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ANALYSIS OF PATHWAYS TO REACH NET ZERO NAVAL OPERATIONS BY 2050, PHASE II

by

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ABSTRACT

A previous analysis of pathways to reach net-zero naval operations quantified Department of the Navy (DON) operational systems emissions and identified potential pathways to meet the 2050 reduction targets prioritized in executive orders and DOD climate strategies. The analysis generalized illustrative pathways allocating reduction potential for alternative fuels, hydrogen, unmanned systems, batteries, operational efficiencies, advanced nuclear energy, renewable energy, and carbon capture and sequestration.

This follow-on, Phase II analysis considered the DON-unique challenges for integrating emissions reduction measures and cited reported climate science to assess the impact of four specific pathways: alternative force structure, advance nuclear energy, platform carbon capture and storage, and sustainable fuels. The analysis assumed the Department will not accept any measure that could reduce operational capabilities on ships or aircraft and deduced that by 2050 conventional gas turbine and diesel engines will still demand up to 28 million barrels of F-76 and JP-5 fuels.

The study concludes that alternative force structure concepts, like unmanned systems, could realize some emissions reductions by 2050; however, because future force design is responding to strategic competition against pacing adversaries, the future force will likely demand more operational energy offsetting those reductions. Advances in nuclear energy and non-drop-in alternative fuels like ammonia and methanol could enable some future capabilities, supporting the added energy requirement and reducing emissions, but will not likely proliferate to scale to support 2050 targets. Advances in platform carbon capture technologies are being tested in commercial maritime applications, but the power demand and CO2 storage requirements will likely preclude commissioned warships and naval aircraft.

Sustainable fuels, and specifically drop-in fuels, offer the greatest potential for significant emissions reductions on naval ships and aircraft by 2050. Prioritization and resources toward government-wide efforts in transportation sector decarbonization are enabling the scaleup of biofuels, hydrogen generation and direct air carbon capture, as well as processes to synthesize drop-in aircraft and marine diesel fuels. The DON must engage in these government-wide efforts to inform DON fuel requirements and support scale-up of sustainable fuels to realize net-zero objectives, and limit climate change impacts.

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I. INTRODUCTION

A. BACKGROUND

Since the start of the industrial age, average global surface temperatures have risen 1.1°C, driving heat extremes, sea ice melting, sea level rise, increased intensity of tropical cyclones and heavy precipitation, increased drought and flooding, and numerous other conditions that challenge global stability. These changes are expected to worsen over the next few decades, causing food insecurity, further spurring global instability, and increasingly challenging U.S. national security and response from U.S. naval forces.[1]

The correlation of global warming and greenhouse gas (GHG) emissions from human activities has been possible by monitoring levels of the various greenhouse gases; analyses of long-term records, tree rings, and ice cores; and computer simulations based on the physics that govern the climate system. The Intergovernmental Panel on Climate Change (IPCC) reports "it is unequivocal that human influence has warmed the atmosphere, ocean and land since pre-industrial times."[2] Global warming and climate impacts are expected to increase over the next several decades, but the severity will depend on global efforts to reduce GHG emissions. Global efforts to limit warming include the Paris Climate Agreement and target limits of 1.5°C and 2°C.[3] In 2021, President Biden released executive orders addressing climate change and setting targets for a government-wide approach to include net zero GHG emissions (net-zero) by 2050.[4] In response, the Office of the Chief of Naval Operations (OPNAV) requested and resourced a research topic for the Naval Postgraduate School (NPS) to assess pathways for naval operating platforms to reach net-zero by 2050. In 2022, NPS executed research

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[1] Intergovernmental Panel on Climate Change. 2023. "Climate Change 2023: AR6 Synthesis Report." Synthesis, Geneva, Switzerland. https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

[2] Intergovernmental Panel on Climate Change. 2021. Climate Change 2021: The Physical Science Basis. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

[3] United Nations. n.d. The Paris Agreement. Accessed September 1, 2023. https://unfccc.int/process-and-meetings/the-paris-agreement.

[4] The White House. 2021. "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability." Executive Order 14057. Washington, DC, Dec 8.

to assess sources and levels of GHG emissions from naval operating platforms and identified specific measures that could realize a net-zero naval force by 2050.[5]

In 2022 the Department of the Navy (DON) released Climate Action 2030 providing Department-specific directives and targets supporting defense and government-wide objectives, including economy-wide net zero by 2050.[6] The Naval Research Program (NRP) funded a follow-on study to further assess pathways and emissions reduction measures having the greatest potential to reduce emission from naval operating platforms. This report summarizes findings from that follow-on research.

B. RESEARCH APPROACH

The year-1 effort quantified DON operational systems emissions and identified potential pathways to meet the 2050 reduction targets directed in executive orders and in DOD and DON climate strategies. The analysis generalized four illustrative pathways allocating reduction potential for alternative fuels, hydrogen, unmanned systems, batteries, operational efficiencies, nuclear, renewable energy, and carbon capture and sequestration. The study concluded that sustainable fuels offered the greatest potential to decarbonize the current force, but several innovative concepts may be more applicable on future force concepts, including small modular nuclear reactors. The study also highlighted potential for carbon capture and storage (CCS), but without specifically considering options for tactical platform integration (ships and aircraft).[5]

This year-2 effort looked deeper into opportunities to integrate sustainable fuels and CCS, and potential for alternative force structure and nuclear energy to support net-zero goals. One key assumption was established early through engagement with stakeholders at OPNAV, the Naval Sea Systems Command (NAVSEA), and the Naval Air Systems Command (NAVAIR):

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[5] K Fletcher, M Lesse, B Naylor, J Lussier, B Johnson. 2022. Analysis of Pathways to Reach Net Zero Naval Operations by 2050. Analysis, Monterey, CA: Naval Postgraduate School.

[6] Department of the Navy. 2022. "Climate Action 2030." Department of the Navy Climate Action 2030. Washington, DC, May. https://www.secnav.navy.mil/Climate/Shared%20Documents/Climate%20Action%202030.pdf.

<u>Key Assumption:</u> The DON will not accept any measures that could reduce combat capability or mission effectiveness.

Further, Title 10 Section 2922h provides language limiting the procurement of drop-in fuels that are not cost competitive with fossil fuels. Both the cost of sustainable fuels and the requirement to maintain warfighting capabilities challenge an aggressive approach to decarbonizing the naval force. For this reason, the research team asked what pathways better meet the intent of language in the various climate strategies, supporting economy-wide and government-wide efforts. The team found that intent is clearly aligned to limiting impacts of climate change by reducing global GHG emissions. Therefore, this study also reviewed and summarized global climate change science and objectives, and assessed impacts of DON emissions and pathways on climate change projections. The following report answers what emissions reduction pathways provide the best opportunity for the naval operating force to support climate change mitigation. It starts with an analysis of the climate science and GHG emissions, then summarizes potential for alternative force structure, nuclear energy, CCS, and sustainable fuels to support global GHG reduction objectives.

C. CLIMATE SCIENCE, REASON TO DECARBONIZE

In this Phase II effort, the project team looked at authoritative sources of climate science and models to assess and summarize the science-based background for decarbonizing. This approach supports the plan detailed in the April 2023 OSD Report, *Department of Defense Plan to Reduce Greenhouse Gas Emissions* which describes the DOD approach and progress toward "science based" emissions reduction targets. OSD's report includes the following definition for science-based emissions targets: *Carbon emissions targets are defined as science-based if aligned with the scale of reductions required to limit global warming below 2°C above pre-industrial temperatures and pursue efforts to limit warming to 1.5°C.* [7]

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[7] Office of the Under Secretary of Defense for Acquisition and Sustainment. 2023. "DOD Plan to Reduce Greenhouse Gas Emissions." Washington, DC, April. https://media.defense.gov/2023/Jun/16/2003243454/-1/-1/1/2023-DOD-PLAN-TO-REDUCE-GREENHOUSE-GAS-EMISSIONS.PDF.

The analysis that follows considers the correlation between GHG emissions and global warming and compares the impacts associated with the current projected warming of 3.2 °C by 2100 with impacts of limiting warming to the 2°C target.

Historical climate data was sourced primarily from the National Oceanographic and Atmospheric Association's (NOAA) "Climate Data Dashboard."[8] U.S. climate impacts, indicators and analyses were sourced from the Environmental Protection Agency's (EPA) "Climate Change Indicators in the United States" website.[9] Climate projections were modeled using the Coupled Model Intercomparison Project Phase 6 (CMIP6) model maintained by World Climate Research Program (WCRP).[10] The CMIP models integrate historical data from U.S. and international activities.

Note, each release of CMIP projections is reviewed and approved by the Working Group on Climate Modelling (WGCM) subcommittee, which includes leadership from NOAA and the National Aeronautics and Space Administration (NASA). This is also the primary tool used by the IPCC. Many of the findings that follow are presented in the IPCC's Sixth Assessment Report (*AR6 Synthesis Report*) but are closely aligned with NOAA's *2022 Annual Climate Report*.[11]

1. Historical GHG Levels and Climate Change

The IPCC reports "unequivocally" and with "high confidence" that greenhouse gas emissions from human activities have caused global surface temperatures to increase 1.1°C above 1850-1900 levels leading to droughts, fires, arctic sea ice melting, precipitation, sea-level rise, tropical cyclones, and other indicators.[12] NOAA's Annual Climate Report also correlates GHG emissions to increasing temperatures, melting sea ice, and sea level rise, as well as unusual drought and precipitation. Figure 1 illustrates the correlation between human emissions and amount of CO2 in the atmosphere since the

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[8] National Oceanographic and Atmospheric Association. 2023. Global Climate Dashboard. Accessed June 1, 2023. https://www.climate.gov/climatedashboard.

[9] Environmental Protection Agency. n.d. Climate Change Indicators in the United States. Accessed 2023. https://www.epa.gov/climateimpacts.

[10] Intergovernmental Panel on Climate Change. 2023. Interactive Atlas: Regional synthesis. Accessed June 15, 2023. http://interactive-atlas.ipcc.ch/.

[11] National Centers for Environmental Information. 2022. Annual 2022 Global Climate Report. Accessed July 1, 2023. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202213.

[12] Intergovernmental Panel on Climate Change. 2023. "Climate Change 2023: AR6 Synthesis Report." Synthesis, Geneva, Switzerland. https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

start of the Industrial Revolution in 1750, and Figure 2 shows corresponding increase in global surface temperature.[13] Analysis of ice cores, tree rings, and other sources have shown that the increase in CO2 levels over the last 60 years is 100 times faster than previous natural increases.[13] The latest IPCC report also summarizes research in natural GHG emissions, like emissions from volcanoes, and correlates a minimal change of ±0.1°C on global surface temperatures, using a baseline period of 1850-1900.[14]

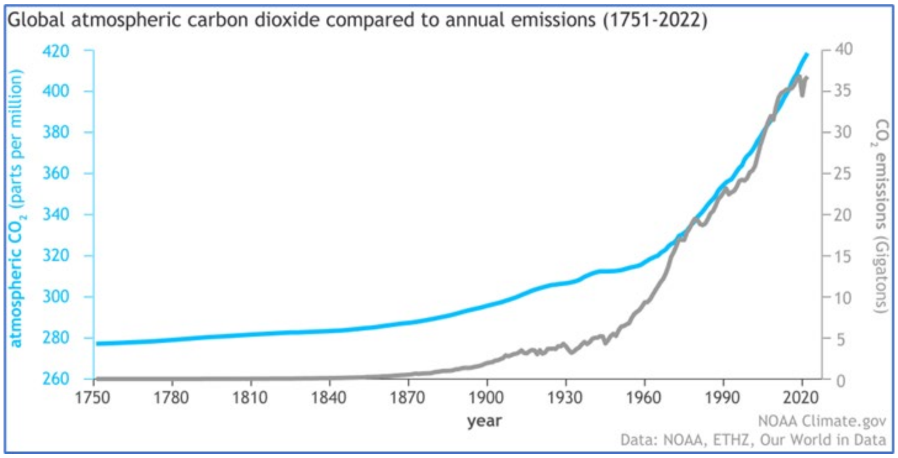

Figure 1. Correlating Emissions with CO2 Levels

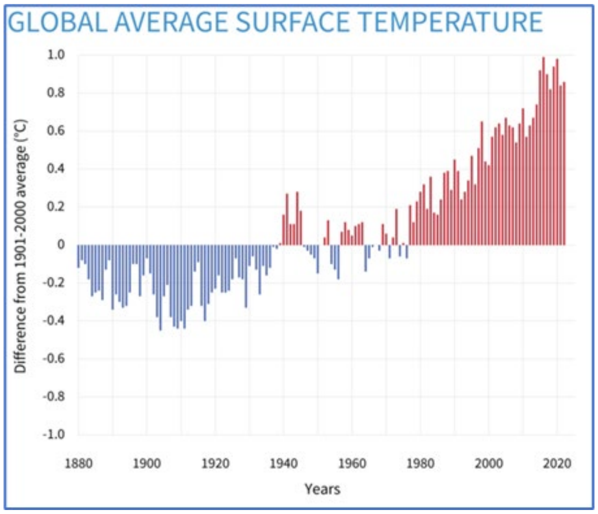

Figure 2. Global Temperature Increase

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[13] National Oceanographic and Atmospheric Association. 2023. Global Climate Dashboard. Accessed June 1, 2023. https://www.climate.gov/climatedashboard.

[14] Intergovernmental Panel on Climate Change. 2021. Climate Change 2021: The Physical Science Basis. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

2. Historical Climate Impacts

Historical trends and analysis of climate indicators are well assessed and presented in NOAA, EPA, IPCC, and other reports. For this study the team used data plots and analysis from the EPA to understand the more harmful physical impacts of climate change and to consider impacts to the United States, as most indicators are dependent on the geographical location. Researchers also reviewed historical data plots for extreme temperatures, tropical cyclones, precipitation, and sea level rise. [15]

a. Historical Climate Impacts: Extreme Temperatures

As global temperatures increase, average temperature in the United States also increases; however, the more impactful indicator is extreme heat events. Figure 3 illustrates the percentage of the land area in the contiguous United States with "unusually hot daily temperatures" in the summer. The EPA describes "unusually hot summer days (highs) have become more common over the last few decades, and occurrence of unusually hot summer nights (lows) has increased at an even faster rate." This trend indicates less "cooling off" at night. The EPA also describes less common "unusually cold winter temperatures."[15]

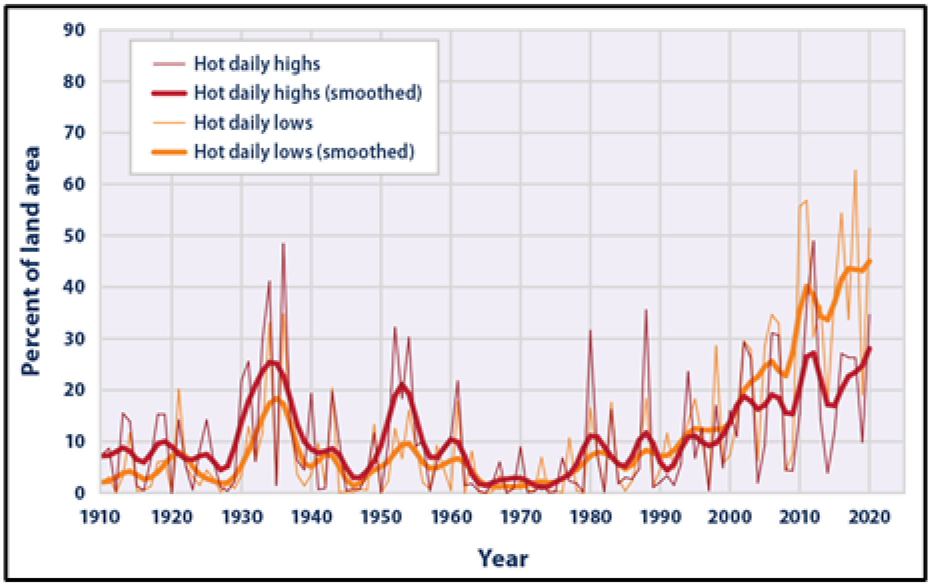

Figure 3. Area of Contiguous United States with Unusually Hot Temperatures

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[15] Environmental Protection Agency. n.d. Climate Change Indicators in the United States. Accessed 2023. https://www.epa.gov/climateimpacts.

Additionally, since 1960, the frequency, duration, and intensity of heat waves have increased in the United States. Data and analysis from 50 large U.S. metropolitan areas taken since 1960 showed that heat waves are occurring more often, from an average of two heat waves per year during the 1960s to six per year during the 2010s.[16]

b. Historical Climate Impacts: Tropical Cyclones (Hurricanes)

Over the period 1878 to 2020 the total number of hurricanes and the number reaching the United States do not indicate a clear overall trend in growth or reduction. However, fluctuating cyclone intensity, represented as Power Dissipation Index (PDI), and a noticeable increase since 1995 are associated with changes in sea surface temperature in the tropical North Atlantic as shown in Figure 4. PDI accounts for cyclone strength, duration, and frequency.[16]

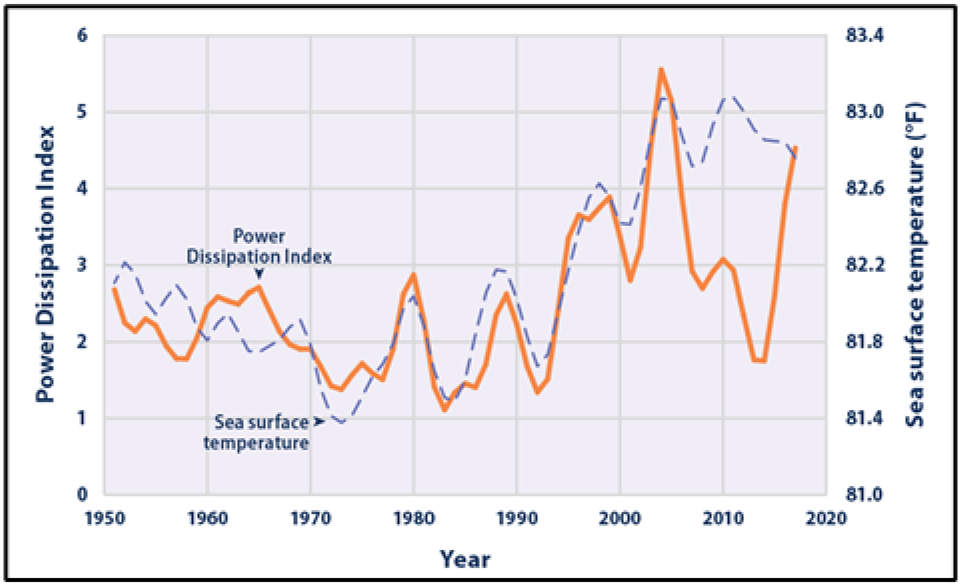

Figure 4. Tropical Cyclone Power Dissipation Index

c. Historical Climate Impacts: Precipitation

On average, since 1901, total annual precipitation in the United States has increased over land areas at a rate of 0.20 inches per decade. However, more concerning

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[16] Environmental Protection Agency. n.d. Climate Change Indicators in the United States. Accessed 2023. https://www.epa.gov/climateimpacts.

is the increase in percentage of precipitation from intense single-day events, shown in Figure 5. The EPA describes, "over the period from 1910 to 2020, the portion of the country experiencing extreme single-day precipitation events increased at a rate of about half a percentage point per decade." These single-day events have resulted in increased flooding, landslides, snowstorms, loss of crops, and soil erosion.[17]

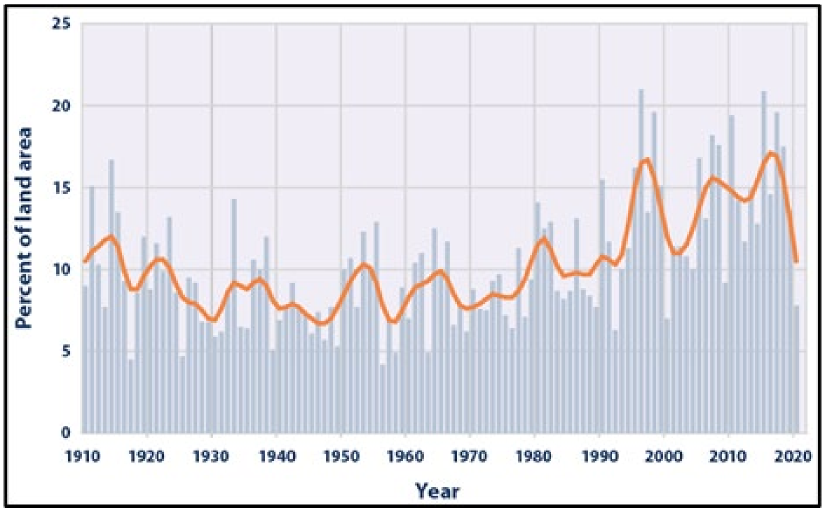

Figure 5. Extreme One-Day Precipitation Events

d. Historical Climate Impacts: Sea Level Rise

The EPA describes that global average sea level has risen at an average rate of 0.06 inches per year since 1880 but has accelerated in recent years. Since 1993 the average sea level has risen at a rate of 0.12 to 0.14 inches per year. In the United States, much of the coastline has registered increases, some exceeding 8 inches including areas of the Mid-Atlantic coast and parts of the Gulf coast. Figure 6 illustrates the changes in relative sea level rise in the United States.[17]

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[17] Environmental Protection Agency. n.d. Climate Change Indicators in the United States. Accessed 2023. https://www.epa.gov/climateimpacts.

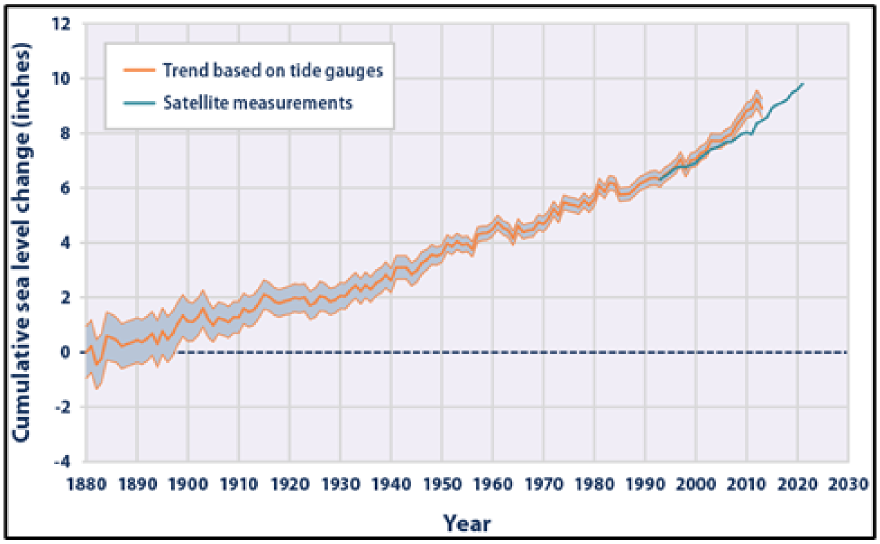

Figure 6. Average Change in Sea-Level in the United States

3. Climate Change Projections

Model projections of future climate change and impacts apply historical data and trends to estimate future continued global warming against different "scenarios" of continued global GHG contributions or reductions. In 2021, the IPCC established Shared Socioeconomic Pathways (SSP) in the Working Group 1 report, *The Physical Science Basis*, baselining scenarios for use in climate modeling. These SSPs, described in Table 1, are now widely used to assess the range of potential GHG mitigations and associated impacts, and they are used in CMIP6 models maintained by the WCRP.[18]

SSP	Description of Represented Pathway
5-8.5	Very high GHG emissions and continued CO2 emission increases through 2050
3-7.0	High GHG emissions and continued CO2 emissions through 2050
2-4.5	**Intermediate GHG emissions and CO2 emissions remaining around current levels until the middle of the century**
1-2.6	**Low GHG emissions and CO2 emissions declining to net zero around or after 2050 followed by varying levels of net negative CO2 emissions**
1-1.9	Very low GHG emission and CO2 declining to net zero around or after 2050 followed by varying levels of net negative CO2 emissions

Table 1. IPCC established Shared Socioeconomic Pathways (SSP)

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[18] Intergovernmental Panel on Climate Change. 2021. Climate Change 2021: The Physical Science Basis. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

Two scenarios were modeled for this study to assess and project how GHG emissions reductions will affect climate impacts to the contiguous United States (CONUS). SSP2-4.5 represents current trajectory, and SSP1-2.6 limits warming to 2°C. The annual GHG reductions needed to realize SSP2-4.5, as reported by the IPCC, are approximately 17 billion metric tons by 2030 and 37 billion metric tons by 2050. CMIP6 projections for mean temperature change, extreme temperatures, precipitation, sea level rise, and sea surface temperature were modeled.[19]

a. Projected Impact: Mean Temperature

Figure 7 illustrates how global GHG levels associated with the SSP1-2.6 and SSP2-4.5 impact mean temperature change in the United States. IPCC and other reports associate a global change of 2°C and 3.2°C; however, the warming in the United States is slightly higher as shown.[19]

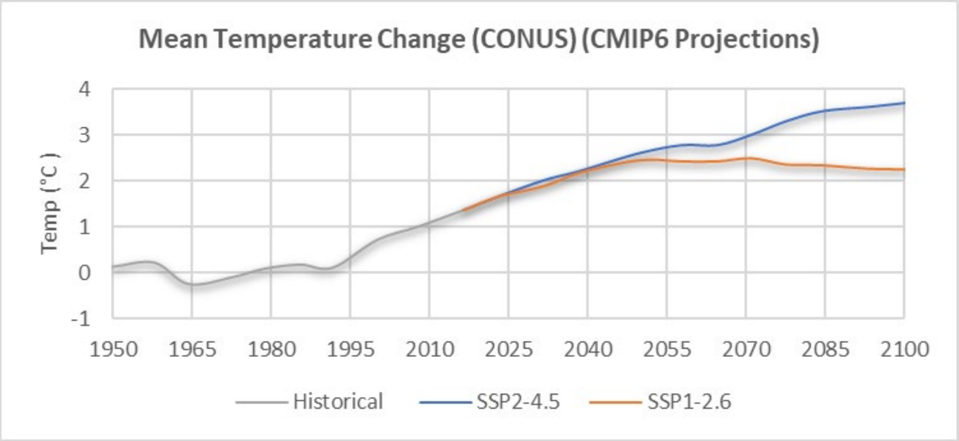

Figure 7. CMIP6 Modeled Projections of Mean Temperature Change

b. Projected Impact: Extreme Temperatures

Periods of extreme heat are projected to increase by 12 days for SSP2-4.5 and increase 3 days for SSP1-2.6, as shown in Figure 8—a difference of 9 days. This includes more heatwaves with greater intensity and longer duration.[19]

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[19] Intergovernmental Panel on Climate Change. 2023. Interactive Atlas: Regional synthesis. Accessed June 15, 2023. http://interactive-atlas.ipcc.ch/.

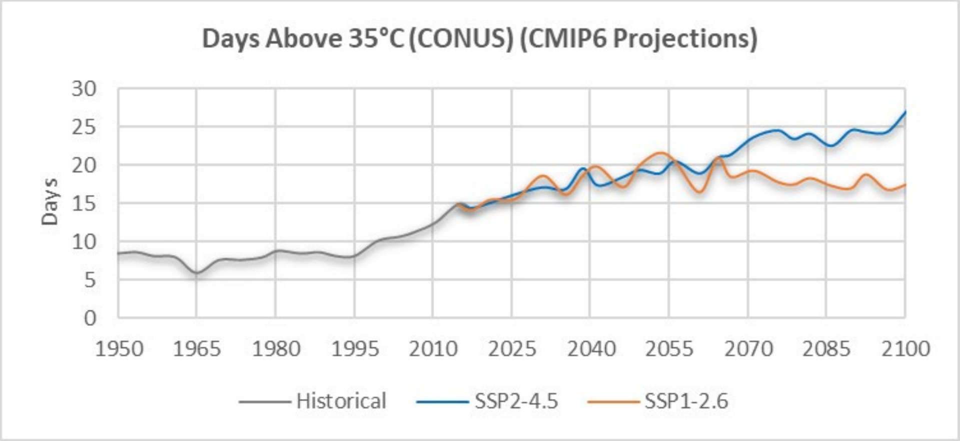

Figure 8. CMIP6 Modeled Projections of Increase in Extreme Heat Days

c. Projected Impact: Precipitation

CMIP modeling of mean single-day precipitation amounts in the continuous United States projects a continued growth and increase of approximately 5.7 mm for SSP2-4.5 and 3 mm for SSP1-2.6 by the year 2100, as shown in Figure 9. These events contribute to flooding, landslides, soil erosion, crop damage, and other indicators.[20]

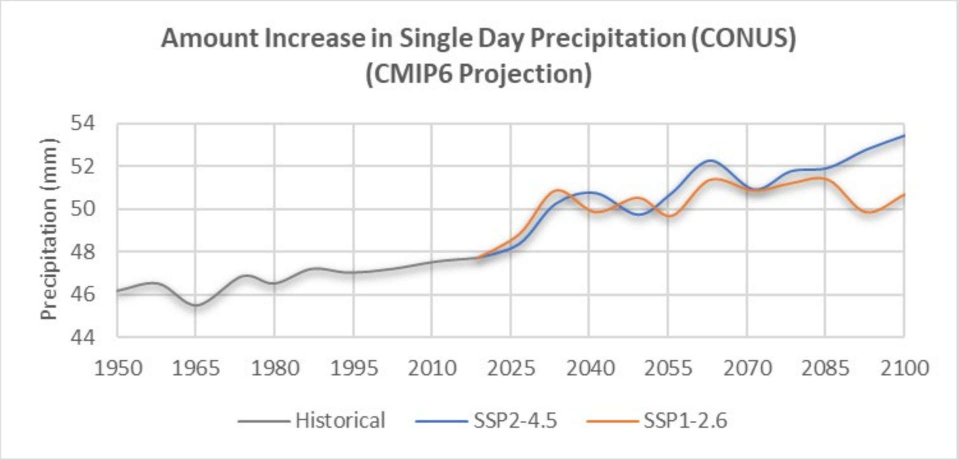

Figure 9. CMIP6 Modeled Projections of Single Day Rainfall Increase

d. Projected Impact: Sea Level Rise

Sea level rise is projected to continue to .47 meters for SSP2-4.5 and .38 meters for SSP1-2.6 by 2100, as shown in Figure 10. Coastlines on the Atlantic are projected to

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[20] Intergovernmental Panel on Climate Change. 2023. Interactive Atlas: Regional synthesis. Accessed June 15, 2023. http://interactive-atlas.ipcc.ch/.

be more impacted than those on the Pacific where land elevation also continues to increase. Much of the reporting from IPCC and other sources describe sea level rise as one of the longer-term impacts that will not rebound as quickly from the reductions in GHG emissions.[21]

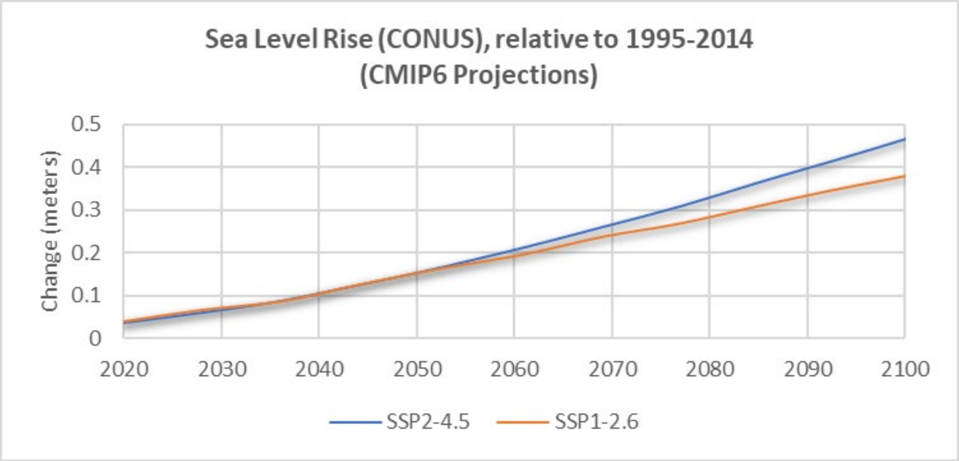

Figure 10. CMIP6 Modeled Projections of Sea Level Rise

e. Projected Impact: Sea Surface Temperature (Tropical Cyclones)

The surface temperature of the Atlantic Ocean is projected to increase in future decades as shown in Figure 11. An increase of 1.84 °C and 1.17 °C are projected for SSP2-4.5 and SSP1-2.6, respectively—a difference of .67 °C. Based on historical correlations, the projections of additional energy in the Atlantic can be correlated to more intense tropical cyclones along the east coast, bringing additional rainfall and extreme wind speeds over longer durations. Modeling to project Pacific Ocean temperature change was not performed.[21]

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[21] Intergovernmental Panel on Climate Change. 2023. Interactive Atlas: Regional synthesis. Accessed June 15, 2023. http://interactive-atlas.ipcc.ch/.

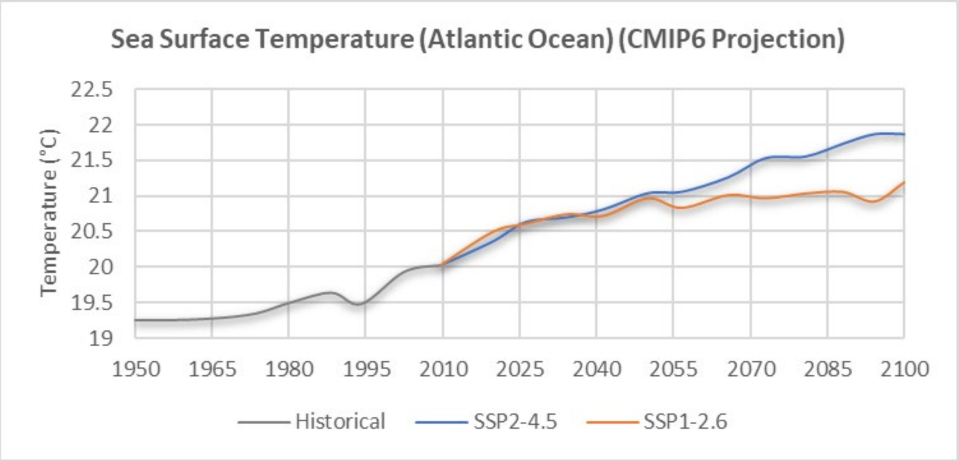

Figure 11. CMIP6 Modeled Projections of Atlantic Ocean Sea Surface Temperature

4. Emissions Reductions Requirement to Support Science Based Targets

The importance of limiting global warming is apparent in the data and supported by Navy and Defense leadership through climate plans and analyses. The “Science Based” targets, limiting warming to 2°C, to minimize impacts to levels described require a global CO2e reduction of approximately 17 billion metric tons (Gt) by 2030 (29% reduction) and a reduction of 37 Gt by 2050 (63% reduction) as illustrated by the IPCC in Figure 12.[22]

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[22] Intergovernmental Panel on Climate Change. 2023. "Climate Change 2023: AR6 Synthesis Report." Synthesis, Geneva, Switzerland. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

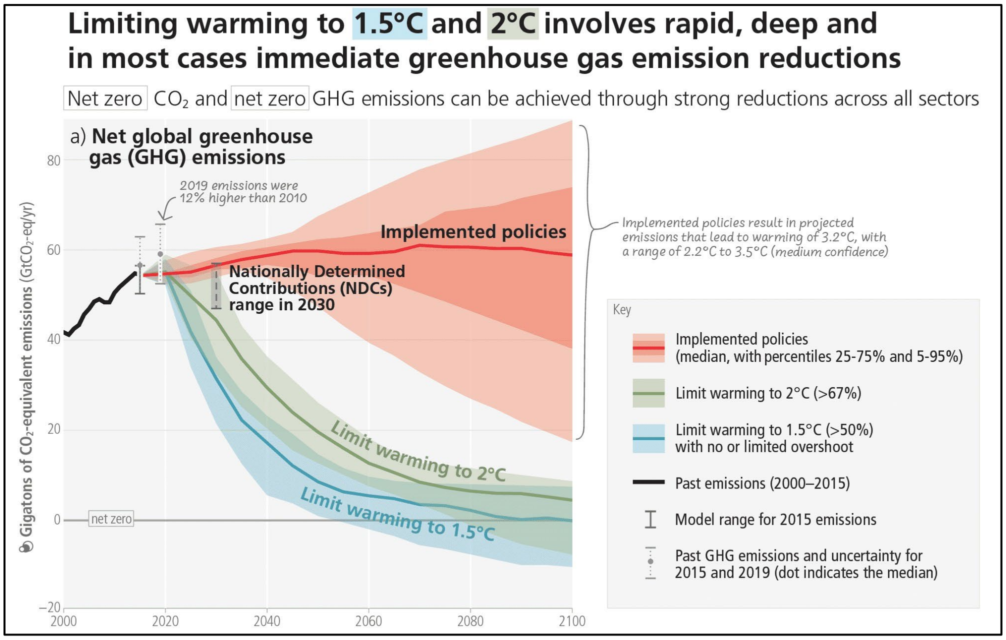

Figure 12. IPCC Illustration of GHG Reductions Necessary to Limit Global Warming

The emissions from the DON's operational platforms are less than 12 million metric tons (Mt) annually. Figure 13 shows emissions calculated from historical fuel use data and projections based on current shipbuilding and procurement plans.[23] Compared to global emissions and global emissions reductions targets, the total of emissions is small. Federal, DOD, and DON climate doctrine direct emissions reductions of 65% by 2030 and net zero by 2050, but those reductions—although they are critical—will not alone limit global warming to 2°C. The approach necessary to realize rapid, deep, and sustained emissions reductions requires a coordinated approach to include government, industry, research, and international partnerships contributing, sharing, and advancing economies through broad and crosscutting efforts that reduce emissions from fossil fuels. The sections that follow in this report highlight an approach that supports federal, DOD, and DON targets while also supporting the broader global approach.

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[23] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/;
Office of the Chief of Naval Operations. 2022. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023." Washington, DC.
https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/PB23%20Shipbuilding%20Plan%2018%20Apr%202022%20Final.pdf.

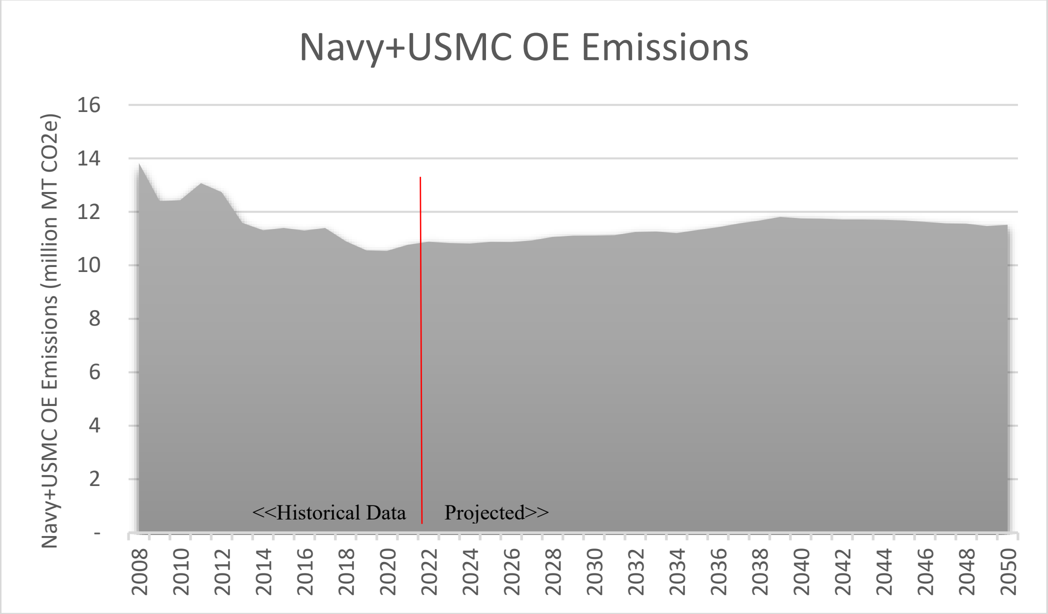

Figure 13. CO2e Emissions Calculated from DON Fuel Use

II. ANALYSIS OF DECARBONIZATION PATHWAYS

A. POTENTIAL FOR ALTERNATIVE FORCE STRUCURE

The next generation naval platforms and force compositions likely offer the greatest potential to integrate new and unconventional propulsion concepts that would emit drastically less GHG emissions. Today's naval ships and aircraft, and the sustainment to support those, are designed heavily around proven internal combustion engines using F-76 and JP-5 fuels. Although some retrofit may be possible, front-running concepts for electrification, alternative (non-drop-in) fuels, and nuclear power on large capital ships and airframes will likely require a new design, and alternative sustainment models. This research considered the lifecycle of the current force structure and the shipbuilding and aircraft procurement plans to understand when the Navy could anticipate integration of these advanced concepts. The research also considered existing proven platform alternatives to consider where optimization could be integrated. The report looks at future ships and future aircraft separately.

1. Opportunities in the Future Surface Fleet (Ships)

The Department's *Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023* (also known as the 30 Year Shipbuilding plan) provides quantities and types of ships and submarines planned through 2052. The plan considers findings from multiple analyses including the Integrated Naval Force Structure Assessment (INFSA) and the Future Naval Force Study (FNFS) and iterates language from the *2018 National Defense Strategy* (NDS) and the *Chief of Naval Operations Navigation Plan 2022* (NAVPLAN) regarding strategic competition driving requirements for a larger, distributed, and more capable fleet. The plan provides three "alternative" battle force inventories having total ship counts of 309, 318, and 360 in 2050. For this study, the middle alternative, representing 318 ships, was assessed. [24]

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[24] Office of the Chief of Naval Operations. 2022. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023." Report to Congress, Washington, DC. https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/PB23%20Shipbuilding%20Plan%2018%20Apr%202022%20Final.pdf.

Since the 2018 NDS, the warfighting concept for distributed operations has been a key focus. In naval strategies, the concept reduces vulnerability in contested environments against pacing threats like China. Since World War II, a "battlegroup" concept has been a fundamental of naval strategy, and today's force is still designed around that concept. The latest shipbuilding plan includes the following language addressing challenges to distributed operations:

> *The concepts of [Distributed Maritime Operations] and Littoral Operations in a Contested Environment (LOCE) / Expeditionary Advanced Base Operations (EABO) require a balanced and different mix of traditional battle force ships as well as new unmanned, amphibious, and logistic platforms. Previous warfighting analysis validated that a progressive evolution of existing platforms combined with revolutionary introduction of new technologies results in a more survivable and more lethal force than previous force structures.*
>
> *To realize these concepts, the Department continues to experiment and analyze a range of solutions to provide lethal capability for sea control and power projection within the framework of DMO. Study areas include, but are not limited to, aircraft carrier force structure, DDG(X), SSN(X), NGLS, amphibious ship mix, and expanded missions for unmanned platforms. This analysis and experimentation, in support of warfighting concepts, is informed by operationally relevant metrics including, but not limited to, capacity, lethality, survivability, operational reach, and affordability.*[25]

Some experimentation and several analyses have identified the benefits and requirement for smaller and longer endurance platforms to reduce logistics demand and enable operations in contested environments. Although several near-term platforms are

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[25] Office of the Chief of Naval Operations. 2022. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023." Report to Congress, Washington, DC. https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/PB23%20Shipbuilding%20Plan%2018%20Apr%202022%20Final.pdf.

already in later stages of acquisition, like FFG-62, Next Generation Logistics Ship, Medium Landing Ship, and Overlord Unmanned Surface Vessel, there is potential to inform follow-on designs and concepts early in development with innovative power and propulsion systems that offset the logistics requirement, increase warfighting effectiveness, and reduce GHG emissions.

More than 95% of the emissions from operating platforms are from the combustion of fossil fuels. To understand the potential to optimize the future surface force for reduced emissions, fuel use from active fuel users, as well as planned (already designed or in design) fuels users, were plotted. Figure 14 applies ship quantities provided in the Shipbuilding Plan, and it uses actual fuel use in FY22 and then class averages (last 3 years) of platform fuel use to project how much fuel active ships will use through 2050 (blue area). Although more than 40 classes of Navy and MSC ships are included in this data, nine classes account for over 80% of the fuel use, as shown in Figure 15, with the DDG-51 Class as the largest user. The plot (Figure 14) shows that many ships active in today's fleet are expected to still be in operation in 2050.[26]

The orange-colored area on the plot illustrates expected fuel use from ships not currently in operation, but which are in the procurement process with initial flights (hulls) already designed or in design. Although later flights of these designs could include alternative propulsion systems, those aren't likely, as the ship's hull parameters (length, width, displacement, etc.) and electrical load are largely designed around the power and propulsion plant. There is an expectation that advanced batteries will be integrated on these platforms to support directed energy weapons and integrated power and energy architectures; the end state will be more efficient operations, but not a significant reduction in emissions. As noted, a key assumption in the pathway to net-zero emissions is that no concept that could reduce the combat capability (lethality) of the warfighting force will be accepted. The orange area includes DDG-51 Flight III ships, additional LPD Class and T-AO 205 Class hulls, and the FFG-62 Class.

The grey area plotted represents notional platform fuel use from ship concepts planned to be in operation, but that aren't yet designed. This trade space is the most

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[26] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

flexible to alternative power and propulsion concepts that could yield reduced or zero emissions.

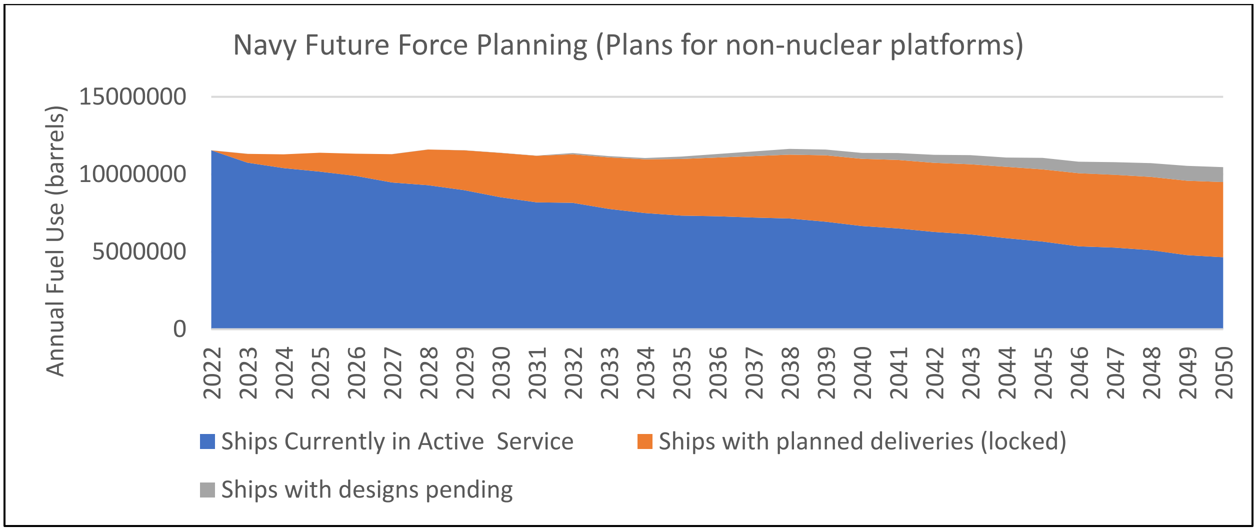

Figure 14. Projection of Surface Ship Fuels Use

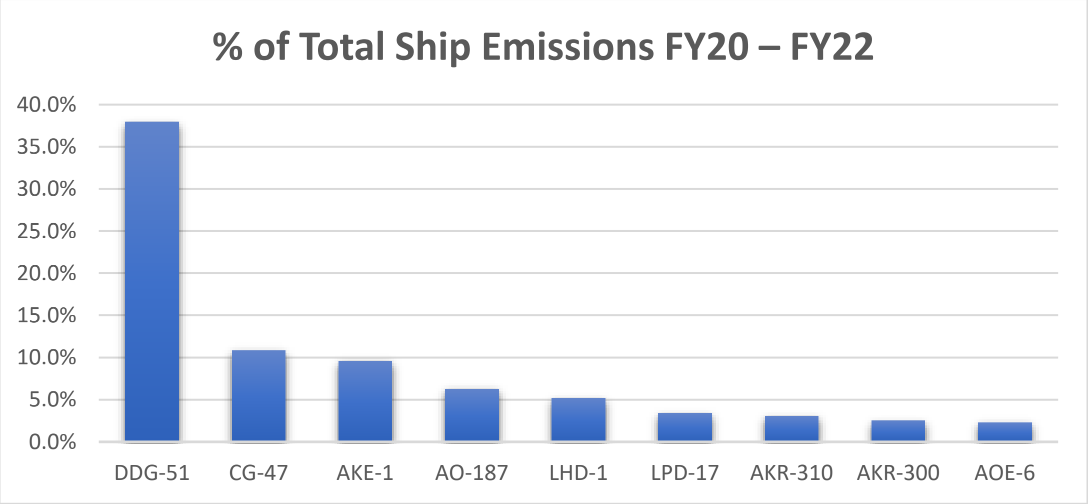

Figure 15. Nine Ships Account for 80% of Total Ship Fuel Use

a. Electrification of Surface Platforms

The benefits of electrification and advanced batteries to global decarbonization priorities are well accepted across the automotive industry and are being realized across non-transportation sectors for energy storage and backup power. The fundamental benefit to climate mitigation is less reliance on fossil fuels in favor of energy from local power utilities that usually include cleaner energy sources like nuclear, solar, wind, etc.

Advances in lithium chemistries over the last several decades are expected to continue and enable more applications to switch from petroleum-based fuels to battery storage, and that includes hard-to-decarbonize sectors like maritime and aviation. However, the primary roadblock for a battery powered naval force is the endurance needed to deploy and sustain combat operations in remote environments.

The DON is currently employing numerous small systems that are powered by batteries and will continue to expand the use of advanced batteries to larger systems, and this electrification is a necessary part of the pathway to net-zero as described in the Phase I report. However, the decarbonization impacts from these systems will generally be experienced at DON installations, as battery charging of these systems is still necessary, and will be provided by fuel-based power generation on Navy ships (except CVNs and SSNs). Small battery powered platforms will have little impact on the emission reductions targets.

The Navy is beginning to experiment with large scale battery backup power for future surface ships to enable pulse power weapons and backup power supplies. These concepts, including Common Uninterruptible Power Supplies, may enable sufficient energy storage to optimize loading on power generation systems and increase the efficiency of the platform. However, it is early to assess how this will impact emissions reductions targets, because as power generation capacity is made available, the Navy will seek to add more capable weapons and sensors that will likely offset fuel reduction benefits.

The NPS Report Electrical Energy Storage Strategy to Support Electrification of the Fleet provides in-depth analysis and recommendations for advanced energy storage across the future naval force.[27]

b. Alternative Fuels Propulsion Systems

The Navy will be following advancements in alternative propulsion fuels, like Ammonia and Methanol, and will be engaged with the commercial maritime industry to take advantage of those advancements when applicable. However, as stated previously, the requirement to optimize for warfighting effectiveness, the Navy energy logistics

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[27] D Camp, N Vey, P Kylander, S Auld, J Willis, J Lussier, R Eldred, D Van Bossuyt. 2022. "Electrical Energy Storage Strategy to Support Electrification of the Fleet." Defense Research, Monterey.

systems, and life-cycle of current and planned platforms will prohibit large-scale adoption of those fuels ahead of 2050. A section of this report is dedicated to alternative fuels and further details those challenges.

2. Aircraft

Like the surface fleet, the future naval aircraft fleet is a function of the assessed future threat. The DON's *Navy Aviation Vision 2030-2035* describes priorities and efforts to align naval aviation into the 2030s, but also describes plans beyond 2035. Over the next few decades, the department will further integrate manned and unmanned platforms and technologies supporting Manned/Unmanned Teaming (MUM-T) and advance concepts to better integrate the total naval force to maximize effectiveness. The Navy Aviation Vision, the CNO's NAVPLAN, and the NDS have made it clear that increased range and speed, platform lethality, and survivability will remain the focus of future naval advancements. However, opportunities in unmanned systems and training may enable some reductions in fuel use and reduce GHG emissions. The Navy Aviation Vision describes the future force and concepts that would potentially support those reductions. This research considered the emissions from aircraft in the current force to understand impact of individual airframes and missions on emissions, then considered the implications of certain concepts on total aircraft emissions.[28]

Figure 16 illustrates the emissions ratios that each type/series of naval aircraft have toward total DON aircraft emissions, which is approximately half of cumulative emissions from naval operating platforms and approximately 35% of total DON emissions. The largest contributors are the F/A-18 and the newer F-35 strike aircraft. Together, the two airframes represent 53% of total aircraft emissions. Patrol and Reconnaissance Aircraft, the P-8 and P-3 airframes, account for 13%, and then the C-130 aerial refueler and the H-60 account for 5% and 4 % respectively. Those 6 platforms account for over 75% of total emissions, and for that reason were the primary focus of this section.[29]

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[28] Naval Air Systems Command. 2021. "Navy Aviation Vision 2030-2035." https://media.defense.gov/2021/Oct/27/2002881262/-1/-1/0/NAVY%20AVIATION%20VISION%202030-2035_FNL.PDF.

[29] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

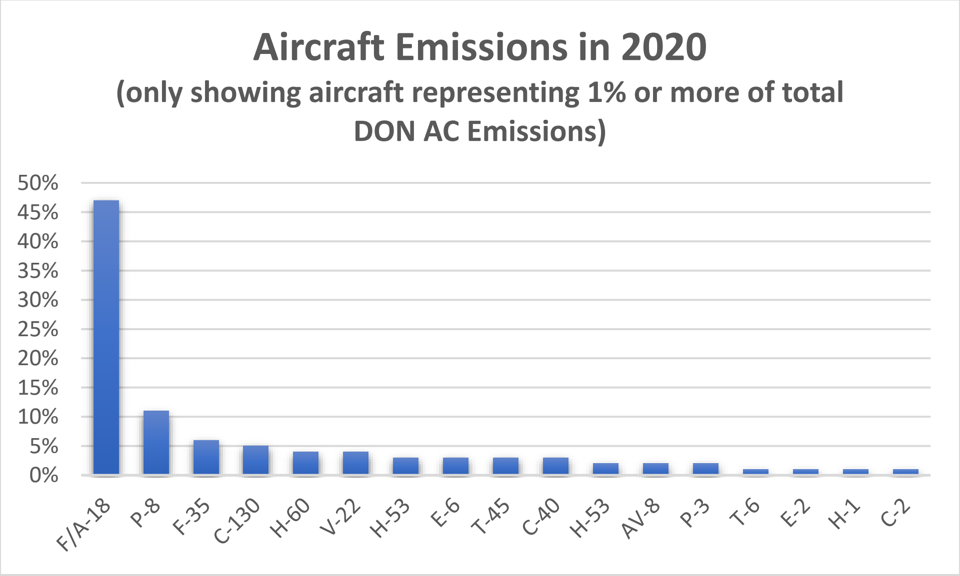

Figure 16. CO2e Emissions from DON Aircraft by Percentage

a. Navy Aircraft Priorities

In the NAVPLAN, the CNO describes the need for a larger, more capable and distributed fleet and introduced a hybrid fleet concept having approximately 3000 aircraft to include manned, unmanned and multi-mission platforms.[30] This message is consistent with the *Navy Aviation Vision 2030-2035* which describes priorities for MUM-T, but also for increased speed and range, long-range collaborative weapons, increased sensor detection range and identification, high-power full-spectrum airborne electronic attack, beyond line-of-sight communications and numerous other capabilities that will increase power demand.[31] Generally, similar to shipbuilding priorities, the cycles for aircraft procurement and deactivation are based on requirements for increasing combat capabilities, which is usually counter to emissions reductions priorities. An assessment of DON energy use between 2008 and 2022 showed an increase in total force burn rate (barrels per hour) of 3.4% supporting the argument that newer platforms demand more

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[30] Office of the Chief of Naval Operations. 2022. "Navigation Plan 2022." Washington , July 26. https://www.doncio.navy.mil/FileHandler.ashx?ID=18929.

[31] Naval Air Systems Command. 2021. "Navy Aviation Vision 2030-2035." https://media.defense.gov/2021/Oct/27/2002881262/-1/-1/0/NAVY%20AVIATION%20VISION%202030-2035_FNL.PDF

energy.[32] A deeper look at the largest consumer, the F/A-18, and its successor, the F-35, also supports this position as the F-35 consumes 3.8% more than the F/A-18. Other comparative analyses may show results counter to this, but on average, energy demand and GHG emissions are increasing per hour of operation. *The Navy Aviation Vision* also describes solutions to increase endurance, including Variable Cycle Engines, which could reduce energy demand, but also reiterates the need for power and cooling for advanced mission systems. It is not reasonable to expect future manned strike airframes will demand less energy, and therefore reduce GHG emissions.

b. Unmanned Aerial Concepts

The Navy Aviation Vision describes benefits of unmanned systems in support of missions like refueling, communications, logistics airborne electronic attack, strike, and ISR (Intelligence, Surveillance, & Reconnaissance) for near- to mid-term requirements. Further into the future, however, the force will also employ the Next Generation Air Dominance (NGAD) Family of Systems (FoS) integrating unmanned platforms, and attritable assets, with the F/A-XX to enable integrated kinetic and non-kinetic fires. To assess the potential for these concepts to reduce emissions, the research team reviewed language for systems currently in operation. The following language from the *Navy Aviation Vision* highlights several priorities and progress in fielding the MQ-4, MQ-8 and MQ-25:[33]

> *<u>MQ-4</u>*
> *The MQ-4C Triton achieved Early Operational Capability (EOC) in January 2020, delivering persistent maritime ISR&T through human-machine and autonomous teaming. When paired with mission management tools, such as Minotaur, Triton will provide sensor agility to locate, track, classify, identify, and report on targets of interest.*
>
> *The continuous investment in advanced ASW acoustic and non-acoustic sensors for the P-8A Poseidon and MQ-4C Triton Multi-INT Unmanned Aircraft System (UAS) enables the Navy to provide continuous coverage and expanded ASW search capability, covering larger areas in less time.*

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[32] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

[33] Naval Air Systems Command. 2021. "Navy Aviation Vision 2030-2035." https://media.defense.gov/2021/Oct/27/2002881262/-1/-1/0/NAVY%20AVIATION%20VISION%202030-2035_FNL.PDF.

> *MQ-8*
> *The MQ-8C Fire Scout unmanned aerial system will deploy for the first time in the near future with an advanced RADAR, Link 16, and the Minotaur mission system.*
>
> *The expected service life for both the MH-60R/S and MQ-8, coupled with a rapidly evolving threat, pose potential rotary wing capability and capacity gaps in the future. Mitigating these gaps will require the recapitalization of current capabilities as well as development of new capabilities as part of the Future Vertical Lift (Maritime Strike) family of systems (FVL (MS))—both manned and unmanned. This new FoS will be designed and built specifically to support DMO. The capabilities envisioned include increased survivability, long-range, persistent ISR-T, integrated air and missiles defense, long-range offensive anti-surface and anti-submarine warfare (ASW), communications and data relay, fleet logistics, and personnel recovery.*
>
> *MQ25*
> *The MQ-25 will be the Navy's first aircraft carrier-based unmanned platform and will increase the lethality and reach of the CVW as a tanker with a secondary ISR role.*
>
> *Along with organic tanking, the MQ-25 will pave the way for unmanned air vehicles on the carrier and manned and unmanned teaming to extend strike range and enhance maneuverability. As unmanned tanking capacity delivers, the manned tanker requirement decreases, making additional service life and capacity available for strike fighter missions.*[34]

Figure 17 represents estimated burn rates of MQ-8 and Q-4 aircraft currently in operation, burn rates of the platforms they're replacing or supplementing, and an estimate for MQ-25 and F/A-XX burn rates, which are rough estimates based on size, capabilities, and discussion with aviation requirements managers.[35] The figure illustrates that unmanned systems' burn rates are significantly less than the manned platform it is supplementing or replacing. A one-for-one swap should not be assumed however, as the manned platforms shown provide multi-mission and additional capabilities and capacity (combat capabilities). This illustration only highlights the potential unmanned systems could represent in a future force. If the future MQ-25, Q-4, and MQ-8 platforms could

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[34] Naval Air Systems Command. 2021. "Navy Aviation Vision 2030-2035." https://media.defense.gov/2021/Oct/27/2002881262/-1/-1/0/NAVY%20AVIATION%20VISION%202030-2035_FNL.PDF.

[35] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

offset 20% of the manned platforms they are supplementing, the emissions reduction would be about 9% of total AC emissions (4.5% of total operational emissions), based on today's operating profile. If future unmanned could replace 50% of those manned platforms, the emissions reduction would be about 22% of total AC emissions, or 11% of total operational emissions.

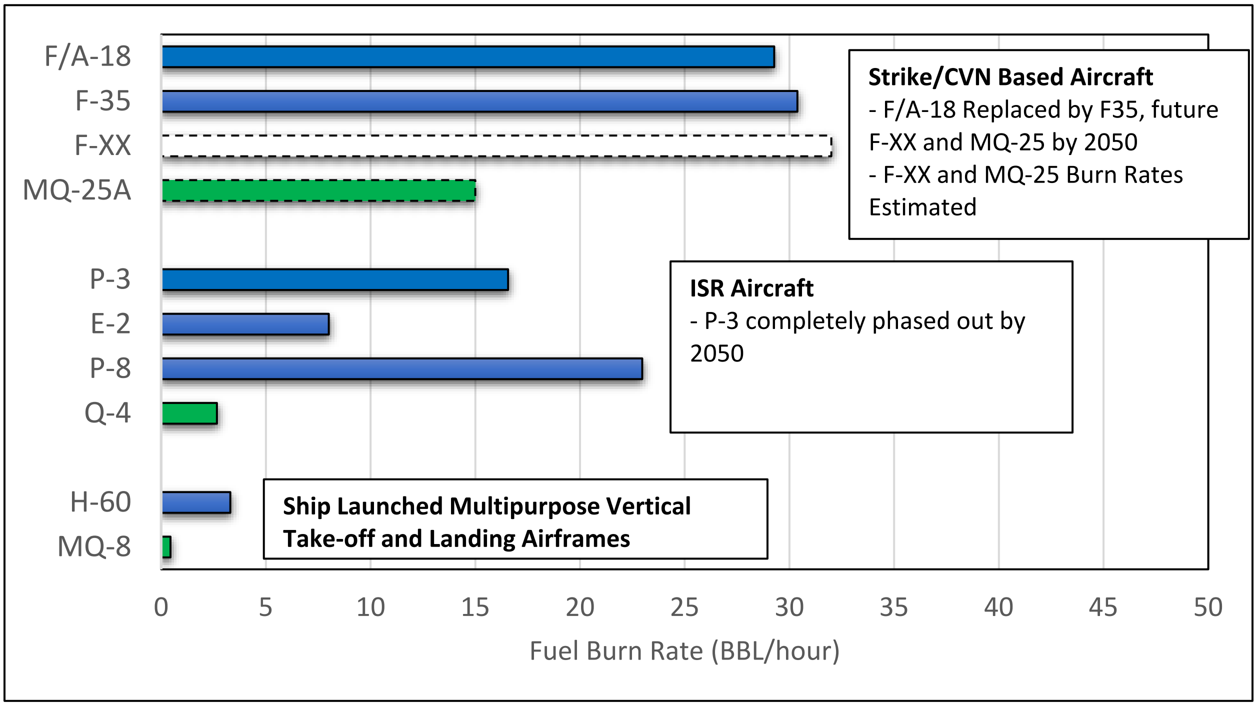

Figure 17. Comparison of Manned and Unmanned Aircraft Burn Rates

Numerous other UAS are in service today supporting manned mission requirements and adding capabilities to the Navy operational force. These include small battery powered UAS and medium sized platforms operating on battery, hydrocarbon fuels, or even hydrogen. The potential for these platforms to offset GHG emissions is difficult to estimate but may be a focus area for a future study.

c. Emissions Reductions from Virtual Training

The *Navy Aviation Vision 2030-2035* also describes advances in training to support future manned and unmanned requirements and benefits of Live/Virtual/Constructive (LVC), Fleet Surrogate, and Distributed Simulator concepts. These concepts apply methods that could reduce fuel consumption from training events and potentially offset GHG emissions. The reference describes those concepts as follows:[36]

> *Live/Virtual/Constructive Training - LVC training will consist of a network of aircrew-operated simulators (virtual) and computer generated airborne and surface forces (constructive) to augment live events, establishing a modernized integrated training environment. At its full capability in 2035, LVC training will enable live units to detect, track, classify, and engage virtual/constructive entities—and vice versa—with both kinetic and non-kinetic effects.*
>
> *The concept of a Fleet Surrogate is to utilize UJTS [Undergraduate Jet Training System] being developed for CNATRA to train fleet aircrew in less demanding mission sets. Advanced trainer aircraft can come with large area displays that can use software loads to mimic fleet aircraft displays. The large-area displays are reconfigurable, allowing for the provision of a cockpit environment capable of simulating various fleet aircraft. The addition of fully developed LVC systems will allow the Fleet Surrogate to emulate blue systems such as RADAR/IRST. The greatest benefits to be realized from the Fleet Surrogate is the actual flight time and training that can be accomplished at a fraction of the cost—potentially for as little as 15% of the cost of fleet aircraft—while simultaneously reducing some of the flight burden on Fleet aircraft.*
>
> *By 2035, all series simulators for the F/A-18, EA-18, E-2, F-35, P-8, MH-60, and MQ-25 will be integrated into the NCTE [Navy Continuous Training Environment] to allow for distributed training from the unit level up to the strike group level. A balance of tactical operational flight trainers and low-cost trainers will be utilized to increase capacity as well as shorten the concurrency window between an aircraft and its associated trainer's software loads.*

The impacts of these training concepts to DON GHG emissions are difficult to quantify, especially as unmanned systems proliferate further and concepts like NGAD FoS and Vertical Lift FoS are employed. Between 2008 and 2020 the Navy's Aviation Simulator Master Plan invested heavily in simulator upgrades to increase aircrew proficiency and reduce aircraft flight hours. Over that period, the DON reduced flying hours by 24%. Not all of the flying hours reduction can be attributed to simulators. As the DON increases the number of platforms as well as the speed, range, and capabilities within those platforms, it would not be reasonable to assume future training concepts would further reduce the flight hours and therefore GHG emission from naval airframes.

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[36] Naval Air Systems Command. 2021. "Navy Aviation Vision 2030-2035." https://media.defense.gov/2021/Oct/27/2002881262/-1/-1/0/NAVY%20AVIATION%20VISION%202030-2035_FNL.PDF.

B. NUCLEAR ENERGY

Nuclear powered ships have a long and proven history of successful use in the U.S. Navy. While they are not commonly included on emissions graphs, all U.S. Navy fleet carriers and submarines are effectively already zero emission platforms thanks to proven nuclear propulsion. The advantages of nuclear power to sustain naval capabilities are well understood and appreciated in the context of warfighting and logistics. Today, the afloat Navy force includes 11 aircraft carriers and 179 submarines operating exclusively on nuclear power. To understand the potential emissions reduction benefits of nuclear in the future force, this analysis compared the fuel use of the Navy's last diesel-powered aircraft carriers with today's fleet and normalized the total force to roughly estimate how much GHG emission are being avoided though use of nuclear power.

Figure 18 shows an approximated annual energy use of the total afloat naval force normalized to millions of megawatt hours (MWh) between 2008 and 2022. Actual fuel use data from Naval VAMOSC was used to plot MSC ships and diesel warships curves.[37] Actual energy use from the Navy's nuclear force is controlled, so to estimate their energy use the average annual fuel use from the final years of the last three diesel aircraft carriers (deactivated in 2008, 2007, and 2002) was applied for all carriers in operation today. Similar operational hours were also applied (3000 hours per year). To estimate the submarine force's energy use, the analysis calculated an approximate reactor loading ratio from the carrier force converting fuel use to MWh and applied that ratio (20%) and the same operating profile (3000 hours per year) across the force. This method produced a conservative estimate of total energy use and shows that approximately 36% of Navy operational energy is nuclear. At 430.14 kg of CO2e per barrel of diesel, it's further estimated that nuclear energy has realized a GHG emissions avoidance of approximately 3 million metric tons annually and will continue that through 2050.

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[37] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

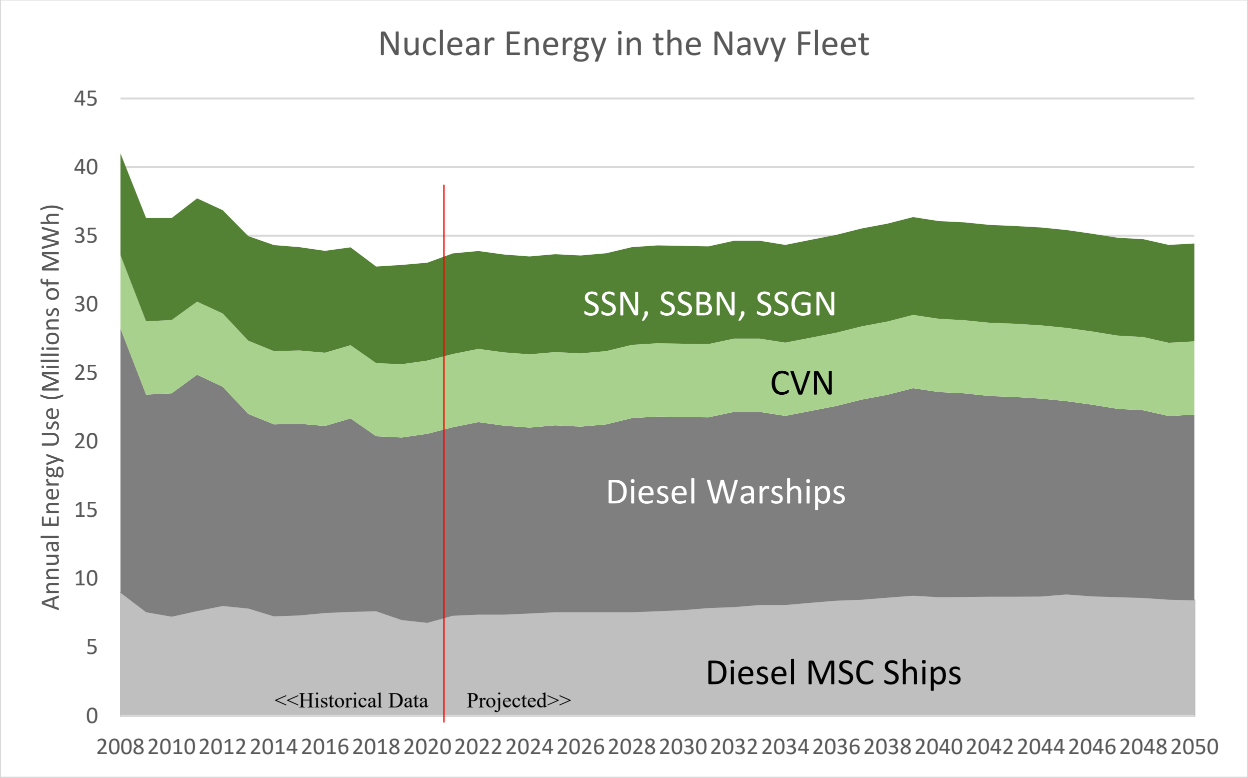

Figure 18. Energy Use of the Total Surface and Subsurface Fleet

Nuclear power also offers capability increases, eliminating the requirement for a refueling supply chain and giving huge amounts of excess power that can be used to power energy hungry systems. Ample power will likely be a key factor in enabling near future sensors and directed energy weapons. The defensive power of high energy laser systems is expected to be an indispensable capability increase, provided host ships can provide enough power to run and cool these new systems. With all that in mind, nuclear is unlikely to offer additional significant emissions reductions in the 2050 timeframe, as new, safer, cheaper reactor designs which are emerging will take time and significant investment to implement onto Navy ships. In the long term, incorporating nuclear power onto larger surface ships like DDGs and LHDs would seem to offer significant emissions reductions while increasing capabilities.

While nuclear has obvious potential to enhance capabilities and drastically reduce emissions for classes of ships like the DDG, there are several issues that reduce its attractiveness for surface combatants. The most important is cost. Nuclear powered ships are expensive to build, but beyond the upfront cost of procurement, the personnel and training requirements for the safe operation of a conventional pressurized water reactor have made past attempts at nuclear powered cruisers and destroyers too expensive to operate, leading to the early decommissioning of the Virginia-class cruisers.[38] If it were possible to design new nuclear-powered ships requiring fewer highly trained personnel, and less expensive refueling, either by reduced frequency or reduced cost, nuclear powered surface combatants would present a better solution to multiple future needs.

Older, conventional style nuclear reactors are costly to build and operate safely, but several new and upcoming reactor designs show potential for wider Navy use: advanced small modular reactors (SMRs) and fusion power. SMRs have been under development for several decades, and are beginning to reach technological maturity, with NuScale's US600 design being certified by the NRC on February 21, 2023.[39] These SMRs differ from conventional reactor designs in two significant ways: They are designed to be mass produced to dramatically reduce cost, and they are typically passively cooled, greatly reducing the complexity and size requirements for the reactor while also increasing safety. Some of the first SMRs are scheduled to be installed and operational in the early 2030s. An additional subclass of SMRs that may be of interest to the Navy has emerged recently: microreactors. Microreactors are even smaller, with projected sizes around the small building to shipping container scale which would make them somewhat easier to install on ships. Additionally, many microreactor designs are made to be passively cooled and unable to meltdown, with the design of the reactor being able to radiate its heat away even if coolant and power are lost from the system. This level of resiliency could make running them cheaper and safer than current reactor designs.

There may be potential to integrate these new reactors into future flights of ships being built as early as the 2030s, but a large engineering effort would be required. In the

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[38] Global Security. n.d. "CGN-42 AEGIS Modified Virginia." GlobalSecurity.org. Accessed July 15, 2023. https://www.globalsecurity.org/military/systems/ship/cgn-42.htm.
Seaforces.Org. n.d. CGN 38 – Virginia - class Guided Missile Cruiser. Accessed June 2023. https://www.seaforces.org/usnships/cgn/Virginia-class.htm.

[39] Office of Nuclear Energy. 2023. NRC Certifies First U.S. Small Modular Reactor Design. January 20. Accessed June 30, 2023. https://www.energy.gov/ne/articles/nrc-certifies-first-us-small-modular-reactor-design.

long term, new, safer, cheaper nuclear power options may present an ideal solution for naval vessels, however it is unlikely that many of these emerging reactor options could be integrated into ships before 2050 without huge redesign costs. Recent breakthroughs in fusion technologies are also beginning to indicate usable fusion reactors are coming soon, although it is impossible to say whether “soon” in the context of fusion means the 2030s or 2100s. With that in mind, once fusion power is mature and miniaturized, it will present the ideal power source for many applications, including Naval vessels.

C. CARBON CAPTURE & STORAGE

The application of Carbon Capture and Storage (CCS) concepts on the Department’s large deck logistics platforms could reduce the total DON operational emissions by as much as 6% by 2050. Other applications however, including naval aircraft and warships, are too limited in available margin for power, weight and volume to integrate carbon capture equipment and storage. Three key challenges exist for CCS across the transportation sector, regardless of the platform or process: those are 1) the power necessary to capture and displace CO2, 2) the storage of the recovered CO2, and 3) the offloading (at sea) of stored CO2. This section summarizes the state of CCS technology and highlights its potential.

1. Opportunity

In the 2020 report *Inventory of US Greenhouse Gas Emissions and Sinks*, the EPA accounts CO2 for 78.8% of total U.S. GHG emissions in 2020. This figure is weighted by global warming potential. The next largest contributors to greenhouse gas emissions are CH4, at 10.9%, and then N2O at 7.1%. It’s apparent CO2 gas represents a large opportunity for GHG emissions reductions.[40]

The EPA also reports that fossil fuel combustion accounts for 92% of the total U.S. CO2 emissions.[40] In naval operations, fossil fuel combustion accounts for nearly all CO2 emissions. As described earlier in this report, the majority of the DON’s ships and aircraft will still employ conventional gas turbine and diesel engines that burn a carbon-

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[40] Environmental Protection Agency. 2023. "Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2021." Washington. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

based fuel past 2050. Although measures for net zero drop-in fuels and efficiencies will eventually be employed, significant amounts of CO2 will be available in platform exhaust. Carbon capture would be complementary to any approach for addressing net-zero objectives on those platforms. Some innovations are showing applicability on transportation sector platforms, including maritime; however, several challenges must be addressed before carbon capture can be applied on naval ships or aircraft.

Generally, carbon capture is associated with terrestrial installations and involves post-combustion capture of CO2 molecules, typically within the exhaust. Applications for ships and aircraft would include CO2 capture from fossil fuel combustion, transport and storage within the platform, as well as transport and storage off the platform.

2. Carbon Capture on Aircraft

The mass of carbon and oxygen molecules generated from combusting hydrocarbon fuel, which essentially swaps the hydrogen atoms with oxygen atoms, is about three times the mass of the hydrocarbon fuel being converted. This becomes a problem on any platform that is limited in space and weight, which is certainly the case on aircraft. In current day-to-day operations, when commercial or military aircraft depart with a fuel load, the weight of the fuel being converted (to thrust) is lost as exhaust, so the aircraft lands lighter than it was at take-off. There is however empty volume within the fuel tanks at that time. If a carbon capture process were integrated onboard those aircraft, a one-for-one swap of jet fuel for CO2 would only allow about a third of the CO2 to be stored without adding weight. Alternatively, if the CO2 could be compressed or volume added to the aircraft, a greater amount of the CO2 could be stored, but weight would be added. Generally, these concepts have not been accepted in commercial aviation, and will not be accepted in military airframes designed for maximum mission performance (lethality, combat capability, etc.).

Figure 19 shows a projection of CO2e emission from DON aircraft, based on current operational tempo described in VAMOSC and growth described in the CNO's NAVPLAN.[41] The illustration shows that DON aircraft will account for an estimated 5.8 million metric tons of CO2e by 2050. The department's largest emissions contributors

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[41] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

are platforms without margin for additional CO2 storage capacity, or margins for the added equipment and power needed for CCS. Figure 20 illustrates distribution of DON aircraft emissions in 2020. F-35 and the future F/A-XX airframes will replace F/A-18 over the next 20+ years.[42]

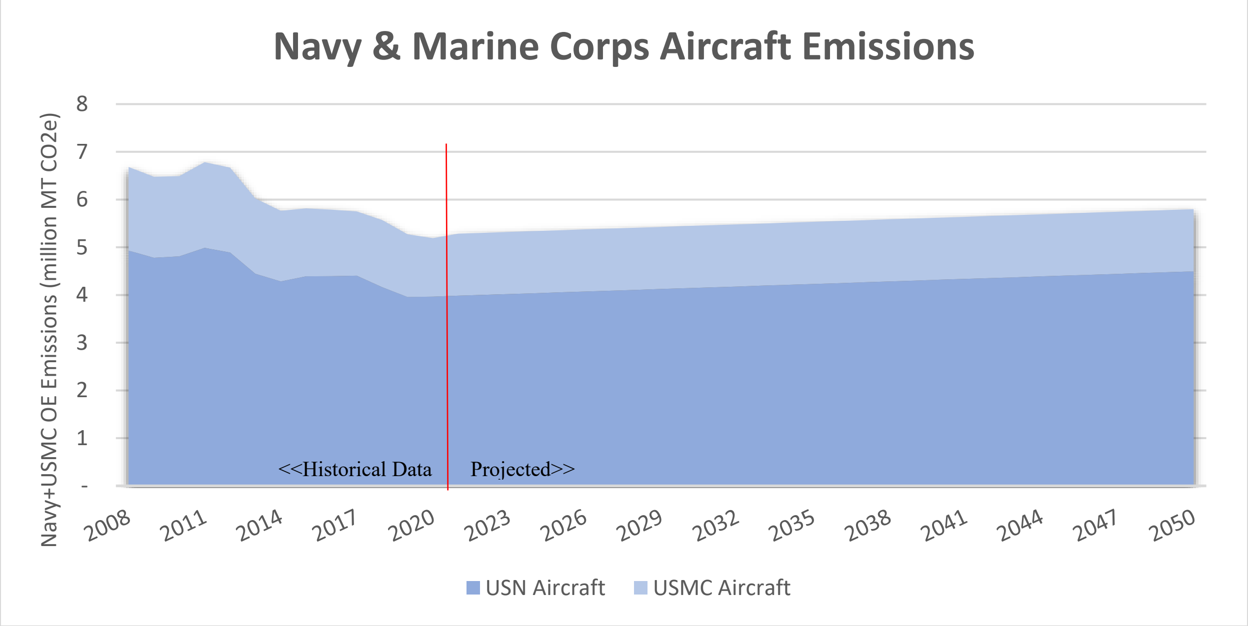

Figure 19. DON Aircraft Emissions

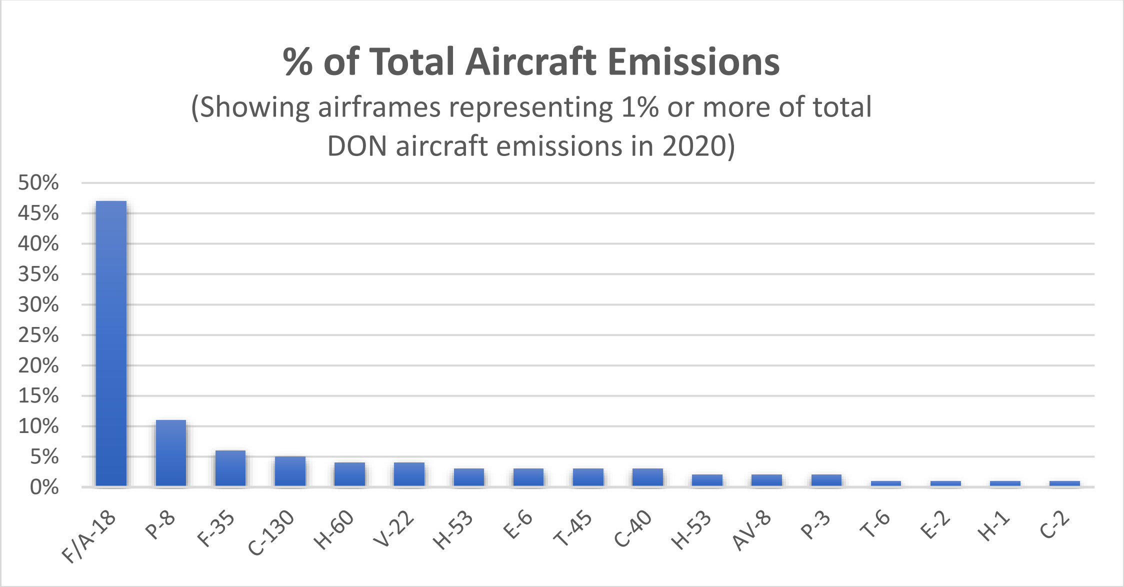

Figure 20. DON Aircraft Emissions Percentage by Aircraft Series

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[42] Office of the Chief of Naval Operations. 2022. "Navigation Plan 2022." Washington , July 26. https://www.doncio.navy.mil/FileHandler.ashx?ID=18929.

Terrestrial/Direct-Air carbon capture is however enabling aviation decarbonization. Generation of Sustainable Aircraft Fuel (SAF) uses captured and stored CO2, combined with hydrogen and additives to synthesize a compatible hydrocarbon jet fuel. The Department of Energy (DOE) and many commercial airlines are investing in this area, supporting the SAF Grand Challenge, but also looking at other options to store CO2 in the ground, or find other uses to sequester the carbon. The options and benefits to this application of carbon capture outweigh the challenge and benefit of aircraft, point-of-source, carbon capture. For this reason, it is not expected that onboard carbon capture will proliferate across commercial aviation. With the necessity to maintain maximum combat effectiveness on military aircraft, it is not expected the DON will integrate the concept before 2050.

3. Shipboard Carbon Capture

Maritime/shipboard carbon capture concepts must also address the CO2 storage challenge, but ships are generally not as limited in available weight and volume margins, and there are concepts in various phases of development to may allow periodic offloading of captured carbon. However, CCS has a significant power demand that will preclude certain platform types. Figure 21 shows Navy ships' CO2 emissions by platform, to include Military Sealift Command (MSC) ships and Figure 22 shows the distribution of ship CO2 emissions by class. Classes representing less than 1% are not shown. The figure highlights the opportunity-space for emissions reductions.[43]

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[43] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

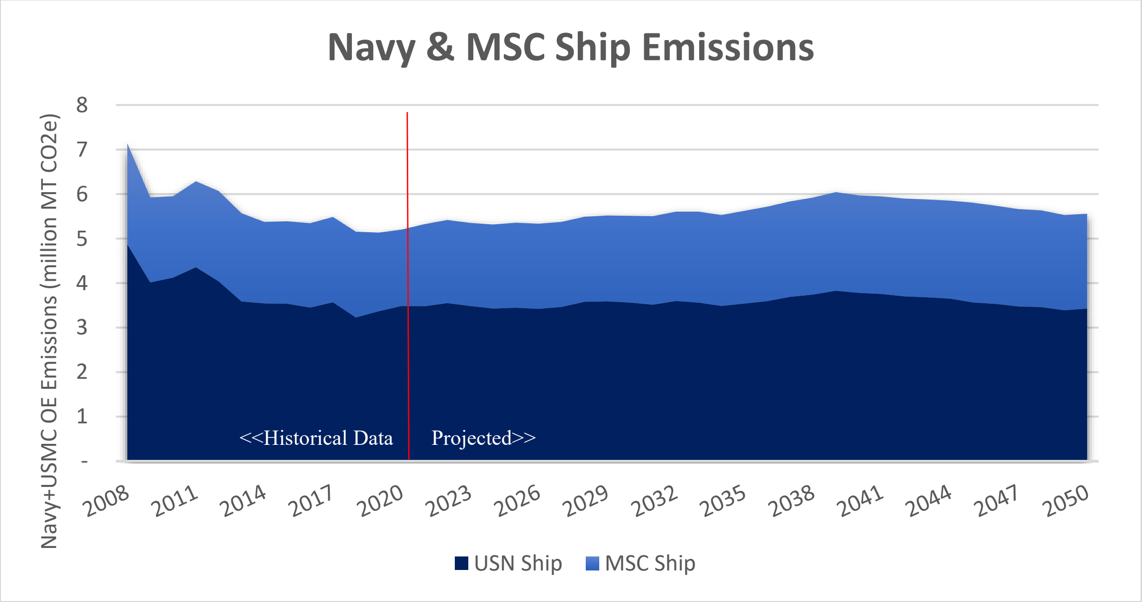

Figure 21. Navy Ship Emissions

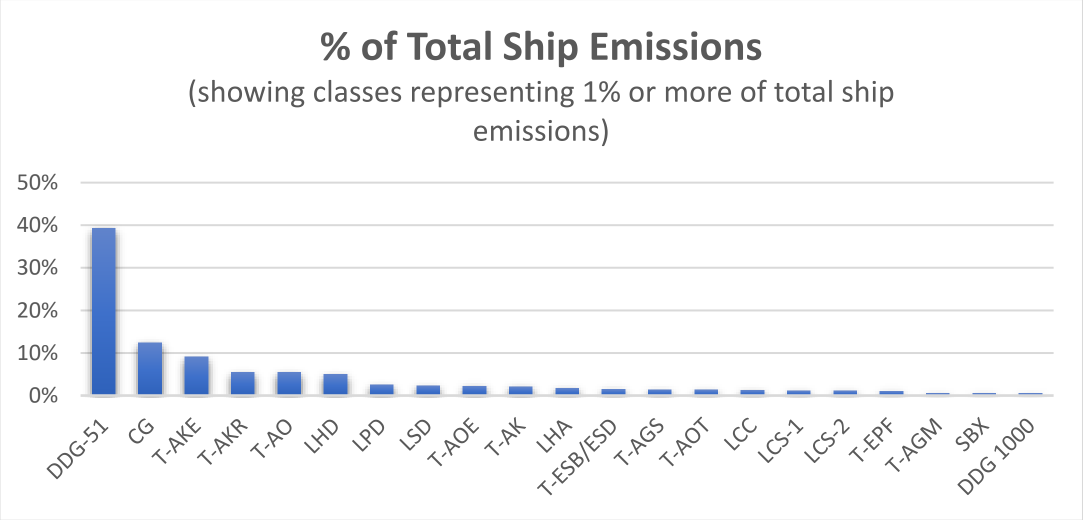

Figure 22. Ship Emissions Percentage by Class

a. Shipboard Carbon Capture Technologies

The more mature technologies currently in development for shipboard Carbon Capture apply concepts already in use for industrial applications, and although numerous processes exist, three technologies are mature enough to get commercial maritime interest: Chemical Adsorption, Membrane Separation, and Physical Adsorption. As suggested in previously, it is expected that Navy ships will still primarily employ conventional gas turbine and marine diesel engines; for this reason, pre-combustion carbon capture concepts, which separate hydrocarbons to form a hydrogen fuel, were not considered applicable.[44]

- **Chemical Adsorption** is considered the most mature carbon capture process. This cycle first pretreats the exhaust gas to reduce SOx and NOx in the exhaust, then pushes the remaining gas through a solvent that absorbs CO2. The remaining exhaust is released to the atmosphere, while the now CO2 rich solvent is cycled through a heat exchanger and stripper to separate the CO2 from the solvent. The solvent continues to cycle, and the CO2 is then stored. This process could capture over 90% of CO2 from industrial exhaust, and is expected to perform similarly in shipboard applications.

- **Membrane Separation** systems use several vacuum pumps and layers of permeable materials in the exhaust stream to filter CO2. The captured CO2 is liquified through a condensation system for storage. This is generally a more compact system than the Chemical Adsorption system, but can only capture 60-85% of the CO2 within the exhaust.

- **Physical Adsorption** systems use a sorbent material, as opposed to a solvent in chemical systems, designed to cause CO2 to adhere to the surface of the material. The exhaust gas is first pretreated to remove moisture, SOx, and NOx, then pressurized through a sorbent bed. Once that bed has adsorbed its limit in CO2 a series of pumps and heat exchangers separate the CO2 from the sorbent, and the CO2 is stored. A sorbent bed cannot adsorb CO2 while CO2 is being removed, so two or more sorbent beds are needed to allow continuous carbon capture and storage. Physical Adsorption could capture over 90% of the available CO2.

Each process for carbon capture is unique in the specific equipment needed, but generally the integration includes multiple pumps, heat exchangers, and sensors, paired with adsorbers/membranes, separators, piping, cabling, and controls. The demand that CC equipment places on power generation and systems integration is significant across all processes. Quantifying the power demand is difficult because the state of the technology, but an analysis performed by LCE of a bulk tanker suggests the added load could increase total platform energy demand over 50% to capture 84% of CO2 emission, and over 20% to capture 40% of CO2. Another study from the Maersk McKinney Moller Center estimated up to 45% increase in energy consumption from capture, liquefaction,

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[44] Life Cycle Engineering. 2022. "Marine Carbon Capture Technology Review." Technical Report, Washington.

and storage to capture 82% of exhaust CO2.[45] Several Chemical Adsorption systems have been retrofitted to commercial tankers; Figure 23 shows the FilTree carbon capture system and provides a good example of the invasive nature of the carbon capture system. CO2 storage is not shown.[46]

Figure 23. Carbon Capture System on EPS-Managed Tanker (EPS)

As described before, the mass of CO2 is over three times the mass of the hydrocarbon fuel being used, therefore only a third of the converted CO2 could be stored without adding weight to the platform. The volume of the CO2 being stored will depend on whether it is stored as gas, liquid, or solid (dry ice). Storing CO2 as gas would require over six times the volume of the displaced fuel, whereas liquid or solid storage offer the potential to maintain or reduced the necessary volume, but both would require compression and/or refrigeration as shown in Table 2.

CO2 Storage*	Density (kg/m^3)
F76 (for reference)	840
Compressed/Refrigerated Liquid (-29° C, 300 psi)	1073
Compressed Gas at Ambient Temperature (800 psi)	128
Compressed Fluid at Ambient Temperature (3000 psi)	828
Dry Ice Storage at Ambient Pressure (-84° C)	1562

Table 2. Density of CO2 in Different States

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[45] Mearsk-McKenny Moller Center for Zero Carbon Shipping. 2022. "The Role of Onboard Carbon Capture in Maritime Decarbonization." Technical Report, Copenhagen.

[46] The Maritime Executive. 2023. First Carbon Capture System Installed on EPS Managed Tanker. February. Accessed July 15, 2023. https://maritime-executive.com/article/first-carbon-capture-system-installed-on-eps-managed-tanker.

As shown in Figure 22, the opportunity for maximum carbon capture is with the DDG-51 and CG Classes, and future large surface combatants (destroyers and cruisers). These are the Navy's most capable combatant ships designed to deliver maximum warfighting effects, including air warfare, ballistic missile defense, surface warfare, and undersea warfare. Power, weight, and volume margins to modernize those platforms are minimal, and are committed to increasing combat lethality, which includes upgrades to radar systems, fire control, weapons, electronic warfare systems, and communications. The integration of carbon capture equipment or CO2 storage tanks will not be prioritized over those upgrades. Further, both classes use seawater compensated fuel tanks to maintain weight and stability; the conversion of the existing fuel tanks or addition of CO2 tanks would be an immense undertaking and would still only allow a third of total available CO2 to be stored without impacting stability. Furthermore, the energy demand necessary to capture and store CO2 would likely be more limiting. These platforms, along with other combatants (LCS and DDG-1000) and the amphibious ships (LHD, LPD, LSD, LHA, and LCC) are expected to operate in distributed and austere environments where platform endurance is critical to mission success. The added power load, and storage weight and volume would be unacceptable additions to these platforms. CCS is not likely to be integrated on Navy combatants and amphibious ships within a period that could support net-zero by 2050.

The Navy's MSC platforms fill a logistics role for the Department and more closely resemble commercial maritime ships. MSCs large-deck platforms, the T-AKE, T-AKR, T-AO, T-AOE, T-AK, and T-AOT class ships (Ammunition, Tanker, and Cargo missions), together account for 26% of total ship emissions. Generally, these platforms have power generation margin available to potentially support CCS and may have volume available in peacetime operations to integrate CCS equipment and store CO2. These ships are also designed and maintained to ABS standards; so as commercial maritime continues to validate CCS on ships, and ABS approves the system integration, transport, and storage, MSC could start integrating those proven technologies. Over the next few decades some of these platforms will be retired and replaced, and some replacement platforms may not have characteristics ideal for CCS, including the Next

Generation Logistics Ship (NGLS) that will enter service around 2030. However, by 2050, if the cost and risk to integrate CCS technology become acceptable, and the logistics to transfer captured CO2 is available, CCS on MSC's large-deck platforms could reduce the total emission from naval operational platforms by about 6 percent. The math assumes energy demand increase of 45% for CCS to recover 90% of exhaust CO2.

4. CCS Summary

CCS technologies for maritime applications are being integrated and tested on commercial tankers and may be an option for the Navy's MSC ships by 2050. The power demand and storage requirement will preclude naval aircraft and warships, as well as smaller support ships, but MSC's larger logistics platforms represent 12% of total emissions from operational platforms, could have sufficient power, weight, and volume margin to integrate CCS. Some integration challenges will be addressed over the next few decades, to include offloading CO2 at sea, and some early concepts to discharge CO2 at sea may also support the pathway.

D. SUSTAINABLE FUELS

Over the next few decades fuel demand is expected to increase with the growth of the naval force described in the shipbuilding plan, the CNO's NAVPLAN, and the *Navy Aviation Vision 2030-2035*. Traditionally, hydrocarbon fuels have come from fossil sources, but new technologies have made sustainable "drop-in" replacements possible. For naval use, these drop-in replacement fuels can be effectively carbon neutral, and come without sacrificing warfighting capability.

Two drop-in fuel sources are gaining momentum. First, drop-in fuels produced by Fischer-Tropsch processes utilizing direct air carbon capture and hydrogen electrolysis, and powered by renewable energy, show high potential for scalability. Significant investment is needed now to scale these technologies to reach required production levels and reduce costs. Second, drop-in fuels made by biological methods, biofuels, also show potential but may have issues with long term cost and scaling due to land and labor requirements.

Several corporations and government stakeholders have already started to invest heavily into technology and integration to scale the various processes. To ensure considerations are made for the Navy's unique needs for high flash point fuels, F-76 and JP-5, coordination and collaboration with these other stakeholders is necessary. Additionally, the cost of scaling renewable fuel production may be too high for any one organization to accomplish alone, so working with partnerships will be necessary to ensure sustainable drop-in fuels are cost competitive with petroleum-based fuels.

1. The DON Fuel Requirement

As established earlier in this report, the DON will likely continue to integrate proven gas turbine and marine diesel engines on aircraft and ships over the next few decades. Given the expected growth in fleet size and capabilities, it is reasonable to expect fuel demand to increase. Assuming operating profiles like today's naval operating platforms, and applying expected growth described in the Navy's shipbuilding plan and the CNO's NAVPLAN, the DON will demand approximately 28M barrels of liquid fuel per year in 2050 (Figure 24).[47]

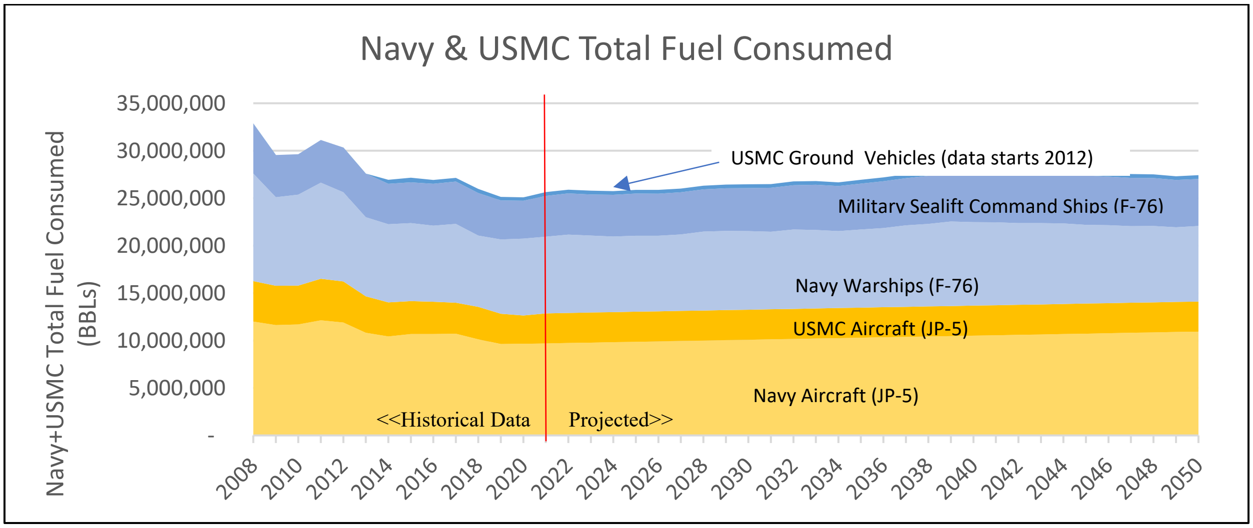

Figure 24. Total DON Fuel Use (Historical and Projected)

Operational ship and aircraft fuel use constitutes most Navy carbon emissions. To make real, significant progress towards reducing emissions, the widespread use of fossil fuels for operational platforms must be eliminated. Realistically, any alternative to fossil fuels must not have a negative effect on warfighting capabilities, as the DON's

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[47] Department of Navy. 2023. Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System. Accessed June 1, 2023. https://www.vamosc.navy.mil/.

primary mission remains to maintain a combat ready force, capable of winning wars and deterring aggression. Toward this end, there are relatively few options for replacing fossil fuels in the operational force. Many options are either technologically immature, compromise warfighting capabilities, or simply do not have the potential to dramatically slash emissions. When considering these requirements, few options for decarbonization remain. Sustainable drop-in replacements for fossil fuels are the leading and, in some cases, only option. Alternative fuels may have limited uses as well, primarily in platforms with less stringent power requirements.

2. Drop-In Replacement Fuels

Sustainable drop-in replacement fuels are fuels generated through renewable means, either through the use of a biological feedstock or directly from atmospheric CO2, water, and energy. These fuels can be used in the same engines as their fossil fuel counterparts with little or no modification. Drop-in replacement fuels can be made chemically identical to current fuels such as JP-5 and F-76, while being produced by carbon negative methods, resulting in net low-carbon or carbon neutral alternatives, as they form a closed loop carbon cycle, as shown in Figure 25.

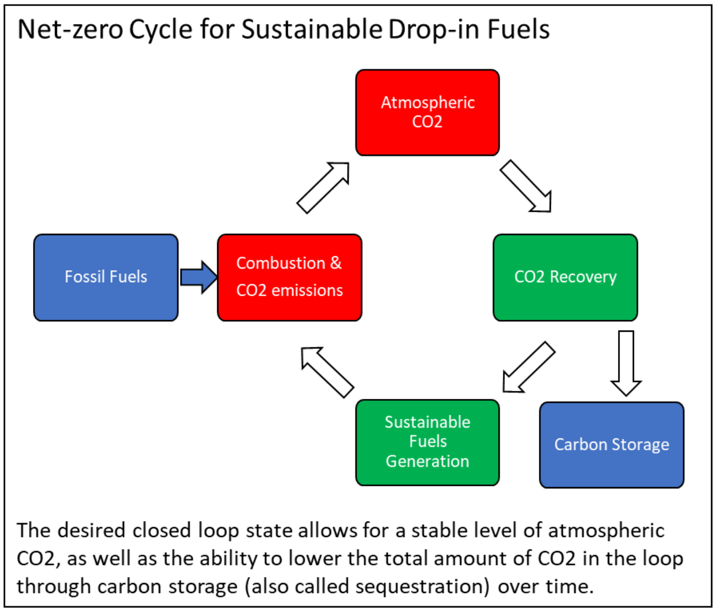

Figure 25. A Closed Loop Carbon Cycle Using Drop-in Alternative Fuels

While drop-in fuels present a nearly ideal option for decarbonization, they will first require massive scaling efforts to reach technological maturity and economies-of-scale. Production of sustainable fuels is currently mostly non-drop-in biofuels such as ethanol. For drop-in fuel production, yearly production values are much lower, in the range of 10,000-100,000 gallons per year, although it is difficult to obtain exact production numbers as the Energy Information Administration (EIA) does not appear to distinguish between alternative fuel types when reporting production data.

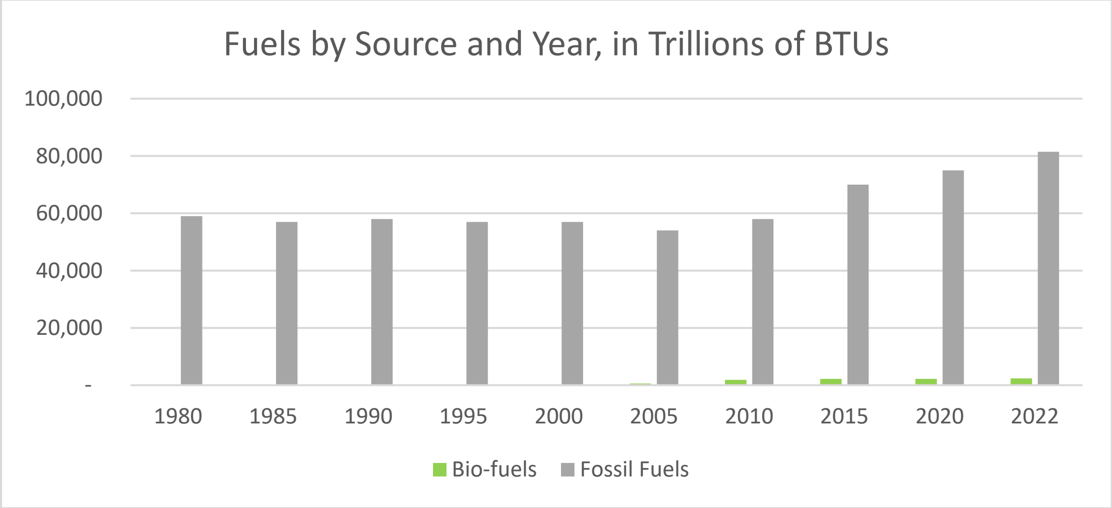

Figure 26. Fuel Production by Year, Based on EIA Data[48,49]

While simple, non-drop-in biofuels are currently produced in relatively high quantities, biofuels are costly and require large amounts of arable land for production, completing with other crops for farmland. A more promising but less industrially mature option for drop-in fuel production are fully synthetic fuels, which are generated directly from air, water, and energy. Industry interest in these fuels is high, but production processes are not yet widely scaled, with annual production in the 10,000-100,000 gallons per year, but rapidly increasing, with the vast majority coming from individual pilot plants from private companies such as Porsche and Twelve.

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[48] Total Energy Monthly Data - U.S. Energy Information Administration (EIA). Accessed October 20, 2023. https://www.eia.gov/totalenergy/data/monthly/index.php.

[49] "Petroleum & Other Liquids - U.S. Energy Information Administration (EIA)." Petroleum & Other Liquids - U.S. Energy Information Administration (EIA). Accessed October 20, 2023. https://www.eia.gov/petroleum/.

3. Alternative Non-Drop-In Fuels

Alternative non-drop-in fuels are those which would require significant resigns to platforms and transportation infrastructure. These fuels are unlikely to meet naval operational energy needs in the 2050 timeframe, although certain fuels (hydrogen) may be good solutions for future platforms and others (ammonia, methanol, hydrogen) may be usable for non-combat logistics such as USNS ships in the sealift command. Within the umbrella of alternative fuels there is a high degree of variability in fuel characteristics. Most critical for military applications is the energy to volume ratio and energy to weight ratio, which varies greatly between different options as shown in Figure 27.

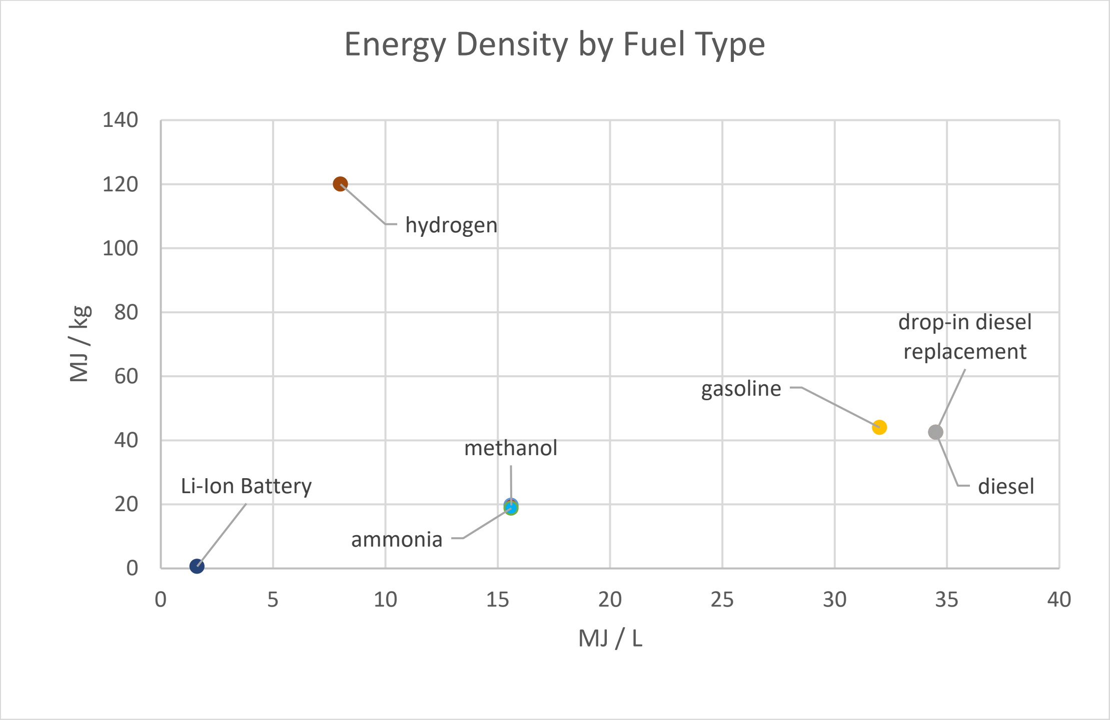

Figure 27. Energy Density of Different Classes of Fuels Compared.

As shown by the graph above, most alternative fuels are significantly less energy dense than diesel, both by weight and volume, making them unlikely to ever be widely adopted for high performance applications. The exception to this is cryogenic liquid hydrogen, which may someday present a strong option for weight critical applications such as aircraft, although it should be noted that substantial advances in cryogenic storage methods will be required to reach that potential. For naval applications in the 2050 timeframe, it is unlikely that any alternative fuel will be ready for widespread use in combat platforms.

Beyond the 2050 timeframe, there is a possibility for liquid-cryogenic hydrogen to replace hydrocarbon fuels as the high-performance fuel of choice for weight critical applications like aircraft, although its utilization will require major platform redesigns to incorporate larger, cryogenic fuel tanks on high performance aircraft.

4. Chemistry and Scale for Drop-In Fuels

This section investigates the chemical processes and demonstrated scale of both fully synthetic and bio based drop-in replacement fuels, and their potential to serve as sustainable versions of JP-5 and F-76. It is found that while biofuels are currently more mature technologically, fully synthetic fuels may have better potential for massive scaling in the coming decades, although both show potential for scaled fuel production. The reasoning for this conclusion is discussed in the following subsections.

All methods of creating net-zero or low carbon drop-in fuels have similar inputs and outputs, but the steps taken to create the fuels vary significantly. At the highest level, all major techniques rely on harvesting CO2 from the atmosphere and hydrogen from water to synthesize hydrocarbons, yielding oxygen as a byproduct. This is functionally a closed loop cycle, as combusting the fuel generated will re-release CO2 and water into the atmosphere. However, creating and storing surplus fuel can theoretically be used to create negative carbon emissions, effectively reversing the fossil fuel emissions cycle.

a. Biofuels

Biofuels are sustainable fuels produced using plants or other biological processes that harvest CO2 and hydrogen. Biofuel generation processes are relatively mature, scaled to industrial volumes, and generally better understood than fully synthetic fuels. Most sustainable fuels produced today are biofuels. Biofuel production has several challenges however: 1) they require large amounts of land, often requiring crop cultivation or deforestation; 2) they also require complex chemical refinement, and 3) they often compete with food crops for land use, which can cause political issues. Biomass can sometimes be refined into low quality fuels directly, although a significant number of steps are required to create high purity “drop in” replacements for diesel and jet fuel equivalents.[50] Depending on the steps required for a given feedstock and end product (for example palm oil to Jet-A), the suitability of biomass as a source for net-zero fuels depends highly on the feedstock source and quality, the desired end-product, and the specific process used to make the fuel, of which there are numerous alternative processes for the same end result.[51] One issue common in using biomass for high grade fuel production is the presence of contaminates in the source feedstock, as the biomass will contain everything present in the source plant or organic mass, including high levels of water and/or other undesirable molecules. These contaminates can lower the power potential of final fuel products if they are not removed through upgrading the fuel or mechanisms in the generation process. While it is commonly possible to upgrade lower grade fuels to higher, the process usually requires more energy, creates additional bi-products, and reduces fuel quantity yielded.

Compared to fully synthetic fuels, biofuels are by far the more widely scaled and demonstrated option for creating alternative fuels. Due to the relative ease of the creation process, biofuel options have been developed with a variety of feedstocks and production methods and represent nearly 100% of the sustainable fuel available in 2023. Although it is important to note that much of current biofuel production is non-drop-in fuels such as ethanol. While the process for making synthetic fuels has the potential to be fundamentally simpler, biofuel technology has been matured at a faster rate, given it can be done with processes derived from well know fossil fuel refinement technologies, and crop cultivation is an established industry. Biofuel production has been steadily growing since the 1980s, with accelerated growth in the 2000-2020 time frame, although much of this is non-drop-in fuels such as ethanol, which is not useful in drop-in fuel generation.

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[50] Sousa Castro, Karoline de, Luís Fernando de Medeiros Costa, Valter José Fernandes, Regineide de Oliveira Lima, Aruzza Mabel de Morais Araújo, Mikele Cândida Sousa de Sant'Anna, Nataly Albuquerque dos Santos, and Amanda Duarte Gondim. 2020. "RSC Advances 11, no. 1." Catalytic Pyrolysis of Palm Oil to Obtain Renewable Hydrocarbons, December: 555-64. https://doi.org/10.1039/d0ra06122k.
Budzianowski, Wojciech M. 2016. "A Review of Potential Innovations for Production, Conditioning and Utilization of Biogas with Multiple-Criteria Assessment." Renewable and Sustainable Energy Reviews, February: 54. https://doi.org/10.1016/j.rser.20.

[51] Pool, Robert P. 2014. "Case Study: The Palm Oil Example." In The Nexus of Biofuels, Climate Change, and Human Health. Washington: National Academies Press.
Zahan, Khairul, and Manabu Kano. 2018. "Biodiesel Production from Palm Oil, Its by-Products, and Mill Effluent: A Review." Energies 11, no 8. https://doi.org/10.3390/en11082132.

Figure 28 illustrates current production rates of biofuels compared to conventional fossil fuels.[52]

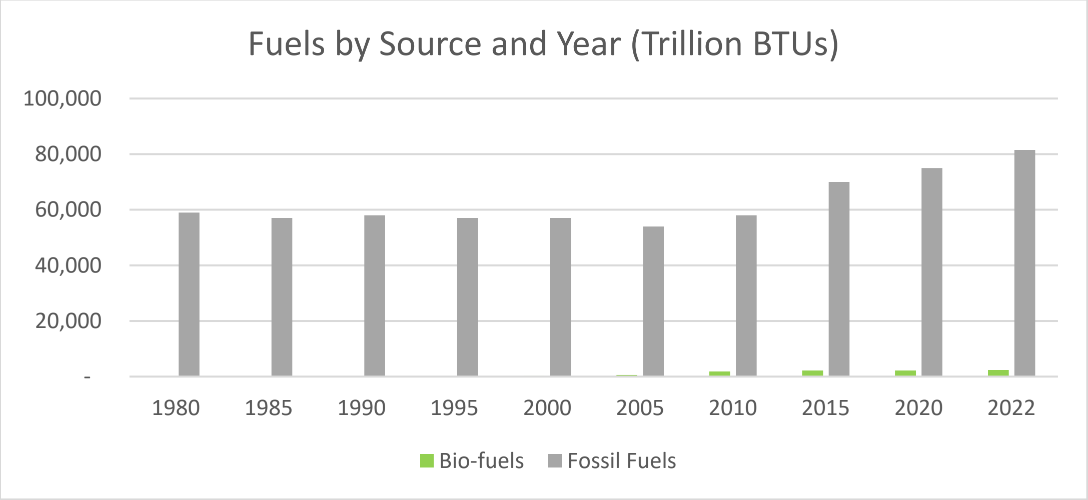

Figure 28. Current and Historical Biofuel and Fossil Fuel Production Rates

While non-drop-in biofuel still accounts for a small overall percentage of total fuel production, it is now within a couple orders of magnitude as fossil fuel production and expected to continue growing.[53]

The advantages of biological processes as a method for sustainable fuel generation are substantial, but it also comes with various drawbacks. Perhaps the most important of which is land use. Biomass for high quality fuels is generally sourced from a dedicated fuel crop, requiring large amounts of arable land suitable to a specific crop type. For this reason, biofuel crops are often competing for highly desirable farmland. When compared to synthetic processes, the land requirements for biofuel generation are a degrading factor. While biological processes can be used to harvest hydrogen and carbon from the environment, synthetic processes such as Direct Air Carbon Capture (DAC) are far more efficient from a land requirements standpoint, with a DAC plant of less than a

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[52] Energy Information Administration. 2023. Petroleum & Other Liquids. Accessed October 20, 2023. https://www.eia.gov/petroleum/.

[53] Energy Information Administration. 2023. "Monthly Energy Review August." Washington. Accessed September 28, 2023. https://www.eia.gov/totalenergy/data/monthly/pdf/sec10_3.pdf;
Energy Information Administration. 2023. EIA Projects U.S. Biofuel Production to Slowly Increase through 2050. Accessed September 28, 2023. https://www.eia.gov/todayinenergy/detail.php?id=43096.

square kilometer being able to harvest the same amount of CO2 as over 800 kilometers of forest.[54] DAC plants also do not share the requirement for arable land, meaning they can be built in deserts and areas of poor soil quality, where biomass farming would be competing with other crop economies.

b. Synthetic Drop-In Fuels (E-Fuels)

Synthetic drop-in fuels are defined in this document as sustainable (low carbon or carbon neutral) drop-in fuels generated by synthetic means rather than through biomass or a similar process. Synthetic fuels can be generated by a verity of methods, although many carbon neutral and carbon negative methods are similar from an inputs and outputs perspective. Most processes harvest carbon from CO2 in ambient air and hydrogen from a water source, either ocean or fresh water, or by pulling moisture directly from the air.

$$CO_2 + H_2O \ + Energy > C_nH_n + O_2$$

Equation 1: The basic equation for most carbon neutral fuel generation. The term "C_nH_n" represents the basic hydrocarbon chain structure which makes up almost all fossil fuels.

While the processes and intermediate steps may vary from process to process, the above chemical equation is at the heart of most carbon neutral drop-in fuel generation. Different processes vary in efficiency, speed, and space requirements, but the fundamental inputs and outputs remain the same. For fully synthetic fuels, the process can be broken into two of significant sub steps: Syngas generation, where carbon and hydrogen are harvested and concentrated, and Fuel synthesis, often through the Fischer Tropsch process, to combine hydrogen gas and CO2 into hydro-carbon chains. The length of the carbon chain can be tailored through tuning the reaction process to produce different types of fuels.[55] For fully carbon neutral processes, syngas is composed of

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[54] Lebling, Katie, Haley Leslie-Bole, Zach Byrum, and Liz Bridgwater. 2022. "6 Things to Know about Direct Air Capture." World Resources Institute, May 2. https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal;
Cook-Patton, Susan C., Sara M. Leavitt, David Gibbs, Nancy L. Harris, Kristine Lister, Kristina J. Anderson-Teixeira, Russell D. Briggs, et al. 2020. "Mapping Carbon Accumulation Potential from Global Natural Forest Regrowth." Nature 585, no. 7826, 545–5. https://doi.org/10.1038/s41586-020-2686-x;
Keith, David W., Geoffrey Holmes, David St. Angelo, and Kenton Heidel. 2018. "A Process for Capturing CO2 from the Atmosphere." Joule 2, no. 8, 1635. https://doi.org/10.1016/j.joule.2018.06.010.

[55] Chen, Chi, Mahlet Garedew, and Stafford W. Sheehan. n.d. "Single-Step Production of Alcohols and Paraffins from CO2 and H2 at Metric Ton Scale." ACS Energy Letters 7, no. 3, 988–92. https://doi.org/10.1021/acsenergylett.2c00214.

carbon dioxide and hydrogen gas, harvested from the environment. Hydrogen is generally electrolyzed directly from water, which is a well-understood and scalable process, although it is energy intensive. By contrast, DAC capture is a relatively new technology, and while research shows it may be far less energy intensive than hydrogen electrolyzation, a large amount of development in scaling and technology maturation is required to incorporate it on the industrial production scale required for future sustainable fuel needs.

(1) Current examples and scale of synthetic fuels

Fully synthetic fuels are a relatively new technology, and fully developed examples are not yet common. Many of the large scale pilot projects currently in development do not share detailed data for corporate reasons. There are, however, some limited examples visible. A number of approaches are under scientific development, with production scales at or around 1 ton per day, however many of these are for the purpose of exploring new and more effective ways for generating fuels. A handful of large-scale corporate projects exist or are in late development with production of 34000 gallons per year at Porsche[56], 70,000 gallons per year at ReadiJet[57], and 40,000 gallons per year at Twelve.[58] For total production worldwide, The International Air Transport Association estimated SAF yearly production to be between 80-110 million gallons.[59]

(2) Carbon capture as it relates to synthetic fuels

Carbon capture is a critical step in generation of fully synthetic sustainable fuels. Under the umbrella of carbon capture, there are a verity of methods for pulling CO2

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[56] Porsche Newsroom. n.d. Efuels Pilot Plant in Chile Officially Opened. Accessed August 28, 2023. https://newsroom.porsche.com/en/2022/company/porsche-highly-innovative-fuels-hif-opening-efuels-pilot-plant-haru-oni-chile-synthetic-fuels-30732.html.

[57] Applied Research Associates, Inc. 2022. ASTM International Approves New Production Pathway for Sustainable Aviation Fuel. January 23. Accessed 2023. https://www.ara.com/news/astm-international-approves-new-production-pathway-sustainable-aviation-fuel/.

[58] Velev, Vasil. 2023. "Twelve Starts Construction of First US Commercial-Scale Plant for Producing Sustainable Aviation Fuel from CO2." Carbon Herald, July 13. https://carbonherald.com/twelve-first-commercial-plant-sustainable-aviation-fuel-co2/;
Twelve. n.d. The Carbon Transformation Company. Accessed September 28, 2023. https://www.twelve.co/.

[59] International Air Transport Association. International Air Transport Association. SAF Production Increases 200% - More Incentives Needed to Reach Net Zero. Accessed September 28, 2023. https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/.

directly out of the air that can broadly be split into two categories: point-of-source carbon capture, which is not a viable solution for the creation of truly carbon neural or carbon negative fuels, and DAC. Please note that the previous sentence does not address point-of-source capture's effectiveness for all applications, just in the generation of scalable and long-term carbon neutral fuels. This is because most point of source capture methods which have been explored to this point are capturing CO2 of a fossil fuel process, such as a natural gas or coal plant. If the carbon captured from that point-of-source is used in a fuel, rather than being permanently stored, all the alternative fuel has done is delay more carbon emissions. For truly net-zero fuels, the carbon used must be pulled from the atmosphere, so as to create a closed loop and halt the release of new carbon into the air[60].

Many historical examples for synthetic fuel generation used already concentrated sources of CO2 or carbon monoxide which were typically byproducts of fossil energy processes. While these examples were and are important scientific steps, they do not represent a fully carbon neutral solution, and must be paired with a true environmental DAC method to be truly carbon neutral. For fully synthetic fuel generation, the DAC process can be simplified, as CO2 simply needs to be separated from the air and concentrated to high levels or purity, as opposed to permanently stored or chemical manipulated. Research shows that this process is potentially far less energy intensive than the electrolyzation of hydrogen. With the demonstrated energy cost per ton CO2 around 1500kWhel and emerging technologies showing promise be as low as 316kWhel per ton CO2[61]. This is in contrast to the energy cost of hydrogen electrolyzation, which generally sits at around 55000-65000kWhel per ton of hydrogen for conventional systems[62].

The nature of DAC is such that it can be done nearly anywhere in the world. The ability to use DAC anywhere is one of its major advantages over processes that need to be located near agricultural areas, or near power plants and other industrial sources of

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[60] International Energy Agency. n.d. Direct Air Capture - Energy System. Accessed September 28, 2023. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture.

[61] Fasihi, Mahdi, Olga Efimova, and Christian Breyer. 2019. "Techno-Economic Assessment of CO2 Direct Air Capture Plants." Journal of Cleaner Production 224 957–80 957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.

[62] Science.org. n.d. Sustainable Hydrogen Production. Accessed September 28, 2023. https://www.science.org/doi/10.1126/science.1103197.

concentrated carbon emissions. While the potential for DAC to scale is obvious, there are several factors which must be optimized for it to be truly effective. Like all ways of generating renewable fuels, it must be compact enough that it does not take up to much land usage, energy efficient such that it can feasibly be powered using existing methods, and cost effective, although the cost effectiveness is likely to become less of a concern as the devastating effects of climate change begin to compound and governments swivel to support progress towards net-zero. When compared to biological processes DAC far more efficient from a land requirements standpoint, with a DAC plant of less than a square kilometer being able to harvest the same amount of CO2 as over 800 kilometers of forest[63]. DAC plants also do not share the requirement for arable land, meaning they can be built in deserts and areas of poor soil quality, where biomass farming would be competing with other crop economies.

DAC is a relatively young technology. While DAC methods have existed for over a decade, heavy industry investment and interest in recent years has revealed several fundamentally new methods, with the potential to reduce the historically large energy and space costs of DAC. While historical methods for DAC rely on chemical sorbents,[64] which would bind CO2 at one temperature and release it at another, usually higher, temperature, new methods using humidity swings[65] or changes in electric charge[66] have recently appeared which have the potential to greatly reduce the energy cost of harvesting CO2 from atmosphere. One important consideration when investigating DAC for use in net-zero fuels is the format of CO2 output. For carbon sequestration carbon form CO2 is

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[63] Lebling, Katie, Haley Leslie-Bole, Zach Byrum, and Liz Bridgwater. 2022. "6 Things to Know about Direct Air Capture." World Resources Institute, May 2. https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal;
Cook-Patton, Susan C., Sara M. Leavitt, David Gibbs, Nancy L. Harris, Kristine Lister, Kristina J. Anderson-Teixeira, Russell D. Briggs, et al. 2020. "Mapping Carbon Accumulation Potential from Global Natural Forest Regrowth." Nature 585, no. 7826, 545–5. https://doi.org/10.1038/s41586-020-2686-x;
Keith, David W., Geoffrey Holmes, David St. Angelo, and Kenton Heidel. 2018. "A Process for Capturing CO2 from the Atmosphere." Joule 2, no. 8, 1635. https://doi.org/10.1016/j.joule.2018.06.010.

[64] Fennell, Paul, Ben Anthony. 2015. "Pilot Plant Experience with Calcium Looping." In Calcium and Chemical Looping Technology for Power Generation and Carbon Dioxide (CO2) Capture. Cambridge: Elsevier Science & Technology.

[65] Lackner, K.S. 2009. "Capture of Carbon Dioxide from Ambient Air." The European Physical Journal Special Topics 176, no. 1 93–106. https://doi.org/10.1140/epjst/e2009-01150-3.

[66] Voskian, Sahag, T. Alan Hatton. 2019. "Faradaic Electro-Swing Reactive Adsorption for CO2 Capture." Energy & Environmental Science 12 3530–47. https://doi.org/10.1039/c9ee02412c.

typically bound in some solid form or as a compressed gas, for use in zero-emission fuel generation, CO2 must typically be supplied as a pure gas stream. While this limits the options in terms of method of capture, simply separating CO2 from the ambient air and concentrating it into a pure stream can be much simpler than finding a permanent storage solution. Stream purity of the captured CO2 is an important factor in final fuel quality. Further research is needed into efficient methods for refining CO2 gas stream, and its effect on fuel generation.

Fuels generated from atmospheric CO2 using zero-emission methods may also be used as a form of permanent carbon sequestration. Storing carbon as hydrocarbon-based fuel might be a dense, stable, and economical option once drop-in fuel production is scaled. Stored zero-emission fuel could also be used as a strategic reserve for the U.S. Navy and military as a whole.

5. Chemistry and Scale for Non-Drop-In Alternative Fuels

a. Challenges Associated with Non-Drop-In Fuels

Most significant alternative fuel options require massive redesigns to platforms and transportation infrastructure. For hydrogen, platforms would require a complete powerplant(engine) redesign, and highly sophisticated storage systems, likely cryogenic, which would add weight and size. Other popular options, such as methanol and ammonia, would require significant powerplant resigns and handling considerations. When considering fuels for military use, perhaps the most critical characteristic is the energy to volume ratio and energy to weight ratio. No alternative fuel option has an energy density which can compete with diesel fuels, except perhaps hydrogen if storage options are significantly advanced in the future.

Hydrogen and other non-drop-in alternative fuels will also require a completely different supply chain. The transportation and storage of these fuels would require new facilities and tankers dedicated to the task. This is especially apparent with hydrogen, which requires cryogenic fuel tanks for storage and transportation. While hydrogen and other alternative fuels may present a good option for specific and highly stable shipping corridors, they are likely not a good near-term fuel option for a naval force which must be able to refuel across the globe in allied ports.

b. Hydrogen

Hydrogen gas can be combusted with atmospheric oxygen to produce power as an alternative fuel option. Hydrogen shows obvious potential as an alternative fuel, given its simple generation requirements and high energy to weight ratio. However, for naval applications there are some challenges which reduce its feasibility. Hydrogen as an energy carrier shows a high energy weight ratio but a poor energy to volume ratio limits its near-term usefulness in space constrained platforms. Storage of hydrogen is also difficult, requiring highly compressed or cryogenic fuel tanks, which add a significant weight and space requirement, although tank weight has the potential to be substantially reduced in coming years. While these considerations make hydrogen non-ideal for platforms with highly constrained size requirements, green hydrogen generation may still be useful for naval applications in the near term. Hydrogen can be used in platforms with less strict size constraints and can be coupled with CO2 capture to produce drop-in fuels more suitable to naval operational energy needs via Fischer-Tropsch and similar processes. The most energy intensive step in creating synthetic drop-in replacement fuels is the generation of hydrogen from water. Technologies and supply chains which produce green hydrogen could easily be used to do much of the heavy lifting in the creation of drop in fuels by serving as a supplier of hydrogen gas for the fuel synthesis process.

c. Methanol and Ammonia

Methanol and Ammonia both show promise for civilian maritime shipping, with relatively simple chemical makeups, and simi-simple storage requirements. When considered for use on operational Navy platforms however, both these options have issues which make them unsuitable for use. Ammonia is highly toxic to handle, while methanol evaporates quickly and has a flash point of 52 degrees Fahrenheit, which is an obvious safety risk for use on aircraft carriers. Additionally, the energy density of both methanol and ammonia is quite low when compared to current diesel-type fuels, making them a poor solution for combat platforms.

These options would also require significant redesigning of all platforms that might use them. While methanol and ammonia might present a good solution for other marine shipping efforts, and they show some potential for use in naval-non-combat use such as shipping and logistics, the combination of platform resigns, safety concerns, and low energy density makes them poor options for combat platforms.

6. Fuels Collaboration with Industry and Government

A global demand for sustainable fuels is driving investment in new fuel sources and types, processes for scaling production, and technologies to enable use. Across the U.S. transportation sector, a government coordinated approach is being led by DOE and the Department of Transportation (DOT). Together, with the EPA and Department of Housing and Urban Development (HUD), a strategy document, The *US National Blueprint for Transportation Decarbonization,* guides decarbonization efforts to include maritime and aviation. Several strategies to scale low-carbon fuels are introduced in that strategy, and with resources from the Inflation Reduction Act the DOE is investing heavily to realize production of these fuels to scale. The following efforts offer opportunities for the DON to engage to support proliferation of low-carbon fuels:

- SAF Grand Challenge: The Sustainable Aviation Fuel Grand Challenge Roadmap is a multi-agency blueprint that identifies key actions to realize SAF Grand Challenge goals, including policy support to cut costs and support rapid scale-up of domestic production of SAF.[67]
- Hydrogen Hubs: The Regional Clean Hydrogen Hubs Program seeks to establish up to ten regional clean hydrogen hubs across America.[68]
- Green Corridors: Green shipping corridors seeks to establish shipping routes between two or more ports that showcase zero- and near zero-emission lifecycle fuels and technologies with the ambition to achieve zero greenhouse gas (GHG) emissions no later than 2050.[69]

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[67] Department of Energy. 2022. "SAF Grand Challenge Roadmap." Announcement, Washington. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

[68] Department of Energy. 2022. Regional Clean Hydrogen Hubs. Accessed September 1, 2023. https://www.energy.gov/oced/regional-clean-hydrogen-hubs.

[69] Department of State. 2022. Green Shipping Corridors Framework. Washington , April 12. Accessed August 7, 2023. https://www.state.gov/green-shipping-corridors-framework/.

- Zero-Emission Shipping Mission: ZESM aims to transition at least 5% of the global deep-sea fleet to zero-emission fuels and ensure that at least 10 ports on three continents can supply zero-emission fuels by 2030.[70]

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[70] Department of Energy. 2022. "U.S. National Blueprint for Transportation Decarbonization." Strategy, Washington. https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf.

III. SUMMARY

In 2022, the phase I *Pathways to Net Zero Naval Operations* study identified measures and illustrated potential for emissions reductions to enable a net zero operating force by 2050. The research report described the state of technologies and challenges for ships and aircraft to include energy efficiency, operational efficiency, low carbon fuels, unmanned systems, battery storage, renewable energy, and carbon capture.

This phase II effort looked deeper into challenges and potential for four specific measures identified in phase I with the greatest potential for emissions reductions. Those measures are alternative force structure, nuclear energy, platform carbon capture, and low-carbon fuels. The research also reviewed climate data and analysis to correlate emissions reductions to the actual mitigation of climate change impacts. Data and analyses from NOAA, EPA, and the IPCC were used to review the historical trends and indicators of climate change, and CMIP6 modeling was performed to project climate change impacts to the contiguous United States. Two scenarios were modeled to represent 1) projections of impacts from global warming associated with the current level of the GHG emissions and trends and 2) projections of impacts correlating with GHG emissions reductions to limit global warming to 2°C. The analysis showed that global GHG emissions reductions of approximately 17 billion metric tons by 2030 and 37 billion metric tons by 2050 are necessary to support global objectives, and limit increases in sea level rise, extreme precipitation events, extreme temperature events, and hurricane intensity in the United States.

DON operations account for approximately 11 million metric tons of CO2e annually – less than .1% of the total reductions needed to realize the lesser impacts associated with limiting warming to 2°C. Efforts to reduce those emissions will have a corresponding impact to global climate change and support a “do our part” approach where global efforts aggregate to address climate change. However, to have the biggest impact to reducing the severity of hazards, measures that propagate beyond DON platforms should be prioritized.

Considering this challenge as well as the assumption the DON will not accept any emission reduction measure that could impact warfighting effectiveness, this research found that drop-in sustainable fuels (F-76 and JP-5) have the greatest potential to reduce GHG emissions before 2050. A significant factor for this finding is that Navy and Marine Corp ships and aircraft have service lives of 30+ years. The research found that advancements in nuclear, non-drop-in fuels, and platform carbon capture will require significant modification and departure from existing platform designs, and the acquisition cycles to de-risk those advancements for the Navy's largest GHG emitters challenge scale-up of those measures ahead of 2050. Advanced nuclear, non-drop-in fuels, and additional unmanned capabilities will benefit mission requirements and climate change mitigation in the future force architecture, and shipboard carbon capture may be an option for non-tactical systems. Whereas sustainable drop-in fuels can be immediately integrated on existing platforms and used in proven gas turbine and diesel engines planned for new platforms over the next 20+ years. Near-term efforts to scale production of SAF and sustainable marine diesel in the US are driving additional innovations that will increase production, lower cost, and allow greater use of low carbon fuels.

To support intent of the president's executive orders, DOD and DON strategies, and global efforts to reduce GHG emissions, the pathway to net zero naval operations by 2050 should engage government and international partners to support near-term scaleup and cost reduction of drop-in fuels, F-76 and JP-5. Additional continued investment in innovation and future force designs that enable integration if unmanned systems, nuclear energy, and non-drop-in fuels will support longer term, beyond 2050 emissions reductions and increase warfighting capability.

APPENDIX

A. SUMMARY OF YEAR ONE EFFORTS

During year one of this study, several key pathways were identified, with each pathway relying on a different makeup of emissions reductions strategies. Strategies included low carbon fuels, hydrogen, unmanned systems, and efficiency increases, among others. In all pathways, low carbon fuels were the single most significant carbon reducing measure, with alternative fuels being the focus for the year one research team. The key emissions reductions strategies of each pathway are summarized briefly below.

Hydrogen: The year one effort identifies hydrogen as an important reduction strategy, although its impact as an alternative fuel will be limited in the short term as platform and infrastructure redesign would be costly and take time. Using hydrogen directly as a fuel also comes with many challenges, such as transportation infrastructure issues and safe storage among others.

Unmanned systems: Unmanned systems have the potential to reduce or increase emissions by changing how platforms are powered and which platforms are needed for a specific mission. Depending on how these systems are implemented and used in the future force, uncrewed systems could have a reducing impact on carbon emissions, or if they are simply used to augment the current force, working in addition to current force structures, they may lead to increased emissions.

Batteries: The inclusion of an energy magazine on future ship designs may be key in enabling the full potential of future weapon and sensor systems such as high energy lasers. An energy magazine could also significantly increase efficiency of fossil fuel powered ships in some cases, thereby reducing emissions. However, using batteries charged by fossil fuel power systems does not truly address the root cause of emissions, and has a severely limited impact on total naval emissions.

Increased Efficiencies: While increasing efficiency can be used to great effect in highly inefficient systems, many naval systems have already been extensively optimized, leaving little power loss on the table. For this reason, increasing efficiency is not a comprehensive solution to reducing emissions, and in many real-world cases, an increase in efficiency instead leads to increased operational tempo and capabilities.

Nuclear Energy: While nuclear energy is touched on in the year one report, it is not considered a good short-term option beyond its current and planned use in CVNs and SSNs, as the year one report identifies significant challenges, such as cost and size, to increasing nuclear power usage throughout the fleet.

Renewable Energy Sources: Renewable energy is growing quickly for installation/grid power applications and is being considered in some limited cases to power maritime shipping. The year one report focuses on renewable energy for operational uses and finds that while there are possible uses in the private sector, it is unclear if renewables can be used reliably on operational naval platforms.

Carbon Sequestration, Capture and Offsets: These technologies are approached cautiously in the year 1 report given some inherent vulnerabilities in their use so far. However, they were included as part of overall emissions reduction portfolios, but not substitutes for reducing emissions over time.

The year one effort identified four illustrative pathways, although only two of those get to net zero by 2050. All pathways are a combination of different strategies. In addition to specific strategies, the year one research team identifies several key factors in reducing emissions to reach net zero by 2050, including a whole of government approach and early investment in promising strategies. The team also cautions against solutions which kick the problem down the road, such as carbon sequestration and offsets.

B. LIST OF REFERENCES

Applied Research Associates, Inc. 2022. *ASTM International Approves New Production Pathway for Sustainable Aviation Fuel.* January 23. Accessed 2023. https://www.ara.com/news/astm-international-approves-new-production-pathway-sustainable-aviation-fuel/.

Budzianowski, Wojciech M. 2016. "A Review of Potential Innovations for Production, Conditioning and Utilization of Biogas with Multiple-Criteria Assessment." *Renewable and Sustainable Energy Reviews*, February: 54. https://doi.org/10.1016/j.rser.20.

Chen, Chi, Mahlet Garedew, and Stafford W. Sheehan. n.d. "Single-Step Production of Alcohols and Paraffins from CO2 and H2 at Metric Ton Scale." *ACS Energy Letters 7, no. 3*, 988–92. https://doi.org/10.1021/acsenergylett.2c00214.

Cook-Patton, Susan C., Sara M. Leavitt, David Gibbs, Nancy L. Harris, Kristine Lister, Kristina J. Anderson-Teixeira, Russell D. Briggs, et al. 2020. "Mapping Carbon Accumulation Potential from Global Natural Forest Regrowth." *Nature 585, no. 7826*, 545–5. https://doi.org/10.1038/s41586-020-2686-x.

D Camp, N Vey, P Kylander, S Auld, J Willis, J Lussier, R Eldred, D Van Bossuyt. 2022. "Electrical Energy Storage Strategy to Support Electrification of the Fleet." Defense Research, Monterey.

Department of Energy. 2022. *Regional Clean Hydrogen Hubs.* Accessed September 1, 2023. https://www.energy.gov/oced/regional-clean-hydrogen-hubs.

Department of Energy. 2022. "SAF Grand Challenge Roadmap." Announcement, Washington. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

Department of Energy. f2022. "U.S. National Blueprint for Transportation Decarbonization." Strategy, Washington. https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf.

Department of Navy. 2023. *Naval Visibility and Management of Operating and Support Costs (VAMOSC) Management Information System.* Accessed June 1, 2023. https://www.vamosc.navy.mil/.

Department of State. 2022. *Green Shipping Corridors Framework.* Washington , April 12. Accessed August 7, 2023. https://www.state.gov/green-shipping-corridors-framework/.

Department of the Navy. 2022. "Climate Action 2030." *Department of the Navy Climate Action 2030.* Washington, DC, May. https://www.secnav.navy.mil/Climate/Shared%20Documents/Climate%20Action%202030.pdf.

Energy Information Administration . 2023. *Total Energy Monthly Data.* Accessed October 20, 2023. https://www.eia.gov/totalenergy/data/monthly/index.php.

Energy Information Administration. 2023. *EIA Projects U.S. Biofuel Production to Slowly Increase through 2050.* Accessed September 28, 2023. https://www.eia.gov/todayinenergy/detail.php?id=43096.

Energy Information Administration. 2023. "Monthly Energy Review August." Washington. Accessed September 28, 2023. https://www.eia.gov/totalenergy/data/monthly/pdf/sec10_3.pdf.

Energy Information Administration. 2023. *Petroleum & Other Liquids.* Accessed August 20, 2023. https://www.eia.gov/petroleum/.

Environmental Protection Agency. 2023. *Climate Change Indicators in the United States.* Accessed July 1, 2023. https://www.epa.gov/climate-indicators#:~:text=Temperatures%20are%20rising%2C%20snow%20and,atmosphere%2C%20caused%20by%20human%20activities.

Environmental Protection Agency. 2023. "Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2021." Washington. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

Fasihi, Mahdi, Olga Efimova, and Christian Breyer. 2019. "Techno-Economic Assessment of CO2 Direct Air Capture Plants." *Journal of Cleaner Production 224 957–80* 957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.

Fennell, Paul, Ben Anthony. 2015. "Pilot Plant Experience with Calcium Looping." *In Calcium and Chemical Looping Technology for Power Generation and Carbon Dioxide (CO2) Capture.* Cambridge: Elsevier Science & Technology.

Global Security. n.d. "CGN-42 AEGIS Modified Virginia." *GlobalSecurity.org.* Accessed July 15, 2023. https://www.globalsecurity.org/military/systems/ship/cgn-42.htm.

Intergovernmental Panel on Climate Change. 2021. *Climate Change 2021: The Physical Science Basis.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

Intergovernmental Panel on Climate Change. 2023. "Climate Change 2023: AR6 Synthesis Report." Synthesis, Geneva, Switzerland. https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

Intergovernmental Panel on Climate Change. 2023. *Interactive Atlas: Regional synthesis.* Accessed June 15, 2023. http://interactive-atlas.ipcc.ch/.

International Air Transport Association. International Air Transport Association. *SAF Production Increases 200% - More Incentives Needed to Reach Net Zero.* Accessed September 28, 2023. https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/.

International Energy Agency. n.d. *Direct Air Capture - Energy System.* Accessed September 28, 2023. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture.

K Fletcher, M Lesse, B Naylor, J Lussier, B Johnson. 2022. *Analysis of Pathways to Reach Net Zero Naval Operations by 2050.* Analysis, Monterey, CA: Naval Postgraduate School.

Keith, David W., Geoffrey Holmes, David St. Angelo, and Kenton Heidel. 2018. "A Process for Capturing CO2 from the Atmosphere." *Joule 2, no. 8*, 1635. https://doi.org/10.1016/j.joule.2018.06.010.

Lackner, K.S. 2009. "Capture of Carbon Dioxide from Ambient Air." *The European Physical Journal Special Topics 176, no. 1* 93–106. https://doi.org/10.1140/epjst/e2009-01150-3.

Lebling, Katie, Haley Leslie-Bole, Zach Byrum, and Liz Bridgwater. 2022. "6 Things to Know about Direct Air Capture." *World Resources Institute*, May 2.

https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal.

Life Cycle Engineering. 2022. "Marine Carbon Capture Technology Review." Technical Report, Washington.

Mearsk-McKenny Moller Center for Zero Carbon Shipping. 2022. "The Role of Onboard Carbon Capture in Maritime Decarbonization." Technical Report, Copenhagen.

National Centers for Environmental Information. 2022. *Annual 2022 Global Climate Report.* Accessed July 1, 2023. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202213.

National Oceanographic and Atmospheric Association. 2023. *Global Climate Dashboard.* Accessed June 1, 2023. https://www.climate.gov/climatedashboard.

Naval Air Systems Command. 2021. "Navy Aviation Vision 2030-2035." https://media.defense.gov/2021/Oct/27/2002881262/-1/-1/0/NAVY%20AVIATION%20VISION%202030-2035_FNL.PDF.

Office of Nuclear Energy. 2023. *NRC Certifies First U.S. Small Modular Reactor Design.* January 20. Accessed June 30, 2023. https://www.energy.gov/ne/articles/nrc-certifies-first-us-small-modular-reactor-design.

Office of the Chief of Naval Operations. 2022. "Navigation Plan 2022." Washington , July 26. https://www.doncio.navy.mil/FileHandler.ashx?ID=18929.

Office of the Chief of Naval Operations. 2022. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023." Washington, DC. https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/PB23%20Shipbuilding%20Plan%2018%20Apr%202022%20Final.pdf.

Office of the Chief of Naval Operations. 2022. "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023." Report to Congress, Washington, DC. https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/PB23%20Shipbuilding%20Plan%2018%20Apr%202022%20Final.pdf.

Office of the Under Secretary of Defense for Acquisition and Sustainment. 2023. "DOD Plan to Reduce Greenhouse Gas Emissions." Washington, DC, April. https://media.defense.gov/2023/Jun/16/2003243454/-1/-1/1/2023-DOD-PLAN-TO-REDUCE-GREENHOUSE-GAS-EMISSIONS.PDF.

Pool, Robert P. 2014. "Case Study: The Palm Oil Example." *In The Nexus of Biofuels, Climate Change, and Human Health.* Washington: National Academies Press.

Porsche Newsroom. n.d. *Efuels Pilot Plant in Chile Officially Opened.* Accessed August 28, 2023. https://newsroom.porsche.com/en/2022/company/porsche-highly-innovative-fuels-hif-opening-efuels-pilot-plant-haru-oni-chile-synthetic-fuels-30732.html.

Science.org. n.d. *Sustainable Hydrogen Production.* Accessed September 28, 2023. https://www.science.org/doi/10.1126/science.1103197.

Seaforces.Org. n.d. *CGN 38 – Virginia - class Guided Missile Cruiser.* Accessed June 2023. https://www.seaforces.org/usnships/cgn/Virginia-class.htm.

Sousa Castro, Karoline de, Luís Fernando de Medeiros Costa, Valter José Fernandes, Regineide de Oliveira Lima, Aruzza Mabel de Morais Araújo, Mikele Cândida

Sousa de Sant'Anna, Nataly Albuquerque dos Santos, and Amanda Duarte Gondim. 2020. "RSC Advances 11, no. 1." *Catalytic Pyrolysis of Palm Oil to Obtain Renewable Hydrocarbons*, December: 555-64. https://doi.org/10.1039/d0ra06122k.

The Maritime Executive. 2023. *First Carbon Capture System Installed on EPS Managed Tanker.* February. Accessed July 15, 2023. https://maritime-executive.com/article/first-carbon-capture-system-installed-on-eps-managed-tanker.

The White House. 2021. "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability." *Executive Order 14057.* Washington, DC, Dec 8.

Twelve. n.d. *The Carbon Transformation Company.* Accessed September 28, 2023. https://www.twelve.co/.

United Nations. n.d. *The Paris Agreement.* Accessed September 1, 2023. https://unfccc.int/process-and-meetings/the-paris-agreement.

Velev, Vasil. 2023. "Twelve Starts Construction of First US Commercial-Scale Plant for Producing Sustainable Aviation Fuel from CO2." *Carbon Herald*, July 13. https://carbonherald.com/twelve-first-commercial-plant-sustainable-aviation-fuel-co2/.

Voskian, Sahag, T. Alan Hatton. 2019. "Faradaic Electro-Swing Reactive Adsorption for CO2 Capture." *Energy & Environmental Science 12* 3530–47. https://doi.org/10.1039/c9ee02412c.

Zahan, Khairul, and Manabu Kano. 2018. "Biodiesel Production from Palm Oil, Its by-Products, and Mill Effluent: A Review." *Energies 11, no 8.* https://doi.org/10.3390/en11082132.