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Quantifying Flexibility for a Ship Power and Energy System Design

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ABSTRACT

The pace of technology maturation and the uncertainty in magnitude and characteristics of future load types on Navy ships drive the need for robust power and energy system architectures that can adapt to future perturbations in requirements. The Naval design community needs a consistent method for evaluating ship system flexibility in the early design stages when informed decision making provides the greatest opportunity to influence the system's performance and lifecycle cost. The research presented herein develops quantitative, measurable metrics and applies them to applicable case studies for Naval power and energy system flexibility: the capability of the system to accommodate change in response to perturbations in requirements.

KEY WORDS

Ship Design; Flexibility; Metrics;

INTRODUCTION AND BACKGROUND

Naval ship design is a complex system-of-systems activity that balances the operational requirements, physical constraints, and logical connectivity of individual systems into an integrated platform. For a surface combatant, missions ranging from ballistic missile defense to antisubmarine warfare drive the required combat system, consisting of sensors, processing, communication, payload, and ordinance. To enable these mission systems, the ship must provide a stable, responsive power and energy system.

The U.S. Navy surface fleet is in a transition period and faces challenges related to the recapitalization of aging ships, the rate of technology change and uncertainty of the combat systems of the future, and the significant cost of investment to design and build new ship classes. The fleet as it exists today reflects a series of decisions based on the global geo-political environment dating back to the 1980s. Most of the Navy's destroyer and cruiser assets were designed and built following the end of the Cold War to host the top-of-the-line combat system technology of that era, the Aegis combat system, and the SPY-1D radar. Today, forty years later, they are approaching the end of their service lives, and the Navy needs new ships designed for the next fifty years of fleet operations.

At the same time, the rate of technology change has increased uncertainty in requirements for the major combat system elements of the future. System value is defined by its ability to affordably maintain mission relevance within an evolving operational context. The maturation of developmental mission system technologies, with new and increased electrical power demands, are driving requirements for emergent properties, or "ilities," for the naval power and energy system beyond the typical functional requirements. The need to understand and characterize these properties is further amplified by service life requirements of thirty to forty years per platform.

Affordability requirements dictate the need to conduct cost versus capability trade studies early in the design process. System metrics are necessary to quantify performance measures and provide the insight required to "right size" the system-of-system (SoS) architectures. The cost constraints of the recent Research and Development (R&D) and Acquisition environment, along with the timelines to develop and test new power and energy system designs, necessitates a robust evaluation of the design

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space to determine a dominant solution. Power and energy system metrics based on the required “ilities” provide the system designer a basis of differentiation between options within a large design space.

Platenberg (2024) presents the findings from a robust literature review of system of systems “ility” requirements and relationships, and methods for differentiating between preferred solutions within a design tradespace. The research was used to develop a hierarchy of “ility” relationships for the naval power and energy system and to generate a framework for decomposing top level requirements and ility-based requirements into metrics for identifying a dominant architecture within an early-stage design tradespace. The framework considers the physical, logical, and operational aspects of the architecture to generate a set of perturbations that are likely to impact the system’s ability to maintain value over its lifecycle. A deep dive into Flexibility, a common “ility” of interest, is presented here with four case studies using proposed metrics for power and energy system flexibility. This work is intended to present metrics that can be integrated within early-stage design tools for generating and evaluating the naval power and energy system.

The Naval Power and Energy System

The power and energy system of a Navy ship is responsible for providing propulsion and shipboard electrical power required to conduct the platform mission requirements. Today’s surface fleet primarily consists of ships with power and energy (P&E) system architectures that decouple propulsion and power generation functions through the implementation of dedicated propulsion turbines connected directly to the propeller shafts and separate ship service generators installed to provide distributed shipboard electrical power. This type of mechanical-electrical configuration has been a favorable and cost-effective design over the last century, as the demand for propulsion power has significantly outweighed the demand for combat system power. The DDG-51 class, for example, has approximately 78 MW of dedicated propulsion power on shaft, compared to 9 MW of separate ship service power.

The Navy's most recent class of destroyers, the Zumwalt class, introduced an alternative power and energy system architecture, the Integrated Power System (IPS), where all power generated onboard is shared between propulsion load demands and distributed electrical power demands, including mission system loads. The ability for this ship to share full power across all platform functions is enabled by the inclusion of electric propulsion motors, enhanced power distribution, and power controls.

Performance characteristics of the P&E system can be traced to the physical, logical, and operational characteristics of the sub-module configuration. It is important to decompose desired functional and non-functional requirements to the lowest level of measurable capability, as they can often be met by a variety of architectural configurations. For example, an IPS architecture provides increased flexible power capacity when compared to a traditional mechanical architecture based on the total installed power residing within the power generation module, vice split between the power generation and propulsion modules as in a mechanical architecture. However, alternative measures of flexibility, such as the ability to service high-magnitude-short-duration pulse load types, may be architecture agnostic and instead may depend more directly on the configuration of a particular sub-module, such as the energy storage module. When comparing alternatives, the designer needs to consider total integrated P&E system capability and the dependencies between applicable modules.

Design decisions are made at the system and subsystem levels throughout the Navy’s ship design process to satisfy overarching performance and cost requirements. The permutation of architectural options within each subsystem domain creates a potential solution space of a high order of magnitude that is challenging to evaluate. Beyond the ability to meet predetermined requirements and specifications, additional performance metrics for non-functional requirements are necessary to evaluate and rank design options within the tradespace.

Development of Metrics for Ilities

Platenberg (2024) presents a hierarchy of ility relationships for the naval power and energy system and proposes a framework for decomposing top level requirements and ility-based requirements into metrics for identifying a dominant architecture within an early-stage design tradespace. The framework considers the physical, logical, and operational aspects of the architecture to generate a set of perturbations that are likely to impact the system’s ability to maintain value over its lifecycle. Potential “preparations” that can mitigate perturbations are examined. Selection of preferred architectures requires a balance between uncertainty, performance, cost, and complexity to “right-size” the system.

The framework for development of metrics pertaining to ilities proceeds through six distinct steps:

1. Define the emergent system property of interest.
2. Characterize the system attributes in terms of their physical, logical, and operational architectures. Define the system boundary and required interfaces within the system logical model.
3. Establish a design tradespace of feasible solutions, defined by the lower-level system attributes of each option.
4. Identify a comprehensive set of potential perturbations impacting the emergent system property of interest.

5. Link potential preparations to the set of perturbations to verify the robustness of the potential design solution space. Decompose preparations into their base attributes within the physical, logical, and operational views of the system.
6. For perturbations of interest, generate design metrics for measuring system value under the influence of change caused by the given perturbation. Utilize the system physical, logical, and operational attributes to identify independent and dependent variables.

This framework was used to develop specific metrics for use in evaluating flexibility of a ship power and energy system; these metrics are described in the remainder of this paper.

LITERATURE REVIEW

A literature review was conducted to survey the existing body of knowledge related to "ilities", especially flexibility, in the design of complex systems-of-systems. The design community was found to use the term "ility" with a range of similar definitions, as summarized below.

Ilities. Beginning with a broad exploration of ilities for complex system of systems, several common themes and definitions were found throughout the published material reviewed. The primary objective of defining ilities centers on maintaining system value over time. This need arises from an identified difference between functional requirements used to define the current system's purpose and ilities used to measure the system's ability to respond to change. A temporal aspect of change is prevalent throughout the literature, including lifecycle performance and value discussions. However, there appears to be conflicting terminology used to articulate these purposes. One commonly discovered conflict is the overlap between the definition of ilities and metrics.

(Ricci, Fitzgerald, Ross, & Rhodes, 2014) define a system-of-systems' ilities by the lifecycle value properties that enable a system to "sustain value delivery over time by responding to exogenous changes in the operational environment." They suggest a temporal aspect of the ility, where the value provided isn't realized until after the system is in operation. This aspect differs from traditional functional requirements, which are set to determine the initial primary value of the system. The authors outline a System of System Architecting with Ilities (SAI) method that presents an example set of evaluation metrics for comparing design alternatives that include "optionability" alongside quantitative criteria such as cost and several uses. They go on to describe the need to evaluate SoS architecture alternatives against various metrics, including "value metrics," such as attributes and costs, and "ility metrics," which are determined by evaluating the impact of shifts in system context or requirements from one moment in time to another.

(Chin, Yau, Kok Wah, & Khiang, 2013) describe ilities as "attributes that characterize a system's ability to respond to changes, both foreseeable and unforeseeable." They are presented as non-functional requirements necessary to ensure value delivery over the lifecycle of a system of systems. The authors make a point to acknowledge the cost of implementing ilities and the potential conflict between certain ilities that would require tradeoff decision-making within the architecture. These considerations emphasize the need for a balanced design approach considering the broader system context and requirements.

(Doerry & Amy, 2019) discuss key requirements for surface combatant power and propulsion system design. The authors present a mixed discussion of three prioritized metrics (size, weight, cost) and ilities (flexibility and survivability) that greatly influence the metrics. They identify drivers of requirement implementation as a mix of metrics and ilities: projected future mission system loads, which is a metric, and system survivability criteria, including CONOPS, which is an ility.

(Guariniello & DeLaurentis, 2014) call out an essential role played by metrics in their definition of ilities as the impact of functional and developmental dependencies "on metrics that characterize global properties of a system of systems over its lifespan." They suggest that metrics represent capability at the individual system level but do not directly translate to the system of systems level. Higher level metrics at the SoS level are called ilities.

Design Metrics. To evaluate alternative power and energy system architectures, (Smart, et al., 2017) identified the need for metrics to distinguish between design alternatives. The study explored the impact of new technologies and alternative topologies. Several metrics were available within the designated design tool, S3D, including weight, volume, component count, and a fuel load-range calculation. The authors proposed several future areas for development within early-stage design tools, including various performance metrics.

(Toshon, et al., 2017) present a method for executing Set-Based Design within the shipboard power systems using metrics available in early-stage design tools. The authors discuss a 5 MW Modular Multilevel Converter (MMC) topology and identify pertinent metrics related to the choice of thermal facilities, power density, and cabinet sizing as selection criteria for preferred architectures.

(McNabb, et al., 2019) present a case study for quantifying the value of a particular electric-ship architecture within a broader tradespace using a methodical approach for implementing architectural variations in a baseline model within a robust design simulation environment. The example presented measured baseline performance metrics, displacement, speed, and range variation.

(Chalfant, Hanthorn, & Chryssostomidis, 2012) discuss several metrics typically used in early-stage P&E system design analysis of alternatives, such as weight, volume, fuel efficiency, and losses (based on location, size, and loading). They present an additional survivability metric, which relies on input data from loads, defined services, connectors, and their associated locations. These metrics and their underlying variables were identified within existing design tools, as they are required for defining the system's physical architectures and functional capabilities.

Options, Perturbations and Preparations. A reoccurring set of terminology was found throughout the literature review of system ilities. To establish a common vernacular, the various approaches for implementing ilities to maintain system value commonly refer to "options in design," "perturbations," and "preparations." To design for an ility and to preserve system value, the term perturbation is used to characterize an influence on the system that necessitates change. Design options are inherent capabilities in the design to accommodate future changes. They provide the system owner the option or right to implement the change later in the system's life once the need is identified (right to take action). Preparations refer to the specific architectural features or capabilities planned into the design to enable the system to positively respond to the perturbation (maintain value, value at cost, effectiveness).

(Ricci, Fitzgerald, Ross, & Rhodes, 2014) define perturbations as "unintended (i.e., imposed) state changes in a system's design, context, or stakeholder needs that could jeopardize value delivery;" and an option as "the ability to execute a design decision or feature at any point in the lifecycle that will change or prevent change to the SoS, to respond to variations in the operational context and in stakeholder preferences." The authors further decompose options into change options, which enable a change in the design in response to a perturbation, and resistance options, which enhance the system's ability to resist change.

(Mekdeci, Ross, Rhodes, & Hastings, 2012) decompose perturbations into disturbances and disruptions in their "Taxonomy of Perturbations." Disturbances and disruptions are defined as types of perturbances, with the distinction that disturbances occur over some period of time, but disruptions are nearly instantaneous.

System Views and Context. The naval power and energy system is a complex multidimensional system of systems, including architectures that perform various duties regarding the generation and supply of electrical power, cooling, and mechanical utilities, among others. (Brefort, et al., 2018) present a framework for analyzing distributed systems of naval ship design by decomposing the system characteristics into three primary architectures: physical, logical, and operational. Relationships between interconnected and interdependent systems are discussed in terms of their spatial, functional, and temporal characteristics. The authors present this framework with survivability specifically in mind but outline the applicability to other desired system characteristics. The primary architectures are defined as follows:

- Physical architecture represents the spatial and physical characteristics of the system and its environment.
- The logical architecture describes the functional characteristics of the system and the linkages between each component of the system, focusing on the multidisciplinary nature of the system.
- The operational architecture describes the temporal behavior of a system, including human-system interactions.

These overlapping areas combine information from each primary architecture to provide a deeper understanding of the design space: the physical and logical architectures produce a physical solution; the physical and operational architectures produce physical behaviors; and the logical and operational architectures produce the functional utilization. All three together produce the system response. This framework underpins our approach to defining flexibility metrics and the associated perturbations and preparations.

Flexibility. Flexibility was found to be a predominant ility considered throughout the literature review. Flexibility is frequently presented alongside the classic ilities of survivability and safety as a mechanism for easily enabling system change in response to various types of perturbations. Within the naval power and energy system community, the desire for system flexibility is clear; however, only a single accepted approach for implementation currently exists. Unlike survivability, where industry, government, and Navy-specific guidance has been issued to define system requirements, flexibility is still in the early stages of definition and implementation. This is partially due to the broad scope of requirements and system attributes commonly categorized as flexibility. Whereas the definition of survivability is widely accepted as being decomposed into susceptibility, vulnerability, and recoverability, the literature on flexibility ranges from intrinsic design properties to real options for stakeholder value.

(Chin, Yau, Kok Wah, & Khiang, 2013) define flexibility as "the degree of ease of effecting change(s) to the SoS, in response to external or internal changes, to maintain its mission effectiveness." They suggest that there are two different types of flexibility – operational: the ability to transition between different modes of operation, and design: the design attribute that enables the system to incorporate changes more easily. Agility, adaptability, and scalability are considered subsets of flexibility.

(Doerry, 2014) identifies eight methods for global ship flexibility and how the electrical power distribution system should be considered within each approach. These flexibility approaches include physical shipboard arrangements of equipment to align with hull features and electrical zones, sizing of longitudinal electrical distribution busses, sizing of power cabling, use of interface standards for support equipment, use of modular equipment, use of commercial equipment, and incorporation of energy storage methods. Doerry specifically highlights the importance of flexibility in the electrical distribution system for servicing future electric weapon systems with significantly higher power ratings and load type demands and proposes several interfaces to be developed, including required power type, amount of power required, ramp rates, power quality, quality of service requirements, and monitoring and control conditions.

(Hein, 2022) defines flexibility as “the measure of a ship’s ability to be upgraded quickly and cheaply to efficiently respond to a known or unknown perturbation.” His thesis develops a framework for identifying and characterizing flexibility in design through cause-effect mapping.

(Doerry & Koenig, 2017) propose a framework for identifying what types and quantities of flexibility will “increase the ability of the ship to be quickly and economically reconfigured in the future.” They acknowledge the temporal aspect of the required change as either a temporary mission capability or permanent reconfiguration. Their paper discusses modularity, adaptability, and flexibility as pertaining to specific types of technologies that can be incorporated, each with an independent impact on overall system affordability. The need for flexibility over the platform’s service life is based on potential extensive unknown requirement changes, including high power and new variant combat and mission systems. The overarching framework is based on the principles of Real Options analysis, where design options are considered with respect to their cost per value delivered. In early-stage design and requirements formulation, this type of analysis is valuable for forecasting potential changes to the system requirements and evaluating cost-effective means for responding in the future, but it requires upfront investment in the design. The authors define a tradespace of type and quantity of modular and adaptable technologies, considering cost impacts in terms of weight/space/design effort. These technologies for a flexible ship are proposed considering future system locations, power capacity, sufficient power conversion and distribution, and cooling capacity to support future systems.

(Page J. , 2012) discusses the value of flexibility options in the early-stage design of naval warships instead of options on a project or design. The author argues that Real Options analysis and Net Present Value (NPV) need to be modified to evaluate capital projects (without revenue) and options in design based on needs, cost, and capability. The author identifies power generation and power distribution as top design considerations for historical ship platform upgrade enabling considerations, following general arrangements. Given the Navy’s budgeting constraints that limit investment in new capabilities through the development of new ship classes, a framework is presented using an Overall Measure of Effectiveness based on a Choice Model for how capability can be added to a single ship class over time. The example compares an inflexible (current Navy) platform to a notional modular platform with several flexible preparations. The author suggests extending this framework to the subsystem-level or SoS-level analysis. The paper also suggests that the flexible platform has lower upfront acquisition costs, contrary to many discussions of the cost of flexibility.

(McCauley, Hannapel, Bassler, & Koleser, 2016) introduce the “SWAP Boxes” concept to decouple the ship payload (combat system) from the platform. This decoupling is intended to counter the observed tendency within Navy design programs to quickly lock in design requirements to reduce design time and constrain the ship's weight to control cost. The authors state that flexibility and modularity are two concepts: “flexibility is the ship design capability to accommodate combat system growth, and the ability to insert new technologies into the ship throughout the lifecycle of the individual ship and its class. Modularity is the platform’s ability to accept a system as a self-contained unit with interface standards.” They define flexibility as a function of four criteria: design flexibility, construction modularity, mission modularity, and mission flexibility. Some key benefits of implementing the SWAP Box approach are the ability to apply targeted system margins versus top-level margins and the ability to conduct sensitivity analysis against the maturity of the intended systems. For impact on the power and energy system, SWAP Box parameters would encompass the mission-related loads used to size distributed systems; however, the method is not obviously applicable to the design of the power and energy system architecture itself.

(Richards, Ross, Hastings, & Rhodes, 2009), in their discussion of various perspectives for defining survivability, introduces the ilities flexibility and robustness as “temporal system properties that specify the degree to which systems can maintain or even improve function in the presence of change.” The authors emphasize that ilities are dynamic, based on changes to system needs, the system itself, or the system context.

(Doerry & Moniri, 2013) cite the need for improved survivability and reliability of naval power and energy systems as the systems evolve from traditional low-voltage systems to meet the demands of new high-power combat systems.

Ility Relationships. The collection of research presented in the literature review points to a common definition of ilities as emergent systems properties that impact the system's ability to maintain value over time. Ilities are not primary functional requirements, such as those defined in an Initial Capabilities Document or Capability Development Document that define the system's purpose, but rather, are attributes used to measure the system's ability to respond to change. Emergence refers to the resulting function or capability when multiple elements of a decomposed system architecture are integrated together. While the design community agrees on the perceived value in analyzing ilities, system architects and decision makers need a consistent method for prioritizing and quantifying ility requirements. U.S. Navy guidance identifies the need to assess such ilities as reliability, maintainability, sustainability, flexibility, and vulnerability. The Ship Specifications will typically detail the expected producibility, operability, and maintainability of the ship. However, these proprieties are typically measured within the late stages of design, once the ability to influence the system architecture has passed. Upfront understanding of the dependencies and relationships between ilities and functional requirements will enable the designer to identify more robust solutions when making architectural decision in the early stages of design.

While survivability is widely accepted as being decomposed into susceptibility, vulnerability, and recoverability, the literature on flexibility ranges from intrinsic design properties to real options for stakeholder value. Informally, in the field of Marine Engineering, the two ilities are interchangeably used to describe the ability to maintain system performance; however, a key distinguishing difference in application comes from the origin of the perturbation on the system, and the identification of enabling system attributes. A perturbation requiring system survivability is posed by a purposeful threat to degrade system performance, whereas flexibility perturbations are based on the own-system competitive performance or stakeholder desired capability. Survivability most closely relates to the short-duration sub-type of flexibility, due to the nature of real-time, finite duration disturbance.

FLEXIBILITY DEFINITION FOR SHIP DESIGN

Flexibility is an ility that frequently appears in the discussion of complex systems-of-systems' attributes and requirements but lacks a clear and consistent definition. From the literature review in Section 0, several authors have identified common characteristics of flexible systems within the context of Naval Architecture and ship design, but at varying levels of specificity. (Chin, Yau, Kok Wah, & Khiang, 2013) addressed a comprehensive maritime system of systems, relating flexibility to the degree of ease of effecting change to maintain mission effectiveness in response to external or internal perturbations. At the platform level, (Doerry & Koenig, 2017) have expanded the definition of "ease" to include a measure of speed, timeliness, and cost, and (Hein, 2022) identifies that the perturbations may be either anticipated or unknown at the time of making the required design decisions that determine the platform's capability. (McCauley, Hannapel, Bassler, & Koleser, 2016) identified the mission system as the driver of platform flexibility, which (Schank, et al., 2016) relates to the ability to change physical platform boundaries by providing excess space and flexible infrastructure.

From the commercial energy industry perspective, the International Energy Agency (IEA) defines power system flexibility as "the ability to respond in a timely manner to variations in electricity supply and demand" (Gutierrez Tavarez, 2019). This industry definition of flexibility can be tailored to the shipboard naval power and energy system application and used to develop metrics for early-stage design evaluation.

The definition of flexibility used in this work is as follows:

> *Flexibility is the capability of a system to accommodate change in response to perturbations in requirements.*

The utility in application of flexibility depends on the defined system boundary and the distinction between near-term and long-term impacts. Requirements, such as Top-Level Requirements or system specifications, refer to the measurable needs of the stakeholders. The requirements can be organized into the system's physical, logical, and operational context to better understand the design drivers and determine the enabling design characteristics.

For the naval power and energy (P&E) system, flexibility is quantified within the system boundary, in response to perturbations from new and changing loads requiring power (**demand**) or changes at the source of an energy flow (**supply**). The following discussion defines the power and energy system within the physical-logical-operational capability construct introduced by (Brefort, et al., 2018). Together, these system views link the "right power, right location, right time, and right conditions" (Doerry, 2014).

Physical. The physical view relates to the spatial configuration of the system and the physical attributes of the individual subsystems and components. The P&E system is a distributed system that spans the full extent of the ship and comprises many components typically listed in a Machinery Equipment List (MEL). In this view, the system can be depicted as a series of nodes representing each component or enclosed subsystem. Each node is assigned a location using a coordinate system to establish integration within the whole ship architecture and to define node locations in relation to each other. The metrics used to measure the system's physical requirements and characteristics include measures of distance and each component's physical attributes, including space, weight, power, and cooling (SWAP-C).

Flexibility within the physical view is system configuration driven. The selection of components that comprise the power and energy system and their integration within the ship platform determine the potential system flexibility. The component capacities are measured against the system requirements for supply and demand. Options for implementing flexibility within system attributes include provision of traditional Service Life Allowance margins on SWAP-C, the installation of excess capacity (e.g., installed power generation) beyond initial platform requirements, and defining system interface standards for future subsystem integration. Spatially, the P&E system architecture should be arranged to align with hull features and electrical zones. Options for implementing physical-spatial flexibility include designing reconfigurable spaces, providing access and outfitting paths, or reserving excess arrangeable area within the defined hull compartmentation. Modularity, the design feature that enables the swapping or plug-and-play capability of various system sub-modules within a defined location and interface standard, is defined within the physical view.

Logical. The logical view describes the functional characteristics of the system and the relationships between system components that enable emergent capability. The power and energy system is multidisciplinary, with components connected across the mechanical, electrical, thermal, and signals domains. Figure 1 depicts the flow of electrical power, thermal auxiliaries (water and air), and data across the electrical, thermal, and signals domains for a representative Integrated Power System architecture. In the IPS configuration, as described in Section 0, the propulsion module is considered within the power and energy system, vice as an external load. In the logical view, linkages are identified to connect the individual subsystem or component nodes established in the physical view. Each linkage requires a direction, type, and magnitude to represent a flow within a designated domain.

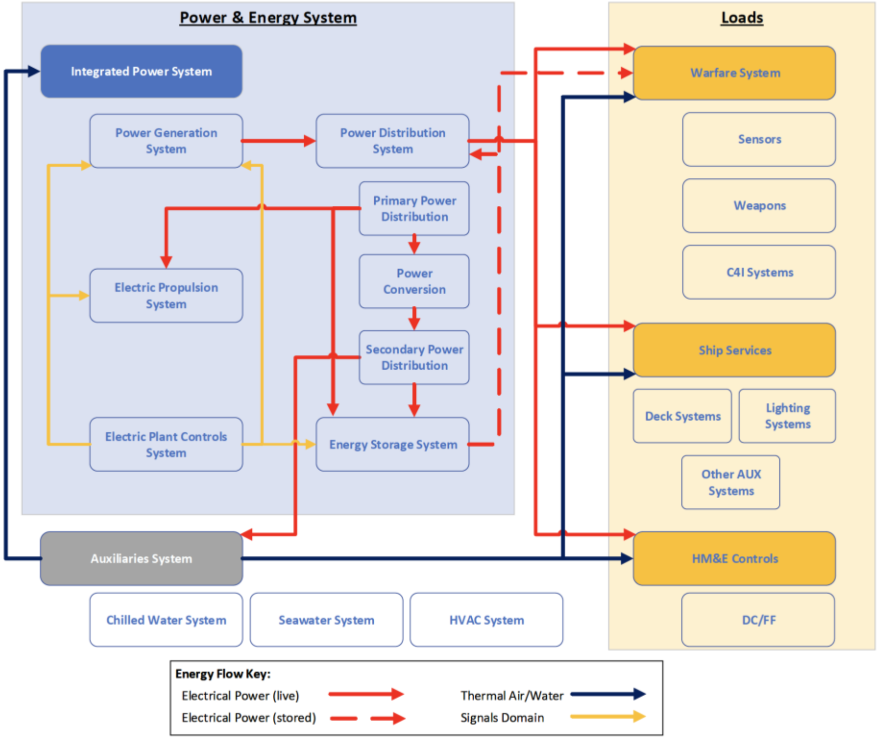

Figure 1: Power and Energy System Logical Model for an Integrated Power System (IPS) for a Combatant

Flexibility within the logical view focuses on the system's ability to provide the required linkages between supply and demand elements within each functional domain when the system realizes future perturbations in requirements. The power and energy system includes a network of distributed systems to enable flows within each domain. The functional flexibility of these systems often centers on the conversion and distribution of the flows and the type of compatible supply and demand elements. To facilitate system sizing and design decision-making, the SWAP Box method introduced by (McCauley, Hannapel, Bassler, & Koleser, 2016) can be used to represent unknown future elements requiring a range of potential P&E system services. The logical view also provides insight into the ability to reconfigure the system in response to realized perturbations.

Operational. The operational view defines the temporal behavior of the system required to accomplish a given mission, including the sequencing of system functions. This view relates a given architecture's physical and logical aspects to the system performance, often referred to as a Measure of Performance. Typical design requirements define the functional capability desired within a particular operating scenario. The time scale of a scenario can range from instantaneous system response to multiyear outlays, such as forecasting of technology maturation and integration. For the power and energy system, these requirements can target specific capabilities of components within each of the specified domains (supply side) or be derived from higher-level platform performance requirements (demand side), such as those related to platform energy consumption.

Operational flexibility is differentiated between requirements for instantaneous response to real-time changes in running conditions beyond the design requirements, and the reconfiguration of the system in response to an emerging requirement change over a large timescale (order of magnitude in years). The various combinations of the demand loads (combat system, ship service, and propulsion loads) requiring service and energy flows within each domain define operational scenarios for the power and energy system. Examples of operational flexibility include the ability to debit power from one category of load to service another, the use of energy storage in response to real-time operational changes or service interruptions, and the ability to incorporate future combat system elements with unique load profiles, such as pulse loads.

METRICS FOR FLEXIBILITY

Design metrics are quantitative or qualitative measures of a system's characterization and value. In the early stages of design, metrics are formulated to assess a system's ability to achieve design requirements and other desired capabilities, including ilities. When evaluating a large multi-attribute tradespace of potential system architectures, alternative designs are compared using metrics to understand the design trade-off and determine the preferred or non-dominated designs. A typical tradespace exploration will evaluate primary and secondary performance measures against cost requirements to uncover trends in system configurations within the open design tradespace.

Attributes of a system within the physical, logical, and operational views serve as the base elements for capability metrics. For ilities such as flexibility, any measure of performance can be traced to the physical attributes of the elements comprising the system; however, the logical and operational properties of these elements within the broader system configuration are required to achieve the desired emergent capability. Flexibility, as the capability to make changes within the system in response to perturbations, requires upfront consideration of how an architecture will respond within each design domain.

For U.S. Navy ship design, flexibility has been traditionally addressed using the Service Life Allowance (SLA) requirement, which equates each vessel's intended years in service to measures of future growth and fatigue capacities based on historical trends such as weight growth and increases in electrical load demands over time. The Navy's design authority, Naval Sea Systems Command (NAVSEA), decomposes SLA into the specific design domains of space, weight, power, and cooling (SWAP-C). These allowances are used to inform the design of the power and energy system and auxiliary systems, size the hullform, and design the hull structure. For the power and energy system, SLA represents flexibility by gross capacity, but doesn't address the necessary decomposition to the subsystem level such as preparations needed within the power distribution and energy storage modules to ensure the intended future capability is achievable.

The following sections identify metrics for evaluating flexibility of the power and energy system within early-stage design space exploration activities. The distinguishing factor of early-stage design is the relatively low amount of design-specific information available to specify a system architecture. Designers and decision makers will typically start with an initial machinery equipment list of components that drive acquisition cost and determine gross system capacity, such as prime movers, generators, power converters and transformers. Sizing and quantities of these components are balanced against first order estimates of load demands based on historical regression or ratiocination, known demands of required mission equipment, and initial system layouts within a conceptual ship stack-up arrangement. The following process traces perturbations to three categories of system flexibility requirements: power capacity, distributable power, and energy storage. Metrics for characterizing capability in each category are proposed using physical-logical-operational system attributes. These metrics should be considered within the overall design space exploration and weighed against functional requirement performance, other ility attributes, and system cost to identify the preferred, "right-sized," solutions.

Power Capacity

Flexible power capacity is dependent on the physical attributes of the power generation subsystem and the design ratings of its components. Within the operational view, flexible power capacity depends on the supply's specified running conditions from the power generation subsystem and demand from the mission system and ship service elements. While the overall power and energy system may be sized based on the prescribed Service Life Allowance requirement, the definition of operating conditions provides a realistic measure of the system's ability to accommodate future potential loads. For an IPS system, power flexibility is determined by the ship's power generation subsystem sizing criteria, including a requirements-driven loading condition. Sufficient power generation is required to energize electric propulsion motors, provide ship service power, and operate onboard mission systems. The requirements-driven loading condition specifies the combination of ship speed and mission system electrical loads requiring simultaneous power supply. Typically, the power generation sizing requirement will specify the propulsion load required to ensure sustained speed, as this is the highest order of magnitude load onboard the ship. The corresponding mission system electrical load depends on the platform's intended use, which may require the ship to operate the most stressing mission load at sustained speed or a representative average of the daily loads experienced.

Flexible Power Capacity (FPC) Metric. Equation (1) defines flexibility power capacity (FPC) as the sum of the total distributable power available (P_{DST}), based on generation and distribution subsystem capacities; minus the sum of all required loads (L_{REQ}) within the system sizing criteria used for the calculation, such as the 24-hour average load or maximum-margined electrical load; divided by the total power installed (P_{tot}). Distributable power includes energy generated onboard that is available for mission systems and ship services, whereas, depending on the architecture topology, the total installed power includes all energy generated. For example, in an IPS architecture the distributable power may be equal to the total installed power, but a mechanical architecture will have separate ship service power generation and dedicated propulsion diesels or gas turbines directedly connected to the shaft line, so distributable power will be significantly lower than total installed power. The FPC metric provides a relative measure of flexibility for alternative architectures that meet similar mission requirements and should not be used to compare platforms of drastically different initial load requirements. For those types of high-level material solution considerations, a measure of total excess capacity in megawatts is more appropriate. Case Study 1 outlines the differences in applying this metric for different power and energy system architectures.

$$FPC = \frac{P_{DST} - L_{REQ}}{P_{tot}} \tag{1}$$

Debitable Power Flexibility (DPF) Metric. A second metric for the employment of flexible power capacity within an IPS architecture, where the total power generated is required to service the propulsion as well as the mission and ship service loads, is debitable power flexibility (DPF). Whereas the FPC Metric considers elements of the system's physical architecture in a defined loading condition, the Debitable Power Flexibility metric considers the operational architecture capability for applicable system topologies across a range of operational loading conditions, defined by combinations of load requirements. Debitable Power is the ability of the IPS system to prioritize the loads receiving power, effectively debiting power from one load category to service another. Because the largest magnitude load by category is the propulsion load at sustained speed (L_{ps}), the debitable power load available (L_{avail}) is the propulsion load used to size the propulsion subsystem (L_{pREQ}) less the propulsion load required to make a minimum acceptable mission speed (L_{pmin}); thus, $L_{avail} = L_{pREQ} - L_{pmin}$. The DPF is then the minimum of the new additional load demand above the initial design requirement (L_{add}) and the debitable power load available, divided by the new load demand; see equation (2). Case Study 2 will discuss the sensitivity of IPS power flexibility against the selected sizing criteria propulsion and mission loads.

$$DPF = \frac{\min\left(L_{add}, L_{avail}\right)}{L_{add}} \tag{2}$$

An observed phenomenon when using this metric to compare power and energy systems in ship concepts of varying hullform efficiencies is that a less efficient hull requires larger installed power capacity to achieve the same top-end speed, thus providing a larger debitable power load available when propulsion requirements are reduced to the minimum acceptable speed. This perceived benefit, however, only sometimes leads to system selection within a tradespace when balanced against other attributes, such as cost. Right-sizing the power generation subsystem to align with the desired operating modes leads to a preferred architecture.

Case 1: Flexible Power Capacity Metric

The following examples demonstrate the application of the Flexible Power Capacity metric, equation (1), for three different power and energy system architectures: an Integrated Power System (IPS), a Hybrid power system, and a Mechanical propulsion system with separate ship service power generation. Within each architecture, the sensitivity to specified load conditions is demonstrated by varying the load criteria for ship service and mission elements between the max-margined and 24-hour average electrical load cases and the propulsion loads between the sustained speed and economical transit (cruise) conditions. Additionally, each demand load is evaluated at the initial delivery and end-of-service life conditions to demonstrate increases in demand over time.

For the basis of this analysis, a notional ship concept was leveraged from the NAVSEA Design Data Sheet (DDS 200-2) for 'Calculation of Surface Ship Annual Energy Usage and Cost' (2012). The concept has a design service life of 20 years, requiring a 15% power SLA. Table 1 shows the electrical loads for each design operating condition, including 50% of the SLA. Economical transit is conducted at 16 knots, surge to theater requires 30 knots, and the underway-mission propulsion load is based on a prescribed speed-time profile from DDS 200-2.

Table 1: Electric Load Conditions at various temperatures and operational scenarios (NAVSEA, 2012)

Temperature (°F)	In port - Shore Power (kW)	Underway - Economical Transit (kW)	Underway - Surge to Theater (kW)	Underway - Mission (kW)
10	1,000	3,000	3,000	4,800
59	500	1,800	1,800	3,200
100	900	2,400	2,400	4,000
Propulsion Load	-	7,100	46,800	7,208

Three representative ships were created using the same hullform, mission system loads, and propulsion requirements, but with three different P&E system topologies: IPS, Hybrid, and Mechanical. The DDS 200-2 representative ship concept was leveraged for the Integrated Power System, consisting of three Large Gas Turbine Generators (LTG), two Small Gas Turbine Generators (STG), and two electric Propulsion Motor Modules (PMM). For this basis of comparison, the hybrid and mechanical architecture alternatives were created to provide comparable power for propulsion and mission loads, as shown in Table 2. In the IPS concept, PMMs are sized to achieve the design sustained speed of 30 knots at eighty percent of the maximum continuous rating (MCR). The power generation subsystem, consisting of LTGs and STGs, is sized to provide sufficient power for the sustained speed condition plus the mission load at the end of service life (EOSL), accounting for motor efficiencies and power transmission losses. For the hybrid concept, the propulsion subsystem consists of PMMs, sized to achieve the economical transit speed of 16 knots, plus two propulsion gas turbines (PGT) directly coupled one to each shaft in an ‘Or’ configuration, such that the PMMs and PGTs do not combine to achieve sustained speed, and the required propulsion demand is supplied by one or the other. The hybrid power generation subsystem is sized to provide full power to the PMMs and mission loads at EOSL. Lastly, the mechanical concept propulsion subsystem consists of four PGTs, two per shaft, and the power generation subsystem is sized to provide mission loads at EOSL with one generator offline for redundancy, referred to as the (N-1) requirement. This (N-1) requirement is not required for IPS or hybrid architectures due to the order of magnitude greater amount of distributable power capacity installed which enables the system to debit propulsion load to compensate for a generator casualty.

Table 2: Major Machinery Equipment Lists

	IPS		Hybrid (Or)		Mechanical	
	Unit Count	Total kW	Unit Count	Total kW	Unit Count	Total kW
Large Turbine Generator (LTG)	3	72,000	0	-	0	-
Small Turbine Generator (STG)	2	6,000	5	15,000	3	9,000
Propulsion Motor Module (PMM)	2	60,000	2	8,000	0	-
Propulsion Gas Turbine (PGT)	0	-	2	60,000	4	76,000
Condition Driving Installed Power Generation	Sustained Speed Propulsion (30kt) + mission at EOSL		Max Electric Propulsion (16kt) + mission at EOSL		Mission at EOSL (N-1)	
Power Generation Required	-	67,370	-	12,938	-	5,136
Total Installed Power	5	78,000	7	75,000	7	85,000

IPS architecture case. In the IPS architecture, it is assumed that the full amount of power generated can be distributed throughout the ship for propulsion or ship mission loads; thus, the Power Distributable (P_{DST}) is equal to (P_{tot}) at 78 MW. In reality, there may be restrictions on the amount of power that can be distributed across a single bus, limiting the power available for non-propulsion loads based on the specific distribution architecture. The load required (L_{REQ}) is dependent on the specific combination of propulsion and mission load demands, and the amount of service life consumed. Table 3 determines the Flexible Power Capacity for the IPS architecture at sustained speed while operating in two different modes: the underway-mission at 10°F condition, requiring the maximum margined electrical load, and the underway-economical at 10°F condition, requiring the 24-hour average electrical load. Each load combination will evolve over the ship’s service life as SLA is consumed and propulsion efficiency reductions are realized. The “at delivery” load required includes the propulsion shaft horsepower required with a 94% PMM efficiency at sustained speed and the stated mission load without SLA. The “at the end of service life (EOSL)” load applies an additional 25% growth factor to the propulsion SHP for hull fouling and plant degradation and a 15% growth factor to the mission loads for consumed SLA. Table 3 also provides the Flexible Power Capacity calculations for the same load conditions at cruise speed, where the PMM efficiency is 91%.

Hybrid architecture case. For the hybrid architecture, where the electric propulsion PMMs are required to cover a smaller portion of the propulsion speed-power curve than the IPS, the distributable power (P_{DST}) is significantly less, at 15 MW. In this configuration, propulsion power at the top end of the speed-power curve is provided by a dedicated PGT on each shaft, which are accounted for in the P_{tot} of 75 MW. In operating conditions with high-speed requirements, the PGTs are online to provide propulsion load, and the L_{REQ} only reflects the ship mission loads. In conditions with speeds up to 16 knots, the L_{REQ} includes the power for the electric propulsion PMMs in addition to the ship mission loads. Table 4 demonstrates the differences between loading conditions requiring PGT and PMM propulsion service. In each example, L_{REQ} is calculated at the max-margined and twenty-four-hour average loads at delivery and at the end of service life, as evaluated in the IPS case. A 94% PMM efficiency factor is applied to the propulsion load in all cruise conditions (16 knots), and a 25% hull fouling and plant degradation factor is applied to the end of service life evaluations.

Table 3: IPS at Sustained Speed and Cruise Speed

	IPS: Sustained Speed				IPS: Cruise Speed			
	Max Margined Load at Delivery (w/o SLA)	Max Margined Load at EOSL (w/ SLA)	24 HR AVG at Delivery (w/o SLA)	24 HR AVG at EOSL (w/ SLA)	Max Margined Load at Delivery (w/o SLA)	Max Margined Load at EOSL (w/ SLA)	24 HR AVG at Delivery (w/o SLA)	24 HR AVG at EOSL (w/ SLA)
PDST (kW)	78,000	78,000	78,000	78,000	78,000	78,000	78,000	78,000
LREQ (kW)	54,253	67,370	52,578	65,444	12,268	14,889	10,593	12,963
Ptot (kW)	78,000	78,000	78,000	78,000	78,000	78,000	78,000	78,000
FPC	0.30	0.14	0.33	0.16	0.84	0.81	0.86	0.83

Table 4: Hybrid with Sustained Speed (PGT) Required

	Hybrid: Sustained Speed (PGT)				Hybrid: Cruise Speed (PMM)			
	Max Margined Load at Delivery (w/o SLA)	Max Margined Load at EOSL (w/ SLA)	24 HR AVG at Delivery (w/o SLA)	24 HR AVG at EOSL (w/ SLA)	Max Margined Load at Delivery (w/o SLA)	Max Margined Load at EOSL (w/ SLA)	24 HR AVG at Delivery (w/o SLA)	24 HR AVG at EOSL (w/ SLA)
PDST (kW)	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000
LREQ (kW)	4,466	5,136	2,791	3,210	12,019	14,577	10,344	12,651
Ptot (kW)	75,000	75,000	75,000	75,000	75,000	75,000	75,000	75,000
FPC	0.14	0.13	0.16	0.16	0.04	0.01	0.06	0.03

Mechanical architecture case. In the mechanical architecture case, electrical power distribution capacity (P_{DST}) is not required for any portion of the propulsion load and, therefore, is sized solely based on the ship service and mission loads. The propulsion demand, an order of magnitude greater than the max margined electric load, is serviced by dedicated PGTs and included in the total installed power (P_{tot}). The load required (L_{REQ}) is calculated at the max margined and twenty-four-hour average loads at delivery and at the end of service life, as evaluated in the IPS and hybrid cases. The mechanical power flexibility, Table 5, is calculated based on the same loading requirements as the sustained speed hybrid case, using PGT propulsion power.

Table 5: Mechanical (not propulsion dependent)

Mechanical: Not Propulsion Dependent				
	Max Margined Load at Delivery (w/o SLA)	Max Margined Load at EOSL (w/ SLA)	24 HR AVG at Delivery (w/o SLA)	24 HR AVG at EOSL (w/ SLA)
PDST (kW)	6,000	6,000	6,000	6,000
LREQ (kW)	4,466	5,136	2,791	3,210
Ptot (kW)	85,000	85,000	85,000	85,000
FPC	0.02	0.01	0.04	0.03

Discussion. When setting a flexible power capacity requirement, the selection of determinant loading conditions should be based on the platform's intended use and CONOPS. The comparison of cases above provides the requirement owner additional context into the differences between resulting architectures that a particular set of requirements will drive the designer to select. Evaluation of the FPC metric within a full-scale design space exploration will link the ility performance of the P&E system topologies to the physical attributes of their integrated platform, such as overall dimensions, displacement, and cost to better identify the preferred solution. Figure 2 depicts the flexible power capacity for each IPS, hybrid, and mechanical architecture considered across the range of potential loading requirements. Each of the eight loading conditions are plotted for the IPS and hybrid architectures, along with the four mechanical load cases. The flexibility metrics are plotted against a normalized balance of power required and power available to service the requirement due to the significant differences in capacities for integrated versus separated power systems. This normalization demonstrates the magnitude of power required for each individual load case versus the physical architecture capacity installed.

The IPS example architecture has installed capacity beyond the minimum requirement for end-of-service life based on the selected combination of LTGs and STGs. The plant lineup identified in DDS 200-2 (NAVSEA, 2012) targeted increased energy efficiency at each operating condition, requiring a mix of low- and high-power-rated turbines aligned to the required load combinations. This configuration provides flexible power capacity in each evaluation condition, including the most stressing case: sustained speed plus maximum-margined electrical load with full consumption of SLA. The IPS example has five times the amount of distributable power as the hybrid example and thirteen times the amount of the mechanical example. When evaluated for Flexible Power Capacity, including consideration of total installed power and propulsion plus ship service loads in each condition, the IPS example scored one and a half times greater than the FPC values of the hybrid PGT-propulsion on average across the four loading conditions, and eleven times greater on average than the FPC values of the mechanical architecture.

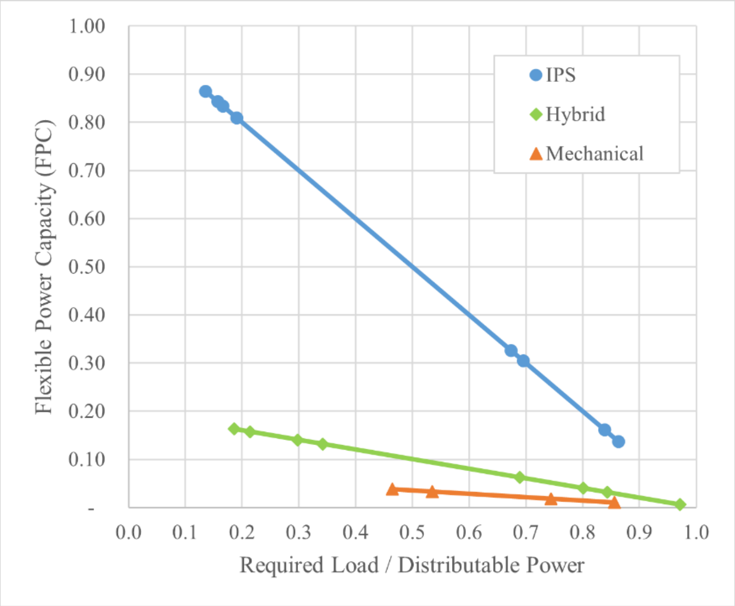

Figure 2: Flexible Power Capacity (FPC) Metrics for IPS, Hybrid, and Mechanical examples versus normalized power capacity, load case required over distributable power

Of interest, the case results determined that the hybrid architecture FPC flexibility is higher at high speeds, while the IPS architecture FPC flexibility is higher at low speeds. In the 'Or' condition with PMMs online (up to 8 MW), the hybrid architecture's measure of flexibility is significantly reduced from the flexible power capacity while using PGTs, as the electric propulsion consumes over half of the available power for distribution. It should be noted, however, that there may be limitations in minimum operating speeds for scenarios able to utilize the flexible power capacity of the PGT-only operating conditions based on the minimum RPM of the propulsion gas turbines and the shaft-propeller design.

The mechanical case requires the greatest amount of installed power of the three architectures, as the required loads for mission and propulsion are isolated to dedicated power supplies, resulting in the lowest amount of distributable power. Additionally, despite the mechanical concept requiring the installation of a redundant/backup ship service power generation to satisfy the (N-1) requirement, the third STG does not contribute to the distributable power.

Case 2: IPS Debitable Power Flexibility Metric

This case utilizes the notional IPS ship concept from DDS 200-2 (NAVSEA, 2012), as described in Case 1, to demonstrate the debitable power flexibility metric. Two variants of the IPS architecture, with a 30-knot and 27-knot sustained speed requirement (L_{pREQ}) respectively, are compared to isolate the impacts associated with a given architecture's sizing criteria for required propulsion load. The debitable power metric for each variant is evaluated for a 1-knot and 5-knot speed reduction in the minimum propulsion load required (L_{pmin}), at both initial delivery and end-of-service life conditions. Three sets of new load demands above the initial design requirement (L_{add}) are then used to represent a range of future mission system requirements.

Table 6 demonstrates the debitable power flexibility (DPF) for the 30-knot IPS architecture, given 1-knot and 5-knot speed reductions for minimum acceptable propulsion load at delivery and EOSL conditions. The additional 25% propulsion factor applied for the EOSL condition reduces the debitable power load available (L_{avail}) by 11 MW in the 1-knot reduction case and 7 MW in the 5-knot reduction case. This results in lower DPF values when assessed against the 15 MW load for the 1-knot reduction case and the 30 MW load for both 1- and 5-knot reduction cases. In all minimum acceptable propulsion conditions, the 30-knot IPS architecture easily accommodates the 2 MW additional load case. The 5-knot speed reduction significantly increases debitable power load availability, a 94% increase in the delivery condition, and a 340% increase in the EOSL condition.

Table 6: Debitable Power 30 knot IPS

	1 Knot Reduction				**5 Knot Reduction**			
	Propulsion Condition	kW	Propulsion Condition	kW	Propulsion Condition	kW	Propulsion Condition	kW
LpREQ	30kt, 100% MCR	62,234	30kt, 100% MCR	62,234	30kt, 100% MCR	62,234	30kt, 100% MCR	62,234
Lpmin	29kt, Delivery	45,014	29kt, EOSL	56,268	25kt, Delivery	28,812	25kt, EOSL	36,015
Lavail		17,220		5,966		33,422		26,219
	Ladd (kW)	DPF	Ladd (kW)	DPF	Ladd (kW)	DPF	Ladd (kW)	DPF
Load 1	2,000	1.00	2,000	1.00	2,000	1.00	2,000	1.00
Load 2	15,000	1.00	15,000	0.40	15,000	1.00	15,000	1.00
Load 3	30,000	0.57	30,000	0.20	30,000	1.00	30,000	0.87

The 27-knot sustained speed variant of the notional IPS architecture assumes the same speed-power curve performance of the hull, but the reduced top-end speed requires less total installed power. Table 7 demonstrates the debitable power flexibility for the 27-knot IPS architecture, given 1-knot and 5-know speed reductions for minimum acceptable propulsion load at delivery and EOSL conditions. Based on the lower speed requirements, which correspond to significantly lower resistance and propulsion demand along the speed-power curve, this concept has less debitable power load available in both speed reduction conditions. Compared to the 30-knot concept, the available loads are 20-25% lower for the 27-knot concept cases. Despite the differences in the magnitude of the loads available in all conditions, the relationship between available load at delivery and EOSL conditions holds for the 27-knot concepts, with a 98% increase for the 1-knot reduction and a 330% increase in the 5-knot reduction cases. In summary, the 27-knot concept scored lower debitable power flexibility in all cases and failed to provide the available load threshold for the 15 MW load case 2 in the 1-knot reduction at delivery case, while the 30-knot IPS concept was able to provide sufficient flexible power in the all cases.

Table 7: Debitable Power 27 knot IPS

	1 Knot Reduction				**5 Knot Reduction**			
	Propulsion Condition	kW	Propulsion Condition	kW	Propulsion Condition	kW	Propulsion Condition	kW
LpREQ	27kt, 100% MCR	45,495	27kt, 100% MCR	45,495	27kt, 100% MCR	45,495	27kt, 100% MCR	45,495
Lpmin	26kt, Delivery	32,535	26kt, EOSL	40,669	22kt, Delivery	19,830	22kt, EOSL	24,787
Lavail		12,959		4,826		25,665		20,708
	Ladd (kW)	DPF	Ladd (kW)	DPF	Ladd (kW)	DPF	Ladd (kW)	DPF
Load 1	2,000	1.00	2,000	1.00	2,000	1.00	2,000	1.00
Load 2	15,000	0.86	15,000	0.32	15,000	1.00	15,000	1.00
Load 3	30,000	0.43	30,000	0.16	30,000	0.86	30,000	0.69

Whereas the flexible power capacity metric considers the architecture-specific installed power generation and electrical loading conditions, the debitable power flexibility metric focuses solely on the demand load conditions, given an established system sizing criterion. Figure 3 graphically displays the increase in available load as the propulsion load is debited for the 27 and 30 knot concepts in their EOSL state. Each curve represents the flexible power available at the given speed, as evaluated in the cases in Tables 13-16. Horizontal grey lines are placed at the three evaluation loads for 2, 15, and 30 MW. Where the dashed horizontal lines are above the L-avail curve, the debitable power flexibility is less than one, with scores decreasing as the distance between the two increases. Vertical arrows are drawn at the speed reductions of 1 and 5 knots, as evaluated above.

The debitable power flexibility metrics for each of the eight conditions are plotted in Figure 4 against the three added load requirements (2, 15, and 30 MW). The figure depicts the point at which each case is no longer able to satisfy the additional load when DPF drops below one. The 30kt IPS concept outscores the 27kt concept in each combination of delivery/EOSL and -1/-5 knot minimum propulsion load due to the exponential shape of the speed power curve. The higher the sustained speed required, the greater the available load when the minimum propulsion load is identified along the exponential curve. Additionally, as expected, we see that the 5 knot reductions for minimum propulsion load provide the largest available load and DPF values in each condition. Lastly, the impact of expected fact of life growth in propulsion load to achieve the minimum acceptable speed at EOSL reduces the available load and DPF for the 15 and 20 MW added loads in each case.

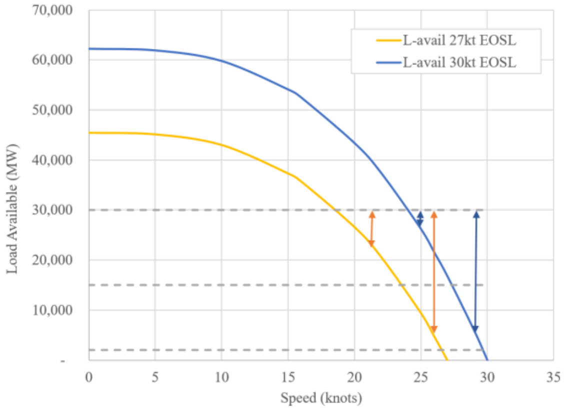

Figure 3: Flexible Power – Load Available at Speed

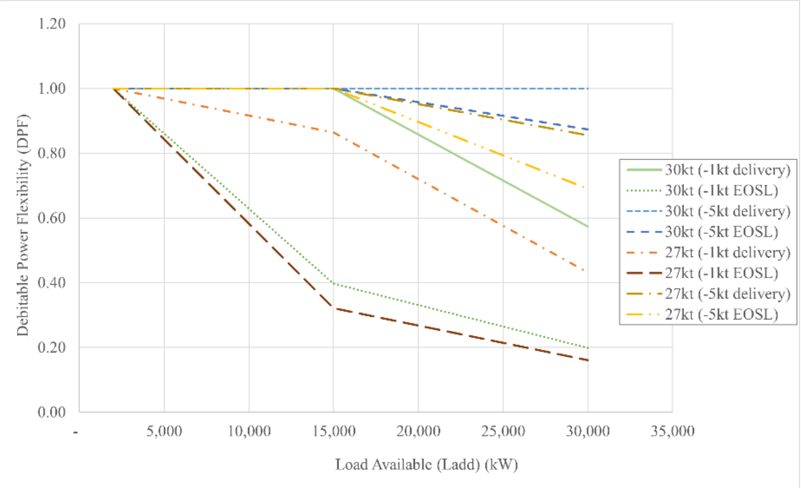

Figure 4: Debitable Power Flexibility versus Load Available for example speed delta cases

Distributable Power

Power distribution system flexibility is required to connect generation capacity to the component-specific load demands throughout the ship. Distribution includes the ship-wide transmission of energy flows and energy conversion into the voltage and quality required by the end users, as shown in the logical view, Figure 1. The physical configuration of the distribution system relies on the maximum distribution capacity, available voltage types and ratings, and the spatial considerations of where the loads are located on the ship, which are typically bound by the assignment of electrical zones. Load requirements will vary within each zone, depending on the interface needed for each individual end user. Therefore, power flexibility depends on each zone's local conversion and distribution capabilities.

Power Distribution System Flexibility (PDSF) Metric. The power distribution system flexibility metric utilizes an ‘evaluation loading set’ to represent the types of interfaces and the classification of potential future load demands within an individual zone. An evaluation loading set is a compilation of potential future load elements, beyond the initial system design requirements for demand services at delivery plus any required service life allowances. The set can be generated to include a variety of load characteristics required for service from the power and energy system to provide, such as voltage type, voltage rating, and power draw. Because propulsion load demands for an IPS ship significantly outweigh the mission and ship service loads in any zone, they are considered separately from the distribution evaluation loading set. Table 8 demonstrates five evaluation loading conditions based on four potential future mission elements and one representative set of their combination.

Each load element is differentiated by voltage type and power demand. The ~1000 VDC demands are typical of high-power mission systems like radar and laser weapons and may draw directly from the primary power distribution bus. Other low voltage demands, such as onboard computing and thermal auxiliary systems, require in-zone power conversion and distribution within the secondary power distribution system. In an early-stage design tradespace exploration, the full permutation of single elements and their combinations can be used to determine a simple and indicative metric for distributable power flexibility. Further along in the design process, ship configuration details such as general arrangements and locations of mission stations are established, and the evaluation loading set should be tailored to reflect the revised open tradespace or uncertainty for a given zone.

Table 8: Example distribution system 'evaluation loading sets' for potential future load demands

Voltage Type:	1000 VDC	800-650 VAC	450 VAC
Load Condition (N)	Element* (Power - kW)	Element (Power - kW)	Element (Power - kW)
N1	Laser (1200)	Base Load (500)	Base Load (2000)
N2	Radar (1000)	Base Load (500)	Base Load (2000)
N3	EW (1500)	Base Load (500)	Base Load (2000)
N4	NA	Base Load (500) Energy Magazine (1000)	Base Load (2000)
N5	Laser (1200) Radar (1000) EW (1500)	Base Load (500) Energy Magazine (1000)	Base Load (2000)

*Electric loads for mission system elements of interest taken from (Smart et al., 2017)

The distribution capacity within a zone depends on the sizing of the primary power distribution system, which brings medium voltage power from the onboard generators, and the secondary power distribution system, which converts medium voltage power to lower voltages and currents directly compatible with end users' demand. The power distribution system can be configured in a variety of topologies, such as a radial bus, distributed, or zonal system, with each option having tradeoffs in space, weight, cost, and performance. The flexibility of a ship's power distribution system ($PDSF$), Equation (3), is the average distribution flexibility: the sum of the distribution flexibility in each zone (DST_{zone}), divided by the total number of zones (N_{zones}). Equation (4) determines each zone's flexibility score by assessing the in-zone distribution capability to satisfy the set of load conditions (N). If the zone has sufficient capacity in all defined assessment criteria categories, (N_j) will be scored as a 1, otherwise, if the distribution architecture cannot satisfy any one of the categories in the load condition, it will receive a 0. This approach provides a measure of the platform's distribution flexibility, regardless of the total number of electrical zones, as described below.

$$PDSF = \frac{\sum_{0}^{zone(i)} DST_{zone}}{N_{zones}} \tag{3}$$

$$DST_{zone} = \frac{N_1 + N_2 + N_3 + \cdots + N_j}{N_{tot}} \tag{4}$$

Flexibility can be incorporated (and purchased) as capacity within the design at the initial delivery of the system, or through design preparations that enable future upgrades to the system when needed. The configuration of the primary and secondary power distribution (ring, distributed, zonal, or other) controls the inherent capabilities of the system that impact flexibility, as measured in equation (4). Table 9 provides three examples of power distribution system features that enable flexibility by increasing the total number of potential load cases either at initial system delivery or as a future reconfiguration. The case study provided below compares a split ring and a zonal distribution system architecture at different stages of the design specification process and at different points in the platform's service life.

Table 9. Examples of flexible distribution system features

Flexible Electrical Distribution	Impact
Dedicated electrical power distribution bus for expected high power loads.	Increases the number of potential load cases by enabling new mission system elements to be installed in any zone, with reduced dependence on in-zone power conversion capacity.
Use of high-temperature superconducting cable – variable current, temperature dependent.	Can increase the power distributed to the zone by decreasing the cable temperature without adding new cables. Requires additional cooling. (Note: not necessarily available instantaneously, design preparations needed)
Use of programmable and/or modular power conversion and power electronics: **- Power Electronic Building Blocks** **- Integrated Power Node Centers**	Reduces the total number of power conversion elements. Provides the ability to customize conversion within any given zone to the needs of future end-users using existing or common distribution equipment.

Case 3: Power Distribution System Flexibility Metric

This case demonstrates how to build an evaluation loading set and use it to assess power distribution system flexibility in P&E system architectures. The case study uses a common evaluation loading set to compare four variants:

- **Conventional split ring bus architecture (early-stage design)**: based on the ESRDC 10,000-ton IPS ship concept (Smart, et al., 2017)
- **Ring bus alternative (later design stage)**: a variant of the ESRDC concept case is presented to demonstrate the maturation of the evaluation criteria as the design space for potential future loads is reduced.
- **Zonal distribution architecture (base model)**: based on the Integrated Fight-Through Power (IFTP) concept described in the 'Next Generation Integrated Power System (NGIPS) Roadmap' (Doerry, 2007)
- **Zonal alternative (future block upgrade)**: a variant of the NGIPS concept is used to demonstrate the increase in flexibility associated with a future upgrade to the initial base architecture.

The evaluation loading set is built as a full permutation of the individual element loads in Table 10, which include the base loads required at delivery plus the potential future mission systems that the platform may be required to host in the future. The voltage types and power ratings for this evaluation set are notional, based on the payload list identified in (Smart, et al., 2017), and do not represent any actual Navy system values. Elements listed with multiple power ratings, separated by a comma, represent different configurations the future system may reflect in the future. Various options per element type may represent uncertainty of element rating or quantity. The two baseload LVAC options reflect potential differences across multiple zones of the ship at delivery. Inclusion of zero kW element loads enables the evaluation set to account for potential zone requirements that do not include the given mission element. A full permutation of these load elements generates 1,728 evaluation conditions; each of these evaluation conditions is assessed against each zone in the given distribution system architecture to determine the distribution score for that zone, then zonal scores are combined for an overall PDSF metric. To simplify the assessment of a given electrical distribution zone, the applicable loads for each set are summed by voltage type category, in this case as 1000V Medium Voltage Direct Current (MVDC), between 650-800V of either Alternating or Direct Current (MVAC/MVDC), or 450V Low Voltage Alternating Current (LVAC). For example, the 300th permutation consists of:

> [500 kW MVAC/DC Base Load, 1500 kW LVAC Base Load, 200 kW MVAC/DC Energy Magazine, 600 kW MVDC Laser, 0 kW MVAC/DC Processing, 0 kW MVAC/DC VLS, 1700 kW MVDC Radar, 4000 kW MVDC SEWIP, 450 kW MVAC/DC Sonar]

which sums to [6,300 kW MVDC, 1,150 kW MVAC/DC, 1500 kW LVAC]. The full set of permutations is available in Platenberg (2024).

Table 10: Evaluation Load Set Elements

Voltage Type:	MVDC (direct feed)	MVAC/MVDC	LVAC
Element	Power (kW)	Power (kW)	Power (kW)
Base Load	NA	500	1500, 2000
Energy Magazine	NA	0, 200, 1000, 2000	NA
Laser	0, 600, 1200	NA	NA
Processing Equipment	NA	0, 200	NA
Missile Launcher	NA	0, 400	NA
Radar	0, 1700, 3300	NA	NA
Electronic Warfare (EW)	0, 2000, 4000	NA	NA
Sonar	NA	0, 450	NA

Variant 1: Ring Bus (early-stage design evaluation). The conventional split-ring-bus architecture, shown in Figure 5, is based on the (Smart, et al., 2017) 10,000-ton IPS concept, with four electrical distribution zones, a primary power distribution system voltage of 10 kVDC, and dual paths of power on port and starboard sides of the ship through the fully connected ring bus. Power generation modules (PGMs) and propulsion motor modules (PMMs) are connected directly to the ring bus via appropriate converters or drives. The baseline architecture included dedicated converters for high power loads to connect two Radars and one Railgun to the primary distribution bus; however, for this case and the evaluation load set, the topology was modified to replace the Railgun converter with converters for the EW and Laser elements in Zone 1, add a second EW converter in Zone 2, and add a second Laser converter in Zone 4. The power conversion modules (PCMs) represent converters and inverters within each zone, connecting all other loads to the port and starboard bus. The sizing of these converters was taken directly from the ESRDC concept, and the total distribution capacity by zone is summarized in Table 11.

Each of the four electrical zones was assessed independently for its ability to satisfy the 1,728 potential future electrical loading conditions (N) in the evaluation set. If the zone had sufficient capacity in each of the three voltage categories, then a score of 1 was recorded for that Nth condition, otherwise, if there was insufficient capacity in any one of the three categories, a score of 0 was recorded. The sum of the 1,728 N-scores divided by the total number of N load conditions determined the zone's flexibility metric (DST_{zone}), as shown in Table 11. The average of the four zones scores determined a total power distribution system flexibility score ($PDSF$) of 0.31.

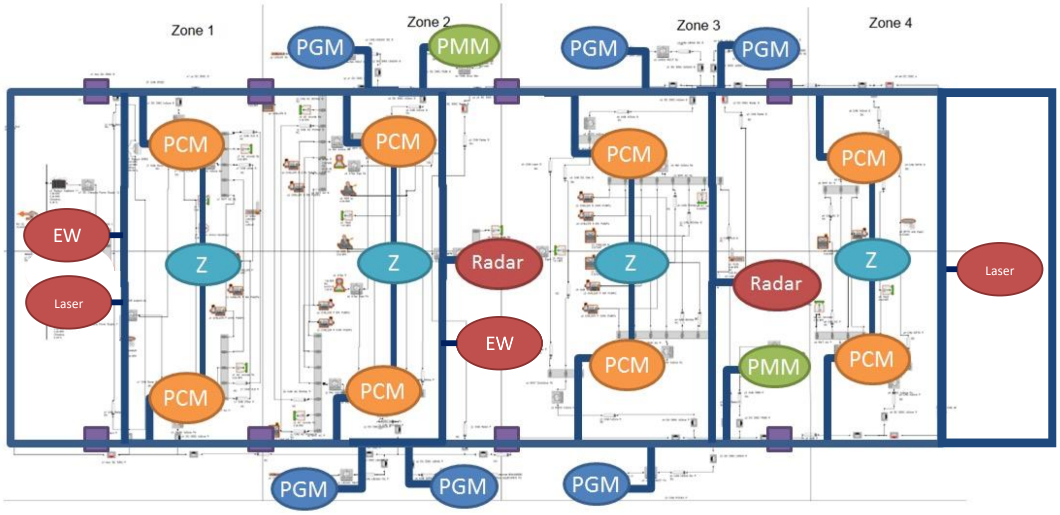

Figure 5: Conventional Split Ring Bus Distribution Architecture Topology. Based on (Smart, et al., 2017).

In each of the four zones, the limiting distribution category is the MVDC converter ratings for the dedicated mission elements. In a design space exploration activity, this finding might lead the designer to investigate the ability of the potential future elements to bring additional dedicated converters when needed for installation in the future, along with verification of the architecture's total flexible power capacity.

Table 11: Conventional Split Ring Bus Distribution Capacity by Zone and voltage category; with each zones distribution flexibility score considering the full evaluation loading set permutation.

	Zone 1 (kW)	Zone 2 (kW)	Zone 3 (kW)	Zone 4 (kW)
MVDC (direct feed)	3,200	3,700	3,300	1,200
MVAC/MVDC	8,000	17,800	12,400	5,800
LVAC	4,200	5,800	7,000	3,100
$\boldsymbol{DST_{zone}}$	0.33	0.41	0.37	0.11

*Distribution capacity based on (Smart et al., 2017)

Variant 2: Ring Bus (later stage design evaluation). To simulate the progression from a distribution flexibility analysis of an early-stage concept design to a more mature preliminary design baseline, the conventional ring bus architecture was used for a second flexibility evaluation. In this case, the design space for potential zone requirements is narrowed and the evaluation loading set is tailored to the requirements for each zone. Table 12 provides the refined requirements for evaluation loading set criteria applicable to Zones 1-4. Zone 1, the forward-most zone on the ship, is designated responsibility for the Sonar, due to shaping of the hullform and location of the sonar dome. Radar requirements are allocated to the zones 2 and 3, which are covered by the deckhouse for mounting the equipment topside. The Laser tradespace is unchanged; however, the energy magazine requirements are reduced to 1 MW and locations based in zones 2-4. The resulting flexibility score improvements are shown in Table 12, and the total power distribution system flexibility score ($PDSF$) improves to 0.64. Note that zone 1 scores a 1.0, as the evaluation loading set requirements were narrowed to match the MVDC converter for the mission elements as intended.

Variants 3 and 4: IFTP (Base Model and Block Future upgrade). The zonal distribution architecture is based on the Integrated Fight-Through Power concept described in the Next Generation Integrated Power System Roadmap (Doerry, 2007), with a notional in-zone topology depicted in Figure 6. For this case, the zonal electrical distribution system concept consists of 4 electrical zones, with a series of Power Conversion Modules (PCM) types to convert power within each zone. A PCM-4 serves as a transformer rectifier to convert MVAC power from the power generation module to 1000 VDC for distribution across the ship. Within each zone, PCM-1As convert 1000 VDC power to a variety of MVDC voltages based on user needs. PCM-2As then convert 750-800 VDC power from the PCM-1A into LVAC in-zone demands. Additionally, for this concept, a notional PCM-X is connected to the 1000 VDC bus in each zone to service high power MVDC loads throughout the ship. It is assumed that the rating of each PCM is scalable based on the number of modular subcomponents included: Ship Service Inverter Modules (SSIM) or Converter Modules (SSCM).

Table 12: Refined Requirements Evaluation Loading Criteria

	Zone 1	Zone 2	Zone 3	Zone 4
MVDC (direct feed) Limiting Criteria	0x Radar 1x EW Unit 1x Max Laser	1x Radar Unit 1x EW Unit 1x Max Laser	1x Radar Unit 1x EW Unit 1x Max Laser	0x Radar 1x EW Unit 1x Max Laser
MVDC (kW)	3,200	4,900	4,900	3,200
MVAC/MVDC Limiting Criteria	1x Sonar 0x Energy Mag	0x Sonar <1MW Energy Mag	0x Sonar <1MW Energy Mag	0x Sonar <1MW Energy Mag
MVAC/MVDC (kW)	1,550	2,100	2,100	2,100
LVAC (kW)	2,000	2,000	2,000	2,000
$\boldsymbol{DST_{zone}}$	1.0	0.65	0.59	0.33

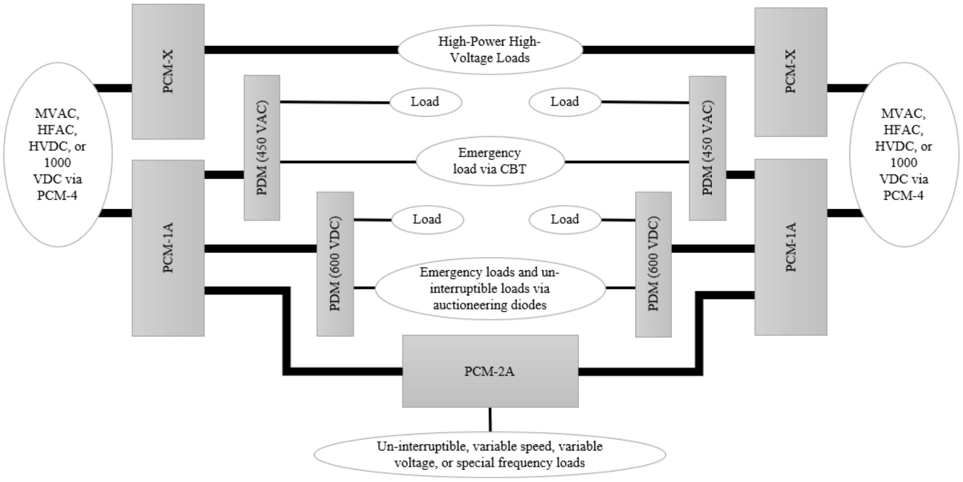

Figure 6: NGIPS Roadmap "Potential Future IFTP" In-Zone Topology, based on (Doerry, 2007)

Two variants of the zonal IFTP concept were evaluated to demonstrate the different flexibility scoring associated with a base model architecture as initially delivered, and a block future architecture, including some planned upgrades to the distribution system. These two zonal IFTP variants are consistent with this approach, as the base model architecture including design preparations in the form of planned PCM growth capacity to accommodate additional SSIM/SSCMs in the future, when needed. The base model is delivered with 5.5 MW of PCM-X, 12 MW of PCM-1A, and 10 MW of PCM-2A capacity, and design preparations for 22 MW of PCM-X and 4 MW of PCM-1A SSCM/SSIMs. Table 13 indicates the PCM capacity for the base model configuration by zone, with the associated zone's flexibility metric (DST_{zone}). The total power distribution system flexibility score ($PDSF$) for this configuration is 0.14. However, once the maximum PCM capacity is installed in the block future configuration, also shown in Table 13, the total PDSF score improves to 0.85.

Table 13: Zonal IFTP Distribution Capacity by Zone, Base Model and Future Distribution

	Base Model				Future Distribution				
	Zone 1 (kW)	Zone 2 (kW)	Zone 3 (kW)	Zone 4 (kW)	Zone 1 (kW)	Zone 2 (kW)	Zone 3 (kW)	Zone 4 (kW)	Total DST Capacity (kW)
PCM-X	0	2,000	3,500	0	6,875	6,875	6,875	6,875	27,500
PCM-1A	3,000	3,000	3,000	3,000	4,000	4,000	4,000	4,000	16,000
PCM-2A	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	10,000
$\boldsymbol{DST_{zone}}$	0.03	0.16	0.32	0.03	0.85	0.85	0.85	0.85	0.85

The four architecture variants' power distribution system flexibility metrics and individual zone flexibility scores are plotted in Figure 7. Each architecture was modeled with four electrical zones, with varying distribution and conversion capacities in each zone, across the MVDC, MVDC/MVAC, and LVAC assessment categories. The ring bus variants, each with the same distribution and conversion capacities, are shown in blue. The early-stage design assessment utilized the full permutation of the evaluation loads sets, whereas the later-stage design assessment tailored the evaluation loads based on other known design decisions to reduce the range of potential future load options desired in each zone. This maturation of design data resulted in a 100% increase in PDSF for the ring-bus architecture. The IFTP base model and block future variants are plotted in yellow, to demonstrate the increase in distribution flexibility provided by including preparations in the design to accommodate future (long-term) perturbations in required load demands. The ship concept for these IFTP variants remains constant other than the installation of additional distribution and conversion modules in the block future, to represent in-line upgrades at the same maintenance availability where the new load demand end-users are installed. In a design space exploration activity, a large number of representative architectures can be defined by their individual zone characteristics, and assessed against a common set of evaluation loads to identify the feasible options. In this limited example, the IFTP option is preferred based on the lower upfront cost of the architecture and the ability to achieve the higher power distribution system flexibility in the future, when the long-term perturbations are realized.

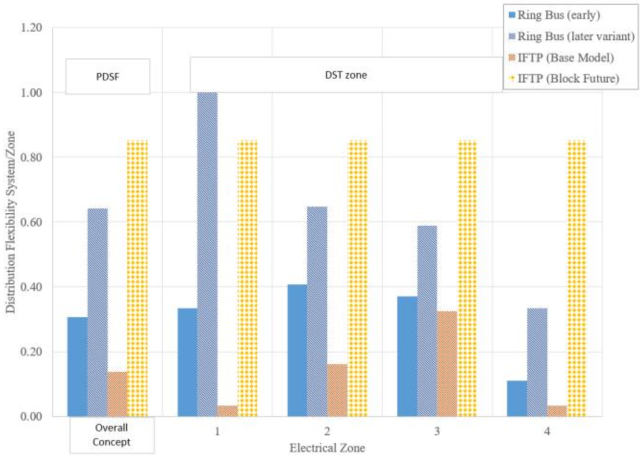

Figure 7: Power Distribution System Flexibility (PDSF) and individual zone (DSTzone) scores

CONCLUSIONS

This paper develops measures of power and energy system flexibility; this specific ility was chosen based on the frequency of its appearance in the literature review and interest within the broader naval design community. Flexibility is defined as the capability of the system to accommodate change in response to perturbations in requirements. For the naval power and energy system, flexibility is quantified within the system boundary, in response to perturbations from new and changing loads requiring power or changes at the source of an energy flow. Three case studies were conducted to develop metrics for Flexible Power Capacity, Debitable Power Flexibility, and Distributable Power Flexibility.

The maturation of developmental mission system technologies with new and increased electrical power demands are driving requirements for emergent properties, beyond the typical functional requirements. The U.S. Navy surface fleet is currently facing challenges related to the rate of technology change and uncertainty of the combat systems of the future, and the significant cost of investment to design and build new ship classes. Uncertainties impact the system's ability to affordably maintain mission relevance within an evolving operational context. Affordability constraints within the Navy acquisition environment, and the timelines for designing new and modified classes of ships, emphasize the need to make informed decisions in early-stage design.

Related and Future Work

Additional metrics were developed in conjunction with this work. Interested readers are referred to Platenberg (2024) for a description and case study of an energy storage system flexibility metric, and for a Real Options Analysis that balances system performance and cost to "right size" the P&E system at delivery with preparations in the design to react to future uncertainty.

The Navy and academic community should pursue validating and implementing the metrics presented here for power and energy system flexibility within the Smart Ship System Design (S3D) program and integrating with the standard early-stage design tools within the Leading Edge Architecture for Prototyping Systems (LEAPS) toolkit.

CONTRIBUTION STATEMENT

D. Platenberg: Conceptualization; data curation, methodology; writing – original draft. **J. Chalfant:** conceptualization; supervision; writing – review and editing. **W. Seering:** conceptualization; supervision.

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