Balancing Operational Capability with Climate Adaptation and Resilience: The Case for a Model-Based Technology Roadmap Architecture

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Synopsis

Naval capability is energy limited. This paper discusses how the U.S. Navy will deliver power to capability, balancing increasing operational capability requirements with the need to navigate the climate crisis. The paper will be organized as follows: first, the importance of power and energy to the warfighter is highlighted, addressing the need for a comprehensive technology roadmap. We then present *why* requirements and operational capability demands are increasing, identifying the energy intensive systems and platforms required to develop and sustain agile and lethal capabilities for warfighting advantage. Next, we outline *what* core product lines are relevant to naval power and energy systems and then explore the application of Model-Based Systems Engineering (MBSE) principles to the technology planning and road-mapping process. We conclude with a detailed discussion of *how* the U.S. Navy can formalize the application of MBSE principles for power and energy systems described in the roadmap to reduce risk and increase flexibility for capability upgrades, against the backdrop of a climate crisis.

Keywords: Model-based systems engineering; technology development; directed-energy weapons;
integrating disruptive technology; combat and platform system evolution

Biographical Notes

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Emily G. Pence is an engineer at the Naval Surface Warfare Center Carderock Division, focused on advancing operational energy research and development initiatives. Previously, Ms. Pence was Senior Consultant at Herren Associates in Washington, D.C. where she worked with government teams to identify and mature energy technologies for shipboard application. Ms. Pence holds a Bachelor of Science in Material Science and Engineering with a minor in Green Engineering from The Virginia Polytechnic Institute and State University.

CDR Victor Sorrentino USN (Ret.) served more than 21 years as a Surface Warfare Officer. Notable tours include Chief of Staff, Standing NATO Maritime Group TWO and Deputy Director, Operational Energy Office on the Secretary of the Navy Staff. Today, Mr. Sorrentino is the Director of Energy Programs at Herren Associates where he has continued to support the US Navy's executive decision-making process for energy innovation and investment. Mr. Sorrentino holds a BA from Boston University and a MS from the American Military University.

1. Introduction

> *"Energy is an enabler of military capability, and the Department depends on energy-resilient forces and weapon systems to achieve its mission. However, contested logistics, reliance on commercial technology and infrastructure, and the imperative to understand the Department's energy use each pose challenges to ensuring energy secure forces in competition, crisis, and conflict."*
>
> Dr. William A. LaPlante
> Under Secretary of Defense for Acquisition & Sustainment
> Department of Defense Operational Energy Strategy, May 2023

1.1. National security imperative: Balancing operational capability with climate adaption and resilience

During this decade, the stage for global geopolitical competition is being set, while the timeframe for addressing challenges continues to contract. The United States finds itself in long-term global strategic competition, while also grappling with the destabilizing force of climate change. For the military, this challenge entails preserving freedom, prosperity, and security in the face of authoritarian regimes with a revisionist approach to foreign policy (Austin, 2022) while also ensuring that climate effects do not negatively impact readiness or operations. As a maritime nation, the U.S. Navy serves as the bulwark, America's most enduring and adaptable instrument of military influence. Along with its partners and allies, the U.S. Navy serves to defend freedom, sustain economic prosperity, and ensure free and open access to the sea (Del Toro, 2023). As an integral part of the Joint Force, the U.S. Navy assumes a forward-deployed posture, working closely with Allies and partners to deter potential aggression and safeguard maritime freedoms. "Operating in uncontested environments, our logistics enterprises operate on business principles. Those business principles were to resupply the force at maximum efficiency so that the American taxpayer dollar could be applied to combat power at the greatest point of need," said Adm. Samuel Paparo, commander of the U.S. Pacific Fleet during the 33rd annual WEST 2023 Conference (U.S. Pacific Fleet Public Affairs, 2023). "In our operational plans for high-end combat, we've got to think less in terms of maximum efficiency and more in terms of maximum effectiveness." This critical position requires the Naval Service to maintain an optimal blend of platforms, capabilities, and capacity to deliver integrated all domain power in competition, crisis, and conflict (see, for example, Figure 1).

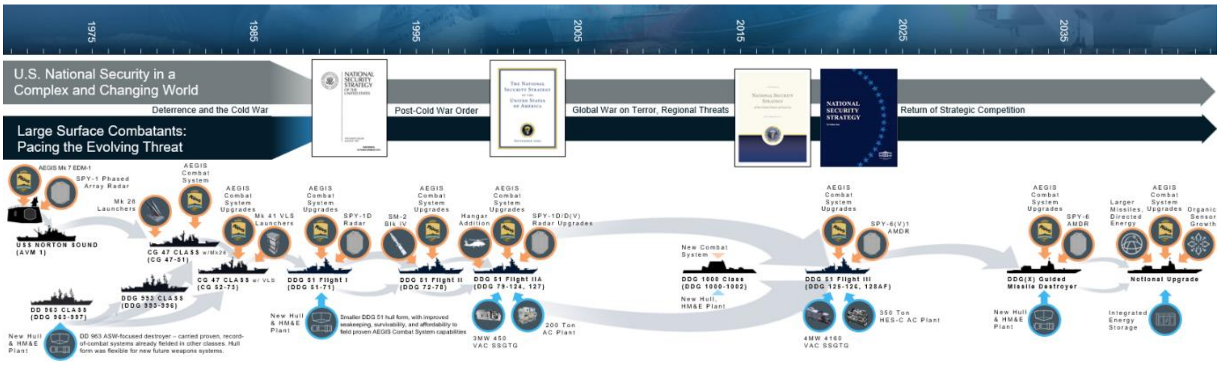

Figure 1: U.S. Navy large surface combatants: Pacing the projected threat with the re-emergence of strategic competition

Within the context of national security, climate change and other transboundary challenges that are likely to exacerbate cross-border geopolitical flashpoints (Office of the Director of National Intelligence, 2021) have been incorporated into the 2022 National Defense Strategy (NDS). According to the most recent *Message to the Force*, Hon. Lloyd J. Austin III, 28th U.S. Secretary of Defense (SECDEF), reiterated the need to meet the climate crisis head on: "Our strategy and planning addresses the security implications of our changing climate. We are developing new platforms that mitigate the logistical risks in contested environments" (Austin, 2023). Ultimately, all naval capability is energy limited. As climate change is expected to intensify the rate of trans-boundary threats, the U.S. Navy and its Allies will need to maintain security in the maritime commons as it faces new challenges from adversaries who are gaining technological advances (Brennan and Germond, 2023). The U.S. Department of Navy Climate Action 2030 strategy (U.S. Department of Navy, 2022), aligned with the U.S. Department of Defense (DOD) Climate Adaptation Plan (U.S. Department of Defense, 2021), recognizes these challenges, and balances the need to tackle both the long-term security risks associated with a changing environment with the near-term demand to increase the operational readiness and combat effectiveness of a forward deployed force.

Table 1: Current and Projected Climate Change Effects and Impacts (adapted from Office of the Director of National Intelligence, 2021)

Effect	*Current (1.1ºC warming)*	*2º C Warming*	*Impacts to Human Society*
Heat	5% of global population exposed to severe heat waves once in 20 years	37% of global population exposed to severe heat waves once in 5 years	More intense and frequent heat waves will reduce labor productivity, increase frequency and intensity of wildfires undermine human health, and lead to loss of life. As temperatures rise and more extreme effects manifest, there is also a growing risk of conflict over water and migration.
Heavy Precipitation and Flooding	25% of land with significant increase in once-in-a-century floods	37% increased frequency of precipitation extremes over land	Increased flooding will lead to economic losses, increased calls for humanitarian assistance, and loss of life
Sea Level Rise	8-9 inches with the rate of increase doubling in the last 30 years compared to the 20th century	Total projected rise of between 11 and 38 inches, with a median of 22 inches	Rising sea levels will increasingly imperil coastal cities and exacerbate storm surges that damage infrastructure and inundate water systems
Arctic Ice Melt	13% decline per decade of sea ice extent since 1979. 90% decline of at least 5-year-old thick ice	Probability of an ice-free summer-defined as less than 15% ice concentration-is one every 5 years	Accelerated melting of Arctic ice sheets will affect ocean circulation and salinity, threaten local ecosystems, and increase competition over resources and transit route access
Tropical Cyclones	Global annual average has remained level since 1980 but geographic distribution has shifted, with more cyclones in the North Atlantic and northern Indian Oceans	Additional 1.4 category-4 hurricanes per year, compared to 2018. Additional 1.2 category-5 hurricanes per year, compared to 2018	More frequent, destructive, and shifting tracks of cyclones will lead to trillions of dollars in economic losses in tropical zones, increase calls for humanitarian assistance, drive population displacement and migration, and lead to loss of life

1.2. The importance of energy to the warfighter

As risks emerge from a fraught and ever-evolving geopolitical landscape, energy, a critical element of both direct and indirect methods of modern warfare, will play an increasingly crucial role across all spectrums of conflict. The historical energy dominance the United States military has enjoyed is now being contested by strategic competitors keen on disrupting the existing security order. This strategic challenge has led to a shift in defense priorities from a primary focus on counter-insurgency operations to an emphasis on global deterrence and strategic competition. The 2022 NDS highlights the re-emergence of strategic competition between nations in the coming decade, with competitors equipped with advanced weapons, robust anti-access and area-denial (A2/AD) systems, and highly sophisticated cyber capabilities. These developments pose substantial threats to the military's ability to supply energy to forward-deployed forces.

This changing landscape directly impacts the U.S. Navy's ability to deploy forward – with Allies and partners – as part of the Joint Force. To effectively respond, the Naval Services must adopt innovative strategies like Distributed Maritime Operations (Levaggi, 2023). To pace the threat, the U.S. Navy is rapidly integrating advanced power and energy technology to enable the emerging capabilities ranging from larger sensors to directed energy weapons. These strategies place a significant burden on the global logistics. To adapt to a new environment, a series of energy wargames have been conducted to evaluate fuel storage, distribution capacity, and the vulnerabilities inherent in military energy supply chains. Notably, the Joint Force War Game, sponsored by the U.S. Indo-Pacific Command, served as a catalyst to identify opportunities to assure delivery of energy to the warfighter (U.S. Defense Logistics Agency Public Affairs, 2019).

Regarding the impact to the Navy’s global energy consumption, a recent study led by Naval Postgraduate School (NPS), sponsored by the Office for Warfighting Requirements and Capabilities, estimate that with current and future technologies considered, U.S. Navy surface ship consumption is expected to grow 4.5% from 2022 to 2030 (Fletcher, et al. 2023). The Fuel Usage Study Extended Demonstration (FUSED) model served as the analytical tool employed by NPS researchers to simulate potential implications of fielding new technologies within the U.S. Navy’s future Fleet architecture. Built on an Excel/VBA based platform, FUSED simulated battlegroups executing specific missions under a variety of operational conditions. Researchers modify these conditions to evaluate the effects of new technologies and employment strategies on Fleet fuel consumption (see, for example, Table 2).

Table 2: FUSED U.S. Navy Surface Ship Fuel Consumption Projection (adapted from Fletcher, et. at, 2023)

FUSED Model Results	***Fuel Use in Barrels***
U.S. Navy Surface Ship Fuel Consumption (2022)	9,030,022 bbls
U.S. Navy Surface Ship Fuel Consumption (2030)	9,433,091 bbls

To place these challenges into a global context, the U.S. Navy consumption challenges are on par with some of the largest and most populous cities in the world. U.S. Navy surface ship consumption represents nearly 2X the entire fuel consumption for freight transport throughout the Greater London area, including both heavy and large goods vehicles with a gross combination mass of over 3500kg (UK Department for Business, Energy, & Industrial Strategy, 2020). From this perspective, the U.S. Surface Forces face similar challenges to major metropolitan regions with the use of freight transport where significant improvements in vehicle technology and greatly improved engine efficiency have not yet resulted in a proportional reduction in overall fuel consumption or dramatically improved efficiency.

1.3. The need for a comprehensive technology roadmap

Technology roadmapping traces its origins back to the 1970s when Motorola employed the technique for strategic planning and technology management within the semiconductor industry (Willyard & McClees, 1987). Motorola's successful application led to the gradual adoption of road-mapping across a number of industries with both commercial and government applications. Within the automotive sector, road-mapping has assisted in navigating the transition to sustainable mobility solutions. Setiawan (2021) highlights its application in identifying alternative fuels for reducing greenhouse gas emissions, while Saritas, O., et al. (2019) focus on its role in the evolution of electric vehicles. In the aerospace industry, technology road-mapping has proven to be a pivotal tool to address long development cycles and high-risk investments. Mankins (2009) discussed its role in NASA's strategic planning, where it has been instrumental in charting the path for space-based solar power by addressing both technological milestones and budgetary considerations. More recently, the U.S. Navy released its latest *Naval Power and Energy Systems Technology Development Roadmap* (U.S. Department of Navy, 2019) guided by Sandia National Labs "Fundamentals of Technology Roadmapping" technical report (Garcia & Bray, 1997). Despite these advancements, emerging trends in roadmapping practice and theory (Vinayavekhin et al., 2023) have only recently begun to address the dynamic relationship between resources, organizational goals, and the introduction of increasingly complex systems in rapidly changing environments. This paper strives to contribute to the advancement of technology roadmap process by exploring the formalized application Model-Based Systems Engineering (MBSE) as a novel method to support the alignment of naval power and energy systems research and other resource investments with overall organizational goals and strategy.

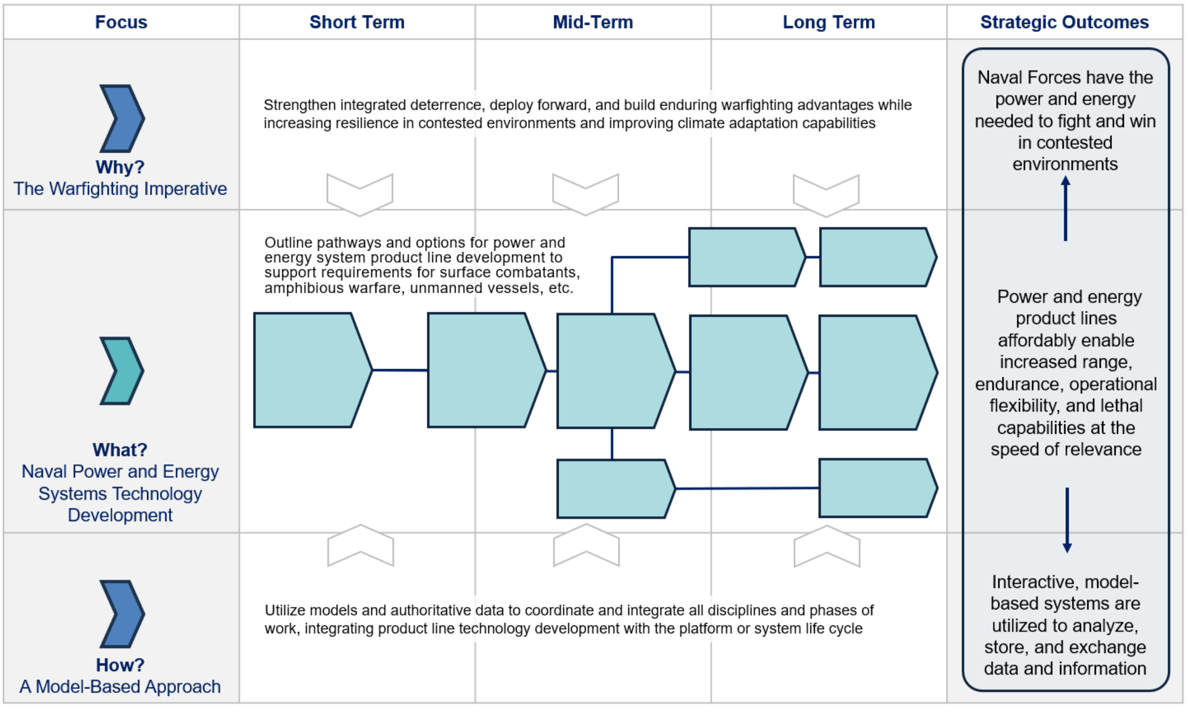

Figure 2: Technology roadmap workshop template (adapted from Phaal et al. 2017)

Technology road-mapping has emerged as a versatile strategic planning tool with applications spanning diverse industries. For the application of naval power and energy systems, its structured, visual format facilitates the alignment of technology or product lines with organizational objectives over time (Figure 2). With an array of methodologies, it can be adapted to address specific challenges faced by the U.S. Navy, in alignment with broader strategies of the U.S. DoD. This paper specifically proposes that technology road-mapping – underpinned by a model-based approach – should be the cornerstone for future technology development efforts. An updated roadmap can serve to facilitate decision-making; help prioritize core scientific and research and development (R&D) initiatives, support resource allocation, and ensure stakeholder alignment through a structured visual representation. Within this context, technology road-mapping should serve as a compass, guiding the U.S. Navy through a complex series of technological advancements and strategic objectives.

The remaining sections of this paper are organized as follow: Section 2 identifies ***why*** U.S. Navy non-nuclear surface ship requirements and operational capability demands are increasing, identifying energy intensive systems and platforms required to develop and sustain agile and lethal capabilities for warfighting advantage. In Section 3, we outline the ***what*** technology product lines are relevant to naval power and energy systems and develop recommendations to apply Model-Based Systems Engineering (MBSE) principles within the technology planning and road-mapping process. We then identify ***how*** the U.S. Navy can formalize the application of MBSE principles for naval power and energy systems in the context of a model-based technology roadmap architecture in Section 4 to reduce risk and increase flexibility for before drawing conclusions (Figure 3). These sections represent an expansion upon earlier work, presented November 2022, at the International Naval Engineering Conference, hosted by the Delft University of Technology, The Netherlands (Sturtevant et al., 2022a)

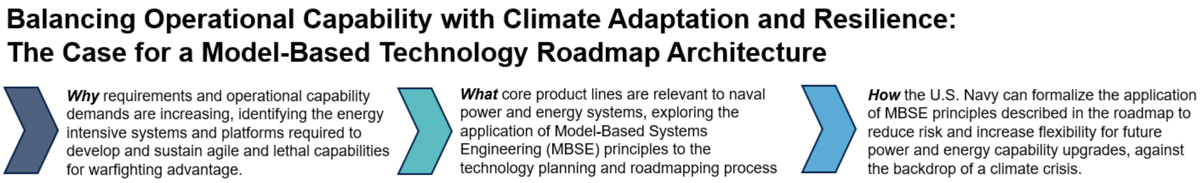

Figure 3: Organization for Remaining Sections of Technical Paper

2. Requirements

In this period of strategic competition, the U.S. Navy is investing in a larger, modernized, globally deployed, and lethal multi-domain fleet to counter emerging threats across all domains. The non-nuclear Surface Navy has recently delivered advanced platforms such as the first Flight III *Arleigh Burke*-class guided missile destroyer, *Jack H. Lucas* (DDG 125), procured FFG 62 Constellation class small surface combatants, while advancing the development of next-generation large surface combatants as part of the DDG(X) program. Decisions, informed by 2022 NDS, necessitate divesting resources from aging, legacy, costly-to-maintain ships, and prioritize the rapid fielding of promising future platforms to deliver a more lethal and distributed force.

2.1. The shift to Distributed Maritime Operations

The U.S. Navy's aforementioned Distributed Maritime Operations (DMO) strategy requires combining the full range of traditional warships with innovative unmanned, amphibious, and logistics platforms. Warfighting analysis supports the need to strike a balance between evolutionary and revolutionary approaches to deliver a ready and lethal Navy within the constraints of finite resources, including a combat system-of-systems (SoS) that combines any sensor, command and control, weapon, and communications capability hosted and integrated across the surface force (Table 2). Ultimately, success will depend on a commitment to continuous analysis, testing, and experimentation to deliver the capabilities required for the future force. DMO addresses challenges the U.S. Navy will face in contested environments, providing the foundation that the force must build on to meet emerging threats. To realize DMO, the Department continues to experiment and analyze various solutions, including the amphibious ship mix and force structure, guided missile frigate, the next-generation guided missile destroyer, as well as to expanded unmanned platform missions, to ensure operational relevance over the expected service life of each platform within the Navy's future force structure architecture.

Table 2: Modernizing AEGIS and SSDS to the Integrated Combat System while driving affordability (adapted from Moore, 2023)

Force Level Coordination	**Integrated Combat Systems (ICS)**	Force level tactical coordination and platform-level execution in multi-mission warfare capabilities designed to conduct Distributed Maritime Operations (DMO) across the range of military operations
Rapid proliferation and continuous delivery to outpace the threat	**Scalable Computer Program**	Elimination of technical debt to smaller, containerized pieces (e.g. microservices) to enable rapid development and testing; brings AEGIS and SSDS together to ICS architecture
	Software Factory/DevSecOps Pipeline	Government owned software development environment to support real-time control system development for weapons; safety, continuous certification, and authority to operate
	Infrastructure-as-a-Service (IaaS)	Decouples hardware and software – enabling faster, more frequent capability delivery to the warfighter

2.2. Charting the course for the future fleet of unmanned systems

Emphasizing unmanned systems, the Department of the Navy (DON) recently released its Unmanned Campaign Framework and established Task Force 59, an unmanned task force chartered to accelerate unmanned and artificial intelligence experiments in the Central Command (CENTCOM) Area of Responsibility (AoR). The Navy's investment in advanced autonomy, improved reliability for critical hull, mechanical, and electrical (HM&E) systems, networks, and enabling systems continues to promote human-machine teaming across the Fleet. The Navy's commitment to a hybrid Fleet architecture incorporates enabling technologies, material reliability, resilient networks, and autonomy. Current efforts, including the iterative development and prototyping of Unmanned Surface Vessel capabilities, will pave the way to introduce uncrewed maritime systems on an accelerated schedule (Table 3). Evaluations are being conducted through wargames, combined exercises, and real-world operations, leading to the development of employment plans and operational concepts.

Table 3: Selected U.S. Navy Unmanned Surface Vessel (USV) Prototyping Efforts (adapted from O'Rourke, 2023a)

Unmanned Surface Vessel	***Recent demonstrations / event***
Sea Hunter / Seahawk Unmanned Surface Vessel	June 2018 naval exercise with a reconnaissance payload; September 2020 exercise incorporating advanced autonomy/perception; Participated in RIMPAC 2022 with Sea Hunter (electronic warfare payload) and Seahawk (towed array of anti-submarine warfare electronics) both controlled by Arleigh Burke class destroyers.
Ghost Fleet Overlord Program Unmanned Surface Vessel	October 2020 and April 2021 autonomous transits from Gulf Coast to West Coast; December 2020 naval exercise with electronic warfare payload March 2022 Strategic Capabilities Office transitioned program to U.S. Navy; Ghost Overlord Program vessels – Nomad and Ranger – participated in RIMPAC

2.3. *Future technology and evolving operational concepts*

Recognizing the rapid pace of technological change and evolving operational concepts, DoD threat-informed analyses highlight the clear requirement for a larger, more capable Navy equipped with energy-intense systems, including advanced radar, electronic warfare systems, electro-optic / infrared sensors, and directed energy weapons (Table 4). To align with the most recent guidance, U.S. Navy leadership submitted a Battle Force Ship Assessment and Requirement Report (BFSAR) to members of U.S. Congress June 2023, leveraging the planning scenario for the 2022 NDS (O'Rourke, 2023b). Identifying force structure requirements beyond a ten-year horizon has proven to be particularly challenging due to rapid technological evolution and emerging operational concepts. Therefore, a range of procurement and inventory alternatives for critical platforms exists beyond the ten-year planning horizon, contingent on resource availability, technology development, and threat considerations. As the Navy's plans are refined and BFSAR is reviewed, the composition and procurement profiles withing the future force structure will be adjusted and will serve to "inform the FY2025 shipbuilding plan" (U.S. Department of Navy, 2023).

Table 4: Selected Radar, Electronic Warfare, Electro-Optic / Infrared Sensor and Directed Energy Weapons (adapted from Hall, 2023)

System	*Capability*
SPY-6 Family of Radars	Unprecedented sensor coverage and range to perform air and missile defense across seven different classes of U.S. Navy surface ships
Next Generation Surface Ship Radar	Short-range, 2-dimensional radar that combined surface search and navigation functions
High Energy Laser Integrated Optical-Dazzler and Surveillance	Counter Unmanned Aerial System (C-UAS) / Unmanned Aerial Vehicle capability
Surface Electronic Warfare Improvement Program	Electronic attack capability for terminal defense

Requirements are expected to evolve to pace the projected threat, and as such, forecasted power and energy demands over the long-term are far less certain than near-term efforts within the five-year Future Years Defense Program (FYDP). Specific requirement values, derived from ongoing, robust analysis, will not be discussed within the scope of this paper. This paper will also not address specific power and energy demands at the individual ship class level, nor will the authors refine or quantify requirements to meet specific systems capability packages. This paper will remain focused on the overarching conceptual framework, acknowledging the complexity and dynamic nature of future naval power and energy system technology requirements.

3. Technology Development

Commercial investments and evolving power and energy technology trends provide valuable insight to the U.S. Navy regarding technical innovations that could potentially support both current and future warfighting capability requirements. At the same time, identifying the technology areas and specific technical characteristics that are of significant interest to the U.S. Navy through a comprehensive roadmap will provide a guide to industry in identifying the most beneficial areas for investment to meet the anticipated needs. This section highlights general areas of interest within naval power and energy systems, outlined across six product lines.

3.1. *Product Lines*

3.1.1. *Energy Storage*

Energy storage is a foundational technology for many emerging warfighting capabilities and is required to improve overall platform capability, efficiency, and reliability (U.S. Department of Navy 2019). The vital role of energy storage to enable weapons systems necessitates a strategy that encompasses the entire lifecycle of battery technology, including its development, safety, integration, fielding, and sustainment across the Surface Navy. Today's weapons, sensors, and platforms are power hungry, and their power demands will continue to grow in the future. While there are several energy storage solutions in various phases of research and development, including super capacitors and rotating machines, space and weight are always limiting factors in design and batteries are the most power dense solution to satisfy the power need. Of the different battery chemistries, the most power dense are lithium batteries. In light of existing warfighting requirements, lithium batteries, should be the primary focus of product line advancements over the forthcoming decade.

The Navy's battery strategy should be designed to align with the *U.S. Department of Defense's Lithium Battery Strategy 2022-2030*, addressing Navy-specific challenges, needs, and implementation strategies. However, stringent regulations, particularly in terms of certification and testing protocols for lithium-ion batteries applications in the maritime environment, presents challenges to the rapid integration of future naval capabilities and concepts. In this context, lithium batteries are crucial to support a full range of systems—from directed energy weapons, high-power mission systems, and advanced shipboard radar to persistent Intelligence, Surveillance, and Reconnaissance (ISR) sensors and platforms and integrated power systems. These batteries contribute to the deployment of capable systems that can mitigate operational risk. Therefore, it will be increasingly important to evaluate the risks associated with advanced batteries against their impact on warfighting risks, crafting a balanced approach to naval energy storage solutions.

3.1.2. Power Conversion

Power conversion is a function to convert a specific voltage/frequency to a differing voltage/frequency. Within power systems, the role of power conversion is two-fold: to satisfy the demands of the electrical transmission/distribution system and to support the requirements of a single connected load or multiple loads that requires variations from what the electrical distribution system provides. Power converters of interest can be categorized into two basic categories: power electronics-based converters and transformers. Although these technologies may diverge significantly, they share the same common function of power conversion.

3.1.3. Power Distribution

Within the realm of power systems, the function of distribution equipment includes the transmission of power, configuration of power systems through the connection or disconnection of systems, and safeguarding interconnected equipment against electrical faults. The suite of distribution technologies encompasses a wide range of equipment, from circuit breakers and protective relays to switchboards and cables. An efficient distribution system enables “increased survivability, flexibility, and over capability” with greater redundancy, more capable power continuity, and enhanced recoverability (Sturtevant, et al., 2022a). The Office of Naval Research (ONR) recently initiated a novel concept in power, energy, and control distribution, known as Power Electronic Power Distribution System (PEPDS). This program includes advanced high-power-density, high-efficiency power electronics, Silicon-Carbide (SiC) power semiconductors, and tools for design analysis and simulation (Petersen, et al., 2020).

3.1.4. Controls

There is a growing demand for an advanced control capacity to manage shipboard power systems effectively. Of note, the Office of Naval Research (ONR) has capitalized on the investments made by the US Department of Energy (DOE) in power control and other resilient, scalable smart/microgrid architectures. This has led to the inception of a Robust Combat Power Control (RCPC) Future Naval Capability (FNC). The FNC's progress is concentrated on devising a shipboard strategy for comprehensive power and energy resources management and prototyping controls, effectively giving the commanding officer tactical energy management capability over every component connected to the power and energy distribution system. The intention behind the FNC is to enhance system state awareness through extensive electric load monitoring. The implementation of control algorithms will quickly reconfigure the power/machinery system (which includes power generation, power conversion, power distribution, and energy storage resources) into configurations optimal for the given situation. Findings from the FNC will inform future investment strategies in shipboard control systems.

3.1.5. Thermal Management

Only a fraction of the energy input into a U.S. Navy surface combatant is converted into useful work that accomplishes the mission. The rest of that energy is lost as it passes through the complex systems-of-systems and is converted into different forms along the way. The majority of that loss is in the form of waste heat that either exits the ship through the exhaust of the prime movers or through another medium, such as chill water or sea water. Thermal management is the collective effort to efficiently deal with these losses from the inefficiencies throughout the system. Through the use of a diversity of components and systems, such as chill water, air conditioning plants, installed ventilation, heat exchangers and cooling skids, sea water, and other fluids with varying thermal properties, the thermal management system transfers the thermal losses and maintains systems, equipment, and working and living spaces at specified temperatures independent of the external environment and the aggregate of the internal thermal loads in a given operational alignment (NAVSEA, 2019).

3.1.6. Prime Movers

Prime movers are a fundamental element of a ship's power plant infrastructure and serve as a primary source of both the propulsion power and electrical power for connected loads. Power and propulsion architectures predominantly align with one of the following classifications: mechanical drive, integrated power systems, or hybrid drive (Doerry and Amy, 2020). Power generation systems encompass, but are not limited to, gas turbine and diesel engines, both for propulsion and generation sets. Opportunities to improve the power, efficiency, power density, and overall lifespan of prime movers are of great interest to the U.S. Navy and has increasingly resulted in the use of integrated power systems and hybrid electric drive for newer combatant ships.

3.2. System Integration Challenges

Technology maturation across product lines in addition to successful integration of systems necessitate early investment to mitigate systems integration risks associated with the first-of-class ships and advanced mission systems identified in Section 2. These up-front investments, and rigorous land-based testing will ultimately accelerate the delivery of new warfighting capability enhancements. To further mitigate system integration challenges over the near, mid, and long-term, the following section will underscore the importance of applying a model-based approach to the implementation of future roadmap efforts. This approach combines the use of authoritative data sources with robust Model Based Systems Engineering (MBSE) methods to manage the complexity from the theatre and systems-of-systems view down to the individual component level.

4. A model-based technology roadmap architecture and implementation framework

Incorporating specified capability requirements within an MBSE framework allows for a structured and consistent representation of the system. Each requirement, representing specific operational scenarios, can be modeled and incorporated into the SoS’ architecture. These requirements can then be linked directly to specific hardware components within the system model thereby providing a clear and traceable allocation of hardware intended to fulfill each requirement. The integration of requirements into system models (Friedenthal, et al, 2006) permits detailed analysis of the sequences of states (or modes) of operation required by these scenarios, enabling simulation, assessment, and optimization of system behaviors under different operational conditions. This process ensures that every aspect of the system’s intended functionality has an allocated solution, and that no requirement is overlooked, thus helping to shape a system design that is responsive to its foundational requirements and capable of fulfilling its intended purpose.

4.1. Creation and management of integrated data models

Digital engineering facilitates the creation and management of integrated models that capture requirements, design specifications, and system behaviors (see, for example, Figure 4). This comprehensive representation is enhanced by advanced modeling and simulation tools that foster an environment for rapid prototyping, testing, and evaluation in virtual environments. Importantly, these modeling efforts can inform high-level, Fleet-wide planning scenarios by providing insights into requirements development, system performance, efficiency, and potential areas for improvement at a large scale. At a lower level, these tools can incorporate laboratory data inputs at the component level through plugins for analytical platforms such as MATLAB and Simulink, ensuring that system functionality is fulfilled quantitatively. This usage of laboratory data for inputs helps to bridge the gap between theoretical design and practical application, making sure the components work synergistically under real-world conditions.

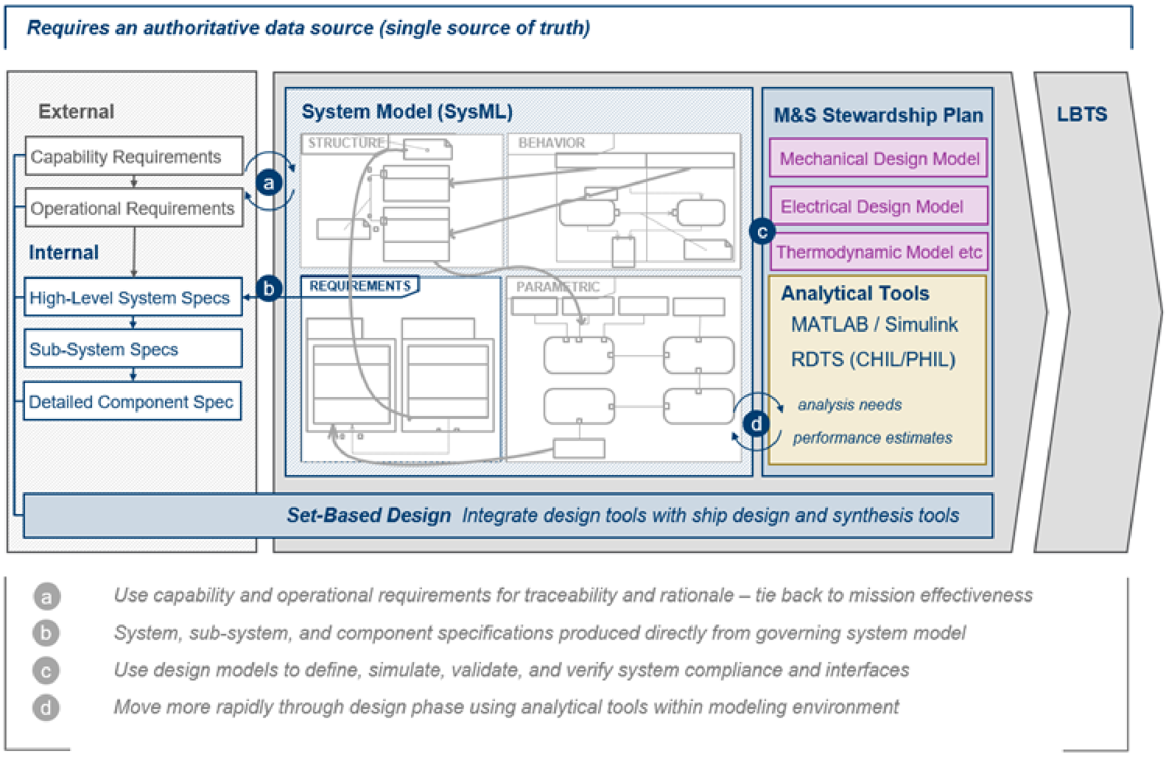

Figure 4: Model-based approach from mapping external capability and operational requirements to conducting land-based testing (adapted from Friedenthal, el al., 2015)

The exploration of system configurations through the use of MBSE tools can help to identify solutions that balance combat capability requirements with climate resiliency objectives. As such, the models serve as crucial tools for strategic planning, enabling the visualization and understanding of how current decisions will influence future capabilities. Figure 4, above, highlighted the multifaceted components of a System Model (Friedenthal, et al, 2015), operating in tandem with external design and analytical tools throughout the ship design process. In essence, the use of models accelerates the developmental process and reduces the time and cost associated with physical testing and recurrent design changes. MBSE methodologies can both inform and be guided by technology road-mapping, helping to ensure that investments in technology development are targeted and effective.

4.2. Incorporating requirements within a model-based systems engineering framework

Incorporating specified capability requirements within an MBSE framework allows for a structured and consistent representation of the system. Each requirement, representing specific operational scenarios, can be modeled and incorporated into the systems-of-systems architecture. These requirements can then be linked directly to specific hardware components within the system model thereby providing a clear and traceable allocation of hardware intended to fulfill each requirement. The integration of requirements into system models permits detailed analysis of the sequences of states (or modes) of operation required by these scenarios, enabling simulation, assessment, and optimization of system behaviors under different operational conditions. This process ensures that every aspect of the system's intended functionality has an allocated solution, and that no requirement is overlooked, thus helping to shape a system design that is responsive to its foundational requirements and capable of fulfilling its intended purpose.

In the face of ever-increasing system complexity, several defense programs have already begun transitioning requirements within a MBSE framework (Henderson, et al., 2023). However, key challenges remain with the evaluation of both the technical viability and long-term economic advantages of fully embracing the transition to MBSE, especially within the budgetary constraints applied at the program level. Key considerations in this transition range from establishing a new digital infrastructure, building workforce capability/capacity, and ensuring relevant legacy models and data fully transition into this new environment (Madni and Purohit, 2019). Within the U.S. Navy, a significant return on investment has been found in the transition from traditional document-centric systems engineering (DCSE) to MBSE. The Submarine Warfare Federated Tactical System (SWFTS) program implemented Model-Based Systems Engineering (MBSE) by managing interface requirement changes in the front-end and conducting back-end testing within the SWFTS system of systems (SoS). This transition resulted in cost savings by reducing front-end systems engineering labor and streamlining integration and testing (I&T) efforts, shifting the discovery of defects from initial platform testing to laboratory integration. Over the course of a decade, research practitioners Rogers and Mitchell (2021) documented the inherent systems engineering and integration (SE&I) efficiencies captured through the adoption of MBSE practices at Lockheed Martin Rotary and Mission Systems (RMS). Their findings underscored that the employment of MBSE not only improved the quality of systems engineering deliverables while reducing the cost of each modification but also enabled their engineering teams to add new baselines and increase the level of SoS complexity, without additional resources.

4.3. Systems engineering frameworks and ensuring seamless data flow

Integrated within traditional systems engineering practices, the Input-Process-Output (IPO) framework offers a holistic perspective of power and energy systems. This approach, implemented through MBSE tools, categorizes system operation into 'inputs' (the energy sources entering the system), 'processes' or 'activities' (the conversion and utilization of these sources), and 'outputs' (the consequential combat effectiveness).

Through this lens and also understanding that designers, engineers, and decision makers responsible for each aspect of inputs, activities, and outputs are not co-located and are often widely dispersed, MBSE employment facilitates robust collaboration between geographically dispersed stakeholders. With proper version management and standardized approaches on inputs/outputs and modelling structure, the concurrent work on a shared model augments communication and bolsters decision-making. It enables each stakeholder to comprehend the system from their unique viewpoint, while appreciating how their decisions influence the broader system. This collaborative process empowers the digital thread implementation, reinforcing seamless data flow and information sharing across the system's lifecycle. Consequently, the cyclical process of continual improvement, knowledge transfer, and the leveraging of insights from previous projects is enriched by this integrated approach.

In parallel, the Integration Definition for Function Modeling (IDEF0) methodology (NIST, 1993) provides a framework that explicitly accounts for external controls and constraints, enabling the system to operate within set parameters (Figure 5). This safeguard ensures resilience against potential risks or discrepancies. Furthermore, it elucidates the enablers and mechanisms integral to the execution of the prescribed processes, thereby establishing clear roles and responsibilities of all involved parties. This precise delineation cultivates accountability, elevates operational efficiency, and promotes the coordinated functioning of all system components.

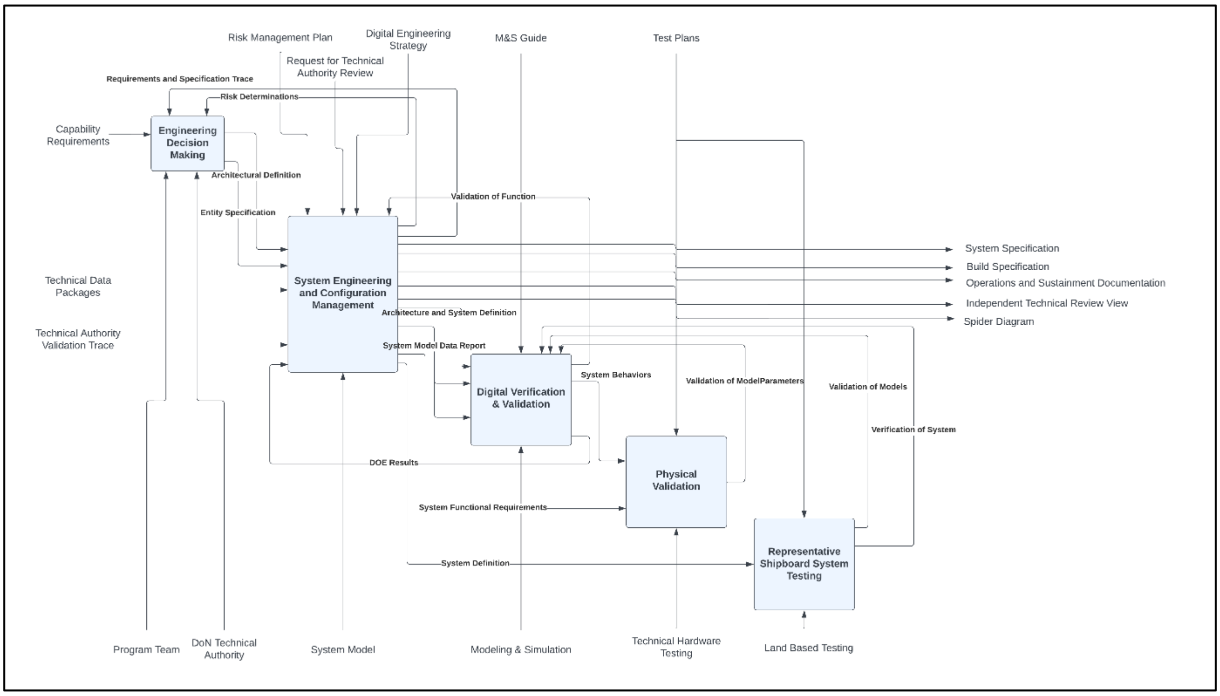

Figure 5: Notional process modeling view from initial capability requirements to land-based testing of representative shipboard systems (adapted from NIST IDEF0 Standard 183, 1993)

4.4. MBSE intended application and use case: The Power Electronic Power Distribution System

In the process of making early strategic investments in science and technology, MBSE methodologies are beginning to play a more significant role (Sturtevant, et al. 2022b). This is illustrated by recent studies funded by the Office of Naval Research (ONR), which examine the application of the Power Electronic Power Distribution System (PEPDS) - a new power, energy, and control distribution concept (Araujo, et al., 2023a). ONR's research initiative, led by the Electric Ship Research and Development Consortium (ESRDC), utilized MBSE to "capture stakeholder needs, behaviors, structures, and measures for PEPDS in a system model" (Araujo, et al., 2023b). The process confirmed the practicality of using System Modeling Language (SySML) to establish a baseline functional system architecture with Cameo Enterprise Architecture (Version 19) - a unified architecture framework profile modeling solution. The research also assessed novel methods for integrating MBSE with new trade space exploration tools, which are crucial for evaluating the potential of emerging technologies (Cuzner, et al., 2023). Through proper implementation, the PEPDS system model and new trade space exploration tools will serve as a valuable foundation for future design decisions while guiding technology development and investment.

5. Conclusion

Looking forward, a model-based technology roadmap architecture will be necessary to effectively balance increasing operational capability demands with climate adaption and resilience. U.S. Navy should leverage MBSE in diverse capacities, from conducting modernization studies and front-end feasibility assessments to validating electric plant load analysis assumptions. In this context, MBSE will facilitate the development of a dynamic, comprehensive model, functioning as a baseline for these tasks. This model will embody the present state of naval systems, streamlining the evaluation of potential modernization strategies, the assessment of feasibility, and the validation of proposed system architecture alterations. Following validation, this all-encompassing MBSE model will transition into an authoritative data source, steering ensuing engineering activities. As a single source of truth for technology development roadmap outputs, it will offer an exhaustive, accurate depiction of the naval system's state, fostering consistency in information exchange across diverse stages of development and among a wide array of stakeholders. Models of this nature will anchor future modifications, enabling traceability and ensuring continuity in design evolution. The use of this model will guide decisions about system upgrades or changes in architecture, informed by insights extracted from this authoritative model. As such, MBSE ensures a methodical, evidence-based approach to naval system development and modernization. In essence, this process constitutes a virtuous cycle of continuous improvement, enhancing the reliability and efficacy of engineering outcomes.

Disclaimer

The opinions presented in this paper are the personal opinions of the authors and the authors alone. Specifically, they do not necessarily represent the views of the U.S. Department of Defense or Department of Navy. Furthermore, the recommendations presented in this paper are for the sole purpose of illustration and may not have an actual relation with past, current, or future shipbuilding programs.

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