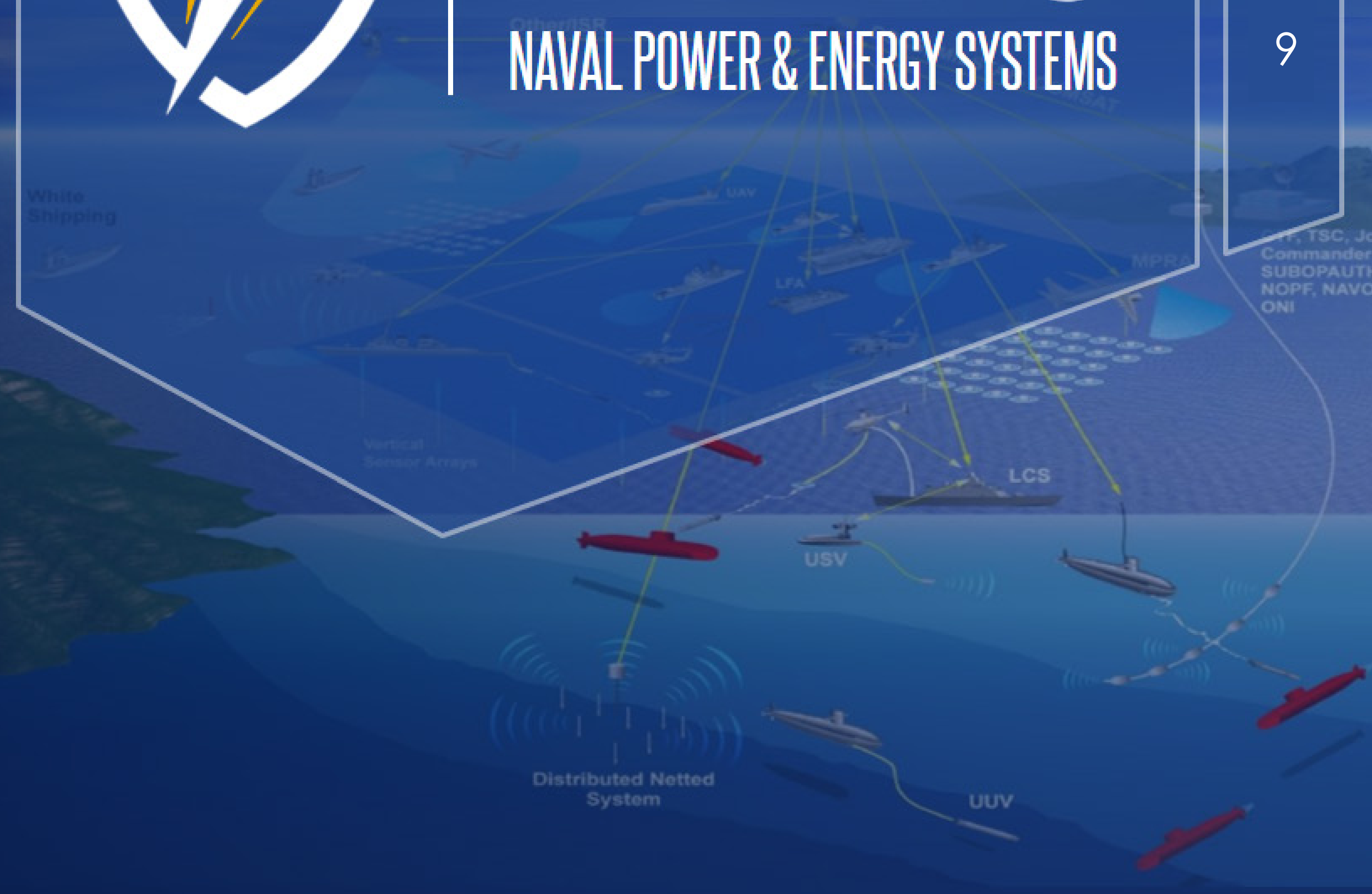
NPES

NAVAL POWER & ENERGY SYSTEMS

2019



NAVAL POWER AND ENERGY SYSTEMS

TECHNOLOGY DEVELOPMENT ROADMAP

THE U.S. NAVY POWER & ENERGY LEAP FORWARD

NAVSEA
NAVAL SEA SYSTEMS COMMAND

FOREWORD

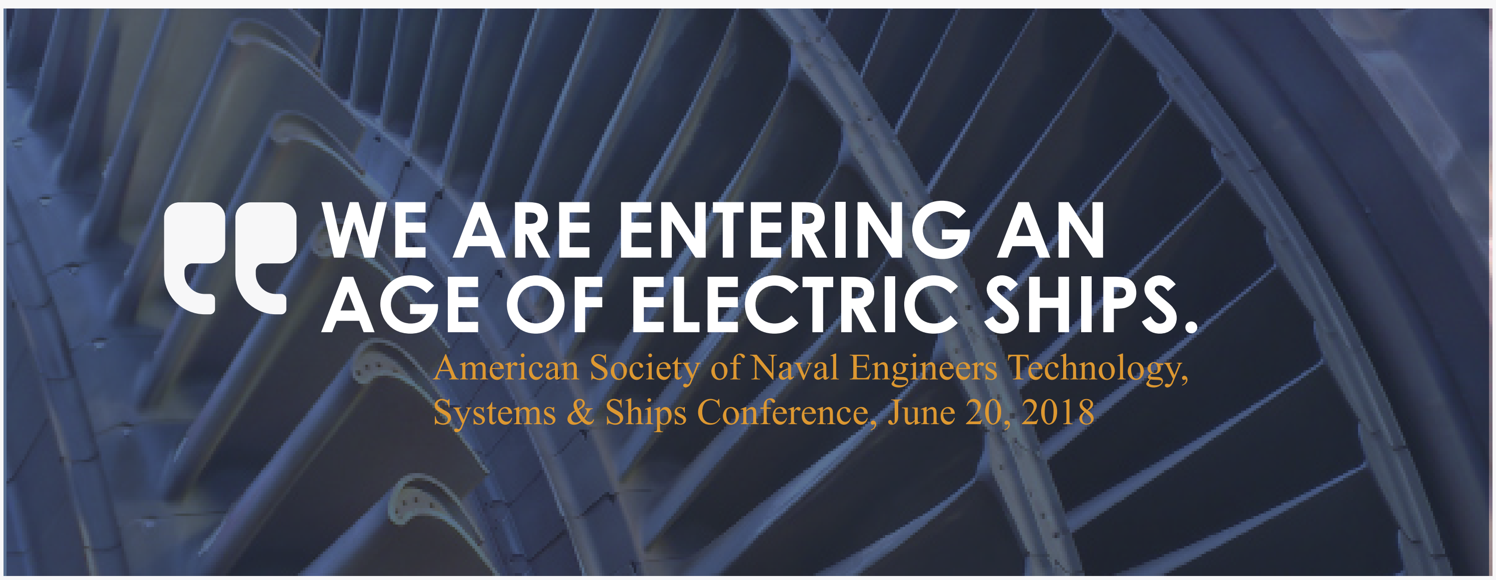
NAVAL POWER & ENERGY SYSTEMS TECHNOLOGY DEVELOPMENT ROADMAP

Ensuring maritime superiority requires a ready and capable fleet, and fundamental to fleet capability is the electric power behind the fleet. This roadmap aligns electric power and energy system development with increasing warfighter power needs, enabling the U.S. Navy to expand our maritime advantage over our adversaries.

The need for a thorough and comprehensive document arises from the tremendous difficulty of the task.

The goal of revolutionizing naval warfare is ambitious and should not be understated. The envisioned change demands intelligent synchronized development.

Existing U.S. Navy power and energy systems represent a century of combined private and public investment. Fundamentally evolving the system requires an exceedingly careful and thorough technology development process, to which this roadmap is the guide.



VICE ADMIRAL THOMAS J. MOORE
Commander, Naval Sea Systems Command

ONE OF THE THINGS THAT IS REALLY IMPORTANT FOR US AS WE BUILD THESE PLATFORMS, IS TO MAKE SURE THAT PLATFORMS HAVE ENOUGH SPACE, WEIGHT, AND POWER SO THAT YOU CAN MODERNIZE AND ADAPT TO FUTURE THREATS.

VICE ADMIRAL THOMAS MOORE
COMMANDER, NAVAL SEA SYSTEMS COMMAND
USNI Navy Maintenance and Maritime Security Conference, June 1, 2017

I'M GOING TO BUY AS MUCH AS I CAN AFFORD. AS MUCH POWER AS I CAN AFFORD. BECAUSE I KNOW BY THE TIME I RETIRE THE SHIP I'LL USE IT ALL.

ADMIRAL JOHN M. RICHARDSON
31st CHIEF OF NAVAL OPERATIONS
Directed Energy Summit, March 29, 2017

PREFACE

Today, the U.S. Navy is on the cusp of revolutionary changes in how warfare at sea is conducted. Akin to the shift from guns to missiles, this revolution will take the form of high-power pulsed mission systems. These include directed energy weapons such as lasers and stochastic electronic warfare systems, radiated energy systems such as the Air and Missile Defense Radar, and advances in kinetic energy weapons, including electro-magnetic railguns. Legacy power systems found on all existing ships do not possess the inherent electrical "inertia" to withstand the ramp-up/down (on/off), or ripple (pulsation) effects of complex power profiles of these advanced mission systems. These effects include excessive generator heating (thermal stress) and negative torques (mechanical stress) applied to prime movers such as diesel and gas turbine engines. Countering these harmful effects requires mitigation such as advanced controls or energy storage.

This 2019 Naval Power and Energy Systems Technology Development Roadmap (NPES TDR) conveys the guide for an evolutionary strategy to meet the challenges of revolutionary weapon and sensor systems. The strategy, derived from the 2018 National Defense Strategy, is broken into two principal time horizons: 1) the current and building fleet and 2) the fleet to come, such as the Future Surface Combatant Force. For the current challenge, the concept of the Energy Magazine serving as the buffer between legacy MIL-STD-1399 AC interfaces and new highly dynamic, high-power DC mission systems is being refined. Developments in battery, flywheel, and capacitor technologies are informing next-generation energy storage systems and, when coupled with power electronics, will provide requisite power quality and the ability to continue fighting.

Integrated Power and Energy System (IPES) offers the potential to provide revolutionary warfighting capability at an affordable cost. IPES utilizes integrated energy storage and power along with advanced controls to provide a distribution bus suitable for servicing highly dynamic mission loads and propulsion demands while keeping the lights on. Additionally, such a system can enhance survivability, reliability, and flexibility while providing new capabilities such as the ability to quietly maneuver solely on energy storage. IPES development is currently focused on a medium voltage direct current (MVDC) system evolved from the DDG 1000 1kVDC Integrated-Fight-Through-Power system combined with shared and distributed energy storage as well as advanced controls with active state anticipation data linkage between machinery and combat systems. Near term Research and Development (R&D) is focusing on DC generation and distribution, while additional research continues to advance technologies across the breadth of AC and DC naval power systems. The current research target electric plant is centered on 12kVDC distribution and control system architecture with advanced power generation to produce DC at the source via variable speed dual wound/dual output generators using variable speed prime movers that can minimize fuel consumption and enhance time on station for a given fuel load out.

The Navy has embraced advanced modeling and simulation techniques currently being employed in power-hardware–in-the-loop (PHIL) component testing in a computer simulated environment, which promises to significantly reduce the cost of developing and testing full-scale hardware. The advent of real-time simulation of complex power systems has enabled rapid early prototyping of systems, and we are at the forefront of an explosive expansion of knowledge that has informed a comprehensive system engineering approach to developing both Energy Magazine and IPES.

The key to future success is continued close engagement between government, academia, and industry. The surface Navy electrical leap forward is truly a partnership between this iron triangle of expertise, transforming potential into reality through our joint efforts. The NPES TDR is our Guidebook.

Mr. Stephen P. Markle, PE
Director & Program Manager
Electric Ships Office (PMS 320)

AN INTRODUCTION

TO THE 2019 NAVAL POWER & ENERGY SYSTEMS TECHNOLOGY DEVELOPMENT ROADMAP

The 2019 NPES TDR reinforces power and energy (P&E) as the foundation of the kill chain. This is supported by Navy studies, literature reviews, wargames, and the Department of the Navy's (DON) needs assessment for the future fleet. This 2019 TDR presents NPES approaches to material solutions, enabling future capabilities and system integration recommendations while proposing a new strategy for delivering capability upgrades in the following structure:

1 **The first section of this roadmap establishes why NPES are a critical part of the kill chain based on the capabilities desired by the Navy over the next 30 years. It emphasizes that, based on recent Navy studies, the Navy must improve its platform lethality and overall capability in the coming years to include material and nonmaterial solutions .**

2 **The second section of this roadmap presents P&E requirements that have been derived from mission systems necessary to support future warfighting needs.**

3 **The third section describes activities that are identified as "required initiatives" based on the required capabilities introduced in Section 1 and the projected electrical requirements presented in Section 2. This section aligns the roadmap to Navy top-level requirements doctrine and maintains the flexibility to enable a variety of mission and ship systems currently under consideration for future platforms.**

4 **The fourth section presents a strategy for modernizing P&E systems throughout their service life so that we can collectively achieve the CNO's call to 'improve faster' and increase naval force projection affordably.**

In summary, the 2019 NPES TDR serves as a guide for implementing the strategies, priorities, and advanced P&E technologies for the evolving force. This document is periodically updated to reflect changes in projected requirements and advances in technology.


U.S. Navy photo

SECTION 1

CASE FOR A POWER & ENERGY LEAP FORWARD

Naval Power and Energy Systems play a critical role in supporting future naval capabilities. An Integrated Power and Energy System, as a material solution for NPES, better supports future capabilities by sharing ships power and energy resources (such as propulsion) across multiple ship functions and users, thus allowing operational trades between large loads (e.g., propulsion and mission systems).

> **THE PACE OF COMPETITION HAS ACCELERATED IN MANY AREAS, ACHIEVING EXPONENTIAL AND DISRUPTIVE RATES OF CHANGE. AS THIS PACE DRIVES YET MORE UNPREDICTABILITY, THE FUTURE IS BECOMING INCREASINGLY UNCERTAIN.**

ADMIRAL JOHN M. RICHARDSON
31st CHIEF OF NAVAL OPERATIONS
"A Design For Maintaining Naval Superiority," December 2018

SECTION 1 (CONTINUED)

COMBAT POWER & ENERGY SYSTEMS INTEGRATION

FRAMEWORK FOR COLLABORATION

In 2007, the Assistant Secretary of the Navy for Research, Development and Acquisition (ASN RDA) established the Electric Ships Office (ESO) within Program Executive Office (PEO) Ships. Known as PMS 320, it was charged with establishing a competitive future electrical posture that maintains pace with "electric power development across industry, the increasing power demands of our ships, and the development of future higher power weapons and radars […]" (ASN RDA Memo, 13 Nov 2007). PMS 320 was also charged with providing centralized leadership to ensure power systems integration across all Navy platforms.

ADVANCED DIRECTED ENERGY AND ELECTROMAGNETIC WEAPONS, AS AN EXAMPLE, REQUIRE FUNCTIONAL CONNECTIVITY BETWEEN WEAPON SYSTEMS AND SHIP ELECTRICAL SYSTEMS.

"U.S. Future Surface Navy's Next Generation Warfare System Top-Level Requirements", Prepared for the Office of the Chief of Naval Operations (October 2017)

Recognizing the interdependencies between advanced mission systems and NPES, in 2014 COMNAVSEA established an Overarching Integrated Product Team (OIPT) for Combat Power & Energy Systems (CPES) to facilitate organizational integration and collaboration between key stakeholders. Co-chaired by PEO Ships, PEO IWS, and the Naval Sea Systems Engineering Directorate, the CPES OIPT enhances and endorses common solutions that enable shared asset utilization and support advanced weapons and sensors. Further, a 2016 ASN RDA memo directed PEO IWS to "ensure tightly coupled coordination with Electric Ships Office (PMS 320) for power system integration."

The CPES OIPT has established Working Level Integrated Product Teams (WIPTs) to bring together subject matter experts from several Navy organizations whose primary role is supporting NPES requirements development in the following areas:

- **Requirements & Concept of Operations**
- **Mission Load System Characterization**
- **Power Systems Technical Architecture**
- **Ship Systems Platform Integration**
- **Design Tools & Methodologies**
- **Business Operations & Costing**

As the Navy emphasizes early comprehensive systems integration as a critical development step towards deploying enhanced capabilities, these requirements form the basis of the P&E system initiatives addressed in Section 3. Future NPES must be developed seamlessly in conjunction with advanced mission systems such as directed-energy weapons.

Technology maturation and systems integration investments are required to de-risk the deployment of advanced mission systems. This will enable the desired capability enhancements as well as the desired upgradeability, survivability, and interoperability in the most capable and affordable manner. Without investments in warfighting capabilities and power system integration, future platform mission capabilities and backfit platform capabilities will be suboptimal and potentially add significant cost risk to correct emerging issues. This roadmap provides a path forward for affordable integration of mission and P&E systems.

The U.S. Navy must reduce the cost and time required for ship construction and modernization availabilities while ensuring ships meet or exceed their planned service life. Although the traditional tightly coupled ship design process produces very effective platforms, high modification costs make this legacy ship design approach impractical for flexibility upgradeability. Future U.S. Navy ships can achieve flexibility by decoupling platforms from payloads and utilizing open standard interfaces to allow for more cost-effective maintenance, modernization, and mission reconfiguration. Innovative approaches are required to increase adaptability, modularity, scalability, and commonality with the objective of achieving greater flexibility and cost-efficiency over the ship lifecycle. The engineering community will lead the drive towards a vision of a U.S. Navy with greater levels of adaptability and cost efficiency is through:

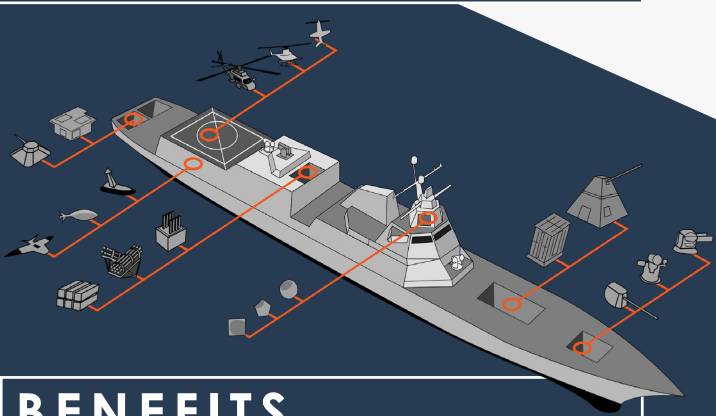
1. the adoption of integrated power and propulsion architectures that support payload flexibility, and
2. enabling technologies such as Energy Magazine for legacy non-integrated applications. Currently, flexibility is based on the concept of quickly modifying/adapting (consume available margins) the ship to support the installation of a new mission or combat system during a ship's availability.

In a general sense, flexibility is the readiness or speed at which a new capability or capability change can be added into the fleet or platform and can be measured in units of time. Flexibility can be applied across all phases of a system's design and life cycle, depending upon the capability change envisioned:

- Enterprise flexibility (how quickly can the engineering enterprise design/build a new system)
- Architecture/design flexibility (how quickly can an existing system be redesigned to enable new capability)
- Modification flexibility (how quickly can a system be modified to support a new capability)
- Operational flexibility (how quickly can a system be reconfigured to support a change in mission)

As flexibility is a new concept to Naval power systems, our system engineers and manufacturers will need to mature capabilities to provide

FLEXIBLE SHIPS FOR NPES



BENEFITS

- Rapid prototyping of payloads enables rapid acquisition of new capabilities
- Modular open systems enable acquisition of new capabilities
- Efficient and more affordable technology refresh and incremental upgrades
- Distributed lethality enabler

FEATURES

- Payloads decoupled from platforms - Treat mission systems as common, modular payloads that can be easily replaced for mission adaptability and new capability insertion
- Standard interfaces - Well defined, common interfaces between payloads and platforms that are prescribed and managed by the U.S. Navy
- Rapid re-configuration - The ability to easily reconfigure ship services and ship spaces minimizing hot work and avoiding major ship modifications as much as practicable
- Planned access routes - Ship structure and arrangement designed for the easy removal and replacement of interior equipment or systems, which requires maximizing the use of hatchable systems
- Allowance margins for modernization - Space and weight allocations for future capabilities, and provision for projected demand on distributed systems such as electric power, cooling and network bandwidth; this includes, but is not limited to, leveraging predictive analysis tools
- System engineering enterprise empowered with methods, processes, tools, and resources to analyze the impact of notional new requirements and design, redesign, or modify a system

EXAMPLES

1. Providing excess cable capacity either by number of cables or size to locations that currently have loads or to areas that are anticipated to have them in the future.
2. Designing the ship upfront to house larger generator sets than initially installed - this would include sizing the machinery rooms, intakes and uptakes appropriately or installing a large generator with a smaller gas turbine (GT) knowing that in the future you may upgrade to the larger GT when necessary.
3. Switchboards and load centers that can be upgraded to provide more power as the demand increases.
4. Fit for but not with – provide electrical, controls, and thermal management interfaces at specified locations to facilitate future installation of power and energy equipment. Practice rigorous "keep out" procedures during design and operation to ensure "real estate as well as distributed services" are preserved for the desired equipment.
5. Integrating energy storage system into the electrical architecture which can provide a stable (uninterruptable) power system and enable reductions in UPS requirements as well as new mission capabilities.

U.S. Navy photo

SECTION 2

FUTURE POWER & ENERGY REQUIREMENTS

This document provides P&E requirements supporting future platforms in the Navy's 2019 30-year shipbuilding plan, shown in Figure 1, as well as current ship designs that are in the fleet or under construction. P&E requirements were developed based on the NPES Characteristics described in Section 1 and are further discussed in the following pages.

Requirements will evolve over time to outpace emerging threats, but future requirements will have less fidelity than near-term requrirements. Specific future requirement values will be derived from a continuous, well-supported analysis and engineering process.

The power and energy requirements of this document will be applied to different ship classes, refined and quantified to support specific capability packages, and allocated to individual ship and warfare system elements.

Ultimately, the requirements presented herein represent the framework needed to achieve an advanced level of performance, integration, and interoperability of P&E systems that can be continually modernized.

Figure 1

30-YEAR SHIPBUILDING PLAN

	FYDP				NEAR-TERM					MID-TERM										LONG-TERM								
FISCAL YEAR	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
AIRCRAFT CARRIER					1					1					1					1					1			
LARGE SURFACE COMBATANT	3	2	3	3	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2
SMALL SURFACE COMBATANT	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
ATTACK SUBMARINE	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
LARGE PAYLOAD SUBMARINE																		1			1			1			1	
BALLISTIC MISSILE SUBMARINE			1			1		1	1	1	1	1	1	1	1	1	1											
AMPHIBIOUS WAFARE SHIP		1		1	1	2	1	1	2	1	1	1	2	1	1	1				1		1	1	1			1	2
COMBAT LOGISTICS FORCE	2	1	2	1	2	1	1	1	1	1	1	1	1	1	1										1		2	2
SUPPORT VESSEL	2	3	1	2	2	1	2	2	1	1	1	2	2	2	2	2	1											
TOTAL NEW CONSTRUCTION PLAN	10	10	10	11	13	11	11	11	12	11	11	11	13	12	12	10	9	8	7	7	8	8	8	8	8	8	12	9

DISTRIBUTION STATEMENT A. Approved for public release.

SECTION 2 (CONTINUED)

U.S. Navy photo

NPES, when implemented as an integrated power and energy system, must fully integrate all generated and stored electrical energy in the ship platform so that it is available to all electrical users, including high power weapons, advanced sensors, and electric propulsion, as mission scenarios dictate. This removes the need for individual Uninterruptible Power Supplies (UPS) now proliferating on ships.

Furthermore, this breaks the paradigm of stove piped energy storage and allows all users to benefit from common, shared sources of energy whether that be for mission systems or providing ride through power for mission critical systems or ship systems. Ship power systems today are limited in the ability to effectively utilize all energy resources to meet demands. Without an integrated architecture, unique system specific energy storage and control systems would be required for new mission systems, negatively impacting ship arrangements, driving costs and potentially limiting the effectiveness of these mission systems. Integrated power and energy systems will deliver system and mission effectiveness benefits for future surface combatants and other candidate ship platforms at a lower cost than current power system architectures.

SECTION 2 (CONTINUED)
NPES RELEVANT CAPABILITY REQUIREMENTS & DRIVERS

The required Capability Enhancements were evaluated for their overall impact on NPES. Additionally, major requirements drivers were identified, and the following is a discussion of those drivers in relation to NPES. Appendix B covers the requirements derivation process with related footnotes for references.

DRIVERS

ADVANCED SENSORS & WEAPONS

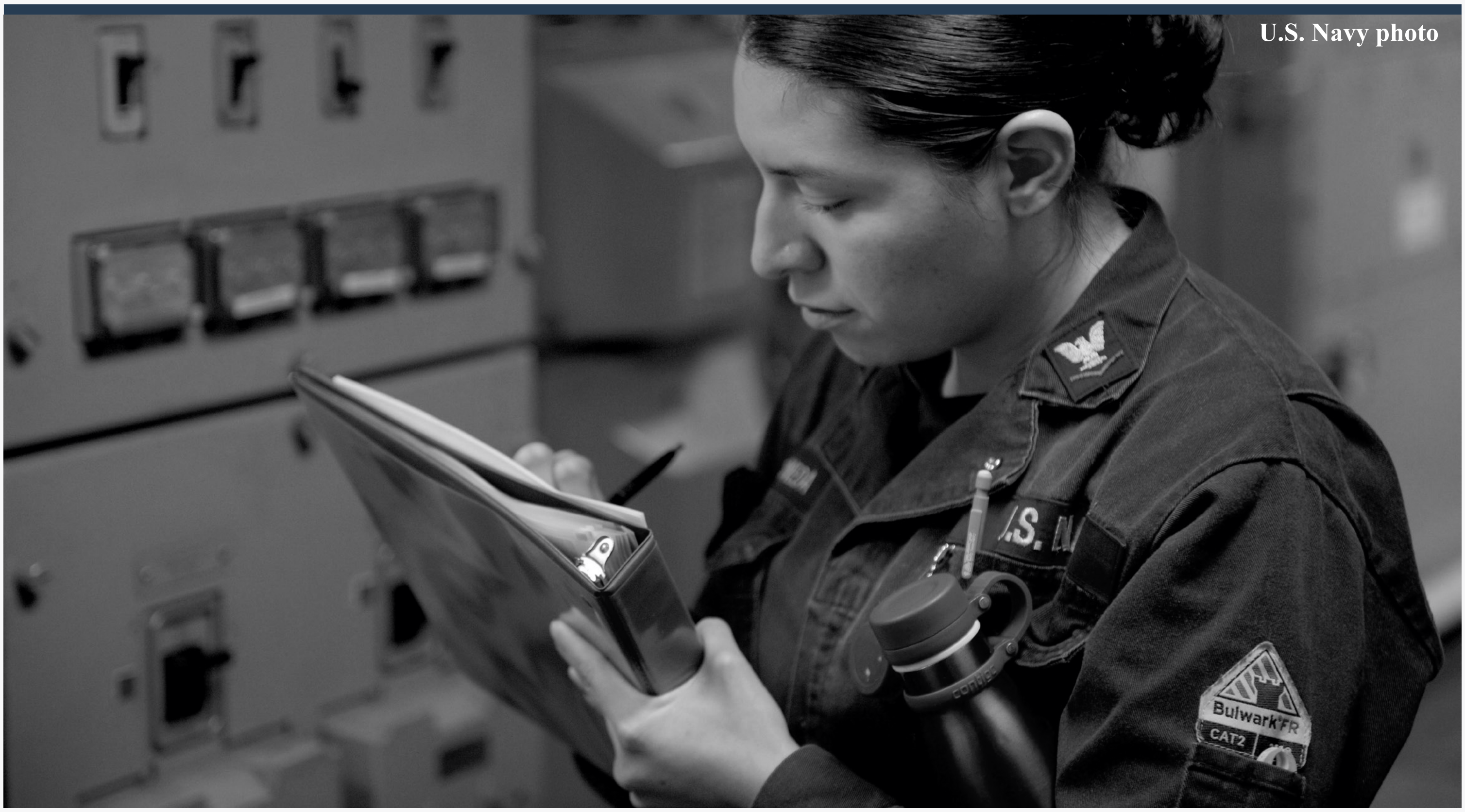
Power and energy capabilities required for advanced sensors and weapons are seen in current guidance documents such as the National Security Strategy, Naval Operations Concept, Quadrennial Defense Review, U.S. Future Surface Navy's Next Generation Warfare System Top-Level Requirements (TLR) Document for Surface Ships (DRAFT) and the Surface Warfare Enterprise (SWE) S&T Strategic Plan. Advanced sensors and weapons are significant drivers of NPES, and these systems impose significant demands on NPES in both average and pulse power requirements.

ADVANCED ELECTRIC PROPULSION

Advanced Electric Propulsion provides significant warfighting capability in the areas of enhanced survivability, future large unmanned platforms, flexible design and upgradeability, and increased platform endurance.

MAJOR DRIVERS OF REQUIREMENTS FOR NPES:

- Advanced Sensors and Weapons
- Advanced Electric Propulsion
- Survivability
- Unmanned Systems
- Communications and Information Security/Cybersecurity
- Flexible Ship/Modularity/Standard Modular Interfaces (see Flexible Ships callout)



U.S. Navy photo

FLEXIBLE SHIP/MODULARITY/STANDARD MODULAR INTERFACES

The Navy continues to pursue flexible platforms with key attributes of adaptability, modularity, scalability, and commonality. Payload systems will be decoupled from ship platforms using standardized interfaces and modular components. These and other flexible ship features will permit parallel development of payloads and platforms, later installation of payloads, more efficient and frequent modernization and technology refresh, and swift mission reconfiguration as needed.

UNMANNED SYSTEMS

Shipboard NPES can be developed to support rapid charging of multiple UxVs without requiring embarkation and deployment, thereby mitigating the possibility of limiting the effectiveness of deployable assets in theater. With the increased utilization of unmanned systems, there is a potential that rapidly charging deployable mission systems can impact ship power distribution systems. IPES advanced controls and power distribution can address issues associated with bulk rapid charging. Additionally, it is conceivable that UxVs can themselves have IPES as their method of ship service, power, and propulsion.

COMMUNICATIONS & INFORMATION SECURITY/ CYBERSECURITY

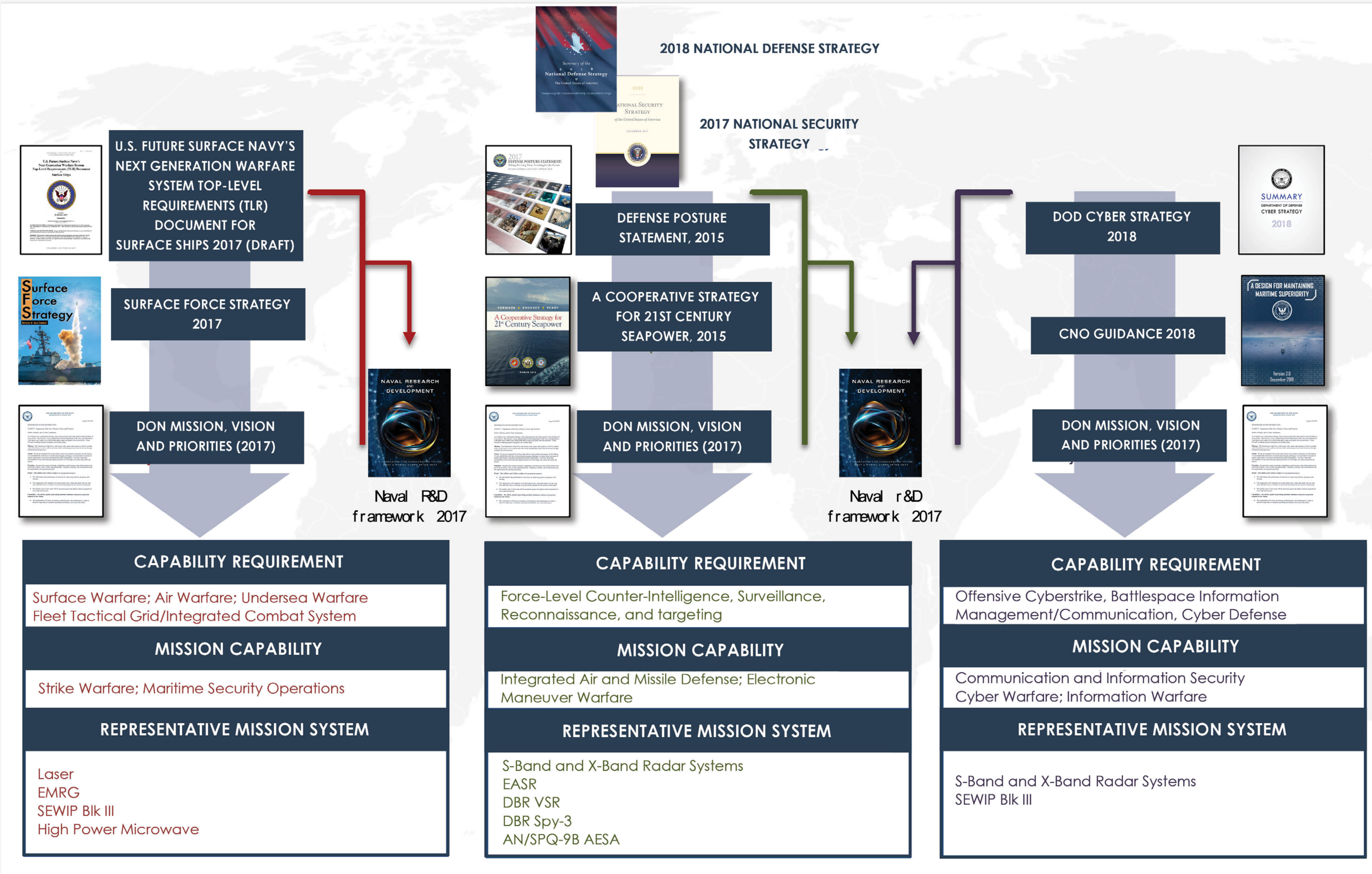
Communications and information security/cybersecurity are included early during specification development and design of all new NPES products and systems.

By assuming a lead versus follow strategy, the U.S. Navy is developing advanced tools and complementary security solutions across enclaves and systems to proactively defend against diverse and unpredictable future cyber threats. Integrated system architectures are being developed to deliver secure mission performance for all P&E systems while ensuring the level of security is appropriate for cybersecurity risks.

Communications and information will be vital to supporting situational awareness and coordinated decision-making. NPES must be designed to maximize power continuity, and this can significantly influence the design of a ship's power system.*

CAPABILITY REQUIREMENTS TRACEABILITY

Figure 2



SECTION 2 (CONTINUED)

SURVIVABILITY

The objective of survivability is to maximize the retention of mission capability in threat environments. A major discriminator of a NPES is how it provides and supports survivability requirements. Survivability is defined in the U.S. Navy Survivability Design Handbook For Surface Ships (reference OPNAV P-86-4-99) as having three capability areas:

- **Susceptibility (hit avoidance): the ability to avoid detection, reduce the probability and number of hits, or seduce weapons to less vulnerable areas**
- **Vulnerability (damage tolerance): the ability to withstand damage, minimize casualties, and maximize the ability to recover**
- **Recoverability (restoration response actions): restoration of key capabilities such as mobility, seaworthiness, critical ship systems, and warfighting capabilities**

Zonal design, equipment enclaving, and separation are design methods to meet vulnerability requirements. However, the operational plant alignments have a major impact on these survivability areas. Currently, power and propulsion systems are designed to bring on additional generation and propulsion power capabilities and align the distributive systems for a less vulnerable and more reconfigurable plant alignment.

The Navy's evolving operational strategy requires ships to be within the enemy's search area on an increasing basis. This may result in "undeclared hostilities" at any time. The NPES of future platforms must support survivability in any condition. This includes the following bulleted key attributes.

- **Extending time on station**
- **Reducing susceptibility**
- **Supporting offensive and defensive capabilities in any plant operational condition**

A highly survivable NPES can also reduce both equipment degradation and the crew workload required to operate/maintain ship systems at a high state of readiness. Integrated energy storage enables increased survivability and the readiness of future platforms. Full energy storage integration in a NPES can also reduce dark ship event times and their frequency, providing critical power to operate emergency loads during such events.

IDENTIFIED & DERIVED ELECTRICAL REQUIREMENTS

Mission systems are generally developed in an evolutionary approach to keep pace with threats by anticipating and filling warfighting gaps. P&E system requirements are derived from these anticipated warfighting and mission system requirements while also focusing on affordability by leveraging opportunities for commonality across multiple applications by developing modular designs, reducing maintenance, reducing parts inventory, providing fuel savings, and increasing ship service life.

Mission systems, those currently in service in the Navy as well as those still in development, were identified and their specific P&E needs derived. Increased average power and pulse requirements, along with required power for all other shipboard systems, will provide new challenges for NPES.

These derived electrical power requirements are foundational for the system engineering, development, and technical implementation recommendations that follow. Electric power requirements also affect other ship systems including controls, thermal management, and cooling. Although those requirements are not listed specifically here, recommendations for system integration, including necessary controls, thermal management, and cooling, are included.

U.S. Navy photo

> IT HAS BEEN DECADES SINCE WE LAST COMPETED FOR SEA CONTROL, SEA LINES OF COMMUNICATION, ACCESS TO WORLD MARKETS, AND DIPLOMATIC PARTNERSHIPS. MUCH HAS CHANGED SINCE WE LAST COMPETED. WE WILL ADAPT TO THIS REALITY AND RESPOND WITH URGENCY.

ADMIRAL JOHN M. RICHARDSON
31st CHIEF OF NAVAL OPERATIONS
“A Design For Maintaining Naval Superiority,” December 2018

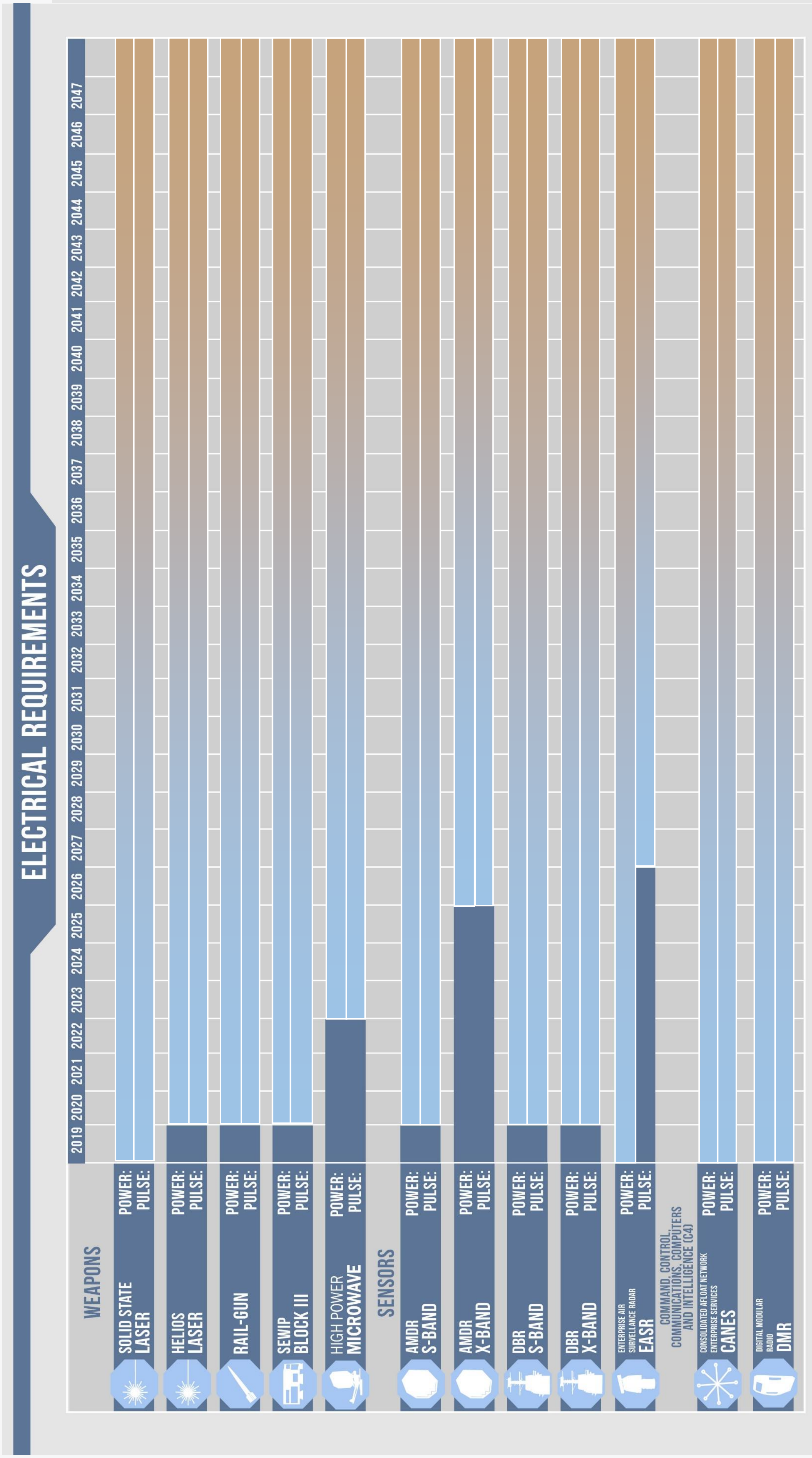


Figure 3

DISTRIBUTION STATEMENT A. Approved for public release.

SECTION 2 (CONTINUED)

Industry's internal research and development (IR&D) investments and technology trends inform the Navy of what technical advances it may leverage to support its needs. Conversely, technologies and technology attributes of interest to the Navy help inform industry where to invest to support Navy needs. This section highlights both industry trends and technology attributes of interest to the Navy. For the purposes of this roadmap, power and energy technology areas are divided into the following categories:

- Energy Storage
- Power Conversion
- Prime Movers
- Power Distribution
- Controls
- Rotating Machinery

A complete discussion of technology benchmarks and trends are in Appendix C. Detailed technology area metrics and intended applications for the 2019 through 2037 period are in Appendices G and H.

ENERGY STORAGE HIGHLIGHTS

Electrochemical capacitor improvements continue to focus on improving energy density while maintaining inherently high-power density. Design improvements include development and integration of higher temperature films, advanced electrolytes, advanced electrode materials, and minimizing equivalent series resistance (ESR). Factors of interest to the Navy with respect to electrochemical energy storage include the ability to maintain state of charge when not in use; change in voltage versus state of charge; charge and discharge capability; the temporary or permanent loss of capacity due to repeated shallow discharges; the ability to shallow charge and discharge or partially charge intermittently during a discharge; battery life considerations such as service-life, cycle-life, and shelf-life; and off-gas properties that affect the level of ventilation and associated auxiliary systems.

POWER CONVERSION HIGHLIGHTS

Industry continues to drive towards increased power density, increased efficiency, higher switching frequencies, and refined topologies with associated control schemes. This is particularly true of the off-shore wind industry. In this application, locating power conversion equipment in the nacelle reduces transmission losses between the generator and associated converter. Today, innovation in power conversion comes primarily from the development and implementation of wide-bandgap devices based on SiC versus Si. The development of vertical GaN and GaO based wide-bandgap devices promise reduction in losses of 3-5 times over silicon carbide. The use of high frequency transformers can provide galvanic isolation with reduced size and weight compared to traditional transformers. Other applications include traction, mass transit, and microgrid converters. Advances in cooling methods will be required to handle larger heat loads associated with higher power operation.

PRIME MOVERS HIGHLIGHTS

Enhanced fuel injection, higher operating temperatures and pressures, and optimized thermal management are critical for future prime movers. Advanced controls for increased efficiency, reduced maintenance, and increased reliability include implementation of digital controls; autonomous and unmanned power control; enhanced engine monitoring, diagnostics, and prognostics; and distributed controls. Advanced designs for increased efficiency include new applications of thermodynamic cycles such as Humphrey/Atkinson cycle for gas turbines and diesels and Miller cycle for diesel.

ROTATING ELECTRICAL MACHINES HIGHLIGHTS

Industry is focusing their development efforts on the following areas:

- Increased magnetic material flux carrying or flux generation capacity
- Improved structural materials and design concepts that accept higher torsional and electromagnetically induced stress
- Improved electrical insulation material and insulation system dielectric strength
- Innovative and aggressive cooling to allow improved thermal management and increased current loading
- Increased mechanical strength, increased thermal conductivity, and reduced sensitivity to temperature
- Increased electrical conductor current carrying capacity and loss reduction

Recent trends in electrical machines also include neural networks; artificial intelligence; expert system; fiber communications and integrated electronics; new ceramic conducting and dielectric materials; and magnetic levitation. High Temperature Superconducting rotors have higher power density than their induction and synchronous rotor counterparts. Wind power generators eliminate excitation losses which can account for 30% of total generator losses. The offshore wind power industry is moving to larger power wind tower generators in the 10MW class. Advanced low resistance room temperature wire and HTS shows promise for these higher power levels because of low excitation losses and low weight due to reduction in stator and rotor iron. HTS motors may be up to 50% smaller and lighter than traditional iron-core and copper machines. They have reduced harmonic vibrations due to minimization of flux path iron and have mitigated thermal cycling failures due to precision control of temperature.

POWER DISTRIBUTION HIGHLIGHTS

Industry has used MVDC transmission as a method to reduce losses across long distances. Complementarily, Industry is developing MVDC circuit protection for use in MVDC transmission variants of approximately 50, 100, and 150 megawatts (MW) at DC transmission voltages of 20 to 50 kV. Analysis includes modeling and simulation to determine methods for assessing the benefits of DC vs AC undersea transmission and distribution systems for offshore oil and gas.

The development of a room temperature, lightweight, low resistance conductor is of great interest to the Navy. Industry and academia continue to invest resources in advanced conductors that have applications in power distribution, power generation, and propulsion. Research is focused on using carbon nanotubes (CNT). CNTs appear to have greater conductivity than copper at room temperature on a mass basis. Copper/CNT combination wire shows great promise for meeting the characteristics of a room temperature, lightweight, low resistance product. This wire can reduce the size and footprint of electric machines, enabling high efficiency, high-power-dense electrical systems.

POWER CONTROLS HIGHLIGHTS

The desire for more distributed control structures has led to the development of control architectures that rely on the concept of intelligent agents that have the ability to reason about system state and enact control policies. A simple example of these agents in a control system is the use of autonomous software coupled with smart meters in a smart grid implementation. The agents, smart meters in this example, can temporarily shut off air conditioning but not the refrigerator in residences during grid peak power usage times when the cost per watt is highest on hot days. The agent software acts autonomously within its authority to comply with programmed customer desires.


U.S. Navy photo

SECTION 3

POWER & ENERGY TECHNOLOGY DEVELOPMENT: THE LEAP FORWARD

INTRODUCTION

This section is the technical context for an evolutionary change to the Navy's approach to P&E systems. An outline of the development activities necessary to meet future Navy warfighting needs in this new paradigm is presented. This alignment between the roadmap and Navy top level requirements doctrine maintains the flexibility to affordably enable a variety of mission and ship systems currently under consideration for future platforms.

THE CASE FOR CHANGE

The Navy expects more out of its future fleet. Ships perform a range of functions from basic mobility to putting kinetic or electromagnetic energy on a target. These functions must be supplied by the energy sources that the ship brings with it: fuel for prime movers or reactive propellants (for traditional kinetic weapons).

Electricity allows moving large amounts of energy from one place to another, controllably and quickly, making the energy resource (power generated by prime movers) extremely fungible. The trend towards electrification of warfighting capability takes advantage of, and relies upon, the fungible nature of electricity. An integrated energy system involves converting energy to the electric weapon or sensor's needs. The vision of integrated P&E systems carries this further, with the end-goal of linking all energy consumers with all energy sources in a single electrical network to maximize flexibility in affecting the ship's functions, namely a total and complete solution for Tactical Energy Management (TEM) that provides capability optimization.

THE CHALLENGE OF INCREASED COMPLEXITY

Enabling TEM requires identifying and controlling the complexity of the integrated systems that comprise it. For any single component or subcomponent of that system "nth" node ('n' being the total number of nodes, producer or consumer), there are n-1 nodes and subnetworks with which it can potentially interact; thus, the complexity of the network grows factorially (faster than exponentially). Additionally, some of the consumers under development have strong interactive behaviors including (but not limited to) high amplitude, high ramp rate pulses, and stochastic behaviors that can adversely affect other nodes and parts of the network.

For a fully integrated system to become a reality, the following capabilities must be developed:

- **Managing system complexity**
- **Maintaining controllability over many possible interactions**
- **Mitigating strong interactions**

Much of the technology required to enable the future warfighting capabilities documented in Section 1 has been, or is currently under development. It is the ability to integrate those technologies into a full system that moves us further down the path of TEM. Regardless of whether a system is AC or DC, medium or low voltage, or high or low current, a systems integration phase is required to field the next electric power system.

CONSTRUCT

The required initiatives presented in the next section are necessary to effectively field the next generation electric power system. The section is arranged as follows:

- System Integration Initiative (FYDP through Far-Term 2019-2047)
- Technology Development Strategies (2019-2037)
  - Energy Storage
  - Power Conversion
  - Prime Movers
  - Rotating Machines
  - Distribution
  - Controls
- S&T Recommendations
- Specifications & Standards Overview, Priority developments and updates

Note: Although this section refers exclusively to technology development, some of the items can be considered prototype products such as Power Generation Module and Energy Magazine. For completeness and simplicity, we have included them in this section of the document.

The systems integration initiatives, as well as the technology development initiatives, include the following information:

- Opportunity – Warfighter Benefit / Required Capability
- Development Approach
- Challenges / Gaps / Barriers / Inhibitors
- Milestones / Interim Schedule Targets
- Required Initiatives (2019-2027)

REQUIRED INITIATIVES

To support projected electrical requirements derived in Section 2, advancements in technology and systems integration will be required.

Note that in the sections that follow, there is a number corresponding to planned activities for the required initiatives described. Those activities are graphically illustrated in Section 3.3 Figure 6: "Required Initiatives" on pages 38-39 of this TDR.

SECTION 3 (CONTINUED)

SYSTEM INTEGRATION INITIATIVE: INTEGRATING POWER & ENERGY (2019-2048)

OPPORTUNITY

Increasingly the Navy is recognizing the need for incorporating flexibility and adaptability into the ship design and acquisition process, and into the individual platforms it delivers to the Fleet. The pace of warfighting technology innovation is rapid relative to a ships service life. As platform designs become more complex, the task of integrating new warfighting technologies into platforms is challenging. This integration of new systems will now be an ongoing challenge throughout a platform's lifecycle in order to maintain warfighting relevancy. An affordable approach to maintaining combat relevancy requires the ability to rapidly outfit new ship designs and fielded ships with new warfighting technologies as they become available. The ability to support advanced electrical payload warfighting technologies requires not only power and energy systems delivered with the flexibility and adaptability to accommodate them, but the Naval power and energy engineering enterprise with the capacity (knowledge, labor, and capital) for continuous systems integration. The approach to IPES System Integration outlined below recommends a strategy for IPES-enabled TEM to maintain relevancy by supporting the fielding of advanced weapons, sensors and other warfighting capabilities on an ongoing basis.

INTEGRATION APPROACH

The high-level strategy for developing an organic Navy capability for continuous P&E systems integration has two primary elements: 1) Industry engagement for knowledge development, knowledge transfer, and technology de-risking and 2) Building a comprehensive modeling* capability ranging from solely computational (i.e., completely virtualized components, systems, and environments) to system models incorporating production or near-production level hardware components.

The challenge to implement Tactical Energy Management is to integrate energy storage, power generation, and interfaces with advanced warfighting systems and controls. Complex problems associated with this integration must be approached by exploring the trade space to acquire the knowledge necessary to reduce the design space. The Navy can more affordably explore this trade space by shifting as much of it as possible into the computational modeling and simulation regime. This enables the Navy to quickly transition TEM capabilities from the virtual world to the fleet.

The Navy power systems community currently has limited small-scale facilities for simulation and emulation activities. The Florida State University Center for Advanced Power Systems (FSU CAPS) facility has been successfully used to develop knowledge regarding energy storage sizing of various media and control schema, to test advanced DC circuit protection devices, and, as of the time of publication, will be testing production power converters for the AMDR. Planning for a system emulation facility with power- and controller-hardware-in-loop test capability is ongoing at NSWCPD. Concurrently, the Navy is planning initial procurements to support initial exploratory studies with IPES at 12kVDC, using a very simple and low-power topology. With investment, these capabilities can be built up and out to encompass larger-scale simulation, emulation, and test capabilities that are more representative of ship-level power and power and control system complexity.

This roadmap recommends a two-pronged approach to building a comprehensive modeling capability:

- Develop power systems real-time simulation capability
- Integrate this simulation capability with components and systems, and their related controls (including an overarching TEM control system) and the test facility to enable high-power emulation and testing

*The term "model" used in this context is much more abstract than the typical Department of Defense usage that refers to a set of code and data that runs in a computationally simulated environment; rather, "model" as used here refers to "any reduced-order representation of a real system". It includes both computational models and system models such as land-based test facilities.

CHALLENGES

While many of the technology development efforts underway may produce deliverables that can be leveraged towards TEM, their potential will not be realized without significant investment in a comprehensive system integration effort. The required capabilities do not exist yet to support an IPES. The knowledge base for implementing and integrating these technologies is limited, and the naval engineering enterprise (government, industry, and academia) needs to undertake various learning activities to analyze, design, and control these new technologies in a complete system.

Regardless of any specific architectures and component technologies, a systems integration activity must take place to deliver a system that enables any new capabilities and provides for the following:

- Continuous and seamless knowledge management from multiple activities and sources
- Engineering expertise
- Knowledge about the trade space
- Ability to capitalize on the industrial base
- Enabling industry engagement with evolving Navy design processes

Table 2: Systems Integration Milestones / Interim Schedule Targets

REQUIRED CAPABILITY	FYDP/NEAR-TERM	MID-TERM	FAR-TERM
System integration initiative	• System and component modeling • Representative hardware and simulated hardware system testing • Part-scale part scope • Full-scale, full scope real tactical hardware testing • Studies and de-risking activities to close knowledge gaps leading to integration	• Continuous learning through studies and de-risking activities to increase and maintain knowledge of advanced electrical power and energy systems • Model, test and integrate upgraded equipment to increase warfighting capability • Continue full scale, full scope real tactical hardware testing	• Continuous learning • Periodic upgrade of specific power system equipment that enhances warfighting capability

REQUIRED INITIATIVES (2019-2027)

The following efforts support systems integration as currently identified:

- Integrate, test and demonstrate an IPES for future naval platforms. This effort should evolve in complexity and enable integration of maturing hardware as it becomes available. The effort should consist of a combination of hardware and real-time digital simulations to support learning and reduce the risks associated with fielding an affordable ship's power system capable of servicing advanced loads and meeting future platform power system requirements, including flexibility and survivability. The effort is further defined in Appendix G. (Depicted in Figure 6 as 1)

- Upgrade the power system through integration of new technologies as required to support advanced mission capabilities.

TECHNOLOGY DEVELOPMENT STRATEGIES (THROUGH MID-TERM 2019-2037)

ENERGY STORAGE (2019-2037)

OPPORTUNITY

By integrating energy storage into the power system, new capabilities are enabled affordably. These include increased survivability, endurance, reliability, flexibility, and adaptability through the ability of energy storage to be shared across multiple systems where this was not previously possible with point-of-use energy storage.

DEVELOPMENT APPROACH

Conduct a series of progressive development and integration steps to mature from the current state of point-of-use energy storage to the long-term vision of multi-function energy storage fully integrated within a ship's distribution system.

SECTION 3 (CONTINUED)

- Near-term efforts focus on developing a common set of building blocks that will be configured to meet the interface requirements of individual loads and develop Navy intellectual capital in energy storage systems integration. Additional activities will focus on shared energy storage systems that can support a suite of advanced weapons and sensors initially on low-voltage sub-systems of the electric plant.

- Mid-term efforts will develop media agnostic energy storage systems, capable of integration onto the low or medium voltage bus, available for multiple users and functions.

CHALLENGES

- Development of energy storage systems that can be qualified for shipboard use
- Development of alternate energy storage technologies (rotational, electrochemical, and electrostatic based)

Table 3: Energy Storage Milestones / Interim Schedule Targets

TECHNOLOGY	FYDP/NEAR-TERM	MID-TERM
Energy Storage	• Deliver intermediate power system that can power a laser load from energy storage alone and has trickle charge capability (2019) • Deliver intermediate power system capable of powering a laser from energy storage and has continuous charge capability (2020) • Load-specific and shared low-voltage energy storage prototype to initial introduction • Fully shared low / medium voltage energy storage demonstration	• Initial introduction of fully shared energy storage • Introduction of ES system: -Low / Medium-voltage - Multiple energy storage technologies -Media agnostic • Intermediate power systems that can power multiple advanced mission loads simultaneously • Energy storage for ships with legacy MVAC distribution systems • Energy storage integration onto the distribution bus to support bus stability

REQUIRED INITIATIVES (2019-2027)

The following efforts support energy storage development as currently identified:

- Intermediate power system that can power a laser load from energy storage alone. Only trickle charge capability. Delivered to Navy for integration testing in 2018. (Depicted in Figure 6 as 2)

- Intermediate power system capable of powering a laser from energy storage. Continuous charge capability while in use. Available for platform integration in 2021. (Depicted in Figure 6 as 3)

- Intermediate power systems that can power multiple advanced mission loads simultaneously (LWS, SEWIP, etc.) and provide power to ship's bus with energy storage. Continuous charge capability. Available for system integration in 2022 with IOC in 2029. (Depicted in Figure 6 as 4) Additionally, develop intermediate power system MVAC variant to support DEW integration with 4160VAC legacy distribution system. Available for system integration in 2029. (Depicted in Figure 6 as 5)

- System that supplies energy storage to the distribution bus while supporting bus stability. This system should be capable of supporting advanced weapons and sensors on ships distribution bus. Additionally, if battery energy storage technology is utilized, this system should provide battery failure containment capability. IOC in 2031. (Depicted in Figure 6 as 6)

- Develop a non-battery based high-density energy storage system capable of supporting both high voltage and medium voltage bus stability available for systems integration in the FY23 timeframe. (Depicted in Figure 6 as 7)

- Develop energy storage for larger UxVs capable of powering advanced weapons and sensors. Note: Development of an off-board charging system is addressed in the power conversion section. Available for platform integration in 2024. (Depicted in Figure 6 as 8)

POWER CONVERSION (2019-2037)

OPPORTUNITY

Power converters provide matching interfaces between non-matching parts of the system. Finer control by utilizing actively-switched power semiconductor devices allows the ability to:

- **Tailor interfaces to optimize system design**
- **Improve control over the supply of power and energy to the advanced mission systems**
- **Increase endurance and capacity using variable speed drives**
- **Increase survivability, reliability, and recoverability through improved power routing**
- **Increase stability through dynamic load balancing**
- **Fault current limitation, permitting graceful degradation versus immediate circuit isolation**
- **Consolidation of functions that were previously dispersed among multiple components or not present at all, (e.g., fault isolation (currently performed by circuit breakers))**
- **Decouple the dynamic behaviors of parts of the system from each other, enabling optimization of overall platform design and its capabilities**

DEVELOPMENT APPROACH

The aim is to continue investing in the development of actively-switched power semiconductor devices. The fast switching time of silicon (Si) devices permits improved control over voltage, frequency, and current. Silicon-carbide (SiC) has been supplanting silicon in many industry applications due to its higher switching frequencies and lower switching losses, thereby reducing waste heat. This allows reducing the size and weight of electromagnetic components associated with power conversion equipment through redesign.

- Focus near term efforts on developing SiC based converters utilizing 1.7kV devices (commercially available)
  - Follow on focus will be on development of SiC power converters based on 6.5kV and 10kV devices (commercially available).
  - Continue basic research into advanced wide bandgap (WBG) semiconductor devices that have improved performance over SiC such as GaN and Ga2O3
- Mid-term goal is SiC-based power conversion serving as the backbone of the primary (medium-voltage) distribution bus of the electric plant.

CHALLENGES

There are system engineering and integration challenges, as well as material challenges, that need to be addressed to leverage the benefits of actively-switched power conversion, among which are:

- Designing and building converters that mitigate adverse system interactions (e.g., instabilities, electromagnetic interference (EMI), and common-mode stress)
- Potentially having increased shipboard thermal management of a converter-based power system
- Developing the knowledge to allocate system functions to power converters
- Providing reliability, resiliency, and quality of service at a system level
- Reducing the size of passive components for power converters (e.g., transformers)
- Reducing the cost for scaling up SiC devices to relevant voltages (e.g., 6.5kV and 10kV dies)
- Scaling (vertical) GaN and Ga2O3 devices requires continuous investment to enable a Ga-based prototype in the mid-term

SECTION 3 (CONTINUED)

Table 4: Power Conversion Milestones / Interim Schedule Targets		
TECHNOLOGY	FYDP/NEAR-TERM	MID-TERM
Power Conversion	• Modular design • More power-dense converters supporting advanced mission systems (e.g., AMDR PCM) • SiC-based converters prototyped at 6kVDC and 4.16kVAC based on 1.7kV devices • SiC-based converters prototyped at 13.8kVAC and 12kVDC	• Initial introduction of SiC converters to the Fleet • Modular design • Low / Medium-voltage • Up to 12kVDC and 13.8kVAC • Prototyping of full scale conversion based on gen 2 WBG devices such as GaN and Ga2O3

REQUIRED POWER CONVERSION INITIATIVES (2019-2027)

The following efforts support power conversion development as currently identified:

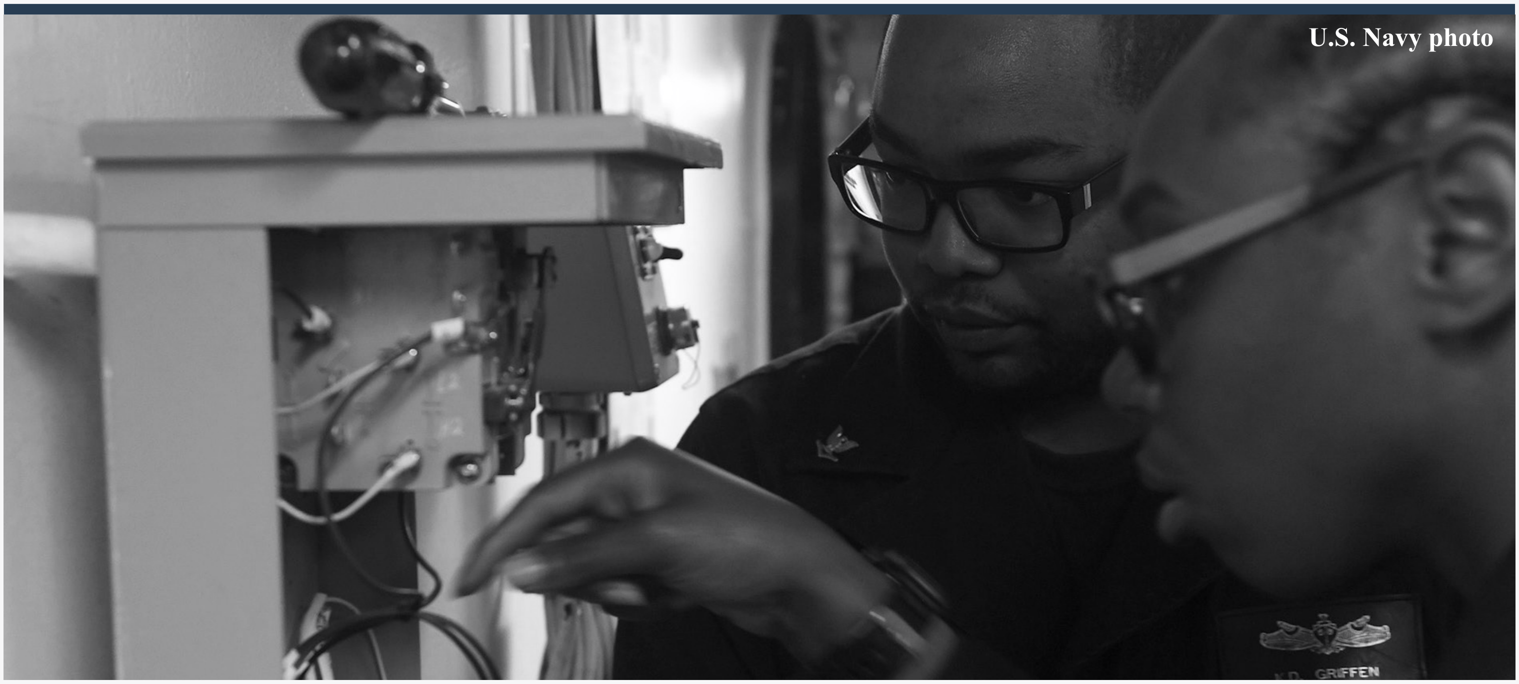
- Develop, test, and initiate low-rate initial production of the Air and Missile Defense Radar (AMDR) Power Conversion Module (PCM). IOC in 2022. (Depicted in Figure 6 as 9)
- Develop and test Advanced Power Conversion Module employing SiC devices suitable for advanced load applications. (Depicted in Figure 6 as 10)
- Develop an affordable and highly reliable Integrated Power Management Center (IPMC) point of use power converter adhering to MIL-PRF-32272A with the exception that efficiencies higher than those specified are desired as well as the incorporation of energy storage. Available for systems integration in 2021. (Depicted in Figure 6 as 11)
- Develop a charging system that enables the ability to charge UxVs without the need to embark and disembark UxVs from Naval ships. Available for systems integration in 2027. (Depicted in Figure 6 as 12)
- Using advanced SiC power conversion modules, develop converters that operate at 13.8kVA 12kVDC and 1kVDC. These converters should be compatible with the Standard Modular Compartments (SMCs) and the Common Ship's Integrated Enclosures (CSiEs) developed by PEO IWS. Available for systems integration in 2026. (Depicted in Figure 6 as 13)

PRIME MOVERS: (2019–2037)

The prime movers section largely focuses on diesel engines and gas turbines. Energy recovery and fuel cells, covered in Appendix F, are also prime movers.

OPPORTUNITY

Right sizing prime movers can enable using fewer prime movers and reduce fuel consumption. Reduction in fuel consumption positively impacts endurance. Prime movers in conjunction with energy storage can enable using fewer prime movers for power and propulsion in certain operating conditions, thereby reducing overall ship fuel consumption. Taking advantage of the variable speed nature of prime movers using non-60Hz generators enables optimizing the turbine operating point with the load.



DEVELOPMENT APPROACH

The Navy does not have sufficient buying power to drive the worldwide engine market; therefore, development is focused on incremental improvements to existing gas turbine and diesel engines.

- Near-term efforts focus on two key initiatives:
  - Develop advanced materials for blade and hot section coatings that can mitigate issues with existing gas turbines, operating at higher loading, without increased maintenance. Turbines that are heavily loaded run hotter which leads to shortened engine life.
  - Couple a GT prime mover with an advanced variable-speed generator to enable operating the turbine at its optimal load points throughout its operation.
- In the mid-term, efforts will focus on developing a 10-15 MW gas turbine-based generator set using a commercial 10-15 MW marinized gas turbine to enable ship design flexibility greater than currently possible.

CHALLENGES

- Currently, there is a limited pool of commercially available marinized gas turbines and diesel engines to choose from.

Table 5: Prime Movers Milestones / Interim Schedule Targets

TECHNOLOGY	FYDP/NEAR-TERM	MID-TERM
Prime Movers	• Develop advanced coatings and materials that support high temperature operations of a gas turbine via Future Naval Capability Program "Gas Turbine Development for Reduced Total Ownership Cost (TOC) and Improved Ship Impact"	• Qualify a 10 to 15 MW gas turbine appropriate for an Advanced Gas Turbine Generator

REQUIRED INITIATIVES (2019-2027)

The following efforts support prime mover development as currently identified:

- Transition advanced coatings FNC. Test engine endurance with new coating and confirm inhibition of damage due to extended high temperature gas turbine operations by 2025. (Depicted in Figure 6 as 14)
- Develop and test ~25MW Advanced GTG – see Section 3.3.2.4 (Depicted in Figure 6 as 15)

SECTION 3 (CONTINUED)

ROTATING MACHINES (2019-2037)

Electrical rotating machines (ERMs) are both motors and generators. For the purposes of this roadmap, the rotating machines of interest are generators associated with prime movers and propulsion motors. These components are of primary interest because they are 1) the largest "single function" components onboard ships, and 2) in the case of generators, the primary source of shipboard power. In Appendix F, the TDR focuses on AC induction, AC synchronous, permanent magnet (PM), and High Temperature Superconducting (HTS) machines.

OPPORTUNITY

Developing denser power generators increases flexibility in machinery arrangements, reduces machinery room size, and potentially increases ship affordability. Also, increasing motor density and the associated drives increases machinery room flexibility. Propulsion motor technologies can facilitate implementation of advanced propulsors (e.g., contrarotating), improving propulsion fuel efficiency. Compact forward propulsors provide fore/aft separation of propulsion capability supporting increased resiliency and survivability.

Development Approach

Generators

The stack up length for main gas turbine generator sets determines the minimum machinery room size, making it a primary driver for ship design.

- Near-term: Develop generator technologies that reduce stack-up length, increase power density, or otherwise improve the ability to arrange these large rotating machines within the overall ship design. Additionally, assess and develop the knowledge base to support a variable speed dual output generator to notionally provide plant resiliency by decoupling port and starboard buses from each other's large-magnitude dynamics.

- Mid-term: Capitalize on the rotational inertia of generators, essentially spinning energy storage currently not exploited. Implementation is currently constrained by the requirements of 60 Hz AC distribution to maintain frequency within tight deviation tolerances. MVDC distribution systems can decouple the frequency interaction between components enabling operational constraints to be lifted.

ELECTRIC MOTORS

- **Near-term: Based on the investment the Navy has made in large electric motor development, minimal R&D investment dollars will be spent on large electric motors in the near term. However, significant engineering dollars will be invested in building electric motors of sufficient power density and power level to meet future ship needs.**

- **Mid-term: Develop a superconductive propulsion motor, leveraging the knowledge from industries' increased use of superconductive materials in the offshore wind industry.**

CHALLENGES:

As discussed above, the advantages that come from decoupling frequency interactions between distribution system and generator set is dependent on a DC distribution system. Initiating a DC distribution system requires a systems integration effort that provides the knowledge to design and build a mature MVDC distribution system.

Table 6: Electric Motors Milestones / Interim Schedule Targets

TECHNOLOGY	FYDP/NEAR-TERM	MID-TERM
Rotating Machinery Generators	• Deliver medium voltage AC Ship Service Gas turbine generator set (AG9160) with increased efficiency for DDG51 FLT III ship service • Develop advanced GTG (20 MW-30 MW): - Increased efficiency - High-Speed Generator - High-Power Density - Compact stack up length - MVDC output converter • Introduce advanced materials that inhibit type 2 corrosion	• Introduction of advanced GTG to the fleet. • Initially introduce SiC converters to the Generator sets • Deliver prototype of 10 to 15 MW GTG for increased power generation capability
Electric Motors	• Deliver large power dense propulsion motor (up to 40 MW)	• Deliver large power dense, low resistance propulsion motor (up to 40 MW)

REQUIRED INITIATIVES (2019-2027)

The following efforts support generators development as currently identified:

- Develop and test a notional advanced 25MW GTG to validate hardware performance and system interfaces to be completed and transitioned to systems integration by 2024. (Depicted in Figure 6 as 15)
- Develop 10-15MW GTG that transitions to systems integration by 2033. (Depicted in Figure 6 as 16)

The following efforts support electric motors development:

- Develop advanced propulsion motor that transitions to systems integration by 2034. (Depicted in Figure 6 as 17)

DISTRIBUTION SYSTEM (2019-2037)

OPPORTUNITY

A distribution system enables increased survivability, flexibility, and overall capability through increased redundancy, more capable power continuity, and increased recoverability. This system can support the reduction in power system size by minimizing the power conversion, power filters, and energy storage that advanced mission loads currently supply to be compatible with today's ships power systems. This new distribution system should meet an updated interface (Draft MIL-STD-1399 Navy Section LVDC and Section MVDC) and enable flexible power generation line-ups and generator frequency decoupling. (Note: this can enable GTGs to operate for optimal fuel consumption increasing a ship's endurance).

DEVELOPMENT APPROACH

The focus is on developing the knowledge and technology (objective quality information) necessary to develop and test an MVDC distribution system up to 12kVDC that enables future load flexibility.

- Near term: Initial efforts focus on the development of a 1kVDC high speed solid state breaker and a high speed 12kVDC solid state breaker. Development of methodologies for managing and eliminating ground faults and common mode issues that can arise in conversion-based distribution systems.
- Mid-term: Leverage advanced conductor development from Office of Naval Research (ONR) to develop a prototype advanced conductor-based cable suitable for Navy application.

SECTION 3 (CONTINUED)

CHALLENGES

MVDC circuit protection has been identified since 2008 as one of the high-risk areas for the implementation of a MVDC distribution system.

- Ultrahigh speed breakers may not be able to differentiate between a fault or a behavior due to a pulse load in operation.
- Ultrahigh speed breakers may have difficulty properly coordinating in a bus topology.
- Implementation of a distribution system designed to enable load growth, increased performance, and flexibility

Table 7: Distribution System Milestones / Interim Schedule Targets

TECHNOLOGY	FYDP/NEAR-TERM	MID-TERM
Distribution	• Deliver an MVDC distribution system up to 12kVDC to meet maximum load demands • Design an appropriate in-zone distribution system architecture • Publish a new 1399 LVDC/MVDC interface • Deliver high speed 1kVDC and 12kVDC solid state circuit protection device ship ready • Test an advanced conductor capable of supporting power distribution	• Build and test a full scale advanced conductor for distribution use.

REQUIRED INITIATIVES (2019-2027)

The following efforts support distribution system development as currently identified:

- Transition the 1kVDC and 12kVDC fast-acting solid-state circuit protection devices currently under development. These devices shall be capable of high-speed detection, clearing, fault localization, and be integration tested by 2023. (Depicted in Figure 6 as 18)
- Develop a disconnect switch to work in conjunction with power conversion to perform circuit isolation functions at 1kVDC and 12kVDC by 2023. This is necessary in power conversion-based circuit protection where power converters are used for fault localization, coordination, and isolation. (Depicted in Figure 6 as 19)
- Develop a power distribution node with the following functionality:
    - o Segments the MVDC Bus
    - o Isolates loads
    - o Isolates sources
    - o Establishes Ground Reference for MVDC Bus
    - o Additional characteristics that enhance shipboard integration by utilizing advanced cables to decrease bend radii, incorporates advanced switches, insulation, and cooling. (Depicted in Figure 6 as 20)

CONTROLS: (2019-2037)

A control system is defined as a system that manages, commands, directs, and regulates the behavior of other devices or systems. These actions are affected by algorithms, the processing units they run upon, and effector devices. Controls will allow optimum management of the energy-time-power problem to provide power when and where it is needed.

The technology development areas discussed up to this point address technology integration into the electric distribution system (network). However, overlaying the electric network is a controls network that manages electrical components to achieve a desired state. The integration of the component technologies previously discussed must necessarily include some level of integration in the control layer(s). Full system integration for TEM is inseparable from advanced control system development and integration effort.

From the perspective of IPES, there are three controls domains of interest:

a) Low-level device and component control (i.e., embedded systems)
b) Supervisory control of the electric plant as a system
c) Ship warfighting control domains, both digital and human

The long-range goals of IPES controls are as follows:

1) Maximize the capability for the electrical system to deliver all available energy where and as required, when given the current state-space (capabilities) of the energy network (domains a and b).
2) Fully inform the ship warfighting control domain of the capabilities and constraints of the energy network (domains b and c).
3) Receive orders (energy delivery to ship mission systems) from the ship warfighting control domain (domains b and c).
4) Implement those orders as fully and responsively as possible (domains a and b).

Effectively, IPES control must constantly solve a resource allocation problem, in coordination with the warfighting control domain.

OPPORTUNITY

An overarching integrated control system:

- Enables TEM
- Allows leveraging individual technology development and future technology insertions while continuing to operate as one cohesive system
- Provides system flexibility to operate at either maximum efficiency or maximum performance as necessary through communication and control between machinery systems, combat systems, and mission systems
- Integrates and updates cybersecurity capabilities as required

DEVELOPMENT APPROACH

The development approach for advanced controls begins with the goal of Navy-owned Common Machinery Controls System Software. This supports creating a unified Architecture for Machinery Control systems that features:

- A common machinery control language
- A reusable control system software baseline
- Flexibility and adaptability for transitioning new technology from a variety of sources and life cycle updates and support in an efficient, consistent, cost effective, and timely manner

Concurrently, develop TEM controls that address the problems of state awareness, optimization, and coordination with the warfighting control domain. Integrate TEM controls with the unified architecture for machinery controls.

CHALLENGES

The challenge in achieving the vision of IPES control for TEM are:

- Developing an advanced autonomous control system that keeps pace with the threat environment
- Developing a control system concurrently and coordinated with the electric plant system engineering and integration. The control system must reflect the full functionalities, capabilities, and constraints of both the electrical network (as a system) and its component nodes. Thus, the partitioning of functionality within the control system must reflect the functional allocation of the electrical system.

SECTION 3 (CONTINUED)

- The control system must be as resilient to casualty scenarios as the electrical network that it controls.
- The control system must be closely coupled with the ship warfighting control domains.
- The control system must be robust and resilient to cyber threats.
- The control system must enable affordable upgrades and on an ongoing basis.

Table 8: Controls Milestones / Interim Schedule Targets

TECHNOLOGY	FYDP/NEAR-TERM	MID-TERM
Controls	• Develop, test and deliver a Control System Reference Architecture, Interface Language, Syntax and Framework • Demonstrate state awareness and optimization algorithms in a representative environment	• Deliver targeted machinery control system upgrades

REQUIRED INITIATIVES (2019-2027)

The following efforts support controls development as currently identified:

- Demonstrate reference architecture with distributed state awareness in 2021. (Depicted in Figure 6 as 21)
- Demonstrate reference architecture with distributed / hierarchical control in 2022. (Depicted in Figure 6 as 21)
- Demonstrate reference architecture with both distributed state awareness and hierarchical control in 2023. (Depicted in Figure 6 as 21)

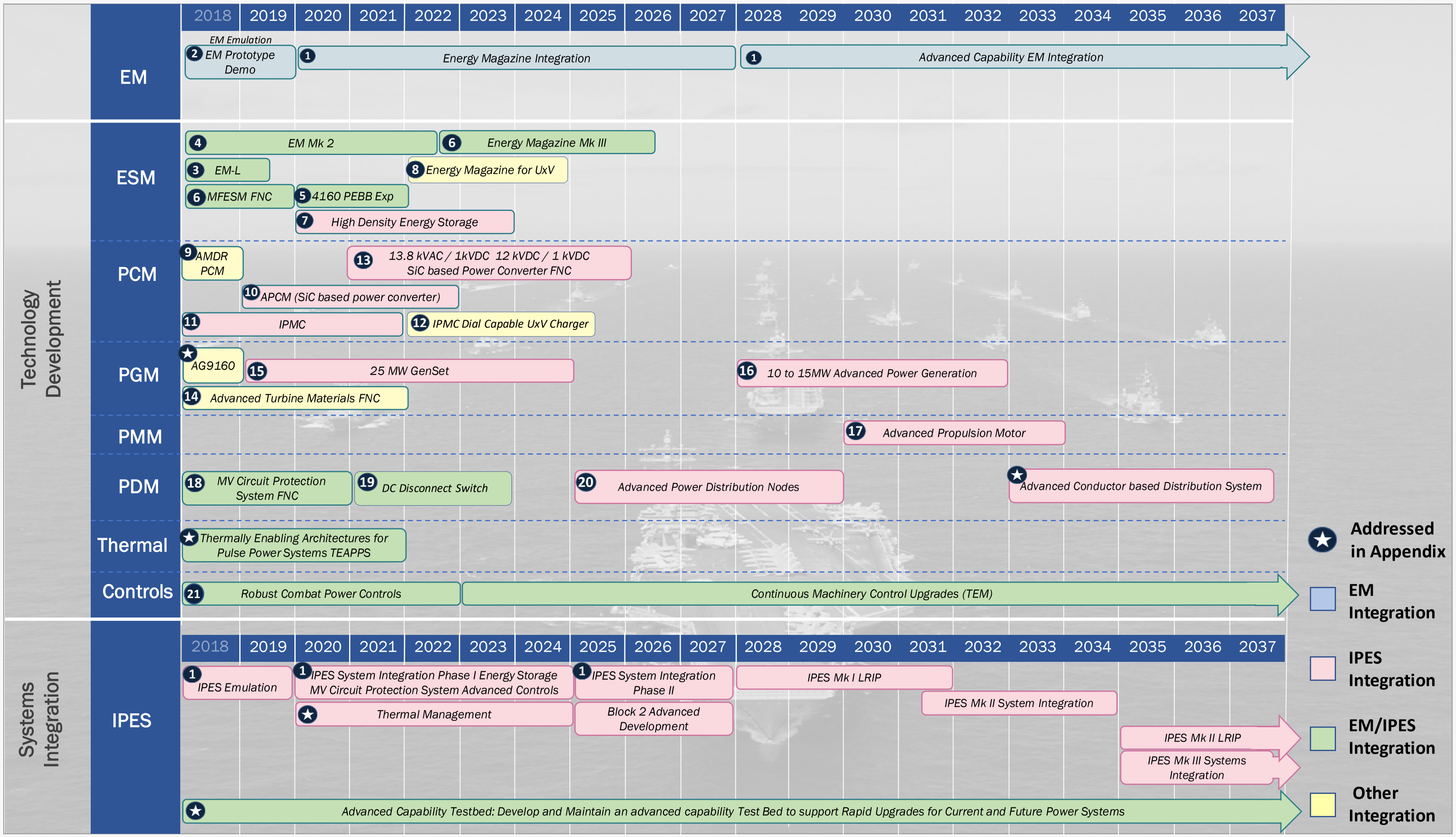
A system of systems framework of requirements that defines a warfare system construct and can implement rapid force-wide capability insertion.

This will enable the agility to scale combat power over time in such a way as to provide dominant capability dictated by threat and mission.


U.S. Navy photo

Required Inititatives (2019-2037)

Figure 6



*(#) corresponds to required initiative that activity supports from Section 3

SECTION 3 (CONTINUED)

THE NEED FOR INNOVATION

According to the 2017 ONR Navy Research and Development Framework, Naval capabilities begin with discoveries made in science and technology. Talented scientists and engineers in the Naval Research Enterprise (NRE), and across ONR partners in industry, academia and government labs, draw upon basic research for new knowledge to develop new technologies that ultimately become new capabilities delivered by the acquisition community. To successfully maximize the benefits of basic and applied research, it is imperative that investments be coordinated as part of a cohesive approach from basic research to operational test and evaluation. It is important to maintain a steady level of investment in key technology areas that benefit Navy warfighters. Investing in technology areas can offset the risk associated with the failure of specific technologies. While specific technologies may succeed or fail, investing in technology areas will maximize the opportunity that one or some of the technologies will be successful and evolve into more mature products for Navy-use. Technologies developed during basic and applied research may transition to multiple products. The following is a discussion of the Navy's Applied and Basic Research areas for P&E systems.

CURRENT NAVY-SPONSORED APPLIED RESEARCH INITIATIVES

ENGINEERING COMPETENCY

Emergent technologies require the Navy to update the Electrical Power Engineering educational curriculum. This updated curriculum should include the latest knowledge (theory and application) of interest to the Navy. This includes but is not limited to study of WBG semiconductors, common mode/differential mode characterization, and electromagnetic interference (EMI) mitigation. Training the Human Resources Enterprise (HRE) in these advanced technologies will boost the knowledge, skills, and abilities (KSA) of the fleet.

ADVANCED CABLE OR ELECTRICAL POWER TRANSMISSION MEDIA

The Navy needs Low Magnetic Signature (advanced materials, advanced insulation) MVDC cable / bus pipe suitable for 12kV MVDC applications. Developers must make the cables / bus pipe suitable for naval combatant applications (i.e., meet applicable inspection requirements tailored for MVDC applications), be scalable, and enable tight bend radii.

DESIGN TOOLS

As the P&E system becomes more critical to enabling a ship's capability requirements, the Navy requires new design tools to determine what P&E system implementation serves their capability requirements best, as well as how to optimize the P&E system to a selected set of capability requirements. Tools and models will have to support interface development and optimization, and be able to near simultaneously perform an analysis of component and system behavior based on each analytical domain (the correct model for the correct analysis of the exact same system). M&S S&T research currently underway include:

- Using Complexity Theory for the Analysis of Architecture
- Implications of Distributed Systems Numerical Methods for CPES Systems

An expansion of M&S S&T research should include:

- Integration of IPES design synthesis tools with ship design and synthesis tools.
- Develop a Ship Continuity and Quality of Power Model that has the capability to perform dynamic end to end analysis from the shipboard voltage interface up to and including the loads. This model must include all interconnected power conversion and energy storage components between the shipboard voltage interface and the loads.

MVDC ANALYSES

Develop advanced analysis methods to support analyzing and determining:

- Power distribution system options
- Energy storage sizing and integration options
- Control systems, power generation systems, and energy storage optimization

This information can be used to support updating specification and standards including but not limited to NSTM 300. (specification and standards are discussed later in Section 3 and in Appendix J)

CURRENT NAVY-SPONSORED BASIC RESEARCH INITIATIVES

P&E RELATED CONTROLS INITIATIVES

The P&E goals of tomorrow's Navy mandate innovations in autonomous and machinery controls. For example, UxVs need robust and resilient autonomous controls. They must be able to adapt and configure to existing and emerging concepts of operations. Manned vehicles will need advanced machinery controls to operate in conjunction with power electronics based power distribution. Operators will depend on these systems to precisely move power and energy from the providing source to the right load at the right time supporting rapid-decision making. Specific areas of interest include controls that are capable of self-adaptation, self-diagnostic algorithms for system evaluation and healing, and advanced power management. An extensive listing of the type of work required to continue is listed in Appendix G.

WIDE BANDGAP (WBG) AND EXTENDED WIDE BANDGAP (EWBG) DEVICE INITIATIVES

WBG (SiC and GaN) and EWBG (Ga2O3 and AlGaN) semiconductor basic scientific research is required to develop the high voltage (20kV), high current (200A), reliable, rad-hardened devices needed to achieve mid-term high power conversion objectives. Basic science will focus on the ability to grow thick epitaxy with minimal background doping and impurities. Additionally, domestically supplied substrates with which to grow the thick epitaxy must be investigated. Technical issues that need to be addressed and improved upon include uniformity, surface morphology, resistance to breakage, and interface resistances.

ELECTRICAL SYSTEM AND COMPONENT BEHAVIOR MODELING

Technologies are constantly emerging. The fusion of these technologies and integration with total ship design synthesis models is required.

S&T must invest in the development of numerical and analytic methods to enable a robust modeling capability that can support the rapid modeling at the component, system, and platform level. Advances in modeling and simulation will be necessary to exercise these new numerical and analytical methods. These advanced models need to operate with existing tools.

Physics-based models of P&E technologies, subsystems, and systems need to be developed to understand and predict behavior with respect to ground faults, common mode, large and small signal stability, zonal arrangements, and other system-initiated interactions.

ENERGY HARVESTING

Energy harvesting technologies are critical to support extending missions for UxVs, USMC Forward Operational Bases (FOBs), and any scenario where increasing the time between "refueling" is desired. Additionally, these technologies can play a critical role in enabling energy recovery to be used to increase power system efficiency.

SOLID STATE ENERGY CONVERSION/THERMAL ENERGY CONVERSION

A specific area of Energy Harvesting of interest to the Navy is the ability to convert heat energy and specifically low quality heat energy to electricity using solid state components. This capability is extremely important to enabling energy recovery systems for land-based vehicles but especially for ships. For additional information see Appendix C.

SOLID STATE POWER CONVERSION

Iron core transformers are efficient but are very heavy and voluminous. Advancements in WBG semiconductors and magnetic materials have enabled high frequency transformers that may be smaller and lighter. More research needs to be done with magnetic materials to increase the power density of a PEBB Least Replaceable Unit (LRU). Research is targeted for magnetic materials that can handle frequencies more than 100 kHz and simultaneously handle power greater than 1MW. It is planned that investments will be made in basic science and later in applied science to investigate magnetic materials that possess high-frequency and high-power requirements but are also thermally manageable. This research will be applied to PEBB 6000, which are explained further in Appendix G.

SECTION 3 (CONTINUED)

ADVANCED INSULATION

As emerging machinery (motors, generators, motor drives, and converters) requirements push high voltage and current gradients (i.e., dv/dt and di/dt), advanced insulation technologies are required to assure high reliability leading to high availability. There are existing efforts in basic research to develop new insulation technology, such as nanoclay insulation, that possess superior mechanical, thermal, electrical, and material properties over legacy mica based insulation systems. These insulation systems are not only applicable to rotating machinery, but can be applied to cable systems handling up to 20 kV and a few thousand amps. Mathematical models are currently being developed, validated by empirical data, that can predict when insulation systems will fail.

ADVANCED DIELECTRIC MATERIALS

- Advanced Dielectric Materials and Film research
  - Dielectric Materials for Capacitive Energy Storage

ADVANCED CONDUCTORS

Researchers continue to develop a more complete understanding of the material science associated with carbon-based electrical conductivity. The electrical conductivity of individual carbon nanotubes (CNT), for example, exceeds the performance of copper. When these nanotubes are combined into a matrix to form carbon-based wire, many factors cause the electrical conductivity of the wire to drop significantly.

CNT and graphene-based materials are being investigated as dopants in hybrid structures with other materials such as copper. The long-term goal is achieving room temperature electrical conductivity at least as high as copper. An interim goal is to achieve higher electrical conductivity than copper at temperatures typically observed in rotating machinery (~150°C). Another interim goal is achieving higher electrical conductivity-to-mass ratios than copper, aluminum, etc. Ultimately, carbon-based electrical conductors have significant potential for reducing weight in Navy components and systems, increasing fatigue strength, affordability, and possibly efficiency. Other important characteristics where carbon-based electrical conductors show promise include potentially better corrosion resistance and thermal conductivity than alternatives. Ongoing efforts aspire to understand terminations and junctions involving crimping of carbon-based electrical conductors.

HIGH TEMPERATURE SUPERCONDUCTING (HTS) COMPONENTS

Ongoing high temperature superconductors research is directed at applications to support power delivery, pulsed current delivery, alternating current (AC) and direct current (DC) magnetic fields, and magnetic energy storage.

Superconducting materials exhibit lossless DC current transport properties that have potential to enable a wide range of high power density applications including motors, generators, and power cables. Progress towards room temperature superconductivity is being pursued through advances in material science to further reduce size, weight, and cost of conductors used in electrical equipment. Characteristics of superconductors also permit unique capabilities and unprecedented efficiency in producing and trapping magnetic fields, storing magnetic energy, and integrating inherent fault current limiting capability in conductors and cable topologies.


U.S. Navy photo

SECTION 3 (CONTINUED)

While superconductors have unique and beneficial characteristics for a new capability, performance is limited by the requisite cryogenic environment and are further reduced by the presence of magnetic field. Progress in the basic and applied research topic areas below is being pursued to enhance the efficiency for sustained warfighter operations and platform level energy storage and efficiency for propulsion and advanced mission systems:

- Superconducting Materials
- Superconducting Tape Processing and Modification
- Superconductors for Novel Applications
- Superconducting State Protection

THERMAL MANAGEMENT

As the demand and complexity of high energy loads, including NPES, increases, so does the demand and complexity of thermal management solutions required to address those thermal loads. This section provides background on current and future thermal management approaches for US Navy platforms and discusses the advancements required to meet the emerging increase and complexity in cooling demands and associated system risks that must be mitigated for successful technology transition and implementation.

Shipboard thermal management systems are responsible for maintaining living spaces, equipment, and systems at specific operational temperatures and ventilation rates, regardless of the external environment and thermal loads imposed from operation. Assessing and optimizing the effectiveness of a thermal management system requires the analysis of thermal energy acquisition, thermal energy transport, and thermal energy rejection, storage, and conversion. The design of the thermal management system aims to transfer the thermal energy loads at the sources to the sinks in the most efficient manner. Additional information on thermal management can be found in Appendix D, Appendix G, and Appendix H.

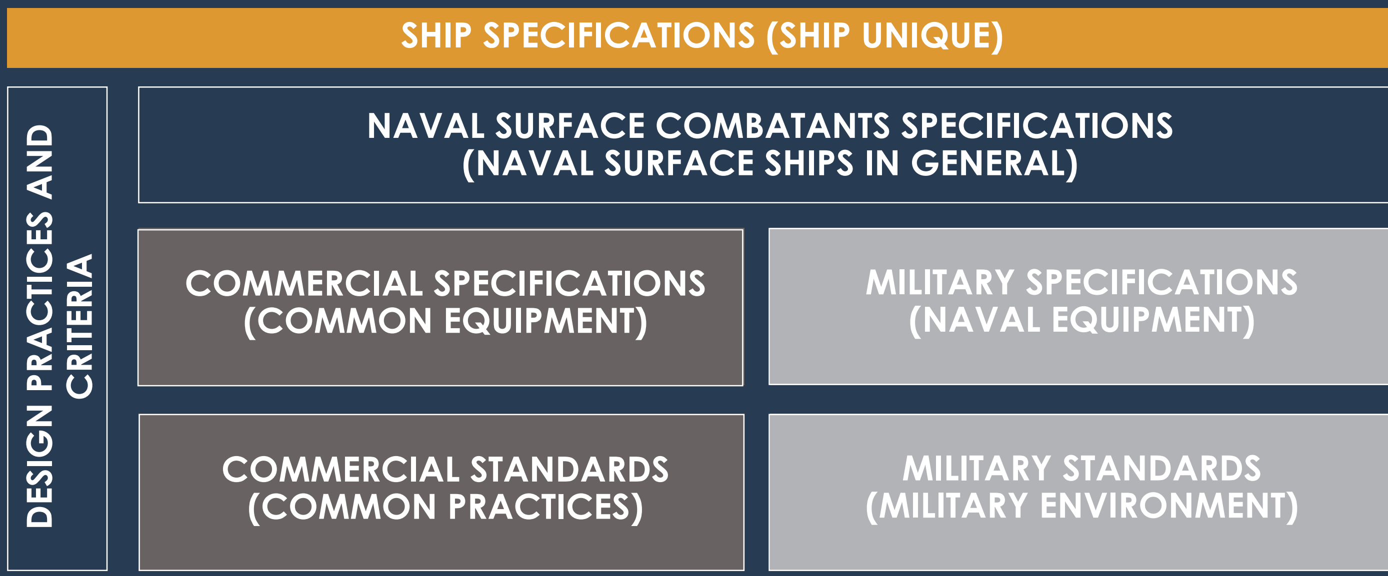


Figure 7: Technical Documentation Relationships

SPECIFICATIONS AND STANDARDS

Specifications, standards, handbooks, design practices, and criteria manuals are essential to institutionalizing new technologies, architectures, and interfaces. These documents are all related but have different functions in the design, development, and procurement of NPES.

Figure 7 shows the relationships of the various technical documents. At the lowest level are commercial and military standards that provide rules, test requirements, best practices, and interface requirements. These standards are usually invoked through commercial and military specifications which collect all the requirements from the commercial and military standards, in addition to equipment requirements, into a document that can, along with owner preferences, be directly employed to procure power system components or equipment. These specifications can either be performance specifications describing the equipment in terms of the performance, interfaces, and testing requirements or detail specifications for the precise equipment design along with manufacturing methods and acceptance test procedures. While the specifications are used to describe the requirements for procuring equipment, the processes for design and design verification are described in military handbooks, design practices, and criteria manuals.

Specifications and standards are viewed as one of the primary transition products resulting from technology development. These documents are the primary enablers for ship and system designers to incorporate and procure products and provide them to the fleet. Through maturation efforts, a specification or standard evolves from a generalized specification or standard (either commercial or military) to a formal specification, standard, or Project Peculiar Document (PPD) developed for incorporation into the ship specification. Specifications and standards also enable industry to produce product lines in anticipation of Navy needs.

The following identifies the Specifications and Standards that need to be addressed immediately to support advanced power system development. Many of those identified are independent of architecture implemented.

INDEPENDENT OF ARCHITECTURE CHOICE

- MIL-STD-1399 LVDC: Develop a low voltage DC interface standard to enable user equipment and power system components to independently develop equipment that can then be affordably integrated. This may be applicable to one or more interface voltages.

SECTION 3 (CONTINUED)

- In-Zone DPCM: Develop an In-zone Design Practices and Criteria Manual for the in-zone design of an electrical power system.

- Intelligent Load Interface Spec (will be referenced by Energy Magazine and MIL-PRF-32272): Develop a control interface specification that includes all layers of the OSI model for negotiating power system - load power interactions. The interface should be extensible. Includes negotiating maximum power and ramp rates as well as soft load shedding.

- Develop key logical integration specifications, such as logical interfaces describing data, data pathways, and system behavior between ship combat systems and the machinery control systems. As these can be "standardized" across combat and machinery control systems and across ship class and platform type, this will enable modularity and common component design in the software and hardware across platform types.

MVDC-SPECIFIC SPECIFICATIONS

- MIL-STD-1399 MVDC: Develop an interface standard for 6, 12, and 18 kV to enable user equipment and power system components to independently develop equipment that can then be affordably integrated.

- MVDC supplement for DPC: Develop a Design Practices and Criteria Manual supplement to guide the development and integration of MVDC systems. Capture lessons learned from ongoing projects and from industry.

- MVDC Switchgear: Develop a generalized MVDC switchgear specification that enables innovative switchgear solutions (other than normal equipment cabinets used in AC systems.) In addition to the enclosure requirements, either directly specify or reference other new specifications for:
  - MVDC circuit breaker specification
  - MVDC disconnect specification
  - MVDC fault management relays (to include MFM if necessary)
  - MVDC grounding circuit specification (if required)

SUMMARY

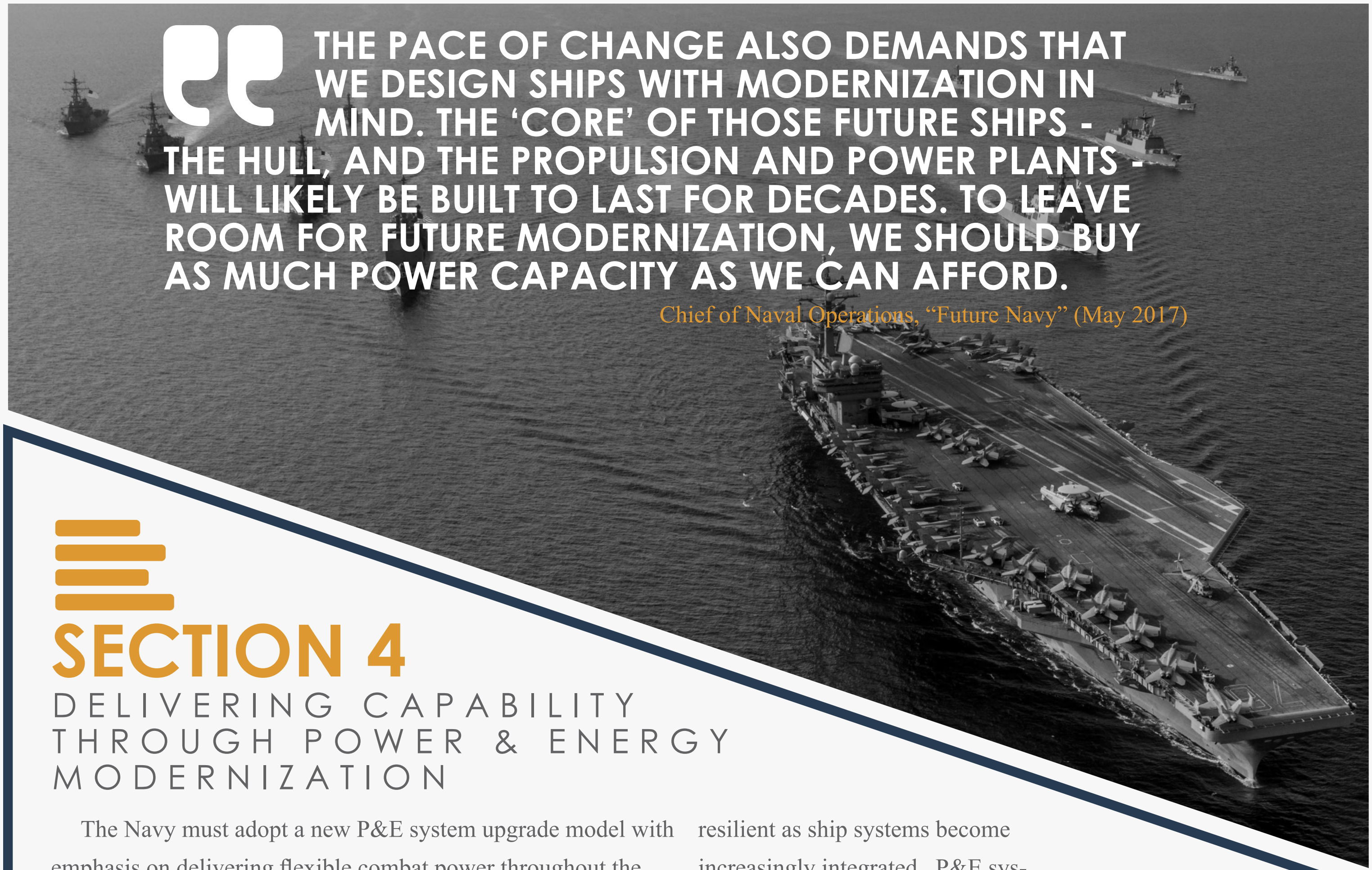
This section provided an overview and identified required initiatives for Systems Integration, P&E technologies, Science and Technology, and Specifications and Standards. Key takeaways from this section include:

- For any changes to the mission systems, power systems, auxiliaries or controls, systems integration is essential to ensure operability regardless of technical architecture choices.

- Tactical Energy Management is critical to enabling full utilization of the capabilities possible from technologies under development.

- Technology developments are underway that can address projected Navy needs provided they are integrated into a system.

- A systems engineering process must capture the knowledge gained from the activities in this section and inform the community at large through specifications, standards, and other documentation.



> **THE PACE OF CHANGE ALSO DEMANDS THAT WE DESIGN SHIPS WITH MODERNIZATION IN MIND. THE 'CORE' OF THOSE FUTURE SHIPS - THE HULL, AND THE PROPULSION AND POWER PLANTS - WILL LIKELY BE BUILT TO LAST FOR DECADES. TO LEAVE ROOM FOR FUTURE MODERNIZATION, WE SHOULD BUY AS MUCH POWER CAPACITY AS WE CAN AFFORD.**
>
> Chief of Naval Operations, "Future Navy" (May 2017)

SECTION 4

DELIVERING CAPABILITY THROUGH POWER & ENERGY MODERNIZATION

The Navy must adopt a new P&E system upgrade model with emphasis on delivering flexible combat power throughout the expected service life of each ship. This document proposes an approach to updating warfighting capability through continuous development and periodic upgrades to the P&E system and associated controls throughout the lifecycle of the platform. This approach will be executed with the CPES OIPT to enable coordinated development with mission system developers in PEO IWS, shipboard integration into future and existing platforms with SEA 05 and NAVSEA ship program offices, and collaboration with other stakeholders such as NSWCPD.

This TDR recommends that NPES are continually developed and periodically upgraded based on other successful programs that provide rapid capability and technology insertion, such as the AEGIS model of advanced capability builds (ACB). The ACB approach allows software advances which provide additional capability to the existing hardware in manageable increments and hardware upgrades as necessary. This allows for affordable upgrades that allow the Navy's combat system to keep pace with an ever-changing threat environment and avoid early obsolescence. This continual development, periodic upgrade approach is essential if the Navy is to remain cyber secure and resilient as ship systems become increasingly integrated. P&E system upgrades should be accomplished using existing program approaches utilizing engineering change proposals.

The CPES OIPT is beginning to address this new P&E system upgrade model by developing the processes, tools, and resources essential to successfully deliver flexible combat power throughout the expected service life of each ship. Continuing down a funded path of earlier, tighter integration and interoperability solutions will avoid the need for further DON power integration governance constructs.

SECTION 4 (CONTINUED)

CONCLUSION

This document's primary intent is to:

- Guide investments in science, technology, research and development for P&E in the Navy and other DoD and government organizations
- Promote communication and collaboration among the many stakeholders in the P&E community
- Deliver industry and academia a path forward for NPES development

New approaches and innovative technologies are required to shape integrated P&E systems for the distributed force to pace the threat and support warfighter needs. By building in adaptability to P&E systems from inception, the Navy can adapt to change quickly and incorporate government and industry innovations. In addition to direct development efforts, the Navy intends to closely monitor and continue to leverage ongoing developments in the commercial sector, including but not limited to:

- Continued use of integrated power systems to reduce the costs of building and operating commercial ships
- Development of smaller, more capable, and more affordable power conversion equipment
- Integration approaches of renewable power sources into commercial micro-grids
- Development of advanced materials
- The trend towards more DC power in renewables, offshore energy and commercial marine applications
- Developments in compact rotating machines

Previous versions of the NPES TDR have provided technology development, system integration and specification, and standard updates without explicitly linking how P&E enables the warfighter. As presented in Sections 1 and 2, P&E is the foundation for future warfighting capabilities and will require a level of investment that paces evolving threats from near-peer and asymmetric adversaries. As presented in Sections 3 and 4, this guiding document provides an approach that enables P&E systems and their associated controls to be continually upgraded during a platform's lifecycle into 2047. Capable and well-designed integrated P&E systems are critical for the Navy to get to the fight faster, avoid direct strike, stay in the fight, fight hurt, recover, and fight again to maintain the global dominance of the U.S. Navy.


U.S. Navy photo