support.

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I. INTRODUCTION AND PROBLEM STATEMENT

This report is based on a broad study of strategies for the Department of the Navy (DON) to achieve net zero global emissions by 2050 to comply with recent Executive Orders and goals set out for the Department of Defense (DOD) and the DON (Melillo, 2022). In January 2021, Executive Order 14008 called for a government-wide approach for meeting climate related challenges in the U.S. and set goals for agencies. In December 2021, Executive Order 14057 set the specific goal of net zero emissions from overall federal operations, including DOD, by 2050 and a 65 percent emissions reduction by 2030.

These are challenging targets for the DOD: 2019 data shows that the DOD consumed 682 trillion BTUs, which represents up to 77% of federal government energy use. The Navy uses fuel for jets, vehicles, ships, ground equipment, and for generating electricity for forces in the field and for powering operations at Navy installations. Fuel is required for mission readiness and fuel demand depends on operational needs and the tempo of operations. Depending on the year, up to 75% of that energy use is operational; for the DON, that means ships and aircraft – two of the most difficult sectors to decarbonize, both in the military and in the private sector.

With the backdrop of net zero emissions as an essential element of national security, this study undertook an analytical approach to evaluate current DON emissions and to understand energy needs to support mission readiness. In this report, researchers present current and proposed low-carbon energy sources as possible pathways for shifting DON to net zero by 2050 with models presenting four pathway options. The research leverages existing net zero strategies and findings developed by the public and private sectors and identifies challenges and gaps to advance future research and analysis to further emissions reduction by the DON.

A. CLIMATE CHANGE RELATIONSHIP TO NATIONAL SECURITY

The relationship of climate change to national security is well-documented. Most recently, the DON opened its climate strategy, Climate Action 2030, with the statement "Climate change is one of the most destabilizing forces of our time, exacerbating other national security concerns and posing serious readiness challenges" (Department of the Navy [DON Climate], 2022). Noting that the climate threat for the DON is existential, the strategy acknowledges increased instability across the globe while simultaneously affecting the DON's ability to respond. Moreover, most DON installations are coastal and sea level rise will test the ability for these installations to continue to meet their missions. Furthermore, the DOD has found that climate change is "reshaping the geostrategic, operations and tactical environments with significant implications for U.S. national security and defense" (Department of Defense [DOD Risk], 2021).

As a destabilizing force, climate change demands new missions of the DOD and DON and can alter the operational environment (Department of Defense [DOD Adaptation], 2021). Climate change exacerbates existing threats, especially in vulnerable parts of the world where the Navy and Marine Corps are called upon for Humanitarian Aid and Disaster Response (HADR) missions and may experience increased conflict from resource competition or scarcity and environmental changes. Impacts of climate change also are felt at installations which affect key warfighting capabilities. It is within this context that the Navy Climate Strategy sets mitigation measures to reduce the impact and speed of climate change by reducing emissions of greenhouse gases (GHG) or taking steps to remove carbon dioxide from the atmosphere. Accelerating these efforts would help to modernize Naval forces and reduce costs and operational vulnerabilities related to fossil fuel-based energy.

B. CLIMATE CHANGE AND EMISSIONS DRIVERS

As noted above, Executive Order 14008 called for the U.S. government, including the DOD, to reach net zero emissions by 2050. Executive Order 14057 set more specific goals of net zero emissions from overall federal operations by 2050 and a 65 percent emissions reduction by 2030. These goals were incorporated into the DON climate strategy, called *Climate Action 2030*, with the following specific targets:

- Achieving a 65 percent reduction in scope 1 and 2 greenhouse gas emissions department-wide by 2030 (measured from a 2008 baseline);
- Achieving 100 percent carbon pollution-free electricity (CFE) by 2030, at least half of which will be locally supplied clean energy to meet 24/7 demand;
- Acquiring 100 percent zero-emission vehicles by 2035, including 100 percent zero-emission light-duty vehicle acquisitions by 2027;
- Achieving a 50 percent reduction in emissions from buildings by 2032; and,
- Annually diverting at least 50 percent of non-hazardous solid waste from landfills, including food and compostable materials, and construction and demolition waste and debris by 2025 (DON Climate, 2022).

Tracking such reductions requires accurate data. Unfortunately, despite efforts, there is currently “no commonly agreed upon way for militaries to measure and report their emissions.” (International Military Council on Climate and Security [IMCCS], 2022) Internationally, the “military emissions gap” has received attention and some efforts to resolve it (Military Emissions, 2022). Even within the U.S., there are data, tracking and reporting challenges. Moreover, some emissions data does not exist yet, at least in the form that would most benefit a pathways study for the DON. As a result, researchers relied upon private sector data in some cases even though it may not directly translate to military use. In addition, when necessary, researchers made certain assumptions in order to calculate emissions or emission savings; those assumptions are noted in the relevant sections.

Even with those shortcomings, there is general data upon which to rely. The U.S. Energy Information Administration provides annual and monthly analysis of energy use and energy related C02 emissions data. Data indicates that the DOD is the single largest consumer of energy in the U.S. and since 2001, has consumed between 77-80% of all U.S. government energy consumption. War, preparation for it, deterrence and training are energy-intensive activities and most of the Naval fleet – ships and aircraft – rely heavily on fossil fuels. Even though overall energy consumption is decreasing, as shown in Figure 1, these sectors are particularly difficult to decarbonize.

According to the FY20 Operational Energy Annual Report, the Navy consumed 34% of the DOD energy use in 2019 and 36% in 2020 (Department of Defense [DOD Energy], 2021). Extrapolating from this, the research team assumes that the DON contributes an estimated 30-36% of all emissions produced by the Department of Defense. It is estimated that, since 2001, the U.S. military has produced more than 1.2 billion metric tons of greenhouse gases (Crawford, 2019). Furthermore, the DOD is concerned not only with its own emissions but with "the social cost of GHG emissions in applicable cost-benefit decisions per EO 13990", its suppliers' GHG emissions, and life cycle GHG emissions of its equipment (DOD Adaptation, 2021).

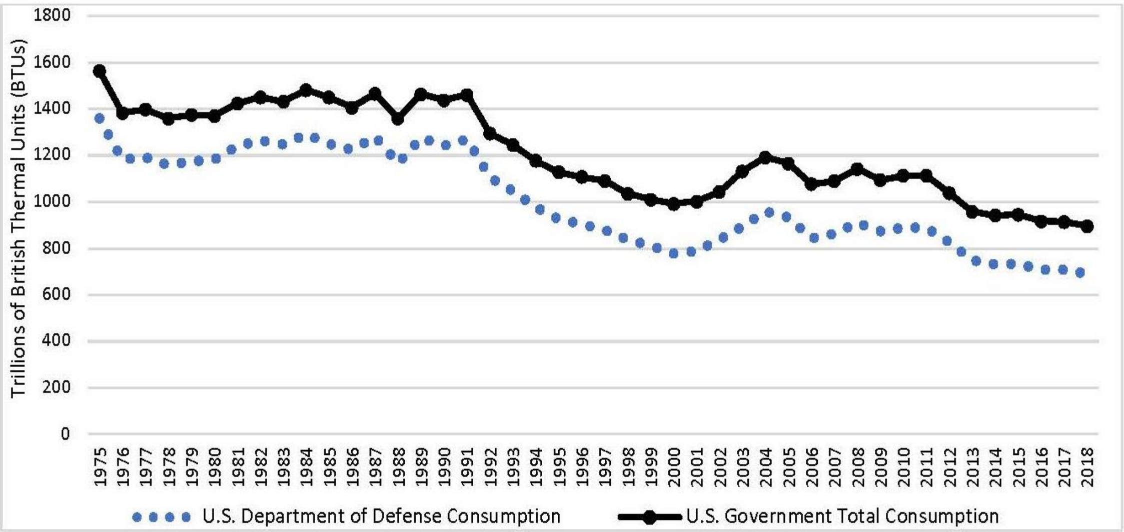


Figure 1. DOD and Total US Federal Government Energy Consumption, FY1975-2018 in Trillions of British Thermal Units (Crawford, 2019 citing U.S. Energy Information Administration).

C. KEY DEFINITIONS: NET ZERO AND OPERATIONS

As the DON moves toward a net zero emissions goal, it is important to define net zero" early in the process of developing pathways. The term "net zero emissions" has received much attention as a goal but has not been well-defined. The problem received academic treatment in 2022 by a set of researchers seeking the various ways that net zero has been defined and whether the different definitions indicate knowledge or process gaps (Loveday, et al., 2022). The findings indicate that while there is acceptance of a general idea of net zero emissions, the specificity required to translate the definition into action is often lacking.

Identifying pathways to net zero in the context of the operational Navy and subsequently translating those pathways into action requires a specific and accepted definition. The Intergovernmental Panel on Climate Change (IPCC) defines it as "Net-zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period."

(Intergovernmental Panel on Climate Change [IPCC], 2021) Working on similar climate security issues, the United Nations defines net zero as: “cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans and forests for instance.” (United Nations, 2022)

Within the DOD, both the Navy Climate Strategy and Army Climate Strategy define net zero as follows.

> *Climate Action 2030* (Navy Climate Strategy): Net-Zero Emissions: negating the amount of greenhouse gases produced by human activity by reducing emissions and implementing methods of absorbing carbon dioxide from the atmosphere. This removal of greenhouse gases could be done through land or natural resource management, and human pollution intervention (DON Climate, 2022).
>
> *Army Climate Strategy*: Net-zero emissions. A condition achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals of those same gases over a specified period (Special Report: Global Warming of 1.5 ºC, 2018). In this strategy, the “specified period” is a rolling 12 months generalized as, but not necessarily synchronized with, a given calendar year (Department of the Army, 2022).

When the Navy Climate Strategy was released in May 2022, the event took place at Marine Corps Logistics Base Albany in Georgia which was acknowledged as the DOD’s first net zero installation. The net zero definition applied to the installation was “the production of as much electricity from renewable ‘green’ energy sources as it consumes from its utility provider measured during a year” (Marine Corps Logistics Base Albany [MCLBA], 2022). In his comments on that day, Secretary of the Navy Carlos Del Toro stated that the base was the first installation in the DOD to “achieve Net Zero energy, generating more energy than it consumes by implementing a range of climate friendly solutions” (MCLBA, 2022). The accomplishments of Marine Corp Logistics Base Albany are significant in the effort to make installations more sustainable and resilient. However, the Navy and Army definitions call for the more stringent standard of removing as much GHG from the air as is released into it.

This report is written in the context of a healthy debate around the definition of net zero. For purposes of this report, researchers follow the definition in the Navy Climate Strategy but add that emissions are balanced over a specified period which is important in assessing energy use and emissions data for the DON and DOD accurately.

Similarly, it is important to define operations. Climate Action 2030 separates operations from installations and while this report does include references to emissions-related savings at installations, the focus is on operations. In addition, while the strategy includes references to optimizing fuel use in combat operations and reducing the footprint of tactical forces, this report’s assessment is based on peacetime and deterrence operations. Deterrence operations are those that are not directly involved in conflict but rather convince adversaries not to take actions that threaten U.S. interests. In other words, if the DON engages in war or conflict by sea or plane, these pathways toward net zero would not necessarily apply. Peacetime and deterrence operations include military operations such as aircraft, maritime vessels, ground vehicles in forward operating bases and camps in foreign countries.

The International Military Council on Climate and Security notes that military GHG emissions "can be differentiated by end-use sectors (building & facilities versus mobility & equipment) and by type of operations (standard operations common to all civilian agencies and non-standard operations specific to the militaries)" (IMCCS, 2022). The bulk of U.S. military emissions are from mobility and equipment (such as aircraft, vessels, tanks) used in non-standard operations (including military operations, law enforcement and other operations). Thus, decarbonizing military mobility – in the Navy's case, aircraft and maritime vessels -- is the key to reducing emissions and reaching, or trying to reach, net zero emissions.

D. RELATIONSHIP OF CLIMATE CHANGE AND ENERGY TO NAVY OPERATIONS

The DOD mission is to provide the military forces needed to deter war and protect the security of the nation, and, should deterrence fail, those forces must be prepared to fight and win. This means the military must remain agile and able across the globe and have access to necessary energy sources. When the energy source is fuel-based, it is a clear vulnerability: NATO estimated that "3,000 U.S. troops were killed or wounded from 2003 to 2007 by being attacked on water and fuel convoys in Iraq and Afghanistan" and by May 2007, about 80% of all the cargo that the U.S. military transported in war zones was fuel (Schogol, 2022). More recently, Russia has targeted fuel storage facilities and other energy infrastructure in Ukraine (Rott, 2022). Releasing the DOD from the tether of fossil fuels and increasing the ability to create fuel and energy in-theater is directly related to meeting the mission and increasing the safety of U.S. servicemen and women. Furthermore, researchers note that even as the DOD and Congress have increased their attention to mitigation of climate change over time, "the momentum behind operational energy efforts has stalled in recent years" (Didawick, 2019).

Until operational energy and climate change challenges are addressed in concert, the DOD is much less likely to be able to reduce emissions. Operational energy demand depends on the type of fuel available in local markets, the tempo of operations, long logistical tails, and need for energy reserves. Given these factors and because operational energy users are less likely to have access to 100% carbon-free energy sources, multiple pathways to net zero must be analyzed and understood.

E. PATHWAYS

Based on the research, this report presents four possible pathways to net zero emissions in section IV. They reflect the difficulties in decarbonizing ships and aircraft, especially when those platforms are for military use, but offer strategies, such as alternative fuels, hydrogen, unmanned systems, batteries and electrification that are seeing growth and potential. Estimates of the percentage of emissions saved are made for each strategy and the top 8 strategies are included in four pathways showing variable findings from now through 2050.

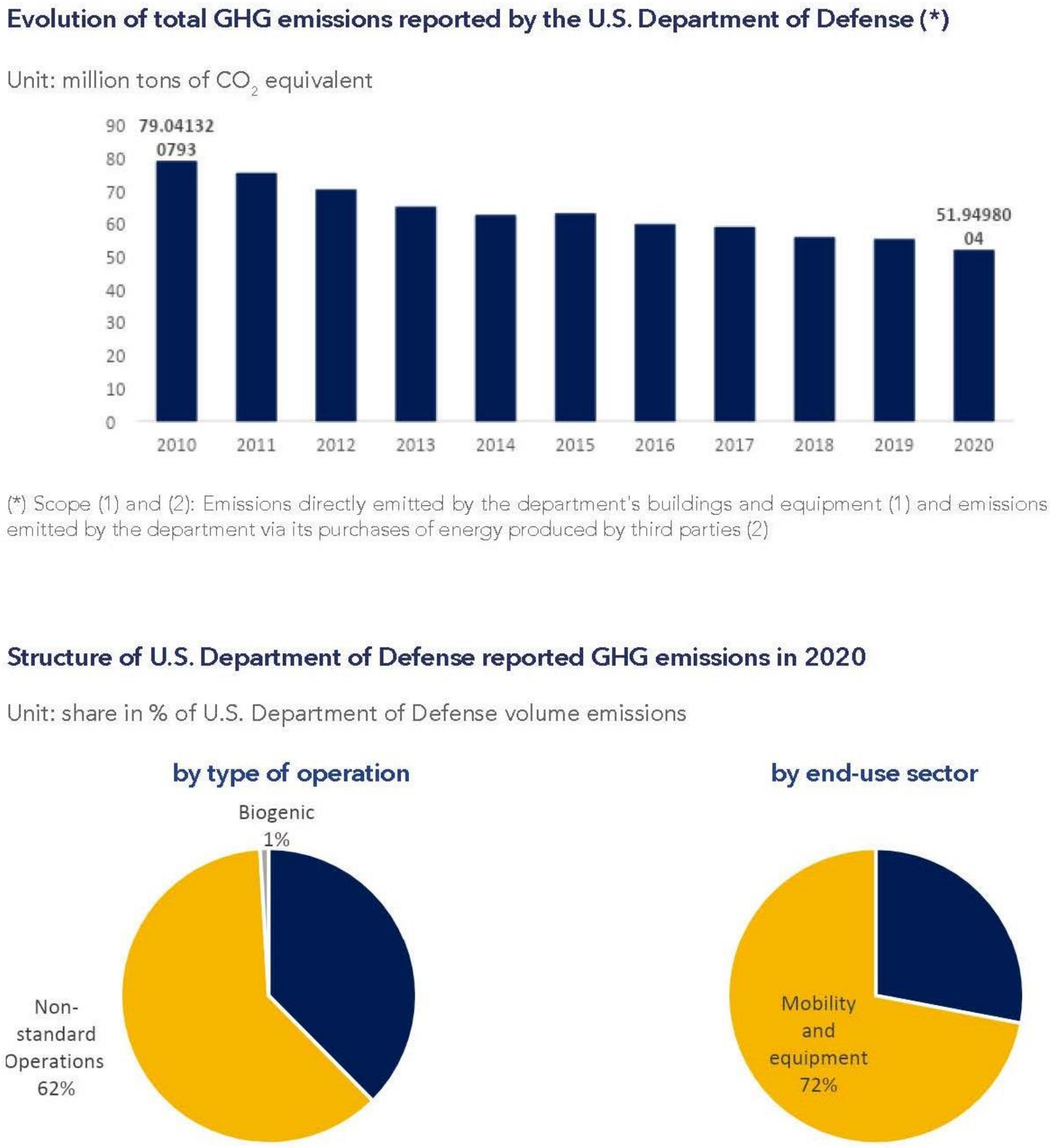
In addition, researchers worked with two capstone teams at NPS. In December 2021, a capstone team of NPS students released a CUI report entitled *Costs of Achieving Net Zero Maritime Operations Through Electric Energy Storage*. They presented a cost benefit analysis of utilizing ships that relied solely on green energy or a combination of energy sources including battery storage. The analysis includes a comparison of the 2019 Navy energy usage of fossil fuels for maritime operations, and the alternative of ships that utilize 100 percent renewable energy and battery storage. The second team will issue its report in December 2022 which will be incorporated into this document. This second team is analyzing the use of alternative fuels in high-emission platforms such as the DDG-51 and F-18 (i.e., highest fuel consumers, as a class, so therefore the highest emitters).

It is the research team’s intention that this report can contribute to the complex challenges facing the DON, DOD, U.S. government and the nation as they move toward emissions reductions. These concepts, over time, can be incorporated into the National Defense Strategy and inform metrics and actionable goals supporting reductions in emissions.

II. DOD AND DON EMISSIONS

Generally, the DOD follows the Greenhouse Gas Protocol standards for tracking and accounting for GHG emissions. Emissions are defined as Scope 1, 2, or 3, depending on where the GHG emissions originate and the ability of an entity to manage or influence the emission sources (World Resources Institute, 2011). Scope 1 includes direct GHG emissions from sources that are owned or controlled by the DOD. Scope 2 includes emissions from the generation of purchase electricity consumed by the DOD. Scope 3 includes upstream emissions from the production of goods and services not owned or directly controlled by the DOD, including upstream and downstream emissions. While this report does not delve into the emissions sources by scope, the protocol standards are important when calculating emissions and understanding their sources.

The DOD’s most recent emissions analysis shows a total of 51 million metric tons of carbon dioxide equivalent (MMTCO$_2$e) in 2021. Figure 2 shows the downward trend of the DOD emissions over time.



Evolution of total GHG emissions reported by the U.S. Department of Defense (*)

Unit: million tons of CO_2 equivalent

(*) Scope (1) and (2): Emissions directly emitted by the department's buildings and equipment (1) and emissions emitted by the department via its purchases of energy produced by third parties (2)

Structure of U.S. Department of Defense reported GHG emissions in 2020

Unit: share in % of U.S. Department of Defense volume emissions

by type of operation

by end-use sector

Figure 2. DOD GHG Emissions (Department of Energy, 2022).

Of this total, 37% were emissions from installations and 63% were emissions from operational sources. Most emissions at the DOD result from fossil fuel combustion, particularly jet fuel. In FY 2021, jet fuel combustion accounted for 80% of operational emissions and 50% of total DOD emissions. The Department of Energy reports that the DOD’s total GHG emissions in 2021 were 76% of the federal government total (Department of Energy, 2022) and equivalent to 1% of the total U.S. emissions in 2020 (Environmental Protection Agency, 2022). Estimates of 2014 emissions by domain and mission are shown in Figure 3.

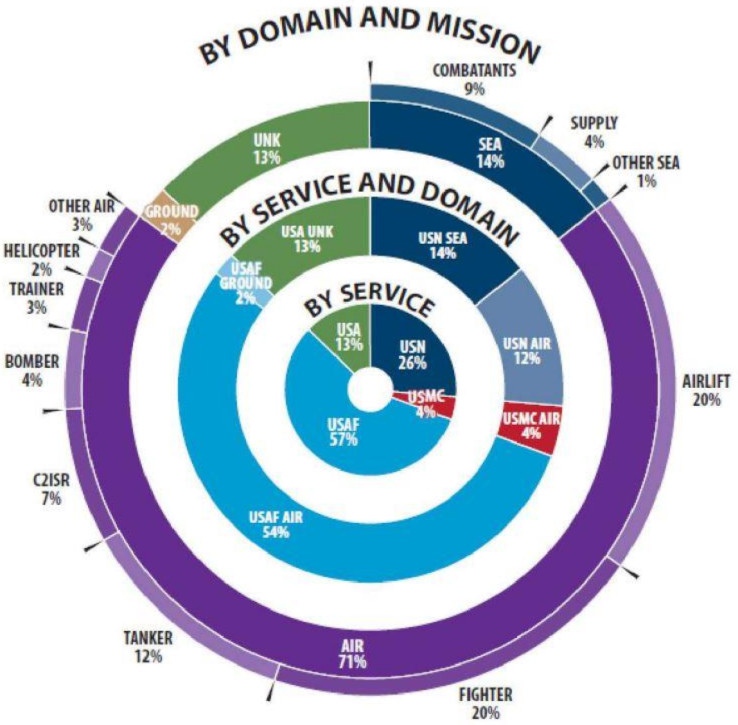
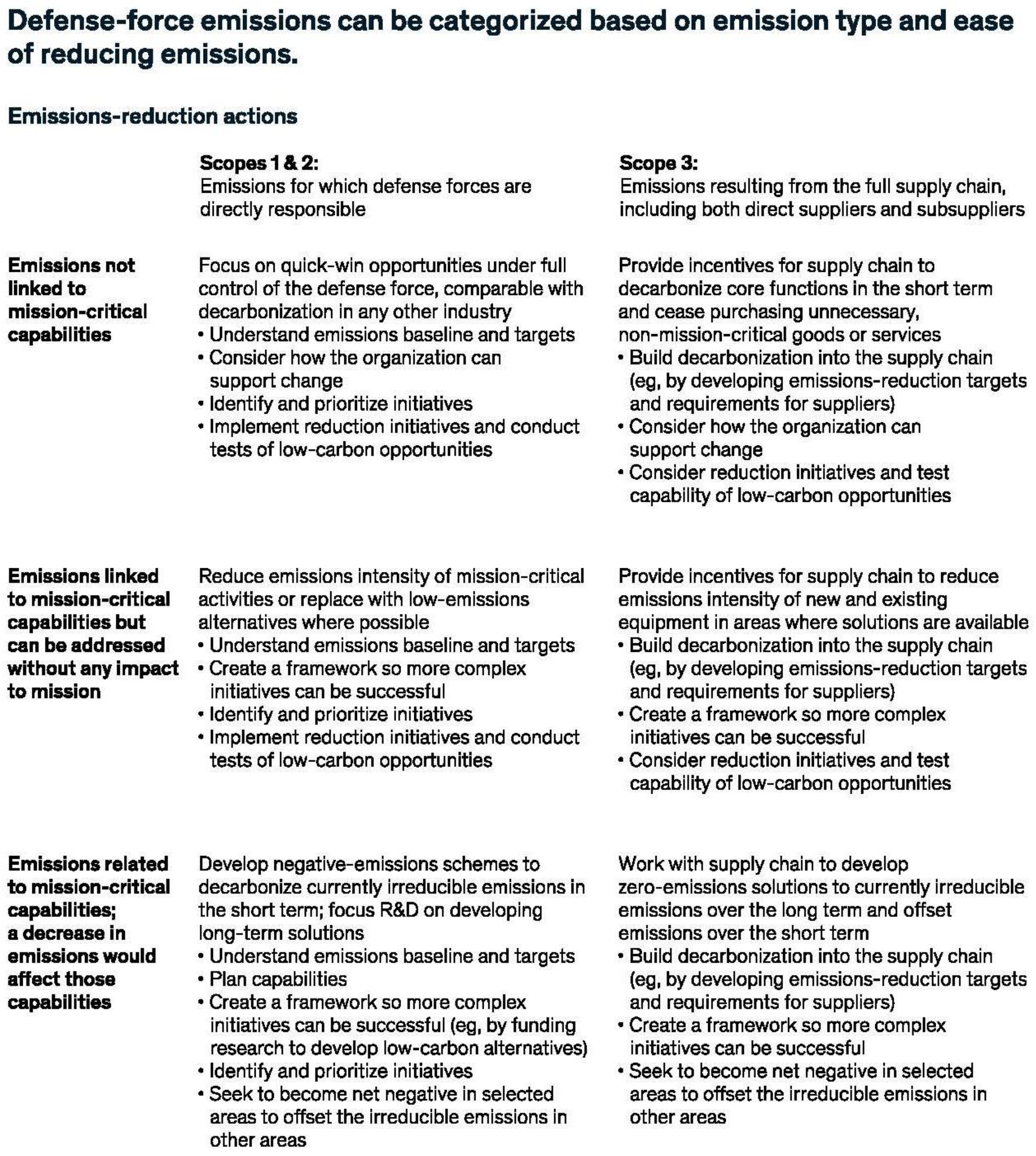


Figure 3. Operational Energy Use by Domain and Mission, FY2014
(DOD Operational Energy Strategy, 2016).

These emissions reports lay the groundwork for understanding the challenge ahead. But, as noted above, the need is broader than just emissions. The DOD is aware of the vulnerability of supply lines, logistics, and transport of fuel. This connection between emissions reduction and mission should be incorporated into analysis of emissions-reduction actions. Figure 4 shows options for categorizing emissions and assessing reductions in relationship to mission criticality and the role that scope 1, 2, and 3 emissions play in the analysis. Future analysis could delve deeper into the various platforms, by mission, and start targeting reduction opportunities as they relate to different asset types.



Defense-force emissions can be categorized based on emission type and ease of reducing emissions.

Emissions-reduction actions

	Scopes 1 & 2: Emissions for which defense forces are directly responsible	**Scope 3:** Emissions resulting from the full supply chain, including both direct suppliers and subsuppliers
Emissions not linked to mission-critical capabilities	Focus on quick-win opportunities under full control of the defense force, comparable with decarbonization in any other industry • Understand emissions baseline and targets • Consider how the organization can support change • Identify and prioritize initiatives • Implement reduction initiatives and conduct tests of low-carbon opportunities	Provide incentives for supply chain to decarbonize core functions in the short term and cease purchasing unnecessary, non-mission-critical goods or services • Build decarbonization into the supply chain (eg, by developing emissions-reduction targets and requirements for suppliers) • Consider how the organization can support change • Consider reduction initiatives and test capability of low-carbon opportunities
Emissions linked to mission-critical capabilities but can be addressed without any impact to mission	Reduce emissions intensity of mission-critical activities or replace with low-emissions alternatives where possible • Understand emissions baseline and targets • Create a framework so more complex initiatives can be successful • Identify and prioritize initiatives • Implement reduction initiatives and conduct tests of low-carbon opportunities	Provide incentives for supply chain to reduce emissions intensity of new and existing equipment in areas where solutions are available • Build decarbonization into the supply chain (eg, by developing emissions-reduction targets and requirements for suppliers) • Create a framework so more complex initiatives can be successful • Consider reduction initiatives and test capability of low-carbon opportunities
Emissions related to mission-critical capabilities; a decrease in emissions would affect those capabilities	Develop negative-emissions schemes to decarbonize currently irreducible emissions in the short term; focus R&D on developing long-term solutions • Understand emissions baseline and targets • Plan capabilities • Create a framework so more complex initiatives can be successful (eg, by funding research to develop low-carbon alternatives) • Identify and prioritize initiatives • Seek to become net negative in selected areas to offset the irreducible emissions in other areas	Work with supply chain to develop zero-emissions solutions to currently irreducible emissions over the long term and offset emissions over the short term • Build decarbonization into the supply chain (eg, by developing emissions-reduction targets and requirements for suppliers) • Create a framework so more complex initiatives can be successful • Seek to become net negative in selected areas to offset the irreducible emissions in other areas

Figure 4. Analysis for Emissions-reduction Actions (Bowcott, 2021).

The amount of emissions from fossil fuels is also linked to costs. As Mills and Limpaecher note, “In 2019 the Defense Logistics Agency, the military’s authority for purchasing fuels, spent over $12 billion to purchase nearly 4.2 billion gallons of fuel for the military, a decrease from the previous year, but still over ten million gallons *per day*. In Afghanistan the military used as much as twenty-two gallons of fuel per day, per deployed soldier. This is a massive increase over the roughly one gallon of fuel needed per soldier during World War II.” (Mills and Limpaecher, 2021) With next generation weapons platforms and operational concepts coming online, many of these use more energy so moving toward emissions reduction now is more critical than ever.

III. REDUCTION STRATEGIES

Researchers identified many potential reduction strategies and focused on those with the most potential for lowering emissions and those under consideration within the DON. It is no surprise that none of these alone can help the DON reach net zero emissions and all have their own challenges and hurdles to overcome. However, as will be shown in section IV with the Pathway models, by diversifying across these strategies, the DON is more likely to reduce emissions and not risk reliance on one or two strategies alone. Certain assumptions had to be made to estimate the reduction in emissions that each strategy may offer; but those estimates can be altered within the pathways to adjust as technologies advance or other low-emissions energy sources are identified.

A. ALTERNATIVE FUELS

Given that the bulk of the DON emissions come from aircraft and ships which are heavily reliant on fossil fuels, the research team included a capstone group of NPS students who focused on alternative fuels such as biofuels and synthetic fuels and, in the aviation context, sustainable aviation fuel. Researchers agree with the IMCCS when it states that “the energy alternatives closest to being readily available are based on alternative fuels.” (IMCCS, 2022). Research shows that, at least in the short term, without lower carbon fuels, the DON will not be able to substantially reduce emissions.

In its FY2020 Operational Energy Annual Report, DOD noted the myriad alternative fuels initiatives that are ongoing within the Services (DOD Energy, 2021). Per DOD Instruction 4140.24, “alternative fuels can be procured for use in operations only when compatible with existing equipment and infrastructure and cost-competitive with traditional fuels” (Office of the Under Secretary, 2019). The DOD has solicited for blends of alternative fuel pathways consistent with fuel specifications and is working with the private sector to produce biofuels for military specifications. The capstone student team analyzed emissions and fuel use within the DON, focusing on two key (and high-emitting) platforms: the DDG-51 and the F-18. Based on this work, the team constructed a high-level conceptual design of a Fuel Decision Support Tool (FDST).

The FDST was developed as a systems engineering process model for executive decision-makers to conceptualize a four phased approach for alternative solutions: phase I is receipt of the mission/directive; phase II is the problem definition; phase III consists of design and analysis; phase IV is simulation and forecasting. The activities and deliverables within each phase are depicted in Figure 5 and detailed in chapter III of the capstone report. The team used this tool to analyze alternate fuel pathways for the selected platforms.

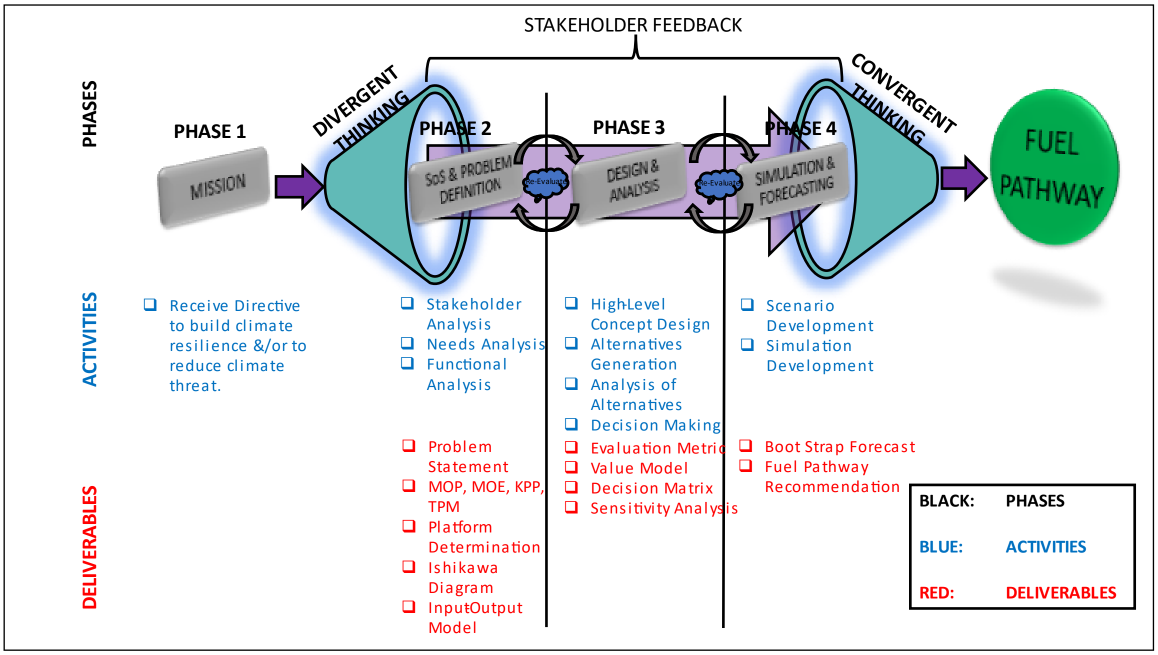


Figure 5. Fuel Decision Support Tool (Forsgren, et al. 2022).

The team then converted drop-in fuel evaluation metrics (energy density, physical state, storage life, blending, and carbon intensity) into ordinal data based on stakeholder prioritization. The results of the analysis of alternatives were determined within phase III of the FDST. The activities within this phase included value modeling, swing weights, a weighted decision matrix, and sensitivity analysis. The highest cumulative score of the analyzed fuels resulted in the two platform fuel recommendations.

The team captured important historical, current, and forecasted trends of fuel consumption and greenhouse gas emissions by asset type based on the data derived from the Naval Visibility and Management of Operating and Support Costs (VAMOSC) management information system. While the data showed a slight decline in fuel consumption and greenhouse gas emissions from 2008-2021, the decline was minuscule compared to the overall fuel consumption by all three Navy mission areas: operational ships, operational aircraft, and military sealift command (MSC) support ships. The Navy consumed approximately 25 million barrels of fuel in 2021, which is challenging given that reaching net zero by 2050 requires substantial progress in reducing fossil fuel consumption. Converting fuel consumption to greenhouse gas emissions in CO2e metric tons (MT) showed that the Navy reduced by 16.67% from approximately12 million CO2e MT to 10 million MT of greenhouse gas emissions since 2008. Lastly, based on a government document titled Department of the Navy Ship Annual Supplemental Data Tables (SASDT) for Fiscal Year 2023, the team concluded that there will be significant growth of fuel consumption and greenhouse gas emissions in the near future as the Navy plans to increase the total number of destroyers from 72 active DDG-51 destroyers in FY22, maxing at 85 active DDG-51 destroyers in 2028 (Department of the Navy, 2022).

Based on the combined results from the FDST and forecasted models, the team recommends that the FDST be further refined for future work, catering to the changing needs of the stakeholders as the operational environments shift over time. While the

FDST was initially designed as a process model that can be templated for future similar fuel issues, the team foresees an expanded FSDT that includes variables of interest beyond alternative fuels. While the FDST provided recommended fuel pathways based on two platforms, the overall data showed that the Navy is not trending positively in reducing greenhouse gas emissions to reach the net zero goal by 2050. The strategies below will become even more important in achieving net zero emissions.

B. NEW TECHNOLOGY

The team includes both hydrogen and unmanned systems as new technology that shows promise for emissions reductions.

1. Hydrogen

For many years, hydrogen has been considered an alternative to carbon-intensive fossil fuels because the use of hydrogen for energy generates no direct CO2 emissions. The International Energy Agency includes hydrogen and hydrogen-based fuels as one of its seven pillars required for the world to reach net zero emissions by 2050 (International Energy Agency [IEA], 2021). Even though it has not shown a widespread economic impact, there are benefits to hydrogen in the military context that are unique. For example, "hydrogen can be generated and used at the tactical edge of the battlefield, whereas petroleum fuels have to be extracted, refined, stored and transported long distances" (Mills and Limpaecher, 2021). In addition, hydrogen can offer performance advantages such as reduced noise, smaller thermal signature, and more efficiency, thereby extending the range and reliability (Mills and Limpaecher, 2021).

The use of hydrogen is not new to the military; in World War I alone, there were over 5,000 hydrogen-fueled missions and lessons have been learned over time (Limpaecher, 2021). There is cutting edge work in the variable use of hydrogen that is promising, especially to meet the need of in-theater fuel and energy production.

Key developments in the past decade show hydrogen as a viable replacement for fossil fuels on small platforms. While the Navy has flown a forty-eight-hour flight of a hydrogen-powered UAV, currently the only generation of hydrogen on a naval platform is in the form of a waste byproduct from electrolysis of water on submarines. In that case, it is discharged overboard. In the Marine Corps, there is a requirement for fuel types of advanced electric, hydrogen fuel cell system on the USMC enhanced combat rubber raiding craft (E-CRRC). This is an "O" Objective requirement. In the larger DOD context, the Army and Air Force are using hydrogen and testing new prototypes such as the hydrogen-fueled prototype ground vehicles (Vergun, 2016) and UAVs, weather balloons and other land-based vehicles.

Research and design breakthroughs that enable hydrogen production include activated aluminum technology which includes a high energy density (16 pounds of batteries = 1 pound of activated aluminum plus water). The Office of Naval Research is evaluating the conversion of aluminum into hydrogen fuel for the Marines' use as a portable, readily available power source (Hochenberg, 2022). The Navy already has a prototype converting seawater into fuel (Libunao, 2016). The Naval Research Laboratory notes that "drawing carbon dioxide from seawater can actually be more efficient than using airborne carbon dioxide, because the concentration of carbon dioxide in seawater is 140 times greater than in air" (Casey, 2012). These developments are consistent with U.S. allies: national strategies of allied nations include key investments in hydrogen production and infrastructure. Five Eye (or FVEY) allies, which include Australia, Canada, New Zealand, and the United Kingdom, have published hydrogen strategies and European priorities include using hydrogen in shipping.

A major promise of hydrogen is the production and generation of fuel in-theater whether on land or shipboard; this could mean fuel generation for contested logistics. Hydrogen paired with unmanned systems (UxS) also show promise. Airships are available that can deploy unmanned systems in remote regions. The Hybrid Tiger is an unmanned aerial vehicle (UAV) that has multi-day endurance flight capability; its capability comes from a "power management system [that] hybridizes solar energy with other on-board energy sources including battery-electric and a hydrogen fuel cell in a light-weight form factor, suitable for airborne craft, as well as ground-based unmanned systems." (Pasquini, 2021)

The challenges to use of hydrogen in the Navy involve safety, supply chain and logistics challenges, lack of infrastructure and operational costs. The safety issues surrounding hydrogen likely seem to be both real and perceived in the transport, storage and use of hydrogen. Because it has a lower ignition energy than gasoline or natural gas, hydrogen can ignite more easily. In addition, some metals can become brittle when exposed to hydrogen so appropriate storage materials are important. Safety considerations also include training in safe handling procedures. Even with these concerns, advocates argue that hydrogen is, in many respects, a safer vehicle fuel than gasoline and has a near perfect combat safety record (Mills and Limpaecher, 2021).

Despite the quickly evolving hydrogen technology, the infrastructure is lagging behind. With refueling a key factor, building the necessary hydrogen infrastructure in the U.S. and allied countries is essential. There are efforts underway; among other efforts, the U.S. Department of Energy has launched H2USA, a "public-private collaboration with federal agencies, automakers, hydrogen providers, fuel cell developers, national laboratories," and stakeholders to advance hydrogen infrastructure in the U.S (Department of Energy, 2022). In addition, international partners are already developing regional hydrogen logistics capabilities; specifically, EUCOM and INDOPACOM allies are building up hydrogen production and transport capability (Limpaecher, 2021). For hydrogen to reach its promise for use by the DOD and DON, demonstrations will need to show operational behavior and further the proof of concept on the next generation of hydrogen technologies. Analysis to reduce the operational costs for hydrogen production can help it be more competitive with traditional fuels in the future.

In the commercial sector, hydrogen products are maturing and becoming more refined, especially in how to reduce emissions in the production of hydrogen; in this way, the success of hydrogen is uniquely linked to the production and development of renewable energy. Currently, most hydrogen is produced from coal or natural gas, although there are many options for production. Some of the most well-known methods include:

- Gray and brown hydrogen. Gray hydrogen is produced from natural gas through steam methane reformation; brown hydrogen is produced from the gasification of coal. The benefit to these methods is a low cost but CO2 emissions are significant.

- Blue hydrogen is produced from fossil fuels (such as coal or natural gas as above) but carbon capture and storage is used to trap the CO2 emissions.
- Green hydrogen is produced through the electrolysis of water. This is the cleanest method to produce hydrogen; the downside is the significant cost (Pribyl and Haines, 2021).

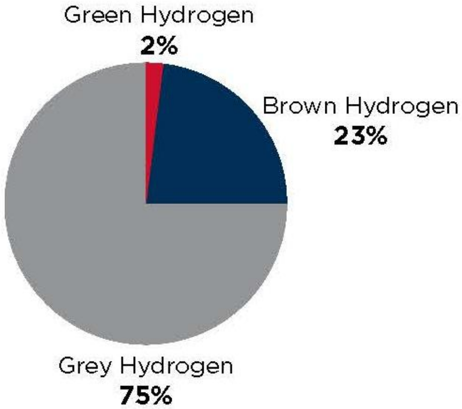


Figure 6. Production Sources of Hydrogen (Statista, 2022).

As seen in Figure 6, most hydrogen fuel is produced via the process of steam reforming fossil fuels; the process of steam methane reforming (SMR), which results in the creation of five times as much CO_2 than H_2 by weight. This furthers the need for an increased investment in renewable energy, as H_2 production from electrolysis that utilizes renewable energy creates absolutely net zero GHG emissions; the only byproduct here is oxygen (Statista, 2022).

Green hydrogen production using renewable energy needs investment to scale-up its potential production as it only accounts for 0.3 percent of the global hydrogen production as of 2020. An increase in investment will also increase the amount and availability of fuel storage and refueling sites, a problem currently facing the commercial vehicle market which can affect availability for the military. While hydrogen powered cars have been on the market for decades, a lack of infrastructure in the form of refueling stations has hampered production and investment; as a result, hydrogen vehicles are a small part of the transportation sector (Statista, 2022).

Projects investigating the technologies used in producing H_2 include the SGH2 project in partnerships with Lancaster, California. This alternative energy production method uses solid waste as the feedstock for the process. The ambitious SGH2 project includes partnerships with the Lawrence Berkley National Lab and aims to make the world’s largest, closed loop, green hydrogen facility (SGH2 Energy, 2022).

In the commercial maritime context, there are also regulatory challenges which, again, can affect how hydrogen as a maritime fuel evolves and affect adoption and development within the defense sector. As Pribyl and Haines explain, “there are no existing federal regulations that specifically cover the design and operation of hydrogen-powered vessels, including hydrogen as a vessel fuel, use of fuel cells for vessel propulsion or hydrogen bunkering." (Pribyl and Haines, 2021). While there is an option in the commercial sector to seek approval from the U.S. Coast Guard for an alternative design, the legal and regulatory gaps are a hurdle.

In addition, port infrastructure is necessary. Japan currently has the most hydrogen fuel stations in the world; the country has 134 stations as of 2021. The availability of Japan's hydrogen fuel network could serve as beneficial to the numerous U.S. Naval bases in the country (Statista, 2022). However, space at ports is at a premium and liquid hydrogen requires approximately five times more volume than petroleum-based fuels (Pribyl and Haines, 2021). Finally, the commercial sector notes that the lack of an established hydrogen market is also inhibiting its development. Thus, many efforts must work in tandem for hydrogen's potential to be realized.

The American Bureau of Shipping notes the following benefits and challenges of hydrogen in the maritime context in Figure 7. The military will need to adjust to these challenges as well.

Benefits	**Challenges**
Carbon and sulfur free	Lack of marine transport experience
Can be stored and transported as a liquid or gas	Possible high fuel cost
Can be produced renewably from electrical energy and bio-renewable processes	Low availability of renewably produced hydrogen
Established commercial product on land	Fuel infrastructure and bunkering need investment
Gaseous, particulate matter and GHG free emissions with fuel cells	Novel power generation systems will require more technology innovation and cost reductions
Highly buoyant and disperses if leaked, even at liquid hydrogen temperatures	High explosion risk in confined spaces
	Low cryogenic temperature challenges (storage, management, leaks, etc.)
	Material challenges (permeability, hydrogen embrittlement, etc.)
	NOx emissions if burning hydrogen in internal combustion engines.

Figure 7. Benefits and Challenges of Hydrogen as a Maritime Fuel (American Bureau of Shipping, 2021).

Even with these challenges, researchers and practitioners in the private sector and military domain agree that hydrogen has promise as an alternative fuel. Because of the challenges noted above, the research team was conservative in its estimate of emissions reduction from hydrogen, especially prior to 2040. However, hydrogen does play a role in a diversified approach and, in the aspirational Pathway 4, it is estimated that hydrogen accounts for a greater percentage of reduction.

2. Unmanned Systems

Unmanned Systems (UxS) are a technology group that is being rapidly developed and increasingly deployed by the DON. Both the Navy and the Marine Corps have incorporated these systems into surface, underwater, air, and ground fleets. UxS enable greater area coverage as stated in the DON's Unmanned Campaign Framework: "The developing abilities of near peer competitors drive the need for increased Naval capability distributed over a wider area" (Department of the Navy, 2021). The usage of UxS increases this capability by essentially eliminating the requirements needed for human centered platforms. Many technologies in the private sector have been shifting toward integrating UxS into their operations and designing platforms to reduce or eliminate dependence on fossil fuels. The utilization of these systems presents an achievable pathway that can contribute to attaining net zero emissions while still meeting complex national security priorities. The commitment to develop and use UxS that reduce or do not contribute to the increase in GHG emissions is the one of the most attainable pathways that the DON can easily achieve.

The DON's current unmanned portfolio includes UxS of varying sizes and abilities. They are categorized into Air, Surface, Undersea, and Ground portfolios. Each category is then further divided into size ranges: small, medium, and large. Based on the findings from the DON's portfolios, most of these systems, especially those in the medium and large size categories, currently use liquid petroleum as the standard fuel type. Many of the platforms use JP-5 and JP-8 fuel. As the fleet of UxS increases, the use of petroleum will also increase if current designs are maintained. At present, the systems may call for efficiency achievements but are currently not designed to reduce emissions. A change in the fuel type for these platforms could offer a quick win for the DON's efforts towards achieving Net zero emissions; in the longer term, designing them as hybrid or fully electrified systems will go even farther.

a. Aerial Systems

Unmanned Aerial Systems (UAS) platforms are used to enhance the maritime domain awareness through providing an increased range and capabilities including Intelligence, Surveillance, Reconnaissance and Targeting (ISR&T) (Department of the Navy, 2021). Some of these platforms look and perform very similarly to conventionally manned systems utilized in the DON. For example, the large UAV autonomous platform MQ-8(B & C) Fire Scout is designed after the commercially available Bell 407 helicopter (*Fire Scout*, n.d.). While this vehicle consumes less fuel than most manned aircraft, this platform still utilizes a fuel that releases GHG via use of a conventional jet engine. A notable UAS example is the Insitu ScanEagle (MQ-27A/B) that also employs the usage of JP-5 and JP-8 to fuel its propulsion system (Insitu, 2020).

b. Surface Vehicles

Depending on the intended mission requirements, Unmanned Surface Vehicles (USV) are designed using existing hull designs of manned ships or could be as simple as a wave glider. Much like the classifications of aerial assets, USVs are categorized into different size classes ranging from small, medium, and large with the latter two in the prototyping stage (Eckstein, 2022). The Sea Hunter (SH1) and Overlord are examples of the medium and large USVs being prototyped for the Navy. A Long-Range USV (LRUSV) has been developed to enhance the Marine Corps maritime reconnaissance, support sea denial and control operations, as well as further capabilities in long-range precision fires (Department of the Navy, 2021). Smaller platforms like wave gliders and Saildrones utilize alternative methods of propulsion that do not require any type of gas or diesel-powered engine. These two USVs use wave, solar, and wind energy to give these platforms long endurance for surveillance (Naval News, 2022).

c. Underwater Systems

Underwater capabilities include designs that mimic existing platforms such as submarines. Unmanned undersea vehicles (UUVs) range in size from small torpedoes to extra-large submarine size. One platform that does not use fossil fuel is the General Dynamic's Bluefin-12 medium sized UUV. This UUV designed for the Royal Australian Navy utilizes four rechargeable batteries that are easily swapped out, and rapidly quickly charged (Abbot, 2019). The similarly designed U.S. Navy Knifefish program (based off of the Bluefin-21 design) enlists nine battery pack for an average of around 25 hours of endurance at around three knots at normal payload (General Dynamics Mission Systems, 2021). Larger platforms such as the Extra Large UUV (XLUUV), Orca, performs with a hybrid battery-diesel generator propulsion system. The diesel generator is triggered when the battery charge has neared empty (Naval Technology, 2020). These platforms are examples of how it is possible to design UxS to perform missions without the exclusive use of gas-powered generators, turbines, and fossil-fuel based engines.

d. UxS Battery Storage

Cutting edge technology points to battery application and electrification. The greatest emissions savings pathway for UxS would be to replace fossil-fuel platforms with fully electrified UxS. The electrification would need to be powered by renewable sources to zero down the emissions. Because of scalability issues, small platforms are more capable of battery cell usage while larger platforms are harder to scale up. The energy densities of common batteries found aboard UAS include Lithium Polymer and Lithium Ion (Li-ion) (Townsend et al., 2020). Li-ion batteries tend to be most suitable for UAS applications as they have a high energy density; they are lighter and smaller than comparable rechargeable batteries and could offer a quieter sound profile than systems utilizing combustible engines. Because the batteries are commonly used in electric vehicle applications, systems similar in size could also utilize the Li-ion batteries instead of the typical fossil fuel engines. Some of the many benefits of including these types of batteries in the design of the unmanned systems are the long lifecycle, low maintenance, and ability to easily swap out batteries and be recharged (Ci et al., 2016).

Other improved technological applications that are increasing production in the private sector include the use of rechargeable batteries and photovoltaic cells in long range UAS platforms (BAE Systems, 2020). The application of these would be most fitting in long range, surveillance, and high-altitude platforms that would normally have a limited range due to the limitations of petroleum fuel usage. A comparison of the different types of power sources for aerial drones concludes that combustion engines are both heavier and larger in size; the sound profile is noisy; and the engines tend to have more frequent and complex maintenance (Townsend et al., 2020). The use of the different types of fuel cells and power sources have benefits and limitations. If employment of new battery technology is not utilized, the construction of improved hull designs that create lighter ships and aircraft, consuming less fuel in both the maritime and air environment could potentially lead to some reduced carbon emissions. The changing of the power source would complete that reduction.

e. Projected Systems

While there is no public build plan of exactly how many and what types of unmanned and autonomous systems will be built, the Navy’s Unmanned Campaign Framework as well as general consensus all indicate an increase of acquisition of these systems (Department of the Navy, 2021). The Chief of Naval Operations Navigation Plan does envision “hybrid fleet to require more than 350 manned ships, about 150 large unmanned surface and subsurface platforms, and approximately 3,000 aircraft” (Chief of Naval Operations, 2022).

It is highly unlikely that UxS will completely replace the current manned fleet, but the integrated usage of manned-unmanned teaming (MUM-T) is being explored. The utilization and integration of adding more UxS versus the construction and deployment of conventional aircraft could potentially offer savings in fuel and reduction in GHG emissions. The new systems that use AI and autonomy offer more efficiency through precise decision making and calculated flights that manned platforms could not attempt (BAE Systems, 2022). The efficiency benefits of autonomous systems are being studied in the maritime shipping industry; one such study compares the cost of a manned shipping vessel with a conceptual autonomous vessel, concluding that an autonomous vessel would save approximately $7 million over a 25-year period (Kretschmann et al., 2015). Unmanned systems also have the capability of extending mission range by going into areas deemed unsafe and unfeasible for manned platforms.

While an efficiency advantage in fuel usage through the utilization of MUM-T might exist, this could mean that the individual platforms have higher payloads which would cancel the benefit of efficiency. Should traditional fossil fuel still be utilized, another potential negative with is that although the mission will be able to go farther and longer, the same amount of fuel would still be used, leading to the same overall emissions.

An example of this potential MUM-T emissions paradox is the usage of the new Boeing MQ-25. The newly acquired MQ-25 Stingray is an aerial asset utilizing heavy fuel (NAVAIR, n.d.). “The MQ-25A Stingray will be the first carrier-based UAS, functioning primarily as a mission tanker to extend the range and reach of the Carrier Air Wing (CVW)” (United States Navy, 2021). The current testing of systems such as the MQ-25 and potential capabilities to assist in the refueling of aircraft gives promise to the aerial fleet going further and farther. Further studies into refueling platforms for small UxS are also needed.

f. Potential Trade-Offs and Gaps

While the use of unmanned systems may initially point toward efficiency at the surface level, there are multiple trade-offs that have the potential to cancel out gains. It is assumed that although unmanned systems could take Naval capabilities further and farther, that could also mean using the same amount of fuel and ultimately not benefiting the reduction of emissions. Private sector studies indicate around six percent (6%) fuel use reduction with the use of unmanned systems, depending on several factors ultimately not guaranteeing actual fuel savings. While many of the smaller platforms are more capable of adapting to cutting edge alternative energy sources, larger ships may require higher-grade fuel. This may add an unfeasible burden to the DON (MI News Network, 2020). Replacement of manned platforms with unmanned systems is ambitious; the complete replacement of the larger manned platforms responsible for the most emissions is unlikely as their missions cannot be met solely by unmanned platforms alone; a pairing of a crewed vessel with an UxS would be more likely.

An energy heavy component of autonomous systems that may not usually be seen as a large emitter of GHG is the increased sector of artificial intelligence (AI) and machine learning. While the system itself is not a physical or deployable platform, the computer element is. This portion of the system draws a great amount of energy. The energy pulled from the computers servers depends on the availability of energy from the connected grid (Ajao, 2022). Ensuring that the grid utilizes renewable energy is ideal. A potential shortfall of the data available to researchers is the categorized data from commands that utilize this technology. The availability of AI emissions data will help ensure the Net zero goals. While modeling and AI offer solutions and insights to tackling many of the issues presented to the DON, the technologies need to be managed properly (Herweijer et al., 2018). The power-intensive technologies and thus, increased emissions, must be considered (Strubell et al., 2019).

The research team also identified gaps. The VAMOSC data used for the fuel usage calculations only provided a few unmanned platforms used by both the Navy and Marines. Because of the missing data, the analysis was unable to capture the full fuel usage of the myriad systems currently used. Another gap is understanding the full scope of which and how many systems will be funded and integrated into the future build plan of the fleet. With this, there is a need for follow-on comparison studies to analyze the trade-offs and potential fuel savings of the deployment of manned ships or aircraft versus their comparable unmanned platforms. UxS usage should be considered, with ideally non-fossil fuel-based systems, in the pathway to net zero emissions.

C. BATTERIES

Chemical Batteries represent a small but quickly growing aspect of the Navy’s energy portfolio. While they are not currently used on a scale comparable to that of fossil fuels, developments in battery technologies and other electrical systems indicate demand for battery-based energy storage will see exponential growth.

This section will cover two areas of particular interest to the Department of the Navy: ship energy storage for hybridization and battery use for UxS. The use of batteries for the hybridization of surface platforms, in particular large surface combatants, may play a role in substantially reducing emissions without hampering operational capabilities. Batteries may further be used in efforts to reduce emissions by acting as the primary energy source for some small and medium UxS. Additionally, they could be implemented as power storage, working in conjunction with intermittent renewable generation systems for shore-based installations. These ideas are investigated through the lens of the capabilities and challenges involved with increased battery use.

On a high level, Li-Ion chemistries are the most likely choice among batteries for many present and future energy storage needs. The Li-Ion family represents dozens of battery chemistries, all characterized by high energy-to-weight (Specific Energy) and energy-to-volume (Energy Density) ratios, long lifetimes, and high discharge rates. Due to heavy investment from the electric vehicle industry, lithium battery performance has nearly doubled in the last ten years and improvements are predicted to continue (Muralidharan, 2022). Progress has also been made in decreasing fire risk and increasing safety. The price per kilowatt hour has also decreased over time to less than half of what it once was (IEA, 2020).

Current Navy use of batteries is heavily focused on small and mobile systems, where batteries enable the operation of small unmanned vehicles, weapons system electronics, and some limited use for backup power on aircraft such as the F-35 (Dow, 2010; Saft, 2020). Some small emissions savings are made from the use of batteries for propulsion power in unmanned systems, such as the RQ-11, RQ-20, Orca (hybrid with diesel), REMUS platforms, Knifefish UUV, and some underwater gilder systems (Dow, 2010). As currently employed, batteries do not have a significant effect on naval emissions, as they are not commonly used for primary power on large or numerous platforms where most emissions are centered. This is likely to change soon, due to advances in technology and changes in policy and mission needs (Gilday, 2022; Rubel, 2021).

1. Cutting Edge Technology

Most cutting-edge battery technology is related to Li-Ion chemistries. Development from the electric vehicle and consumer electronics industries has caused massive increases in performance over the last 20 years, with the price of lithium batteries dropping approximately a quarter, while the energy density has more than doubled (IEA 2020; Ziegler 2021). Heavy investment in the private sector continues in refining battery design and scaling production capabilities.

It is likely that the performance and safety of lithium batteries will continue to increase in the coming years, although Li-Ion chemistries have a theoretical limit in energy density and specific energy which is well below that of liquid fuels. In the long term, other battery chemistries may be developed to compete with liquid fuels. Lithium-Air batteries have a theoretical energy density and volumetric energy density comparable to diesel fuels, although it has not been proven at any scale (Girishkumar, 2010). With current technology, batteries can be used at scale with other cutting-edge technologies to reduce net emissions over time. Batteries can be used to complement installed energy generation systems on surface ships, to power small unmanned systems, and to store energy on bases. Except for small UxS, for which they are an ideal power source, all the uses of batteries mentioned above work to reduce emissions by increasing the efficiency or capabilities of other systems.

2. Hybrid Electric Drive and Integrated Power System

The concept of using hybrid technologies for destroyer class ships has existed for more than a decade (McCoy, 2007). The gas-only configuration like those used in aviation, currently relies on large gas turbines, to power ships. Most ships, especially large destroyer and cruiser class ships, have two separate sets of gas turbines: one turbine set for propulsion, and a separate set generating electricity for the ship's grid. In modern U.S. destroyers, the gas turbine engines which generate power for the ship and power for the propellers operate most efficiently at higher power settings. When the ship is going slow or not running many systems, more fuel is being used per unit of energy generated due to the loss of efficiency from operating turbines at lower power settings (Corey, n.d.). It is theoretically possible to use the smaller turbines normally used for a ship's electricity generation to move a ship at lower speeds, thereby increasing efficiency, depending on the configuration of a ship's power system.

The configurations and technologies on destroyers that enable hybrid operation are called Hybrid Electric Drive (HED) and Integrated Power System (IPS). IPS is a more comprehensive system than HED ships, and is used on ships specifically designed for it, while HED can be retrofitted onto existing ships. In theory, a hybrid warship will be able to operate more efficiently and with more flexibility than one equipped in a standard configuration, and there have been several efforts to bring these technologies to the fleet. The hybrid electric drive has been tested on the *USS Truxtun*, and the integrated power system is in use on all *Zumwalt* class destroyers. The basic concept of a hybrid electric system employs an electric motor to optionally power a ship's main driveshaft(s). The electric motor is powered through the ship's electrical system with a variety of power generation options. Future integrated propulsion systems could be combined with battery energy storage for further increased performance and efficiency.

Gas turbines cannot instantaneously increase power output, which in practice means that more power must be generated at any given time than is used. This results in significant overgeneration of power at times, as any extra power made by a turbine system is not able to be stored and is simply lost. In a hybrid configuration it is possible to use batteries to cover any short spikes in energy demand, thereby reducing the size and number of generators which need to be running at any given time. Batteries may be useful as a buffer for generator power level changes, enabling the turbine generators to only produce what power is currently needed, instead of generating what power could potentially be needed at any time.

Many of the current and near-term weapons and sensor systems on a destroyer platform require large amounts of energy on very short notice. This kind of pulsed power response is something that gas turbine generators alone are not well suited for. For example, the use of a high energy laser to intercept an incoming anti-ship cruise missile is one of the use cases for planned shipboard laser systems. This would require a great deal of energy with perhaps only a couple of seconds of notice (Gattozzi, 2015). Due to the inertia of large gas turbine generator systems, the time required for a turbine generator to increase its power output is longer than the engagement window of some targets for a high energy laser. For this reason, many plans for cutting edge weapons require dedicated power storage for high power electrical systems such as high energy lasers (Sylvester, 2014). An integrated battery system could provide efficiency benefits for the rest of a ship's platform when not actively utilized by a specific pulse load weapon or sensor system (Gattozzi, 2015).

It is also worth noting that battery energy storage solutions and hybrid designs would likely integrate well with eventual renewable energy generation systems such as hydrogen power and biofuels, as they work to increase the overall efficiency of any energy generation system they are installed with.

3. Small and Medium Size Unmanned Systems, Swarm Compatibility

For many future mission sets, distributed networks and swarm systems are being developed to increase capabilities without putting valuable assets at risk. In the CNO's NAVPLAN 2022, emphasis has been specifically placed on smaller, cheaper, and more distributed manned and unmanned platforms (Gilday, 2022). The definition of a small to medium-sized platform is somewhat flexible, but for the purposes of this report, small UxS can be understood as on the scale of 10s of kilograms or less for aerial platforms, and 100s of kilograms or less for surface and undersea platforms. For small unmanned systems of all types (aerial, surface, undersea, ground, etc.) batteries can present an ideal solution for power, as battery powered systems are often small and cheap, with additional benefits from low maintenance, simple designs, and cheap costs. Without the need for a fuel tank, engine, and energy conversion systems, small and medium sized platforms using batteries can require much less maintenance than gas powered systems. Many small unmanned systems are already fully battery powered, and it is likely that electric power is a viable pathway to net zero emissions for most small and medium sized unmanned systems. While the calculation changes for each application, there is evidence that the energy density limitations of batteries are less pronounced in small systems, as the simplicity gained by not having a complex engine, fuel tank, control system, etc., can save weight (Logan, 2012). In addition to comparable range performance, less frequent and easier maintenance, and lower cost when compared to gasoline powered systems, battery powered small unmanned systems are also better suited for distributed networks. These networks of systems can be easily recharged and, in some cases, utilize energy generation directly from solar or wind. The ample availability and ease of generation of electricity means battery powered platforms may profit from an increase in effective time on station while deployed, as less time is spent in refueling or transit to and from areas where fuel is available. Electrically powered platforms also have a greatly reduced thermal signature, allowing for lower observability.

4. Grid Energy Storage for Shore Installations

While batteries do not present an ideal solution for some mobile systems that demand low weight and high range, there are some shore-based applications that are more well suited to the use of batteries. In the coming decades, a shift is expected in power generation moving away from fossil fuels to renewable sources such as wind and solar. While great effort has been put into developing wind and solar technologies to be capable of generating enough power to take over from fossil fuel sources, renewable sources are by nature intermittent generation systems, unable to provide power when the wind is calm or the sun is not shining. Most grid energy consumers need constant, reliable power, especially in the case of military installations. Some battery systems are ideally suited to work with renewables to provide constant, reliable power.

There has been significant development in recent years by the public sector in the use of lithium batteries to provide energy storage for the grid, with a wide diversity of technologies and chemistries under active development (Farivar, 2022; Mongird, 2020). While Lithium batteries are a short-term grid energy storage solution, several other battery chemistries are under active development which are tailored to grid energy storage applications. A 2022 study by MIT found that Redox flow, sodium-sulfur, and metal-air batteries all show promise for both near and long-term grid energy storage (Armstrong 2022). Although lithium batteries are already designed for lightweight high-performance applications, new battery chemistries for grid energy storage are being developed to be cheaper, use more common materials, have a higher safety factor, and last longer. It is likely that the Navy could leverage these rapidly developing technologies, in conjunction with renewable generation, in the 2030 and 2050 time frames to achieve net zero emissions for its shore based installations.

5. Challenges

While batteries are becoming more useful every day and can be leveraged to increase capabilities and reduce emissions in many areas, there are serval challenges which must first be understood and overcome. Energy density limitations, fire risks, as well as design for recycling and limited cycle life are all important challenges or limitations. These must be accounted for when implementing battery systems for naval use.

a. Energy Density, Range Limitations

While the current generation of batteries have many advantages and possible uses, they are not advantageous for large systems where extreme range and performance are needed. Even the best Li-Ion batteries fall far behind the performance benefits of liquid fuels, principally diesel type fuels, in the categories of specific energy density [measured in Watt-hours per Kilogram (Wh/kg)], and energy density [measured in Watt-hours per Liter (Wh/L)]. Due to fundamental differences between chemical batteries and liquid fuels, Li-Ion batteries will always hold much less energy than a fuel tank of the same size or weight. Diesel fuel has a specific energy of roughly 12,000 Wh/kg and an energy density of roughly 10,000 Wh/L (Fossil and Alternative Fuels - Energy Content, n.d.). Current Li-Ion batteries have a maximum specific energy and energy density of around 265 Wh/kg and 670 Wh/L (University of Washington 2020). In practice, diesel fuels do not perform as well compared to batteries as the theoretical numbers would suggest, due to losses in energy during combustion and the weight and size of engine systems, but these losses are minimized in larger platforms. Liquid fuels are generally a far better choice for platforms where weight and range are important metrics.

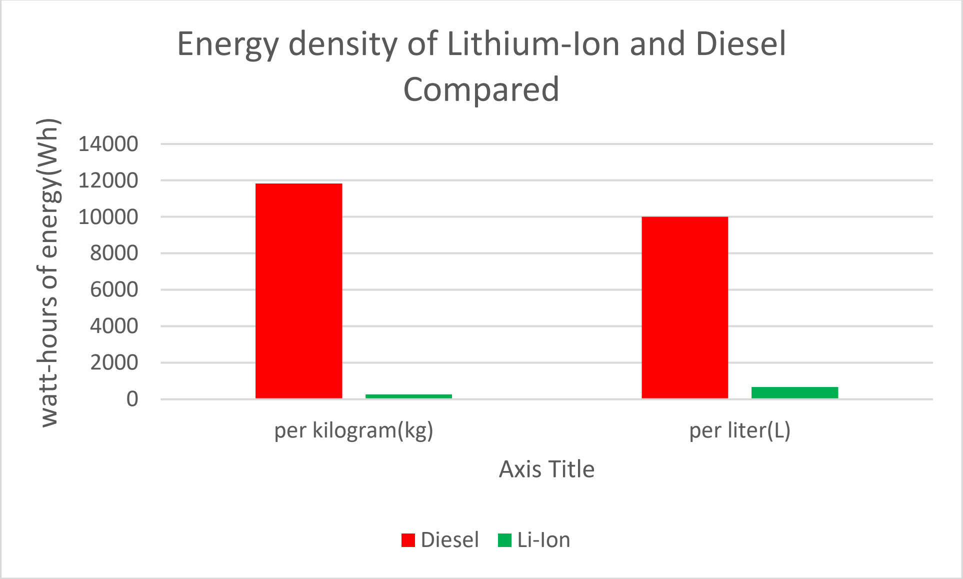


Figure 8: Energy Density of Li-Ion and Diesel Compared (Girishkumar, 2010).

The energy density discrepancy between batteries and liquid fuels means that batteries are not a likely choice for fully replacing fossil fuels in large platforms which require high performance and range. Batteries are not a viable primary power source for manned surface combatants such as destroyers and frigates, or manned aircraft such as the F-18, F-35, and C-130. Those systems require high performance and long range, and with less than 1/20 percent of the energy-to-weight ratio and energy-to-space ratio, current generation batteries simply do not have the power to provide the same capabilities as a gas turbine engine and liquid fuel. In the long term, Lithium-Air batteries have a theoretically competitive weight and size ratio to liquid fuels, but those battery types have not been fully developed (Girishkumar, 2010).

b. Fire Risks and History

The causes of lithium battery fires have been the subject of a great deal of research in the past decade, and the understanding gained from that research has led to increased safety and predictability. While thermal runaway can cause serious fires and has the potential to limit the usefulness of battery systems for operational Navy use, several methods can be used to reduce risk. Like early gasoline fuel tanks, batteries have historically been a fire hazard because the reasons they catch fire were not well understood, and the people operating systems which utilized batteries had often not been trained on the dangers. As adoption of this technology has increased, this potential hazard has changed. Improvements in proper training, battery management systems, battery-specific fire detection and suppression systems, and better design and manufacturing have greatly reduced fire risk. Because of these improvements, well-designed lithium batteries are used widely in everyday life with very few incidents.

c. Battery Management Systems

Many of the possible causes of a battery fire come from improper use. Events such as overcharging where batteries are enduring a buildup of heat, or being drained too quickly can cause the onset of thermal runaway which frequently leads to a fire. Newer and better designed battery management systems (BMS) can prevent users from abusing the batteries and thus prevent fires. These systems can account for and prevent many of the causes of a battery fire and are highly effective in preventing fires in many commercial applications.

d. Offgas Detection with BMS

Battery specific smoke detectors can be employed to catch battery failures before they lead to thermal runaway. Smoke detectors which have been modified to be sensitive to the byproducts of an offgas event, which occurs when a battery cell is physically damaged or suffers a failure and starts to decompose, can be key in shutting a damaged battery cell down before it leads to a fire. While BMS plays an important role in preventing battery fires, abuse from external factors can cause thermal runaway or cell failure by physically damaging the battery. If the failure is not detected, a small fault can lead to the whole system catching fire. In most cases, a well-designed BMS can detect the failure by moderating the change in voltage of each cell. When BMS is used in conjunction with offgas sensors that can detect the byproducts of a cell decomposing, the chances of a battery fire are greatly reduced (Gully, 2019; Swartz, 2017).

e. Better Design and Training

While lithium batteries have historically been at great risk of causing intense and difficult to extinguish fires, a great deal of research and testing has gone into understanding the mechanics of once poorly understood causes of battery fires. Despite advances in technology, lithium batteries can still contribute to a risk of catastrophic fire, as demonstrated by the burning of the Felicity Ace in February of 2022. However, with proper design, testing, manufacturing controls, battery management systems, offgas warning systems, fire suppression, and training, the fire risks from lithium batteries can be mitigated to nearly zero. Due to advances in the many design factors above, current lithium batteries are much safer than past generations (Chen, 2021).

f. Design for Life Cycle and Recycling

Most chemical batteries have a limited lifespan, both in years and in the maximum number of cycles before they can no longer carry a useful charge. Given this, any platform or use case for batteries needs to plan for end of life, both in how they are replaced and ensuring the old batteries are recycled.

For ships, drones, and other mobile platforms, design considerations must be taken to ensure any battery systems are easily accessible and removable. Designing easy access for removal can be especially challenging for the shipboard case, as the ideal location for a battery bank may be deep in the ship where the battery’s weight does not reduce stability. Beyond environmental reasons, design consideration for ease of replacement and recycling is important for operational and strategic reasons as well. Operationally, batteries have a lifespan that is likely to be less than that of the platform they are installed on, especially for ships. Most systems with significant battery energy storage will need to have the batteries replaced several times over the lifetime of the system to avoid decreases in performance and risks of total battery failure. For this reason, modular design for replaceability is important.

While almost all battery chemistries can be nearly completely recycled, they often contain toxic metals and other chemicals which are highly damaging to the environment if not recycled. Common Li-Ion battery chemistries contain high amounts of lead, cobalt, nickel, lithium and other toxic metals which can leak into the environment if not properly disposed of (Kang 2013). It is imperative that battery systems are recycled, as the potential emissions savings from shifting systems to include batteries can be overshadowed by the effects of heavy metals and other toxic chemicals leaching into the environment. Lithium batteries should be easily recyclable in the future, as demand for lithium and some of the other elements used in modern batteries drives recycling costs down. Currently there is rapid development of techniques and industry for Li-Ion battery recycling, with promising small-scale examples of near 100% recyclability for heavy metals and economically profitable business examples of closed loop recycling (Jung, 2021; Recyclico, 2022).

There is also a strategic reason for recycling batteries: reducing economic dependance on imported materials. With electronic vehicle markets growing rapidly, battery materials are becoming strikingly important to many of the largest industries in the U.S. However, most of the world's lithium battery production and materials processing is controlled by China (IEA 2022). It is therefore important that the U.S. continues recycling lithium batteries, as recycling offers a highly effective long-term source of battery materials, thereby reducing dependance on foreign suppliers for critical materials.

While batteries are easily recyclable, and doing so is even profitable in most cases, it is important that replacing and recycling battery systems is taken into account early in the design process. Design for replacement and recycling is a small and usually easy part of an overall system's design, but it is one that can lead to huge problems in the lifecycle of a system if overlooked. Proper design considerations for recycling batteries can provide cost savings in the long term and extend the lives of systems substantially.

D. INCREASED EFFICIENCIES

Between now and 2050, it is expected that various increases in efficiency will occur through improved technology and changing the way the Navy operates, but these efficiency improvements will be fighting against other factors that are expected to increase operational energy demand. While technology and increased operational proficiency has the potential to increase the efficiency of energy use, other factors will demand more from the operational Navy thus diminishing the emissions impact of those efficiency gains. Given current trends, it is expected that the Navy of the future will operate a larger, more distributed fleet which means more ships and aircraft burning hydrocarbons and more supply ships shuttling fuel to combatants distributed over a wider area. Even if technological improvements and operational practices allow for increased efficiency, the net result may be very modest GHG reductions, or potentially even an increase in emissions. This section addresses expected efficiency changes, operational energy demand changes, and modeling efforts that were used to evaluate how the sum of these changes is expected to impact emissions going forward.

1. Current Status

As of 2022, there are several initiatives that will have impacts on operational energy use and efficiencies in the fleet, and by extension, GHG emissions. The DON has recognized that operational energy is a key combat enabler and is taking steps to increase efficiencies to get more out of every gallon of fuel, but at the same time is exploring operational models and weapon systems that will increase energy demand. There are plans to build more ships, engage in a distributed operations model in the Pacific, and the conflict between Russian and Ukraine has caused an uptick in deterrence operations (Osborn, 2022). The Navy is also experimenting with high energy lasers and rail guns. These developments all point to an increase in energy use. Counter to this, the Navy is also rolling out hybrid electric drives in new ships and retrofits, trying to promote an energy-aware culture, and exploring alternative fuels and other energy-efficient technologies. While these technologies have the potential to increase energy efficiency, it is expected that the current rate of energy demand increase will outpace efficiency gains for at least the near future.

As the Navy pivots to increasing operations in the Pacific theater, the tyranny of distance will play a greater role in driving energy consumption and emissions. The Navy will be required to cover an expansive area of operations far from friendly ports, which means that massive amounts of fuel will be needed to move ships and supplies between homeports and combatants operating in faraway seas. The pivot to a distributed expeditionary advanced base operations model in the Marines further exacerbates the issue as the Navy will be responsible for delivering fuel not just to the Navy ships operating throughout the Pacific, but also to Marine bases distributed across many island chains (U.S. Marine Corps, 2021). Any efficiency gains the Navy makes in getting more fight out of each gallon of fuel will be fighting against the need to cover a greater area moving forward.

To increase global presence and power projection, the Navy is also planning to build more ships and increase the size of the fleet (Chief of Naval Operations, 2022). While one might expect the Navy to decommission some older less efficient ships, the renewed era of great power competition has made this unlikely at least in the near term. There are currently contracts in the works to build more Destroyers, design a new class of Frigate to be built later, and retrofit existing platforms (Shelbourne, 2022). While some of the new ships being built incorporate electric propulsion and other efficiency improvements, they are also being designed with larger electric generation and distribution capacity to incorporate higher energy weapon and electronic warfare systems. Older ships are also to be retrofitted with these new energy-intensive systems, so it is reasonable to expect that the Navy's energy demand will continue to increase for the foreseeable future.

The carbon emissions from these distributed operations and new platforms could potentially be lessened by sourcing sustainable bio or synthetic fuels that are produced in a carbon-neutral or negative way, but it is unclear how much if any of this type of fuel will be available in theater. Even if sufficient quantities of alternative fuels were readily available, there are still limits to the proportional blend of alternative and traditional fuels the Navy will allow to run in its engines. It is possible that the Navy will be able to source greater quantities of alternative fuels by 2050 and could potentially accept a higher proportional blend of a less carbon-intensive fuel, but this supply chain would rely heavily on U.S. partners overseas being able to produce vast amounts of these alternative fuels. Being able to produce and process sufficient quantities of synthetic or biofuels would require huge investments in renewable or nuclear energy in many countries around the globe, so it is uncertain if the Navy can count on adoption of carbon-neutral or less carbon-intensive fuels as a significant portion of reduce GHG output.

2. FUSED Modeling

The Fuel Usage Study Extended Demonstration (FUSED) model was used to model how these upcoming developments could be expected to impact global Navy energy use and, by extension, GHG emissions in the fleet. FUSED is an Excel/VBA model where a set number of battlegroups are tasked with carrying out a user-defined mission under variable operational parameters, and these parameters can be adjusted to model the impact that different technologies or practices would have on fleet fuel demand. FUSED was used to model battlegroups conducting transits, training, and deterrence operations across a distributed area under different operational and technology conditions that are expected to occur between now and 2050.

FUSED estimates fleet fuel consumption by using known engineering data for fuel consumption under certain engine loading and extrapolating this data on an hour-by-hour basis determined by each ship's tasking. For each ship, there is a known reference table of hourly fuel consumption for the propulsion plant for a given movement speed and engine configuration, and published data regarding the relationship between electrical generator fuel consumption and electric load. By modeling what each ship is doing in a given hour, the FUSED model is able to reference these sets of information to create an accurate projection of how much fuel the ship would be using over the course of an operation. If sufficient data is available for aviation fuel consumption FUSED can also model how much aviation fuel the ships have available and use both the aviation fuel and marine fuel numbers to estimate replenishment requirements and schedule combat logistics fleet ships to replenish the combatants.

To validate the scenario and parameters used in the model, the current state of fleet operations was modeled with parameters that reflect the current state of operational practices, operations tempo, and technology deployed. The number and composition of battlegroups used in the FUSED scenario was reflective of the U.S. Naval Institute Fleet Tracker update for August 22, 2022. At the time the model was run, there were currently three carrier strike groups (CSGs), three amphibious readiness groups (ARGs), two destroyer squadrons, and one cruiser squadron deployed throughout the world. These battlegroups were modeled to conduct transits and operations proportional to a full year of naval activity, and the resulting fuel consumption estimates were compared against FY2021 reported fuel consumption values to gauge the accuracy of the model.

Department of the Navy FY21 Fuel Use* (Barrels)		Gallons
Navy Ships	8,485,073	356,373,048
MSC Ships	3,778,848	158,711,602
Navy Aircraft	9,734,935	408,867,281
USMC Aircraft	3,168,576	133,080,192
USMC Ground	307,998	12,935,927
	25,475,430	1,069,968,050
*All data except USMC Ground based on VAMOSC. USMC Ground is report fuel purchased.		

Table 1: Reported Navy and Marine FY21 Fuel Use (VAMOSC).

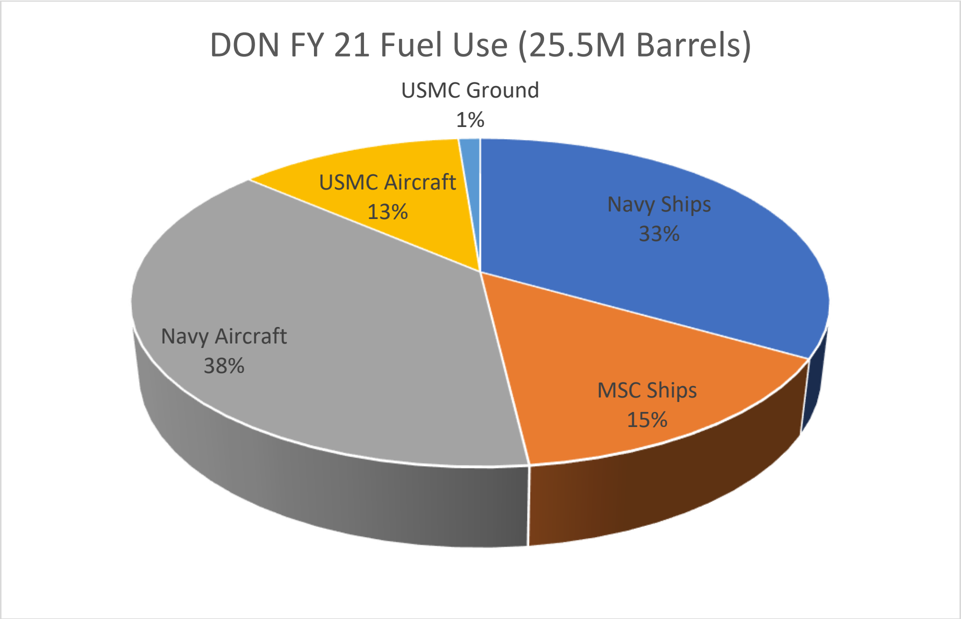


Figure 9: Navy and Marine FY21 Fuel Use Proportions

FUSED Model Results	Fuel Use in Gallons
Navy Ship Fuel Consumption	379,260,924
Navy Aircraft Fuel Consumption	298,048,476

Table 2: FUSED Model Results for FY22 Operations

In the FUSED FY22 model, the surface fleet consumed 6.4% more fuel and the aircraft 27.1% less fuel than was reported for FY21, but these values fell well within expected ranges for validating the accuracy of the model. It was expected that the surface fleet fuel consumption would be higher than in FY21 because of the recent uptick in deterrence operations following the conflict in Ukraine. Modeled aircraft fuel consumption was significantly less than reported because FUSED was only designed to account for flights launched off carriers and large deck amphibs and cannot account for other flights. The research team also consulted with N94 to confirm that the FUSED results were within an expected range and the assumptions made in the model were reasonable. While the N94 representative was unable to comment on the aviation fuel numbers, he did confirm that the surface fleet fuel consumption results were representative of actual reported values.

3. FUSED Projections

After validating that the results from FUSED painted an accurate picture of current and near-term fuel consumption, various modifications were made to the model to predict how upcoming technology, tasking, and force structure changes would impact energy demand, efficiency, and by extension, emissions. These changes were designed to reflect the rollout of new energy-intensive systems, the deployment of a larger fleet, and changes in operating both new and existing platforms. Each change made to the model was designed to reflect the Navy’s attitude that energy is a key operational enabler that must be used efficiently, but that efficiency can’t come at the cost of capability. All scenarios modeled assumed normal peacetime operations including a mix of regular deterrence and training operations.

The FUSED model projected that surface fleet fuel use would increase while aviation fuel would increase through 2030 due to further deployment of the F35 Lightning aircraft. It is expected that by 2030, the surface fleet will transition to a single fuel operating model where the ships and aircraft use the same type of fuel. This will simplify logistics and may reduce fuel consumption for the combat logistics fleet, but it will increase fuel consumption for the surface fleet because running JP5 through the ships’ engines requires added lubricants, reducing the efficiency by as much as 3%. The Navy is also expected to complete construction of and deploy several frigates by 2030, which will further increase energy use. Counter to this, the Navy is in the process of rolling out new energy awareness and planning software such as the GENISYS toolset that has the capacity to help ship operators run their ships more efficiently (Naval Sea Systems Command, 2021). One example of this would be the incorporation of Mixed Mode Fuel Minimization transit planning that has been demonstrated in other tools but not yet formally adopted. There is the potential to reduce aviation fuel consumption by incorporating more simulation-based training, although this technology may not make it onto the ships by 2030.

To model these new developments expected to take place by 2030, the FUSED model was updated to reduce ship electricity generation and propulsion efficiency by 3% to account for the switch to JP5, two frigates were added to the scenario, and transits were set to use the Mixed Mode Fuel Minimization transit planning method. Because there is no data available on the efficiency of the frigates, they were modeled to use the same propulsion and electrical generation efficiency of the recently decommissioned FFGs. The new frigates would probably have greater efficiency but higher electrical energy demand, so it is expected that these differences will more or less offset each other.

FUSED Model Results	Fuel Use in Gallons
Navy Ship Fuel Consumption 2022	379,260,924
Navy Ship Fuel Consumption 2030	396,189,852

Table 3: FUSED Surface Fleet Fuel Consumption Projection, 2030

Although it was expected that the fuel used by aircraft onboard the carriers would increase due to increased deployment of the F35 Lightning, the research team was unable to find reliable data to project how much this increase would be. It is also possible that aviation fuel use would decrease slightly with the rollout of new simulation training reducing the need for pilots to fly as many training missions. The range of aviation fuel projects is much less certain, but the possibilities are broken down by surface platform in the following table.

	-10%	-5%	FUSED Baseline	+5%	+10%
CSGs	235,360,485	248,436,068	261,511,650	274,587,233	287,662,815
ARGs	29,361,490	30,992,684	32,623,878	34,255,072	35,886,266
Other	4,485,783	4,734,993	4,984,203	5,233,413	5,482,623
Total	269,207,758	284,163,744	299,119,731	314,075,718	329,031,704

Table 4: Aviation Fuel Projections

Surface ship fuel consumption in the year 2040 may decrease from 2030 estimates, yet still be higher than the 2022 baseline as estimated by the FUSED model. It is expected that by 2040 there will be more frigates in operation, with a projected group of four deployed frigates used in the model. The surface fleet is expected to use the same operational efficiency improvements such as the Transit Fuel Planner or OTTER that were assumed in the 2030 projections. While total technology efficiency had decreased in the 2030 model due to the adoption of a single fuel operating concept, it is expected that the technology on ships will be more efficient in total by 2040 due to the rollout of things such as battery energy storage and hybrid electric drive on ships. The total efficiency change used in the model was a 5% increase from the 2022 baseline. While it is expected that the new technology deployed on ships will be more efficient, it is also expected that the electrical demand on ships will be greater due to things like new radar and weapon systems. The net result in the model was that each ship was set to operate with a 500kw greater electric load.

FUSED Model Results	Fuel Use in Gallons
Navy Ship Fuel Consumption 2022	379,260,924
Navy Ship Fuel Consumption 2030	396,189,852
Navy Ship Fuel Consumption 2040	388,323,732

Table 5: FUSED Surface Fleet Fuel Consumption Projection, 2040

By 2050, it is expected that fleet will be much more efficient than the 2022 baseline while still servicing the greater electrical demand seen in 2040. This assumption is based on the projected retiring of older less efficient ships, changes in operational practices, and the continued rollout of ships with greater battery energy storage, electrification, and hybrid electric drive technology. In the FUSED model, this was modeled as an overall 15% increase in efficiency vs the 2022 baseline. The net result is that by 2050, it is expected to see a minor decrease in total fuel used by the surface fleet compared to present day.

FUSED Model Results	Fuel Use in Gallons
Navy Ship Fuel Consumption 2022	379,260,924
Navy Ship Fuel Consumption 2030	396,189,852
Navy Ship Fuel Consumption 2040	388,323,732
Navy Ship Fuel Consumption 2050	354,556,452

Table 6: FUSED Surface Fleet Fuel Consumption Projection, 2050

4. Modeling Conclusions

The FUSED model projects that fuel use will increase over time as the fleet and mission grows, before tapering back down to current levels as technological improvements offset growth in energy demand. In regard to GHG emissions, this means that emissions will increase between now and 2050 before returning back down to baseline levels as well. It is possible that net emissions could decrease with the sourcing of alternative fuels, but it remains to be seen whether the Navy can source enough carbon-neutral alternative fuel for this to make a major impact. The model was not able to give a good projection on aviation fuel use given the lack of available data. Aviation fuel use constitutes a huge portion of Navy emissions, so this will need to be a topic for further study.

E. NUCLEAR

While the demand for fossil fuels in military operations remains high, it is important to integrate alternative sources of energy into the DON’s portfolio, notably renewables. However, some of these sources of energy can be intermittent and might rely on variable weather or seasons. While batteries and other storage capabilities have the potential to offset this intermittence, the increased deployment of nuclear technology offers another pathway towards Net zero and resilience; energy through nuclear fission does not create or contribute any GHG emissions.

The DON has taken advantage of the use of nuclear power for many decades. After World War II, U.S. Navy Captain Hyman Rickover solidified the transition of military usage of nuclear power for propulsion in 1954 when the *USS Nautilus* became the first American nuclear-powered submarine (National Nuclear Security Administration, 2008). Application to surface ships began in 1961 with the construction and commission of the first nuclear powered aircraft carrier, the USS Enterprise (CVN-65). Previously, the U.S. had several nuclear-powered cruisers that were built and deployed but were short lived. This included the Arkansas, Bainbridge, California, Long Beach, Mississippi, South Carolina, Texas, Truxtun, and Virginia. The now decommissioned nuclear cruisers required a bigger crew and continued to be more expensive to man and build, and ultimately refuel. The nuclear cruisers were replaced with the Ticonderoga class of conventionally powered and gas-turbine propelled cruisers (White, 2020).

Nuclear power remains an important energy asset to the Navy. To this day, all submarines and aircraft carriers utilize nuclear power propulsion (Naval History and Heritage Command, 2021). More than 700 ocean going vessels throughout the world, including carriers, submarines, and icebreakers, have utilized traditional nuclear reactor power for their propulsion and has been primarily led by the U.S. Naval sector (Hirdaris et al., 2014).

1. Cutting Edge Technology

Nuclear reactors emit zero GHG while being operated. Similar studies in the private sector that have added nuclear power as a pathway to net zero emissions in ocean shipping cite a drastic reduction in emissions, often leading to near 100% results (Eide et al., 2013). Recent research that offers a balance to the intermittent sources of renewable energy has introduced small-scale nuclear reactors, also known as Small Module Reactors (SMRs). This cutting-edge technology offers multiple benefits that have the potential to be operationally and logistically more feasible than other fueling options. Compared to diesel generation, SMRs are estimated to provide low-carbon power at a more affordable price while being as efficient as a renewable microgrid. Longer refueling cycles offer applications in off-grid and remote situations. While SMRs are a modern concept and fairly new, the research behind them leans heavily on the previous research and experience from larger nuclear reactor application (Michaelson & Jiang, 2021).

Another benefit of SMRs is the potential ability to utilize the technology on a ship or on land. Although retrofitting existing ships with nuclear reactors is unlikely and unfeasible, the use of SMRs for ships is still applicable. SMRs could provide pier-side shore power availability via microgrid configuration. This set up could be a potential replacement for cold-ironing practices. While in port, the ships still need power to run the various ancillary systems. Usually, a ship will run the auxiliary power systems as well as connecting to the associated installations power grid. It is estimated that approximately 55 percent of the total emissions in ports across the globe are due to ships (Budiyanto et al., 2021). Developing and installing SMRs for this purpose would reduce the emissions released while in port, and for the installations overall. Other applications of small scale nuclear reactors include nuclear microreactors that can be transported via truck, giving forward deployed expeditionary troops a potentially safer option than frequently transported diesel fuel (Office of Nuclear Energy, 2021).

While only two nuclear powered aircraft carriers are identified in the current ship building plan as well as a handful of nuclear submarines, long term increases in nuclear powered ships in the fleet should be considered. Melting sea ice in the Arctic indicates a current and future increased need for naval presence in the region. While the U.S. Navy currently does not operate any Ice Breakers, the U.S. Coast Guard currently operates two, with six more being developed and built (Lopez, 2022). Should the U.S. Navy launch and operate their own Ice Breaker, a nuclear-powered vessel would offer resilience against the harsh and isolated polar environment. Russia continues to be the only country currently operating and planning nuclear powered ice breakers (United States Coast Guard [USCG], 2017).

2. Percent Reduction and Other benefits

One of the greatest benefits of nuclear power is the zero emissions when operating a nuclear reactor. A study examining the potential for CO_2 abatement in maritime shipping analyzed potential pathways that included the use of nuclear propulsion. The main observations include that the maximum potential for emissions reduction spans from 20% to 77% when not including nuclear power as an alternative power source. When including nuclear power as alternative power source, maximum reduction potential reaches 100% when in operation (Eide et al., 2013). Nuclear power means longer periods without refueling. Ships utilizing "conventional fuel" such as fossil fuels depend on frequent replenishment, especially when operating at sea. Ships that operate in environments such as the Arctic have greater difficulty when refueling conventional fuel. Nuclear refueling takes place in more reasonable environments and time periods, making refueling while underway unnecessary (Hoque et al., 2018). In addition to less frequent needs of refueling, nuclear power could be used as a primary energy source to produce other alternative fuels such as hydrogen. The use of nuclear electricity to create low carbon fuels for other platforms, including UxS, is another potential pathway that should be explored further (Willauer et al., 2015).

3. Challenges

Although nuclear provides a near zero emissions fuel option, this pathway is not the most cost efficient option and should be considered a high trade-off investment between cost and emissions reduction (Eide et al., 2013). In addition to the high cost of infrastructure, a highly trained crew is necessary to run and operate the reactors on ships. Space for the reactors to be safely contained is also an issue. The space needed for the reactors means that existing platforms are not likely able to be converted to nuclear. New and retrofitted existing platforms would both need greater space for reactor infrastructure, leading to less space for other systems. The larger ship would also need to consider larger ports and areas that the ship is able to pull into.

Increased nuclear investment should be considered a long term goal, with other renewable energy sources prioritized in the near term (Department of Energy, 2021). Other challenges of utilizing nuclear power include security concerns and legal issues. Security issues include weapons proliferation and uranium refinement as potential impediments in the rapid and safe deployment of nuclear propulsion. While refuels of nuclear power material occur extremely less frequently than that of conventional fossil fuel, radioactive waste disposal is an important consideration in the lifecycle of this type of fuel (Lengefeld & Smith, 2013). Legal issues that continue to hinder the near-term development and investment of nuclear-powered ships include permissions by the port state, nuclear waste cycling, and congressional and governance oversight in the approval process of building new platforms. These types of considerations are likely out of the DOD and DON control but are important and should be included in the analysis of feasibility.

F. RENEWABLE ENERGY SOURCES

Renewable energy sources have grown significantly in recent years from the effectiveness of technology to the number of renewable energy sources and the use of it. The International Energy Agency finds that “Policy makers need to put clean energy at the [center] of recovery efforts to secure a structural downward trend in carbon emissions” (International Energy Agency [IEA], 2020). Like any energy source, renewables are subject to external influences; the agency’s findings for 2022 and 2023 note the renewable capacity increases, despite supply chain challenges and increasing costs for raw materials (IEA, 2022). Figure 10 shows that record growth is expected to continue with solar leading the way but with growth in wind, hydropower and bioenergy.

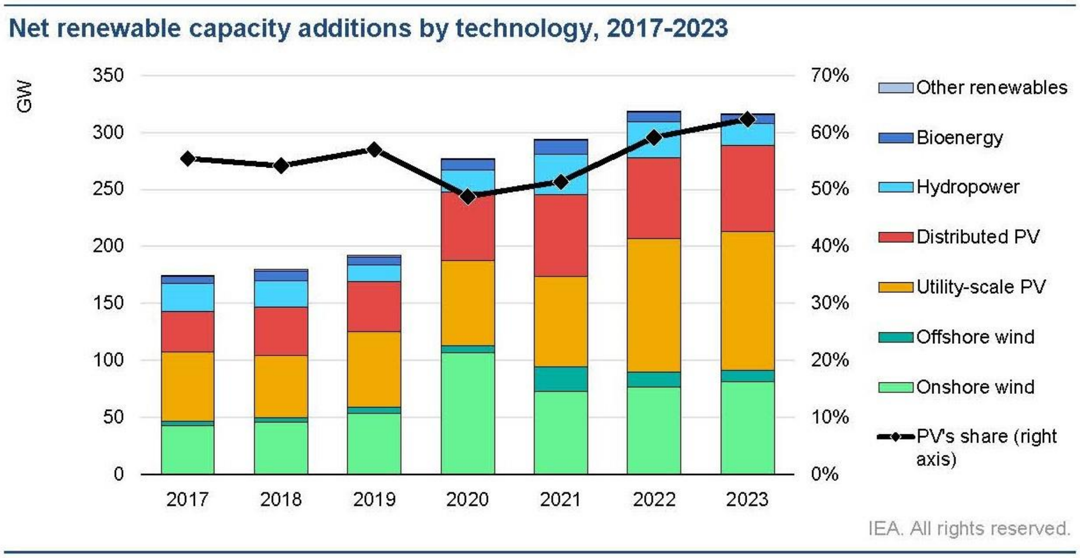


Figure 10. Growth in Renewable Energy (IEA, 2022).

While many renewable sources are of most value to installations, there are also renewables that can and do contribute to operations. This chapter will focus on the latter, with an emphasis on how renewables can help to decarbonize or at least lower the Navy’s operational emissions with an eye toward the future.

1. Sources: Solar, Wind and Hydropower

Solar photovoltaics (PV) convert sunlight into electrical energy. Individual solar cells are connected in series and parallel combinations to form modules and arrays that deliver power. A major advantage of PV is its modularity; it enables the fabrication of systems ranging from a few watts to megawatts (Ginley and Cahen, 2011). Relevant to the U.S. Navy Fleet, PV systems are already used in the marine environment for remote electrical energy applications such as uncrewed surface vessels or buoys. There is growing interest in using the surface area of lakes, rivers, reservoirs, and oceans to deploy floating solar PV systems. Solar PV systems are almost always used in conjunction with energy storage such as rechargeable batteries.

There are challenges to the use of PV on vessels such as limited deck space, extreme weather, and impact hazards that might shatter the PV panels (D. Hume communication, August 1, 2022). However, solar PV devices can be mounted directly onto the deck or integrated into the structure of some vessels, helping offset energy consumption. For example, in the commercial setting, solar PV can be integrated into the tops or sides of shipping containers, particularly refrigerated containers that require energy inputs to power the refrigeration system that keeps the containers' perishable contents cool.

The Navy is no stranger to wind energy; Navies around the globe were reliant on wind energy for centuries. The Navy officially transitioned from sails to steam in the 1890s. Wind energy used in operations can come from a variety of sources. For example, kites and rotor sails convert the kinetic energy of wind into forward thrust, which is applied to the vessel, thereby reducing, or completely offsetting the energy, and thus fuel, required to propel the ship. In the commercial shipping setting, towing kites are deployed off the bow of a ship and are flown high above the deck to harness the power of the higher-altitude winds. They are typically parafoil-shaped and are 1,000 square meters or more in size. Kites have several advantages over more conventional forms of wind propulsion, including the fact that they can be actively controlled to increase apparent wind speed and increase pulling force, they fly at higher altitudes with higher wind speeds, and involve no masts taking up deck space. (Naaijen and Koster 2007) Streamlined deployment and stowage of kite systems is critical to preventing interference with ship operations.

Rotor sails are spinning vertical columns that provide supplemental propulsion. They are typically 18 to 30 meters tall, 1 to 3 meters in diameter, and are installed on the deck of a ship. As wind comes across the deck of the ship, the spinning rotors generate forward thrust by using the Magnus effect, a phenomenon wherein a spinning body generates a forward thrust when exposed to a perpendicular fluid flow. The resultant forward thrust thus replaces or supplements the propulsive power of the main engines. Rotor sails can be quite large relative to ship size and care must be taken to not affect vessel stability. Rotor sails work best when the wind direction is roughly perpendicular to the direction of vessel travel. While these systems may not be ideal for typical military use, the diverse portfolio of systems in the future may make these applications more appealing.

Wave energy converters are devices that convert the kinetic and potential energy of ocean waves into useful mechanical or electrical energy. Onboard vessels, wave energy can be used for energy harvesting, propulsion, or stabilization (Bøckmann and Steen 2016). An example of wave-powered propulsion can be found on several smaller surface craft, such as the unmanned surface vehicles Wave Glider (built by Liquid Robotics) or the Autonaut, which both use oscillating hydrofoils to generate a forward propulsive thrust. This method of propulsion using wavefoils can be scaled for larger applications such as commercial vessels. Wave energy can also be used to induce a gyroscopic motion that can be used for ship stability (gyrostabilizers) (Perez and Steinmann 2009) or for producing power (Townsend and Shenoi 2012; Bracco, Giorcelli, and Mattiazzo 2011) by harvesting energy from the wave-induced rotational motions of a marine vessel. In these systems an input torque (rolling of a ship) causes a variation in the spin axis of a flywheel acting at an angle of 90 degrees to the input spin, which produces a torque that can be used to drive a generator.

Current energy technologies use kinetic energy from flowing water to harvest energy. These systems most often take the shape of turbines that use lift or drag from the flowing fluid over the turbine blades to create rotation, which then drives a shaft connected to an electrical generator and produces electricity. There are two ways that a current turbine may be fitted to a vessel. One method is to use a modified vessel propeller, the other is to have a stand-alone turbine attached to the hull. These systems are common in the sailing and yachting industry and are often referred to as hydro-chargers or hydro-generators. With a modified propeller, the propeller blades have a variable pitch that can be angled in different directions relative to the water current direction so that it can be used for propulsion or energy harvesting. In the second method a small current turbine is deployed in the water as needed to recharge vessel batteries and is then stowed when not needed. The power output of these turbines varies with size and speed, but is typically in the range of 50–500 watts, though larger systems on the order of kilowatts are possible (Yutuc 2013).

2. Challenges of Renewable Sources

The key challenges of renewable sources of energy for Navy operations include relying heavily on private sector data, the addition of renewable energy technology interfering with shipboard operations and/or radar and noise signature, and the need for a trained crew in new technologies. In addition, the intermittent nature of renewable energy generation highlights the need for energy storage to maintain a stable, on demand power source.

Research findings are heavily reliant on private sector data. There is not a lot of literature indicating the feasibility of renewable sources on military vessels, especially at a large scale. There is the potential for the addition of new renewable energy sources to interfere with shipboard operations. Using renewable energy technologies such as solar PV, wave energy converters, as well as rotors and kites aboard vessels can create challenges for ship operation. For example, solar PV and supplemental wind propulsion technologies require deck space which is often at a premium, particularly aboard military vessels.

There are questions about the impact of renewable sources on the radar signature or the noise signature of some vessels or platforms. Rotor sails and kites can add large vertical profiles to a ship, which make them more easily detected on radar. While this is not an issue in the commercial maritime sector (indeed, it may sometimes even be desirable), it may adversely impact stealth characteristics for combatant vessels. Such systems would need to be designed to reduce their radar cross-sections. Conversely, wavefoils and hydroelectric generators may impact the noise signature of a vessel, though this needs more research.

Crew would need to be trained to understand and repair these systems. It can take time to build these core competencies in equipment operation and maintenance. Finally, the energy efficiency impact of these technologies on commercial vessel operations is still an area of active research. While some technologies have shown clear benefits for some vessel types and routes, this performance data is often hard to come by and there are fewer examples in literature of these technologies being applied to Navy assets. Pilot tests on private sector vessels and Coast Guard vessels may reduce challenges for Navy ships in the future.

3. Expected Reductions

There are few examples of solar PV being used on commercial vessels. In one study that investigated the feasibility of solar panels on a Roll-On/Roll-Off vessel as a source of auxiliary power, the researchers determined that the vessel had 2,593.5 m2 of available surface area for solar PV, which would produce 334,063 kWh/year of power. This would allow for an offset of 7.8 percent in energy production and avoid more than 47 tons per year of low sulfur fuel oil and 26 tons per year of diesel oil (Karatuğ and Durmuşoğlu 2020).

The energy impacts of supplemental wind propulsion will of course depend on vessel size, voyage length, and wind speed and direction. Generally, these technologies are believed to offer reductions in fuel consumption and emissions on the order of between 1 to 20 percent (Airseas, 2022) although some research on modeling kite performance suggests fuel savings potentials of up to 50 percent (Naaijen and Koster 2007). The actual impacts will depend on vessel route, wind speed, and direction among other factors.

A retractable WaveFoil system deployed on a passenger ferry is claimed to reduce fuel use by 5–15 percent (Business Norway, n.d.), which agrees with scaled modeling in which researchers found that wavefoils attached to a commercial tanker vessel could reduce ship resistance by 9–17 percent and also lead to reductions in heaving and pitching (Bøckmann and Steen 2016). In one modeling study of a hydroelectric generator integrated onto a large tanker vessel, the researchers determined fuel savings on the order of 3.5 percent were possible (Yutuc 2013).

With these estimates from private sector use, the report presents conservative emissions reduction estimates for renewable energy in operations. Renewables are not likely to have a huge impact on operational platforms, especially manned platforms, but the technology is much more relevant to installations and other shore-based operations. While beyond the scope of this report, when approached through a DOD-wide or whole-of-government approach, transitioning forward operating bases and installations to renewable energy can have an impact on the overall emissions portfolio and efforts to reach net zero by 2050.

G. CARBON SEQUESTRATION, CAPTURE AND OFFSETS

Carbon capture, sequestration and offsets are often included in pathways to net zero emissions as ways to remove carbon already emitted *and* as a way to offset future greenhouse gas emissions. Researchers have found that these processes and technologies may be part of the overall portfolio but are not substitutes for the reduction of energy demand and emissions over time. In fact, the literature is ripe with examples of the utility of these strategies being overestimated and overemphasized. Given the prevalence of these strategies in many public and private sector pathways analyses, they are included here; however, the team recommends caution when moving forward with too heavy of reliance on carbon capture, sequestration and/or carbon offsets as there are pitfalls and vulnerabilities embedded in them.

Much research is underway within the public and private sectors. Figure 11 shows the process of carbon capture, utilization, and storage as laid out by the American Bureau of Shipping (ABS).

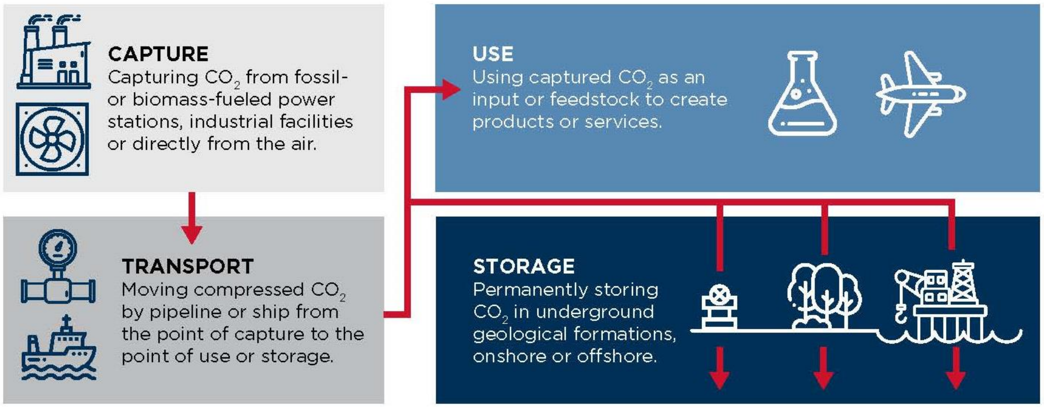
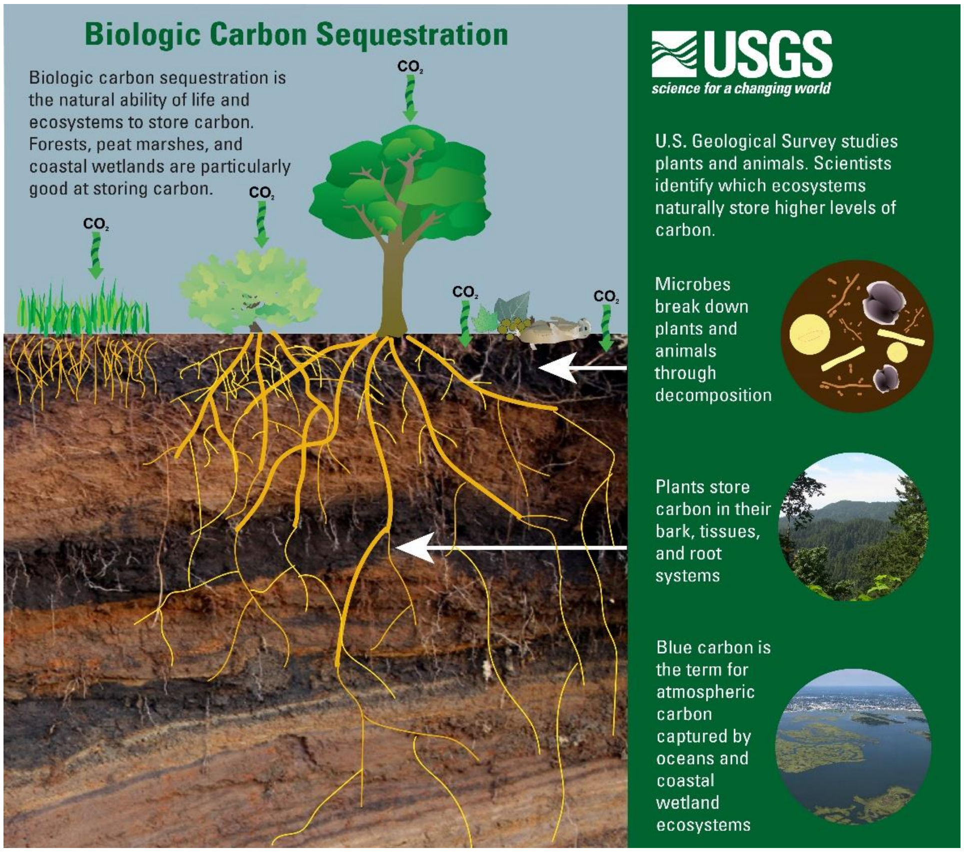


Figure 11. Processes by which CO2 can be Captured, Cleaned, Dehydrated, Liquefied, Transported and Stored or Utilized at a Final Location (American Bureau of Shipping, 2021).

ABS notes that the IPCC "presented four scenarios for limiting global temperature rise to 1.5°C in their Special Report issued in 2019. All the scenarios included carbon capture and three required the involvement of major use of carbon capture" (ABS, 2021). In 2021, the IEA hailed the advances made in carbon capture, utilization and storage technologies and its role in meeting net zero emissions, especially for high-emission sectors such as heavy industry like cement. However, even proponents acknowledge that there have been setbacks such as project cancellations and programs that "failed to deliver" (McCulloch, 2021).

1. Carbon Sequestration

The U.S. Geological Survey is researching both geologic and biologic carbon sequestration. Geologic carbon sequestration is the process of storing CO2 in underground geologic formations; biologic carbon sequestration is the storage of CO2 in vegetation, coils, wood, and aquatic environments (United States Geological Survey [USGS], 2022). The agency found in 2013 that the U.S. can store potentially 3,000 metric gigatons of CO2 (USGS, 2013). It has also assessed biologic carbon sequestration capability for several U.S. regions and the blue carbon potential across the U.S. Figure 12 shows the USGS description of biologic carbon sequestration.



Biologic carbon sequestration is the natural ability of life and ecosystems to store carbon. Forests, peat marshes, and coastal wetlands are particularly good at storing carbon.

U.S. Geological Survey studies plants and animals. Scientists identify which ecosystems naturally store higher levels of carbon.

Microbes break down plants and animals through decomposition

Plants store carbon in their bark, tissues, and root systems

Blue carbon is the term for atmospheric carbon captured by oceans and coastal wetland ecosystems

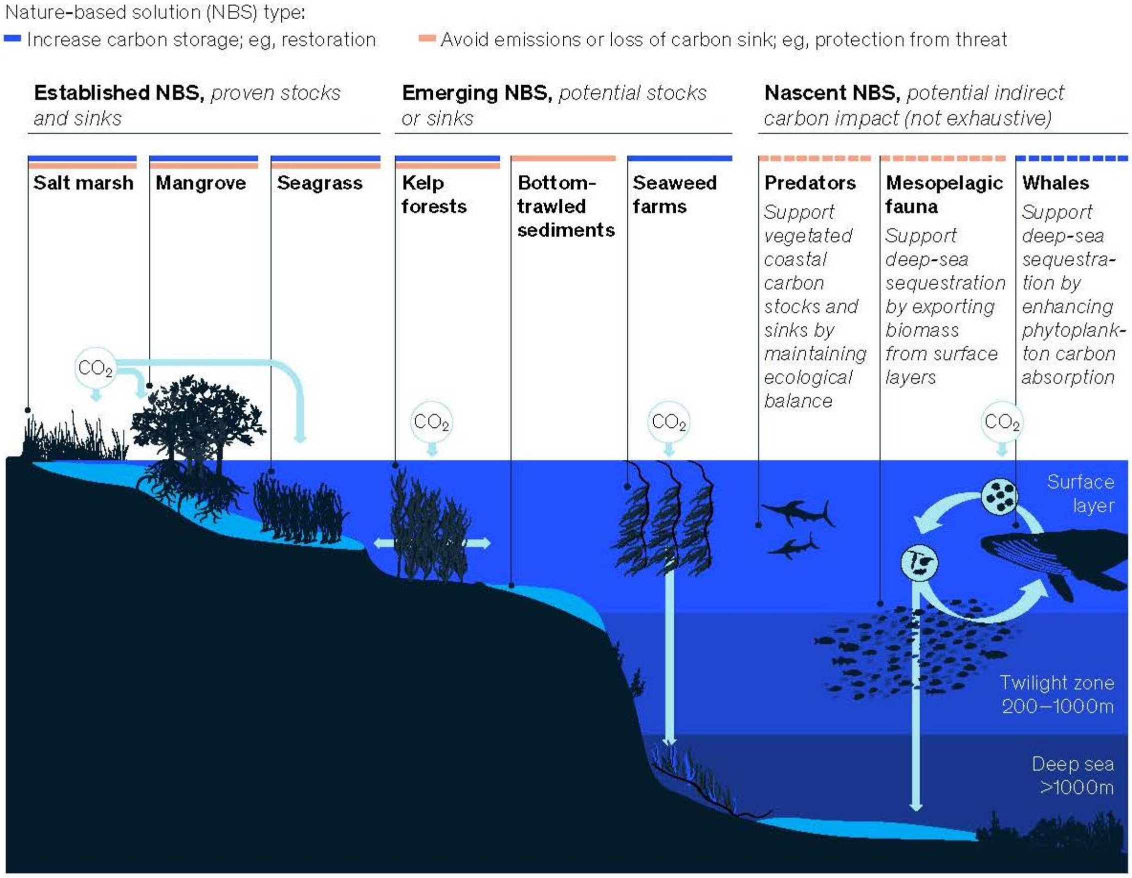
Figure 12. USGS Description of Biologic Carbon Sequestration (USGS, n.d.).

The DOD efforts related to carbon sequestration are directly tied to how much land it holds and the condition of those lands, including tree cover, soil quality, and type of coastal wetland habitat. By far, the U.S. Army holds the most acres of land within the DOD real property portfolio inside the U.S. with over 13 million acres; by comparison, the Navy and Marine Corps have just under 5 million acres and the Air Force holds over 8 million acres (Department of Defense Real Property Portfolio [DOD Portfolio], 2017). Given that the DON holds the least amount of land, the DON would benefit most from a DOD-wide land-based carbon sequestration strategy. It would allow for the consideration of over 20 million acres of land (as opposed to less than 5 million within the DON) and allow for a larger bank of which to access high- or higher-quality lands. However, the Army has acknowledged some inherent challenges with this land-based strategy. The agency found that while a “significant body of literature and products (including predictive models) exist for carbon accounting, due to the highly variable and unique nature of DOD lands and land uses, the applicability of these models for DOD lands is not known” (U.S. Army Corps of Engineers [Corps], 2017). It balances that finding with the conclusion that “Compared to engineering projects such as solar mirrors and pumping atmospheric carbon deep into the earth, soil carbon sequestration through changes in land management strategies is one of the few atmospheric carbon reduction efforts that could be implemented relatively quickly, over a large scale, and potentially at low cost” (Corps, 2017). Finally, installation-based sequestration strategies may be fairly claimed by installations in reaching their own emission reduction goals; i.e., these strategies would help installations reach net zero emissions but may not be available to the operational side of the emissions equation. For the operational Navy to take advantage of such reductions, a whole-of-government approach would be needed, as noted in Section IV.

2. Promising Strategy: Blue Carbon Sequestration

Blue carbon refers to atmospheric carbon captured by oceans and coastal wetlands which includes salt marshes, mangrove forests and seagrass meadows. These coastal ecosystems are among the most productive on the planet and show great promise for storing carbon. One study calls the ocean and coasts “Earth’s climate regulators” (Claes et al., 2022). Unfortunately, coastal wetlands are also some of the most vulnerable habitats across the globe; it is estimated that wetland habitats “have lost more than a third of their area over the past half-century” (Pew Charitable Trusts [Pew], 2021). In addition, while coastal wetlands store approximately 50% of all carbon buried in ocean sediments, when these habitats degrade, they release the vast stores in the form of CO2, methane, and nitrous oxide which are all greenhouse gases (Pew, 2021). Therefore, the largest benefits will be seen from not only creating or restoring healthy coastal wetland ecosystems but also protecting those in existence.

Figure 13 shows three categories of nature-based, blue-carbon solutions.



Source: McKinsey analysis

Figure 13. Three Categories of Nature-Based, Blue-Carbon Solutions (Claes, J., 2022).

Blue carbon sequestration is of significant benefit to the DON given it is a coastal landowner. Based on discussions with installations staff working on net zero emissions, the sequestration options of submerged lands at installations are not yet being considered; thus, researchers include them here given their significant potential. While part of the submerged lands on these coastal installations is developed (such as covered with cement or otherwise altered and therefore, less productive) to meet training, docking and other mission needs, there are also submerged lands that serve as security buffer areas around many coastal installations that host healthy coastal ecosystems.

Unlike the land-based acreage of the DOD real property portfolio, the number of submerged lands owned by the Navy are not as readily available; rather, it appears they are tracked on an installation-by-installation basis. However, this information is available for some installations: the Guam Submerged Lands Management Plan details the Navy-owned submerged lands, their uses, the habitats including special areas, and management issues and measures. Figure 14 shows the submerged lands held by the Navy in Guam and how they overlap with protected areas. Overlapping with protected or managed areas is a plus; it means monitoring already occurs and, likely, the habitat is more productive and therefore would sequester more carbon.

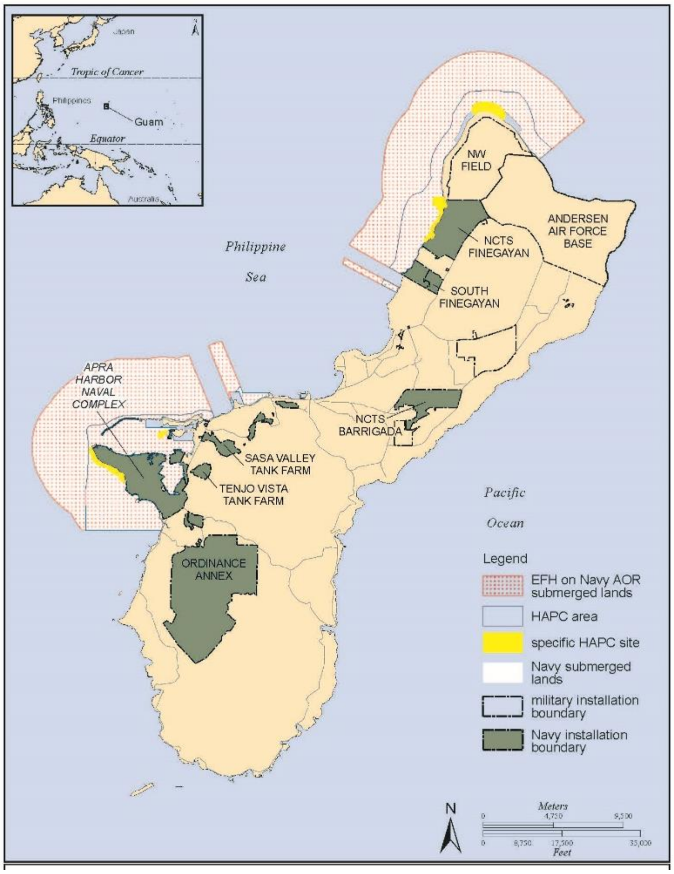


Figure 14. Navy Submerged Lands in Guam (PCR Environmental, 2007).

The Guam plan states that “Wetlands within Apra Harbor area were delineated and mapped in 1998; more than 138.9 [hectares] in 48 separate wetlands were found to occur within the Navy's boundaries. These wetlands range in size from 0.01 to 35.9 [hectares] and include shallow freshwater and brackish water habitat" (PCR Environmental, 2007).

Accounting for the acreage of submerged lands is only one part of the equation; assessing the ecological health of the submerged lands, their uses and habitats is essential to determining how much carbon can be sequestered per acre. If that can be accurately assessed, the potential of sequestration on healthy submerged lands offers substantial hope. This report's estimates on sequestration potential of intact coastal habitats comes from the Pew report on blue carbon. It estimates the following sequestration potential from different types of submerged lands. Note that the measurements are pounds of carbon per year rather than CO2.

From 2021 Pew Report, Coastal "Blue Carbon"	
Salt Marshes	1940 pounds of carbon/acre/year
Seagrasses	1230 pounds of carbon/acre/year
Mangroves	2016 pounds of carbon/acre/year

Table 7. Blue Carbon Estimates (Pew, 2021).

3. Private Sector Carbon Offset Programs

Carbon sequestration, capture and storage, and carbon offset programs are sometimes used interchangeably. In this report, carbon offset programs refer to those that allow the purchase of carbon credits which are "certificates representing quantities of greenhouse gases that have been kept out of the air or removed from it" (Blaufelder et al., 2021). Many studies of military reduction in emissions find that pursuing carbon offsets is critical to compensating for the unlikely complete elimination of defense emissions. A 2021 McKinsey study noted that "a net zero defense force will therefore need to find ways to compensate for these remaining emissions, such as pursuing offsets in countries with high climate-change risk or by pushing for decarbonization beyond their own emissions" (Bowcott, et al., 2021).

Carbon offset programs issue credits to projects that purport to avoid greenhouse gas emissions or remove carbon dioxide from the atmosphere, usually in the form of biologic carbon sequestration methods as described above such as the creation or preservation of forests, wetlands, or other natural carbon sinks. Such offset programs are common in cap-and-trade programs as well as to satisfy pledges made under the Kyoto Protocol but there are problems in their design that have not yet been addressed. The programs assume that offsets reflect equivalent climate benefits achieved elsewhere. In other words, "These climate-equivalence claims depend on offsets providing real and additional climate benefits beyond what would have happened, counterfactually, without the offsets project." (Badgley, et al., 2021) But, the literature indicates that few meet this goal.

Some inherent challenges within carbon offset programs include difficulty in measuring the true impact of the offset. In 2017, the European Commission found that "85% of carbon offset projects under the UN's Clean Development Mechanism failed to reduce emissions" (Anyachebelu, 2021). Most carbon offset programs also fail to address the locality issues. First, communities that suffer the consequences of the emissions (such as air pollution) are not benefiting from the offsets which occur in other places. Second, offsets can be harmful to the communities where the project is located; there is documentation that it can displace indigenous people or vulnerable communities (Dartmouth, 2019). Finally, carbon offset programs can distort climate action; users of these programs tout their use as climate consciousness while failing to divulge possible negative impacts or spending equal or more money to lobby against climate policies (Anyachebelu, 2021). Instead, climate scientists note that the priority should be on reducing emissions and removing CO2 from the atmosphere instead of allowing more emissions while relying on carbon offsets. Given the challenges inherent in the programs, this report recommends great caution if relying upon offset programs in reaching net zero emissions.

4. Carbon Capture/Removal Technology

For the military, carbon capture may hold more promise. Carbon capture and storage (CCS) is the process of capturing and storing CO2 before it is released into the atmosphere; thus, the carbon emissions have already been emitted but are trapped before entering the atmosphere. CCS has gained momentum in recent years as a mechanism to reduce emissions from heavy industry with some success. The National Energy Technology Laboratory hosts a CCS Database with includes information on CCS projects across the globe that are active, proposed or terminated (National Energy Technology Laboratory, 2022). As of 2018, over 300 projects had been identified across more than 30 countries.

Most of these projects are private or government run but not used by the military yet. Deploying CCS generally involves three steps: capture, transportation, and storage. There are several technologies in use at these projects for capture including post-combustion carbon capture, pre-combustion carbon capture and oxy-fuel combustions systems. Once CO2 is captured, it is compressed and chilled into a fluid to be transported to a storage site. Finally, the CO2 may be injected into deep underground geological formations where it is stored long-term rather than released into the atmosphere (Gonzalez, et al., 2022).

The utility of CCS for the military is still in the research stage, although industry advocates cheered the involvement of the military. The FY20 National Defense Authorization Act called for the Pentagon and departments of Energy and Homeland Security to “research ways to make fuel out of carbon dioxide pulled directly from ocean water and the ambient air” (Magill, 2020). One of the most significant hurdles, in both the private and military sector, is cost which can vary widely. In addition, researchers recognize the impact of public perception as well: many see CCS as a way to prolong the use of fossil fuels and express concern about the safety of transportation and storage of CO2 (Gonzalez, et al., 2022).

Research is moving beyond simple capture and storage. The Air Force, for example, has worked with the private sector to demonstrate technology that could convert CO2 into operationally viable aviation fuel. There is also progress in the concept of carbon utilization; capturing carbon and storing it in potentially useful and commercially viable products. Figure 15 shows current and potential uses of CO2.

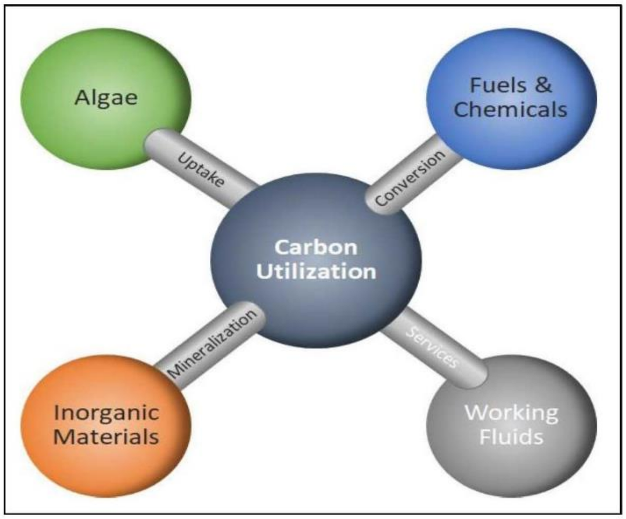


Figure 15. Illustration of Current and Potential Uses of CO2 (Department of Energy, n.d.).

Research of direct air capture and direct ocean capture is also showing promise. Direct air capture technologies remove CO2 from the atmosphere, even if that CO2 was released many years ago. Direct ocean capture takes CO2 from the ocean. These technologies are not without their challenges including being capital-intensive and energy-intensive. In addition, the low value of CO2 presents a hurdle to commercialization for both technologies (Jones, 2020).

5. Challenges

As noted above, numerous challenges exist within these strategies. Critics note that it is essentially kicking the can down the road; in other words, it is an easy approach to claiming success related to emissions reductions rather than tackling the tougher challenges of actually reducing reliance on fossil fuels, successfully transitioning to cleaner technologies, and reducing demand. In addition, uncertain emissions reporting and accounting mechanisms and claims of fraud must be analyzed carefully before these strategies are used to claim reduced emissions.

Nature-based solutions, such as blue carbon strategies, appear to provide the most benefits in terms of carbon sequestration and may be the most efficient for the Navy to embrace. Blue carbon strategies can provide additional benefits such as ecosystem health which, in turn, can support economic growth. As these areas recover, “fish and marine fauna populations will expand, supporting both fisheries and nature-based tourism, as well as bolstering coastal protection and filtering runoff” (Claes et al., 2022). A full accounting of the societal benefits from nature-based solutions would provide a clearer picture of the value of investments in these substrategies.

Given the pros and cons of this strategy, the research team includes carbon capture and sequestration in the pathways analysis but takes a conservative approach to claiming emission reductions from capture, sequestration or offset programs.

IV. PATHWAYS AND RECOMMENDATIONS

Based on the research and strategies analyzed for the Operational Navy, there are no easy answers for decarbonization. While there are some promising technologies in development, they need to work in the military context and provide significant reductions to reach the net zero milestones set out in the executive orders.

In order to show the pathway options, the team borrowed the model used for the Air Transport Action Group which shows four pathways to offer a look at different levels of investment or advancement over time (Air Transport Action Group, 2020). Data is part of an excel table (shown in Table 8 below) that can be adjusted to reflect the different needs for investment in particular strategies over time or the removal or addition of a strategy. It is important to note that the pathways are shown as *illustrative*; i.e., researchers estimated the percentage of savings each strategy would offer over time. To align with the pathway models, those estimates change over time in each strategy but are based on the team's research including the state of technology today and pathways for that technology to scale up in time to help reduce emissions. The pathways present the diversified portfolio of strategies based on the following 4 scenarios.

Pathway 1: Baseline – represents a continuation of current trends
Pathway 2: Advancing - represents some pushing of technology and operations
Pathway 3: Aggressive – represents more aggressive approaches to several strategies
Pathway 4: Aspirational – represents several breakthroughs to reach net zero emissions

The numbers used to reach the pathways are estimates of what is needed to reach net zero emissions by 2050. More detailed work is needed to go beyond estimates; numbers based on detailed platform-based analysis could show more feasible pathways to net zero by 2050.

Pathways 1 and 2 show that continuing current trends or merely advancing slightly does not do enough to reach net zero emissions by 2050. Pathway 2 does show slight improvement in all strategies but relies heavily on low carbon fuels and carbon sequestration/capture/offset strategies.

Pathways 3 and 4 require additional investment in all strategies to reach net zero by 2050. The investment differs between these two, but it is important to note that in Pathway 4, the DON is much less reliant on carbon sequestration/capture/offset programs. Low carbon fuels are essential in each strategy and Pathway shows the impact of emissions reductions from increased investment in each strategy but particularly in hydrogen and unmanned systems. The following figures show the data table and four pathway models.

Strategy	Estimated Reduction %			
	Base	#2	#3	#4
Energy Efficiency	5.0%	7.0%	8.0%	9.0%
Operational Efficiency	5.0%	7.0%	8.0%	8.0%
Force Structure	0.0%	0.0%	0.0%	0.0%
Low Carbon Fuels	20.0%	22.5%	25.0%	25.0%
Hydrogen	7.0%	7.0%	8.5%	15.0%
Unmanned Systems	4.0%	5.0%	8.0%	11.0%
Battery Storage	4.0%	7.5%	10.0%	10.0%
Renewables	5.0%	7.5%	10.0%	9.0%
CCS/CCUS	20.0%	22.5%	22.5%	13.0%
Remaining Emissions	3.31	1.54	-	-

Table 8: Table of Estimated Reductions by Strategy. These percentages are estimates that represent a proportion of the 2050 baseline platform-based emissions that are unmitigated and could be reduced via the strategies noted above.

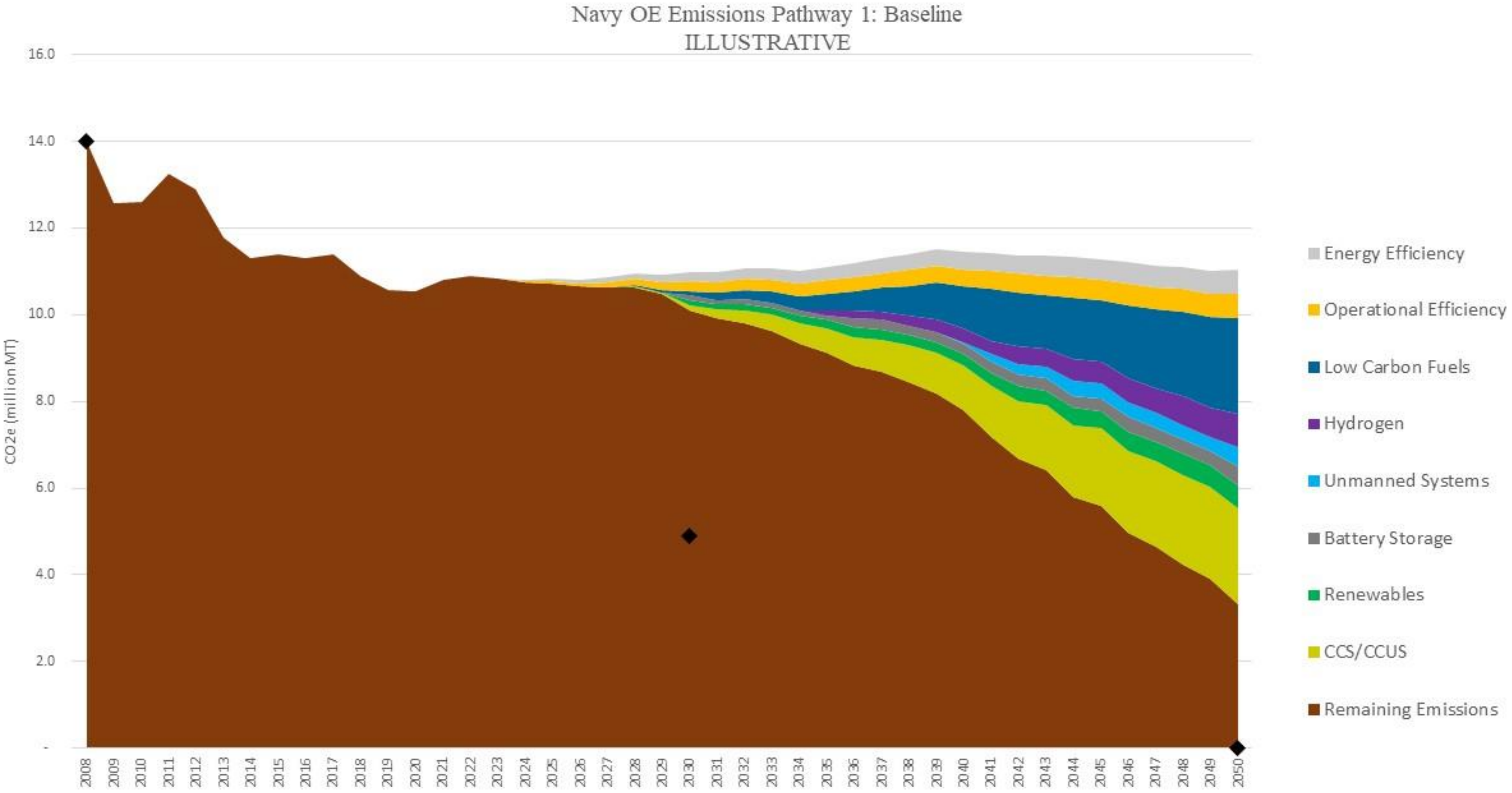


Figure 16. Pathway 1: Baseline

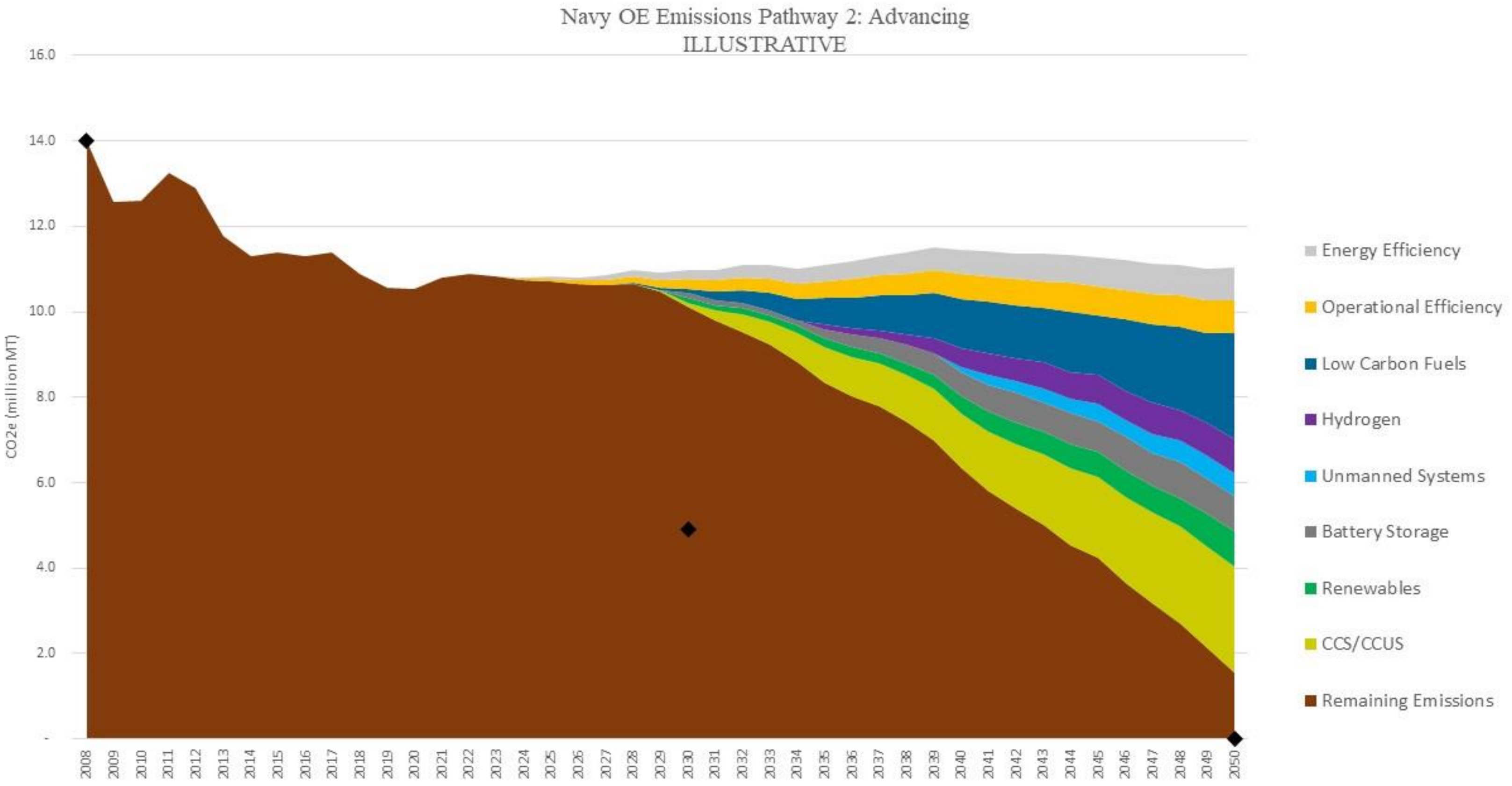


Figure 17. Pathway 2: Advancing

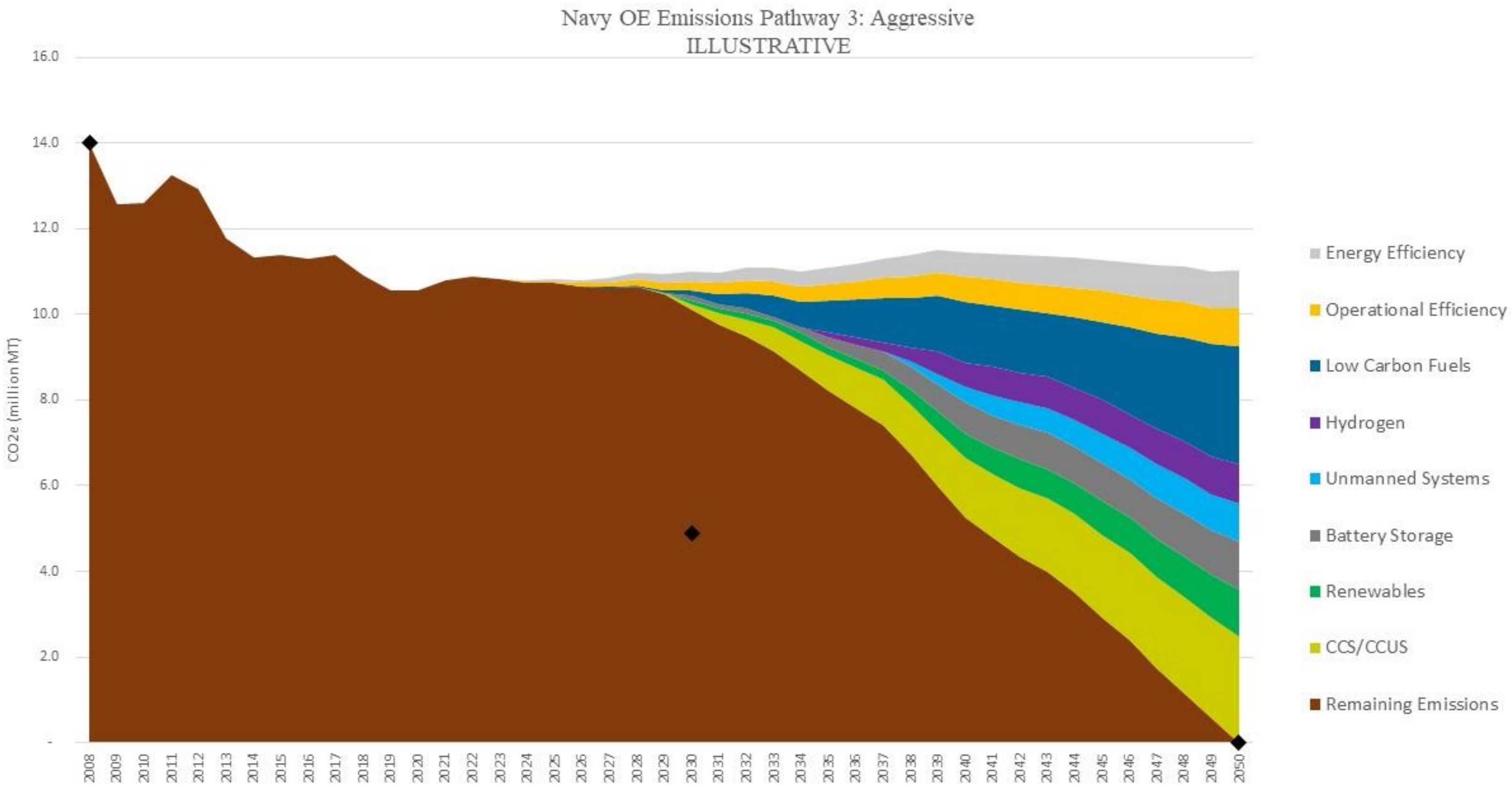


Figure 18. Pathway 3: Aggressive

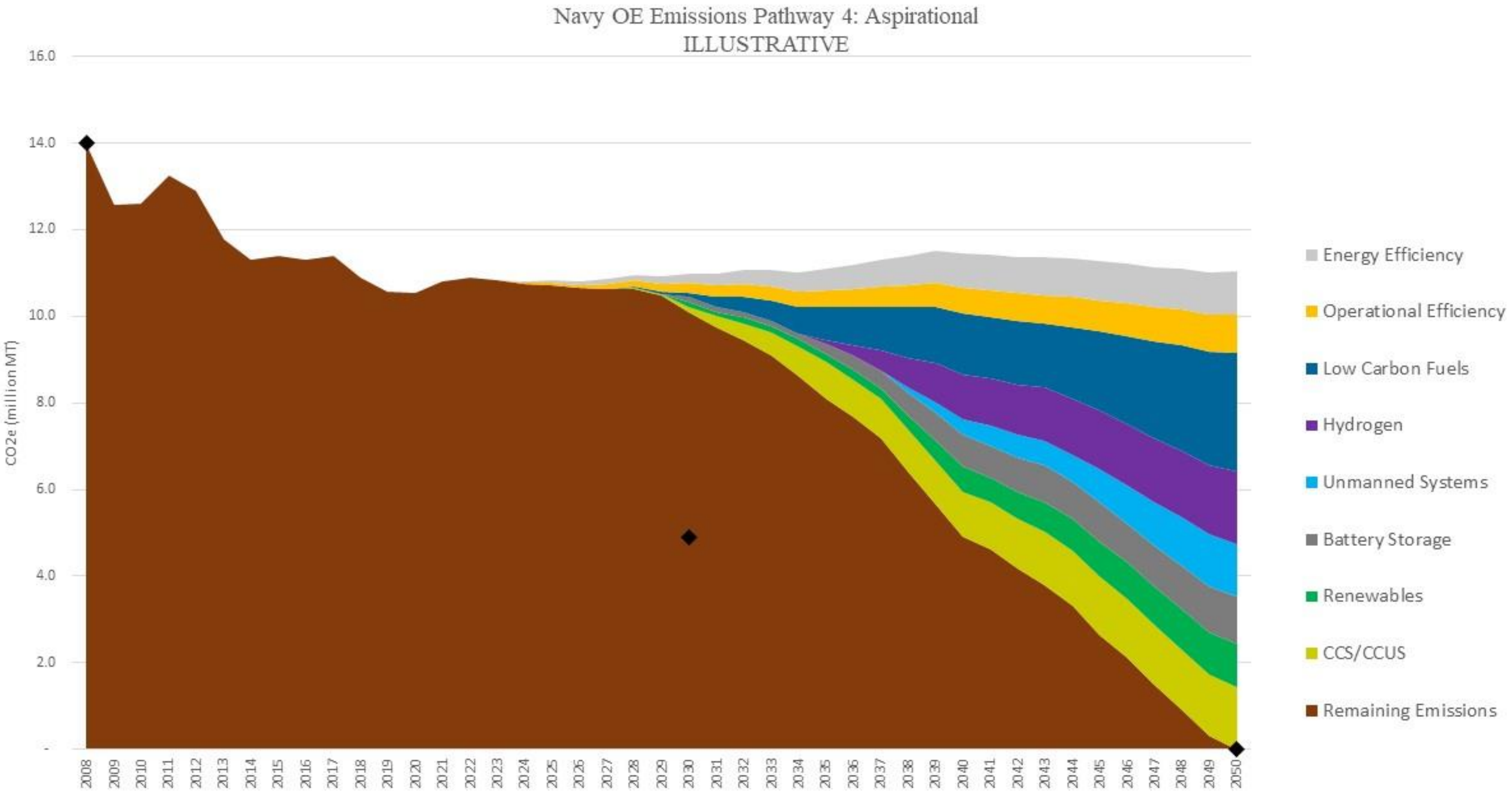


Figure 19. Pathway 4: Aspirational

Based on these pathways, the research team's core findings include the following.

A Whole-of-Government Approach: If technology does not advance as anticipated, it may not be realistically achievable for the operational Navy to reach net zero emissions because of its reliance on the hard-to-decarbonize platforms of ships and aircraft. The operational efficiency of those platforms can only get the Navy so far toward its goals. However, if the lens through which net zero is viewed is changed to a whole of Navy approach, reaching net zero seems more possible. Installations have some advantages in reaching net zero and relying on community and regional partners to adjust their strategies. If the view is drawn back even farther to a whole-of-DOD or whole-of-government approach, then the equation changes again: additional lands are included for potential carbon sequestration and other parts of the government may be able to adjust quicker to lower carbon emissions than the operational Navy.

Investing Now: While some strategies require additional research and development, for the DON – and for the DOD as a whole – addressing future investments in the acquisition process must happen now. The acquisition timeline for platforms is many years and those platforms are in use for decades. By investing now in platforms that are wholly dependent on fossil fuels without an eye to reducing emissions, the department sets itself up for failure. Military leaders recognize that improved investments will lessen the logistics challenges and perils inherent in delivering fuel across the globe.

Promising Strategies: Research indicates that alternative fuels, batteries and electrification, and new technology including hydrogen & unmanned systems are the most promising strategies for the DON to consider moving forward. These strategies prioritize mission readiness while addressing the need to reduce emissions and reduce reliance on fossil fuels. As shown in Pathways 3 and 4, when these strategies are significantly contributing to the emissions reductions, net zero emissions are met without heavy reliance on efficiencies or carbon sequestration.

Priorities for Research: To advance these promising strategies, the team recommends prioritizing research in the following areas:

- Deeper analytical dive into the various platforms and missions they perform in order to better target R&D investments and align with acquisition program requirements;
- Analysis to turn the illustrative pathways into achievable pathways;
- Creation of fuel/energy in-theatre such as hydrogen technologies and seawater to fuel;
- Demand reduction including operational efficiencies, technology changes and culture and behavior shifts;
- Airplane & shipboard decarbonization including developing roadmaps to operationalize decarbonization technology rapidly once it is proven effective such as carbon capture from ships;
- UxS studies to show the impact of transitioning certain platforms and missions to unmanned and what level of emission reductions can be achieved; and,

- Understanding how these efforts align with U.S. allies' efforts on emission reductions.

Cautions: The research team recommends less emphasis on strategies that "kick can down the road" such as carbon sequestration and carbon offset programs. These strategies show an actual or perceived lack of effort in demand reduction and operational decarbonization. Carbon sequestration and offsets have their own inherent vulnerabilities that would need to be addressed before relying on them for significant reductions.

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