Naval Power Systems

Technology Development Roadmap

PMS 320

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Technology Development Roadmap

PMS 320

Electric Ships Office
PMS 320
Directing the Future of Ships Power

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Date

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Executive Summary

This Naval Power Systems (NPS) Technology Development Roadmap (TDR) aligns electric power system developments with war fighter needs and enables capability based budgeting. The NPS TDR updates the Next Generation Integrated Power Systems (NGIPS) Technology Development Roadmap (TDR) issued in November 2007. It reflects significant Navy changes since 2007 and includes back fit of technologies into ships already in service and ships under construction as well as forward fit into new ships. This update also reflects an approach to deriving electrical requirements and evolving technology alternatives to reflect the needs of the Navy community. OPNAV resource sponsors, acquisition program offices, and the Navy technical community participated in a rigorous roadmap process that evaluated capabilities and technologies, projected NPS needs, aligned technologies with needs to identify technology gaps, and provided recommendations to fill those gaps.

Future requirements are identified in the 30 year shipbuilding plan and other Department of Defense (DoD) and Navy guidance documents. Given historical technology development cycles and insertion time periods, now is the time to take advantage of the planning time horizon and begin to influence technology developments to support out year ships. The primary driver for NPS is to enable capability for legacy platforms and mod repeat hulls while simultaneously supporting future ships. The TDR is responding to the emerging needs of the Navy and while the plan is specific in its recommendations, it is inherently flexible enough to adapt to the changing requirements and threats that may influence the 30-year ship acquisition plan.

In the near-term planning period, available platforms are limited to existing ships, flight upgrades, a new amphibious platform (LX(R)), and the SSBN(X). Advanced weapons and sensors are expected to continue to drive electrical system requirements as are energy security considerations.

Specific recommendations for near-term development are numerous. Major recommendations over the next ten years include:

- An Energy Magazine to support advanced weapons and sensors
- Development of energy recovery
- Prototypes and demonstrations for advanced versions of Energy Magazine, ship power management controller, and energy recovery
- Advanced medium voltage DC (MVDC) technologies as an alternative to AC
- Continued discovery and invention (D&I) basic research efforts

The mid-term planning period introduces several new platforms: DDG(X) in FY 2031, LCS(X) in FY2030, a large deck amphibious ship in FY 2024, and potentially an additional variant of DDG 51 in the FY2022-2024 timeframe. Advanced weapons and sensors with higher power demands as well as energy security will continue to be the primary electrical requirement drivers during this period. Capabilities such as arctic operations, platforms with mission modules, and low observability may play key roles. The power system envisioned for new ships in the period supports a modular approach to allow the electric plant to scale up with changing weapons systems and loads over the life of the ship. Recommendations are provided to continue successful/relevant near-term efforts and demonstrate NPS for mid-term platforms.

The far-term involves additional uncertainty, but it is expected that additional directed energy weapons requiring even more power will become available as well as higher-powered sensors and rail guns of increasing size and capability. It is likely that Navy platforms will operate these systems simultaneously. The Navy will also introduce additional modular ships with modular mission payloads and electric power systems will be required to provide improved power system flexibility. Far-term power systems are anticipated to become more autonomous and simple to operate, smaller, lighter and less costly.

This roadmap focuses and aligns the investments of the Navy, DoD, and industry with the innovative power of academia. Near-term actions are required to support future naval power systems and capabilities identified in current acquisition schedules. Ship implementation of future technologies will require innovation that crosses engineering disciplines. Relevant advances in naval architecture, electrical engineering, material science, etc. are all expected to contribute to improvements in naval power systems. The intent of this TDR is to inform innovation decisions by all concerned at all stages of the NPS technology development process. This TDR will be updated approximately every two years to provide revised predictions as legacy challenges are answered and new ones identified.

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I. Introduction

Purpose

The purpose of this Naval Power Systems (NPS) Technology Development Roadmap (TDR) is primarily to align electric power system developments with war fighter needs and to enable capability based budgeting. Additionally, this NPS TDR is intended to:

- Establish planning information in order to provide appropriate, mature technologies to meet platform timelines
- Establish a common thread for electric power systems requirements across Navy platforms
- Guide Navy and DoD investments in electric power technologies and products
- Develop common terminology and increase communication with industry
- Influence investments by other government agencies, academia and private industry

The NPS TDR retains several tenets from the 2007 NGIPS TDR. These include a focus on reducing total ownership costs, cross platform commonality, providing suitable quality of service, power continuity, and open architecture.

This NPS TDR is not intended to provide the acquisition strategy or development strategy for individual ship platforms or programs. The specifics of individual development efforts will vary in terms of funding, progress, technical and programmatic issues and future plans. Specific plans and actions are more properly addressed in the context of those particular programs.

Background

In 2006, the Chief of Naval Operations directed that a Flag Level Steering Board be established to provide guidance and oversight of power systems development, conduct a comprehensive review of the technical challenges and recommend a path for fielding electric power systems subsequent to DDG 1000 class. The Board was directed to consider both surface ship and submarine future requirements and the power infrastructure for electric weapons and sensors, as well as opportunities to back fit technology to improve the capability and fuel utilization of the current fleet. It was further directed to consider the proper pacing and focus of these efforts with respect to the available Science and Technology (S&T) / Research and Development (R&D) budgets.

In 2007, as a result of that Flag Board’s recommendations, ASN (RDA) established the Electric Ships Office (PMS 320) within PEO Ships to develop and provide smaller, simpler, more affordable and more capable electric power systems for all Navy platforms.[1] The Electric Ships Office Executive Steering Group (referred to as PMS 320 ESG after PEO Ships instruction dated 30 November 2007) was established to provide centralized leadership.

The PMS 320 ESG issued the Next Generation Integrated Power Systems (NGIPS) Technology Development Roadmap (TDR) in November 2007, which outlined the way ahead for future integrated electric power and propulsion system development.[2] The 2007 NGIPS TDR described potential future integrated power systems (IPS) developments in terms of various architectures as well as a functional breakdown of modules and architectures.

Significant changes have occurred since the publication of the 2007 NGIPS TDR including:

- The truncation of the DDG 1000 program at three ships
- The elimination of the CG(X) cruiser from the 30 year shipbuilding plan
- The shift of DDG(X) from FY 23 to FY 31
- The higher priority on fuel savings and energy security for both in-service platforms and those under development

In response to these changes, PMS 320 has developed this update to the 2007 NGIPS TDR. This update is broader in scope than the 2007 NGIPS TDR and includes back fit of technologies into ships already in service and ships under construction, as well as forward fit into new ships in the 30 Year Shipbuilding Plan. This update reflects the focus on energy efficiency and energy security, the current NAVSEA corporate alignment, a new approach to deriving electrical requirements, and evolving technology alternatives. The 2007 NGIPS TDR has therefore been renamed the “Naval Power Systems Technology Development Roadmap” (NPS TDR).

Technology Development Roadmap Construct

In developing the NPS TDR, the Navy adopted the Fundamentals of Technology Road mapping approach developed by Sandia National Laboratories[3] and tailored it to meet the needs of Naval Power Systems. The approach outlines the following as key steps in developing a technology roadmap:

- Identify the “product” that will be the focus of the roadmap (NPS TDR)
- Identify the critical system requirements and their targets (Requirements Pull)

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[1] United States. Department of the Navy, PEOSHIPS INST 5400.8, 30 November 2007

[2] Naval Sea Systems Command, Washington, DC. “Next Generation Integrated Power System: NGIPS Technology Development Roadmap,” 30 November 2007

[3] Sandia National Laboratories; Fundamentals of Technology Roadmapping; SAND97-0665 Distribution Unlimited Release Category UC-900; Printed April 1997; Marie L. Garcia & Olin H. Bray

- Specify the major technology areas, their drivers and their availabilities (Technology Push)
- Align technologies as available with requirements
- Identify technology availability gaps based on required needs and provide development recommendations

Figure 1 illustrates the approach used by the TDR authors in drafting this roadmap. The Sandia Process was modified to suit the Navy's unique environment.

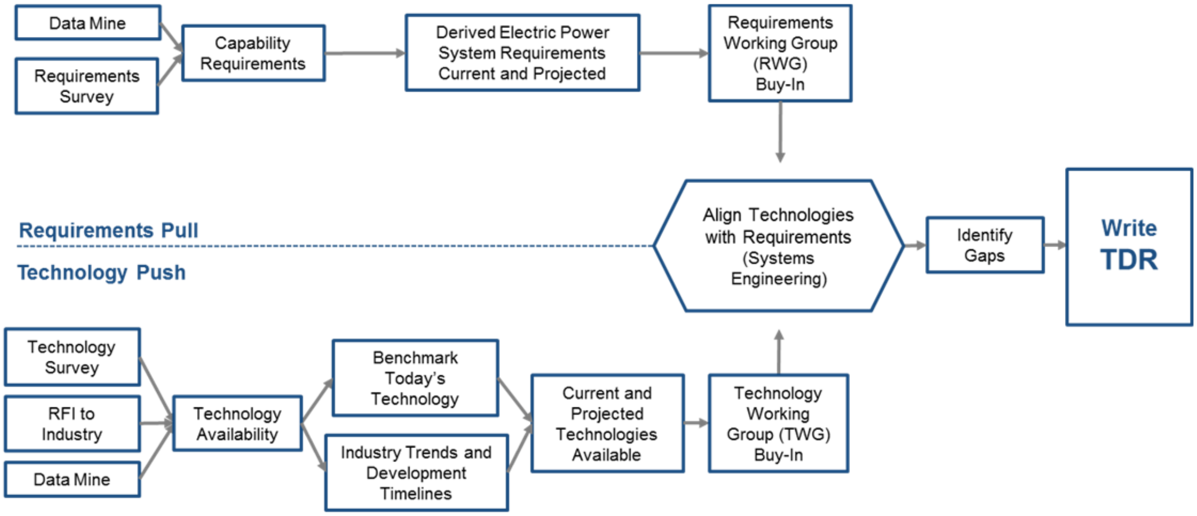

Figure 1: TDR Writing Approach

To facilitate the roadmap update, PMS 320 established both a Requirements Working Group (RWG) and a Technology Working Group (TWG) with representation from all organizations in the PMS 320 ESG as shown below in Table 1:

Table 1: TDR Writing Organization

Requirements Working Group
Lead: PMS 320
Naval Reactors
OPNAV N97
OPNAV N96
OPNAV N95
OPNAV N45
PEO Subs
PEO Carriers
PEO IWS
PEO LCS
PMS 405
UK Royal Navy (ESG Member)

Technology Working Group
Lead: PMS 320
Naval Reactors
NSWCCD
OASN RDA
ONR
PEO SHIPS
PMS 405
SEA 05Z
SEA 05T
Subject Matter Experts as needed

The function of the RWG was to establish capability requirements from which current and projected electric power systems requirements could be derived. The function of the TWG was to benchmark today's technologies, determine industry trends, and establish current and projected available technologies. RWG and TWG activities were conducted in parallel and later aligned through a systems engineering approach to identify gaps where future electric power system requirements could not be met by available technologies.

II. Deriving Requirements

Establishing capability requirements was the responsibility of the RWG. The RWG used a combination of direct interviews and surveys of stakeholders as well as a thorough review of overarching Department of Defense and Navy guidance documents to extract capability requirements statements. From these data sources, Navy fleet capability requirements were documented and later organized into categories. These requirements began with basic “need” or “shall” statements that described certain capabilities. For example, “Shall Project Power Despite Anti-Access/Area Denial Challenge” is a capability requirement derived from the National Security Strategy.

The identified capability requirements were then grouped based on the Universal Naval Task List (UNTL), ensuring a common reference framework for requirements across the Navy, Marine Corps, and Coast Guard. The established groupings represent general areas that the sourced capability requirement statements fall into, with the understanding that more analysis must be completed to determine exact mission systems and electrical power requirements.

This NPS TDR identifies mission systems that satisfy Naval capability requirements and affect Naval Power Systems technology developments for the near term (0-10 years), mid-term (10-20 years), and far-term (20-30 years). These three timeframes align with the Navy’s FY13 30-year Shipbuilding Plan shown in Table 2. Mission systems currently integrated in the Navy and those programs in development were all considered and recorded. Through collaboration with the appropriate program offices and leveraging recent investigations, mission systems that require significant electrical power were identified and their specific power needs derived.

Table 2: FY13 30-year Shipbuilding Plan

	Near-Term (5-10 yrs)										Mid-Term (10-20 yrs)										Long-Term (20-30 yrs)									
	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Aircraft Carrier	1					1					1					1					1					1				
Large Surface Combatant	2	1	2	2	2	2	2	2	2	2	3	2	3	2	3	2	3	2	②	2	2	2	2	3	3	3	3	3	3	3
Small Surface Combatant	4	4	4	2	2	3	3	3	3	3	3	3	3	3				①		1		1	1	2	3	4	4	4	4	2
Attack Submarines	2	1	2	2	2	2	2	3	2	3	2	1	2	1	1	1	1	1	1	1	①	1	1	1	1	2	1	2	1	2
Ballistic Missile Submarines									①			1		1	1	1	1	1	1	1	1	1	1							
Amphibious Warfare Ships					1	①		1		1		②		1		2	1	1	1	2				1				2		1
Combat Logistics Force				1		1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1								
Support Vessels	1	1		2		1	1	2		2	3	2	1			1	1	2	2	3	2	2								
Total New Construction Plan	10	7	8	9	7	11	8	12	9	12	13	12	10	9	6	9	8	9	8	11	8	8	5	7	7	10	8	11	8	8

Note: Date corresponds to MSB of ship

○ = New Ship Class Insertion

Figure 2 illustrates the general path to establishing capability requirements, determining applicable mission systems, and then deriving electrical power system requirements to accomplish those capabilities.

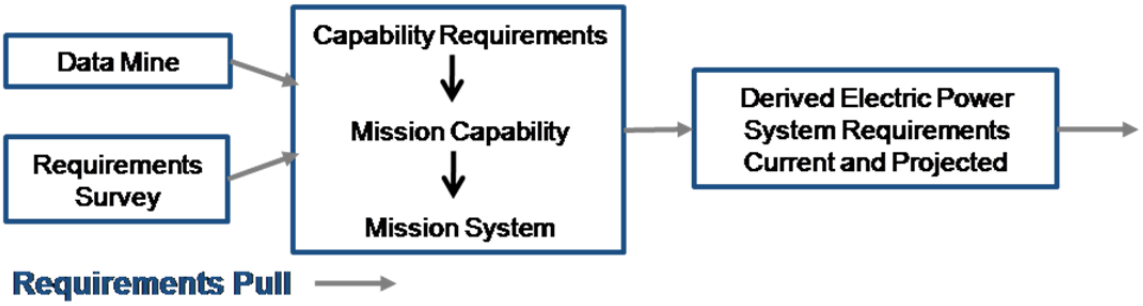

Figure 2: Capability Requirements Approach

The capability requirement groupings were evaluated for their overall impact on Naval Power Systems. Meeting average power and pulse power requirements have the greatest impact on NPS. Thus advanced sensors and advanced weapons are identified as “Primary Drivers” for NPS. Energy security is also considered a primary driver. Those capability requirement categories that require further analysis have been identified as “To Be Determined.” The remaining capability requirement groupings with lesser NPS impacts were identified as “Secondary Drivers.” Based on this process, Table 3 below shows the relationship based on the capabilities relevant to naval power systems.

Table 3: NPS Relevant Capabilities

Operational Task	Primary Drivers	Secondary Drivers	To Be Determined
Deploy/Conduct Maneuver		Advanced Propulsion	
Develop Intelligence	Advanced Sensors		Mission Modules / Interfaces Arctic Operations
Employ Firepower	Advanced Weapons	Active Protection	
Perform Logistics & Combat Service Support	Increased Energy Security	Renewable Energy Alternative Fuels	
Exercise Command & Control			Communications & Information Security
Protect the Force			Low Observability

Increased average power and pulse requirements, along with required power to all other shipboard systems, will provide new challenges in the near, mid, and far-term Naval Fleet. Next generation radar systems have large power requirements to operate continuously and effectively, as well as require pulse (ripple) power. Advanced Weapons mission systems also have increasing derived power requirements.

These escalated power and pulse requirements occur in the near-term (5-10 years) and only increase further with additional capability developments. For ships with electric propulsion, large amounts of electric power will be required to deploy and maneuver, and the need to manage and reallocate power to mission systems will increase. The fuel efficiency potential of a common electric power bus for propulsion, weapons, and ship service enabling the use of the most efficient prime mover lineup will be examined as part of the ship acquisition process. A compounding requirement is the goal to reduce fleet fuel consumption by 15% by the year 2020.[4] This is not a derived electrical requirement, but will drive and affect Naval Power Systems. The fuel reduction goal does not have a baseline year determination with specific numerical statistics and therefore will require further analysis for electrical requirements comparison. Overall, this goal creates an operating environment where additional power is required with

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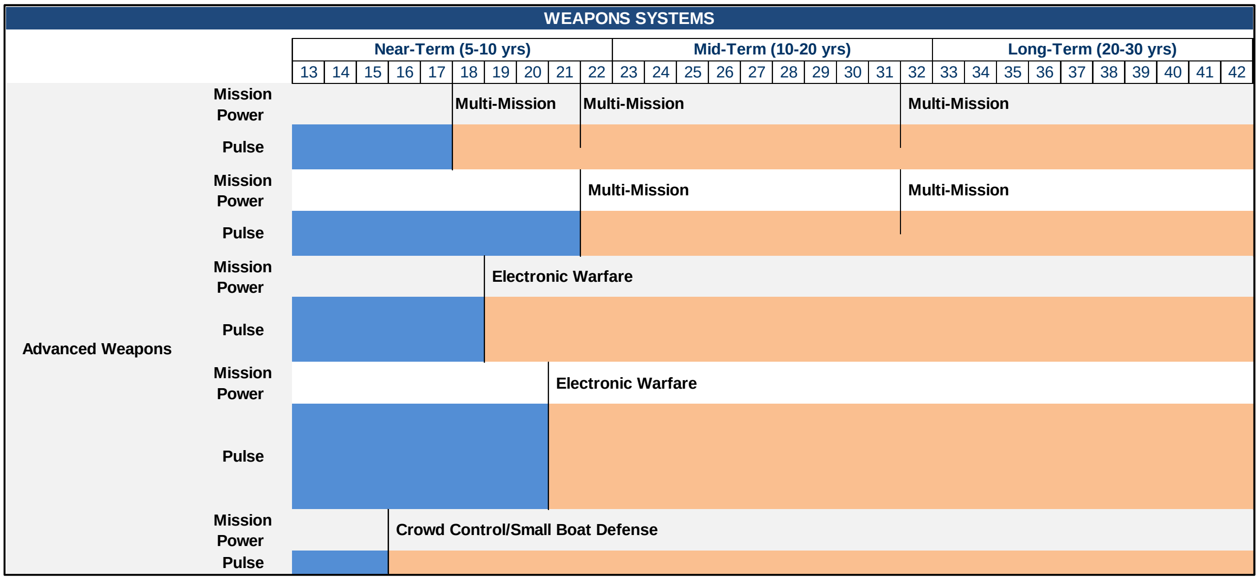
[4] United States. Department of Defense. *Operational Energy Strategy: Implementation Plan.* Assistant Secretary of Defense for Operational Energy Plans & Programs. 2012. Web.

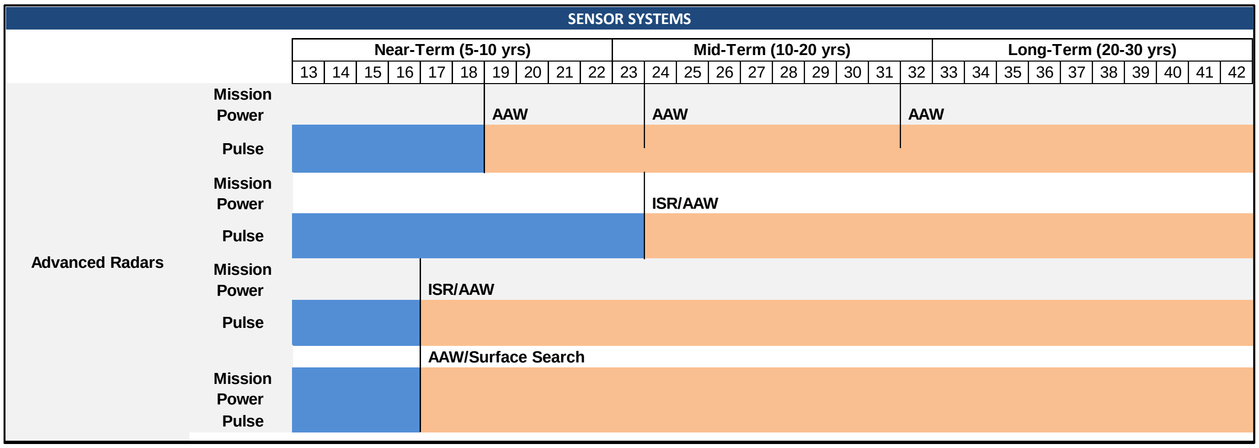
greater fuel efficiency. Therefore, the derived capability requirements for the near, mid, and long-term all require increased power production with increased operational efficiency. Table 4 shows derived electrical requirements for anticipated future advanced sensor, weapons, and energy security.

Table 4: Derived Electrical Power Requirements



WEAPONS SYSTEMS

		Near-Term (5-10 yrs)										Mid-Term (10-20 yrs)										Long-Term (20-30 yrs)									
		13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Advanced Weapons	Mission Power						Multi-Mission				Multi-Mission										Multi-Mission										
	Pulse	🟦	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Mission Power										Multi-Mission										Multi-Mission										
	Pulse	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Mission Power							Electronic Warfare																							
	Pulse	🟦	🟦	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Mission Power									Electronic Warfare																					
	Pulse	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Mission Power				Crowd Control/Small Boat Defense																										
	Pulse	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧



SENSOR SYSTEMS

		Near-Term (5-10 yrs)										Mid-Term (10-20 yrs)										Long-Term (20-30 yrs)									
		13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Advanced Radars	Mission Power							AAW					AAW								AAW										
	Pulse	🟦	🟦	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Mission Power												ISR/AAW																		
	Pulse	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Mission Power					ISR/AAW																									
	Pulse	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	Mission Power					AAW/Surface Search																									
	Pulse	🟦	🟦	🟦	🟦	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

🟦 In Development
🟧 Operational

There were also capability requirements whose mission systems must be further analyzed to determine electrical power requirements. Examples of these include the capabilities facilitated through the use of Mission Module / Interfaces (e.g. LCS Mission Modules). Mission Module / Interfaces cover a wide variety of capability requirements across multiple naval mission systems and the definitive requirements for each platform or mission system are not yet known. These systems must be individually analyzed to determine the specific capability requirement they provide and the electrical power requirements for each.

Arctic Operations is another capability requirement category that will require further analysis to determine Naval Power System impact. It may evolve into a ‘high’ impact capability requirement in the near-term. The specific requirements and associated mission systems are scheduled to be defined by the Arctic Roadmap due to be published in 2014.[5] The overall impact on Naval Power Systems of Alternative Fuels and Renewable Energy is also currently low, but due to future energy needs and global political tensions, these categories could produce capability requirements that have a significant impact on Naval Power Systems.

Communications & Information Security currently maintains many Uninterruptible Power Supply (UPS) requirements, while requiring increased bandwidth and information security. Evidence suggests that the proliferation of UPS's aboard ships is creating an undue maintenance and logistics burden for the fleet. This suggests that a uniform strategy for handling the very high quality of service requirement for computers and communications equipment may be required. Overall, this capability requirement category needs additional information for emergent power continuity and quality of service requirements.

In addition to derived electrical requirements, other requirements were identified that are consistently described in the majority of data-mining sources and utilized by almost every stakeholder and subject matter expert. These requirements, which are referred to in this NPS TDR as ubiquitous requirements, are considered universally important to the Navy and generally had varying metrics. In this NPS TDR, ubiquitous requirements are used as "measures of goodness" to determine best solution set that meets a set of derived electrical power requirements.

The NPS TDR identifies the following ubiquitous requirements:

- Improved Personnel and Ship Safety
- Reduced Operations and Sustainment Cost
- Reduced Acquisition Costs
- Reduced Manpower
- Improved Survivability, Maintainability, Reliability
- Reduced Environmental Impact
- Performance improvements above threshold
- Commonality, Modularity, Open Architecture

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[5] United States. Department of the Navy. *U.S. Navy Arctic Roadmap.* Vice Chief of Naval Operations. 2009. Web.

These ubiquitous requirements will adapt with time and will be updated in future NPS TDR iterations. The ubiquitous requirements are listed below in no particular order (Table 5).

Table 5: Ubiquitous Requirements

Ubiquitous Requirements
Improved Personnel and Ship Safety
Reduced Operations and Sustainment Costs
Reduced Acquisition Costs
Reduced Manpower
Improved survivability, maintainability, reliability, and availability
Lowered environmental impact
Performance improvements above threshold
Commonality, modularity, open architecture

III. Technology Availability, Benchmarking, and Trends

Establishing the current and projected technologies available was the responsibility of the Technology Working Group (TWG). The TWG consisted of members from various organizations throughout the Navy spanning a variety of technical areas, including the Office of Naval Research, Naval Reactors, NAVSEA 05, ASN RD&A, Directed Energy and Electric Weapons Systems program office (PMS 405), PEO Ships, PEO Carriers and NSWCCD-SSES.

The Technology Working Group (TWG) was responsible for:

- Categorizing naval power system technologies
- Determining the relevant metrics to track by category
- Baselining current metrics for each technology area
- Determining industry trends and metrics in each category for the next 30 years
- Identifying opportunities for commonality
- Identifying technology application opportunities and development timelines

Figure 3 below illustrates the general process followed by the TWG:

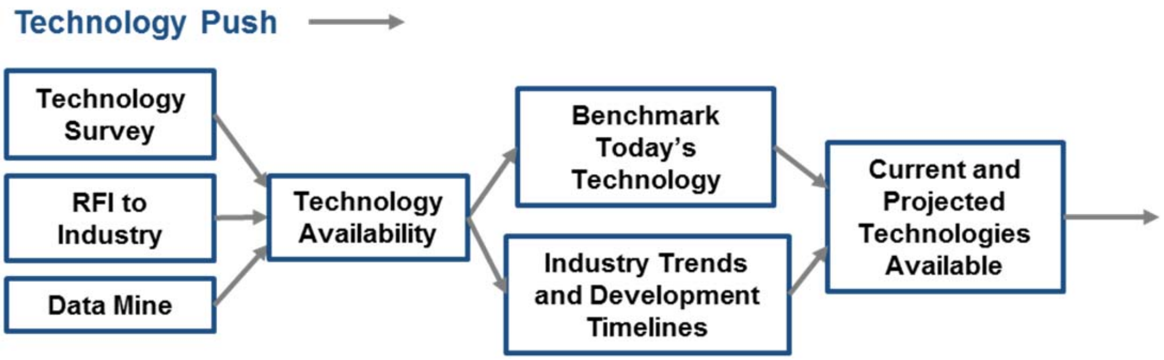

Figure 3: Technology Process

The TWG collected documents from sources that include but are not limited to the oil and gas, telecommunications, automotive, renewable energy and power industries. This data set of industrial information was reviewed and used to determine baselines and trends. This section of the TDR is focused on benchmarking the current state of the art and identifying industry trends.

It is important to note the following sections report on industry technology baselines and trends without the injection of Navy investment. This industry centric perspective was adopted to understand what developments are ongoing now and will occur in the future without Navy intervention. This viewpoint provides an understanding of the areas where industry will develop technologies that can support Navy systems and the level of investment the Navy will have to make in areas where there is a gap between what the Navy needs and what industry is developing.

Once the industry trends are identified, potential navy applications are discussed along with a brief analysis of some of the design constraints imposed on technologies for military applications. This section fundamentally seeks to address the following questions: what technologies existing in industry today can directly transition to the fleet, which technologies need modification or further development prior to transition, and which technologies will not transition? The answer to these questions requires a thorough understanding of the Navy application, the performance requirements needed for the Navy application, the operating environment and the technical specifications for the commercial device.

Where applicable, some of the key metrics to trend and benchmark each of the product areas are included. The goal of these descriptions is to highlight where industry is today and determine what the key drivers for industry will be going forward. Based on the knowledge of where industry is going, the Navy can determine how to apply those expected technological developments and begin to bridge gaps between what the Navy needs, what industry will be able to provide, and when industry will provide it.

TWG action officer technology surveys, subject matter expert interviews, and an Industry RFI were used as additional sources of information for this TDR. The TWG grouped the technologies into the following six (6) product areas that were determined to be the main building blocks of the power system.

- Controls
- Distribution
- Energy Storage
- Electrical Rotating Machines
- Power Converters
- Prime Movers

Product areas are defined as the categorization of technologies, equipment, and products by function. The products the Navy has developed or intends to develop in each product area constitute the Navy’s product line. Metrics were developed to show how each category evolves over time as well as to compare products within each category. This comprehensive set of metrics was also used to baseline each product area.

Technology trends for each product area are discussed below and were developed by investigating selected metrics determined by the TWG to have the most effect on the future of Naval Power Systems.

Controls

Industry Controls Benchmark

The traditional study of control systems is typically limited to the fields of applied mathematics that lend themselves to the stability and control of dynamic systems. However, in practice, control systems are multi-disciplinary constructions that apply methods and concepts from a wide range of engineering fields. As such, when analyzing the benchmarks for industry's control systems, one must look outside the traditional realm of control theory as it is defined in the academic sense.

At the highest level, a control system can be broken down into three main areas. These areas are not mutually exclusive; however, they serve to allow one to decompose a particular control system implementation and to compare it to other designs. They also allow for decomposition of the technology development problem one is faced with when attempting to characterize the types of research investments that are required to advance our capability to perform the control function. The three areas are architectures, algorithms, and communications.

Architectures refer to several aspects of the control system. In centralized control architectures, all the control decisions are made at a centralized location and communicated to the actuators. In centralized control architectures, all information upon which control decisions are based is processed at a single location. Distributed control architectures distribute system intelligence from the enterprise or plant level down to individual systems and components, enabling encapsulation of the consequences of failures. Other control architectures of interest include hierarchical, heterarchical, and hybrid structures.

Algorithms refer to the policies by which control decisions are made. At the lowest level, feedback control algorithms such as proportional, integral, derivative (PID) or full state feedback methods are used to stabilize and control individual elements in the system. For example, a PID controller may be used to control the speed of a motor or the behavior of a power converter. Monitoring algorithms refer to the ways in which data, typically from sensors, are utilized and turned into information. Human system interface (HSI) algorithms refer to ways in which data is manipulated to make it appropriate for human interface with the control system, as well as methods which enable the human and the autonomy in the control system to interact and provide inputs to the system in a synergistic manner. Optimization algorithms are a class of algorithms which are used to determine the most appropriate allocation of system resources.

Communications refers to the host of technologies that are employed to transfer data and information across the control system. This includes field bus technologies that allow for communications at the lowest level of the control system, communication protocols which standardize communications and allow for the development of interfaces, and networked control system communication methods such as agent communication languages.

Benchmarks for control systems require further definition and quantification because they aren't standardized across industries; measures tend to be application and industry specific. General areas of interest for this TDR fall into the three control system main areas and are generically outlined below:

Algorithms

- Decision/response time
- Quality of response
- Usability (operator training requirements, operator intervention required)
  - Appropriate autonomy
  - Intuitive, user optimized human machine interface (HMI)
- Stability

Architectures

- Location of control intelligence (local, central, distributed)
- Degree of openness

Communications

- Expressiveness (communicate correct info)
- Succinctness (ability to communicate quickly enough)
- Bandwidth and efficiency (throughput)
- Interfaces and protocols
- Security (Information Assurance, Anti-tamper, Cyber security)

Key Industry Control Trends

The following industries drive controls technology improvements:

- Automotive (production, vehicle maintenance and control)
- Aviation
- Computing
- Oil and gas
- Smart grid, renewables, utility interface
- Telecommunications
- Process control industries

Control algorithms will trend toward optimization solutions for determining which power sources and distribution paths shall be utilized given available power resources, distribution paths, and demand signals from numerous sources including weapons systems. This optimization will require more computing speed or mathematical techniques to rapidly solve complex equations, enabling real time or near real time control. Advances in hardware speed and capability will enable faster and better quality responses by control algorithms, architectures, and communications. Resilient control including cyber security algorithms will provide defense in depth to casualty situations, errant sensors, and cyber attacks, allowing the control system to continue to function. These control techniques will be completely autonomous.

How Industry Controls Trends Apply to Naval Power Systems

Power system nodes and the associated input/output signals and control functions will continue to increase to support future power system architectures. These architectures, resulting from a technology pull created by high power sensor and weapons technologies, drive more autonomy into power system management, a major function of the machinery control system. Autonomic control will be a requirement of the power management system as the complexity of control decisions is increased to optimize electric plant configurations for a mission or scenario. Power management systems will autonomously determine and actuate electric power systems such that: the optimal amount of power is available for mission and user systems, power is controlled in a resilient and robust way, computation and communication occurs rapidly enough to maintain power during steady state and transient operation, and systems are capable of physical plant recognition for optimal reconfiguration during casualty events. Power system management must also be cost effective and enable energy efficient operation, system and device prognostics, and real time situational awareness for the operator. Lastly, the system will be subject to certification, such that it meets the Technical Warrant Holder’s standards as a mission critical system.

The Navy will rely primarily on commercially developed technology for computing hardware platforms, displays, networking technology, sensor technologies, and other associated controls hardware. Computer hardware platforms will likely be based upon digital control system or programmable logic controller (PLC) technology. Systems will be open architecture and ensure commonality across systems and platforms to reduce cost. Advancements in control architectures, algorithms, and communications implemented in the power management software will be key areas of research and development to supplement advancements in smart grid/micro-grid control. Centralized control architectures are very common for small systems and on legacy navy machinery control systems, but for larger distributed systems problems such as robustness and communication complexity lead designers to look for other options.

Communications technology will likely leverage commercial technology advancements. In addition, connectivity with mission systems or combat systems will increase, driving authentication of data transmitted between systems. This may require development of techniques that authenticate in very near real time.

Generally, it is anticipated that future Naval Power Systems will be increasingly complex and require increasing levels of autonomy. The Navy is in process of defining the minimally acceptable requirements for the benchmark areas of architectures, algorithms, and communications. Navy control systems should be compatible with evolving open architecture objectives.

Distribution

In power systems, the distribution equipment exists to transmit power, to configure a power system via connecting/disconnecting equipment and to provide protection of the connected equipment from electrical faults. The distribution technologies include, but are not limited to, circuit breakers, fuses, protective relays, switchboards and cables. While low voltage power distribution equipment will still exist within naval power systems, this discussion on distribution is focused on medium voltage 1-13.8KVAC or 1-20kVDC equipment to support emerging higher power needs (discussed in sections IV and VI).

Industry Distribution Benchmark

Circuit Isolation and Fault Interruption

In medium voltage applications vacuum breakers have replaced air, SF6 and oil technologies[6,7]. Typically medium voltage breakers do not incorporate any protection features and protection is performed entirely by external protective relays. Vacuum circuit breakers (VCBs), fused vacuum contactors, and fused disconnects dominate the medium voltage AC circuit isolation and fault interruption market.[8] Presently, ANSI or IEC certified VCBs provide superior control and protection of medium voltage power equipment. Typical VCBs handle continuous and fault currents of approximately 3-4kA and 40-60kA respectively. VCBs are applicable to medium voltages in range of 1-35kVAC.

Industry use of medium voltage medium frequency distribution is not common, but VCBs appear applicable with appropriate deratings. VCBs used in AC systems are not directly applicable to DC systems as VCBs rely on the zero crossing of the alternating current waveform. DC fault isolation is typically accomplished using large air circuit breakers or employing a power converter in combination with upstream AC circuit breaker. IEC standards for DC air circuit breakers are generally applicable up to 3000VDC, but breakers are available up to 3600VDC at 4000A with interrupting ratings of 100kA for locomotive and industrial applications.[9]

Protection and Control Logic

The relay functions include metering, protection, automation, control, digital fault recording, reporting and HMI. Multi-function relays use sensors and logic for control and are easily tailored, comprehensive and dependable. The fastest algorithms that have no intentional delay (i.e. differential or instantaneous overcurrent) respond to faults in about one electrical cycle or approximately 16 msecs. Arc fault protection systems can detect the visible light emissions from arcing faults in several milliseconds. When

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[6] http://www.csanyigroup.com/comparison-between-vacuum-and-sf6-circuit-breaker

[7] Eaton White Paper WP083001EN *"Replacement of hydro plant generator oil circuit breakers with modern vacuum technology."* September 2012.

[8] http://electrical-engineering-portal.com/circuit-breakers-classified-by-interrupting-medium

[9] http://www.secheron.com/uk/products-services/gamm4-dc-circuit-breakers.html

combined together, the circuit protection and relay total response time (fault initiation to isolation) are typically in the sub second range, with fastest responses in approximately 100 msecs. On-line partial discharge systems are available for electrical insulation systems for fault risk analysis and condition based maintenance.

Switchboards

The protection relays and breakers are integrated into switchboards that are typically naturally or forced air cooled. ANSI standards define metal enclosed and metal clad construction for switchboard enclosures. These are large enclosures and tailored based on various driving requirements including: enclosure tightness (NEMA or IEC ingress protection), degree of electrical isolation and compartmentalization (metal clad vs. enclosed construction), and arc fault resistance. Typically, up to two breakers can be stacked within a single vertical section unit when the continuous currents are below 1-2kA per breaker. Above this level only a single breaker can be installed per vertical section based on thermal limitations.

DC switchgear is typically available up to about 3000-4000VDC. IEC series specifies requirements for DC switchgear and control gear and is intended to be used in fixed electrical installations with nominal voltage not exceeding 3000VDC. The breakers cannot be vertically stacked as significant vertical space is necessary for arc chutes.

Cables and busways

There are a variety of cable and busway technologies, including: cabling, bus-duct and bus-pipe. Cabling is the most widely used technology because of its low cost, flexibility, and field adaptability by installation electricians. Most medium voltage cable insulations use XLPE (cross-linked polyethylene), TR-XLPE (Tree-Retardant XLPE) or EPR (ethylene propylene rubber). Overall, the lifespan of existing cable (aluminum or copper) technology is quite good so long as it is installed per its design specifications. Cables in service in most industrial applications have shown lifespans of 30-40 years.[10]

Where higher power density, modular installation capability, higher mechanical/ environmental protection, or tight bend radius is required then bus-duct or insulated bus-pipe (IBP) may be selected. Bus-duct and IBP use rigid conductors. Bus-duct typically uses a combination of air and insulation to provide medium voltage rating. IBP uses solid insulation materials and can be encased in a stainless steel pipe. These technologies are installed in sections and bolted together.

Copper and aluminum are the industry standards for conductors and which one is used depends on the application. Where weight is an issue, aluminum provides a better solution because it is lighter than copper, however when more power density is needed, the higher conductivity (and thus smaller size) of a copper cable is selected.

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[10] http://www.windpowerengineering.com/design/electrical/cables/2012-trends-in-cables/

Industry Distribution Trends

In addition to cost and efficiency, developments in power distribution are driven by the following:

1. Safety - Recent recognition of the dangers of arc faults based on updates to NFPA 70E and IEEE 1584 have led to the increased use of fault current limiters, multifunction relays, arc fault detectors, remote racking systems, and arc resistant switchboards.
2. Reliability - Reducing the scope and frequency of outages is a key driver for electrical distribution systems. The Primary trends that enable this goal are:
    a. System Networking – connecting distribution systems together to provide greater power handling and redundancy
    b. Additional isolation - divides the distribution system into smaller sections and reduces the interrupted area
3. Distributed Generation - The introduction of power from wind, solar, energy storage and co-generation of power from factories requires that the grid accommodate distributed generation sources. Renewable power systems such as solar and wind are increasingly utilizing DC distribution.

Circuit Isolation and Fault Interruption

For AC systems the circuit isolation and fault interruption trends appear to be evolutionary improvements in size and reliability of VCBs. Developments will continue in fault current limiters, including solid-state and high temperature superconducting. The fault current limiters support the introduction of distributed generation and increased system networking without experiencing fault currents problems. There is little effort on technologies specific to medium voltage medium frequency. DC air circuit breakers will continue evolutionary developments. Additional DC solutions are being investigated and developed for medium voltage DC circuit isolation include:

- Building protection concepts into power conversion
- Solid state and Hybrid circuit protection
- Other advanced DC breakers technologies [11,12]

Protection Logic

The networking of systems, increased number of isolation points, and increased use of distributed generation have driven the need for more comprehensive and complex protective relaying. Protective digital relays continue to incorporate more and newer functions within a single relaying unit at reasonable cost. Increased communication between relays enables a system view for better overall coordination response. Multiple

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[11] Yinger, R.J.; Venkata, S.S.; Centeno, V.A.; , "Southern California Edison's Advanced Distribution Protection Demonstrations," *Smart Grid, IEEE Transactions on* , vol.3, no.2, pp.1012-1019, June 2012

[12] Yang, J.; , "Protection issue discussion of DC network development: Circuit breaker or fault-tolerant converter," *Developments in Power Systems Protection, 2012. DPSP 2012. 11th International Conference on* , vol., no., pp.1-6, 23-26 April 2012

settings groups allow protective responses to be tailored based on system operating configurations. The adoption of advanced communication and adaptable settings leads to greater automated operation and service restoration increasing safety and power reliability.[13] Additionally, these multifunction digital protective relays are being adopted into lower power and voltage systems, further increasing reliability, safety and control granularity.

Cables

The wind power industry utilizes cables in environmental conditions that can expose them to temperatures as low as -40 degrees C leading to insulation break down. The wind power industry also uses low smoke cables and places a strong emphasis on cable flexibility due to tight confines in the nacelle.[14] HTS cables are being installed throughout the world as a means to efficiently address increased power demands. HTS cables have negligible resistance and therefore can increase overall system efficiency by reducing the cable losses and provide up to 9x increase in current density.[15] Recent technical investments have focused on reducing the size of terminations and improving cooling systems. Carbon nanotubes present promising conductor technology with up to 5 times the conductivity of copper at room temperatures. Nanostructure carbon (Covetics) and carbon nanotubes can be incorporated with metals such as copper and aluminum to significantly increase the conductivity.[16,17]

Industry Distribution Trends Relation to Naval Power Systems

The Navy has 4160VAC air circuit breakers (ACBs) and 13.8kVAC VCBs and the associated protection relays and switchboards. In the near-term, the Navy will continue to adopt commercial VCBs and protection relays with minimal modifications. Navy derating of circuit breaker ampacity is typical based on navy's operating environment and testing requirements. Circuit ampacities should be kept below approximately 3000-4000A to leverage commercial devices. In some applications the associated switchboards will be similar to commercial marine where space permits. However, many planned ships will not be able to accommodate the physical size of typical commercial marine switchboards. The Navy will need to develop militarized switchboards accommodating state-of-the-art commercial VCBs and protection relays. These switchboards will need to address the naval operating environment for shock, vibration, EMI, high ambient temperatures, confined maintenance space, and water-mist fire suppression systems. The physical size must be similar to Navy's present ACB based 4160VAC switchboards and incorporate newer safety capabilities where possible (i.e. closed door test position, grounding methods, continuous thermal monitoring, arc

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[13] Jecu, C.; Raison, B.; Caire, R.; Chilard, O.; Grenard, S.; Deschamps, P.; Alibert, P.; , "MV distribution protection schemes to reduce customers and DGs interruptions," *PowerTech, 2011 IEEE Trondheim* , vol., no., pp.1-7, 19-23 June 2011

[14] "Cables in Renewable Energy Systems: A New Market or More of the Same?" ICF News July 2008.

[15] Hirose, Masayuki et al. "Study on Commercialization of a Superconductor". SEI Technical Review No. 62, June 2006.

[16] http://www.helixmaterial.com/Ordering.html

[17] "Global Nanomaterials Opportunity and Emerging Trends". Lucintel Brief, March 2011.

fault detection, arc resistance, etc.). The physical size limitations may drive ampacity rating limits to approximately 1200-2000A to ensure two circuit interrupting devices can be stacked vertically using natural convection cooling. Forced air cooling or other cooling methods will likely be required to extend current handling above these levels for stacked breakers.

Navy medium voltage cabling/bus systems must pass gas-flame circuit integrity and watertightness testing. For many Naval applications cabling is a mature, relatively low risk component with specifications and characteristics defined by MIL-DTL 24643, MIL-DTL 24640, MIL-DTL 915 and characterized in MIL-HDBK 299. The Navy uses copper conductors and silicon glass insulation (up to 4160VAC) for its cables. As voltages increase above 4160VAC the silicon glass insulation system is no longer applicable and the Navy has opted to use ethylene propylene rubber.

The Navy will need to invest in distribution equipment that enables advanced power systems to clear faults faster and eliminate power interruptions to high power loads with high Quality of Service (QoS) requirements. The power density at the power levels required for future Navy applications and the shock and vibration requirements will drive the Navy to develop its own switchboards. In medium voltage DC applications the Navy will likely also need to develop the circuit interruption and protection relay systems that are power dense, address combat faults, and can respond in milliseconds (approximately 1-10). The power density and speed of this protection equipment does not appear to be met by current industry trends. Industry MVDC circuit protection and possibly fault current limiter technology developments may be relevant to this Navy effort.

These future Naval power systems will require medium voltage, high current capacity, tight bend radius and low volume cabling/bus systems. There are a number of options that should be monitored or developed by the Navy. While it has not passed Navy testing to date, IBP may prove advantageous[18] to meet these requirements. IBP would introduce new integration challenges. Long IBP runs, connections between IBP sections, and interfaces through watertight boundaries present challenges associated with hull flexure, survivability, electrical continuity, and electromagnetic considerations. Carbon Nano-tubes, metals infused with carbon nano-tubes and Covetics should provide significant improvements, but presently these technologies are immature and are heavily focused on material science.

While the Navy can leverage technology developments used in commercial HTS power systems, these commercial HTS systems focus on liquid nitrogen cooling at 77K, which is prohibitive in most Navy applications due to boil-off and expansion in emergency conditions.

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[18] http://www.nsrp.org/6-Presentations/Joint/100411_Ship_Installation_of_Insulated_Bus_Pipe_Burley.pdf

Energy Storage

An energy storage system generally includes the energy storage media and any power conversion components for interfacing with the electrical power system/load. The energy storage media is the actual repository of stored energy. Media of interest include batteries, capacitors, and flywheels. This section focuses on rechargeable energy storage media (with associated monitoring/management controls).

Industry Energy Storage Benchmark

Today, Industry uses energy storage for many functions including:

- Generation/distribution management
    - Load leveling (store energy during off-peak hours when generation cost is low and use it when cost is high during high electrical demand)
    - Bridging power (maintain power levels during lulls in renewable sources, e.g. wind changes)
    - Peak demand service (augment generation source for short duration)
    - Reactive power compensation
- Load management
    - Uninterruptible Power Supply (UPS) – (e.g. data centers, telecommunications)
    - Filtering to reduce harmonic distortion
    - Buffer between grid and uniquely demanding manufacturing loads (e.g. arc furnace)
    - Propulsion power (Hybrid and all electric vehicles)
- Consumer electronics

The applications described above have different energy and power requirements as well as different operating profiles. Three fundamental parameters of interest when describing and comparing energy storage media are capacity, rate, and cycle.

- Energy capacity is the total amount of energy that can be stored, measured in Joules (J), or equivalently as power for a duration of time, such as Watt-hour (1 Wh = 3.6 kJ).
- Power or energy transfer rate (energy per time) represents how fast that energy can be transferred to/from the energy storage media. This is measured in Joules/second (J/s) = Watts (W). Energy transfer to/from the media occurs at the charge/discharge rate. These rates are governed based on chemical/mechanical/thermal limitations and design.
- Cycle is the reversible process of charging the media (charge rate) and discharging it (at the discharge rate). Conceptually, the number of times an energy storage media can be charged and discharged represents its cycle life. Cycle life varies by the relative amount of energy discharged (shallow or deep),

the amount of recharge (full or partial), the energy transfer rate (fast discharge, trickle charge, etc.), and age.

The different applications described above have various energy and power requirements as associated with their diverse operating profiles (i.e. capacity and rate). Support of these applications is provided by different types of energy storage media, based upon their energy and power capabilities. Figure 4 is a general representation of the relative capabilities of various energy storage media in a graph of energy density vs. power density commonly called a Ragone plot.[19] Note that the graph is logarithmic and that technologies can have orders of magnitude differences in capabilities. In general, batteries have the highest energy density and lowest power density. Thus, while batteries are optimum for applications which require sustained operation (i.e. lots of energy), that energy cannot be transferred as quickly as it can with capacitors and flywheels. It is important to note that energy storage technologies can be biased for high power or sustained energy. This is why it is critical to analyze technologies with respect to energy versus power content. Only then can a determination be made as to which technology is best suited to address a particular need.

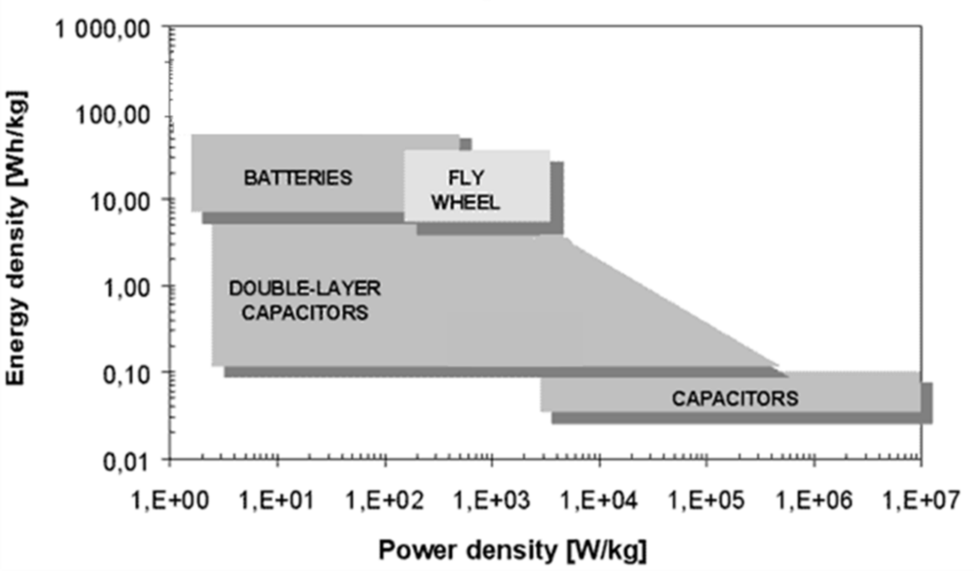

Figure 4: Comparison of energy storage media energy and power densities[20]

Batteries

Batteries are devices that produce electricity from a chemical reaction. The fundamental chemistry, the cellular configuration, and the overall design of the battery affect its characteristics. A battery management system is required to maintain state of charge and state of health, balance cells, prevent overcharging, and predict maintenance and repair actions. Today, the lead acid chemistry based battery is the most widely used and commercially accepted energy storage media. It is robust, tried,

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[19] Named after David Ragone of Carnegie Mellon University.

[20] http://www.mpoweruk.com/alternatives.htm

tested, affordable and rechargeable. Large stationary systems predominantly use flooded lead acid systems that are maintenance intensive. Recently, valve-regulated lead acid (VRLA) batteries have offered an alternative to flooded lead acids. Their slightly higher cost is offset because they need no maintenance except for periodic testing to see if they have held charge. Lead acid batteries have the following characteristics:

- Acceptable energy density for many applications
- Marginal loss of charge
- Limited cycle life
- Limited life (typically 3 to 5 years)

Recent increased power and energy demands for small consumer electronics, portable tools, and hybrid/electric vehicles have driven the demand for advances in battery chemistries. Two competing battery chemistries are Nickel Metal Hydride (NiMH) and Lithium. The Nickel Metal Hydride battery dominated the early hybrid electric vehicle market. It has better power density and better energy density than the lead acid battery. Most recently, Lithium based chemistries have shown great promise in applications where high energy density and good power density are required. Relative energy densities (gravimetric and volumetric) for some battery chemistries are shown in Figure 5.

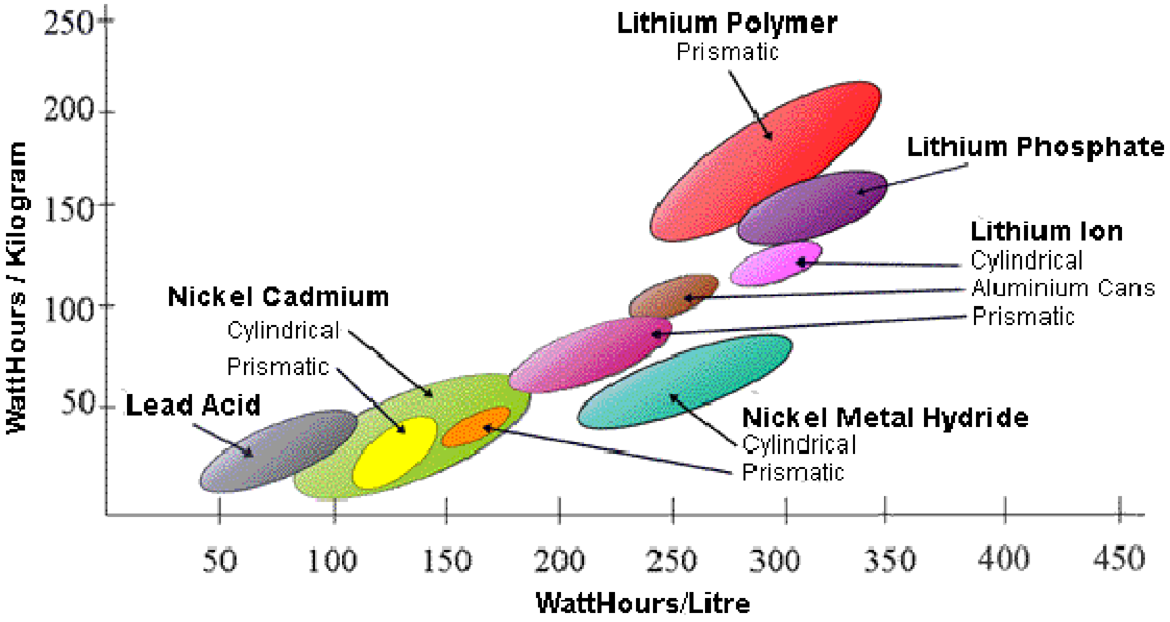

Figure 5: Energy densities of various battery chemistries and configurations[21]

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[21] http://www.mpoweruk.com/chemistries.htm

Some other considerations that may influence a decision to use a battery are listed below.

Battery advantages:

- Suitable for applications that require the supply of relatively large amounts of energy storage (greater than 1 MWh) over long periods of time (15 minutes or more), where rapid recharge is not necessary and where maintenance can be reasonably performed.
- Convenient voltage characteristics (limited voltage delta vs. state of charge)
- Convenient, modular sizing
- Low self discharge rate
- Extensive design history

Battery disadvantages:

- Potentially not suitable for environmentally sensitive sites, remote locations, or applications that require rapid discharge and absorption of energy.
- Recharge rate is typically an order of magnitude lower than discharge rate
- Some batteries off-gas during the reversible chemical reaction, releasing products (such as hydrogen) that may require ventilation or other associated auxiliary systems.
- Safety concerns dependent on the particular chemistry. For example, lithium batteries can experience propagating cell failures (thermal runaway).
- Capacity loss (sometimes referred to as memory effect) of certain battery chemistries (i.e. repeated shallow discharges can cause reduction in available power / energy).

Capacitors

Capacitors are devices which store energy in an electric field. Capacitive energy storage has been used predominantly in the role of power filtering and reactive power compensation. The typical energy density of standard capacitors has made them of little use for storage of any substantial quantities of energy. Ultracapacitors use either a high surface area carbon or an asymmetric electrode scheme which combines a battery electrode into the capacitor. They offer higher energy density with similar retained power capability.

Capacitor advantages:

- High cycle life
- Typically low series resistance
- High charge (and discharge) rates
- Can be “floated” without substantial concern of damage or significant electronics and controls

Capacitor disadvantages:

- Certain capacitor materials (electrolytes, certain dielectric materials, etc.) introduce safety and isolation complexities
- Near-instantaneous discharge capability and high voltage capability of individual components present challenges for safely configuring within dense, serviceable packages

Flywheels

Flywheels store energy in a rotating mass (rotor). The amount of stored energy is dependent on the mass, form, and rotational speed of the rotor. An accelerating torque causes a flywheel to speed up while storing energy, a decelerating torque causes a flywheel to slow down while providing energy. A flywheel requires a motor generator to convert between mechanical and electrical energy. The electrical power that can be transferred is typically limited by the motor generator characteristics. Critical to the design of flywheels is the capability to support bearing, torsional and potentially gyroscopic loads and forces with extremely low friction to keep losses low.

Flywheel advantages:

- Potentially high efficiency of cyclic operation
- High cycle life
- No reactive chemicals or gassing characteristics
- Charge and discharge rates have parity, determined by motor generator torque No safety risks when motionless

Flywheel disadvantages:

- Complex designs for support, cooling, vacuum, and protection
- Safety containment, particularly for metallic flywheels operating at high rotational speeds

Industry Energy Storage Trends

Industry trends are toward improved energy and power density across the board. On Ragone plots, that means movement up and to the right for the various technologies.

Battery trends include:

- Improved safety, especially of lithium based batteries
- Improved service life and total ownership cost (shelf life, cycle life, temperature performance/degradation, etc.) including VRLA, Li-ion, etc.
- Increased recharge rate capabilities with sustained cycles
- Advanced thermal management (battery system cooling for both cells/batteries and casing)
- Sophisticated battery management systems

Capacitor trends include:

- Improved service life (ideally 30-40 years)
- Reduced self-discharge (increased fully charged endurance time)
- Improved energy density while maintaining high rates of charge/discharge
- Improved Safety
- Large scale applications for higher voltage arrays
- Cooling where applicable

Flywheel trends include:

- Improved service-life
- High-rate with high efficiency designs, including recharge
- Safety containment
- Self-destructing mechanism for protection

Industry Energy Storage Trends Relation to Naval Power Systems

Naval power system energy storage needs include pulse power support for advanced weapons and sensors, load leveling, emergency power, and generator transient support and fuel savings initiatives. Emerging pulse power loads vary from fractional second/very high power (radars) to a few seconds/medium power (lasers) to a few seconds/high power (aircraft launch). Combining energy storage with the ship's power system instead of individual energy storage for every need is desired to reduce overall energy storage footprint. A multifunctional capability which capitalizes upon the operational characteristics of individual devices to form a system is desired. Such a system could offer different ramp rates, multiple-transient take-up capability, and serve a combination of short and long-term loads. Integrated energy storage will require coordination between devices with different timescales and response characteristics.

Navy specific technology needs include:

- Shock hardening of energy storage media
- High temperature stability for ship application
- Low temperature performance for airframe and undersea/other applications

- Navy-standard battery management system
- Improved safety: damaged battery containment, prevention of thermal runaway (Lithium batteries), and firefighting techniques for all battery chemistries
- Increased cycle and service life
- Decreased total ownership cost
- Integrated cooling to maximize power density
- Horizontally mounted flywheels
- Reduced volume of the energy storage system (including media and conversion)

It should be noted that this TDR addresses naval power systems, but does not address all Navy power needs. For example, offboard vehicle energy storage and man portable batteries are of interest to the Navy but are not yet drivers for the ship's electrical power system. As offboard vehicle technology advances and Navy use of these vehicles increases, it is anticipated that vehicle power needs will become important for the ship's electrical power system.

Electrical Rotating Machines

Electrical rotating machines (ERMs) are prevalent throughout all segments of industry worldwide as both motors and generators. Types of machines of interest for this TDR include asynchronous AC induction, wound field AC synchronous, and permanent magnet (PM) AC synchronous (many other machine types are in use today but these are the predominant types considered in this TDR). Machine ratings vary from fractional kW for small motors to hundreds of MW for utility power generators.

Industry Electrical Rotating Machine Benchmarks

ERMs are typically classified by size and for this TDR, will be discussed in two categories - standard and large machines. Standard machines have a well-established market demand, come in standard frame sizes, are built to industry or military specifications, are typically purchased without customization, and therefore can be considered commodities. The vast majority of standard motors are air cooled AC induction motors and most standard generators are wound field AC synchronous.

Large machines tend to be custom designs ranging from hundreds of kW to tens of MW for motors and 100s of kW to 100s of MW for generators. In general, they are ordered in small quantities for specific applications and cannot be purchased “off the shelf.”

Large Motors

Large motor use in industry is typically for pumping fluids, such as water, oil or natural gas, or for process manufacturing in paper, steel and mining industries. The induction motors range in power up to tens of MW and are used over a wide speed range from 1-200 RPM for direct drive rolling mills and low speed pumps with some high speed machines in compressor applications running at up to ~6000 rpm or higher. Wound field synchronous motors are often used in the low speed range as well, depending upon the customer’s specific requirements. Some PM synchronous machines are seeing increasing use, especially at the higher RPM ranges. Air cooling (or totally enclosed water to air cooled, TEWAC) is normally used for all large motors to minimize cost since space is not a major design driver for land applications. Minimal cost and high reliability with existing or established technologies are the primary design drivers for large industrial motors.

Commercial ships have primarily used wound field synchronous motors up to 20 MW per motor for ship propulsion, although in recent years, squirrel cage induction machines are starting to appear at the higher power levels, as are PM machines in the lower power levels. These large motors are typically slow speed (< 200 rpm) and are TEWAC machines. Minimal cost and excellent reliability with established technologies are also the key design drivers for ship propulsion motors. The cruise ship industry was one of the early adopters of electric propulsion with most cruise ships today featuring that propulsion type. Electric podded propulsion first appeared in about 1991 with the first cruise ship fitted with pods in about 1998. The shift towards podded propulsors has been driven by a number of factors including hydrodynamic efficiency, increased maneuverability, a shift to all electric machinery plants, reduced ship construction time and cost, and an increasing focus on ship volume dedicated to non-machinery spaces. Most of the drive towards podded propulsors in the cruise industry is directly or indirectly tied to economics. Increased hydrodynamic efficiency is directly correlated to fuel consumption, azimuthing pods and bow thrusters allow ships to enter ports unassisted by tugs, and increased ship volume afforded by moving propulsion motors outside the envelope of the ship have allowed more space aboard ship for other uses.

Large Generators

The largest generators employed in industry today are those in the electric utility industry. Electric utilities use 3000 or 3600 rpm wound field synchronous generators to produce high voltage at 50 or 60 Hz in the tens to hundreds of MW ratings. Direct cooling of generator armature windings, which improves power density, is the norm for these very large, turbine driven generators. Cooling is normally accomplished with deionized water or hydrogen for stator windings and hydrogen for rotor windings. Medium speed diesel generators (500-1800 rpm) in the hundreds of kW to ten MW range also use wound field synchronous machines; they are often used as emergency or local standby power sources for utilities, industrial facilities, hospitals, and other users demanding high reliability.

The offshore and on shore oil/gas industry, commercial ships, and process industries (paper, steel, mining, refining) use medium to high speed wound field synchronous generators in the hundreds of kilowatts to tens of megawatts range for localized power generation. Capital cost and reliability/maintainability are the primary metrics with efficiency and power density also being important in continuous use mobile applications such as ship or off shore power generation. These generators are typically based on a TEWAC style design.

The wind power industry is a relatively recent large user of many thousands of medium to very low speed generators in the 15 to 1800 rpm range, at 1 to 8 MW, with the majority of units in the 1 to 3 MW size. Most wind turbines are gear-driven, high-speed generators, although low speed direct drive units have been built and tested in some locations. The torque level of these direct drive units is very similar to that of direct-drive ship propulsion motors. Size, weight and reliability are the driving metrics of interest. Weight minimization in the nacelle at the top of the wind tower is a driving design requirement which is fostering commercial investment into both permanent magnet and superconducting technologies. This industry is in the midst of a paradigm shift from mostly doubly-fed induction generators to synchronous machines as a result of technology improvements and regulatory changes.

Industry Rotating Electrical Machine Trends

No trends were identified specifically for standard machines, aside from increasing emphasis on efficiency as energy costs continue to rise. Industry trends for the large/custom machine sector involve improvements in basic machine construction or materials that improve overall efficiency or power density. Industry is focusing their development efforts on the following areas:

- Magnetic material flux carrying or flux generation capacity increase and loss reduction (Increase torque/power density, efficiency)
- Electrical insulation materials and insulation systems dielectric strength, mechanical strength, thermal conductivity and reduced sensitivity to temperature, (increase torque/power density, rated operating temperature, reliability/life, cost)
- Structural materials and concepts that accept higher torsional and electromagnetically induced stress. (Increased torque/power density, increase reliability)
- More innovative and aggressive cooling to allow increased current loading and loss removal. (Increased power/torque density, reduce maximum temperature/increase life)
- Electrical conductor current carrying capacity increase and loss reduction (increased torque/power density and efficiency)

While all these improvements are not necessarily in progress today, ongoing basic research may provide evolutionary changes that apply to large/custom and standard machines. Some specific mechanical and electromagnetic trends applicable to custom ERMs for Navy applications are listed below:

- Embedded sensing for improved reliability
- Actively controlled magnetic bearing designs for high speed applications
- Refined stator/rotor windings for lower slot harmonics at high speed
- Low form-factor designs for reduced active mass and cost
- Active harmonics control (by injecting controlled distorted excitation)
- Accurate 3-D modeling of machines for static dynamic and transients behaviors
- Use of Vanadium Cobalt Iron bistable magnets in machine design
- Amorphous Core Materials (Use of amorphous and low Iron loss high saturation flux density core materials)
- Advances in magnetic coupling technologies
- Refined stator/rotor design for reduced harmonics

Industry Electrical Rotating Machine Trends Relation to Naval Power Systems

Navy platforms have hundreds of standard militarized motors (commodities), a few generators, and perhaps large custom motors for propulsion. Navy machine designs are constrained by naval architecture and unique Navy performance considerations which levy increased torque/power density and other requirements on vendors. The challenge for machine development will be to maintain or improve efficiency while increasing power density and meeting Navy performance.

Standard motors aboard Navy ships are in the few kW to a few hundred kW range and dominated by AC induction motors, closely mirroring industry. General improvements that increase efficiency and/or reduce cost are expected to continue for standard motors. Given their commodity nature, the Navy will benefit from these industrial improvements by purchasing new machines as needed.

Navy motors larger than a few hundred KW tend to require custom design for application (e.g. propulsion motors for hybrid electric or electric drive ships). The Navy has been investigating warship application of pods for many years but power density and military features (i.e. shock and signatures) have not yielded viable results. Some recent motors developed specifically for navy applications include:

- Advanced induction propulsion motor ~ 20 MW (DDG 1000, UK Type 45 Destroyer)
- Ruggedized commercial off the shelf (COTS) induction propulsion motor ~ 4MW (in service on LHD 8)
- MIL spec PM propulsion motors for hybrid electric drive ~ 1.5MW (prototype)
- Synchronous PM motor ~ 36 MW (prototype)
- High temperature superconducting (HTS) ~ 36 MW (prototype)
- COTS wound field synchronous propulsion motor ~ 20 MW (T-AKE 1, MLP)

Navy generators tend to fall into the range of hundreds of kW for emergency generators, a few MW for most ship power generation, and tens of MW for ships with very high electrical demands such as IPS ships and recent CVNs. As with motors, power density improvements are desirable; these may be achieved by higher rotational speeds and use of newer technologies including thermal management improvements.

For all navy rotating machines, the ship implementation challenges described in Section IV of this document are germane. The Navy will increasingly demand advances not necessarily in alignment with commercial applications. Anticipated future Navy needs not aligned with industry include:

- Reduced acoustic signature for increased stealth and mine warfare concerns
- Use of generators with higher rotational speeds for higher power density
- Affordable high temperature superconducting conductors and associated cryogenics for higher power density and increased performance
- Use of advanced cooling techniques
- High energy product PM materials for higher power density

Power Converters

Power conversion equipment changes voltage and/or frequency to a different voltage and/or frequency. In power systems, power conversion exists to meet the demands of the electrical transmission/distribution system or to meet the demand of a load or loads that require something other than what the electrical distribution system naturally provides. The power converter product area for Naval Power Systems focuses on the use of transformers and power electronics based converters. General categories include conversion from/to AC/DC (rectifier), DC/DC (converter), DC/AC (inverter) and AC/AC (transformer or cycloconverter). In general, a power converter may incorporate more than one stage of power conversion. For example, an AC to DC power converter may incorporate a transformer (AC/AC) connected to a power electronic rectifier (AC/DC).

Industry Power Converter Benchmarks

Power Converters of interest include two basic categories: power electronics based converters and transformers. The technologies are vastly different, though both perform a power conversion function. Transformers are often included in power electronic power converters. This subsection is split into power electronic power converters and transformers.

Power Electronic Power Converters

Power electronic converter capability is determined by switching component devices (transistors, diodes, thyristors, etc.), their topology (configuration), and control schemes. The devices are controlled to switch between on (pass current, minimum voltage drop) or off (block current, voltage drop determined by topology). When the devices are combined with inductors and capacitors that act as energy storage and filters, the desired smooth output waveform (voltage, frequency) is delivered. Multiple topologies exist, and as devices and controls have advanced some topologies have gained wide favor. For example, the three level neutral point clamped inverter which converts DC to AC is the dominant pulse width modulation topology found in industry today. Soft switching topologies which use zero-voltage and zero-current switching are sometimes used to reduce switching losses at the cost of additional components and more complex control.

Power electronic power converters have a wide variety of applications. Variable speed drives (VSDs) for motors enable soft starting (reduced inrush current) and continuously variable speeds for many motor applications. VSDs typically vary voltage and frequency to maintain a constant volts/Hz ratio for most efficient drive/motor operation. Applications for VSDs vary from ventilation systems to heavy equipment to ship propulsion motors. Hybrid electric drive automobiles have bidirectional power converters that combine the functionality of a VSD with charging the vehicle’s energy storage battery. Extremely high power versions of power converters have enabled high voltage DC transmission for electric utilities. An example is the 2000 MW Sandy Pond, Massachusetts load station which takes high voltage DC and converts it to high voltage AC to feed the New England Power Pool section of the grid. Renewable sources such as wind power and photovoltaic may require power conversion to change variable frequency (wind power) or DC (photovoltaic) to grid frequency. Power converters are also pervasive in low power applications such as consumer electronics (computers, microprocessor controlled equipment, telecommunications, data centers, etc.).

A plethora of power electronic devices have evolved over the last 30 to 40 years. Insulated gate bipolar transistors (IGBTs) coupled with antiparallel diodes are currently the main devices used in medium power, medium voltage applications while metal-oxide-semiconductor field-effect-transistors (MOSFETs) are used in low power, low voltage applications. Utility high voltage applications use thyristors which can handle higher voltages.

Unfortunately, all power electronic devices have losses. When on (conducting), devices have a small on-state resistance producing I^2R losses. During switching transitions (on to off, off to on), the instantaneous losses are much greater than on-state losses. Thus, higher switching frequencies which enable better power quality also create more heat. Soft switching designs can mitigate losses during switching. To remove heat, devices are mounted on heat sinks which reject heat to air or other cooling media (water, ethylene glycol, etc.). The higher the power and/or switching frequency, the more complex and important the thermal management system is because power electronic devices have limited operating temperature ranges.

Benchmarks for power electronic devices and power converters are difficult to define in a rapidly changing and evolving product area. Devices are predominantly silicon (Si) based because they are affordable, easily manufactured, operate efficiently, and have proven dependable. Device metrics of interest for power applications include:

- Voltage rating
- Current rating
- Switching frequency
- Efficiency (conduction and switching losses)
- Operating temperature range

Device voltage and current ratings drive the number of devices in a converter as well as the power circuit topology. In general the more devices a converter has, the less efficient it is because of switching and conduction losses. More devices also increases control complexity. Some IGBT ratings of interest in 2012:[22]

- Voltage rating: up to 6500V (other standard ratings 4500V, 3300V, 1700V) for medium voltage applications
- Voltage rating: up to 1700V (other standard ratings 1200V, 600V, and lower) for low voltage applications

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[22] Values are from a market survey. Voltage rating refers to off-state voltage, the current rating refers to on-state current. Devices are not capable of handling both at the same time.

- Current rating: up to 750A for 6500V, up to 1200A for 4500V (generally higher current rating at lower voltages)
- Switching frequency: up to 30 kHz
- Temperature limit: 125 degrees C

The automotive industry (including cars, trucks, buses) is considered a major driver today for device ratings because of the emerging electric vehicle market. Table 6 shows typical ratings and components for various automotive applications.

Table 6: Typical Power Requirements in Automobiles that use semiconductors [23]

Applications	Peak Power Ratings	Semiconductor Devices	Current Ratings	Voltage Ratings	Switching Frequency
Inverters for Propulsion Motor and/or Generator	20-100 kW	IGBTs, Diodes	100-600 A	600-1200 V	5-30 kHz
DC/DC Voltage Boost Converters for Battery or Fuel Cell Stack	20-100 kW	IGBTs, Diodes	100-600 A	600-1200 V	5-30 kHz
Inverters for Air Compressors in Fuel Cell Stacks	10-15 kW	IGBTs, Diodes	20-50 A	600-900 V	5-30 kHz
Inverters for Air Conditioners	2-4 kW	IGBTs, Diodes	10-20 A	600-900 V	5-30 kHz
DC/DC Converters for 14 V Power Needs	1-2 kW	Power MOSFETs, Diodes	20-40 A	400-600 V	50-200 kHz
14 or 42 V Power Converters or Load Switches	<1 kW	Power MOSFETs, Diodes	1-20 A	40-100 V	.1-100 kHz

Overall, the benchmarks of interest for power electronic power converters are efficiency and power density. Power quality is also of interest, though not easily quantified. Table 7 shows the current industry benchmarks for single stage power conversion.

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[23] Z. J. Shen and I. Omura, "Power Semiconductor Devices for Hybrid, Electric, and Fuel Cell Vehicles," Proceedings of the IEEE, Vol. 95, No. 4, pp. 778-789, Apr., 2007.

Table 7: Key Benchmark Power Electronic Power Conversion Metrics

Metric	Benchmark	Comment
Efficiency	95-98%	Based on topology
Power Density	1 MW/m3	Approximate

Transformers

Transformers are AC/AC voltage converters that do not change frequency. Transformers are generally more efficient (>98%) than power electronic converters, and used extensively throughout industry. Transformers have three main component parts associated with them: the core (steel with desirable magnetic properties), insulation, and windings (copper). A fourth component may be associated with cooling. Dry type transformers use convection cooling with air (sometimes forced air) up to only a few thousand kVA. Larger transformers use mineral oil for cooling, with heat rejected via an oil to air or water heat exchange. Utility and industrial/commercial oil cooled transformers are physically isolated, either by distance or location in a vault inside a facility, to contain damage in the event of failure.

Transformers are very heavy compared to power electronic converters. Higher frequency transformers are used in the airline industry and other applications that require higher gravimetric power density. The cross sectional area of a magnetic core of a transformer is approximately inversely proportional to the frequency of operation. Thus the weight of the transformer core (not including the windings) of a 240 Hz. transformer would be expected to be about ¼ the weight of a 60 Hz transformer.

Industry Power Converter Trends

Power electronic trends are expected to dominate improvements in power converters. As capability increases and prices fall, some transformer applications will likely shift to power electronic converters. For the same functions, transformers will remain around the same size (big and very heavy) while power electronic converters will shrink in size, weight, and relative cost. Trends for both are presented in the subsections below.

Power Electronic Power Converter Trends

Continuous improvement in both capability and efficiency has been the most notable industry trend in the power electronic power conversion market. Increasing efficiency is critical for power systems and thus more efficient power conversion is constantly in demand. The basis for power electronic converter improvement is improvement in the actual power electronic devices. Devices will become smaller, more efficient, and more powerful. They will operate at higher temperatures and handle higher switching frequencies. More complex and refined topologies and control schemes enabling smaller filters will follow. All improvements will lead to more power dense, efficient, and robust power conversion modules.

Power electronic device capability is trending toward a leap in capability with the introduction of new semiconductor materials. Si device designs are approaching their material physical limitations. Wide bandgap semiconductors can perform better than Si because they have higher material limits for off-state voltage, on-state current, and operating temperature combined with higher thermal conductivity. Wide bandgap semiconductor materials with ongoing development include Silicon Carbide (SiC), Gallium Nitride (GaN), and even Diamond. They are generally expected to at least double the power density of a power system and cut switching losses in half, with commensurate increases in efficiency. For example, SiC can operate at 350 degrees C while current Silicon based IGBTs can operate at 125 degrees C and MOSFETs can operate at 150 degrees C.[24] This high temperature feature is especially important in automotive applications where the cooling medium operates at 100 degrees C or higher.

A significant wide bandgap device improvement over Si is the ability to switch at higher frequencies. For power converters, this will lead to better power quality with less filtering (fewer and/or smaller capacitors and inductors). Some power converters may be more optimally designed with a mid-converter voltage conversion stage using small high frequency transformers. These transformers would provide the galvanic isolation required in many applications. All of these higher switching frequency improvements will contribute to smaller converter sizes.

Wide bandgap devices are beginning to transition from development to market with expected sales in excess of a billion dollars by the end of the decade. SiC Schottky diodes are commercially available either as stand-alone devices or packaged as antiparallel diodes for Si IGBTs. SiC MOSFET’s are now available in discrete packages up to 1200 volts, 20 amps with higher rated devices on the horizon.

SiC is the most mature, and well suited for medium voltage applications. GaN is better suited for low voltage applications. GaN devices up to 600V have already been produced and the trends show that up to 1200V operation is possible. There is the possibility that GaN devices could overlap SiC applications up to 1kV. This overlap could slow down SiC's market penetration because consumers may opt for a more affordable GaN on Silicon substrate option in the overlapping range. Incorporation at that level would produce many units and drive down the cost further. SiC will most likely remain desired in higher power applications due to its improved thermal management properties when compared to GaN. Diamond has the widest bandgap but is the least mature of the three.

Device yield is a manufacturing challenge for wide bandgap devices. Yields are much lower than for Si devices, forcing very high (compared to Si) market prices for wide bandgap devices. It is anticipated that these manufacturing challenges will be overcome over the next 10 years, leading to further industry adoption of wide bandgap devices in power converters.

Devices that are more affordable, more power dense, and more efficient are expected to continue to enter the market. Expected increases in power density and efficiency

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[24] DoE Vehicle and Fuels Electrical and Electronics Technical Team Roadmap. Dec 2010.

over the next 30 years are summarized below in Table 8 for single stage power conversion.

Table 8: Key Power Converter Trends

	Near-term (5-10 years)	**Mid-term** (10-20 years)	**Far-term** (20-30 years)
Efficiency	98%	>98%	>98%
Power Density	1.25 MW/m3	2 MW/m3	3 MW/m3

Transformer Trends

Transformers have been in use for more than 100 years. Electric utilities will drive high power transformer development. Industry transformer trends include:

- Increased efficiency (core geometry and material, reduce hysteresis and eddy current)
- Improved insulation
- Increased voltage and power ratings
- Alternative cooling media (environmentally friendly, non-flammable)
- Cooling improvements
- Prognostic failure diagnosis
- Higher frequency (reduced size)

Industry Power Converter Trends Relation to Naval Power Systems

Future Naval Power Systems will need to support higher power and energy loads. Power conversion will be required to interface these loads with the power system and any associated energy storage. Combining power electronics with transformers allows frequency to be decoupled from a distribution system and can provide galvanic isolation and ease of conversion between multiple voltages and frequencies. The power density at the power levels required for future Navy applications and the shock and vibration requirements will drive the Navy to either repackage commercial converters or develop Navy-unique power conversion equipment. However, the concepts and underlying technologies, such as advance power electronic devices, transformers, converter topologies and control philosophies, and passive filtering improvements developed by industry will provide the basis for naval power conversion equipment and should influence the direction the Navy goes in selection of interfaces.

It is important to keep an eye on the wide bandgap device markets as these technologies mature. Both of these emerging technologies are game changing for future Naval Power Systems, however it will be the commercial markets that drive production and cost of switching devices, circuit topologies and power converter development.

The Navy will follow industry improvements in transformers. Mineral oil filled transformers are not used in Navy applications because of the fire hazard. Most Navy transformers are convection dry type, with a few large propulsion transformer applications using forced air TEWAC. Propulsion and hybrid electric motor drives already use a synthetic ester for cooling because of the high power levels.

Prime Movers

The prime mover product area for naval power systems focuses primarily on diesel engines and gas turbines. Energy recovery and fuel cells are also discussed. Steam turbine prime movers for naval nuclear propulsion applications are not within this roadmap's purview.

Industry Prime Mover Benchmark

Diesel and gas turbine engines are used in a variety of commercial transportation, power generation, and industrial applications. In the transportation industry, gas turbines are the primary source of propulsion and power for aviation applications. Gas turbines have application in commercial marine propulsion where power density and/or emissions are important; examples include fast ferries and cruise ships. Marine turbines are aero derivatives and not industrial frame gas turbines. In commercial large and medium scale power generation, gas turbines are increasingly used as alternatives to coal-fired steam plants due in large part to environmental laws, availability of natural gas, lower capital costs, and industry deregulation encouraging independent power producers. In these applications the gas turbine is often operated in a combined thermodynamic cycle configuration with a waste heat recovery system, based typically on steam as the working fluid. This significantly increases system efficiency, with engine waste heat converted for a variety of uses, including steam for process and building heating or electrical power, depending on the application requirements.

Gas turbines are also used extensively in the oil & gas industry. They are the primary power source for natural gas pipeline compression stations with over 80% of that market (electric motors make up the other 20%). Gas turbines are also being used more often to provide electric power to offshore oil rigs where very high power is required and deck space is a premium.

Diesel engines are the primary source of propulsion and power for overland transportation applications such as trucking and locomotives, as well as the vast majority of commercial marine applications where power density is not a primary design consideration. In small scale or emergency power generation applications, diesel engines are the primary source of power. Diesel and gas turbines share common attributes of quick starting from cold iron to full power, good transient performance to load changes in power generation applications, and good efficiency. Primary discriminators for applications include power density and efficiency. The increased power density of gas turbines may be offset by the large airflow requirements in some applications. Diesel engine efficiency is fairly uniform across the operating range of the engine while gas turbine efficiency deteriorates at part power operation.

Industry Prime Mover Trends

Industries that drive prime mover trends for gas turbines are:

- Transportation (aviation)
- Commercial Marine (fast ferries, cruise ships)
- Oil and Gas (off shore, remote location power)
- Electric Utilities (Power Generation)

Industries driving prime mover trends for diesels are:

- Transportation (rail, truck)
- Commercial Marine (ship propulsion and power generation)
- Heavy Equipment (construction, mining, etc.)

Commercial research is focused primarily on improving engine efficiency, reducing emissions (legislated), increasing maintainability, and lowering life cycle cost. This is common to both gas turbine and diesel applications. Developments for commercial marine engines address operation in a more corrosive atmosphere driven by the presence of sea salt in air, as well as the use of less expensive fuels. Advances in combustion technology address environmental compliance, efficiency, and transient performance, as well as accommodating and leveraging the effects of fuel variability.

MARPOL[25] Annex VI sets limits on sulfur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances. Annex VI compliance has forced the commercial shipping industry to evaluate emissions from their prime movers and is a driving force behind the adoption of alternative fuels such as Liquefied Natural Gas (LNG). Dual fuel (liquid and gas) nozzle designs exist and are offered on many industrial gas turbine product lines.

Some general trends apply to both diesels and gas turbines. Others are specific to one or the other. These trends are divided into separate lists in the remainder of this section. General prime mover industry trends include:

- Legislated reductions in engine emissions
    - Diesel Engines: reductions in oxides of nitrogen and particulates
    - Gas Turbines: reductions in Nitrogen Oxides (NOx)
- Cleaner fuels
    - Fuel additives for reduced emissions
- Fuel-Flexible Engines

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[25] The International Convention for the Prevention of Pollution from Ships (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes.

    - Utilization of alternate/multiple fuels
- Implementation of Digital Controls
    - Enhanced engine monitoring, diagnostics, and failure prediction
    - Active control for emissions, combustion, performance and efficiency improvements
    - Distributed controls
- Improved engine efficiency
    - Alternate thermodynamic cycles
    - Higher temperatures and pressures
    - High temperature materials
- After-treatment technologies for reduced emissions
- Improved maintainability designs
- Composite structures and enclosures
- Increased application of ceramic engine parts for corrosion resistance, reduced wear, and high temperature operation
- Advanced High Temperature Alloys and Coatings
- Enhanced fuel injection and combustion
- Intercooling
- Advanced Controls Technology
- Model based controls
- Optimized thermal management
- Prognostics & diagnostics
- Simplified maintenance
- New applications of thermodynamic cycles (Miller, Humphrey, Atkinson, etc.)

For diesel engines, technologies tend to be implemented first for the smaller engines (automobile, truck, emergency generators) then to the medium sized engines (locomotive, heavy equipment) then finally large propulsion diesels featured in commercial marine applications. General diesel engine trends include:

- Retrofittable technology insertion packages
- Diesel after-treatment technologies tolerant of lower quality/high sulfur content fuels
- Sulfur Oxides (SOx) resistant catalysts
- Low Temperature Combustion Modes
    - Homogenous Charge Compression Ignition (HCCI)
    - Pre-Mixed Charge Compression Ignition (PCCI)
    - Reactivity Controller Compression Ignition (RCCI)
- Stratified combustion
- Variable Valve Timing and Actuation

- Variable Area Turbine Nozzle (turbocharger)
- Turbo-compounding
- Common Rail Fuel Injection
- Stress wave bearing monitoring (crosshead, connecting rod, or main bearing)
- Rotary valves
- Camshaftless low speed diesel engines
- In-line continuous oil condition monitoring
- Variable valve timing
- Selective catalytic reduction
- Exhaust Gas Recirculation

For gas turbines, new core engine technologies tend to be implemented first in military and commercial aviation applications, and advanced (complex or combined) cycles implemented in commercial power generation. Gas turbine performance and efficiency improvements are driven by increases in overall pressure ratio and firing temperature enabled in large part by improved high temperature, high strength materials, coatings, advanced component designs and implementation of complex/variable thermodynamic cycles. General gas turbine engine trends include:

- Technologies to reduce airflow (e.g. Reheat combustion)
- Technologies to increase power (e.g. Inlet cooling)
- Variable area turbine nozzle/ variable free power turbine
- Compact power turbines
- Compact module package designs
- Integration with waste heat recovery/recuperation
- High temperature working fluids
- Integration with fuel cells
- Hot section coatings for corrosion resistance/life
- Trapped vortex combustion
- Active clearance control
- Modulated cooling flows
- Variable/complex cycle engines
- Advanced low emissions combustors
- Microturbines for distributed power generation

There is a separate trend in industry toward alternatives to existing prime movers. Fuel cells exist commercially. They primarily use hydrogen and or methane for fuel. Fuel cells are currently used to generate power for hotel complexes and remote communities and in the automotive industry to enable clean fossil fuel free transportation,

Energy/waste heat recovery to increase overall fuel efficiency is beginning to appear in commercial marine applications. Generally, waste heat can be used to improve engine performance directly (included in the lists above) or provide a reduction in required engine output by contributing heat or electrical energy to reduce prime mover load. Areas pursued commercially include topping and bottoming cycles, cogeneration, and combined cycles. As mentioned previously, steam is the typical working fluid used in waste heat recovery today. General waste heat recovery trends include investigation and advancements in steam and other working fluids, cycles, and materials such as:

- Organic Rankine Cycle
- Super Critical CO2
- Air Bottoming Cycle
- Thermoelectrics
- Waste Heat Absorption
- Robust, low-loss heat exchangers (material, fabrication/brazing, thermal cycle tolerant)

Industry Prime Mover Trend Relation to Naval Power Systems

The Navy's need for more efficient, lower cost, more maintainable prime mover designs is consistent with industry needs. For diesel engines, the Navy relies primarily on commercial developments. Carryover technologies implemented in naval diesel applications are typically first introduced commercially and subsequently qualified for military use. For gas turbine engines, a similar relationship with commercial developments exists but it should be noted that many commercial gas turbine developments are supported by robust engine development activity for military aviation applications, especially at the engine core level. Consequently, many new commercial gas turbine engine designs being introduced are rooted in military core engine technology.

Historically, Navy unique requirements are associated with shock, operating environment, operational profiles, and signatures. Compliance with shock requirements may require redesign to provide the necessary robustness. Operating in the marine environment may require the incorporation of special materials and/or coatings to provide the necessary life and durability. Naval engines typically operate with relatively high intake/uptake duct losses, which may impact steady state and transient performance. In addition the Navy rates its engines at a 100 degrees F ambient condition resulting in a generally lower power rating than at the industry standard 59 degrees F ambient condition. Navy fuel is much higher grade than commercial marine fuel but naval prime movers may be required to operate on lower quality fuels if constrained by availability in the operational theater.

The Navy generally operates engines very differently than the commercial sector. Where commercial applications typically maintain constant speed at design load, Navy prime movers typically experience large accelerations/transients and long times at part load.

Energy/waste heat recovery technology shows promise for navy ships. The highly transient operation of US Navy engines and the shipboard space constraints will limit the application of commercial availability systems. Highly transient prime mover operations can cause high thermo-mechanical stresses resulting in fatigue and material failures of traditional heat exchangers.

Fuel Cell Systems show promise as a way of providing quiet distributed power generation on board future navy ships. Fuel Cell system technologies will require advances in fuel processing or additional resistance to fuel contaminants in order to be a viable generation alternative.

IV. Navy Ship Implementation Challenges

The previous section presented a general analysis of industry benchmarks, trends, and potential naval applicability. Follow on sections describe the systems engineering analysis process, review the requirements analysis, and provide development recommendations for the next 30 years. This section describes some of the challenges associated with the Navy shipboard environment and general considerations that developers should take into consideration. The intent is to give the developer an understanding that will inform innovation decisions at all stages of the NPS technology development process.

Shipboard Environment

Power system technologies of interest to the Navy are ones that are relevant to Navy needs, are improvements over previous technologies (e.g. less expensive, more reliable, smaller, lighter), and provide an increase or improvement in capability. Relevant means the technologies must be compatible with the Navy shipboard environment. Physical size constraints are dictated by naval architecture considerations (space, weight, stability, etc.) and ship missions. Navy ships tend to be more maneuverable, faster, and have a more variable operational profile when compared to oceangoing commercial marine vessels. They have payloads such as weapons systems and advanced sensors which don’t have commercial equivalents. These payloads generally have more demanding electrical power requirements than commercial vessels. Large power demand drives the physical size of power generation and power system equipment to be a major consideration in the overall ship design. For smaller warships, compact power systems enable a greater fraction of the ship to be dedicated to combat systems. Power system elements must physically fit within a space-limited ship design; for example, stack-up length of equipment must be small enough to fit within watertight boundaries. For larger warships, power density of the electrical system has value, but only if affordable.

Navy warships have unique military performance requirements. Essential ship systems must be designed to not only survive but continue to operate while in harm’s way. A naval power system is subjected to a shock and vibration environment that ranges from calm peacetime transits to battle damage conditions. System redundancy combined with physical separation of components and multiple system distribution paths are inherently required to continue ship operation with flooding, fire, and/or battle damage. Support considerations including providing the crew with the ability to rapidly repair systems at sea (line replaceable units, technical documentation, etc.) are important. Navy ships generally require equipment to operate in a wider range of ambient temperatures than commercial equipment. Future electrical loads are likely to be more power dense (increasing local heat loads in selected ship compartments) and overall require higher power (increasing total ship heat load); advances in thermal management capability and capacity will be required to complement these future loads. Electromagnetic interference and electromagnetic compatibility (EMI/EMC), airborne noise, structureborne noise, and signatures are additional design considerations for

Navy ships, with naval systems required to meet much more stringent requirements than commercial ships. Another major design consideration is that all projected improvements must be critically evaluated for cost effectiveness.

Ship Electrical Power Systems

Ship electrical power systems can be globally defined by key electrical parameters. Design tradeoffs include these technical design parameters, budget constraints, allowance for growth, and naval architecture considerations discussed above. The following specific electrical parameters and issues are discussed in more detail in the following paragraphs:

- Frequency
- Voltage
- Load characterizations
- Distributed system layout
- System integration

Frequency measured in Hertz (Hz) is a basic electrical parameter. The US commercial standard and the standard Navy ship frequency is 60 Hz. Worldwide, the standard is either 50 Hz or 60 Hz. Navy ships predominantly generate and distribute power at 60 Hz (three phase), with the majority of loads directly powered at 60 Hz. All ships generate power using AC generators. DDG 1000 is unique with its generation at 60 Hz and a DC electrical distribution system fed by transformer-rectifiers. There is a trend towards DC in commercial niche markets such as server farms, solar farms, offshore wind energy, and some process applications as well as a number of High Voltage DC (HVDC) transmission lines in the world's various power grids. Frequency selection for future ships will be determined based on a variety of considerations. Higher frequencies enable smaller transformers and filter components which mitigate naval architecture space/weight issues, and also allow smaller, higher speed rotating electrical machines. Physics based concerns mandate derating some equipment at higher frequencies (cables for skin effect, circuit breakers for arc extinguishing time before restrike voltage). While DC distribution uses fewer cables, AC generation is the norm; conversion to DC for distribution introduces losses. This TDR invites innovation to determine what shipboard frequency (or combination of frequency alternatives) best meets the needs of future platforms.

Voltage level for generation and distribution is primarily determined by platform's design power requirements. The Navy's predominant generation and distribution voltage has been 450VAC while more recent designs have used 13.8kV, 6.6kV and 4160V. Commercial and foreign navy ships use all of these voltages as well as some others, notably: 480V, 690V, 3.3kV and 11kV. (Selection of voltage level is driven by limitations of the electrical distribution system, see IEC 60038 for a complete listing of standard voltage levels.) Higher voltages result in lower currents to deliver the same amount of power. There are natural breakpoints where engineering and naval architecture considerations dictate higher voltages. Available circuit breakers have limited continuous current ratings, and commercial design practice is to use a higher voltage rather than develop breakers to handle higher continuous currents. Higher voltages impose additional considerations for physical separation (creepage and clearance) requirements and cable insulation. Ship distribution cables are heavy (approximately 6 lbs./foot), and lower current means fewer cables thereby reducing distributed system weight. In general, it is expected that future Navy ships will use industry standard voltages and current ranges to take advantage of available product lines as long as they can meet military performance demands.

Shipboard loads can be characterized in terms of application, magnitude of the load, transient and power interruption tolerance, desired input (voltage, frequency), etc. Major applications include motors (pumps, fans, propulsion, etc.), heating and lighting, computers and electronics, and combat systems loads (radars, sensors, weapons). Tolerance to power interruptions is covered under QoS and described in detail in NAVSEA DDS 310-1 Rev.1[26]. Quality of Service is invoked in the IEEE 1709 and IEEE 1826 standards. Different loads also have different inherent power needs that result in a preference for AC or DC power. Fan and pump motors are predominantly AC induction motors. These loads are relatively insensitive to momentary fluctuations in frequency or voltage or short term disruptions in power. Heating and lighting are traditionally AC fed because ship distribution systems are AC, and are also tolerant of momentary to longer term power interruptions.

Computers / electronics and combat systems loads require some or all power to be DC, and incorporate conversion from the distribution input (required for AC, may be required for DC) to the specific load DC voltage level. These loads are very intolerant to transients and power interruptions (especially COTS based equipment), and often incorporate an uninterruptible power supply (UPS) to maintain power continuity. Equipment level UPS result in increased cost and maintenance. System reboots due to power quality problems are inconvenient commercially but unacceptable in a combat situation. A major shipboard implementation challenge is to provide loads the power they need, most efficiently, with appropriate QoS for different loads, while minimizing the number of UPS and dedicated load power converters.

The ship electrical power system is a distributed system, with multiple generators (and sometimes emergency generators), multiple switchboards, and redundant paths to power vital loads. Improvements in components that distribute power (switchboards, circuit breakers within switchboards, cables or alternative distributed transmission means, etc.) are of interest, as well as better methods to distribute power to loads that demand different types of power.

Other ship implementation challenges are grouped here as system integration challenges. Navy warships must be able to continue to fight under adverse circumstances. This imparts a system design philosophy (and associated requirements) that keeps power going through faults (to allow isolation), through

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[26] NAVSEA DDS 310-1 Rev 1, "Design Data Sheet: Electric Power Load Analysis (EPLA) for Surface Ships," 17 September 2012.

generator casualties (allowing time for load shed), and by switching to an alternate source (for vital loads). Generators and associated equipment must be robust enough to ride through overloads, provide fault current to enable automatic circuit protection actions (trip circuit breakers), handle large step load changes, and return to providing specified power as soon as possible following emergency transients. Several ship implementation challenges and opportunities exist since the Navy is interested in faster fault identification and clearing, smarter and better circuit protection schemes, more robust machines and controls, and components that improve existing responses to casualties and emergencies. Information Assurance (IA) is a growing requirement that merits attention in power management components and systems to ensure effective implementation. All solutions must respond during the worst cases of shock, vibration and environmental conditions as the warship goes into harm’s way.

Architecture

Shipboard power system architectures are enabled by their supporting technology and associated developments to meet future ship integration challenges. Historically, the power demands of most naval ships were modest enough such that most power was generated as 450VAC three phase power and most loads employed the same type of power. A radial architecture simplified circuit breaker coordination, but required additional cabling for those few vital loads requiring a high degree of power continuity.

As electronic mission systems became more numerous onboard ship, many of these loads were designated as vital and required considerable cabling to provide redundant power. In the 1990’s, the radial power system was replaced by a zonal power system on destroyers, primarily to reduce the cost and weight of the distribution system. This zonal power system improved power system robustness and maintained the same level of power quality and power continuity. The evolution of Navy primary distribution and power to ship and mission ship systems is shown in Figure 6 below. An important technical innovation that enabled this transition was the Multi-Function Monitor that enabled proper coordination of the breakers on the longitudinal power buses.

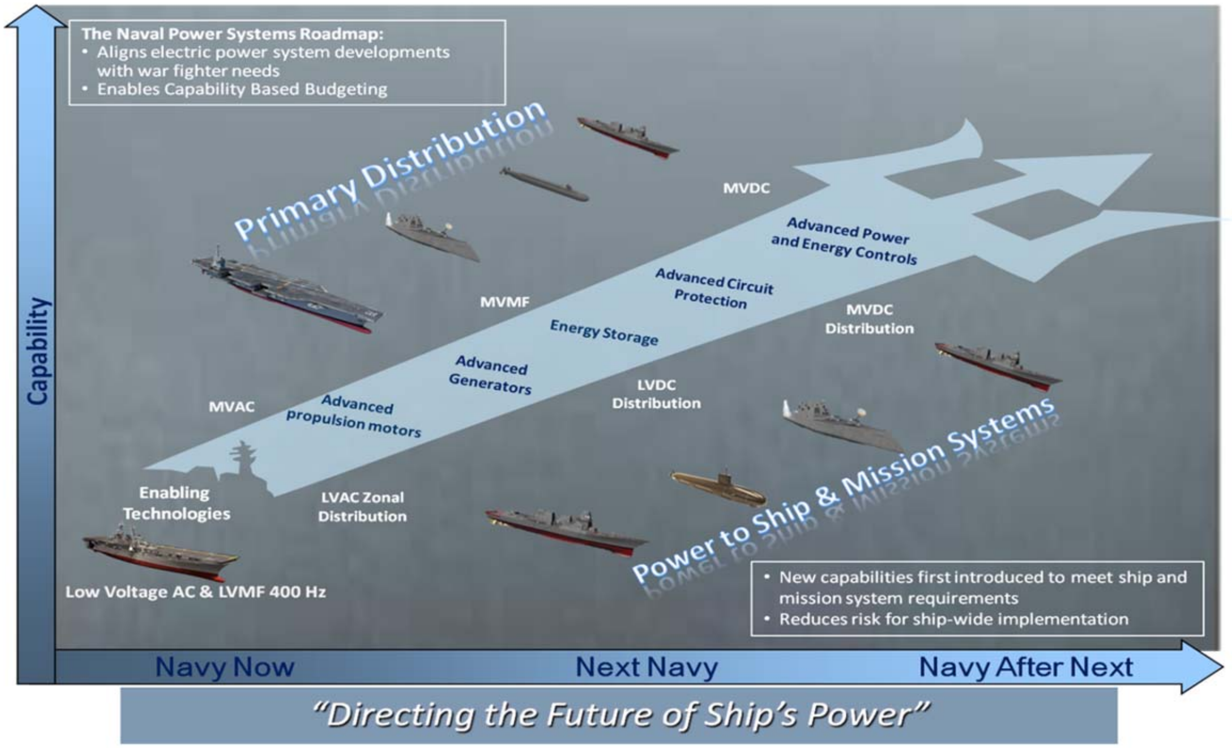

Figure 6: "Directing the Future of Ship's Power"

The total electric load onboard ships grew substantially during the 1990's. LHD 8 is a good example of this trend. Chilled water loads grew to satisfy the cooling needs of numerous electronic mission systems while the replacement of steam heating increased electric heating loads. As these loads increased, generating and distributing medium voltage ac power to zonal transformers became more affordable and lighter than employing a 450VAC only system. This trend not only applies to auxiliary systems such as heating and cooling loads but mission loads as well.

In this emerging paradigm, increased electrical load power demands can rival the power demands of propulsion during many operational scenarios. The ability of integrated power systems to more affordably meet these power demands was an important driver for its introduction into the T-AKE 1 class and DDG 1000. IPS enables the installation of fewer prime movers on a ship, and enables the more efficient use of those prime movers. Some key technologies that enabled IPS were the development of propulsion motors, their drives, harmonic filters, and advanced machinery control systems. More recently, hybrid electric drive on LHD 8 provides significant operational fuel economy, but did not enable a reduction in the number of prime movers.

The growth in sensitive electronic loads that cannot tolerate power interruptions has led to the proliferation of UPS onboard ship. Until the introduction of electronic systems, service interruptions on the order of 1 second were tolerable. The initial response to the introduction of sensitive electronics into naval ships was to require these loads to provide their own UPS. Centralizing this function and incorporating the capability to service un-interruptible loads directly from the power system was designed into the Navy's Integrated Fight Through Power (IFTP) system, which uses a medium voltage

DC (1000VDC) bus, advanced power electronics, and machinery controls. The recent development of QoS and its incorporation into standards will assist the design of future power systems in affordably meeting the power continuity needs of the loads.

Developing technologies, components, and systems offer further opportunities to provide more affordable shipboard power systems that meet the needs of ship loads. Energy storage technologies are rapidly improving and offer the opportunity to introduce more affordable components such as twin-spool gas turbines, enable single generator or reduced generator operations to decrease fuel consumption, provide a source of power for un-interruptible loads, eliminate the need for dedicated harmonic filters, provide load leveling, and perform power factor correction in ac systems.

The development of affordable semi-conductor devices that can directly switch medium voltage efficiently at relatively high speeds (> 10 kHz) may enable medium voltage DC systems to compete with medium voltage AC systems in the future. Additional technologies that are needed for affordable medium voltage DC systems include:

- New standardized fault detection, localization, and isolation techniques that can operate with power electronics sources and loads
- Refined techniques for power sharing among sources
- Refined grounding methods
- Power controls systems that interface/integrate with machinery control systems
- Development of scalable, open architecture, medium voltage to low voltage power conversion.

The anticipated introduction into future warships of advanced weapons systems such as high power radars, rail guns, and lasers will drive new power system architectures and components. In particular, these loads will drive development of energy storage, their control, and medium voltage power conversion.

Within electrical zones, the development and standardization of low voltage power conversion will enable elimination of low power distribution system layers. Many loads will be powered directly from these standardized converters with other loads separated from a standardized converter by only a single power panel. The additional ability of the power system to manage overall power consumption by large loads will enable improved load shedding for QoS and mission prioritization, reduced need for energy storage, and at potentially lower cost than currently possible.

Gaining the potential improvements in cost and performance of the technologies described in this document will require acceptance of evolutionary and/or revolutionary change. This acceptance includes codifying the technology in specifications, standards, handbooks, design data sheets, and design criteria and practices manuals. It also means ensuring the workforce and industry can affordably implement the technology into naval power systems and eliminate obsolete technologies and methods from consideration for new power system designs. Supporting these institutionalization efforts is implicit in the proposed technology development efforts described in this TDR.

The specific architectures and technologies that will be employed by a particular ship design will be chosen by the responsible ship design team. Typically, the ship design team will use the Design Criteria and Practices Manual for electrical systems to develop its power system options. The goal of this TDR is to ensure technologies are sufficiently mature for the ship designers to have at least one affordable and effective power system alternative to choose from.

V. Systems Engineering Approach to Aligning Requirements and Technologies

The primary objective of aligning derived electrical requirements with available technologies is to determine if available technologies can satisfy the derived electrical requirements in the timeframe required. If technologies are not or will not be available, then a gap exists which must be filled by a development effort. Given the long lead time between identification of a gap and when a functioning system is installed onboard a ship, this roadmap seeks to identify future gaps via a systematic and disciplined technical approach.

Figure 7 below shows an overview of the process used to align derived electric requirements with available technologies. Based on this process, the following information is required in order to determine if a gap exists:

- The derived electrical requirements
- The projected platforms and timeline
- The available or projected to be available electric power system configurations
- The technologies, products, systems available or projected to be available when the solution is required
- The relevant specifications or standards that affect the solution
- A prioritization of the ubiquitous requirements

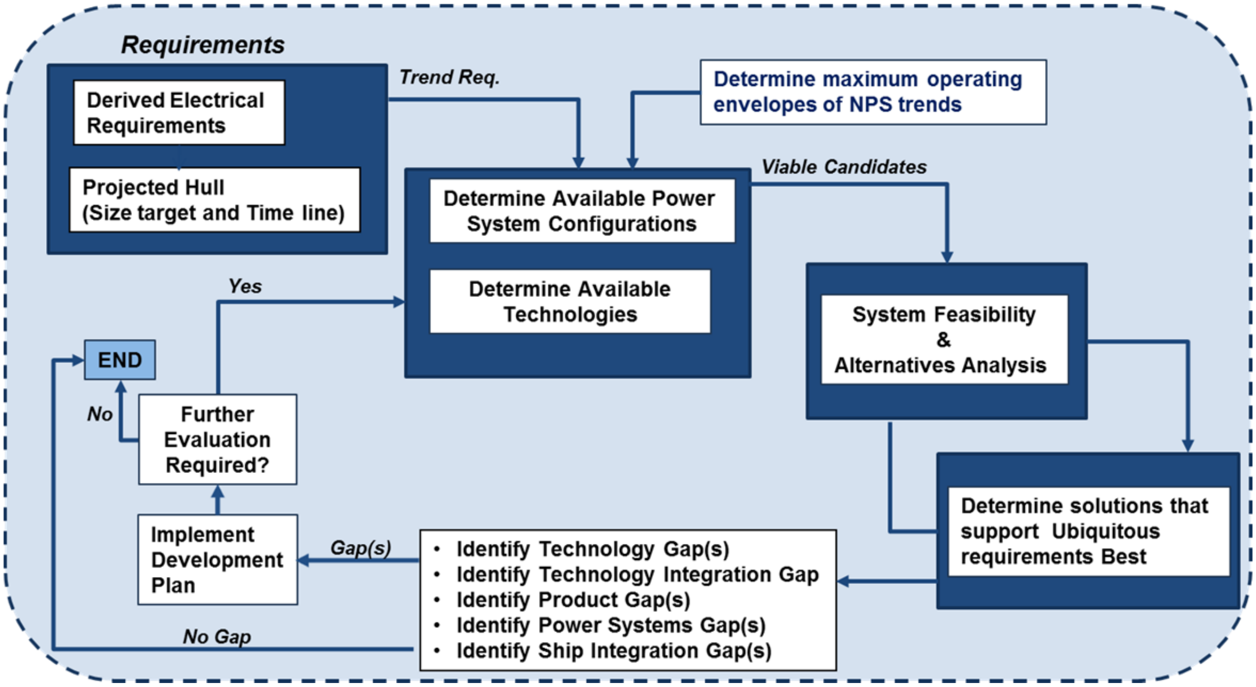

Figure 7: Systems Engineering Analysis Approach

When a gap exists, the Navy must initiate the appropriate Science and Technology (S&T), engineering and or systems integration development efforts to meet the requirement. The activities associated with increasing the maturity of technologies, products, and systems at varying levels will differ. Figure 8 below provides an overview of the Navy's approach to naval power systems development. There is a logical progression where individual technologies mature into products which further mature and are integrated into the NPS to provide the final capability on the ship.

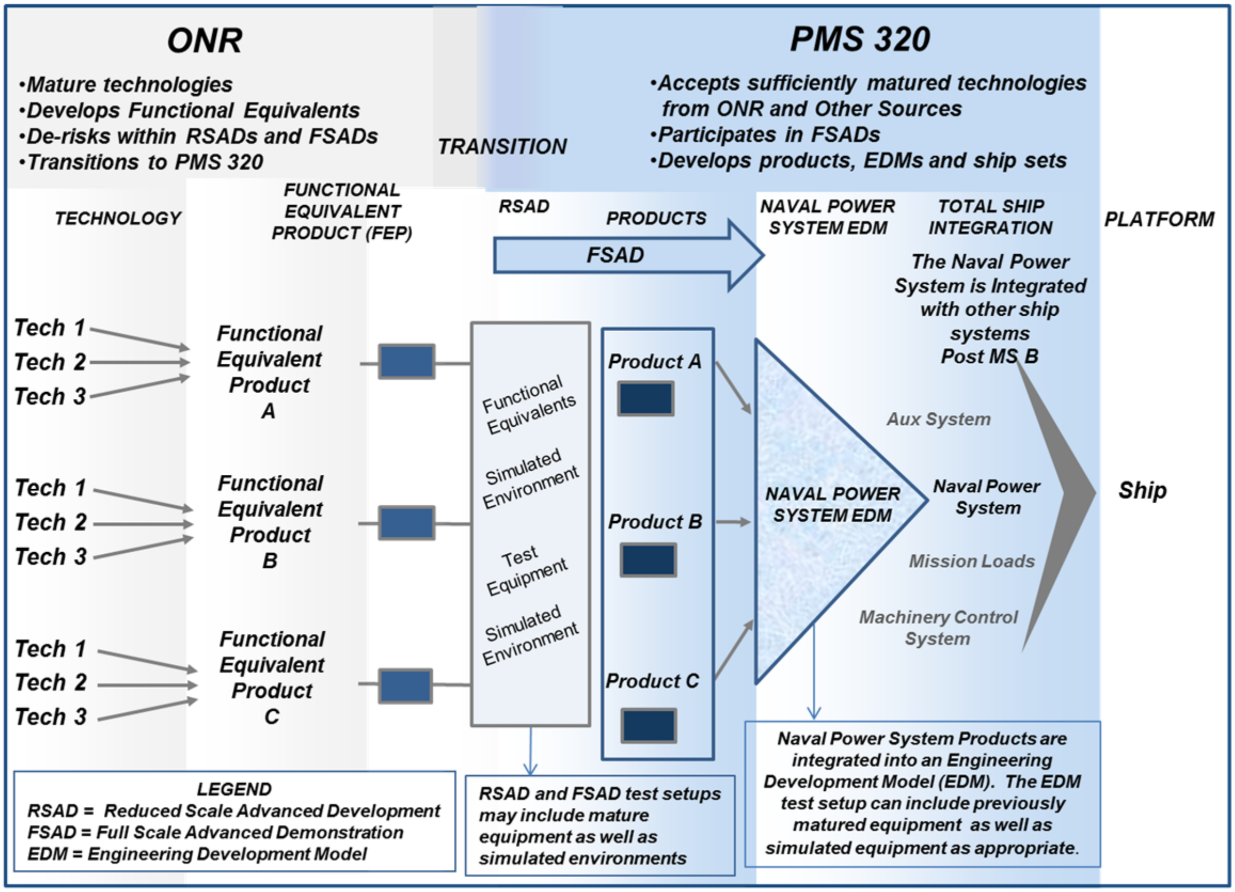

Figure 8: Naval Power Systems Development

The gaps identified by the systems engineering analysis approach can exist at any point in the NPS development process depending on the maturity of the product or system. A brief description of the types of gaps is provided below:

- Technology gap:
  - The fundamental knowledge has not been realized to create a technology capable of meeting an emerging requirement.
- Technology integration gap:
  - The enabling technologies have not been integrated into a functional equivalent product.
- Product gap:
  - The functional equivalent product has not been further matured into a product suitable for use on a Navy platform.
- Electrical system integration gap:
  - The products that make up the NPS have not been integrated to operate as an electrical power system.
- Total ship integration gap

    - The NPS has not been integrated into the total ship system, including physical integration of components as well as integration into the ship's control system and auxiliary systems.

The NPS development process involves many organizations including the Office of Naval Research (ONR) or other S&T focused agencies, PMS 320, the platform program office, the platform ship design manager within SEA 05D who is responsible for total ship integration, the appropriate technical authorities, DoD and other government departments/agencies, commercial industry, and academia.

ONR is generally responsible for developing new technologies and their integration. Typically, this integration includes the development of a functional equivalent product. The functional equivalent is tested via a Reduced Scale Advanced Development (RSAD) or Full Scale Advanced Development (FSAD). The result of testing the functional equivalent enables the development of initial performance specifications. Utilizing the knowledge attained through the functional equivalent development process (hardware and initial performance specifications), PMS 320 develops a product consisting of Navy ready hardware and software that can be procured either by the Navy or prime contractors. This product is tested in a Land Based Test Site. Several products may be integrated into an Engineering Development Model (EDM) of a ship electrical system. Products are developed with the intention that either subcomponents or the entire product may have multiple applications to enable commonality across the fleet as often as is practical.

Figure 9 shows the NPS development timeline and its relationship to the ship acquisition timeline. Overlaying this naval power systems development approach onto a new ship acquisition timeline is complex. The development timeline includes a number of simulated environments in order to adequately build, integrate, and test developmental products and systems. These environments are the result of electrical system modeling and simulation (M&S) efforts which are critical to determining system requirements and examining potential solutions in the early stages of development and in providing realistic, relevant environments for integration and testing in later phases of development.

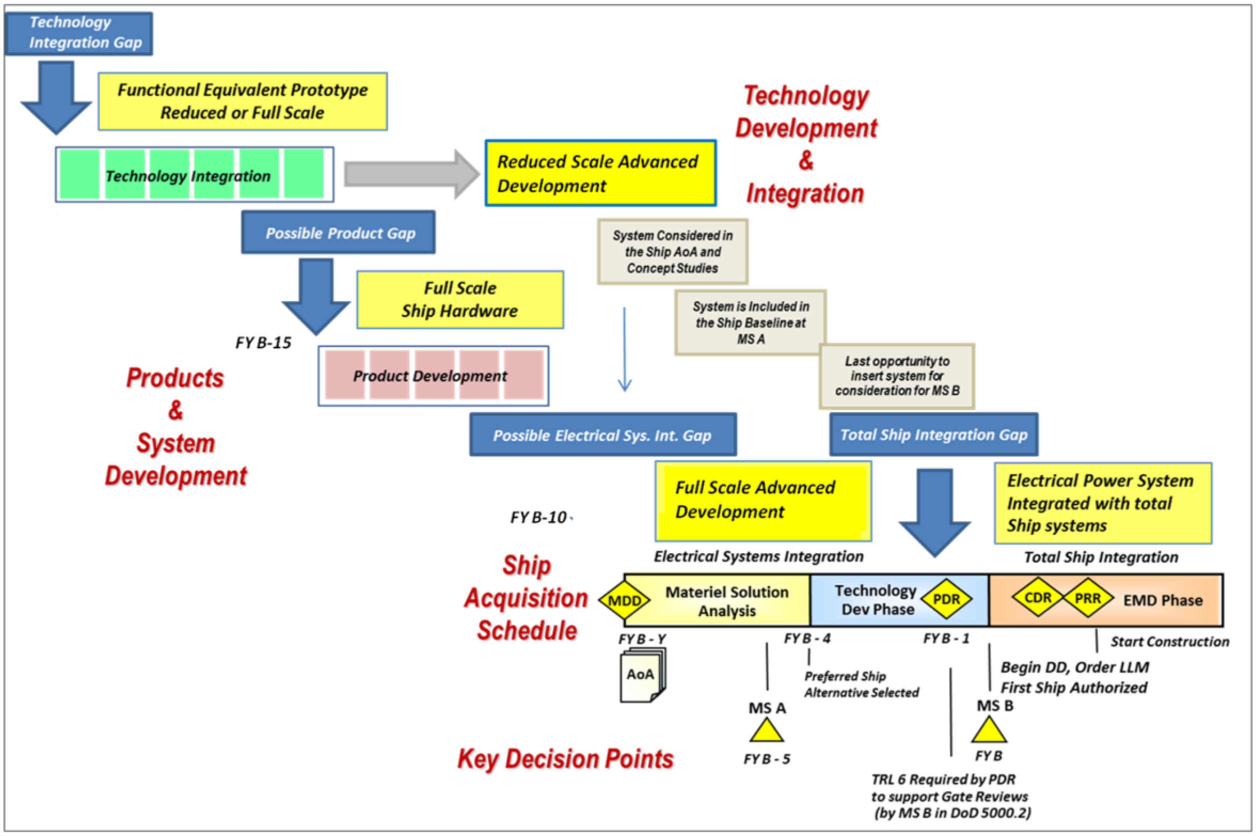

Figure 9: Notional Naval Power Systems Development Timeline Overlay

The key take away from this overlay is that the candidate electrical technology, systems, and overall electrical power system options must be considered years before the formal DoD ship acquisition process begins. The Navy selects a preferred alternative ship, usually from the Analysis of Alternatives (AoA) conducted prior to Milestone A. This preferred alternative ship is based on a naval power system also selected from a variety of options. In order to be considered as a viable alternative suitable for inclusion in the AoA, any major change to traditional naval power systems must be developed at least to the point where full scale hardware has been demonstrated and integrated and considered low risk prior to Milestone B. The total time required for technology development and integration from S&T to Milestone B is approximately 15 to 18 years.

The development timeline for a forward fit application insertion would be similar to that shown in Figure 9, with the year of target ship authorization corresponding to MS B and a parallel timeline added for development of the Engineering Change Proposal that begins approximately four years prior to the year of ship authorization.

Back fit of new products into existing platforms follows a different, but similar process, in which the Ship Change Document for fleet modernization is developed in parallel with electrical product integration. One year prior to the start of the industrial availability for installation all Ship Installation Drawings (SIDs) must be complete and all long lead-time material must be ordered. It follows that the initial product factory testing for production hardware and all associated system testing at a Land Based Engineering Site must also be completed at this time.

VI. Near-term (2013-2022) Requirements Analysis

The near-term for the purpose of the NPS TDR is the next 10 years, 2013 – 2022. In the near-term, advanced weapon and sensor loads already being developed will primarily drive electrical system requirements. Expected weapon and sensor loads of interest in the near-term include:

1. Advanced radars and sensors
2. Directed and pulsed energy weapons

Additionally Naval platforms will be required to perform their missions with greater energy efficiency than before. Platforms of opportunity in the near-term are limited to existing platforms, flight upgrades, and the one new platform identified in the 30 year shipbuilding plan (LX(R)).

In the near-term, each of these new weapons and sensors will be introduced in well-defined platforms with well-known electric power system capabilities and characteristics. Each mission load will interface with an existing or planned MVAC or LVAC power system that is 13.8kVAC, 4160VAC or 450VAC at 60 Hz. In order to meet the MIL-STD-1399 sections 300 and 680 electrical interface requirements, the mission load to ship interface will require power conversion and likely energy storage to be compatible. A variety of solutions can satisfy the derived electrical requirements. The radar power interface and power conversion module are currently under development for a specific platform. The interface and conversion modules will be the foundation for additional platform application as a common weapon and sensor interface and conversion module.

Advanced weapons will require various power levels and voltages. Small directed energy weapons will require hundreds of kW of power and present a pulse load to the DC power source. A directed energy power system between the small directed energy weapon load and the ship's AC electrical power system will be required. It is anticipated that this directed energy power system, hereinafter referred to as Energy Magazine, will incorporate power conversion and may have energy storage to meet ship and load power interface requirements. Figure 10 shows a notional Energy Magazine configuration.

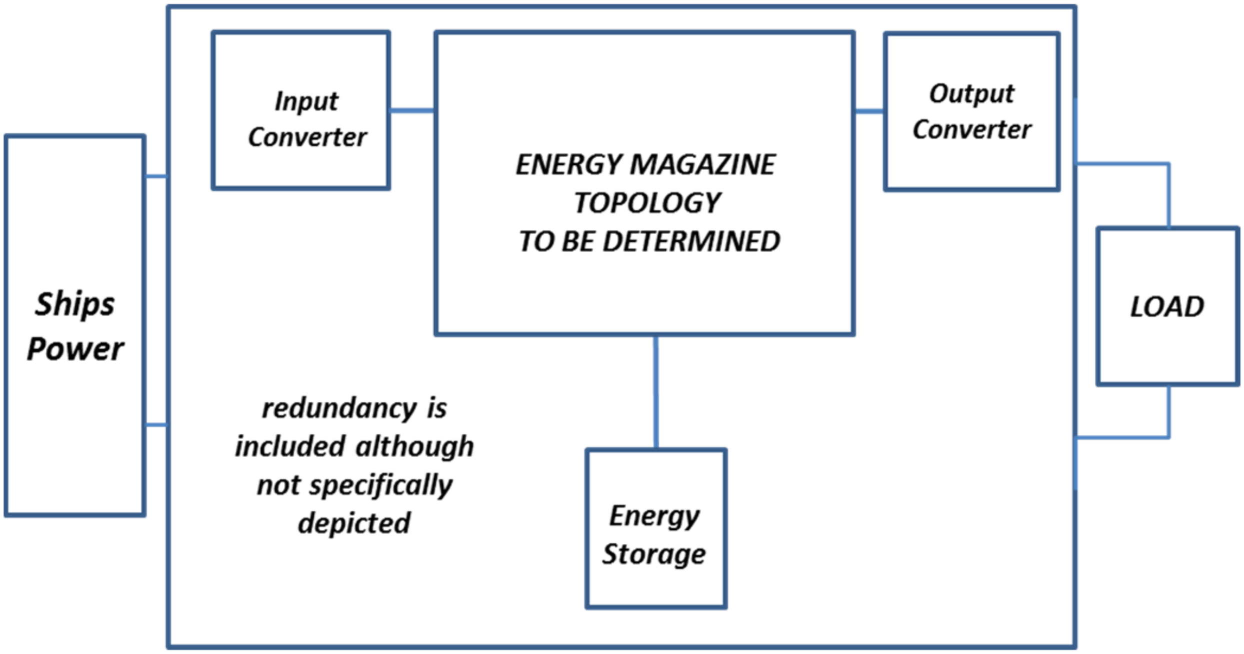

Figure 10: Energy Magazine

The notional Energy Magazine in Figure 10 is meant to represent the trade space for an Energy Magazine, with the final functionality to be determined. It is drawn with multiple power conversion options and energy storage. The trade space includes directly powering the load via conversion with no energy storage, using energy storage to augment power directly supplied from the ship, and powering the load solely via the energy storage. Energy Magazine will be initially designed to integrate small directed energy weapons on a legacy platform with a 450VAC ship's power interface. The Energy Magazine should be isolatable from the main ship service bus, power dense, and efficient.

The Energy Magazine as a system will combine advances in energy storage media, power conversion, distribution and associated protection schemes. Energy capacity, power, and unique load demand (ramp rate, pulse repetition rate, etc.) will drive Energy Magazine requirements. Load interface definition early in design will enable parallel development of Energy Magazine and advanced weapons and sensors. The input converter that provides the interface with the ship service bus may be bidirectional so that the energy storage can support overall power management, load leveling and/or emergency power.

As multiple new mission loads become available for ship integration, the Energy Magazine can be expanded to accommodate multiple loads by providing the appropriate power conversion and energy storage. This multifunctional Energy Magazine may be a distributed system which may introduce design complexity. Advanced controls will be required; different loads may require different interfaces, placing different demands on the Energy Magazine. A standard set of load interface definitions for future weapons and sensors will enable an open architecture approach for a multifunctional Energy Magazine. A notional Energy Magazine with multiple loads is shown below in Figure 11.

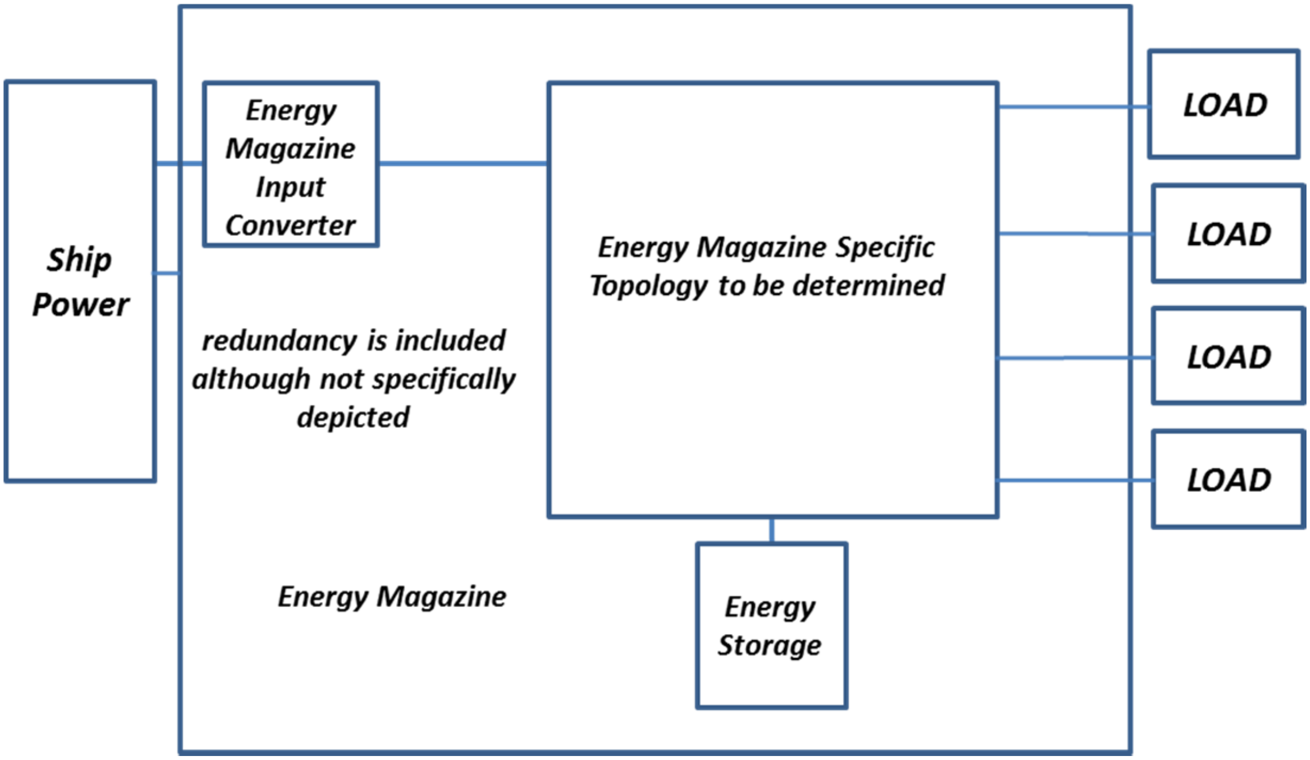

Figure 11: Energy Magazine with multiple loads

Energy Magazine will be an extension of the ship's electrical power system instead of just a load interface. The intent is to optimize the ship electrical power system as a whole vice sub optimizing conversion for each load individually. Bidirectionality will enable Energy Magazine to contribute to ship electrical demands in addition to specific advanced weapon load demands. The ability to feed multiple loads will enable meeting ubiquitous requirements and minimize overall size by maximizing energy and power density in already space constrained platforms.

VII. Near-term (2013-2022) Development Recommendations

Near-term development recommendations are broken into the following four areas:

- Derived requirements driven product and system development
- Ubiquitous requirements and ship integration driven product and system development
- Advanced prototype system development
- Discovery and Invention and future ship power systems

Requirements drive development to meet future capabilities. Section II derived requirements analysis identifies two primary drivers of naval power system electrical requirements - the initial introduction of advanced loads such as weapons and sensors and reducing fuel consumption. These initiatives lead to the following development recommendations which are shown in an integrated technology development and acquisition schedule in Figure 12 at the end of this section.

- An Energy Magazine
    - This system must be flexible enough to accommodate integration with existing distribution voltages on multiple platforms.
    - It must maintain system stability while providing quality power to the load.
    - A power dense, galvanically isolated, bidirectional power converter will provide the most operational flexibility.
    - A power dense, safe, energy storage module capable of rapid charge and discharge may be required.
    - The system should be available between 2018 and 2020.

- An advanced mission systems power upgrade:
    - Capable of integration with a direct energy power system (Energy Magazine) that can support a new high power radar with follow-on applicability to rail gun.
    - Expected to be MVAC
    - Maintain power system stability while providing quality power to the loads
    - Leverage past development efforts in power conversion and energy storage
    - Available by 2022.
    - Supports the Secretary of the Navy’s directive on Energy Security.

- An energy recovery system compatible with both gas turbine and diesel prime movers.
    - Energy recovery systems are used today in commercial ships.

  - The US Navy has several experiences with energy recovery that are considered less than successful. Lessons learned from these previous programs need to be gathered and analyzed.
  - A cost benefit analysis for energy recovery should be performed prior to any hardware development cycle.

Technology advances with potential naval applicability were identified in Section III. These advances can be used to meet ubiquitous requirements and mitigate ship integration challenges. Innovations with immediate expected benefit to the Navy require near-term focus. These focus areas will help mature and advance NPS technologies by leveraging industry advances towards products suitable for Navy use, tailoring and demonstrating system solutions unique to the Navy's needs and fostering innovation and research in development in areas that might not be pursued by Industry alone. In product and system development the Navy should focus on:

- Developing mil-qualified medium voltage (4160V) Vacuum Circuit Breaker (VCB) switchboards that fit within the existing Air Circuit Breaker (ACB) switchboard envelopes by 2015. This development is low risk because the Navy has already developed a 13.8kV VCB solution.

- Developing a scalable, readily adaptable heat exchanger prototype suitable for the high thermal transient operation of naval prime movers, available by 2020. Previous Navy experience in energy recovery systems has demonstrated that the scalability of the heat exchanger was a primary impediment to implementation. Generally, commercial heat exchangers in the size ranges required for naval power systems are not currently in use in naval environments. Note: this effort would be initiated by a detailed cost benefit analysis for energy recovery on a given platform as a precursor to the hardware development cycle.

Section V shows that moving system testing as early as possible in the development cycle is advantageous. Reduced scale testing using functionally equivalent devices allows the Navy to begin to understand complex system behavior and make advances at more affordable investment levels. These demonstrations enable meeting timelines for candidate NPS for mid-term ships.

- Demonstrate a Reduced Scale Advanced Development (RSAD) MVDC power distribution system in the 2018 timeframe. The MVDC RSAD further evolves a notional MVDC ship electrical power system as a candidate for the mid-term ship classes. The RSAD for the DDG(X) / LCS(X) power system EDM confirms technical feasibility of an expanded Energy Magazine and derisks the following:
  - Shared Energy Storage
  - Advanced MVDC Circuit Protection
  - System level functionality to service multiple, high pulse loads

- Develop advanced MVDC circuit protection (devices, controls, etc.) with faster response times to be available in 2019. Reduce the size of MVDC equipment to sizes appropriate for shipboard applications. Develop circuit protection capable of operating above approximately 4kV. This activity is covered under the FY2014 ONR Future Naval Capability (FNC) entitled “Efficient and Power Dense Architecture and Components.”

- Develop an advanced energy magazine functional equivalent available in 2020. This activity is covered under the proposed FY2015 ONR Hybrid Energy Storage Module (HESM) FNC.
    a. This effort is necessary because:
        - The introduction into future warships of advanced weapons systems such as high power radars, rail guns, and lasers will drive new power system architectures and components. In particular, these high pulse rate loads will drive development of energy storage, their control, and medium voltage power conversion.
        - Given the inherent size and weight limitations of ship platforms, dedicated energy storage using existing technology will be too large and too heavy.
    b. Objectives of the energy magazine functional equivalent are:
        - Enable safe operation of energy storage systems
        - Enable affordable high power and energy dense storage
        - Enable multi-function system development and support sharing energy storage capacity among different applications
        - Support back fit on existing platforms and operate with future systems on new platforms

- Develop a universal ship’s power management controller prototype available in 2021
    a. This effort is necessary because:
        - Historically each platform has developed its own unique naval power management system. Further, power management requirements were limited.
        - Requirements analysis project a dramatic increase in power system complexity to meet advanced load requirements. A power manager is required to:
            - Shift to universal type controllers from dedicated, point of use type controllers
            - Optimize use of energy storage for mission systems
            - Optimize ships power system for energy security

        - Service a diverse set of loads while also meeting power continuity and power quality

b. The objectives of the universal ship's power management controller prototype are to:
    - Enable plug and play loads and sources and further enable the adoption of a Modular Adaptable Ship
    - Maximize the flexibility of power management controls to interface with a variety of Machinery Control Systems (MCS)
    - Enable the definition of a common power management interface with MCS

While the preceding investment areas are largely evolutionary in nature, disruptive technology may play a role in future power systems. High risk, high reward technologies pursued in the near-term may influence mid and far-term term ships. Discovery and Invention (D&I) investments are focused on Basic Research and often referred to as 6.1/6.2 funding. Discovery and Invention investments in the following areas have been identified as beneficial to continued advancements in naval power systems.

- Advanced conductors to:
    - Reduce the size, weight and cost of conductors used in electrical equipment on future ships.
    - Improve the efficiency of the naval power systems and components
    - Further advance towards room temperature superconductivity by applying advances in material science such as HTS, carbon nano tubes and covetics.[27,28]

- Advanced solid state energy recovery :
    - Enable thermo-electric energy recovery - quiet, reliable, and no moving parts
    - Allow simplified energy recovery from prime movers through a reduction in required auxiliary system complexity. With additional development, future heat exchangers could either contain thermo-electrical material or be constructed entirely out of thermo-electric material.

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[27] http://www.ysusef.org/wp-content/uploads/2012/05/EV.TM2_.David_.Miller1.pdf
[28] http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA555871

These technologies are heavily material dependent with the current focus on obtaining desirable material properties and acceptable costs. Figure 12 displays an integrated technology development and acquisition schedule for the near-term:

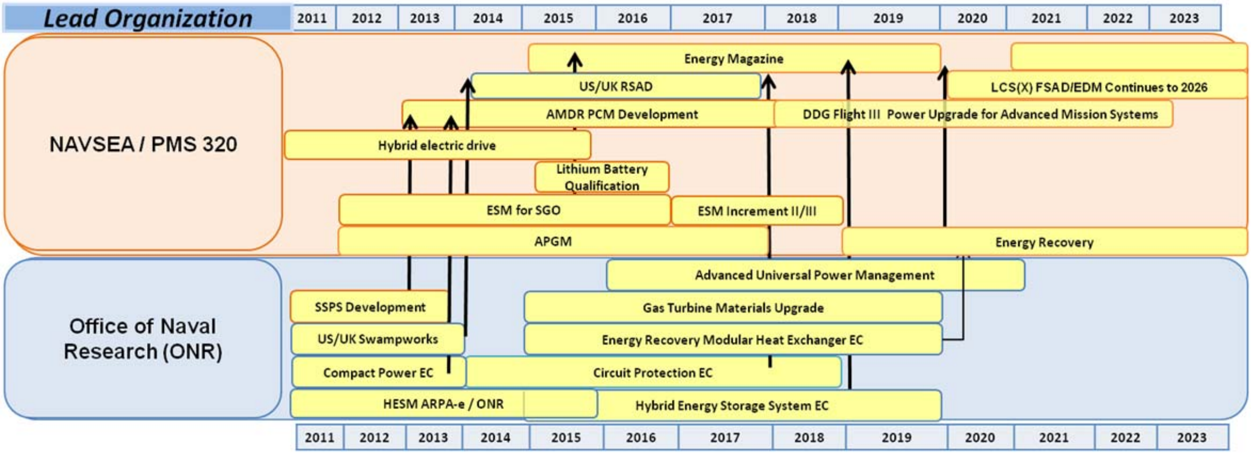

Figure 12: Integrated technology development and acquisition schedule (2013-2023)

Table 9 table below contains the list of Product Areas and their near-term target metrics. The metrics listed in the TDR are not necessarily focused on individual products but based on the hardest to obtain category and designed to establish targets for industry. Near-term investments should focus on meeting or exceeding the performance identified in the table below.

Table 9: Near-term Functional Area Metrics

Component	Critical Metrics	Benchmarks	Targets
Electric Machines		**LHD-8 Induction Motor**	
	Nominal Power Level	3.73 MW	2-4 MW
	Power Density	200 kW/m3	300 kW/m3
	Motor or Generator	Motor	Dual Function (Bidirectional)
	Packaging	Military Hardened	Military Hardened
Energy Storage		**COTS Lead Acid Battery**	
	Nominal Power Level	600 kW	12-13 MW
	Nominal Energy Storage	72 MJ	3.6-4.0 GJ
	Package	Shock mounted enclosure	Shock mounted enclosure
	Lifetime	1200 cycles	2000 cycles with 80% Depth of Discharge
	Large Format Safety	Yes	Meets Naval safety regulations
	Discharge capability	Full discharge: 15 minutes to 4+ hours	Full discharge in approx. 2 minutes
	Charge capability	Full charge in 4-8 hours	Full charge in 12-15 minutes
	Package Power Density	177 kW/m3	750-850 kW/m3
	Package Energy Density	21.3 MJ/m3	225-250 MJ/m3
Converters		**IFTP PCM 4**	
	Nominal Power Level	3 MW	800 kW - 4 MW
	Package	Military Hardened	Grade A
	Cabinet Power Density	0.25 MW/m3	0.33 - 1MW/m3
	Efficiency	96%	98%
	Interface-1 voltages	4160, 450 VAC	13.8kV, 4.16kV,

Component	Critical Metrics	Benchmarks	Targets
			1kVDC, 440VAC
	Interface-2 voltages	1000 VDC	70-1000VDC
	Functionality	Unidirectional Galvanically Isolated	Bi-directional Galvanically isolated
	Transformer with:	**LHD-8**	
	Nominal Power Range	3 MVA	3-5 MVA
	Volumetric Power Density	300 kW/m3	600 kW/m3
	Gravimetric Power Density	.3 kW/kg	0.6 kW/kg
Distribution			
Circuit Breakers	**Vacuum Circuit Breaker with:**	**LHD8 / LHA8 / DDG 51 FLT III 4160 VAC Switchboard**	
	Switchboard Level Power Density	8.5 MVA/m3 (single breaker)	10-13 MVA/m3 (two breakers)
	Improved Safety		Dead-front, grounding means, continuous thermal monitoring, arc-fault protection
	Section Cost	$400K (Current cost w/ACBs)	$200K
	Breaker/System:	**Existing Navy Shipboard Circuit Protection Equipment**	
	Voltage	AC	1kVDC ungrounded
	Current	4800A (450V); 2000A (4160V)	100-2000A
	Response Time	128 ms	< 8 ms
	Volumetric Power Density	40 MW/m3	40 MW/m3

Component	Critical Metrics	Benchmarks	Targets
	Lifetime	8,000 cycles	10,000 cycles
	Air-gap Provision		Provided
	Interfaceable with	Existing Philosophy and interface with generators, converters and batteries	Ability to interface with a Generator, Converter, Battery, Capacitor
	Protection Capability		Bidirectional supporting various architecture configurations, Eliminates false trips, Ensures smart reconfiguration of electrical system
Cables	N/A	**Legacy Navy MV & LV cabling**	Legacy MV & LV cabling
Prime Movers		**Ship Service Prime Mover**	
	Nominal Mechanical Power	4 MW	4.5 MW
	Specific Fuel Consumption at 100%	.29 kg/kW-hr	0.29 kg/kW-hr
	Volumetric Power Density	2 MW/m3	2 MW/m3
	Gravimetric Power Density	5.2 kW/kg	5.2 kW/kg
Controls			
	Ability to handle multiple types of energy storage	**TBD**	
	Ability to pass power bi-directionality and to enable multiple loads fed from same energy storage system		
	Ability to energy/power manage in Energy Magazine to control pulse loading seen on electrical system.		

VIII. Mid-Term (2023-2032) Requirements Analysis

Aligning technologies to requirements in the mid and far-term periods involves additional uncertainty for both mission systems and ship platforms. Nearly all of the new construction platforms will be procured during the mid and far-term periods, thus the power system requirements for these platforms are yet to be determined. The NPS TDR approach is to posit future systems, project future power needs based on these systems, and predict systems engineered solution approaches that will require development. This section discusses the posit/project/predict approach and results for mid-term requirements. The intent is to remain flexible enough to enable any or all predicted mission/ship system derived electrical requirements and allow compatibility with a future modular adaptable ship.

The analysis is based on developments to support a DDG(X) and LCS(X) as shown in the 30 year shipbuilding plan. Projected upcoming sensor and weapons systems will be combined into new mission suites in the mid-term. These suites may include enhanced radars, more capable electronic warfare systems, lasers (already projected for fielding in the near-term), future directed energy weapons, and rail guns. Predicted derived electrical requirements for the mission suites include:

- Higher power
- Larger power pulses
- Multiple power interfaces
- Increased Hull, Mechanical & Electrical (HME) power requirements to support increased thermal management

The mission suite electrical requirements predicted above were evaluated for power system options to support mission load requirements. In a first cut at the power system design space, candidate solutions were analyzed using notional projected ships for the DDG(X) (a 10,000 ton, 30 knot ship) and LCS(X) (a 5,000 ton, up to 40 knot ship) to understand the basic HME implications of higher power for mission systems. Three candidate power systems were identified. All require some sort of energy magazine to meet the mission interfaces. The results are presented below in general terms.

The first candidate power system retains the traditional status quo where ship service generators provide power for mission and other electrical loads. Generation must in total provide enough power to meet maximum demand with one generator offline. Thus, prime movers and their associated generators must be in size ranges to provide this power. Larger power levels involve some combination of increased generator set capacity and more generator sets in the design. Predicted power levels for the notional DDG(X) are in the 10 MW range, which also calls for medium voltage generation and distribution.

The second candidate power system augments ship service generators with a hybrid generation capability such as propulsion derived ship service (PDSS). This solution may eliminate the need to install additional or larger prime movers by using a power takeoff from the propulsion train. If able to operate in reverse, the PDSS could provide limited propulsion.

The third candidate power system involves an IPS which adds propulsion as a ship electrical load. Selection of IPS is attractive if the size of the mission load is within an order of magnitude of the propulsion load. IPS opens trade space to provide less overall ship power (electrical for IPS vs. electrical and mechanical for other candidates) if full speed is not required concurrently with full mission load.

The mid-term development recommendations in the next section incorporate aspects of all three candidate power systems. Additionally, all candidates require an enhanced energy magazine capability to meet mission interfaces. Energy Magazine capability improvements include:

- High power AND high energy performance
- Ability to intelligently prioritize multiple mission loads (may be an input to the Energy Magazine based on operator priorities)
- Common or selectable mission system interface

Other general mid-term requirements include the ability to meet new and emerging capability requirements, upgrade legacy systems, provide extended service live, and improve performance associated with ubiquitous requirements. Meeting these requirements involves continued investment in D&I and advancing the state of the art across all technical areas associated with naval power systems. Medium voltage advances, both for AC and DC, are of particular interest as total ship electrical power demand increases with time. Successes from near-term developments should be pursued if still applicable, especially breakthroughs that could lead to mid-term revolutionary changes.

IX. Mid-Term (2023-2032) Development Recommendations

Mid-term development recommendations are dominated by NPS EDMs for the DDG(X) and LCS(X). Time phasing of NPS development for the mid-term is critical. Engineering Development Modules (EDMs) supporting the Milestone B FY 2030 and 2031ships should be completed and ready for testing by approximately FY2025. Thus, any EDMs requiring development will be POM-20 or POM-21 issues. Any Science and Technology (S&T) development required needs to begin in FY-15 or 16. The following mid-term development recommendations are provided:

- An EDM focused on MVDC
    - Because of increases in loads, the FY2030 combatant will require more generation capacity than can be provided using a segregated plant on a DDG 51 hull.
    - To provide power to all of the loads, DC power distribution appears to be appropriate technology. Previously conducted shipyard studies have shown the advantages of DC power distribution in the long term.
    - The additional generation and distribution requirements indicate this ship will have some sort of integrated power system. A goal of this EDM is to conduct the necessary investigation into the loads, physical integration and power requirements studies to determine if the system is a mechanically or electrically integrated NPS.
    - In order to support MVDC for a FY2030 ship, EDM efforts must initiate in the early FY20s timeframe. Prior to the EDM, FNCs have to start in FY2015 and work towards full scale demonstrators in FY2020. These activities will support AoAs in the FY2025 / FY2027 timeframe.

- A 2031 DDG(X) Naval Power System target delivery date 2026 that may require:
        - Modular Capability (Based on the development timelines, it is recommended that the naval power systems currently under development for insertion on the FY 30 and 31 medium and small surface combatants be compatible and enable “modular capability.)
        - An advanced high power density propulsion motor and motor drive system
        - An advanced high power density power generation system
        - Advanced circuit protection
        - Fully integrated advanced Energy Magazine
        - High efficiency prime movers with energy recovery capability
        - Advanced NPS power management controls

- A 2030 LCS(X) Naval Power System target delivery date 2025

- Enable significantly increased power to LCS mission modules
- PEO LCS identifies Power and Energy (P&E)/Energy Efficiency as a Technology Enabler in their *Science & Technology Investment Strategy and Implementation* document:
  - “The P&E roadmap developed for PEO LCS focuses on maximizing P&E efficiency for the Seaframes.”
  - “Over time, this increased efficiency will allow more P&E budget being allocated to the Mission Packages, thus enabling more capable weapons and sensors.”
  - “Additionally, unmanned maritime systems require improved P&E technologies to enable longer endurance.”

Table 10 below contains the list of Product Areas and the target metrics necessary to meet the navy’s power system goals in the mid-term.

Table 10: Mid-Term Product Area Metrics

Component	Critical Metrics	Benchmarks	Targets
Electric Machines			
Motor/ Generator	Efficiency	97.9%	97-98.5%
	Packaging	Military Hardened	Military Hardened
Propulsion Motor	Nominal Power Level	32-34 MW	21-36 MW
	Gravimetric Torque Density	12 N*m/kg	28-50 N*m/kg
	Volumetric Power Density	200 kW/m3	650-900 kW/m3
	Gravimetric Power Density	0.2 kW/kg	0.5 - 0.8 kW/kg
	Speed	< 170 rpm	< 170 rpm
Generator			
	Nominal Power Level	4 MW & 21-36 MW	4-6 MW & 21-40 MW
	Volumetric Power Density	.2 MW/m3 and .5 MW/m3	.26-.38 MW/m3 and 3.5-4 MW/m3
	Gravimetric Power Density	.24-.65 kW/kg	1.5 - 2 kW/kg
Gas Turbine Genset	Machinery space stackup length	39 feet	39 feet
Energy Storage		**COTS Lead Acid Battery**	SSL & railgun minimum threshold + margin
	Nominal Power Level	600 kW	18-20 MW
	Nominal Energy Storage	72 MJ	5.4-6.0 GJ
	Package	Shock Mounted Enclosure	Shock mounted enclosure
	Lifetime	1200 cycles	6000 cycles with 80% DOD
	Large Format Safety	Yes	Meets Naval safety regulations
	Discharge capability	Full discharge: 15 minutes to 4+ hours	Full discharge in approx. 2 minutes
	Charge capability	Full charge in 4-8 hours	Full charge in 12-15 minutes
	Package Power Density	177 kW/m3	750-1800kW/m3
	Package Energy Density	21.3 MJ/m3	225-540 MJ/m3
Converters	**High Power Converter**	**Navy Motor Drive Converters**	
	Nominal Power Level	21-40 MW	21-36 MW
	Packaging	Shock Mounted	Shock mounted

Component	Critical Metrics	Benchmarks	Targets
		Enclosure	enclosure
	Cabinet Power Density	.35- .78 MW/m3	1.25 - 2 MW/m3
	Efficiency	98-99%	98 - 99%
	Functionality	Medium Voltage Low Harmonic Drive	Medium Voltage Low Harmonic Drive
	Interface voltages	4160 V AC, 13.8 kV AC	6kVDC, 20kVDC, 4160VAC, 13.8kVAC
	Low Power Converter	**Navy Converter Benchmark**	
	Nominal Power Level	2-10 MW	2-10 MW
	Packaging	Shock Mounted Enclosure	Shock mounted enclosure
	Cabinet Power Density	.25 MW/m3	1.25 - 2 MW/m3
	Efficiency	96%	97-99%
	Functionality	Bi-directional Power Converter, galvanically isolated	Bi-directional Power Converter, galvanically isolated
	Interface 1 voltages	4160 VAC, 13.8 kVAC, 1 kV DC	4160 VAC, 13.8 kVAC, 6 kV DC, 20 kV DC
	Interface 2 voltages	70-1000 V DC, 440-460 VAC	70-1000 V DC, 440-460 VAC
Cables		**Navy Cable Benchmark**	
	Style	Legacy MV Cabling	Advanced MV Cabling
	Packaging	Shock Harden	Shock Harden
	Bend Radius	8 times diameter	24 inches
	System Weight per meter	8.2-9.7 kg/m	3 kg/m
	Voltage	4160 VAC, 13.8 kVAC, 1 kV DC	4-15 kV AC or 6- 20 kV DC
	Gas flame circuit integrity @ 4-20 kV	3 hours	3+ hours
	Rated Current	400 A / cable	4000A
Distribution			
	Transformer with:	**LHD-8 Transformer**	
	Nominal Power Range	3 MVA	3-5 MVA
	Volumetric Power Density	300 kW/m3	900 kW/m3
	Gravimetric Power Density	.3 kW/kg	3.0 kW/kg
	Breaker/System:	**Current Navy Circuit Protection**	
	Voltage	AC	up to 13.8 kV AC, up to 20 kV DC
	Current	4000	50-4000 A

Component	Critical Metrics	Benchmarks	Targets
	Response Time	128 ms	0.5-8 ms
	Volumetric Power Density	40 MW/m3	43 MW/m3 threshold, 48 MW/m3 objective
	Lifetime	8,000 cycles	10,000 cycles
	Air-gap Provision		Provided
	Efficiency		99.5-99.8%
	Interfaceable with	Existing Philosophy and interface with generators, converters and batteries	Ability to interface with a Generator, Converter, Battery, Capacitor
	Protection Capability		Bidirectional supporting various architecture configurations, Eliminates false trips, Ensures smart reconfiguration of electrical system, Minimize collateral damage to ships environment, Eliminates tenable space casualty due to arc fault event
Prime Movers		**Ship Service Prime Mover**	
	Nominal Mechanical Power	21-40 MW	25-40 MW
	Volumetric Power Density	2 MW/m3	2 MW/m3
	Gravimetric Power Density	5.2 kW/kg	5.2 kW/kg
	Efficiency	36% @ 100 percent load (Large GTG) 28.6% @ 100 percent load (Small GTG)	5-20% efficiency increase from benchmarks
Controls			
	Ability to handle multiple types of energy storage	Existing MCS	TBD
	Ability to pass power bi-directionally and to enable multiple loads fed from same energy storage system		

X. Far-term (2033-2042) Requirements Analysis

Anticipating both required capabilities and available technologies in the far-term involves additional uncertainty, but certain trends have become evident that build upon the assessments performed for the mid-term. It is expected that additional directed energy weapons requiring even more power will become available in the far-term as well as higher powered improved sensors and rail guns of increased size and capability. It is likely that Navy platforms will have many of these systems operating simultaneously, that the Navy will introduce additional modular ships with modular payloads, and that electric power systems will be required to continue to improve in the following areas:

- Provide improved power system flexibility
- Power system simplification will be desirable (less parts reduce cost)
- Power system cost reductions will be desirable
- Power system volumetric and gravimetric density increase will be desirable
- Power system modular upgradeability

XI. Far-term (2033-2042) Development Recommendations

The following supporting product and system developments will be required in the far-term:

- Build and test a solid state energy recovery system
    - Advanced materials that can support waste heat scavenging hold promise as additional sources of power on future ships.

- Build and test a full scale 500kW fuel cell power generation system capable of using logistic fuels
    - The use of logistic fuels present in the Navy today is a critical requirement for widespread adoption of fuel cells as a prime mover on future Navy ships. This effort builds on the body of knowledge achieved by the navy and industry thus far in powering fuel cells from marine diesel and other distillate fuels.
    - Innovation here could potentially lead to wider adoption of fuel cells aboard future Navy ships and even allow multiple, smaller point of use type prime movers.

- Build or adopt advanced electrical cables for shipboard use
    - Drastically reduce distributed system weight for cables
    - Reduce bend radius for the same ampacity
    - Increase maximum ampacity per cable

- Build and test advanced innovative electrical distribution system circuit protection
    - Eliminate centralized load centers/switchboards (inline circuit protection, converters, etc.)
    - Reduce electrical distribution system weight
    - Reconfigurable power transmission paths

- Promote D&I for advanced wide bandgap semiconductor devices
    - Emergent technologies that could be the target of D&I funding should be monitored

- Eliminate separate Ethernet cables
    - Combine Ethernet/control signals over power lines
    - Transmit Ethernet/control signals wirelessly

XII. Conclusion

The stated purpose of this TDR is to align electrical power system developments with warfighter needs and enable capability based budgeting. It is meant to be a living document, updated biannually, that invites innovation and guides investment by DOD, government, industry, and academia to achieve synergistic advances in naval power systems. Recommendations have been provided based on available information, engineering judgment, and projected requirements. The historic timelines for major component and large system development such as the gas turbine engine and IPS can take up to about 20 years to transition to the fleet whereas smaller subsystems such as the LHD 8 hybrid electric drive can take up to 8 years. During the same length of time, the Navy 30 year Shipbuilding Plan changes, ship programs are initiated and terminated and threats to our security change constantly. This TDR proposes multiple paths to continue providing targets in the face of uncertainty.

Long term trends directly leading the development of Naval Power Systems are expected to continue. In general, they are:

- Navy platforms will require more electric power, on demand, to meet the needs of ever improving mission systems.
- The power density of the electric power system will need to continue improving to meet the increasing demand in the same foot print.
- Economic realities will force the Navy to keep current platforms in service longer than originally planned
- These platforms will be looked upon to service advanced weapons and sensors due to emerging threats.

A fundamental tenet in technology development and transition is to have the right technology, at the right time, for the right task. Under this construct, the overall capabilities present the “right task” and the Roadmap presents the “right technologies, at the right time” to sync up with the planned shipbuilding cycle. This roadmap promotes communication and collaboration and eliminates the need for industry to guess where the Navy is headed. It seeks to create an environment that enables industry to better understand Navy investment priorities and also enables the Navy to leverage industry investments.

Technological superiority is critical to maintaining the US Navy’s position as the world’s premier naval force. This roadmap supports that technological superiority by focusing and directing investments and developments. It integrates the investments of the Navy, other DoD, and Industry with the innovative power of Academia. It tells all of our stake holders where we see our needs in the future to the extent that those needs can be forecast today.

List of Acronyms

AAW Antiair Warfare
AIM Advanced Induction Motor
AMDR Air and Missile Defense Radar
AoA Analysis of Alternatives
ASN RDA Assistant Secretary of the Navy for Research, Development and Acquisition
CBRN Chemical, Biological, Radiological, and Nuclear Defense
COTS Commercial Off The Shelf
DBR Dual Band Radar
DEW Directed energy weapon
D&I Discovery and Invention
DoD Department of Defense
ECP Engineering Change Proposal
EDM Engineering Development Model
EMRG Electromagnetic Railgun
ESG Executive Steering Group
ESM Energy Storage Module
FNC Future Naval Capability
FSAD Full Scale Advanced Development
GaN Gallium Nitride
HCCI Homogenous Charge Compression Ignition
HFAC High Frequency Alternating Current
HME Hull, Mechanical & Electrical
HMI Human Machine Interface
HSI Human System Interface
HZ Hertz
I^2R Current squared times resistance (equals power loss)
IFTP Integrated Fight Through Power
IGBT Insulated-gate bipolar transistor
IPS Integrated Power System
ISR Intelligence, Surveillance and Reconnaissance
IWS Integrated Warfare Systems
J Joule
JCIDS Joint Capabilities Integration and Development System
kW Kilowatt
LBES Land Based Engineering Site
LIPS Load Interface Power System
LNG Liquefied Natural Gas
LVAC Low Voltage Alternating Current
M&S Modeling & Simulation

MARPOL The International Convention for the Prevention of Pollution from Ships
MOSFET Metal oxide semiconductor field effect transistor
MVAC Medium Voltage Alternating Current
MVDC Medium Voltage Direct Current
MW Megawatt
NAVSEA Naval Sea Systems Command
NGIPS Next Generation Integrated Power System
NOx Nitrogen oxides
NPS Naval Power System
NSWCCD Naval Surface Warfare Center Carderock Division
ONR Office of Naval Research
OPNAV Office of the Chief of Naval Operations
PCCI Pre-Mixed Charge Compression Ignition (PCCI)
PCM Power Conversion Module
PCON Power Control Module
PCS Power Control System
PDM Power Distribution Module
PDSS Propulsion Derived Ship Service (PDSS)
PEO Program Executive Office
PGM Power Generation Module
PID Proportional–integral–derivative
PLC Programmable Logic Controllers
PLM Power Load Module
PM Permanent Magnet
PMS Program Manager, Ship
PPS Pulse per second
PSC Power Systems Controllers
QoS Quality of Service
RCCI Reactivity Controller Compression Ignition (RCCI)
RFI Request for Information
RPM Revolutions per minute
RSAD Reduced Scaled Advanced Development
RWG Requirements Working Group
S&T Science and Technology
SCD Ship Change Document
SEWIP Surface Electronic Warfare Improvement Program
SiC Silicon Carbide
SID Ship Installation Drawing
SOx Sulfur oxide
SSES Ship Service Engineering Station
SSL Solid State Laser

TDR Technology Development Roadmap
TEWAC Totally enclosed water to air cooled
TRL Technology Readiness Level
TWG Technology Working Group
UNTL Universal Naval Task List
UPS Uninterruptible Power Supply
VSD Variable Speed Drive
W Watt
ZEDS Zonal Electrical Distribution System

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