NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

NAVY DECARBONIZATION RESEARCH CONSORTIUM:

OPERATIONAL NAVY DECARBONIZATION ROADMAP

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Distribution Statement A.

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EXECUTIVE SUMMARY

This Decarbonization Roadmap was developed in coordination with the Office of Naval Research (ONR) and participants of the Navy Decarbonization Research Consortium. The Naval Postgraduate (NPS) led this effort and worked with the Consortium participants, made up of academic research institutions, Navy and ONR colleagues, other government agencies and private sector entities in developing this initial Roadmap to guide ONR S&T activities in platform decarbonization.

While the Department of Defense (DOD) and Department of the Navy (DON) have not officially defined decarbonization, for purposes of this Roadmap, researchers used a decarbonization definition consistent with recent IPCC publications and have defined it as “the process by which entities aim to reduce or completely eliminate carbon emissions.” For the DOD and DON, decarbonization is a key component of the U.S. goals to reach net zero by 2050. Even with these goals, it is important to note that the Navy’s pursuit of decarbonization will align with the maintenance and enhancement of warfighting capability and mission effectiveness.

To decarbonize, the Navy’s efforts will require action along multiple avenues, including integration of lower carbon fuels, efficiency enhancing technologies and carbon capture and storage. Continued efforts on demand reduction and efficiency technologies will be critical for early emission reduction efforts. Integration of new technologies on naval platforms is a challenge, and most of the current Navy investment that may have impact on decarbonization objectives have been undertaken with the primary goals of increasing combat capability and addressing contested logistics challenges. Decarbonization is now an additional challenge the Navy must tackle.

The Roadmap lays out priorities in the context of Navy-specific challenges and the requirements that make decarbonization of Navy platforms unique. It provides 1) a thorough review of existing decarbonization and Net Zero strategies of other public and private sector entities, 2) a review of existing Navy activities in the operational energy and climate space, 3) identification of potential opportunities for additional investment, and 4) identification of priority research focus areas for S&T investment. The Roadmap lays out a path for the future, consisting of a Collaboration Strategy and Key Actions to help meet the Navy’s climate goals for decarbonization. It is expected that this Roadmap will be a living document, with regular updates as research and technologies advance.

Finally, the Navy's efforts cannot be undertaken alone. Increased and ongoing collaboration with the Department of Energy (DOE), Department of Transportation (DOT) and across the DON and DOD is critical to meeting the decarbonization challenge.

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In support of the Office of Naval Research (ONR), the Naval Postgraduate School (NPS) was tasked with developing a Decarbonization Roadmap in conjunction with and in support of the Navy Decarbonization Research Consortium. NPS worked with the Consortium members, made up of academic research institutions, Navy and ONR colleagues, other government agencies and private sector entities to develop this initial Roadmap to guide ONR S&T activities in platform decarbonization.

Through this collaborative approach, and as shown in Figure 1 below, the team developed a Roadmap organized into three (3) major Sections as follows.

Section 1 primarily consists of background material, providing a high-level summary as to why decarbonization is necessary economy-wide, what key directives have been issued that are guiding the Navy's approach, and Navy specific challenges and unique requirements that make decarbonization of Navy platforms a unique challenge.

Section 2 then takes a structured approach to define the opportunities available to the Navy in platform decarbonization, through 1) a systematic review of existing decarbonization and Net Zero strategies of other public and private sector entities, 2) a review of existing Navy activities in the operational energy and climate space, 3) identification of potential opportunities for additional investment, and 4) determination of priority research focus areas for S&T investment. This effort supported the award of multiple grants to research teams who proposed promising decarbonization technologies.

Section 3 starts to lay out a path for the future, consisting of a Collaboration Strategy and Key Actions to continue efforts towards meeting the Navy's climate goals for decarbonization. It is expected that this Roadmap will be a living document, with regular updates being made to the strategy and pathways as the Year 1 Research Agenda is executed, technologies are developed and mature, and collaboration activities with other partners illuminate new promising areas of research that can help the Navy to do its part to meet the climate challenge.

Figure 1. Decarbonization Roadmap

II. MISSION STATEMENT AND OBJECTIVE

A. MISSION STATEMENT

Launched in February 2023, the Navy Decarbonization Research Consortium is a public-private collaboration that advances interdisciplinary research to help the Navy meet the complex challenges of platform decarbonization, with a focus on ships and aircraft. The Consortium will evaluate and identify technologies that show promise for adaptation on naval platforms, especially ships and aircraft, and accelerate adoption as appropriate.

B. OBJECTIVE

The role of the Navy Decarbonization Research Consortium is to create a collaborative approach to answer the complex problems of platform decarbonization for the Navy. The Consortium's goals are to:

- Establish a consortium that includes individuals, institutions and companies necessary to meet platform decarbonization and whose membership and structure is adaptable over time;
- Create this Decarbonization Research Roadmap for ONR that includes interdisciplinary research and analysis and identification of future research opportunities; and
- Continue the Consortium into FY24 and beyond to collaborate on research to solve complex problems of platform decarbonization, evolve the Roadmap as technologies and new research avenues advance, and identify technology transition opportunities.

While the Roadmap focuses on research opportunities directly related to the decarbonization work of ONR, the framework developed considers the larger scope of decarbonization across the U.S. government and the complexities of the energy transition in both public and private sectors.

III. WHY DECARBONIZE?

A. DECARBONIZATION AND CLIMATE CHANGE

1. Definition

While DOD and DON have not officially defined decarbonization, for the purpose of this report, the research team used a definition consistent with recent Intergovernmental Panel on Climate Change (IPCC) publications. In IPCC SR15, Special Report: Global Warming of 1.5°C, decarbonization is defined as: “The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. This typically refers to a reduction of the carbon emissions associated with electricity, industry and transport.” Most organizations seeking to decarbonize products, processes or platforms recognize two aspects to decarbonization:

1) Reducing the greenhouse gas emissions released through their operations; and
2) The drawdown and storage, use or sequestration of carbon that continues to be emitted.

The Decarbonization Consortium Roadmap applies both abovementioned aspects to achieve DON decarbonization targets, including net-zero by 2050.

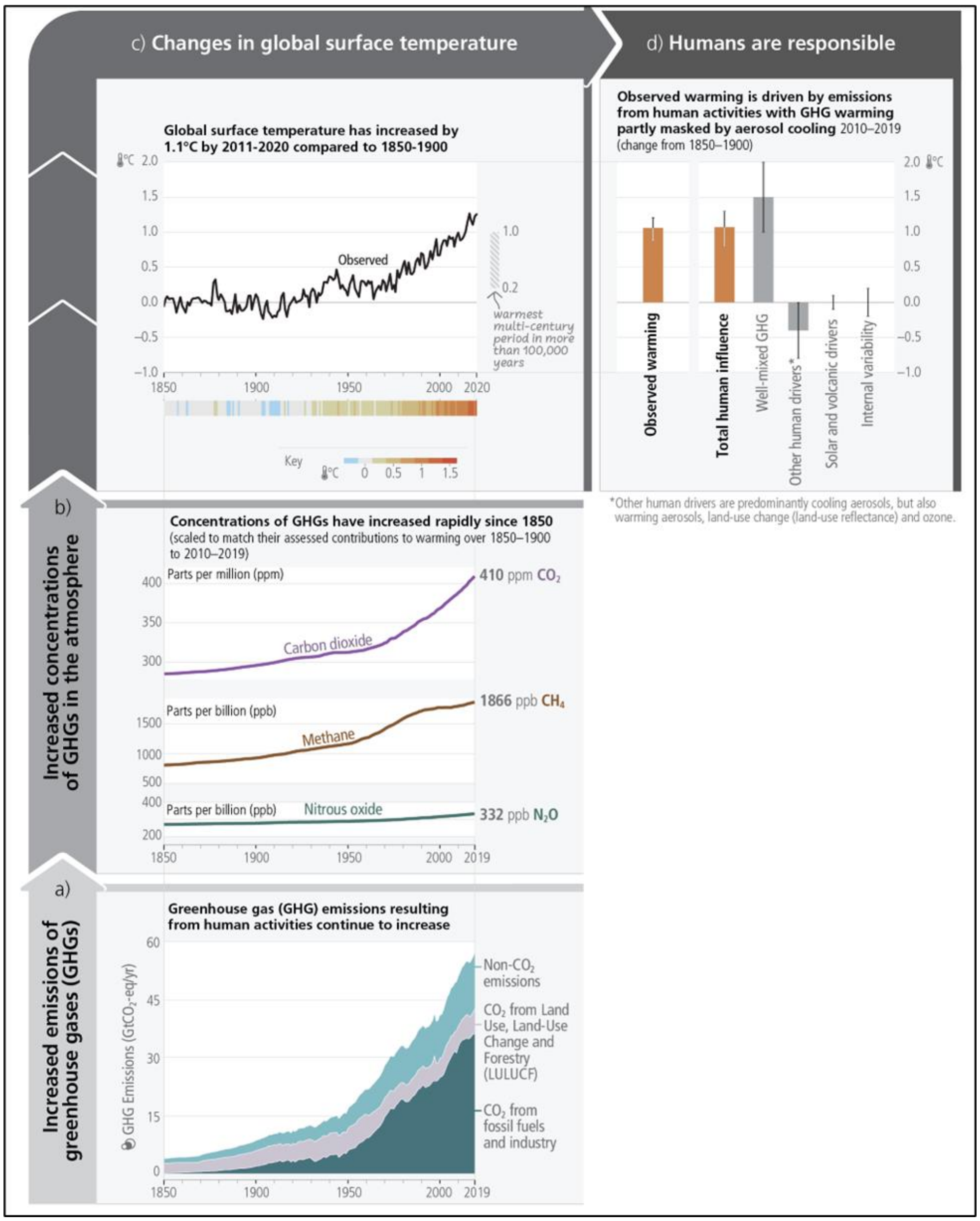
2. Climate Science

In 2023, the IPCC released the AR6 Synthesis Report summarizing the latest analysis of data correlating greenhouse gas (GHG) emissions, global warming, and climate impacts. The analysis stresses three key points underpinning decarbonization objectives:

1) Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020.
2) The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels.

3) Limiting human-caused global warming requires net zero CO_2 emissions.

Figure 2 describes the correlation between human activities, specifically GHG emissions, and global warming since 1850. Not shown in the figure are natural GHG emissions, like those from volcanoes; however, the latest IPCC synthesis correlates a minimal change of ±0.1°C on global surface temperatures from those natural sources.

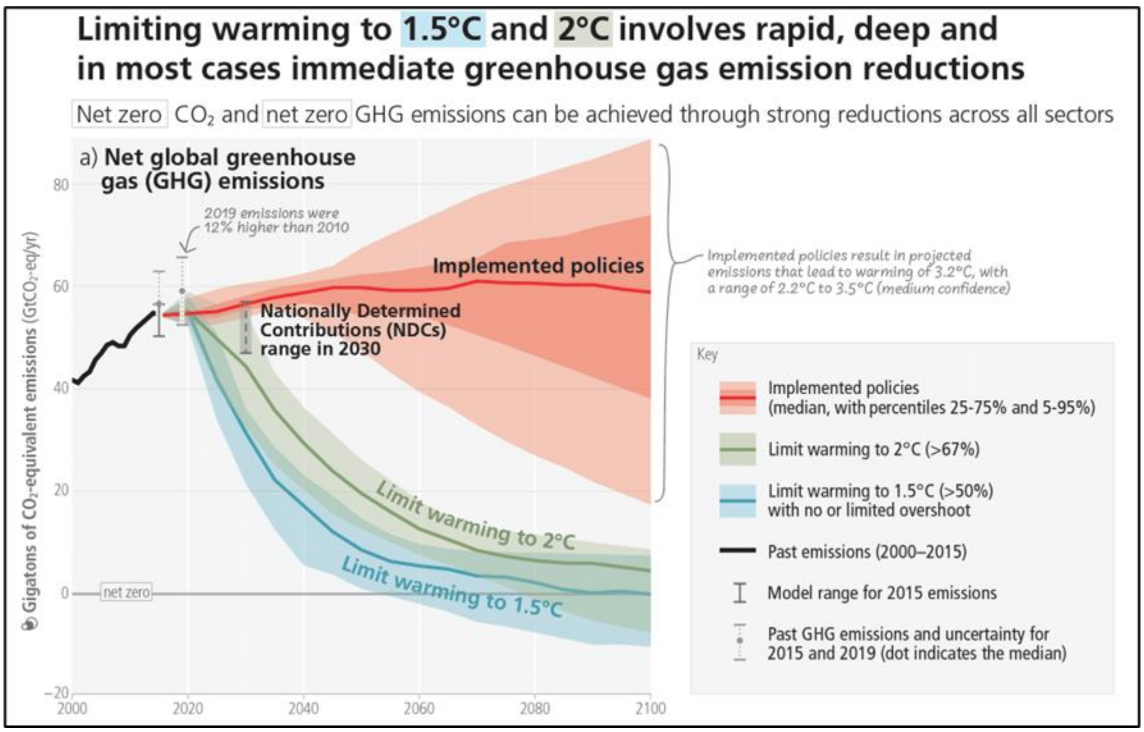


Source: IPCC

Figure 2. IPCC reported, Global Warming from Human Activities

Figure 3 shows the projected levels of GHG emissions based on implemented policy at the end of 2020, reductions needed to limit warming to 1.5°C, and reductions needed to limit warming to 2°C. The projection suggests warming of 3.2°C is likely based on 2020 trends.

Note that U.S. policy, including White House Executive Orders, and DOD and DON climate strategies, support emissions reduction requirements, but the modeling of those impacts have not yet been reported.



Source: [IPCC]

Figure 3. IPCC Projection of Emissions Pathways

The correlation between global warming and climate impacts is also well analyzed and reported in the IPCC synthesis, but the details are largely regionally specific. Generally, as the temperature increases, climate extremes become more severe.

The following general statements can be extrapolated from the IPCC report:

- Additional warming will lead to more frequent and intense marine heatwaves and is projected to further amplify permafrost thawing and loss of seasonal snow cover, glaciers, land ice and Arctic sea ice.
- Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation, and very wet and very dry weather and climate events and seasons.
- The portion of global land experiencing detectable changes in seasonal mean precipitation is projected to increase with more variable precipitation and surface water flows over most land regions within seasons and from year to year.
- Ocean acidification, ocean deoxygenation, and global mean sea level will continue to increase in the 21st century. However, increased acidification and deoxygenation are expected primarily in the global open ocean.
- A general pattern of fresh ocean regions getting fresher and salty ocean regions getting saltier will continue in the 21st century.

The IPCC synthesis report draws a clear correlation between GHG emissions and climate impacts and highlights the importance of emissions reductions to prevent the more severe consequences of climate change. The U.S. has aligned policy and resources to support emissions reduction targets, to include the Decarbonization Consortium.

B. CLIMATE CHANGE IMPACT ON NATIONAL SECURITY

The relationship of climate change to national security is well-documented. The 2023 Annual Threat Assessment of the U.S. Intelligence Community unequivocally stated that “Climate change will increasingly exacerbate risks to U.S. national security interests as the physical impacts increase and geopolitical tensions mount about the global response to the challenge” (Annual Threat Assessment, 2023). In 2022, the DON opened its climate strategy, *Climate Action 2030*, with the statement “Climate change is one of the most destabilizing forces of our time, exacerbating other national security concerns and posing serious readiness challenges” (DON Climate Action 2030, 2022).

Noting that the climate threat for the DON is existential, the strategy acknowledges increased instability across the globe while simultaneously affecting the DON's ability to respond. In addition, most DON installations are coastal and sea level rise will test the ability for these installations to continue to meet their missions. Furthermore, the 2021 DOD Climate Risk Analysis stated that "Climate change is reshaping the geostrategic, operations and tactical environments with significant implications for U.S. national security and defense" (DOD Climate Risk Analysis, 2021).

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

With this backdrop of net zero emissions and mitigation of climate change as an essential element of national security, the Consortium has undertaken research and analysis on decarbonization of Navy platforms in the near- and long-term.

IV. DIRECTIVES AND KEY GUIDANCE DOCUMENTS

In order to guide the Roadmap development, the team reviewed official U.S. Government, DOD and DON doctrine that provide high level direction for Navy climate activities; these are summarized in the Primary References section below (Section A). The team also performed a literature review to identify the most relevant strategies, efforts, reports or initiatives that address the hard-to-decarbonize sectors of maritime and air transportation, which are of most relevance to the operational Navy. These are summarized in the Secondary Reference section below (Section B). Details for all references can be found in the “List of References” section at the end of this report.

A. PRIMARY REFERENCES

The following six (6) references were identified as containing the high-level guidance necessary to provide appropriate scope and direction for the Decarbonization Roadmap effort:

1) Executive Order (EO) 14008: Tackling the Climate Crisis at Home and Abroad *(January 2021)*
2) DoD Climate Adaptation Plan *(September 2021)*
3) DoD Climate Risk Analysis *(October 2021)*
4) EO 14057: Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability *(December 2021)*
5) Federal Sustainability Plan *(December 2021)*
6) DON Climate Action Plan *(May 2022)*

Existing and expected impacts from climate change have driven the U.S. policy goal of net zero emissions by 2050. In January 2021, Executive Order 14008 called for a government-wide approach for meeting climate related challenges in the U.S. and set goals for agencies. In December 2021, Executive Order 14057 set the specific goal of net zero emissions from overall federal operations, including DOD, by 2050 and a 65 percent emissions reduction by 2030.

These goals were incorporated into the DON climate strategy, *Climate Action 2030*, with the following specific targets:

- Achieving a 65 percent reduction in scope 1 and 2 greenhouse gas emissions department-wide by 2030 (measured from a 2008 baseline);

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

B. SECONDARY REFERENCES

While there are undoubtedly many other papers and efforts that could have been included here, the following eleven (11) references from other government agencies were identified as having both significant relevance to the specific challenges faced in decarbonizing Navy platforms, as well as laying out timelines and targets for various decarbonization priorities:

1) US National Blueprint for Transportation Decarbonization (*January 2023*)
2) FAA Aviation Climate Action Plan (*2021*)
3) IMO GHG Strategy (*2023*)
4) DOE Hydrogen Shot (*June 2021*)
5) U.S. National Clean Hydrogen Strategy & Roadmap *(June 2023)*
6) Clean Fuels & Products Earthshot *(June 2023)*
7) DOE SAF Grand Challenge (*Septe 2022)*
8) USAF Climate Action Plan (*October 2022*)
9) US Army Climate Strategy (*February 2022*)
10) USCG Climate Framework (*January 2023*)
11) Net Zero Efforts Across World Military (*NPS – 2023*)

C. GUIDANCE DOCUMENT TIMELINES

Many of the seventeen (17) core guidance documents included specific targets and dates by which these targets should be met. Table 1 shows a summary of the targets laid out in these references that are most relevant to operational Navy platforms. As can be seen, most of the targets align with 2030 and 2050 targets dates, with a few that fall in the intervening decades.

Key Guidance Document	*Target*	2020s	2030s	2040s
EO 14057 & Navy Climate Action 2030	• 100% carbon-free electricity (CFE), including 50% 24/7 CFE • 65% reduction in scope 1 & 2 GHG emissions • Net zero emissions economy-wide	★ ★	2030 2030	2050 ★
US Transportation Decarbonization Blueprint	• 5% of the global deep-sea fleet are capable of using zero-emission fuels • Net zero emissions from international shipping • Reduce aviation emissions by 20% • Net-zero GHG emissions from the U.S. aviation sector • Catalyze the production of: - at least three billion gallons of SAF/year - ~35 billion gallons by 2050	★ ★ ★	2030 2030 2030	2050 ★ 2050 ★ 2050 ★
IMO GHG Strategy *(2023 update)*	• Reduce carbon intensity of international shipping by at least 40% • Uptake of zero or near-zero GHG technologies, fuels and/or energy sources • Reduce the total annual GHG emissions form international shipping by: - At least 20%, striving for 30% - At least 70%, striving for 80% - Reach net-zero GHG emissions by or around	★ ★ ★	2030 2030 2030 2040 ★	2050 ★
DOE Hydrogen Shot	• Reduce cost of clean hydrogen by 80% to $1 per 1 kg in 1 decade (*1-1-1*)		★ 2031	
DOE SAF Grand Challenge	• Scale up domestic production of SAF with a minimum of 50% life cycle GHG reduction (*reflected in Transportation Blueprint above*)	★	2030	
USAF Climate Action Plan	• Increase operational energy intensity of flying missions by: • Complete successful pilots of drop-in compatible SAF at two operational AF locations, with 10% SAF blend at same or lower cost	5%/2027 ★ 2026 ★	★ 7.5%/2032	
World Military Activities	• General trend towards net zero by			2050 ★

Table 1. Key Guidance Documents with Target Timelines

V. NAVY EMISSIONS

Total DON GHG emissions in FY21 were approximately 16.7 million metric tons of CO2e. Figure 4 below shows the breakdown of DOD-wide emissions, with the centered highlighted portion showing the breakdown between operations and installations. Navy emissions are roughly in line with this split, with 70% coming from operational platforms and the remaining 30% from Navy Installations. Operational Navy GHG emissions are almost entirely due to the combustion of fuel, and that fuel usage is split roughly 50/50 between jet fuel (JP-5) and ship fuel (F-76). In addition, it is widely recognized within industry that maritime and air transport are part of the "hard to decarbonize" sectors of the overall economy, underscoring the first part of the challenge Navy faces in platform decarbonization.

Source: DoD

Figure 4. DOD Total Energy Consumption Summary

Figure 5 below depicts historical Navy GHG emissions from 2008 to present, as well as an illustrative projection of a potential future emissions pathway.

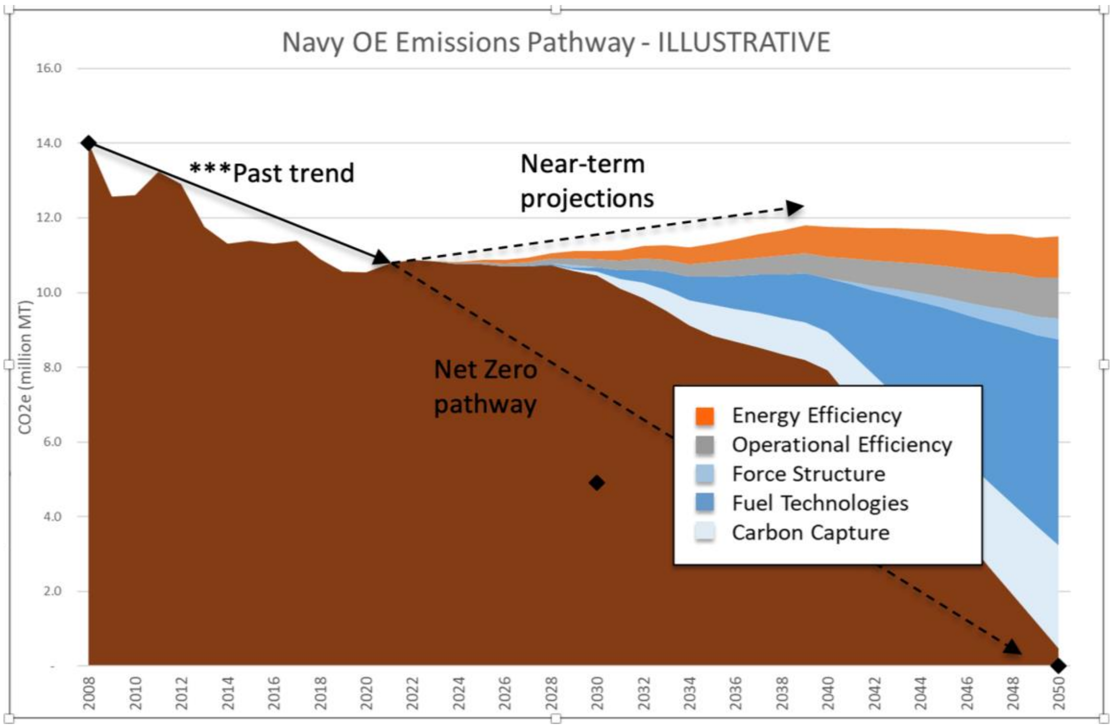


Figure 5. Navy OE Emissions Pathway – Illustrative

There are a few important points to draw from Figure 5. The historical emissions track to historical fuel usage, as combustion of fuel is the main driver of Navy operational emissions. However, most of the emissions reductions realized since 2008 are attributable to reduced operating hours and reduced speed, which are not solutions that are extendable going forward. This low-hanging fruit has been harvested, and it is imperative to note that **the past trendline is not indicative of the future trajectory** for Navy fuel usage, and therefore GHG emissions, all else remaining equal.

A second important point to note from the figure is the future emissions trajectory. As will be explained in the following section, Navy energy usage is projected to increase in the future, due to a growth in new platforms and increased energy demand onboard new and existing platforms.

The third key point, shown in the sand layers of potential solutions, is that there is no single solution to this problem, and that a portfolio of technologies and solutions will be required to address the Navy's decarbonization challenges.

VI. NAVY UNIQUE CHALLENGE

In the prior section, it was noted that the first part of the Navy's challenge in platform decarbonization is related to the "hard to decarbonize" maritime and air sectors. The second part is due to the uniqueness of the Navy's mission and the constraints that it places on the potential solution space. These unique aspects and the constraints are summarized in the six key points below.

1) Platforms in-service/in-design today will be in the fleet past 2050, and these platforms are powered by conventional diesel and gas turbine engines. The long service life of Navy ships (30+ years) as well as the long design and procurement cycles, dictates that much of the surface force we have today will still be the surface force in 2050. Therefore, **retrofit solutions for the current fleet must be a priority.**
2) Energy demand is increasing, both due to growth in the number of new platforms (to include unmanned vessels) and due to increased onboard energy demand to support more powerful systems and directed energy weapons (on new and existing platforms). For this reason, the **Navy must prioritize both retrofit options and forward-fit solutions that inform future designs.**
3) Navy ships must maintain the ability to refuel underway and at remote locations – they operate forward, distributed, and in contested environments. Underway replenishment (UNREP) is a key capability that supports maintaining a forward presence and power projection. Navy vessels do not have the luxury of pulling into port for repairs or resupply, and they must be prepared to operate anywhere across the globe on short notice. For this reason, the logistics tail of operations is a key focus area, and the Navy must ensure that any technology or operational changes do not degrade capability in this respect.
4) The Navy must maintain interoperability with partners and allies, so as new fuel technologies are proposed and analyzed, the impact on U.S partners must be a key consideration.

5) The space, weight, power, and cooling margins for Navy ships are significantly limited, so any additional technology insertion must take this into account.
6) The integration of technologies on new and existing ships must meet strict standards (MIL-STD and Technical Warrant Reviews), which increases the testing requirements and can significantly lengthen the timeline for technology adoption.

It is important to highlight that Navy will only pursue decarbonization measures that maintain or enhance warfighting capability and mission effectiveness. Energy efficiency measures, for example, have the potential to lower emissions by decreasing fuel consumption, which also helps to extend the range and endurance of Navy operational platforms. Lower carbon fuels, if produced closer to the point of need, can help to address the contested logistics challenge. Other solutions must also serve to maintain or enhance capability if they are to be pursued.

Figure 6 below identifies the Navy surface fleet platforms that are key drivers of fuel usage, and therefore GHG emissions; eight (8) ship classes account for over 80% of the total surface fleet emissions. Highlighted in blue below are the ship classes that should be considered priorities for potential back-fit solutions, either due to the fact that new hulls are still being delivered to the fleet, or that they are relatively young and have significant service life remaining. Note that the CG-47 class is not prioritized, as these vessels are in the process of being retired, and future service life extensions could impact other classes. Also note that future unmanned systems are not included in this chart, as they are not a significant component of the fleet today. However, due to projected growth, unmanned platforms should be considered key targets for potential solutions to be integrated in future design and construction.

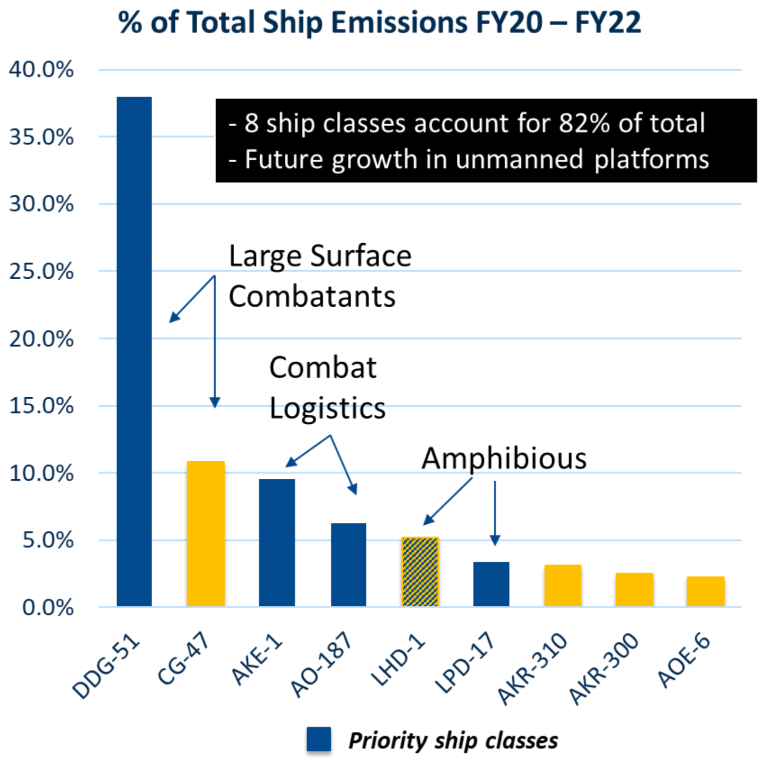


Figure 6. Percent of total emissions FY20 – FY22

VII. DECARBONIZATION THRUSTS FOR NAVY OPERATIONS

A. SUMMARY

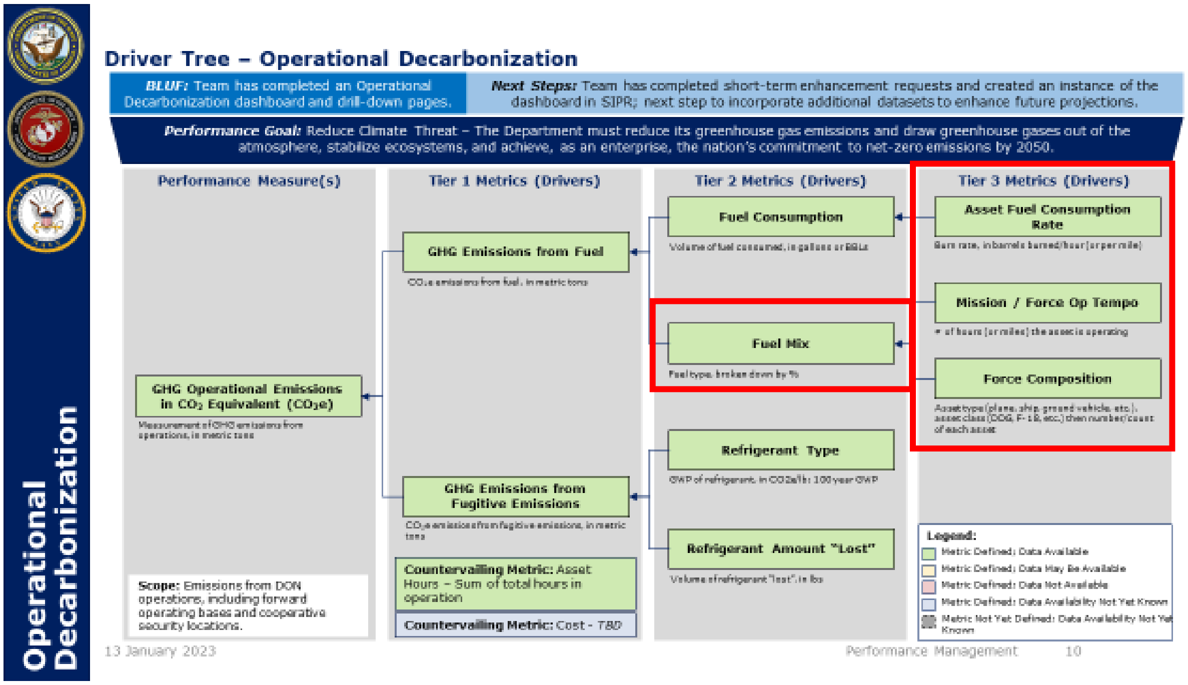
While initially focused only on maritime platforms, the Roadmap is intended to serve as a framework for broader Navy decarbonization efforts, and enable this structure to be applied to air or ground platforms in the future. With this in mind, the team prioritized the study and analysis of other decarbonization and Net Zero strategies, to ensure that the framework developed would be in alignment with not only Navy strategy, but also with other government and private sector decarbonization efforts.

As detailed in the following sections, the results of this effort were the identification of five (5) major decarbonization thrust areas, supported by four (4) cross-cutting initiatives, and Rough Order of Magnitude (ROM) levels of potential emissions reduction impact for Navy platforms.

B. DECARBONIZATION THRUST DEVELOPMENT PROCESS

To properly assess potential R&D opportunities in platform decarbonization, the first step required reaching a common understanding of the full set of options that are available to the Navy to reduce the carbon footprint of its operational force. While this Year 1 effort is focused on maritime platform decarbonization, an explicit goal for this Roadmap is to develop a robust framework that could be more broadly applicable to other platform types, specifically aircraft and potentially ground vehicles in the future.

As noted previously, high level guidance is provided via Executive Orders, various DOD strategy documents and the Navy *Climate Action 2030* strategy. In addition to these documents, additional guidance was drawn from the Operational Decarbonization driver tree effort undertaken during the development of the Navy climate strategy in early 2022. A draft copy of this driver tree is shown in Figure 7. Outlined in red are the four major drivers of Operational Navy's GHG Emissions from Fuel: 1) Asset Fuel Consumption Rate, 2) Mission/Force Op Tempo, 3) Force Composition, and 4) Fuel Mix.



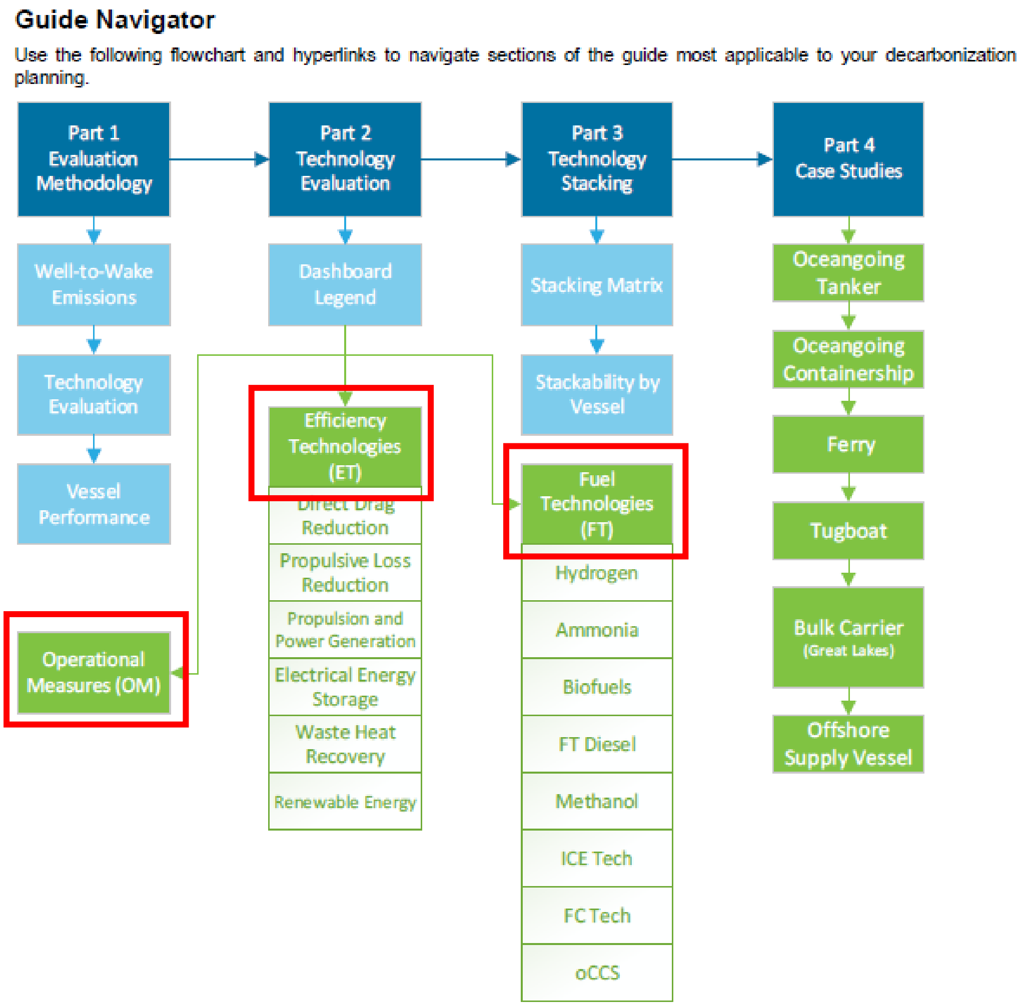
Source: US Navy

Figure 7. Operational Decarbonization Driver Tree

In addition to the driver tree shown above, four other reports proved to be integral in the development of the Decarbonization Thrust Areas, as discussed in more detail below.

1) Released in November 2022, a report titled *"Energy Efficiency and Decarbonization Technical Guide"* provides a detailed analysis of the state of energy efficiency, fuel technologies, operational measures and other emerging technologies that can contribute to GHG emission reductions and energy efficiency improvements for maritime vessels, now and into the future. The report was authored by Glosten, under the management, oversight and financial support of the U.S. Maritime Administration (MARAD), Maritime Environmental & Technical Assistance (META) program. Figure 8 shows the organization of this report, and highlighted in red are the categories that they used to organize the Technology Evaluation portion of the report. These 3 categories, as shown below are: 1) Operational Measures, 2) Efficiency Technologies, and 3) Fuel Technologies. Also note the summary sub-categories under each of the main

categories, which provide guidance on the development of the detailed technology options supporting the Decarbonization Thrusts areas of this Roadmap.



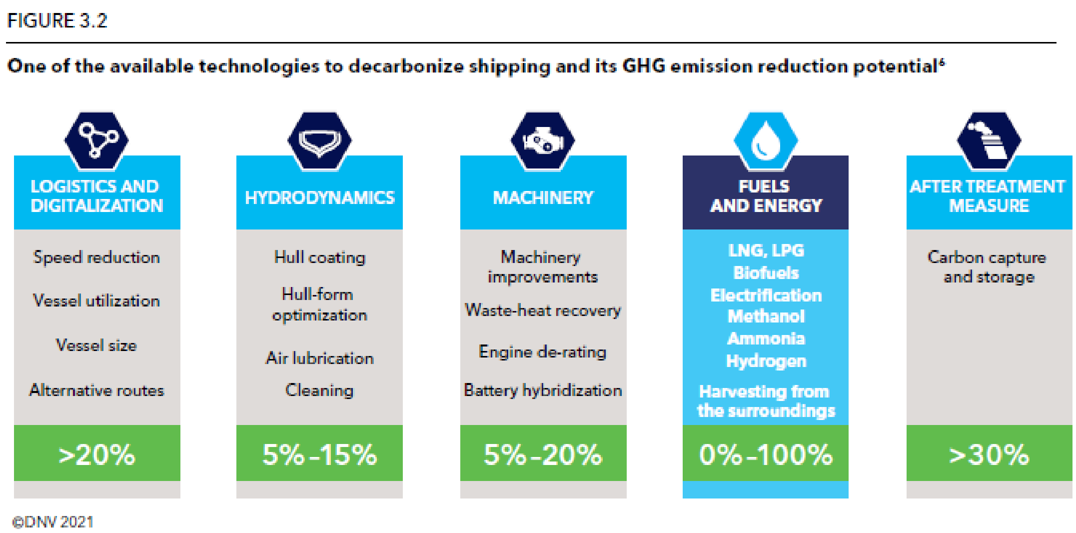
Source: MARAD

Figure 8. Glosten Report – Technology Evaluation Categories

2) A white paper published in 2022 by DNV, titled *"Alternative Fuels for Naval Vessels"* provides an overview of the advantages and disadvantages of various alternative fuels. Alternative fuels, in the context of this report, are defined as "anything beyond traditional fossil-based fuels such as marine gas oil." While the focus of this report is on alternative fuels, Figure 9, taken from the report, shows the five (5) groupings that DNV used to categorize the available GHG emissions

reduction technologies. Also note the high level estimated reduction potential, developed by DNV and sourced from a prior DNV publication.

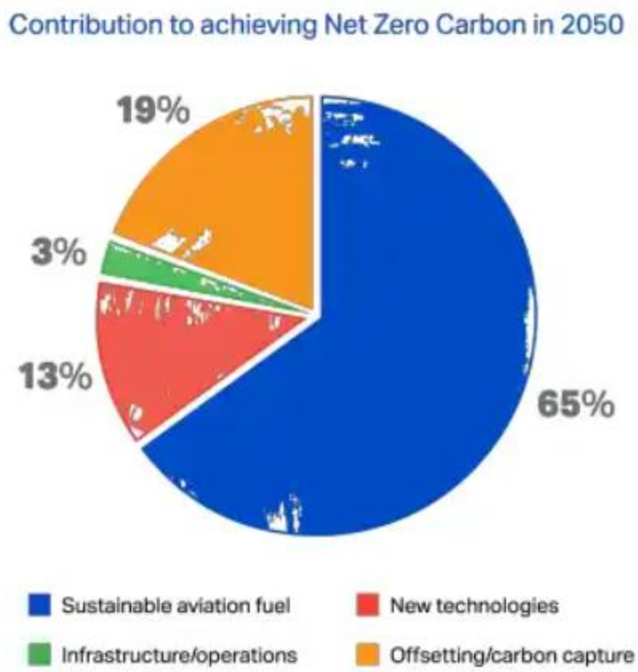
In addition to this DNV report, the American Bureau of Shipping (ABS) has released five (5) whitepapers on alternative fuel options for the maritime industry, each of which takes a deep dive into LNG, ammonia, methanol, hydrogen and biofuels. These whitepapers can be found in the List of References at the end of this report.



Source: DNV

Figure 9. DNV Decarbonization Technology Categories

3) In 2021, the International Air Transport Association (IATA) launched their Fly Net Zero campaign. Recognizing the projected growth in air travel over the coming decades and the impact air travel has on GHG emissions, the IATA developed a 2050 Net Zero strategy that laid a pathway to address the enormous technical challenge of air transport decarbonization. Figure 10 shows a summary of the major components of their 2050 Net Zero projection. It is important to note in the forecast that sustainable aviation fuel (SAF) is targeted to account for 65% of their Net Zero goal, and the impact of new technologies is forecast as 13%. Note also that the “new technology” category includes new aircraft technology, to include new aerodynamic technologies, as well as alternative propulsion such as battery-electric and hydrogen.



Source: IATA

Figure 10. IATA Fly Net Zero Summary

4) An article published in 2017 by the Journal of the Transportation Research Board entitled "*State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review*" provides the 4th major report used in the Decarbonization Thrust development. This publication reviewed approximately 150 studies, with the intention to provide a comprehensive overview of the state of various technology solutions, as well as quantify the reduction potential of these solutions. Figure 11 provides a high-level summary of results. Two important takeaways from this summary are that 1) fuels stand out as an outlier with the potential to provide the most emission reductions for maritime vessels, and 2) the bulk of the other technology solutions are grouped in the 0-20% reduction potential range, before any consideration of Navy specific constraints and mission requirements.

E.A. Bouman et al. / Transportation Research Part D 52 (2017) 408–421

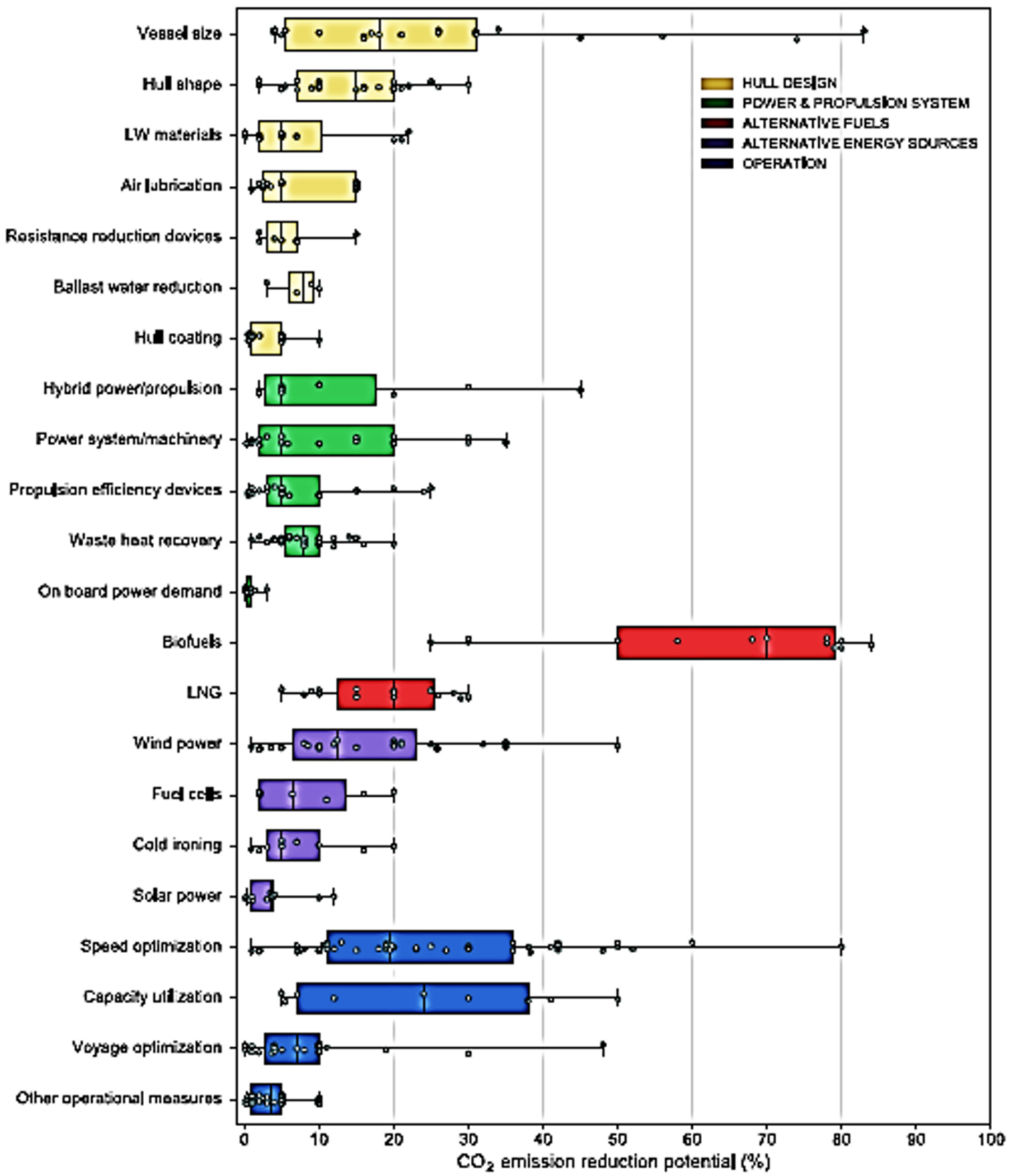


Fig. 2. CO_2 emission reduction potential from individual measures, classified in 5 main categories of measures.

Source: [Journal of Transportation Research Board]

Figure 11. Journal of Transportation Research Board - Maritime Technology Summary

C. OPERATIONAL NAVY DECARBONIZATION FRAMEWORK

Synthesis of the information from the above publications and discussions and feedback from the Consortium members resulted in the Navy Decarbonization Framework depicted in Figure 12 below.

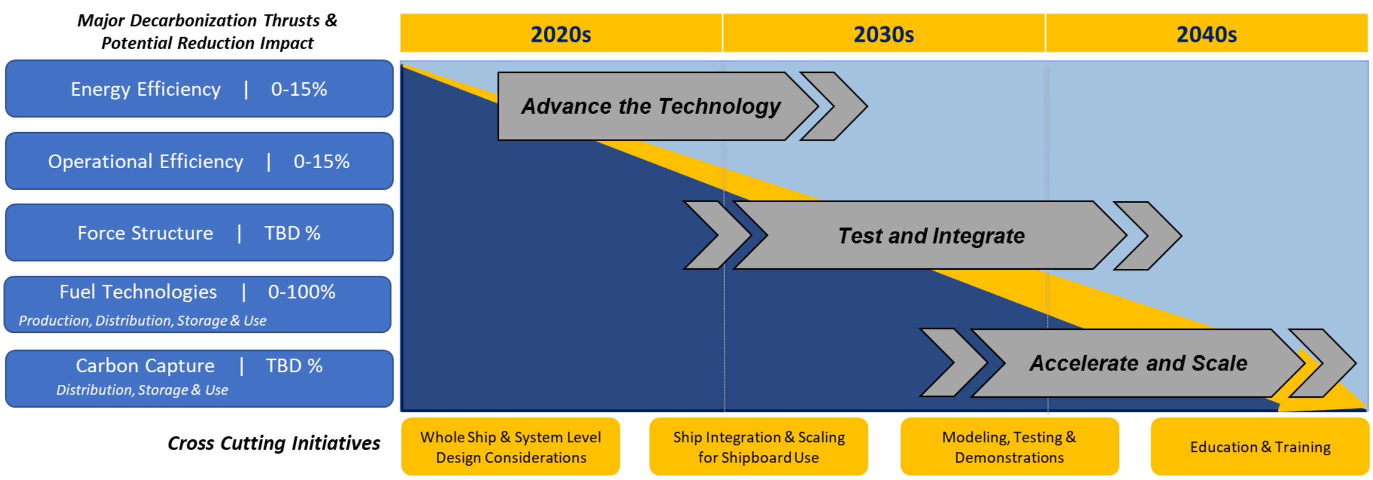


Figure 12. Operational Navy Decarbonization Framework

The major components of the above Framework are described in more detail in the sections below.

1. Major Decarbonization Thrust Areas and Potential Reduction Impact

In synch with the Operational Decarbonization Driver Tree and leveraging the aforementioned Glosten and DNV resources for guidance, technologies were grouped into the following five (5) major thrust areas:

1) Energy Efficiency Technologies – This thrust area is intended to cover a broad range of efficiency technologies that can be integrated into the physical platform itself, either in initial design or via retrofit. Emissions reduction potential for the category is estimated at 0-15%, in line with estimates from other publications, some noted previously. This category also considers that Navy prioritization of resources and modernization of warfighting platforms is driven by requirements to employ and sustain more combat power at greater distances, which typically

offsets at least a portion of the gross emissions reductions from adopted energy efficiency measures.

2) Operational Efficiency Improvements – This thrust area includes changes to operations, routing and plant settings versus physical technology insertion onto platforms. Emissions reduction also is estimated at 0-15%, for the same reasons as noted prior, for energy efficiency technologies.
3) Force Structure – This thrust area is a broad category intended to include the development of new Navy platforms, with specific attention paid towards unmanned systems, as well the assessment of how new platforms, including unmanned systems, have the potential to alter Navy CONOPS. The emissions reduction potential of a new force structure has not yet been assessed.
4) Fuel Technologies – Broadly acknowledged across government and industry as having the highest potential to impact platform decarbonization, this category, as part of an overall Navy approach to decarbonization, includes the production, distribution, storage and/or use of lower-carbon fuels. It is important to note when discussing various fuel technologies, consideration of total life cycle emissions, often referred to as Life Cycle Analysis (LCA), must be considered. For maritime platforms, this is often referred to as "well-to-wake" (WTW) emissions. Emissions reduction potential for this category was assessed at 0-100%; this wide range will be primarily driven by the actual volume (volume itself being driven by cost and availability) of any lower-carbon alternative fuels that Navy platforms may utilize in the future, as well as the LCA of those fuels.
5) Carbon Capture – The final thrust area encompasses mobile or onboard carbon capture technologies and systems and does not include any land-based applications. Consideration needs to be given not just to the capture of the carbon from any combustion or transformation processes, but also to the distribution and storage of the carbon once it has been captured. The MARAD Glosten report mentioned earlier suggested capture rates of 60% or greater were potentially achievable. However, due to space and mission constraints for military vessels, it is highly unlikely that capture rates for Navy vessels will approach these levels. For this reason, and due to the fact that many of these technologies are in an early

stage of development, especially for platform-based applications, the overall emission reduction potential for Navy vessels has not yet been assessed.

2. Cross-Cutting Initiatives

To support these five major thrust areas and taking into consideration the difficulty of integrating new technology onto Navy ships, the importance of indirect supporting thrusts should not be overlooked. Four (4) cross-cutting initiatives were identified as critical to ensuring that any future technological innovation has a pathway to eventual incorporation onto a Navy platform. They include the following:

1) Whole ship and system level design considerations;
2) Ship integration and technology scaling for shipboard integration;
3) Modeling, testing and demonstrations; and,
4) Education and training.

Emissions reduction potential attributed to the cross-cutting initiatives was not assessed in this Roadmap effort, but some of these activities, such as energy education and training, do have the potential to have a significant positive impact on energy usage, and therefore carbon emissions.

3. Technology Development Timeline

Another aspect of the Framework to which to draw the reader's attention is the technology development timeline depicted in Figure 12. Roughly speaking, the Roadmap envisions a three stage technology development and integration timeline for Navy platforms, with the three stages being defined as: 1) Advance the Technology, 2) Test and Integrate, and 3) Accelerate and Scale. These are roughly aligned to a decadal approach, with stage 1 being the focus for the 2020s, stage 2 in the 2030s and stage 3 in the 2040s. The timelines shown here naturally overlap and are not intended to be rigid or prescriptive. However, they convey the fact that the integration of new technology on Navy platforms is challenging and is a lengthy, time-consuming process, and the fact that mission constraints and the long service life of Navy assets pose a challenge in how quickly new technologies can be implemented across a fleet of platforms.

D. DETAILED TECHNOLOGY THRUST AREAS

As mentioned previously, decarbonization technology options were collected from a variety of sources, including the aforementioned publications, discussions with Consortium members, and analysis of Navy and other government agency investments. These were assessed, deconflicted and grouped into the 5 major decarbonization thrusts. However, to guide an additional research focus, a more detailed breakdown is required. Table 2 below shows the 29 sub-categories of decarbonization technologies that have been included in this initial version of the Roadmap, which are intended to capture the broad potential solution space for Navy platform decarbonization efforts. Although initially focused on maritime platforms, the stated goal of the Roadmap effort was to develop a robust framework that would be broadly applicable to other Navy platforms, such as air and ground vehicles. As such, it is not expected that all of these categories will have direct applicability to Navy ships, however it is believed that this level of detail will provide guidance to decarbonization R&D efforts into the future. In addition, as the Consortium efforts continue, and the research agenda progresses, it is expected that the categorization shown here may evolve, so changes in future versions of the Roadmap are likely to occur.

	Approx. Impact to Operational Navy Decarbonization (%)	Category	Sub-Category
Major Thrust Areas	0% - 15%	Energy Efficiency	Propulsive efficiency improvements & direct drag reduction
			Propulsion & power generation improvements
			Electrification, hybridization & energy storage
			Waste Heat Recovery (WHR)
			Electric load reduction
			Lightweight materials
	0% - 15%	Operational Efficiency Improvements	Route optimization
			Plant line-up & speed optimization (single generator ops, etc.)
			Trim optimization
	TBD	Force Structure	New/emerging CONOPS (to include manned/unmanned teaming)
			Mission optimized future platforms (including unmanned, attritable, single-use assets, etc.)
	0% - 100%	Fuel Technologies, Production, Distribution, Storage and/or Use	Blended or drop-in fuels (bio-, renewable-)
			Non drop-in liquid fuels (ammonia, methanol, etc.)
			Hydrogen
			Nuclear
			Renewable energy
	TBD	Carbon Capture, Use and Storage	Shipboard
			Terrestrial
			Other emissions capture/reduction
Cross-Cutting Initiatives	N/A	Whole ship and system level design considerations	Ship design process
			System level design considerations
	N/A	Ship integration & technology scaling for shipboard use	Ship integration (e.g., retrofit-ability, durability, etc.)
			Scaling for shipboard use
	N/A	Modeling, test sites and demonstration capability	Modeling & data analytics
			Bench scale testing
			Demonstrations & testing
	TBD	Education and Training	Education & training

Table 2. Decarbonization Thrusts: Detailed Sub-Categories

VIII. ASSESSMENT OF CURRENT ACTIVITIES AND RESEARCH FOCUS AREAS

A. CURRENT ACTIVITY ASSESSMENT SUMMARY

A review and analysis of the current activities and investment in relevant decarbonization technologies was undertaken, discussed in more detail below, the results of which can be summarized as follows.

- Navy prioritizes investment in efficiency, electrification, and force structure to enable, improve and sustain the combat effectiveness of the naval fleet.
  - To date, Navy investment in lower carbon fuels and carbon capture technologies are primarily focused on fuel generation in theater.
- DOE is active across all relevant sectors, funding fuels R&D under a wide range of initiatives, including the following:
  - SAF Grand Challenge
  - Energy Earthshot – Clean Fuels and Production
  - Zero-Emissions Shipping Mission (ZESM)
- DOT partnered with DOE on ZESM and is active in maritime decarbonization with a focus on Low Carbon Fuels, Electrification, Energy Efficiency, Carbon Capture, and Green Shipping Corridors.

B. CURRENT ACTIVITY ASSESSMENT PROCESS

After developing an understanding of the “playing field” of potential platform decarbonization technologies, the team sought to analyze and summarize the level of activity and investment that Navy and other core partners (such as DOE and DOT) were already engaged in across these technology areas. This analysis proved to be fairly challenging for several reasons.

For the Navy, due to core warfighting and mission needs, there is a significant amount of investment already going into a wide range of operational energy technologies, to extend range and increase combat capability. While there are various reporting requirements in place across the Navy enterprise, there is not a “one stop shop” where information on all S&T, R&D and demonstration efforts is collected.

In addition, the often-robust reporting that is already in place is typically focused on operational energy needs, and these efforts have substantial, but not complete, overlap with climate, decarbonization and emissions reductions needs. In the end, the team utilized two different existing internal reporting products, one for operational energy and one for climate, as well as discussions with several Navy colleagues, to do a high-level assessment of Navy “activity” in each of the decarbonization technology categories.

For DOE, many of these technology areas (hydrogen, for example) have Program Offices working the full spectrum of potential solutions, and there are sizeable amounts of investment, as well as ongoing/regular announcements regarding new programs and activities. Because the Consortium has not yet embarked on a robust collaboration strategy with DOE, the team generally used publicly available information from the DOE website, as well as a handful of ad hoc discussions with DOE personnel, to give a qualitative view of the broad scope of relevant DOE activities.

For DOT, the team relied heavily on discussions with the MARAD META program to understand and provide a qualitative assessment of their activities in this space.

C. CURRENT ACTIVITY ASSESSMENT DETAILS

Table 3 provides a summary of the assessment process described above. For the Navy, only data for FY22 and FY23 projects were included. Data on the number of projects, the investment amount, and the “top three technology areas addressed” for each identified project effort were collected and used to do a “quantitative/qualitative” assessment and ranking of activity levels for each category. The number of ◊s indicates the rough level of activity in that technology area, with more ◊s indicating more “activity”. For DOE and DOT, since the same level of project detail was not available at this time, the team placed an X in each category that was known to have some level of effort ongoing.

As detailed in the Collaboration Strategy (reference Chapter XI), it is the intent of this Consortium to put in place a more robust and consistent collaboration routine with a variety of different partners, to include not only Navy, DOE and DOT, but also to extend to the other DOD services, other USG entities and international partners. Through this effort, the team intends to develop a much more detailed view of current investment efforts. It is the intention that the team will be able to update these summaries in the future, and will be able to use this data to more keenly focus S&T efforts going forward. Further details on relevant projects and activities for Navy, DOE and DOT can be found in Appendix A.

	Category	Sub-Category	NAVY	DOE	DOT
Major Thrust Areas	Energy Efficiency	Propulsive efficiency improvements & direct drag reduction	◊◊◊	X	X
		Propulsion & power generation improvements	◊◊◊◊◊	X	
		Electrification, hybridization & energy storage	◊◊◊◊◊	X	X
		Waste Heat Recovery (WHR)	◊◊	X	
		Electric load reduction	◊◊◊	X	X
		Lightweight materials		X	
	Operational Efficiency Improvements	Route optimization	◊		
		Plant line-up & speed optimization (single generator ops, etc.)	◊		
		Trim optimization			
	Force Structure	New/emerging CONOPS (to include manned/unmanned teaming)	◊◊		
		Mission optimized future platforms (including unmanned, attritable, single-use assets, etc.)	◊◊		X
	Fuel Technologies: Production, Distribution, Storage and/or Use	Blended or drop-in fuels (bio-, renewable-)	◊◊◊	X	X
		Non drop-in liquid fuels (ammonia, methanol, etc.)	◊	X	X
		Hydrogen	◊◊	X	X
		Nuclear		X	
		Renewable energy	◊◊	X	X
	Carbon Capture: Distribution, Use and Storage	Shipboard	◊		X
		Terrestrial		X	
		Other emissions capture/reduction (high GWP refrigerants, etc.)	◊		

Table 3. Assessment of Current Investment Activity

D. RESEARCH FOCUS AREAS IDENTIFICATION

The research team worked with ONR, Consortium participants and external partners to develop an understanding of what research was being addressed and to identify the priority areas for year 1 research. Based on a review of project information above, two conclusions were fairly self-evident:

1) Navy already has significant activity across a wide range of energy efficiency technology areas, driven by current mission and operational needs; and
2) Both DOE and DOT have significant activity ongoing in Fuels, and while Navy is somewhat active in this space, this presents an opportunity ripe for a more collaborative approach.

Figure 13 below summarizes how the project team currently views the drivers of Navy focus in the five decarbonization thrust areas:

- Navy currently invests significant resources in energy efficiency, operational efficiency and force structure to address current mission and contested logistics challenges; and
- In the future, Navy will need to continue focus on these areas, but needs to expand the scope to focus more on lower-carbon fuels and carbon capture, to address the long-term challenges posed by climate change.

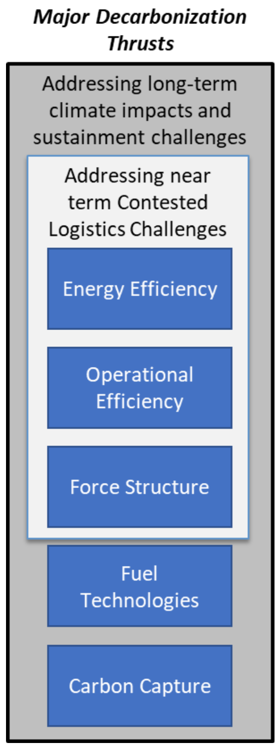


Figure 13. Focus Areas

As a result of this review and analysis, the Consortium determined key focus areas for the Year 1 Agenda to be:

- The ***use*** of lower carbon fuels in Navy relevant prime movers;
- Shipboard carbon capture technologies;
- Energy efficiency technologies (*continued focus*); and,
- Modeling and analysis of energy systems, ship design process and systems architecture.
- *Note; Operational Efficiency and Force Structure were not prioritized for Year 1 research efforts.*

IX. YEAR 1 RESEARCH AGENDA

Consistent with the Focus Areas defined above, ONR selected a variety of projects for approval as part of the Year 1 Research Agenda. Titles for each funded project are shown below, categorized consistent with the Roadmap Decarbonization Thrust Areas.

Fuel Technologies & Carbon Capture

- Collaboration of USC, CSU, PSU, USNA
  - University of South Carolina: Fuel Flexible Gas Turbine Technology Integrated with Exhaust Gas Recirculation and Hydrogen Carrier Fuels
  - Colorado State University: Liquid-Fueled Solar Centaur 40 Gas Turbine Testing with High EGR Fraction to Support Carbon Capture System Integration
  - Penn State University: Fuel Flexible Gas Turbine Technology Integrated with Carbon Capture and Utilization
  - US Naval Academy: Working Towards Zero-Carbon Naval Energy Technologies with Midshipmen at the USNA
- University of Wisconsin: Enabling mixing-controlled combustion of low carbon fuels in naval reciprocating engines
- University of Illinois: Sustainable Power for Decarbonization of Naval Vessels

Energy Efficiency: Electrification & Hybridization

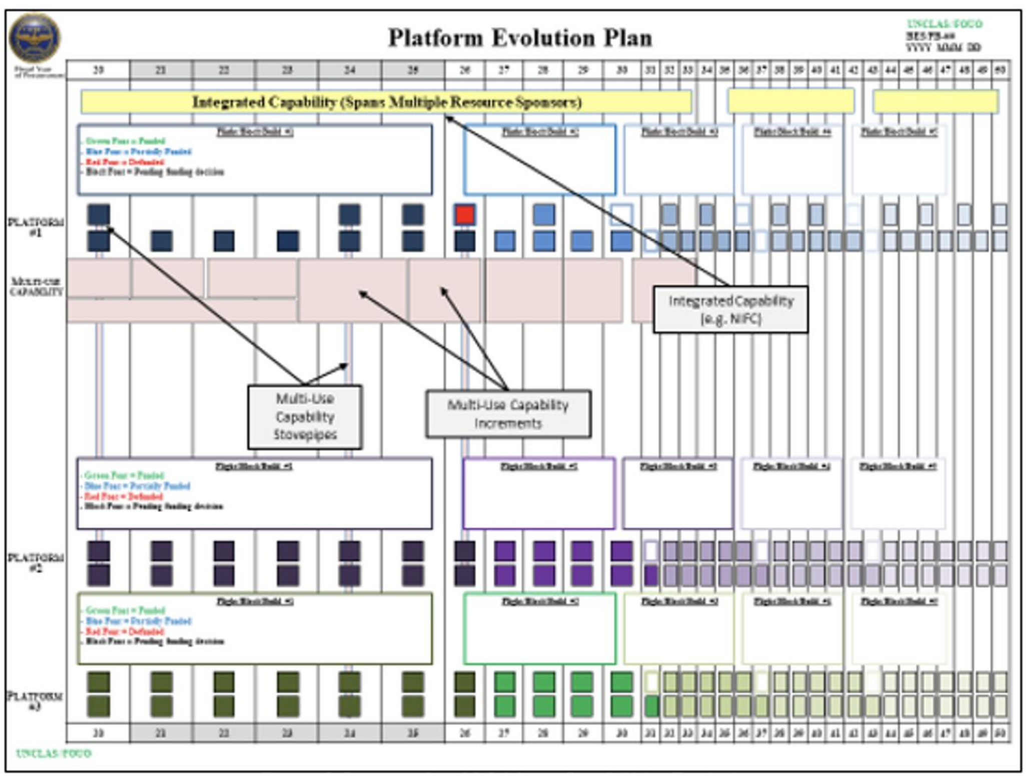
- Naval Surface Warfare Center (NSWC) Philadelphia: Evaluation of Propulsion Derived Ship Service and Weapons Power to Support Decarbonization

Cross-Cutting: Modeling - Energy Systems, Ship Design, System Architecture

- Collaboration of GWU, NPS, USNA, American Bureau of Shipping
  - George Washington University: Energy Systems Modeling, Prediction, and Planning Tool for Navy Decarbonization Technologies
- NPS: Trade space exploration for climate impact and quality attributes for navy ships
- NPS: High-level system architecture, modeling and performance evaluation of a fleet of green-energy ships producing hydroelectric energy and hydrogen at sea

X. ADVANCE THE TECHNOLOGY – S&T EVOLUTION

Given the timelines and challenges involved in integrating new technologies onto naval platforms, the team felt it was important to start these projects with the "end in mind". Per the *Capability Evolution Plan Guidebook*, "Capability Evolution Plans (CEPs) are the OPNAV N9 Resource Sponsors means of coordinating multiple lines of effort to develop and deliver future warfighting effects." CEPs are intended to have an easily understandable format, and to be a powerful tool to show stakeholders how development and fielding efforts underway support capabilities that improve the warfighting capabilities of the Navy. A sample CEP format is shown in Figure 14 below.



Source: US Navy

Figure 14. Sample Capability Evolution Plan Format

The team felt it was important to keep these early-stage S&T efforts focused on the end goal of delivering capability to the fleet, but also wanted to clearly recognize that these are in fact S&T efforts, that not all S&T efforts will be successful in transitioning to a platform, and there are many steps (and years) between technology development and platform fielding. In support of this view, the graphic in Figure 15 below was developed to highlight the core activities that are required in each "stage" of technology development, specifically as it relates to the CEP process and the eventual integration of technologies on a platform. It is also intended to highlight the fact that the efforts that are currently being undertaken as part of the Year 1 Research Agenda are in the first stage of this process, the Advance the Technology stage. As such, fully developed CEPs are not possible at this stage, but each project team, with support from ONR and Navy, should be developing their project with this "end in mind".

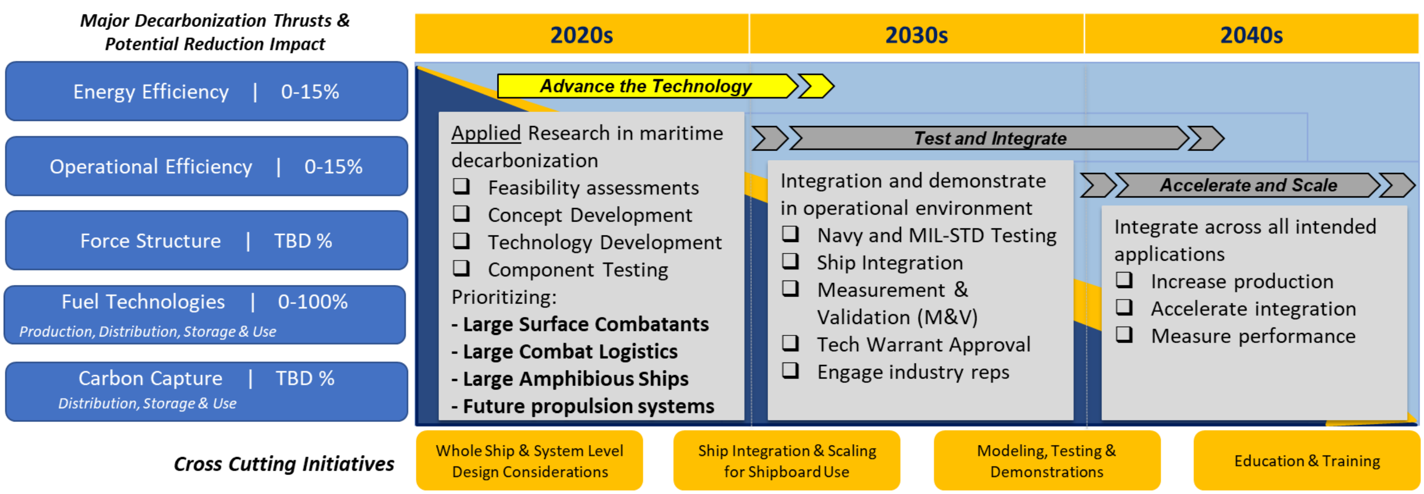


Figure 15. Advance The Technology – S&T Evolution

XI. COLLABORATION STRATEGY

During the Roadmap development process, it became clear that a robust collaboration strategy was needed to best attack the decarbonization challenge. As climate science has improved, and as the global consensus has grown that real progress needs to be made, investment activity across a wide range of governments, industries and economic sectors has exploded in recent years. While Navy does carry with it unique challenges, there are undoubtably many areas of overlap and potential to leverage others' work to further the Navy mission. ***Collaboration is key***.

In recognition of this fact, the team has identified six (6) core communities for increased collaboration activity and is in the process of developing a strategy to engage each community. This collaboration will be a significant part of the Year 2 Consortium efforts and will support both the success of the Year 1 Research Agenda, as well as the setting of new focus areas for Year 2 and beyond. The 6 core communities are the following.

- Current Consortium – foster increased collaboration amongst Consortium members
- Internal Navy and other DOD – operational energy, climate and resilience constituencies
- Other USG Agencies – DOE/ARPA-E, DOT, and others (e.g. NASA, EPA, NOAA, etc.)
- International partners – NATO, TTCP*, Pacific Islands Partnership, etc.
- Industry – potentially via the DOT/MARAD U.S. Center for Maritime Innovation (in work)
- Academia – identify leading researchers in other technology areas

**The Technical Cooperation Program*

The team has set two major goals for this collaboration activity:

- To better understand ongoing efforts and identify the most impactful areas of research to guide and prioritize the research agenda for upcoming years; and,
- Identify appropriate Navy “role” in various thrust areas, considering:
    - Government-wide approach and R&D portfolios of other partner entities; and
    - Navy unique requirements that may not otherwise be addressed.

XII. ROADMAP – KEY ACTIONS

In support of the Navy's overall climate strategy goals and the goals of the Decarbonization Research Consortium, Key Actions for the 2020s, 2030s and the 2040s have been developed, and are shown in the following tables. These are intended to describe high-level actions and provide guidance for near- and longer-term activities. An important focus for the Consortium and the research teams is to continue to mature the technologies, expand and mature the Roadmap itself, and keep focus on transition opportunities and timelines. Platform decarbonization is a difficult challenge and requires a Whole of Government Approach to be successful, which underscores the importance of the collaborative approach that has been stressed throughout this document.

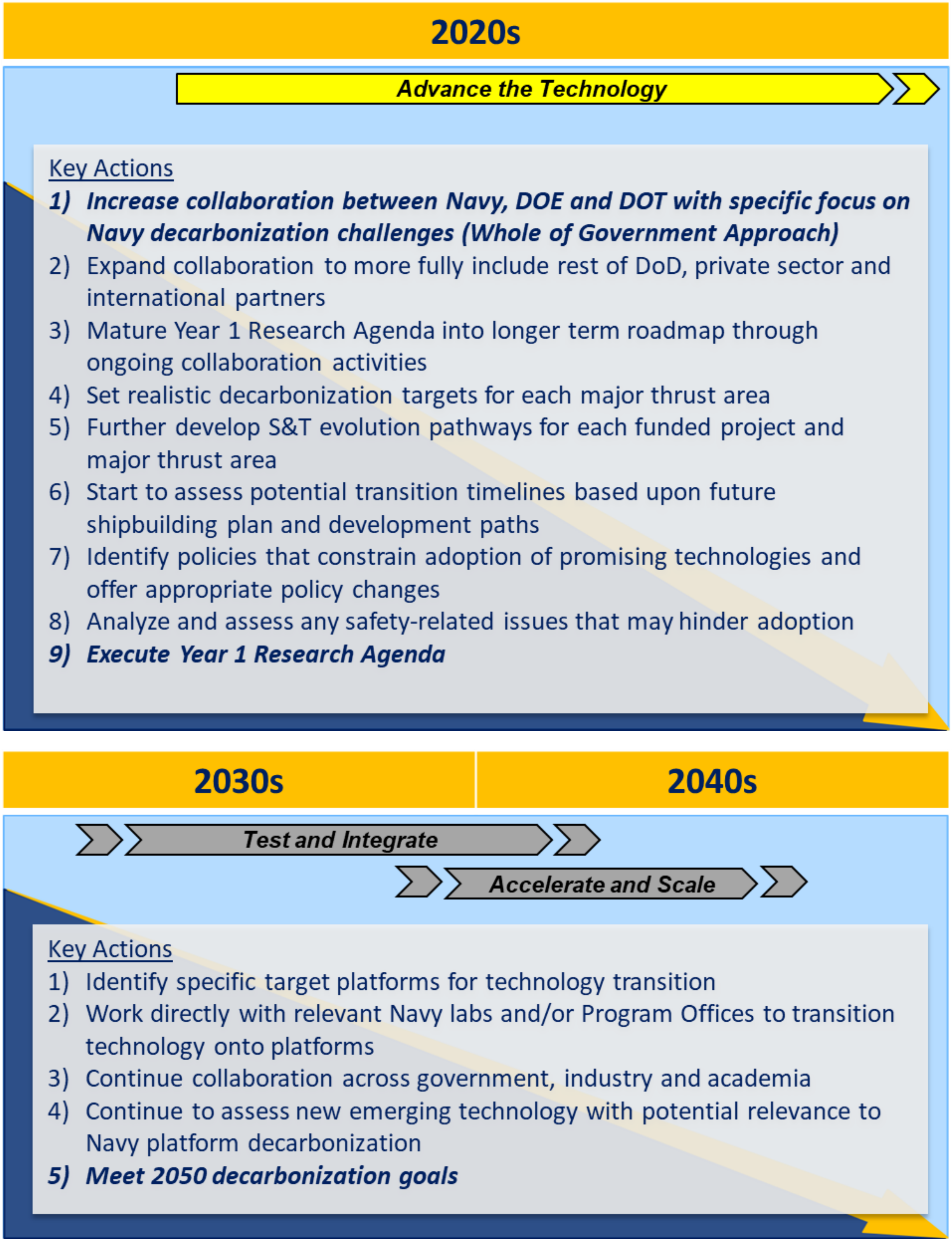


Figure 16. Roadmap - Key Actions

XIII. NEXT STEPS

At the conclusion of these Year 1 efforts on Roadmap development, the NPS team, in concert with ONR, identified some near-term actions that are deemed important for the success of the overall Consortium effort. As such, they are not included as part of the Roadmap itself, but more as a guideline for Year 2 efforts in the running and operation of the Consortium. These five (5) core actions are detailed below.

1) Implement Collaboration Strategy – Collaboration is key to addressing the decarbonization challenge for the Navy. Leveraging others' efforts, to the greatest degree possible, will allow the Navy to focus critical resources on areas that will have the most impact on its own operations. Communication of Navy requirements to the broader community will ensure that Navy needs are being considered when other communities tackle these hard issues. Collaboration will drive the Whole-of-Government Approach that is necessary for success.
2) Support execution of Year 1 Research Agenda – Providing support and assistance to the Year 1 project teams, through data collection efforts, supporting cross-team collaboration, providing Navy operational context to each research pathway, and facilitating access to Navy SMEs, as needed, will be critical to the success of the research agenda, and will support expansion of these efforts in future years.
3) Assess research impact on Navy objectives – In keeping with the spirit of this Roadmap being a "living document," work needs to continue with the project teams to better understand their efforts and research results. Identifying potential transition pathways and developing targets for the potential emissions reduction impacts of each project and/or Thrust Area will support the maturation and further development of this Roadmap and will help to target new potential research areas going forward.
4) Alignment with other roadmap and data collection efforts – A challenge in data collection of relevant efforts in the energy space with impact on decarbonization was noted in prior sections. As other roadmap efforts advance, both within the Navy and external to it, this team needs to stay abreast of those developments and

incorporate relevant updates into the Roadmap. Regarding data collection, alignment with any other efforts looking to develop data repositories for S&T and R&D efforts should be supported, as leveraging these other efforts will be beneficial to the overall mission.

5) Extend Consortium efforts - Finally, look to leverage this Roadmap framework and extend it to other aspects of the Navy decarbonization challenge, starting with aircraft, but also potentially consider ground vehicles and installations in the future.

APPENDIX A

Table 4. Summary of Current Activities – Navy

Major Thrust Areas	Category	Sub-Category	Navy: Summary of Major Efforts
	Energy Efficiency	Propulsive efficiency improvements & direct drag reduction	LCS Stern Flaps; Finlets; Hull Husbandry
		Propulsion & power generation improvements	PA6B Electronic Fuel Injection; Variable Cycle Advance Technology; T-AO 205 Efficient Replacement Engines; Aircraft Turbine Engine Recuperator; Aircraft, Engine Blade Scanning and Coating
		Electrification, hybridization & energy storage	Integrated Power Systems; Electric Ship Research and Development Consortium (ESRDC); Power Electronics Building Block; Silicon Carbide Power Modules; ESARCA – Electrical Ship Assets; Energy Magazine; Energy Storage Flywheel; Electrochemical Materials; Microbial Fuel Cells; Common Affordable Safe Energy Storage (CASES); Battery Development and Safety; Commercial Advanced Batteries; Battery Commonality; Battery Certification; Large Format Lithium Ion Batteries; COTS Battery Phase II
		Waste Heat Recovery (WHR)	Aircraft, Integrated Thermal and Power Management Modelling; Thermal Science and Engineering Program
		Electric load reduction	LED Lighting; Efficient Transmit/Receive Integrated Multichip Modules (TRIMMs); Variable Frequency Drives (VFDs)
		Lightweight materials	
	Operational Efficiency Improvements	Route optimization	Integrated Climate Weather and Ocean Decision Support; Aerial Refueling Drogue Stabilization
		Plant & speed optimization (single generator ops, etc.)	Global Energy Information System (GENISYS); Robust Combat Power Control (RCPC); Condition Assessment System
		Trim optimization	
	Force Structure	New/emerging CONOPS (to include manned/unmanned teaming)	
		Mission optimized future platforms (including unmanned, attritable, single-use assets, etc.)	MQ-25A Unmanned Aerial Refueler; Long Endurance Unmanned Surface Vessel; Robust Unmanned Platform Power System (RUPPS); H2 Stalker

	Category	Sub-Category	Navy: Summary of Major Efforts
	Fuel Technologies *Production, Distribution, Storage and/or Use*	Blended or drop-in fuels (bio-, renewable-)	Mobility Fuels Program; Service Review of Commercially Approved SAF; Direct Air Capture and Blue Carbon Removal Technology; STTR Topic N23A-T015: Scalable Net-Zero JP-10 Production from Non-Fossil Fuel Resources
		Non drop-in liquid fuels (ammonia, methanol, etc.)	Reactor-at-sea, NH_3 synthesis, powder catalyst
		Hydrogen	Shipboard Hydrogen R&D; Refueling & Support Package (RASP)
		Nuclear	
		Renewable energy	Alternative Energy S&T; Subsea & Seabed Warfare (SSW) Energy Harvesting; Biocentric Technology; Ocean Renewable Energy
	Carbon Capture, Use and Storage	Shipboard	Direct Air Capture and Blue Carbon Removal Technology; SBIR topic N232-107: Shipboard Carbon Capture and Storage
		Terrestrial	STTR Topic N23A-T020: Scalable Production of Carbon-Based Composites from Sequestered Environmental Carbon
		Other emissions capture/reduction	
Cross-Cutting Initiatives	Whole ship and system level design considerations	Ship design process	
		System level design considerations	
	Ship integration and technology scaling for shipboard use	Ship integration (e.g., retrofit-ability, durability, etc.)	
		Scaling for shipboard use	
	Modeling, test sites and demonstration capability	Modeling & data analytics	Theater Energy Model; Modeling & Simulation; Digital Twin Science and Technology
		Bench scale testing	
		Demonstrations & testing	
	Education and Training	Education & training	Workforce Development

Table 5. Summary of Current Activities – DOE

Major Thrust Areas	Category	Sub-Category	DOE: Summary of Major Efforts
	Energy Efficiency	Propulsive efficiency improvements & direct drag reduction	EERE – Vehicle Technologies Office: Lightweight and Propulsion Materials; Fuel Efficiency and Emissions EERE: Marine Decarbonization
		Propulsion & power generation improvements	EERE – Vehicle Technologies Office: Lightweight and Propulsion Materials EERE: Marine Decarbonization
		Electrification, hybridization & energy storage	EERE: Marine Decarbonization EERE – Vehicle Technologies Office: Plug-in Electric Vehicles and Batteries; Fuel Effects on Advanced Combustion
		Waste Heat Recovery (WHR)	EERE: Advanced Manufacturing and Industrial Decarbonization; Waste Heat Recovery
		Electric load reduction	EERE: Advanced Manufacturing and Industrial Decarbonization; Industrial Efficiency and Decarbonization Office
		Lightweight materials	EERE – Vehicle Technologies Office: Lightweight and Propulsion Materials
	Operational Efficiency Improvements	Route optimization	
		Plant & speed optimization (single generator ops, etc.)	
		Trim optimization	
	Force Structure	New/emerging CONOPS (to include manned/unmanned teaming)	
		Mission optimized future platforms (including unmanned, attritable, single-use assets, etc.)	
	Fuel Technologies: Production, Distribution, Storage and/or Use	Blended or drop-in fuels (bio-, renewable-)	EERE - Bioenergy Technologies Office: Bioenergy Technologies; Transportation Biofuels; Sustainable Marine Fuels; SAF Grand Challenge EERE: Marine Decarbonization EERE - Vehicle Technologies Office: Advanced Engine and Fuels Technologies; Fuel Effects on Advanced Combustion EERE: Clean Fuels & Products Shot

	Category	Sub-Category	DOE: Summary of Major Efforts
		Non drop-in liquid fuels (ammonia, methanol, etc.)	EERE - Bioenergy Technologies Office: Sustainable Marine fuels EERE - Vehicle Technologies Office; Advanced Engine and Fuels Technologies; Fuel Effects on Advanced Combustion EERE - Hydrogen and Fuel Cell Technologies Office: Novel Hydrogen Carriers – i.e. ammonia or natural gas EERE: Clean Fuels & Products Shot
		Hydrogen	EERE - Hydrogen and Fuel Cell Technologies Office: Hydrogen Shot; U.S. National Hydrogen Strategy and Roadmap; H2@Scale Office of Clean Energy Demonstrations: Regional Clean Hydrogen Hubs EERE - Vehicle Technologies Office: Advanced Engine and Fuels Technologies
		Nuclear	Office of Nuclear Energy
		Renewable energy	EERE - Bioenergy Technologies Office: Sustainable Maritime Fuels; Marine Decarbonization EERE - Vehicle Technologies Office: Advanced Engine and Fuels Technologies
	Carbon Capture, Use and Storage	Shipboard	Office of Fossil Energy and Carbon Management - Office of Carbon Management: Carbon Negative Shot EERE: Marine Decarbonization
		Terrestrial	EERE: Advanced Manufacturing and Industrial Decarbonization; Industrial Efficiency and Decarbonization Office
		Other emissions capture/reduction	

**Note: EERE is the Office of Energy Efficiency & Renewable Energy*

Table 6. Summary of Current Activities – DOT

Major Thrust Areas

Category	Sub-Category	DOT: Summary of Major Efforts
Energy Efficiency	Propulsive efficiency improvements & direct drag reduction	Hull Fouling
	Propulsion & power generation improvements	
	Electrification, hybridization & energy storage	Battery Electric Workboat Technoeconomic Analysis; Battery Electric Tug Boat Demonstration; Battery Electric Ferry Demonstration; Fuel Cells - SF BREEZE, ZERo/V, etc.
	Waste Heat Recovery (WHR)	
	Electric load reduction	Emission Reduction Technology - Energy Efficiency White Paper, Energy Efficiency and Decarbonization Technical Guide (2022)
	Lightweight materials	
Operational Efficiency Improvements	Route optimization	
	Plant & speed optimization (single generator ops, etc.)	
	Trim optimization	
Force Structure	New/emerging CONOPS (to include manned/unmanned teaming)	
	Mission optimized future platforms (including unmanned, attritable, single-use assets, etc.)	Autonomous Systems for Environmental Applications; workboat demonstration of autonomous vs manned for emissions
Fuel Technologies, Production, Distribution, Storage and/or Use	Blended or drop-in fuels (bio-, renewable-)	Fuel-related Initiatives - various bio-fuel and bio-diesel reports; Methanol testing on 4-stroke marine engine (ORNL/DOE)
	Non drop-in liquid fuels (ammonia, methanol, etc.)	Emission Reduction Technology - Lifecycle Analysis of the Use of Methanol for Marine Transportation; Ammonia testing on a 4-stroke marine engine (in partnership w/ ORNL & DOE)
	Hydrogen	Fuel Cells - Hydrogen Gas Dispersion Modeling
	Nuclear	

		Renewable energy	Regional studies on future energy options for Great Lakes; California Harbor craft; GOM offshore supply vessels and tugs/tows on the lower Mississippi
	Carbon Capture, Use and Storage	Shipboard	Maritime Decarbonization - Carbon Capture and Storage Study; Technoeconomic analysis for Carbon Capture; Engineering design study for carbon capture on tanker
		Terrestrial	
		Other emissions capture/reduction	
Cross-Cutting Initiatives	Whole ship and system level design considerations	Ship design process	
		System level design considerations	
	Ship integration and technology scaling for shipboard use	Ship integration (e.g., retrofit-ability, durability, etc.)	
		Scaling for shipboard use	
	Modeling, test sites and demonstration capability	Modeling & data analytics	GHG emissions calculator for vessels
		Bench scale testing	
		Demonstrations & testing	
	Education and Training	Education & training	

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