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From R&D to Readiness: Navigating Technology Transitions with the Naval Power and Energy Systems Technology Development Roadmap

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From R&D to Readiness: Navigating Technology Transitions with the Naval Power and Energy Systems Technology Development Roadmap

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Abstract

Power and energy will remain fundamental to maintaining the U.S. Navy's decisive maritime advantage, enabling advanced sensors, electronic warfare, directed-energy weapons, resilient power and propulsion systems, and operationally dominant integrated combat system capabilities. In an increasingly competitive and rapidly evolving threat environment, the Navy will chart a course to strengthen today's Fleet and accelerate capability delivery for next-generation surface ships and systems. The Naval Power and Energy Systems Technology Development Roadmap (NPES TDR) should serve as a strategic mechanism to synchronize research and development (R&D) across the acquisition community, ensuring that emerging capabilities will mature in lock step with the operational requirements.

By applying insights from established roadmapping theory, this paper demonstrates how the next NPES TDR should guide gap analyses, stakeholder collaboration, and iterative technology readiness evaluations. Through an illustrative case study, a laser weapon system, part of the Navy's solid-state laser technology maturation effort, it explains how the roadmap could streamline technology transition timelines, minimize risk, and align with complex budget cycles. The analysis also addresses enduring challenges, such as bridging the extended expected service life of naval platforms. Concluding with targeted recommendation—such as conducting regular roadmap updates, adopting scenario-based planning, and deepening public-private partnerships—this paper asserts that technology roadmaps such as the NPES TDR are essential to increasing lethality, accelerating warfighting capabilities, and improving readiness amidst fast-changing technical and strategic conditions.

Keywords: defense industrial base, requirements management, technology transition, adaptive acquisition framework/rapid acquisition, engineering and technical management

Introduction

"The versatility of our surface force deters adversaries globally and enables rapid, coordinated responses to emerging threats. Our ships must be prepared to engage the full spectrum of threats, from existing capabilities to emerging ballistic and hypersonic missiles."

Admiral James W. Kilby, Vice Chief of Naval Operations
Statement on the Readiness of the U.S. Navy before the Senate Armed Services Committee, Subcommittee on Readiness and Management Support, March 12, 2025

In an increasingly complex and contested global environment (Kilby, 2025), power and energy systems will serve as a cornerstone of the Navy's combat effectiveness. These systems will provide the power necessary for lethal effects, accelerate warfighting capabilities, and sustain Fleet readiness. However, despite investments in advanced electrical power systems since the early 1990s, the Navy will continue to face challenges integrating advanced power electronic equipment—such as high-current semiconductor devices—into current and future ship systems (Doerry & Amy, 2024). Modern power and energy solutions will demand rigorous attention throughout the development life cycle to preempt costly redesigns if adequate size, weight, and power (SWaP) margins are not allocated for the platform's expected service life (Doerry & Amy, 2020; IEEE, 2023). This complexity—combined with uncertainties in linking early-stage research to real-world fleet adoption—risks perpetuating the valleys of death (see, for example, Figure 1) experienced where promising technologies fail to transition at various points of development before transitioning to a formal program of record (Letts, 2024). Technology roadmaps, such as the 2019 *Naval Power and Energy Systems Technology Development Roadmap* (NAVSEA, 2019), will require continuous updates and function as a "living document." Through iterative updates, the Fleet should maintain access to robust, scalable power solutions aligned with mission capabilities—from surface warfare and conventional strike to integrated air and missile defense to assert dominance and project power.

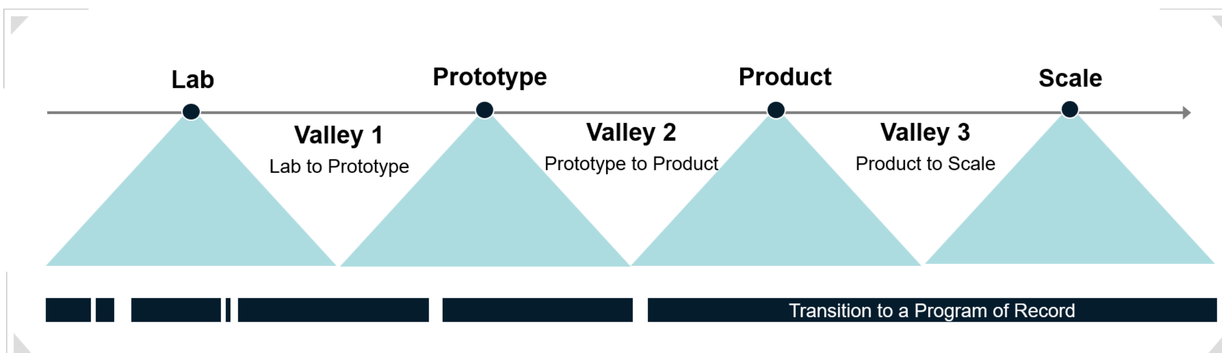

Figure 1. Crossing the U.S. Department of Defense Valleys of Death (Adapted from McEntush and Hay, 2025)

To address these challenges, updates to the Naval Power and Energy Systems Technology Development Roadmap (NPES TDR) should coordinate closely with government laboratories, technical authorities, program offices, industry partners, Fleet stakeholders, and resource sponsors, aligning technology transition efforts with the Navy's longer-range strategy. By embedding risk reviews, readiness thresholds, and cross-functional collaboration, the NPES TDR will incorporate a mission-led capability perspective, where iterative feedback loops replace linear innovation (Moore, 2024). This paper examines how the NPES TDR could further streamline the path from early-stage research to Fleet adoption of vital power and energy systems. Specifically, it shows how roadmapping principles can help structure phased testing, optimize resource allocation, and adjust technical priorities when necessary (Phaal et al., 2024).

This paper begins with an examination of technology roadmapping, defined by Kerr and Phaal (2022, p. 13) as "the application of a temporal–spatial structured lens" to support research and development decisions by identifying critical technologies and gaps (Garcia & Bray, 1997). The Roadmap as a Strategic Planning Tool section positions the NPES TDR within broader strategic planning frameworks used within the naval acquisition community, underscoring the theoretical underpinnings of the roadmap approach. The NPES TDR in Action: Key Processes section then explores the roadmap's operational processes—such as data gathering, industry engagement, gap analysis, and cross-functional collaboration—and outlines how they will keep the NPES TDR adaptive and outcome-focused. The Research to Readiness: Key Outcomes and Lessons Learned section presents tangible outcomes and lessons learned, including the successful demonstration of directed-energy weapons enabled by energy storage technologies progressing from early laboratory research to real-world applications. Discussion: Challenges and the Way Ahead addresses ongoing challenges, such as the extended expected service lives of surface ships, budget constraints, and the integration of emergent digital engineering practices. Finally, the Conclusion offers forward-looking recommendations to ensure the NPES TDR remains a living document, retaining practical relevance amid evolving technological and operational demands.

The Roadmap as a Strategic Planning Tool

Definition and Scope of Technology Roadmaps

Technology roadmaps will become integrative planning tools that coordinate upcoming ship and system-level milestones, resource allocations, and mission scenarios within a unified, time-phased framework (Phaal et al., 2021). By fusing "technology push"—the outputs of laboratories, industry, and academia—with "requirements pull"—the operational needs of the surface navy—this roadmap will offer a holistic strategy for directing innovation. In contrast to linear Gantt charts, they will incorporate iterative readiness gates, stakeholder engagement points, and forward-looking force development objectives (Garcia & Bray, 1997).

For the U.S. Navy, these attributes will prove vital. Complex warfighting capabilities require synchronization across propulsion, ship-service power generation systems configuration, any available energy storage systems (Araujo et al., 2024; Doerry & Amy, 2017; McCoy, 2025). A well-structured roadmap will help senior decision-makers envision how one emerging area of research and development—such as a modular universal converter building blocks (Lawson et al., 2024)—might intersect with broader modernization initiatives or doctrinal shifts. By combining near-term readiness checkpoints with longer-range objectives, technology roadmaps could accelerate capability maturation and better align R&D (Kerr, 2023).

The Value Proposition of NPES TDR

The NPES TDR will represent a mission capability-led adaptation of general roadmapping principles (Figure 2). By placing naval power and energy solutions within acquisition timelines and ship modernization availabilities, the NPES TDR will align R&D milestones with operational readiness (Markle et al., 2021). Moreover, it will integrate structured risk assessments and validation trials, ensuring no technology proceeds into Fleet integration without targeted readiness reviews. This sequential approach—comparable to standard Technology Readiness Levels (TRLs)—is expected to promote transparency, allowing acquisition milestone decision authorities to authorize procurement only after a system meets prescribed maturity thresholds (Olechowski, 2020).

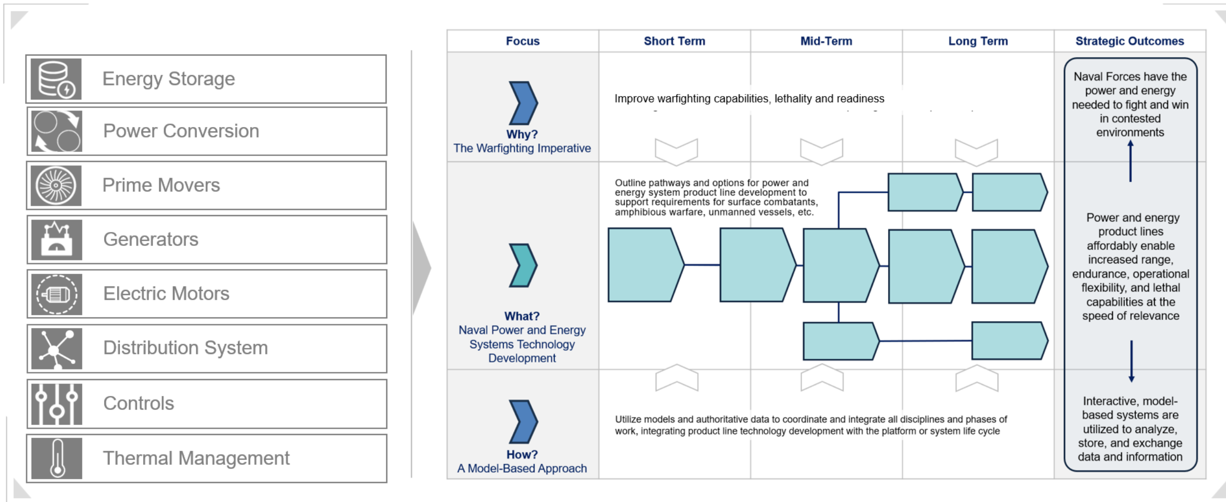

Figure 2: Governing Technology Roadmapping Framework (Adapted from Phaal, 2024)

Another key feature of NPES TDR will be its capacity for recalibration. Although the initial roadmap will define near-, mid-, and long-term objectives, it will incorporate feedback loops that respond swiftly to newly emerging technologies or threats (Chakraborty et al., 2022). In so doing, NPES TDR will replace static planning documents and stand-alone technical reports and act instead as a dynamic guide that balances established milestones with agile responsiveness to evolving needs (Ding & Ferràs Hernández, 2023).

Aligning Research with Acquisition Cycles

Historically, misalignment between R&D progress and formal acquisition steps within the Department of Defense (DoD) has often stemmed from organizational siloes (Kotila et al., 2023). Naturally occurring due to distinct functional areas, specialized expertise, and separate budgetary streams, siloes create communication gaps, narrative drift, and divergent timelines (Jeske & Olson, 2024). As a result, promising technologies developed in research laboratories frequently face delays or fail to transition effectively into acquisition programs, leading to underutilized capabilities and diminished operational advantage (Wong et al., 2022).

The NPES TDR aims explicitly to bridge these siloes by embedding clearly defined readiness-level checkpoints within the strategic roadmap. By stipulating specific maturity benchmarks (Ma, 2021), such as achieving TRL 6 or higher—which indicates successful demonstration of power and energy systems/subsystems in relevant operational environments—the roadmap systematically aligns technological advancements with formal acquisition processes. This alignment ensures that once these systems reach a designated readiness threshold, they become candidates for immediate consideration within funded programs of record (Stotts et al., 2010), specifically outlined in the Future Years Defense Program (FYDP).

Supported by this structured approach, the NPES TDR facilitates better synchronization between technology developers, program managers, and acquisition officials. Consequently, it reduces the historical gap between cutting-edge laboratory developments and tangible fleet capabilities (Tuinstra, 2022). The strategic, iterative decision gates built into the roadmap provide a mechanism for continuous evaluation and refinement, further enhancing communication across departmental boundaries (Cilli, 2015). Ultimately, the structured, strategic roadmapping methodology inherent to the NPES TDR—characterized by rigorous, proactive assessments and timely interventions—promotes more efficient technology adoption, optimizes resource allocation, and enhances overall defense readiness.

NPES TDR in Action: Key Processes

The NPES TDR should serve as a continually updated strategic plan, aligning power and energy system development with new and emerging warfighting requirements. It should be structured to provide a time-phased trajectory (2025–2035+) for the evolution critical power and energy systems, with executive steering group governance—consisting of SYSCOM stakeholders, Program Executive Offices (PEOs), Resource Sponsor, Fleet representatives, and all associated technical authorities—reviewing it regularly. This governance approach would integrate analytical foresight (Garcia & Bray, 1997; Hussain et al., 2017; Phaal et al., 2021) with acquisition imperatives, ensuring that the NPES TDR guides R&D activities within the Navy, industry, and academia. Four interrelated processes: (1) data gathering and requirements analysis, (2) industry engagement, (3) gap analysis and prioritization, and (4) cross-functional collaboration, will keep the NPES TDR relevant and flexible (Kerr & Phaal, 2021).

Data Gathering and Requirements Analysis

Data gathering and requirements analysis forms the foundation of the NPES TDR, aligning strategic objectives with technological feasibility. First, top-level directives (e.g., the National Security Strategy [NSS], National Defense Strategy [NDS], CNO's Navigation Plan [NAVPLAN]) form a strategic framework for U.S. national security, with the NSS outlining broad national security goals (Anderson & Karambelas, 2024), the NDS detailing how the DoD will contribute to those goals (Harman et al., 2024), and the NAVPLAN focusing on the Navy's role in achieving those objectives (Ullman, 2024). Next, fleet force structure reviews identify platforms and their operational profiles. Simultaneously, PEOs, SYSCOM technical authorities, Navy Surface Warfare Center (NSWC), and the broader Naval Research Enterprise will supply technical data, including power margins and load growth forecasts.

Mission-driven scenario modeling and digital engineering approaches (Ames et al., 2024; Voth & Sturtevant, 2022) should reveal challenges to future power distribution or availability for specific platforms (Figure 3). Upon validation, these shortfalls can be identified as potential capability gaps. Data from naval technical authorities, subject matter experts, RFIs and market surveys will refine assumptions about technology readiness, enabling near-real-time revisions of performance targets. This adaptive roadmapping approach (Phaal, 2024) will incorporate diverse sources of data, preventing NPES TDR from stagnating or becoming outdated.

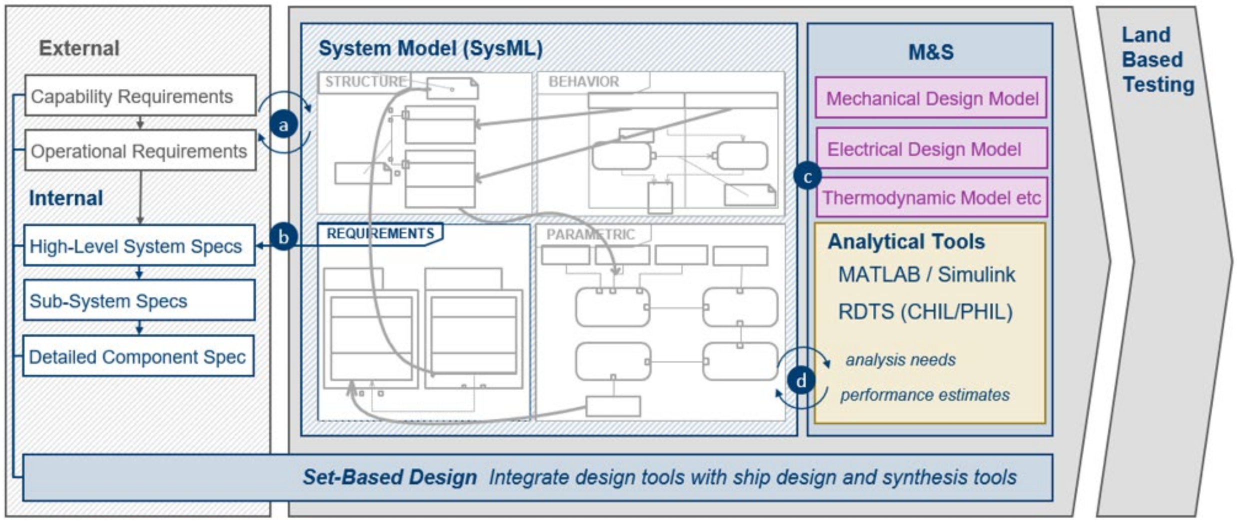

Figure 3. Cut Through Complexity with a Formalized Application of Modeling to Support System Requirements, Design, Analysis, Verification, and Validation ctivities for all Naval Power and Energy Systems (NPES)

Requests for Information and Industry Engagement

NPES TDR will rely on robust collaboration with industry, acknowledging that naval power and energy innovations frequently emerge from commercial and academic research. Regular requests for information (RFIs) and industry days will allow the Navy to identify technology maturation and research breakthroughs in key areas (e.g., prime movers, power electronics, battery systems). These exchanges will help shape both Navy requirements and future industry investment considerations. Purpose-driven technical meetings will delve into specific technologies tied to roadmap milestones (e.g., advanced wide-bandgap semiconductors). The roadmap will also track developments from Allied partners through existing channels (e.g., government-to-government agreement that provides official mechanisms for the exchange of research and development information). By actively incorporating commercial and global expertise, the NPES TDR will remain relevant and leverage the broader marketplace to emphasize solutions that meet short- and long-term naval requirements.

Gap Analysis and Prioritization

Gap analysis will be central to the NPES TDR. Future demands—such as pulsed power for directed-energy weapons—will be compared with the limitations of current shipboard systems, highlighting challenges in capacity, endurance, or speed of power delivery. These gaps will be quantified, and their impacts and time horizons will be delineated. The roadmap will use urgency, strategic value, and feasibility as prioritization criteria. Key needs often include the need for hybrid power systems, integrated power system technology architectures or modular energy storage. Once adopted in the roadmap, these priorities inform broader R&D goals and acquisition strategies. By delineating near-, mid-, and long-term objectives, the NPES TDR will ensure that emerging technologies progress methodically through the Planning, Programming, Budgeting, and Execution (PPBE) process.

Stakeholder Collaboration

Cross-functional collaboration will complete the process. Through formal governance forums, SYSCOMs, PEOs, Warfare Centers, the Naval Research Enterprise, and the Fleet will merge progress updates, re-sequence milestones as needed, and integrate emergent insights (Kerr & Phaal, 2022). If new operational data reveals a capability shortfall—like potential reliability issues under stressing combat loads—teams will be positioned to adjust the roadmap's emphasis. This method will coordinate technology investment, ship design, and acquisition timeframes. For example, once the roadmap highlights a key technology, relevant programs will incorporate it into prototype development. Ongoing feedback from technical, operational, and program personnel promote transparency and sustain a capability-focused culture. This collaborative structure will maintain the NPES TDR's "living" quality, allowing the Navy to introduce advanced power and energy capabilities when they are needed to support warfighting requirements.

Research to Readiness: Key Outcomes and Lessons Learned

Framework for Technology Transition

By systematically applying recognized roadmapping frameworks (Garcia & Bray, 1997), updates to the NPES TDR can continue to accelerate the transition of technologies onto naval platforms. Early identification of critical enablers—such as integrated energy storage and power controls—and well-coordinated efforts across government, industry, and academia have produced concrete advances, including at-sea demonstrations of directed energy weapons. These outcomes confirm the roadmap's effectiveness in forecasting and driving technology maturation under operational constraints. Equally important, the NPES TDR has reinforced that a roadmap must be adaptive (Kerr & Phaal, 2022). Periodic revisions will accommodate unexpected technologies or changes in mission need, maintaining strategic coherence and ensuring tangible results.

Identification of Critical Processes

Three intertwined processes will be crucial for bridging the traditional "valley of death" (Moore, 2024). First, comprehensive data analysis and modeling will yield more accurate projections and power load profiles. Second, multi-stakeholder gap evaluations will clarify priorities for bridging technology transition challenges. Third, iterative readiness reviews will align transitional technologies with established acquisition checkpoints and decision gates. This synergy will be important to mature advanced energy storage systems, which could progress from laboratory bench tests to land-based demonstrations and eventually to system-level integrations (Markle et al., 2021). By explicitly tracking each enabler, the NPES TDR will account for technical, organizational, and workforce factors to expedite transitions while minimizing risk.

Collaboration Models for Sustained Innovation

Implementing the NPES TDR will involve extensive cross-sector engagement. Public–private partnerships will leverage industry's expertise in power electronics, energy storage, and advanced controls, with the Navy providing robust tactical testbeds and clear operational requirements. Research collaborations, such as the Navy's partnership with the Electric Ship Research and Development Consortium, unites the combined programs and resources of leading electric power research institutions, including Florida State University's Center for Advanced Power Systems (FSU CAPS) and the University of Texas at Arlington's Pulsed Power and Energy Laboratory (UT Arlington PPEL), to advance near to mid-term electric ship concepts.

Inter-agency and joint service efforts will also broaden this ecosystem, standardizing best practices and accelerating lessons-learned exchanges across other high-power platforms. Fleet participation from the outset will anchor technology evolution in real operational experiences, thereby shaping design refinements and fostering user acceptance. By integrating these distinct collaboration paths, the Navy will build a resilient innovation network extending beyond individual programs and accelerating the pace of technology adoption.

Case Study: Directed Energy Weapons

A significant example of the 2019 NPES TDR's research-to-readiness approach is the Navy's deployment of shipboard laser weapons. Identified in the roadmap as a transformative capability, Directed Energy Weapons (DEW) require robust power generation, energy storage, and thermal controls (see, for example, highly stochastic loads provided in Figure 4). Although the Office of Naval Research (ONR) spearheaded the overall technology maturation effort, the NPES TDR synchronized energy storage technology development and defined the appropriate testing venues.

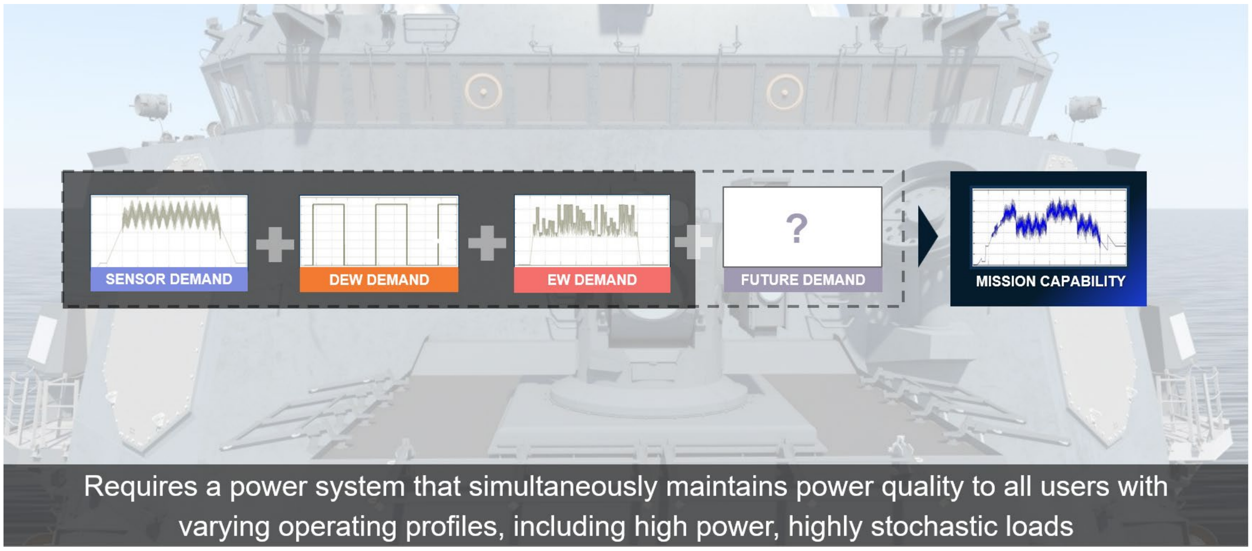

Figure 4. Rapidly Integrating Naval Power and Energy Systems to Enable Emerging Warfighting Capabilities

An indirect descendant of these developments is the AN/SEQ-3 LaWS: a solid-state laser system with variable power, designed specifically to combat unmanned aerial vehicles (UAVs) and small maritime threats (Bernatskyi et al., 2024). Initially installed on the U.S. Navy destroyer USS *Ponce* in 2014, LaWS successfully demonstrated operational effectiveness during annual testing (Chandler, 2014; LaGrone, 2014). Building upon the LaWS experience, USS *Portland* (LPD 27) served as the most recent demonstration of the Solid-State Laser Technology Maturation (SSL-TM) system, integrating a more powerful 150 kW solid-state laser coupled with appropriate pulsed-power energy storage system. The SSL-TM system validated its operational feasibility through successful at-sea tests in 2020, during which it disabled a UAV, marking a critical step toward the integration of directed energy systems across the Fleet (5th Fleet Public Affairs, NAVCENT, 2021).

Subsequent efforts shaped by these demonstrations include the High Energy Laser with Integrated Optical-Dazzler and Surveillance (HELIOS) currently installed on Arleigh Burke-class destroyer USS *Preble* (DDG 88), illustrating how NPES TDR–guided demonstrations feed into strategic acquisition decisions (Johnson, 2025). Additionally, other concurrent laser system developments within the Navy Laser Family of Systems (O'Rourke, 2022), such as the Optical Dazzling Interdictor, Navy (ODIN)—are leveraging lessons learned from SSL-TM's integration and operational employment (O'Rourke, 2022; O'Rourke, 2024).

The staged "crawl–walk–run" progression—moving methodically from lower-power prototypes, such as LaWS on USS *Ponce*, to higher-power and more advanced systems like SSL-TM—effectively manages stakeholder expectations and refines technical solutions. Early Fleet input on operational employment, energy storage requirements for pulsed loads and additional cooling requirements helps mitigate risk. Ultimately, the successful demonstration of directed-energy weapon capabilities underscores the NPES TDR's increasingly important role in guiding complex systems effectively from laboratory concept to the Fleet.

Discussion: Challenges and the Way Ahead

Risk Mitigation Across Life Cycles

The Navy will need to hold periodic NPES TDR reviews aligned with new construction and major ship modernization availabilities to address the challenges between a 35+ year surface ship Expected Service Life (ESL) and more rapid technological and warfighting capability evolution. Embedding digital engineering and distributed test environments early will help validate systems, well before shipboard integration occurs.

Adapting to Technological Shifts

Scenario-based planning and routine market assessments should identify potential breakthroughs—such as innovative supercapacitors or newer battery chemistries—and shift resources accordingly. Existing RFIs and industry workshops will feed into NPES TDR updates, ensuring that possible technologies receive near- and mid-term evaluations without unsettling acquisition timelines.

Enhanced Collaboration and Funding Alignment

To realize the full potential of the NPES TDR, consistent funding and cross-program cooperation will be vital, especially when large-scale integrated power solutions transcend conventional boundaries. Close and consistent coordination with broader DoD initiatives—like directed energy weapons—may augment the NPES TDR's influence. Strengthened public-private partnerships, including those with FSU CAPS and UT Arlington's PPEL will only further accelerate prototype validation for emerging capabilities. Sustaining financial support often proves difficult across multiple budget cycles. Balancing near-term achievements with longer-term research will be key to align efforts across portfolios in similar mission-focused areas. The roadmap's ability to more effectively linking platform and new warfighting capability schedules with key technology power and energy system developments should also help mitigate potential funding shortfalls.

The Roadmap as a Continuous Learning Ecosystem

Maintaining the NPES TDR as a "living" roadmap will require proactive data collection from fleet demonstrations, wargaming, and concurrent R&D projects. Annual or biennial workshops at major milestones could serve to blend current operational findings with industry forecasts, reinforcing the roadmap's adaptive nature. This iterative structure would enable the Navy to continuously refine power and energy priorities in alignment with real-world operational demands.

Conclusion

The updated NPES TDR should serve to showcase how a systematically constructed roadmap can continue to help guide naval power and energy systems from R&D to Fleet operations. By encouraging collaboration among government and industry stakeholders and embedding iterative readiness reviews, NPES TDR updates will facilitate early risk mitigation and help optimize resource prioritization. Ultimately, these processes will ensure high-impact technologies achieve timely integration into acquisition pipelines, essential to increasing lethality, accelerating warfighting capabilities, and improving readiness.

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