# Combined Seapower: A Combat Power Perspective

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## Synopsis

Power and energy have become a strategic and operational imperative for both the Royal Navy and United States Navy. The 21st century pace of change is unparalleled, with threats evolving at increased range, complexity, and sophistication. State and non-state adversaries are gaining technological advances and expanding their ability to conduct combined operations. Rapid fielding and seamless integration of advanced power and energy capabilities, such as power continuity across systems and electrically-powered weapons and sensors, will be critical for allies and partners to keep pace. As energy is one of the primary drivers for enhanced warfighting capability, these capabilities will be spurred by advances in power, energy and integrated system level controls. Further, the evolution of asymmetric threats will require disruptive and technologically superior solutions that create resilient networks and operate in a fully distributed manner.

*Keywords:* International Partnerships; Future Warfighting Capabilities; Power System Design; Shipbuilding

## 1.0 Introduction

> *"As technology advances on both sides of the Atlantic, there will undoubtedly be new, mutually beneficial opportunities for rapid development, deployment and cost sharing[...] hot-on-the heels of US progress on energy weapons and rail guns, the UK not only plans to test its own directed energy weapon at sea within the next two years, but we're also looking at the role of electric flywheel technology to generate and store the power required for these novel weapons."*
>
> Admiral Sir Philip Jones KCB ADC
> First Sea Lord and Chief of Naval Staff, Royal Navy
> Speech to the Cohen Group – UK/US Naval Partnership, 17 May 2016

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[1] **Authors' Biography**

**Ann M. Lowe** is a Senior Associate at Herren Associates in Washington, D.C. Her experience using systems thinking principles has helped key Navy acquisition and engineering programs prioritize investment portfolios, manage complex systems, and mitigate uncertainty. Ms. Lowe is a Lean Six Sigma Master Black Belt and has completed graduate programs in organizational leadership and change management at Georgetown's McDonough School of Business and Yale's School of Management. She was awarded a Bachelor of Science in Industrial Engineering with highest honors from Montana State University.

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**Jeffrey M. Voth** is the President of Herren Associates, an engineering and management consulting firm with offices in Washington, D.C., Virginia, and Maryland. He is responsible for leading a diverse team of consultants serving the federal government across a wide range of markets - including national security, energy and environment, health care, IT modernization and cyber. An alumnus of Harvard Business School, Voth read for an MSc at the University of Oxford, and holds a joint master's degree from Georgetown University and Escola Superior d'Administració i Direcció d'Empreses (ESADE).

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With continual increases in the rate of technological advances in the 21st century, both the Royal Navy (RN) and United States Navy (USN) recognize the need for evolutionary capabilities to pace the threat and maintain dominant seapower. Enhanced sensors and new warfighting capabilities will need to provide greater detection range, increased discrimination accuracy, and spectrum dominance. Laser turrets, such as the RN's Dragonfire system and the USN Laser Family of Systems (NLFoS), will provide a directed energy engagement element to augment close-in weapon systems with defensive capability to counter several asymmetric threats and provide enhanced lethality (Figure 1). Hypersonic technologies will be able to deliver long-range, precision volume fires that increase stand-off range and decrease time-to-target. While the vision for these advanced technologies is clear, the maturation of these capabilities requires a new way of thinking regarding Power and Energy (P&E) production, distribution, management, control, and delivery.

**New Warfighting Capabilities**

Laser directed energy offers measured weapon effects, matched with deep magazine capability to defend against a range of emerging threats posed against Naval surface forces

- Deep-weapon magazine preserves kinetic weapons to address anti-access threats
- Ability to tailor output to specific targets and missions with scalable effects
- Rapid engagement of targets
- Precise, low-collateral damage capabilities
- Low cost per engagement (compared to conventional kinetic weapons)
- Reduce or eliminate energetics

Figure 1: New Warfighting Capabilities

The first section of this paper introduced important changes within the Naval environment. Next, a background is provided that reviews salient national strategic documents highlighting US-UK collaboration aligned with the 2014 *Combined Seapower* vision. The third section addresses national shipbuilding strategies and the need for more flexible platform designs and robust systems integration activities to support Integrated Power and Energy Systems (IPES) for an increasingly distributed force. This section also examines IPES design elements that should be considered to support future warfighting capabilities, providing a detailed discussion on the pulsed high energy systems that will drive requirements for energy storage and advanced controls. The final section will present a shared perspective on the future strategic environment and outline key IPES design considerations to ensure flexible combat power is delivered throughout the ship lifecycle.

## 2.0 Background: The national security imperative

> *"Seapower is integral to the prosperity and security of the US and UK due to our extensive worldwide interests, globalized economies, and international responsibilities. Both the US and UK depend on unhindered access to the sea and the unimpeded flow of trade for our economic prosperity"*
>
> Rear Admiral Kevin Donegan
> Deputy Chief of U.S. Naval Operations, Plans and Strategy (N3/N5)
> Navy Live, 8 January 2015

The US and UK have a longstanding heritage of maritime cooperation and collaboration, rooted in common strategic and operational objectives related to seapower (Jones, 2018). In 2014, the RN and USN jointly released *Combined Seapower: A Shared Vision for Royal Navy-United States Navy Cooperation*, outlining key tenets of mutual cooperation over the next 15 years (Zambellas & Greenert, 2014). *Combined Seapower* describes the RN and USN dependence on sea access to promote and maintain uninterrupted trade freedom and economic prosperity, the imperative of projecting power and influence to protect national security interests, and the importance of both US and UK investments in future capabilities in order to remain secure and globally influential.

The central issues outlined within the US and UK National Security Strategy (NSS) documents referenced in *Combined Seapower* provide meaningful insight as both governments place high value on their respective strategies. Government departments and legislative bodies rely on these documents to offer direction on select national security issues. NSS documents provide the executive branches of both nations an internal consensus on issues ranging from economic strategies to defense and foreign policy issues, and national leaders often reference key messages contained within the NSS when engaging both national and international stakeholders. Additionally, these seminal strategy documents provide clear signals to potential adversaries who might threaten national security objectives. Importantly, the strategies also inform legislative bodies (i.e., Congress and Parliament) to substantiate what resources each strategy requires in support of ongoing appropriations processes. Since the 2014 release of *Combined Seapower*, both nations have issued updated NSS documents aligned with evolving national priorities and the shifting global environment.

Broadly, the December 2017 US NSS aligns with the UK NSS presented to Parliament in November 2015. Incorporating the larger goal of ensuring a favorable balance of power, a cornerstone of US policy for decades, the 2017 US NSS is framed with four pillars: protect the homeland, promote American prosperity, preserve peace through strength, and advance American influence. The 2015 UK NSS outlines three complimentary national objectives: protect our people, project our influence, and promote our prosperity. Aligned with many of the same security interests later identified in the US strategy, the 2015 UK document highlights the importance of a transatlantic partnership, noting that "the UK and the US are at the centre of NATO's collective defence and security" with a combined military capability that "plays a major role in guaranteeing our national security." In effect, both the 2015 UK and 2017 US NSS reaffirm the *Combined Seapower* cooperation commitment centered around deterrence, sea control, power projection and influence, and maritime security.

## 3.0 Innovative and adaptive shipbuilding

Naval forces are among the most flexible instruments of military power, and shipbuilding programs are essential elements of an effective grand strategy for nations (Taylor, 2018). Guided by their respective NSSs, policymakers have begun to invest in recapitalizing both navies through several new major programs to balance increasing global tensions, and aggressive RN and USN shipbuilding plans have been set forth to maintain dominance of the seas.

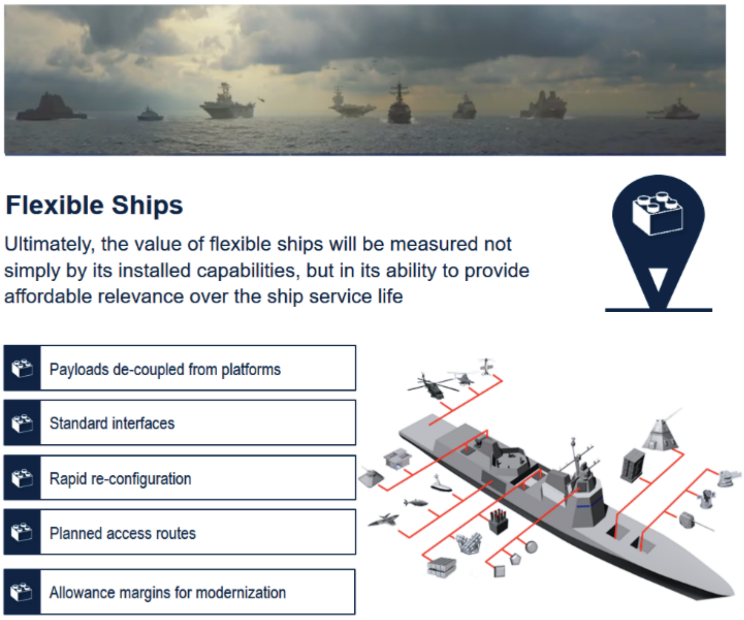
> *"The prioritized shipbuilding plan affords the opportunity to quickly adopt new capabilities in response to emerging capabilities – move to a new modernization effort, or move to a new platform design."*
>
> Deputy Chief of U.S. Naval Operations, Warfare Systems (N9)
> Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2019

The 2018 National Defense Authorization Act (NDAA) directs the USN to attain a fleet of 355 warships, and this directive serves as the blueprint for the USN's most recent 30-year shipbuilding plan (Deputy Chief of Naval Operations, 2018). Within this plan, there is a strong focus on the future of Surface Combatants as these platforms will likely witness increasingly rapid evolution based on emerging technologies regarding aspects such as sensors, payloads, and state-of-the-art manned and unmanned systems. To provide commanders with dynamic capabilities that will allow them to dominate all theaters in which the USN operates (above and below the sea, in the air, and on land), the USN's Surface Capability Evolution Plan (SCEP) emphasizes the need for real-time information, stealth, speed, lethality, and plug-and-play components in future platforms.

> *"Our vision is that the Royal Navy has more ships, which are modern and capable of being incrementally modernized and improved, are exportable and can work with allies."*
>
> UK Ministry of Defence
> National Shipbuilding Strategy, The Future of Shipbuilding in the UK (2017)

For the UK, the Strategic Defence and Security Review (SDSR) outlines the government's five-year NSS plan and implementation strategy. Specifically, the SDSR describes the UK government's commitment to maintaining a minimum of 19 frigates and destroyers by replacing the current 13 Type 23 frigates with five General Purpose Frigates and eight Type 26 Global Combat Ships (GCS) as well as constructing two additional Offshore Patrol Vessels (OPVs). Additionally, the SDSR indicates the possibility of a future effort to "further increase in the total number of frigates and destroyers". In September 2017, the RN followed up on the 2015 SDSR by presenting its 30-year national shipbuilding strategy (Ministry of Defence, 2017).

Along with the sheer volume of ships envisioned for both the RN and USN, each nation's plan offers not only details regarding scheduling and capabilities but an ambitious transformation in how ships are planned, procured, and operated. Realizing these objectives demands moving away from tightly integrated systems and towards modularity where ships can be built more quickly, more cost-effectively, and with inherent interoperability capabilities to maximize open architectures and extend ship lifecycles via rapid systems upgrades (Figure 2). Maintaining maritime dominance in the 21st century will require decoupling modular systems from platforms so that parts of the ship that change more rapidly can be modernized quickly without causing problems with the parts of the ship that change more slowly (Schank, 2016; Greenert, 2012). This evolution will necessitate fundamental changes to how ships are designed, constructed, maintained, and modernized (Spero, 1971; Gates, 1985). The consistent emphasis is on enabling ships with rapidly evolving technologies, including advanced P&E capabilities.



**Flexible Ships**

Ultimately, the value of flexible ships will be measured not simply by its installed capabilities, but in its ability to provide affordable relevance over the ship service life

- Payloads de-coupled from platforms
- Standard interfaces
- Rapid re-configuration
- Planned access routes
- Allowance margins for modernization

Figure 2: Flexible Ships

Recognizing the need to address common challenges as both the RN and USN move forward with shipbuilding strategies, the Naval Sea Systems Command (NAVSEA) hosted a US-UK Surface Combatant Acquisition Workshop with over 50 participants in February 2018. Encompassing aspects of both ship design and ship building, the event was an opportunity to share knowledge, experiences, best practices, and lessons learned on the rapid acquisition of naval Surface Combatants. Ultimately, the outcomes from the workshop are intended to inform USN Future Surface Combatant and RN Type 31 Surface Combatant acquisition programs to compress ship design and shipbuilding timelines and identify future UK-US collaborative opportunities. Most notably, integrated P&E solutions emerged as a key enabler critical for acquisitions considerations in order to realize the UK and US collective strategic vision for enhanced capabilities and future technology evolution.

### 3.1 *The power and energy imperative*

> *"I'm going to buy as much as I can afford. As much power as I can afford.*
> *Because I know by the time I retire a ship I'll use it all."*
>
> Admiral John M. Richardson
> 31st U.S. Chief of Naval Operations
> Directed Energy Summit, 29 March 2017

Aligned with the *Combined Seapower* call for interoperability and mutual technology investment, the US Department of Defense's *International Science and Technology Engagement Strategy* underscores the commitment for coordinated support of global technologies and collaboration among partner nations (Shaffer & Webster, 2014). The strategy focuses on prioritizing and investing in international activities to enhance capabilities and interoperability to ensure technological superiority over common adversaries. It encourages leveraging global research and development, including engagement with industry to identify and advance emerging technologies and applications. Among many areas of interest, P&E technology is cited as a key focus area for international collaboration. The UK and US recognized the need to partner on P&E solutions several years ago, and that collaboration remains active as both navies work together to define future P&E requirements, challenging industry to develop innovative solutions.

While the proposal to reinvigorate the RN and USN fleets incites enthusiasm and excitement across the naval community, actualizing this vision is highly dependent on overcoming the fundamental challenge of ensuring that ships of the future can meet the required power demands of highly complex and evolving systems. Advanced mission systems and the highly complex power systems needed to support future RN-USN platforms require earlier investment in research and development activities to prototype and demonstrate feasibility in an operational environment. Adequate investment in de-risking systems through time-based simulations and land-based test facilities will allow mission and warfighting technologies to be deployed more optimally. Power is the foundation of the kill chain, making power a key component in translating concepts into tangible realities that benefit the warfighter.

The significance of realizing systems where shared power and energy is available *when* and *where* it is needed cannot be overstated. However, attempts to support new and advanced mission systems with conventional power systems may be insufficient and could ultimately degrade mission performance. Supporting increased future loads is not simply an issue of needing more power to support higher power loads. New sensors and weapons require a different type of power system that can respond to highly stochastic demand signals characterized by high ramp rates with short recharge times. These new types of demands drive the configuration and design of energy storage solutions. Historically, energy storage systems on ships were often relegated to only one dedicated purpose and lacked common and aligned energy storage architecture, leading to system specific energy storage being introduced in back and future-fit ship development. The need for energy built into the distribution system is what allows a ship to modernize and upgrade capability over her lifetime.

Emerging pulsed high energy loads of future combat systems are driving requirements for energy storage, advanced controls, and electrical optimization at an ever-increasing pace. Navies must also emphasize earlier and more comprehensive systems integration as a critical development step towards deploying new capabilities. An Integrated Power System (IPS), currently used on the USN's DDG 1000 and the RN's Type 45 Destroyers, allows energy and power to more easily move around the ship and be used alternately for ship loads or propulsion. This is a significant upgrade to the power system than that of an older, segregated model where power can fundamentally only be used for propulsion or for ship loads. As the ship loads increase, in the form of advanced sensors, weapons, or electronic warfare, the demand for electricity grows. An evolutionary approach to advancing the Navies' power systems introduces energy; evolving from an IPS to an IPES. IPES will provide the flexibility, adaptability, survivability, efficiency, and overall endurance required pace the threat and maintain warfighting dominance for the decades ahead (Figure 3). The addition of energy into the ship's electrical plant allows the ship to respond to the immediate nature of pulse loads such as lasers, highly stochastic loads such as electronic warfare, or to level the load of high power advanced radars. With enough energy supporting an integrated plant, this could allow a ship to operate silently without generators, or to supplement propulsion for faster cruising speeds.

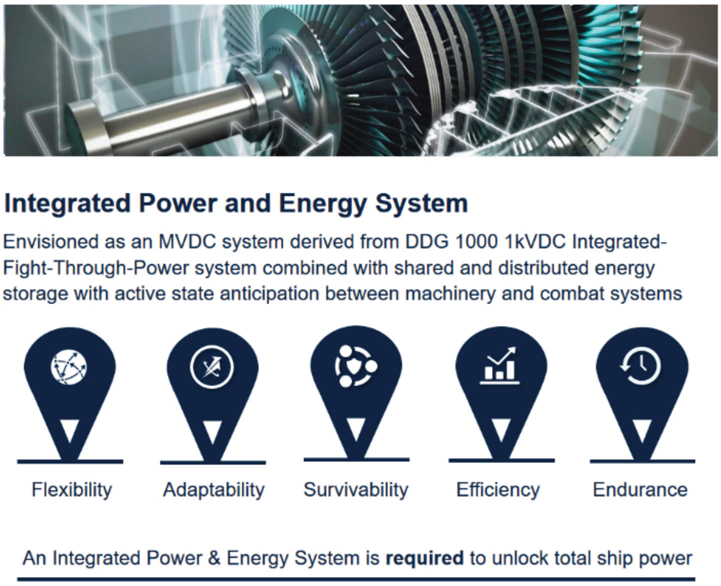


Figure 3: Integrated Power and Energy System

IPES is described in the 2015 U.S. Naval Power and Energy Systems Technology Development Roadmap (NPES TDR) as "an advanced power architecture that incorporates multi-use distributed energy storage as well as advanced controls and energy management" (Kuseian, Markle, & Hilarides, 2015). Economical and efficient use of future IPES depends largely on the size and number of configured Gas Turbine Generators (GTG)s and Auxiliary Turbine Generators (ATG)s, as well as the seamless integration of energy storage with the power generation system. Well matched combinations of GTG, ATG and energy storage system ratings will allow the IPES to operate the engines efficiently across the entire IPES power range which will minimize fuel burn, maximize range and operational configuration and optimize engine overhaul in terms of cost and schedule. The latter is of particular importance when considering the engine Through Life Cost (TLC) and availability, which may impact ship affordability and mission performance respectively. This key topic will be discussed further in the following section.

### *3.2 Power system design to support future warfighting*

Designing for total ship power is perhaps the greatest challenge facing the IPES design community. Previous research in this field highlights the adverse impacts that pulse type combat system loads have on conventional AC power systems (Daffey & Hodge, 2004) (Lewis, 2006) (Tsekouras, Kanellos, Prousalidis, & Hatzilau, 2010). Whitelegg (2016) concludes that typical AC power system design practices are not robust enough to withstand the rigors of high power pulse load integration. Furthermore, Smolleck, et al., (1991), Baldwin (2004), Dehkordi, et al. (2007), Whitelegg (2016), and Boehmer & Temkin (2018) all conclude that pulse load dynamics not only present power quality issues for other electrical consumers, but may also place unexpectedly large stresses on power generation system components with finite life. This is particularly critical in the case of the prime mover generator (Baldwin, 2004) (Dehkordi, Parsapoor, & Hooshmand, 2007), where increased component stress may result in a reduced Mean Time Between Overhaul (MTBO) that results in an increased engine TLC. Analysis of rapid start, cold start, load-shed and rapid shutdown have all been shown through internal studies to be dynamic load events that cause a more rapid accrual of damage and a shorter MTBO than a simple slow start, moderated ramp, constant operation, measured deceleration and shutdown. An unassisted pulse load applied to the prime mover generator has been compared through simulation to maximum rate acceleration and a load-shed with no time to thermally stabilise, which is logically concluded to shorten MTBO. How the GT is warmed up and cooled down will also affect the damage accrued by pulse loading. The resulting reduced MTBO may subsequently reduce engine availability, degrading mission performance. Therefore, designing for total ship power requires departure from conventional electric power system architecture.

The migration from AC to DC, as described by NAVSEA in the NPES TDR (Kuseian, Markle, & Hilarides, 2015) and extensively by Doerry & Amy (2015) (2018), lays the foundations for solving these design challenges. The decoupling of prime mover speed from electrical frequency presents the opportunity to increase engine efficiency and isolate engine dynamics from quality of electric power supply to some extent, although issues surrounding the stability of DC power systems may arise under transient load conditions (Hodge & Flower, 2014). Power system stability aside, increased engine component stresses will persist. This is because supplying a finite amount of energy over a finite amount of time requires the core engine to make an identical maneuver, whether configured in an AC or DC power system. Therefore, to ensure engine MTBO is equal to or better than current generation warships, the engine load dynamics must be smoothed to represent those expected when providing power for conventional ship power and propulsion applications.

### *3.2.1 Engine dynamics and energy storage*

A well-documented method of smoothing engine dynamics is the provision of an Energy Storage System (ESS) to provide for short term power and energy demands that exceed those of the power generation system capacity or transient performance capability (Whitelegg, 2016) (Khan & Faruque, 2017) (Boehmer & Temkin, 2018). Because an ESS can respond to dynamic changes in load demand in the sub-second timeframe, it is able to respond to load steps with fast rise times that stabilize the load and smooth the core engine power profile effectively. Thus, the ESS can supply transient load demands that would otherwise cause repeated cycles of the core engine, possibly reducing MTBO.

Although much has been published on the control of this type of ESS to smooth electric power system dynamics (Gonsoulin, Vu, & Diaz, 2017) (Khan & Faruque, 2017) (Langston, Stanovich, Schoder, & Steurer, 2017), ESS requirements to ensure engine MTBO at least equal to that of current generation warships have not been fully articulated. Hence, the following section explores the requirements of the ESS to maintain acceptable engine MTBO while also meeting the P&E requirements of a large pulsed load.

### *3.2.2 Defining IPES ESS requirements – analytical analysis*

Here, we consider the MVDC IPES presented by Khan & Faruque (2017) from Florida State University, in which the power generation system comprises two 36 MW GTGs and two ATGs. For the purposes of this analysis, it is assumed that one of the 36 MW GTG sets is supplying power to the pulsed load as defined by Wolfe, et al.

(2005) and a 2 MW base load. This is consistent with the approach taken by Whitelegg (2016), when examining an AC power system. The resulting load profile is shown in Figure .

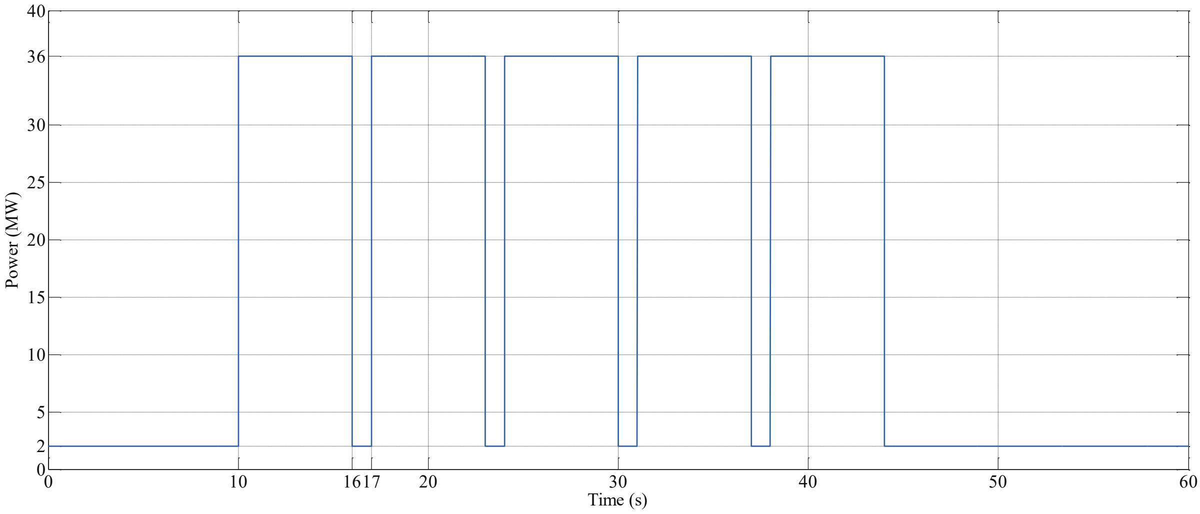


Figure 4: Pulsed load profile

When calculating the ESS requirements to yield an engine load profile consistent with conventional ship power and propulsion applications, three characteristics of the pulse load profile should be considered: the ramp up period, the inter-pulse period, and the ramp down period.

### Ramp up period

During the ramp up period, the capacity of ESS required is calculated by integrating the difference between the GTG output power ($P_{GTG}$) and the pulse ($P_{pulse}$), as shown by equation (1). This is equivalent to finding the shaded area in Figure .

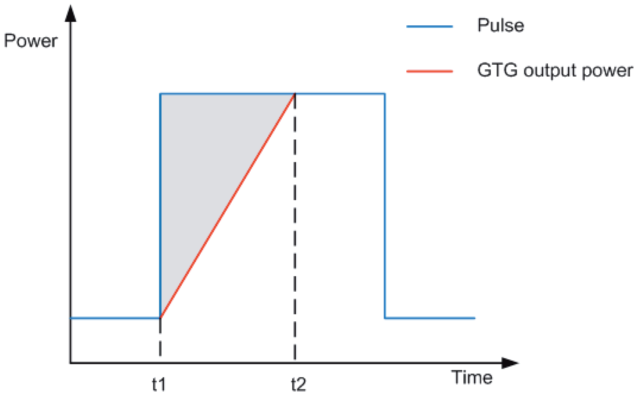


Figure 5: Example power profile during ramp up period

$$E = \int_{t1}^{t2} (P_{pulse} - P_{GTG}) dt \qquad (1)$$

The ESS capacity required during the ramp up period is therefore defined by the GTG ramp rate limit. The greater the allowable ramp rate, the lesser the ESS capacity requirement.

### Inter-pulse period

When defining the ESS requirements during the inter-pulse period, it is important to balance the energy transferred to and from the ESS to prevent a build-up of charge during pulse load operation. Doing so would place a capacity driver on the ESS, limiting the operation of the pulse load to a finite time. One way of managing this is to first determine the surplus energy during the charging phase ($t_1$ in Figure 6) and the excess energy during the discharge phase ($t_2$ in Figure 6) and then set the demanded GTG power ($P_{demand}$) such that the two are equal. The ESS requirement during the inter-pulse period is therefore defined by the pulse load duty cycle.

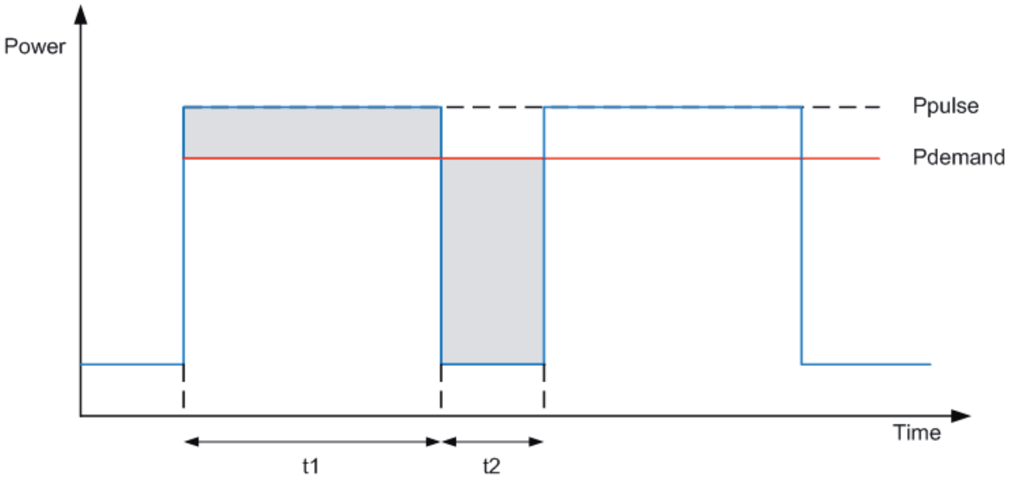


Figure 6: Example balanced energy transfer during inter-pulse period

For a square wave pulse profile and a constant GTG output power, such as seen in Figure , the demanded power can be determined using equation (2).

$$E = \int P\,dt$$

$$E_1 = E_2$$

$$\left(P_{pulse} - P_{demand}\right) \times t_1 = \left(P_{demand} - P_{base}\right) \times t_2$$

$$P_{demand} = \frac{t_1 P_{pulse} + t_2 P_{base}}{t_1 + t_2} \qquad (2)$$

With reference to Figure 4 and Figure 6, $P_{pulse}$ is 36 MW, $P_{base}$ is 2 MW, and $t_1$ and $t_2$ are 6 s and 1 s, respectively. The demanded power, $P_{demand}$, is therefore 31.14 MW.

Finally, it is significant to note the power rating of the ESS ($P_{ES}$). The ESS must be able to charge and/or discharge at a high enough rate to compensate for the difference in power between the load profile ($P_{pulse}$) and the GTG output ($P_{GTG}$). $P_{ES}$ is found simply using equation (3).

$$P_{ES} = P_{pulse} - P_{GTG} \qquad (3)$$

### Ramp down period

During the ramp down period, the capacity of ESS required is calculated by integrating the difference between the GTG output power ($P_{GTG}$) and the pulse ($P_{pulse}$), as shown by equation (4). This is equivalent to finding the shaded area in Figure .

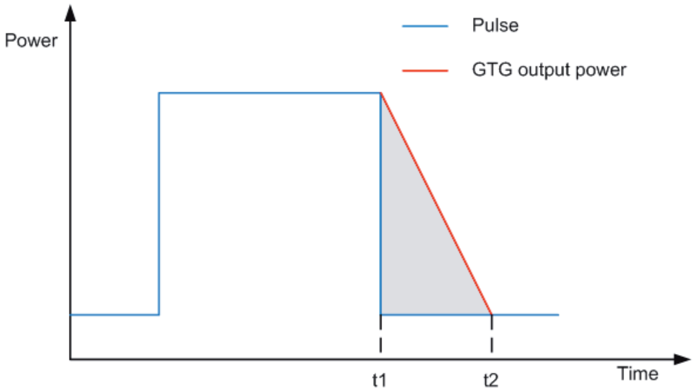


Figure 7: Example power profile during ramp down period

$$E = \int_{t1}^{t2} (P_{GTG} - P_{pulse})dt \tag{4}$$

The ESS capacity required during the ramp up period is therefore defined by the ability of the GTG to ramp down following sudden loss of load. The more quickly the GTG can ramp down, the lesser the ESS capacity requirement.

### *3.2.3 Defining IPES ESS requirements – modeling results*

This section presents the results of time-based simulation, which was used to model the mathematical analysis described in the previous section. The use of time-based simulation allows the three stages of the pulse load profile and the resulting ESS P&E requirements to be examined as one result. The time-based model was created in Matlab Simulink and consisted of the Rolls-Royce MT30 GTG set transient performance model coupled to a simple generator model.

The main generator characteristic of interest in relation to these results is inertia, which includes the low-pressure turbine and high-speed coupling shaft. Should future generators have a different inertia, this may affect the power ramp rate limits and the resulting ESS requirements. This is a recognized design trade.

Scenario 1

The results of Scenario 1 are presented in Figure . In this first scenario, the GTG power is ramped up in a controlled manner from the commencement of the pulse load at time 10 s to meet the peak power demand of the pulsed load. The GTG then supplies 31.14 MW ($P_{demand}$) for the duration of the pulse load period. At time 44 s, the GTG ramps down in a controlled manner. With reference to Figure , the resulting power profiles are shown in the top plot, the power surplus and deficit are shown in the middle plot, and the energy storage capacity requirement is shown in the bottom plot.

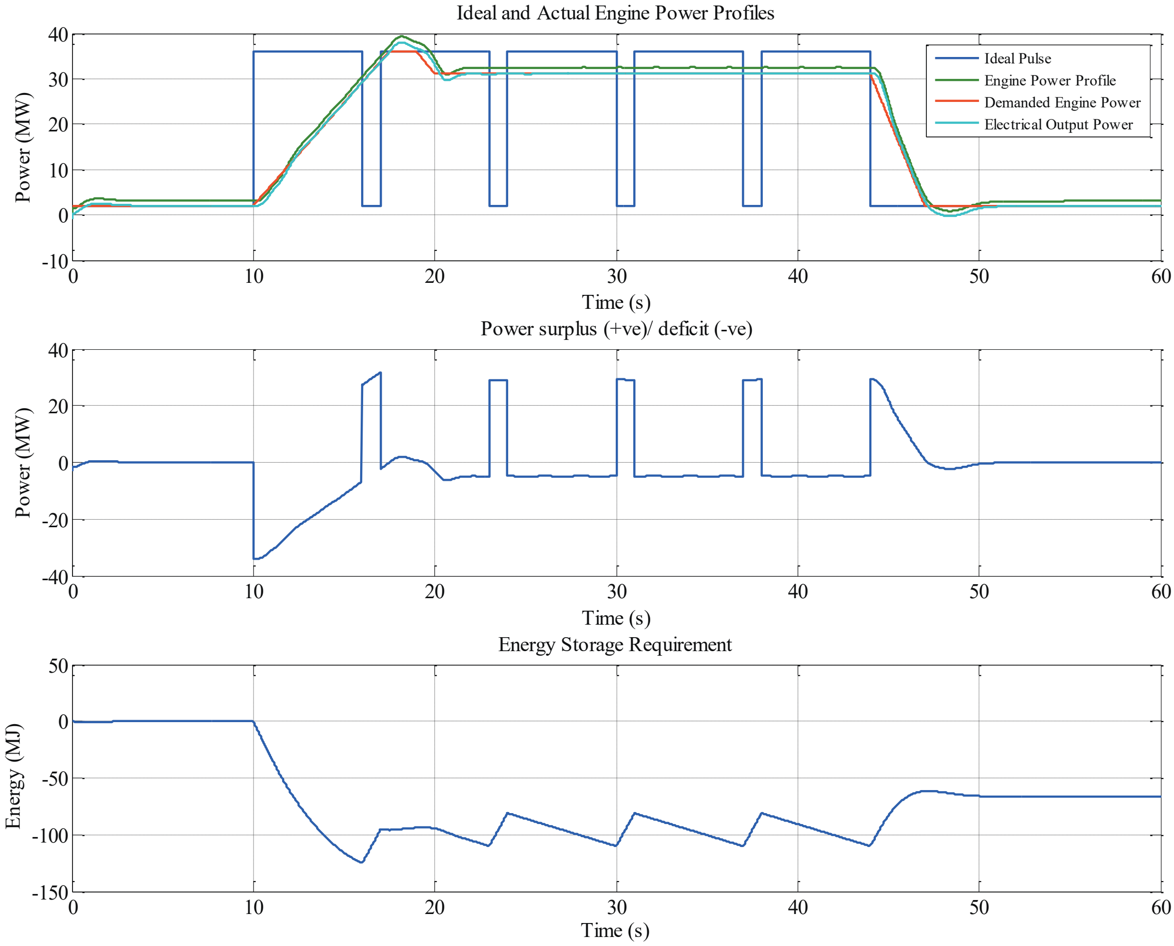


Figure 8: ESS power and energy requirements against time - Scenario 1

Key observations are as follows:

1. The initial ramp drives the capacity of the ESS. The ESS must be at least 125 MJ.
2. The ESS must be pre-charged with 125 MJ.
3. The peak power of the ESS is driven by the initial ramp. This is 34 MW.

The results presented in Figure  demonstrate that the initial ramp period places a significant design driver on the capacity of the ESS, with the ESS capacity requirements of the inter-pulse period appearing lesser in comparison. The ESS capacity requirement during this period could be reduced by pre-charging the ESS before the pulse period commences, in response to a feed-forward signal from the ship's combat system. Hence, active state anticipation may reduce the overall ESS capacity requirement. This statement is examined further in scenario 2.

Scenario 2

The results of Scenario 2 are presented in Figure . In this scenario active state anticipation is implemented. The GTG power is ramped up in a controlled manner from time 6.1 s, in response to a feedforward signal from the ship's combat system, to meet the peak power demand of the pulsed load. The GTG then supplies 31.14 MW ($P_{demand}$) for the duration of the pulse load period. At time 43 s, in response to a feedforward signal from the ship's combat system, the GTG ramps down in a controlled manner. With reference to Figure , the resulting power profiles are shown in the top plot, the power surplus and deficit are shown in the middle plot, and the energy storage capacity requirement is shown in the bottom plot.

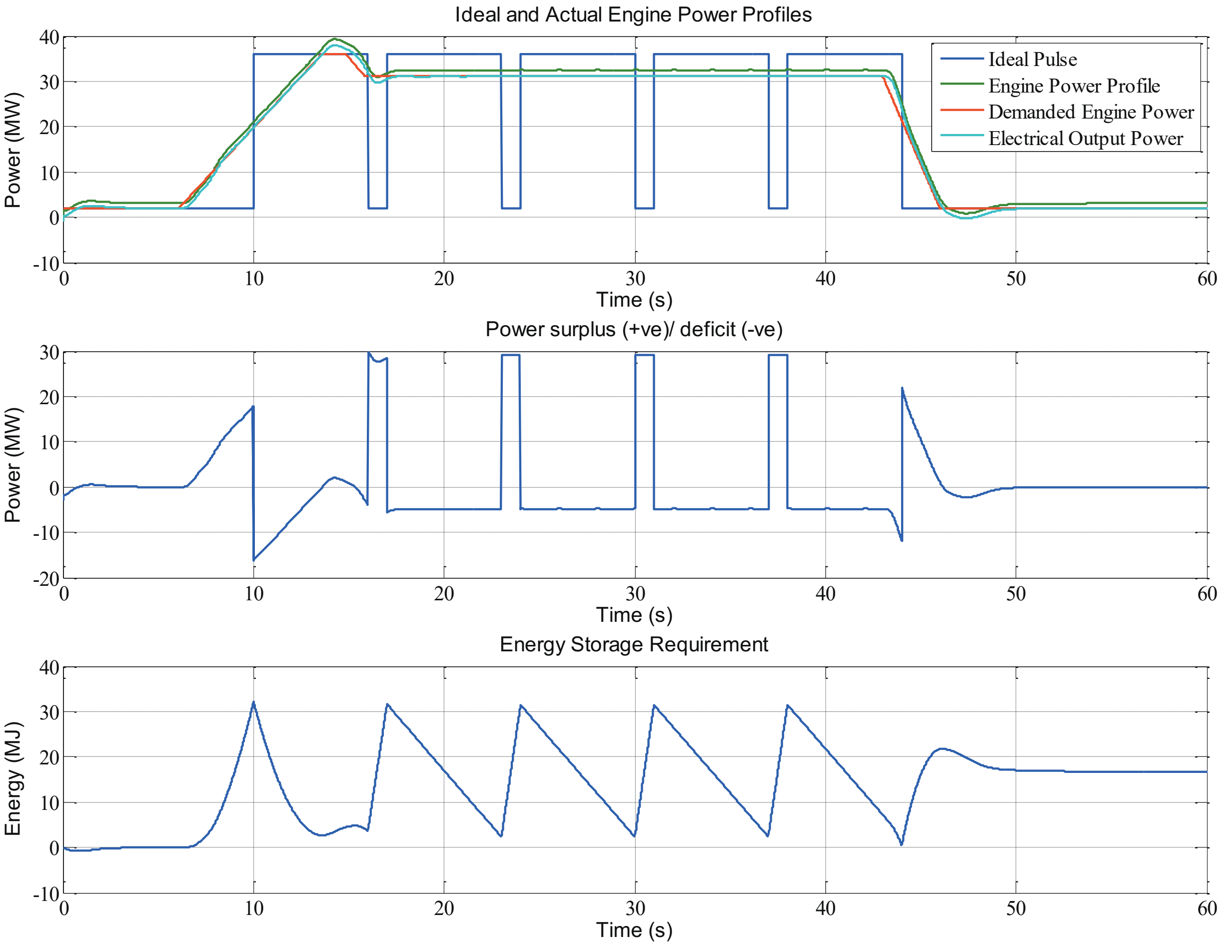


Figure 9: ESS power and energy requirements against time - Scenario 2

Key observations are as follows:

1. The initial ramp and the inter-pulse period equally drive the capacity of the ESS. The ESS must be at least 32 MJ.
2. The peak power of the ESS is driven by the inter-pulse period. This is 30 MW.

In comparing Scenario 2 with Scenario 1, the required capacity of the ESS is 32 MJ compared with 125 MJ. This represents a 75% reduction, owing to the introduction of active state anticipation. The required power of the ESS is 30 MW compared with 34 MW. This represents a 12% reduction.

### *3.3.4 Discussion*

The analysis and results presented in this section suggest that pulsed high energy systems will drive requirements for energy storage and advanced controls. The analysis presented in Section 3.2.2 and the results presented in Section 3.2.3 demonstrate that an ESS could be used to smooth electric power system dynamics and therefore help to ensure engine MTBO is at least that of current generation warships. Furthermore, the results presented in Section 3.2.2 demonstrate that active state anticipation can reduce the ESS capacity and power requirement by 75% and 12%, respectively. In the effort to realize the IPES and develop an ESS with the requirements defined in this paper, these results could prove significant.

## 4.0 Conclusion

As the RN and the USN work to transform their respective fleets to adapt and respond to evolving threats and providing the warfighter with the greatest possible advantage in theatre, power is crucial. Systems that deliver power where and when it is needed are the necessary foundations to achieving ship lifecycle extension in an era of ever-increasing power demands. This paper has framed discussion on the combat power and energy imperative required to underpin the strategic and operational requirements of both the RN and USN future fleets. Following this, the technical analysis, results and discussion presented in this paper have demonstrated that the correct specification of the GTGs, ESS and the implementation of active state anticipation within the IPES architecture will be critical in ensuring the availability and affordability of all future electric warships in terms of mission performance and TLC. Aligned with the longstanding partnership and adherence to principles outlined in the *Combined Seapower* document, RN and USN collaborative work must continue to tackle power, energy and control challenges, among other tough technology trials, in order to maintain dominance of the seas.

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