Characterizing Naval Ship Systems Power and Energy Metrics through Modeling and Analysis

By

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ABSTRACT

This research introduces a framework for analyzing shipboard power and energy systems as a repeatable process to differentiate between preferred solutions within a design tradespace. The Naval design community needs a consistent method for evaluating non-functional requirements, called "ilities," in the early design stages when informed decision making provides the greatest opportunity to positively influence the system's performance and lifecycle cost. Ilities are defined as emergent properties that impact a system's ability to maintain value over time. The pace of technology maturation and the uncertainty in magnitude and characteristics of future load types drive the need for robust power and energy system architectures that can adapt to future perturbations in requirements. This research proposes a framework for developing metrics that can be used to identify preferred options with the design space. 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. The proposed process is exercised to develop quantitative, measurable metrics for Naval power and energy system flexibility: the capability of the system to accommodate change in response to perturbations in requirements. Four case studies are presented, developing metrics for Flexible Power Capacity, Debitable Power Flexibility, Distributable Power Flexibility, and Energy Storage Flexibility. A fifth case presents the application of Real Options Analysis for balancing system performance and cost to "right size" the P&E system at initial delivery with preparations in the design to react to future uncertainty.

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Table of Contents

ABSTRACT **3**
ACKNOWLEDGEMENTS **4**
1 Introduction **11**
1.1 The Naval Power and Energy system *12*
1.2 Design Requirements *13*
1.3 Early-Stage Design *14*
2 Literature Review **16**
2.1 Ilities *16*
2.1.1 Ility Hierarchies 17
2.2 Design Metrics *20*
2.2.1 Measures of Effectiveness 21
2.3 Methods of Design Space Exploration *22*
2.3.1 Cause-Effect Mapping 22
2.3.2 Differential Analysis 23
2.3.3 Scenario-Based Evaluations 24
2.4 System Views & Context *26*
2.5 Ility - Flexibility *28*
3 Problem Statement **30**
4 Research Summary **30**
4.1 Ility Relationships *31*
4.2 Framework for Design Space Exploration *33*
5 Flexibility for Ship Design **34**
5.1 Power and Energy System Flexibility *35*
5.1.1 Physical 35
5.1.2 Logical 36
5.1.3 Operational 38
5.2 Perturbations for Flexibility *39*
6 Metrics for Flexibility **46**
6.1 Power Capacity *47*
6.1.1 Case 1: Flexible Power Capacity Metric 49
6.1.2 Case 2: IPS Debitable Power Flexibility Metric 54
6.2 Distributable Power *58*
6.2.1 Case 3: Power Distribution System Flexibility Metric 60
6.3 Energy Storage *66*
6.3.1 Case 4: Energy Storage System Flexibility Metric 68
6.4 Interface Control *72*
6.5 Real Options Analysis *73*
6.5.1 Case 5: Real Options Analysis of a Future Integrated Power System 74
7 Conclusions **86**
7.1 Future Work *87*
Bibliography **89**
Appendix A Zone Load Evaluation Set Options 92
Appendix B Notional Energy Storage System Design Space 115
Appendix C Energy Storage System Flexibility Evaluation MATLAB Code 117
Appendix D Element Load Profiles 127

List of Figures

Figure 1: JCIDS and Defense Acquisition Process (DAU, 2023) 14

Figure 2: Notional U.S. Navy Ship Acquisition Phases, activities, and Products 15

Figure 3: Ility co-occurrence in literature review with implied dependence (deWeck, Ross, & Rhodes, 2012) 18

Figure 4: Ility configuration-context-needs space (Richards, Ross, Hastings, & Rhodes, 2009) .. 20

Figure 5: Framework for assessing flexible designs (Doerry & Koenig, 2017) 26

Figure 6: Representation of the physical-logical-operational framework for a given scenario (Brefort, et al., 2018) 27

Figure 7: Power & Energy System "Ility" Hierarchy 32

Figure 8: Power and Energy System Logical Model for an Integrated Power System (IPS) for a Combatant 37

Figure 9: Propulsion Speed-Power Curve (NAVSEA, 2012) 49

Figure 10: Flexible Power Capacity (FPC) Metrics for IPS, Hybrid, and Mechanical examples versus normalized power capacity, load case required over distributable power 53

Figure 11: Flexible Power – Load Available at Speed 57

Figure 12: Debitable Power Flexibility versus Load Available for example speed delta cases..... 58

Figure 13: Conventional Split Ring Bus Distribution Architecture Topology. Based on (Smart, et al., 2017). 62

Figure 14: NGIPS Roadmap "Potential Future IFTP" In-Zone Topology (Doerry, 2007) 64

Figure 15: Power Distribution System Flexibility (PDSF) and individual zone (DSTzone) scores . 66

Figure 16: Radar power profile (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023) ... 70

Figure 17: Electronic Warfare system power profile (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023) 70

Figure 18: Laser Weapon power profile over a 70-minute operating time. Insert of 200-second period. (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023) 71

Figure 19: DDG-51 Mission Type-Time Operating Profile (Anderson, 2013) 75

Figure 20: Notional generator efficiency as a function of power level (Smart, et al., 2017) 79

Figure 21: Performance – Flexible Power Capacity (FPC) CDF for base case with uncertainty .. 83

Figure 22: Net present value CDF for power distribution system base case with uncertainty 83

Figure 23: Performance – Flexible Power Capacity (FPC) CDF for Real Options 84

Figure 24: Net present value CDF for power distribution system Real Options 85

List of Tables

Table 1. Ility definitions 32
Table 2. Framework for Establishing Ility Metrics 34
Table 3: Short-term (operational) perturbations beyond initial design requirements requiring Flexibility. 41
Table 4: Long-term perturbations (realized at future maintenance period) beyond initial design requirements requiring Flexibility. 43
Table 5: Service Life Allowances required for 20 and 30 years 46
Table 6: Electric Load Conditions at various temperatures and operational scenarios (NAVSEA, 2012) 49
Table 7: Major Machinery Equipment Lists 50
Table 8: IPS at Sustained Speed 51
Table 9: IPS at Cruise Speed 51
Table 10: Hybrid with Sustained Speed (PGT) Required 52
Table 11: Hybrid with Cruise Speed (PMM) Required 52
Table 12: Mechanical (non-propulsion dependent) 53
Table 13: Debitable Power 30 knot IPS - 1 knot Reduction 55
Table 14: Debitable Power 30 knot IPS - 5 knot Reduction 55
Table 15: Debitable Power 27 knot IPS - 1 knot Reduction 56
Table 16: Debitable Power 27 knot IPS - 5 knot Reduction 56
Table 17: Example distribution system ‘evaluation loading sets’ for potential future load demands 59
Table 18. Examples of flexible distribution system features 60
Table 19: Evaluation Load Set Elements 61
Table 20: Conventional Split Ring Bus Distribution Capacity by Zone and voltage category; with each zones distribution flexibility score considering the full evaluation loading set permutation. 63
Table 21: Refined Requirements Evaluation Loading Criteria 64
Table 22: Zonal IFTP Base Model Distribution Capacity by Zone 65
Table 23: Zonal IFTP Block Future Distribution Capacity by Zone 65
Table 24: Example load profiles for potential future operational scenarios requiring energy storage flexibility 68
Table 25: Notional Energy Storage System Design Space Bounding Parameters 68
Table 26: Case 4 Operational Scenarios for Energy Storage Flexibility 69
Table 27: ESS Design Space Flexibility Results for 125 Total Concepts 72
Table 28: CONOPS Condition-Loading Profile 75
Table 29: ESRDC 10,000 ton Ship Concept Mission System Battle Power Condition (Smart, et al., 2017) 76

Table 30: PCM Assumptions 77
Table 31: Cost Parameters 78
Table 32: Power Generation Lineups 79
Table 33: Mission system load uncertainty input factors 80
Table 34: Decision Criteria 81
Table 35: Flexibility Option Capacity Limitations 81
Table 36: Fixed Input Parameters 82

List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
AIM	Advanced Induction Motor
AoA	Analysis of Alternatives
BCC	Basic Construction Cost
CBA	Capabilities Base Assessment
CDD	Capabilities Development Document
CDF	Cumulative Distribution Function
CEM	Cause-Effect Mapping
CF	Concept Formulation (Design Phase)
CONOPS	Concept of Operations
DAU	Defense Acquisition University
DD&C	Detail Design & Construction
DDNA	Development Dependency Network Analysis
DG	Diesel Generator
DoD	Department of Defense
DPF	Debitable Power Flexibility
DRM	Design Reference Mission
EOSL	End of Service Life
ESM	Energy Storage Module
ESRDC	Electric Ship Research and Development Consortium
ESS	Energy Storage System
ESSF	Energy Storage System Flexibility
EW	Electronic Warfare
FDNA	Functional Dependency Network Analysis
FPC	Flexible Power Capacity
GTG	Gas Turbine Generator
HTS	High Temperature Superconducting
ICD	Initial Capabilities Document
IEA	International Energy Agency
IEP	Immediately External Perturbations
IFTP	Integrated Fight-Through Power

Abbreviation	Definition
InTop	Integrated Topside
IPNC	Integrated Power Node Centers
IPS	Integrated Power System
JCIDS	Joint Capabilities Integration and Development System
JROC	Joint Requirements Oversight Council
KPP	Key Performance Parameter
KSA	Key System Attribute
LEAPS	Leading Edge Architecture for Prototyping Systems
LTG	Large Gas Turbine Generator
LVAC	Low Voltage Alternating Current
MADM	Multi-Attribute Decision Making
MCR	Maximum Continuous Rating
MDAP	Major Defense Acquisition Program
MEL	Machinery Equipment List
MIL-SPEC	Military Specifications
MIL-STD	Military Standards
MMC	Modular Multilevel Converter
MOE	Measures of Effectiveness
MOGO	Multi-Objective Genetic Optimization
MOP	Measures of Performance
MVAC	Medium Voltage Alternating Current
MVDC	Medium Voltage Direct Current
NAVSEA	Naval Sea Systems Command
NGIPS	Next Generation Integrated Power System
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&S	Operation and Sustainment
OMB	Office of Management and Budget
OMOE	Overall Measures of Effectiveness
OMOR	Overall Measure of Risk
OMOV	Overall Measure of Vulnerability

Abbreviation	Definition
P&E	Power and Energy System
PCM	Power Conversion Modules
PCON	Power Control Module
PD	Preliminary Design (Design Phase)
PDM	Power Distribution Modules
PDSF	Power Distribution System Flexibility
PEBB	Power Electronic Building Block
PGM	Power Generation Module
PGT	Propulsion Gas Turbine
PLM	Power Load Module)
PMM	Propulsion Motor Module
PMM	Permanent Magnet Motor
QoS	Quality of Service
R&D	Research and Development
RFP	Request for Proposal
ROA	Real Options Analysis
RPM	Rotations per Minute
RSDE	Rapid Ship Design Environment
S3D	Smart Ship System Design (software)
SAI	System Architecting with Ilities
SBD	Set Based Design
SEWIP	Surface Electronic Warfare Improvement Program
SHP	Shaft Horsepower
SLA	Service Life Allowance
SoS	System of Systems
SSCM	Ship Service Converter Modules
SSIM	Ship Service Inverter Modules
STG	Small Gas Turbine Generator
SWAP-C	Space, Weight, Power, and Cooling
TDP	Technical Data Package
TIES	Technology Identification, Evaluation, and Selection
TOPSIS	Technique for Order of Preference
VC	Vital Components

1 Introduction

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, seaworthy hull system and a power and energy (P&E) 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 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.

This thesis 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 with five case studies using proposed metrics for power and energy system flexibility. This work is intended to present a repeatable process for developing metrics that can be integrated within early-stage design tools for generating and evaluating the naval power and energy system, such as the Smart Ship System Design (S3D) design environment currently under development within the Electric Ship Research and Development Consortium (ESRDC).

1.1 The Naval Power and Energy system

The power and energy system 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 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 DDG-1000 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. This ability for this ship to share 78 MW of power across all platform functions is enabled by the inclusion of electric propulsion motors, enhanced power distribution, and power controls. The power and energy system can be further decomposed into seven basic module types, as described in the Navy's Next Generation Integrated Power System Roadmap (Doerry, 2008):

- Power Generation Module (PGM)
- Propulsion Motor Module (PMM)
- Power Load Module (PLM)
- Power Distribution Modules (PDM)
- Power Conversion Modules (PCM)
- Energy Storage Module (ESM)
- Power Control Module (PCON)

Performance characteristics of the power and energy 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 over 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 overall architecture agnostic and depend more directly on the configuration of a particular sub-module, such as the energy storage module. When comparing power and energy system architecture alternative, the designer needs to consider total integrated system capability and the dependencies between applicable modules.

1.2 Design Requirements

U.S. Navy ship design programs are most frequently classified as Major Defense Acquisition Programs (MDAPs) within the Defense Acquisition System and subject to the Joint Capabilities Integration and Development System (JCIDS) processes for Acquisition, Requirements, and Funding. JCIDS supports the Joint Requirements Oversight Council (JROC) responsibility for validating warfighting capability requirements. Figure 1 depicts the JCIDS and Defense Acquisition process per the 2021 JCIDS Manual, with the core elements of capability requirements development and validation, as described by the Defense Acquisition University (DAU, 2023). High level operational requirements, including capability gaps and mission needs, are identified during a Capabilities Base Assessment (CBA), and captured within an Initial Capabilities Document (ICD) for resulting outcomes that recommend approval of a material solution. An Analysis of Alternatives (AoA) compares potential material solutions based on mission-level requirements for their “operational effectiveness, suitability, and life-cycle cost” (DAU, 2023). The results of the AoA inform the development of a draft Capabilities Development Document (CDD), comprised of threshold and objective performance values for Key Performance Parameters (KPP) and Key System Attributes (KSA). The draft CDD is matured throughout the Technology Maturation and Risk Reduction Phase, which corresponds to the Preliminary Design Phase for U.S. Navy ship design.

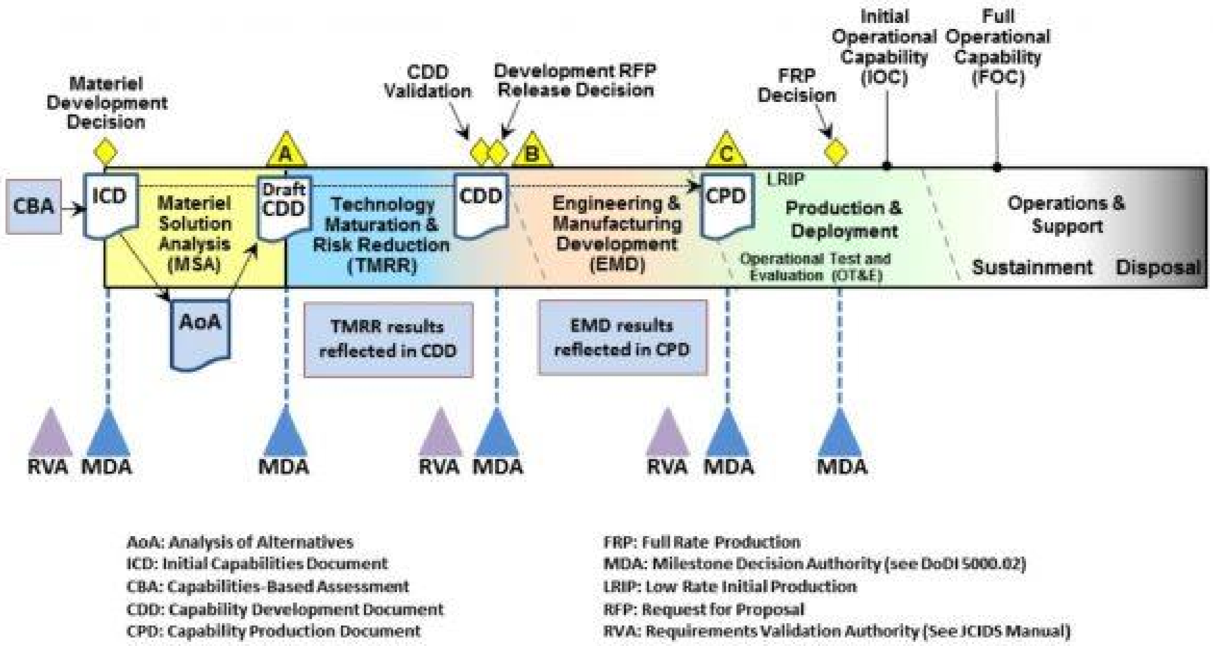

Figure 1: JCIDS and Defense Acquisition Process (DAU, 2023)

In Navy ship design, the CDD requirements are decomposed, assigned, and allocated to individual systems within the ship SoS, using the principles of Systems Engineering, to guide the design. In addition to CDD capability requirements, the ship design will be subject to other design criteria, including Department of Defense (DoD) and Navy-specific Military Specifications (MIL-SPEC) and Military Standards (MIL-STD) technical requirements. The Ship System Specification document is developed alongside the system and subsystem design activities to capture the total set of requirements subjected to the platform, applied down to the subsystem level. These Specifications identify design criteria and standards, constraints, and system interfaces required to meet the platform performance requirements. The Ship Specification document is required to support the Milestone B program review and is a major component of the Technical Data Package (TDP) representing the ship baseline design to be included in the Detail Design & Construction (DD&C) Request for Proposal (RFP).

Design decisions are made at the system and subsystem levels throughout the 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.

1.3 Early-Stage Design

Early-stage design covers a variety of engineering activities conducted prior to Acquisition Milestone B. It includes the trade studies and analyses performed during the Capabilities Based Assessment and Analysis of Alternatives within the requirements development process, as well as the initial system architecting efforts within the Material Solution Analysis and Technology Maturation and Risk Reduction periods. In ship design parlance, early-stage design is conducted within the Concept Formulation (CF) and Preliminary Design (PD) Phases. Figure 2 depicts the design phases for a notional Navy ship acquisition program. In this construct, requirements development activities, including cost versus capability trade studies, are performed to determine Top Level Requirements during the Concept Formulation phase that feeds into the Draft CDD. Preliminary Design commences once a stable set of system requirements are established, and the design program can demonstrate the ability to achieve them within a feasible baseline ship concept. The early-stage components of PD focus on major system selections and sub-system identification.

Design Phase	Concept Design	Preliminary Design		Contract Design	Detail Design
Engineering Activity	Set Based Design			Functional Design	Production Design
Products	• Balanced Requirement Set • Program plans, budget, processes • Identification of sets, System of System (SoS) • Initial Specifications • Feasibility assessments • Systems engineering process • System development plans	• Global ship configuration, dimensions lock • Subsystem definition • Specifications tailored to subsystems • Identification of critical risks and approved mitigation plans	• Functional baseline specifications • Acceptable SoS cost • Verification Requirements met • Risk mitigation activities complete • System, equip. procurement specification development	• Allocated baseline specifications • Bid package for construction contract award • 3D product model • System lanes and routing, deconfliction • Vendor selection and contract • Producibility assessment	• Production work packages • Final cost assessment • Required spec mod. approved departures from specification • Production schedule • System activation plans • Systems Engineering validation

Figure 2: Notional U.S. Navy Ship Acquisition Phases, activities, and Products

The notional program description of Figure 2 depicts the use of a Set Based Design (SBD) approach to Concept Formulation and Preliminary Design. (Page J. E., 2022) describes the implementation and organization of the Set Based Design process currently being executed by the U.S. Navy's next generation large surface combatant program, DDG(X). SBD relies of the principles of concurrent engineering, delaying decisions, and increased design space exploration to make design decisions through the process of elimination. This is accomplished through the decomposition of the SoS by design domains or competencies and establishing sets of alternative solutions. (Page J. E., 2022) describes the SBD execution through the following three contiguous design activities:

1. Articulate the set of every conceivable solution to the problem that has been presented.
2. Remove from this set the subset of all solutions that are not feasible.
3. Remove from the remaining set all solutions for which there is a better (dominating) solution.

Modern Naval ship design relies on a mix of computer-aided tools capable of early characterization of synthesized ship concepts and high-fidelity definition of specific system architectures. For the Naval power & energy system, ESRDC's Smart Ship System Design is a U.S. Navy-developed tool for defining, analyzing, and understanding power and energy flow performance in distributed systems. It enables the designers to quickly characterize the physical implications of a notional power and energy system architecture in terms of weight, volume, and location of associated components during early-stage design activities. Logical and physical connectivity between system components is defined across multiple disciplines, including electrical, mechanical, and piping subsystems. Currently, S3D is used to analyze the energy flows across all subsystems and components to verify power supply, demand, and distribution requirements are met within the larger system. The ability to incorporate additional performance and non-functional requirement metrics within such a toolset will provide the system designer greater insight into making design decisions within a set tradespace based on feasibility and dominance.

2 Literature Review

A literature review was conducted to survey the existing body of knowledge related to "ilities" 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 in Section 2.1. This research was conducted at the outset of the thesis process to provide context to the state of published work related to the utilization of ilities and design metrics in a broad range of SoS engineering processes and to identify priority design focus areas within the specific discipline of naval power and energy (P&E) systems. Two initial hypotheses were formulated for structuring the research, with intended applicability within a new early-stage P&E design framework. The first was that relationships exist between individual ilities such that the optimization of one may have a coincident positive or negative impact on others. The second was that, in the design of complex systems-of-systems, the lowest level of system definition is the selection of design variables that combine to form the metrics used to measure ilities.

The following review documents the state of practice and implementation as published through various professional and academic forums. Several consistent themes were found related to the interconnectivity of individual ilities and the common ways they are prioritized to improve system value functions. Various methods for analyzing performance and cost value when comparing alternative architectural decisions are captured below within three categories: Cause-Effect Mapping, Differential Analysis, and Scenario-Based evaluation. A separate line of research is also discussed, which decomposes a system based on its spatial, functional, and temporal characteristics. Lastly, additional focus is placed on the emerging ility "flexibility" and how it relates to more frequently prioritized system characteristics.

2.1 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, discussed in Section 2.3.2, 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.

2.1.1 Ility Hierarchies

Various hierarchies and ility decompositions were found throughout the literature to further define ilities into measurable system attributes. Some specific ilities, such as survivability, were identified to have strong roots in traditional system requirements, while others, such as evolvability, are less easily defined. This decomposition shows that there are clear relationships between individual ilities and multiple ways to approach a desired system attribute. Many of the ilities discussed broadly in the literature review are desired attributes of the naval P&E system.

Research by (deWeck, Ross, & Rhodes, 2012) to uncover the relationships between system lifecycle properties resulted in the proposal of a “means-ends hierarchical relationship amongst ilities.” The authors first acknowledge that certain ilities, such as safety and reliability, have been historically prevalent in the system of system designs, despite being considered secondary requirements to those that are quantitatively testable by traditional processes. Through the authors' own experience and subject matter expertise, they developed a list of twenty ilities. They conducted a research survey to collect data on frequency and co-occurrence of citations, to develop a model of potential relationships between ilities, shown below in Figure 3.

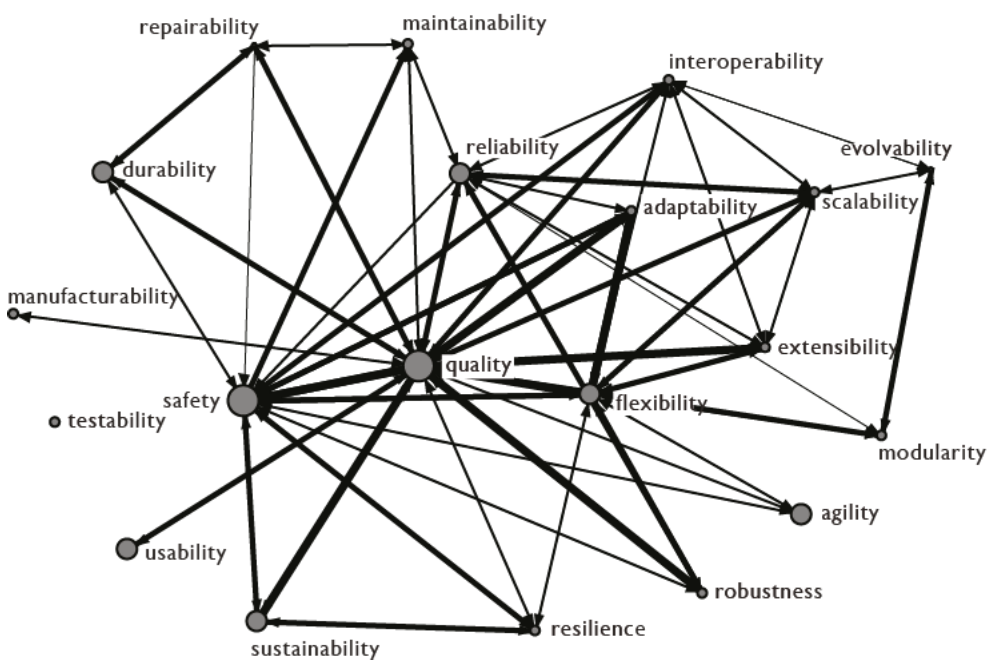

Figure 3: Ility co-occurrence in literature review with implied dependence (deWeck, Ross, & Rhodes, 2012)

Based on the prevalence and co-occurrence of certain ilities, the authors proposed a means-ends hierarchy structure of ilities, by which one ility may serve as the means for accomplishing another or the ends. The authors recommend considering ilities in terms of system properties versus capability in one specific area. The authors identified a potential means-ends hierarchy by conducting a preliminary exercise with a group of researchers with experience working with ilities and given a common set of definitions for the twenty ilities. Of interest to this thesis literature review, further exploration into the initial set of twenty ilities identified survivability, changeability, and robustness as “ends” at the top of the hierarchy, flexibility within the middle of the hierarchal relationship, and modularity and interoperability as sample “means” at the bottom of the hierarchy. Figure 7 within Section 2.1.1 will further define these ilities of interest and demonstrate their relationships within the context of the Naval power and energy system.

(Chin, Yau, Kok Wah, & Khiang, 2013) present a framework for managing a system of systems ilities through identifying an ility hierarchy. The authors propose that two specific ilities, robustness and evolvability, are essential for maintaining the SoS's ability to meet baseline operational requirements and future unforeseen requirements later in the system's life. Because SoS architectural requirements are capability driven, they are typically evaluated against predefined missions and scenarios. These ilities ensure that the system can meet the performance requirements once "operational contingencies" are introduced to the value-driving scenario. Within their system hierarchy, the authors decompose robustness to include survivability and sustainability. Their framework goes on to identify flexibility and interoperability as key enabling ilities.

(Richards, Ross, Hastings, & Rhodes, 2009), in his 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, as depicted in Figure 4. Survivability is defined as "the ability of a system to minimize the impact of a finite-duration disturbance on value delivery, achieved through (I) the reduction of the likelihood or magnitude of a disturbance, (II) the satisfaction of a minimally acceptable level of value delivery during and after a disturbance, and/or (III) a timely recovery." The author differentiates survivability from robustness, although both are "measures of the ability of systems to reduce the sensitivity of their outputs to changes in the environment." In this way, survivability is considered a case of robustness, where the system must mitigate finite changes in context or impulse events. An eight-phase multi-attribute tradespace exploration for the survivability process is presented, with the end measurable survivability metrics of time-weighted average utility loss and threshold availability.

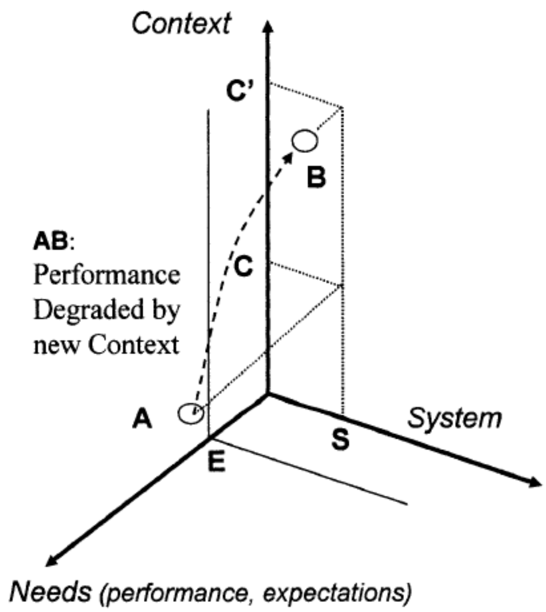

Figure 4: Ility configuration-context-needs space (Richards, Ross, Hastings, & Rhodes, 2009)

(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.

2.2 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.

2.2.1 Measures of Effectiveness

At the beginning of this literature review, an initial theory was that a relationship is present between methods used to determine a system of systems utility, overall measures of effectiveness (OMOE), and ilities. The common connection found between the various ways of establishing design priorities was using scenario-based evaluations to elicit the value of system alternatives.

(Berrow, Parsons, Shane, Kara, & Brown, 2022) present a method for conducting mission capability modeling, requiring interfacing between logical-operational-physical architectures. This analysis relies on the determination of Measures of Effectiveness (MOEs), Measures of Performance (MOPs), and a Design Reference Mission (DRM). The authors define MOEs as metrics assigned to each evaluated mission to measure quantitatively or qualitatively how well an assignment is completed and MOPs as metrics to characterize how well a task is performed by the capability that enables it. The DRM is a specific set of operational scenarios and requirements used to determine the overall measures of effectiveness when comparing early-stage design concept architectures.

(Mierzwicki & Brown, 2004) identify a two-phased approach for conducting a risk assessment for comparison against cost and performance in multi-attribute design evaluation. An Overall Measure of Risk (OMOR), dependent on design variables, is proposed for early-stage concept exploration. Variable risks are based on expert opinion and are related to performance, cost, and schedule. An accompanying quantitative Overall Measure of Effectiveness was defined based on design variables and defined mission thresholds and goals. The probability of success is referenced as robustness. The second phase is presented for later stages of concept development when higher fidelity evaluation is required, utilizing risk probability distribution functions.

(Bottero & Gualeni, 2022) address the application of systems thinking within the traditional naval architecture design process. They propose a capability-based approach, by which a ship's functions (vice focusing on systems required) are decomposed from Key Performance Parameters (ship function), High-Level MOPs (ship level), Low-Level MOPS (system level), and TPMs (parameters).

(Goodfriend & Brown, 2018) proposes an Overall Measure of Vulnerability (OMOV) be incorporated within an existing design space evaluation tool called the Multi-Objective Genetic Optimization (MOGO) framework. The OMOV relies on identifying and prioritizing vital components (VC), the location of the VCs within the hull compartmentation geometry, and probabilistic vulnerability analysis. The statistical component factors in the types of threat, potential hit locations, the probability of killing a VC given a hit occurs, and the probability of system kill given the aggregate assessment of equipment deactivation after damage.

2.3 Methods of Design Space Exploration

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 the 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 influences from the perturbation.

(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.

The following sections discuss several current methods used to characterize the value of alternative system architectures or decisions within the early-stage design. The overarching design process relies on a large number of architectural decisions that require data and an understanding of tradeoffs between design alternatives. There are several effective methods for conducting this comparison of alternatives, including design space exploration and set-based design. In addition to identifying system value in the face of changing context and requirements, the various methods discussed below rely on the designer's ability to define the system boundary.

2.3.1 Cause-Effect Mapping

(Hein, 2022) presents a framework for identifying and characterizing flexibility in design using Cause-Effect Mapping (CEM) or causation chains. This approach uses key perturbations, preparation, and option elements to provide the designer insight into the value of flexibility.

Hein suggests proper perturbation characterization is like risk assessment, which uses the elements of likeliness and severity to describe the potential occurrence. Within the framework, preparations are tied directly back to the perturbations they intend to mitigate and are characterized by cost and complexity. The author defines a preparation as “something that can be done in the present that mitigates, eliminates, or enables options to mitigate or eliminate the negative effects of future events.” This paper identifies six important principles for identifying appropriate perturbations, including the definition of system ownership (the affected system), organization, and the concept of Immediately External Perturbations (IEPs). IEPs are useful in defining the scope of impact directly on the system of interest. They can be categorized as mission change, projected operational environment change, capability change, or non-technical decision. No metric is presented for prioritizing or determining the value of each preparation, including any relationship back to likeliness.

(Mekdeci, Ross, Rhodes, & Hastings, 2012) outline the process for conducting cause-effect mapping to elicit unknown-unknown perturbations effectively. In their application, cause-effect mapping considers system context, Concept of Operations (CONOPS), and perturbation chain reactions so the system architect can categorize and address identified effects. The resulting taxonomy defines categories of value loss connected to perturbation types: capability loss, capability degradation, change in the mode of operations, cost increase, or change in stakeholder expectations. The discussion of value robustness is presented within the context of system survivability, broken into aspects of prevention, mitigation, and recovery.

2.3.2 Differential Analysis

(Ricci, Fitzgerald, Ross, & Rhodes, 2014) Present the System-of-System Architecting with Ilities method for quantifying tradeoffs between design options required to target specific ilities, resulting in tailored system requirements. The eight-step process is laid out in detail, from the initial definition of system needs and value determination, identification of potential perturbations to elicit the desired system ilities, and generation of alternative architectures with ilities in mind. The identification of perturbations organized into fixed periods of time, called epochs, to categorize the context of the system and how its change will influence the SoS value.

In SAI, desired ilities are identified after surveying potential SoS perturbations and stakeholder needs. The evaluation of different options elucidates the desired ilities, providing contingent value in the event a perturbation is realized. The logical flow of research is a method for uncovering ilities and metrics.

(Guariniello & DeLaurentis, 2014) suggest that some sets of ilities have competing interests and effects on the design, architecture, and evolution of the system of systems. They propose a framework for conducting trade-off analysis that combines elements of functional dependency network analysis (FDNA) and development dependency network analysis (DDNA) to assess the impacts of both types of dependencies on ilities. These ilities are measured in terms of operability over time, as assessed against a range of development and perturbation scenarios.

A notable utility of this analysis is the ability to model and account for partial capabilities within the SoS development process. Robustness is assessed in mission scenarios when some capability loss has occurred, resilience is considered when a disruption occurs, and partial capability can be recovered due to system interoperability. Flexibility is evaluated within the context of the development cycle, which requires mission coverage from other connected systems within the SoS.

(McNabb, et al., 2019) presented the Technology Identification, Evaluation, and Selection (TIES) methodology for identifying system tradeoffs and assessing designs against "Figures of Merit." In this methodology, technology evaluation depends on a simulation environment to determine the impact of probabilistic design parameters. Through the discussion of a case study for quantifying the value of a particular electric-ship architecture within a broader tradespace, the authors outlined the Technique for Order of Preference (TOPSIS) as a means of conducting Multi-Attribute Decision Making (MADM), which is a weighted means of identifying the best or worst designs in a given tradespace.

2.3.3 Scenario-Based Evaluations

(Chalfant, Hanthorn, & Chryssostomidis, 2012) present a method for analyzing electric ship distribution system topologies based on two ways of scoring system survivability. The approach involves determining a prioritized ranking of serviceable loads and their defined services, connectors, and locations. The first score determines the overall ability to provide and distribute power after damage based on the sum of a weighted priority of the loads remaining and the amount of power or other resource capacities, such as cooling capacity, provided to that load. This approach requires establishing a damage case scenario or a series of damage cases based on blast profile assumptions. These cases can be either explicitly set or determined stochastically. The second metric is used to characterize the severity of damage by identifying the highest priority load that cannot be filled, following the same analysis method for the first metric.

(Chalfant & Chryssostomidis, 2011) present a relatively simple application of an operational profile for a ship's power and energy system based on the percentage of time per year the platform spends at each combination of speed and electrical load. This data, combined with the system component characteristics for propulsion and power generation, allows for calculating a condition-based fuel consumption profile.

(Chin, Yau, Kok Wah, & Khiang, 2013) present an example evaluation of system robustness by defining a set of scenarios to test the SoS's ability to meet its operational requirements, with the analysis presented as Measures of Effectiveness.

(Cramer, Sudhoff, & Zivi, 2007) define a method for determining continuity of service metrics to predict the worst-case scenario for the survivability of a layered system, such as the power and energy system. The technique involves the definition of an "event" (cross-product of external environments, configurations of the IEP, and possible disruptions) and the "operability-metric" (continuity of service to vital loads given the time-dependent requirements of the scenario).

(Stevens, Opilia, Cramer, & Zivi, 2015) present a method for establishing operational vignettes for assessing electric ship power and energy systems. A vignette is defined based on the sequencing of stochastic load modeling in cruise and battle conditions and operational propulsion scenarios over a specified period. Implementing this method requires a notional or baseline power system architecture, including propulsion, power generation, complete load set - lumped load parameters (max/min power ratings, ramp rates, pulse width, repetition), and spatial arrangement (zones). Stochastic modeling of various mission load power demands is presented for pulse load number, unit power level, and pulse length. This method allows for evaluating different high-level system architectures and topologies.

(Sabah, Ojo, & Cramer, 2021) describe operability-based performance metrics as the ability of a system to perform in a single scenario, given battle damage, unique load profiles, cyber disruptions, and others. The authors emphasize the unique demand profile of an electric warship for "dynamic" capability, in order to conduct relatively short-duration missions as a rationale to support shifting the focus from load-centric (linear power flow) operability in early-stage design to mission-centric (nonlinear relationship between the power source and mission effectiveness). The authors present an example evaluation of three system configurations (energy storage differences) and expected performance across three different mission scenarios to obtain probabilities of successful performance.

Within the development of a framework for assessing the flexibility of naval warships, (Doerry & Koenig, 2017) propose a method for defining an "uncertainty vector" for assessing the performance of a tradespace of flexible designs over time. The uncertainty vector is configured to capture a series of scenarios at different points in the system's projected service life and contains a variety of assessment criteria related to potential changes in requirements for warfighting capability and technology maturity. The uncertainty state, or combination of uncertainty parameters within the vector at a given time step, can be either fixed or determined stochastically. The proposed framework is depicted in Figure 5, showing how the uncertainty space is used to evaluate the design vectors and configuration vectors.

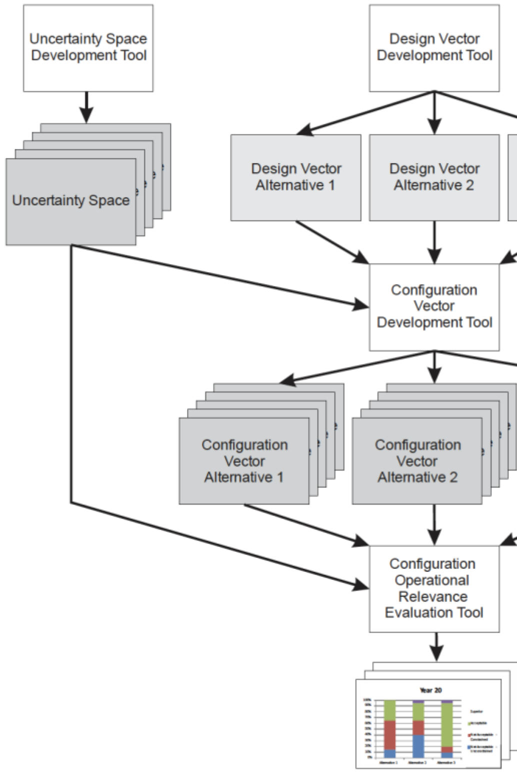

Figure 5: Framework for assessing flexible designs (Doerry & Koenig, 2017)

2.4 System Views & 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. Within the literature review, ilities are discussed in the context of individual components of the multifaceted system and within the higher-level integrated system. Traditional design processes focus on optimizing a specific system domain depending on the requirements and priorities of a desired system. (Brefort, et al., 2018) claim, “The growth in system complexity and interdependence has made systems significantly more difficult to understand and design, partly due to increased potential for emergent properties that only arise once the system is complete and in operation.”

(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 framework intends to provide deeper insight into complex systems, such as the integrated power system, within the early design stages. The authors present this framework with survivability specifically in mind but outline the applicability to other desired system characteristics. The disparate nature of the three primary architectures has traditionally produced different information types requiring multiple toolsets. The authors define the primary architectures 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. The logical architecture is where the primary focus is placed on the multidisciplinary nature of the system.
- The operational architecture describes the temporal behavior of a system, including human-system interactions to some extent.

Figure 6 depicts the three primary architectures and their interrelations: the physical solution, functional utilization, physical behavior, and system response. These overlapping areas combine information from each primary architecture to provide a deeper understanding of the design space.

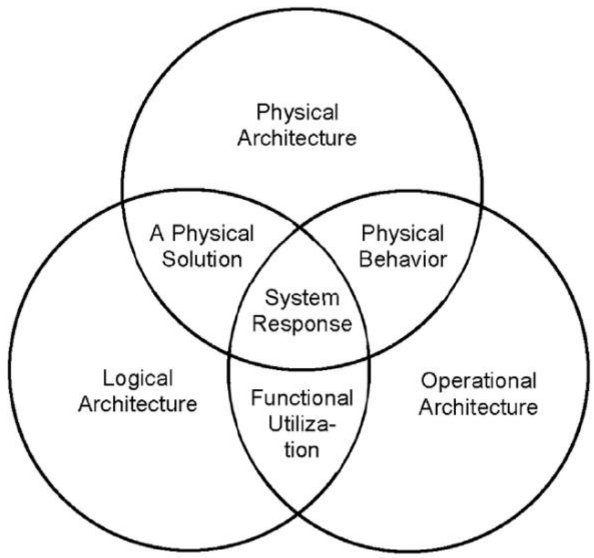

Figure 6: Representation of the physical-logical-operational framework for a given scenario (Brefort, et al., 2018)

(Cramer, Sudhoff, & Zivi, 2007) introduce the Integrated Engineering Plant as the system that provides electrical power, mobility, and thermal services. The authors define a method for determining continuity of service metrics to predict the worst-case scenario for the system's survivability. A layered approach is outlined for the Integrated Engineering Plant, including spatial, automation, AC, DC, seawater, and thermal layers to capture the behavior and functionality of each component. The framework for assessing survivability involves defining an "event" and "operability" to produce metrics, including average operability and minimum system dependability.

(Jansen, et al., 2020), within their discussion of an early-stage ship design vulnerability assessment approach, differentiate between two system model types for distributed system design: the physically oriented ship perspective and the operationally oriented system perspective. These perspectives provide logical, operational, and physical descriptions of distributed systems. The system perspective defines the topology of interrelated elements and focuses on values such as capacity, flow, and thermodynamics (load balancing). A topology is defined by nodes and edges representing major elements and their logical relationships. The ship perspective focuses on physical integration within the ship, including system routing (mass and volume balancing). Methods for assessing vulnerability are organized by design phase and perspective: max-flow-between-hubs (energy flow, deterministic, large # nodes), Markov (state/transition/capacity, probabilistic, small # nodes), and hurt-state-percolation (damage cases/scenarios, deterministic, large # nodes).

2.5 Ility - Flexibility

Flexibility was found to be a predominant ility considered throughout the literature review. As discussed in Section 2.1, 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. Where 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.

(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, 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 Integrated Power Node Centers (IPNC) to convert power for end users, Electronic Modular Enclosures to isolate commercial equipment and provide power conditions and conversion, 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. Traditional Service Life Allowance (SLA) is discussed from the perspective of Interface Control Documents. The author suggests that these documents need to define the explicit intent of the specific SLA.

(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.

3 Problem Statement

The review of published materials has identified several key elements of SoS ilities for further refinement and implementation within the Naval power and energy system design process. The Naval design community needs a consistent method for evaluating non-functional requirements in the early design stages, when informed decision making provides the greatest opportunity to positively influence the system's performance and lifecycle cost. This research proposes a framework for developing metrics that can be used to identify preferred options with the design space. The proposed process is exercised to develop quantitative, measurable metrics for Naval power and energy system flexibility, a non-functional requirement of significant interest to the design and acquisition community but has lacked a common basis of understanding. This research and its implementation are framed by the problem statement:

> **To** quantify non-functional requirements for early-stage design decision making
> **By** developing metrics for Naval power and energy system Flexibility
> **Using** a framework for characterizing potential perturbations influencing system change and measuring the value of potential design options in terms of their physical, logical, and operational system impact.

4 Research Summary

This research 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. Selection of preferred architectures requires a balance between uncertainty, performance, cost, and complexity to "right-size" the system. A deep dive into Flexibility, a common ility of interest, is presented with four case studies using proposed metrics for power and energy system flexibility. This work is intended to present a repeatable process for developing metrics that can be integrated within early-stage design tools for generating and evaluating the naval power and energy system.

4.1 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.

This research investigates the relationships between system ilities and the underlying characteristics that may be common to certain types or families of ilities. Figure 7 depicts an ilities hierarchy for the Naval power and energy system, based on the means-ends approach presented by de Weck, et al. (2012). There are certainly more ilities than depicted, but this representation is intended to focus on those that are significant to maintain power and energy system value. The means-ends approach is represented by the arrows directed upward from the lower level ilities that enable attributes above. The overall objective of the ility hierarchy is to enable Value Robustness, or value retention under the influence of change. At the base of the hierarchy are the physical, logical, and operational attributes of the system that serve as the foundation for emergent properties, as will be discussed in Section 5.1. The subsequent sections of this research will focus specifically on Flexibility as a priority system property due to the current rate of change in functional demands on the P&E system.

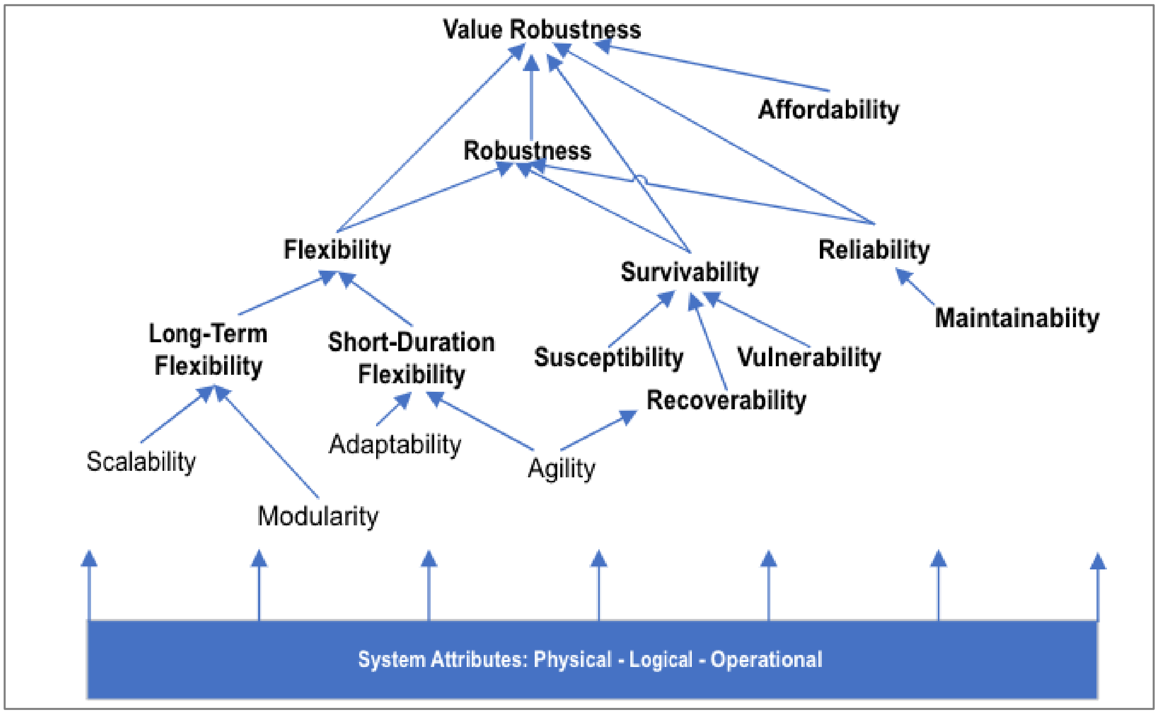

Figure 7: Power & Energy System "Ility" Hierarchy

Table 1. Ility definitions

Ility	The ability of a system…
Adaptability	to be changed by a system-internal change agent with intent*
Affordability	to minimize the acquisition and lifecycle cost of maintaining value
Agility	to be changed in a timely fashion*
Flexibility	to make changes within the system in response to perturbations
	Note: Flexibility is decomposed further based on temporal responses, as defined in Section 5.
Maintainability	to be maintained routinely so that failure does not occur.
Modularity	to be composed of modules (at varying degrees of module composition)
Recoverability	to recover the system in a timely manner (at varying measures of timeliness)**
Reliability	to operate without issue, as measured over a period of time
Robustness	to maintain its level and/or set of specified parameters in the context of changing system internal and external forces*
Scalability	to change the current level of a specified system parameter*
Survivability	to minimize the impact of a finite duration disturbance on value delivery*
Susceptibility	to reduce the likelihood or magnitude of a disturbance**
Value robustness	to maintain value delivery in spite of changes in needs or context*
Vulnerability	to maintain a minimally acceptable level of value delivery during and after a disturbance**

** verbatim from (de Weck, et al., 2012, p.7)*
*** framed by (Richards, 2009, p.61)*

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.

4.2 Framework for Design Space Exploration

Within early-stage design, assessment criteria for determining preferred solutions can be challenging to decipher. Often, the designer is faced with a large number of feasible architectures that satisfy the primary functional requirements. This research presents a framework for establishing metrics that quantify the value of system ilities, as a means for identifying the preferred solution within the design space. It is applied here, in evaluation of the power and energy system to account for the multi-disciplinary aspect of the system of systems. It was hypothesized that, in the design of complex systems-of-systems, the lowest level of system definition is the selection of design variables that combine to form the metrics used to measure ilities. This framework demonstrates that a common set of architectural attributes can be linked in purposeful ways to develop system metrics and characterize ilities. The output of the P&E system framework focuses on "Right-Sizing" the system, finding the balance between uncertainty, performance, cost, and complexity. The ility framework for design space exploration consists of the elements within Table 2.

Table 2. Framework for Establishing Ility Metrics

Step	Action
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. Maintain the perspective of the Immediately External Perturbation (IEP), as proposed by Hein (2022), tracing the chain of effects caused by broader influences on the system of systems down to the perturbation occurring directly at the subsystem boundary.
5.	Begin linking potential preparations in design 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.

These steps are demonstrated in Sections 5 and 6 to develop metrics for measuring the flexibility of the Naval power and energy system and how to balance performance against system affordability.

5 Flexibility 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 2, 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.

5.1 Power and Energy System Flexibility

Flexibility is the capability of the 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, within Sections 5.1.1 through 5.1.3, 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).

5.1.1 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). The following list of attributes, within the context of the physical view, can be used as parameters and variables to develop power and energy system metrics.

Power and Energy System - Physical Attributes

- Location
- Access, required removal routes and reservations
- Distance between nodes
- Gross number and percentage of ship compartments touched
- Stackup length
- Number of components by type
- Direct Cost

- Control system computing and processing equipment
- Component level
    - Spatial: area and volume
    - Weight
        - Component weight
        - Weight per meter (for distribution components)
    - Power level (supply and/or demand)
        - Installed power versus available power (by type)
    - Cooling level (supply and/or demand)
    - Efficiencies and losses
    - Fuel consumption
    - Power density
    - Specific power
- System level (sum of components by type)
    - Spatial: area and volume
    - Weight
    - Power level (supply and/or demand)
        - Installed power versus available power (by type)
    - Cooling level (supply and/or demand)
    - Efficiencies and losses
    - Fuel consumption
    - Power density
    - Specific power

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.

5.1.2 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 8 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 1.1, 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.

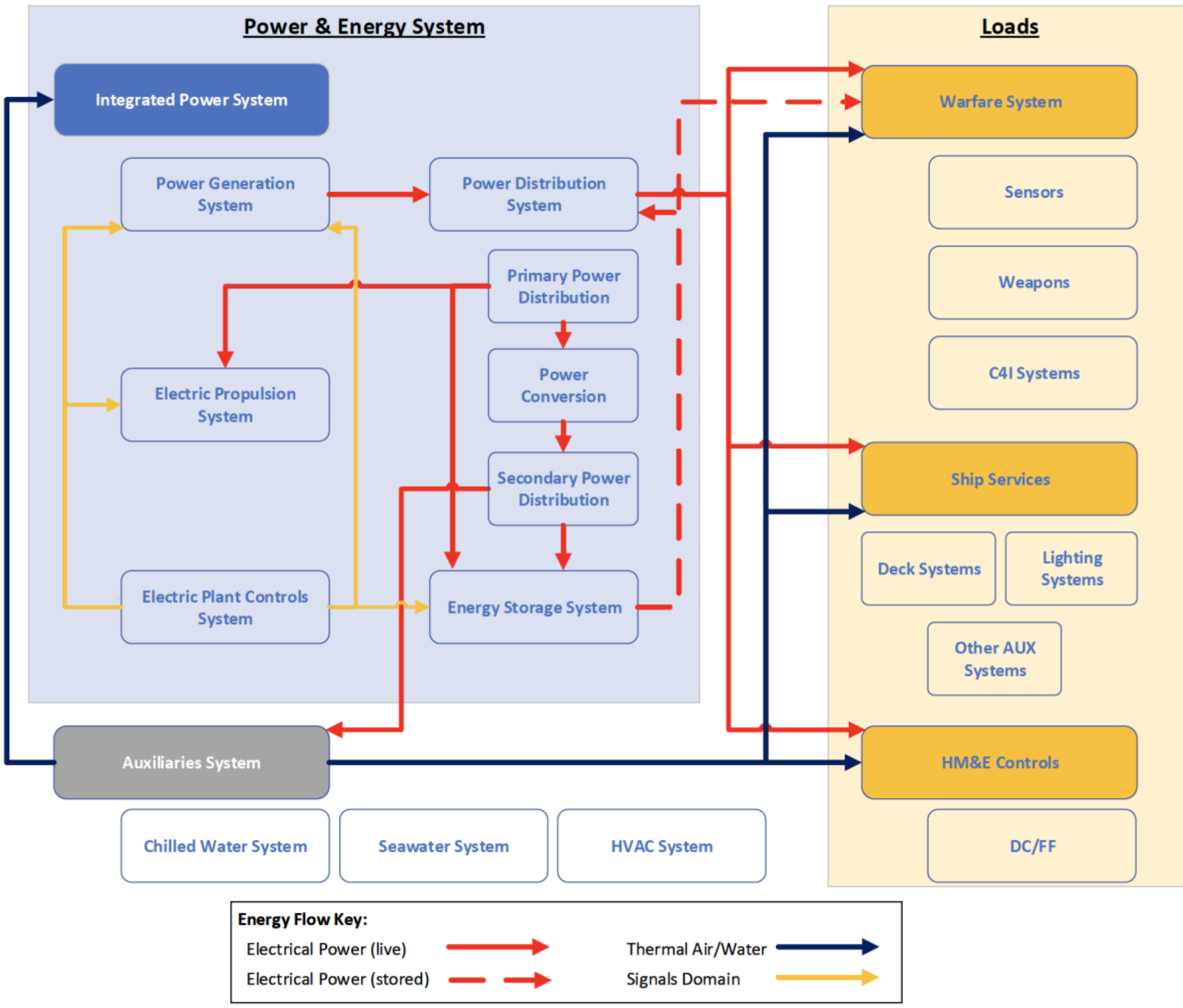

Figure 8: Power and Energy System Logical Model for an Integrated Power System (IPS) for a Combatant

The following list of "ility"-specific attributes, within the context of the logical view, can be used as parameters and variables to develop power and energy system metrics.

Power and Energy System - Logical Attributes

- Number of flow types
- Number of linkages at each node (total and per domain)
    - Supply links
    - Demand links
- Standard interfaces (type and quantity)
- Energy flow(s) capacity

- Number of alternative paths for a given energy flow
  - Time and cost required to switch between paths
- Mechanical Domain
  - Equipment type: motor, gas turbine, diesel
- Electrical Domain
  - Equipment type: battery, gas turbine, diesel, fuel cell
  - Distribution type: frequency, voltage, current (combinations of)
- Thermal Domain
  - Water system type: chilled water, fresh water, seawater
  - Air system type: ambient, forced air, air-conditioned
- Signal Domain
  - Control system type: localized, enclaved, networked
  - Control system interface types
  - Control system direction: bi-direction, single direction

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.

5.1.3 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, as identified in Section 1.2, 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. The following list of attributes, within the context of the operational view, can be used as parameters and variables to develop power and energy system metrics.

Power and Energy System – Operational Attributes

- Operating duration
- Opportunity cost
  - Upfront cost
  - Reconfiguration cost
  - Cost of alternative investment
- Classification of supply sources and demand loads
  - Vital vs non-vital
  - Mission essential
- Number of required operating (loading) modes
- The scale of each required operating (loading) mode
- Loading condition:
  - Number and magnitude of Loads serviced (power)
  - Number and magnitude of Loads serviced (thermal)
  - Ship Speed
  - Flow rates
- Component Lifetime
- Battery charge and discharge rates
- Response time (e.g., breakers, signals, generator start, backups and spares)
- Pulse loading
- Mechanical Speed, rotations per minute (RPM)
- Specific fuel consumption at speed and loading conditions
- Dynamic simulation outputs

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.

5.2 Perturbations for Flexibility

Perturbations in requirements beyond the initial system design criteria drive the need for flexibility. For the power and energy system, perturbations are traced from a broader system-of-systems context to the direct impacts at the system boundary within the logical view, Figure 8. They are easily identified based on the impacts related to the source of energy-flow generation (Supply) and required loads (Demand). This method for localizing influences on the system is based on the concept of Immediately External Perturbations (IEP), proposed by (Hein, 2022). The process of identifying IEPs is essential to establishing the metrics needed to determine the value of a system within the context of any ility requirement.

Table 3 and Table 4 identify perturbations in the P&E system that require flexibility to maintain system capability and value. They are differentiated by the response time required for the system to change. Short-term perturbations are realized while the system is in operation; they require flexibility solutions in place for the P&E system to maintain acceptable performance with the existing system components and configuration, including software and controls. The identification of operational perturbations must be balanced against the range of required operating conditions the system will be designed to achieve, such that the perturbations represent a new requirement or unanticipated criteria to maintain desired operability. Long-term perturbations are realized over an extended period of time, often projected years in advance of realization, and can be satisfied with planned future upgrades to the system.

The following sets of perturbations are considered against potential preparations in design requiring flexibility within the physical, logical, or operational system views. The perturbations may further apply to the evaluation of the P&E system in the context of other ilities but will require tailoring of the associated system impacts. The basis for operational flexibility in the power and energy system strongly correlates to perturbations for survivability and reliability, namely the perturbations derived from equipment failures and maintenance actions. (Doerry & Amy, 2011) define design metrics for a related ility, quality of service (QoS), to address unanticipated service interruptions, which can lead to perturbations in operating requirements and conditions. Each perturbation below is not limited to the direct impacts and applicable design preparations listed but has the potential to generate cascading effects that trigger additional perturbations related to flexibility and other required ilities.

Table 3: Short-term (operational) perturbations beyond initial design requirements requiring Flexibility.

Perturbation	Subtype	System Design Preparations	Examples
Change in propulsion load from design to new conditions	Propulsion load demand varies from design condition • e.g. propeller, shaft, gear, motor, drive efficiencies • changes in how the ship plans to operate in service (e.g. twin vs trail shaft)	• physical: installed capacity (power & cooling); component type selection • operational: change operating mode; debit energy flow from other demand	• IPS architecture: pairing of power generation and propulsion supply & demand to maximize efficiency across desired operating modes
Change in mission/combat/ship service loads from design to new conditions	Load variations from expected design condition: • combat/mission system elements • auxiliary elements • ship service elements	• physical: installed capacity (power & cooling); location of distribution elements (including zones) • logical: number and type of energy flows required • operational: change operating mode; debit energy flow from other demand	• IPS architecture: reduce propulsion demand to increase mission load • primary/secondary/combat system power distribution architectures • HTS cable • Capacity and control of power electronics, load centers, SWBDs • hosting & servicing offboard vehicles (energy and control)
	Variations of power quality anomalies and differences from expected design condition: • frequency • voltage • current	• physical: size and location of distribution and conversion elements; use of specialty equipment • logical: number and type of distribution and conversion elements	• Power Electronic Building Block (PEBB) • modular power converters
	Demand element cooling type differs from design condition	• physical: cooling system capacity, configuration and routing • logical: number and type of cooling sources • operational: define loading conditions, change operating modes	• chilled/fresh/sea water and HVAC systems design: capacity, redundancy, location, loading conditions
Operating environment	Change in temperature: • atmospheric • cooling water source • internal compartment air	• physical: auxiliary system capacity • logical: number and type of alternate auxiliaries/backups • operational: change operating mode; debit energy flow from other demand; change in flow rate	• defined operational modes for load shedding • interoperable auxiliaries (FW/SW/CW)
	Threat/signature	• physical: specialty equipment required; specified location of elements; number required elements per energy flow • logical: controls system management operational: change operating mode	• design for signature mitigation in select operating modes • signature augmentation

	Change of fuel type	• physical: generation equipment selection; fuel input system type(s) • operational: efficiency	
	Reduced fuel availability	• operational: change operating mode	
Unique load types	Pulse load, variations from design expectation	• physical: include specialty conversion, distribution, and energy storage equipment; location of distribution and conversion equipment; sizing of supply and distribution elements to maintain system inertia • logical: control system management; number and type of distribution and conversion elements • operational: sequencing and logic of load conditions and operating modes; debit energy flow from other demand	• integrated energy storage - type and capacity • batteries, flywheel, capacitor • IPS architecture - dynamic loading capability
	High power-short duration load, variations from design expectation		
	Ramp-rate, variations from design expectation		

Table 4: Long-term perturbations (realized at future maintenance period) beyond initial design requirements requiring Flexibility.

Perturbation	Subtype	System Design Preparations	Examples
P&E system configuration change	Change in power generation component	• physical: weight and arrangeable space margin; access/removal routes; distribution system sizing • logical: energy flow compatibility (voltage, frequency, current, auxiliaries); modified control system logic • operational: change operating modes; change in efficiency	• swap generator (GTG/DG) • add additional generators to existing plant
	Modified distribution system	• physical: weight and arrangeable space margin; preplanned arrangement and routing • logical: modified control system logic; number and type of electrical and auxiliary support connections • operational: change in operating modes; change in efficiency	• replace conventional with high-temperature superconducting cable, or MVDC cable (cable bundling, number) • modular power nodes • defined interfaces (spatial and physical) • accessible cable trays, cable corridors, cable disconnects
	Improved power electronics and switchboards	• physical: SWAP-C margin; preplanned arrangement and routing; hazard mitigation • logical: modified controls; change in energy flow quality • operational: change in operating modes, change in efficiency	• PEBB • modular SWBD, load center cabinets, electrical bus
	New/additional secondary distribution loops (purpose driven)	• physical: weight and arrangeable space margin; preplanned arrangement and routing • logical: modified control system logic; number and type of electrical and auxiliary support connections • operational: change in operating modes; change in efficiency	• dedicated combat system distribution • specified power quality defined interfaces • accessible cable trays, cable corridors, cable disconnects
	Change propulsion system elements	• physical: propulsion system rating; weight and arrangeable space margin • logical: shafting system compatibility; number and type of auxiliary support connections	• higher rated or more efficient: turbines (mechanical), electric motors (IPS) • change motor type (AIM/PMM/HTS/Podded) • change to motor drives

		• operational: change operating profile; change in efficiency; debit energy flow from other demand	
	Change propulsion system topology	• physical: SWAP-C margin; preplanned arrangement and routing subsystem capacities (generations, distribution, conversion, auxiliary) • logical: number and type of energy flows required; modified controls • operational: change in operating modes	• conversion mechanical to hybrid
	Change energy storage system	• physical: SWAP-C margin; preplanned arrangement and routing; hazard mitigation • logical: number and type energy flows; auxiliary interfaces; modified controls • operational: change in operating modes; change in efficiency	• Expand energy capacity (additional point-of-use system capacity or integrated energy storage) • Change in technology or combinations of battery type, rotating machines, etc. • required - firefighting and safety systems
Changes to loads: mission/combat system, ship service, auxiliaries	New load types (pulse loads, ramp rates, etc.).	• physical: SWAP-C margin; inclusion of specialty equipment; preplanned arrangement and routing • logical: modified controls; number and type of energy flow connections • operational: change in operating modes	• Interface Control Documents for planned future upgrades • Integrated energy storage • dynamic loading capability
	Increased demand: • vital/nonvital • load case conditions	• physical: generation, distribution, conversion, auxiliary subsystem capacity • operational: debit from other energy flow; change in operating modes	• IPS architecture - reduce propulsion demand to increase mission load • Interface Control Documents for planned future upgrades
	New responsiveness (agility) requirements	• physical: inclusion of specialty equipment; SWAP-C margin • logical: number and type of energy flows; modified controls • operational: change in operating modes	• inclusion of energy storage and power electronics
	Change in demand location	• physical: weight and arrangeable space margin; distribution and conversion capacity, preplanned arrangement and routing	• Interface Control Documents for planned future systems • flexible infrastructure

	Secondary impacts realized in auxiliary systems	• physical: weight and arrangeable space margin; auxiliary system capacity • operational: debit from other energy flow; flow rate	• ability to run multiple water-cooled systems to a given load • thermal battery • additional AC plant
	modified damage control and firefighting requirement (response to other configuration change)	• physical: arrangeable space; preplanned arrangement and routing • logical: modified controls system; specified interfaces • operational: change in operating modes	• reconfigurable zones • planned piping runs, standard piping connections or valves • HVAC intersects and connections; fan rooms arrangement
	Increased manning	• physical: HVAC and electrical capacity; location of demand • logical: electrical and auxiliary flow connections	
Changes in command and controls	Introduction of Artificial Intelligence (AI)	• physical: processing capacity; inclusion of specialty hardware (sensor-processor-actuator); • logical: HW/SW data connections; controls logic • operational: change in operating modes; internal/external communications; P&E system maintenance; signatures/security	• P&E system designated: Modular electronics enclosures • platform/system networking configuration • distributed and multifunctional control stations • off platform communications and controls
	Requirement for autonomous operations; reduced manning		
	HM&E controls		
	Electric Plant/IPS controls		
Operating Environment	Artic operations	• physical: HVAC and electrical capacity; location of demand • logical: electrical and auxiliary flow connections	• plugin loads (heat/de-ice)
	Environmental regulations	• physical: generation equipment selection; energy storage sizing; fuel type • operational: change in operating mode; change in efficiency	

6 Metrics for Flexibility

Design metrics are quantitative or qualitative measures of a system's characterization and measured 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 two or more sets of 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, such as those identified in Sections 5.1.1 through Section 5.1.3 for the power and energy system, 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 the selected architecture will respond within each design domain.

For U.S. Navy ship design, a standard measure of flexibility is 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. Table 5 shows the Service Life Requirements defined in NAVSEA's 'Naval Combatant Design Specifications' (2014) across each SWAP-C criteria, for ships of varying expected service life durations.

Table 5: Service Life Allowances required for 20 and 30 years

Service Life Allowance	20 Years	30 Years
Space	0%	5%*
Weight & KG	10% & 0.3m	10% & 0.4m*
Power **	15%*	20%
Cooling	15%*	20%

*Notional values, not prescribed in NCDS

**Values based on traditional separated ship service power system vice IPS

The following sections identify metrics for evaluating flexibility of the power and energy system within early-stage design space exploration activities, such as concept formulation, preliminary design, analysis of alternatives, or requirements evaluation and development. 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 is 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 stackup arrangement. The following process traces perturbations identified in Section 5.2 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. This process can be utilized to develop ility metrics for incorporation within early-stage design tools, such as the suite of Leading Edge Architecture for Prototyping Systems (LEAPS) product model tools, including Smart Ship System Design (S3D) for energy flow analysis.

6.1 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 during mission operations.

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. 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. Section 6.1.1 outlines the differences in applying metric (1) for different power and energy system architectures.

$$FPC = \frac{P_{DST} - L_{REQ}}{P_{tot}} \qquad (1)$$

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), equations (2). Where the FPC Metric considers elements of the systems physical architecture in a defined loading condition, Debitable Power 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}). The DPF is then the minimum of the new load demand above the initial design requirement (L_{add}) and the debitable power load available, divided by the new load demand. Case 2 will discuss the sensitivity of IPS power flexibility against the selected sizing criteria propulsion and mission loads.

$$DPF = \frac{\min(L_{add}, L_{avail})}{L_{add}} \qquad (2)$$

where $L_{avail} = L_{pREQ} - L_{pmin}$.

An observed phenomenon when using this metric to compare power and energy systems integrated within ship concepts of varying hullform efficiencies is that the 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.

6.1.1 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, a Hybrid power system, and a Mechanical propulsion system with separated 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 6 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 of propulsion power, and the underway-mission propulsion load is based on a prescribed speed-time profile in DDS 200-2. The propulsion speed power curve for the required shaft horsepower (SHP) per knot is shown in Figure 9.

Table 6: 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

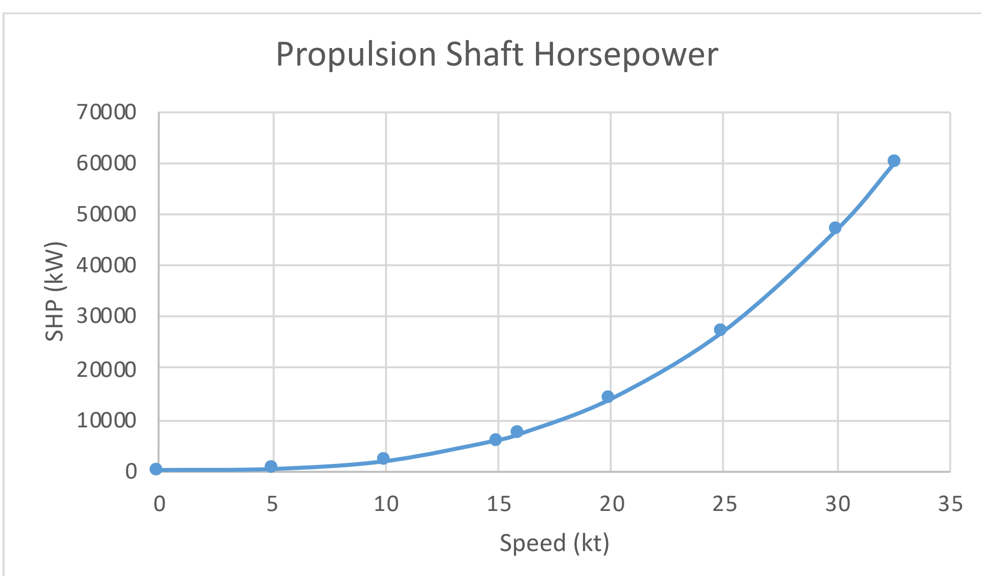

Figure 9: Propulsion Speed-Power Curve (NAVSEA, 2012)

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 7. 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 applied to 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 7: 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 EOSL		Max Electric Propulsion (16kt) + mission EOSL		Mission 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 8 determines the Flexible Power Capacity for the IPS architecture at sustained speed while operating in two different modes: the underway-mission at 10° Fahrenheit condition, requiring the maximum margined electrical load, and the underway-economical at 10° Fahrenheit condition, requiring the twenty hours average electrical load. Each load combination will evolve over the ship's service life as SLA is consumed and fact of life 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" 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 9 provides the Flexible Power Capacity calculations for the same load conditions at cruise speed, where the PMM efficiency is 91%.

Table 8: IPS at Sustained Speed

IPS: Sustained 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)**
PDST (kW)	78,000	78,000	78,000	78,000
LREQ (kW)	54,253	67,370	52,578	65,444
Ptot (kW)	78,000	78,000	78,000	78,000
FPC	0.30	0.14	0.33	0.16

Table 9: IPS at Cruise 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)**
PDST (kW)	78,000	78,000	78,000	78,000
LREQ (kW)	12,268	14,889	10,593	12,963
Ptot (kW)	78,000	78,000	78,000	78,000
FPC	0.84	0.81	0.86	0.83

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 10 and Table 11 demonstrate 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 10: Hybrid with Sustained Speed (PGT) Required

Hybrid: Sustained Speed (PGT)				
	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
LREQ (kW)	4,466	5,136	2,791	3,210
Ptot (kW)	75,000	75,000	75,000	75,000
FPC	0.14	0.13	0.16	0.16

Table 11: Hybrid with Cruise Speed (PMM) Required

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)**
PDST (kW)	15,000	15,000	15,000	15,000
LREQ (kW)	12,019	14,577	10,344	12,651
Ptot (kW)	75,000	75,000	75,000	75,000
FPC	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 12, is calculated based on the same loading requirements as the sustained speed hybrid case, using PGT propulsion power.

Table 12: Mechanical (non-propulsion dependent)

Mechanical: Non-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. Figure 10 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.

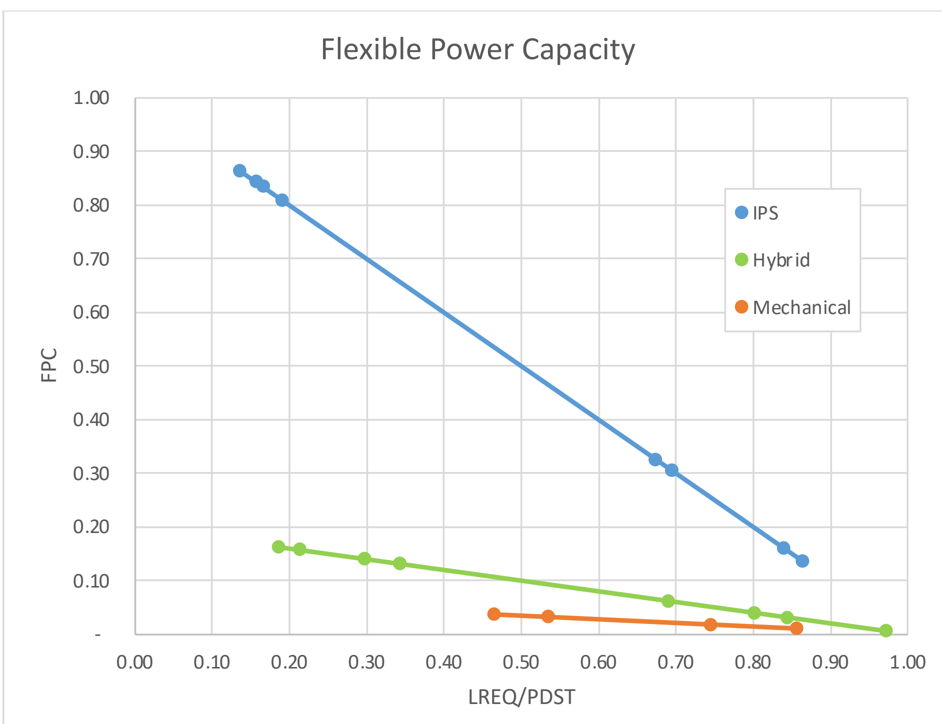

Figure 10: Flexible Power Capacity (FPC) Metrics for IPS, Hybrid, and Mechanical examples versus normalized power capacity, load case required over distributable power

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.

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 most 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.

6.1.2 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 13 demonstrates the debitable power flexibility (DPF) for the 30-knot IPS architecture, given a 1-knot speed reduction for minimum acceptable propulsion load at delivery and EOSL conditions. Table 14 calculates the DPF metric for the same architecture but with a 5-knot reduction in speed for the minimum acceptable propulsion load. The additional 25% propulsion factor applied for the EOSL condition reduces the debitable power load available (L_{avail}) by 11 MW in the 1-know 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 13: Debitable Power 30 knot IPS - 1 knot Reduction

	Propulsion Condition	kW
LpREQ	30kt, 100% MCR	62,234
Lpmin	29kt, Delivery	45,014
Lavail		17,220
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	1.00
Load 3	30,000	0.57

	Propulsion Condition	kW
LpREQ	30kt, 100% MCR	62,234
Lpmin	29kt, EOSL	56,268
Lavail		5,966
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	0.40
Load 3	30,000	0.20

Table 14: Debitable Power 30 knot IPS - 5 knot Reduction

	Propulsion Condition	kW
LpREQ	30kt, 100% MCR	62,234
Lpmin	25kt, Delivery	28,812
Lavail		33,422
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	1.00
Load 3	30,000	1.00

	Propulsion Condition	kW
LpREQ	30kt, 100% MCR	62,234
Lpmin	25kt, EOSL	36,015
Lavail		26,219
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	1.00
Load 3	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 15 demonstrates the debitable power flexibility for the 27-knot IPS architecture, given a 1 knot speed reduction for minimum acceptable propulsion load at delivery and EOSL conditions. Table 16 calculates the debitable power metric for the same architecture but with a 5-knot reduction in speed for the minimum acceptable propulsion load. Based on the lower speed requirements, which correspond to exponentially less 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 fail to provide the available load threshold for the 15 MW load case 2 in the 1-knot reduction at delivery case, where the 30-knot IPS concept is able to provide sufficient flexible power in the 1-knot reduction case.

Table 15: Debitable Power 27 knot IPS - 1 knot Reduction

	Propulsion Condition	kW
LpREQ	27kt, 100% MCR	45,495
Lpmin	26kt, Delivery	32,535
Lavail		12,959
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	0.86
Load 3	30,000	0.43

	Propulsion Condition	kW
LpREQ	27kt, 100% MCR	45,495
Lpmin	26kt, EOSL	40,669
Lavail		4,826
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	0.32
Load 3	30,000	0.16

Table 16: Debitable Power 27 knot IPS - 5 knot Reduction

	Propulsion Condition	kW
LpREQ	27kt, 100% MCR	45,495
Lpmin	22kt, Delivery	19,830
Lavail		25,665
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	1.00
Load 3	30,000	0.86

	Propulsion Condition	kW
LpREQ	27kt, 100% MCR	45,495
Lpmin	22kt, EOSL	24,787
Lavail		20,708
	Ladd (kW)	**DPF**
Load 1	2,000	1.00
Load 2	15,000	1.00
Load 3	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 focuses solely on the demand load conditions, given an established system sizing criteria. Figure 11 graphically displays the increase in available load as the propulsion load is debited for the 27 and 30 knot concepts in their EOSL state. The area under each curve, bounded on the low end by Lpmin speed, is the flexible power available, 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 shaded area does not overlap with the horizontal lines, 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.

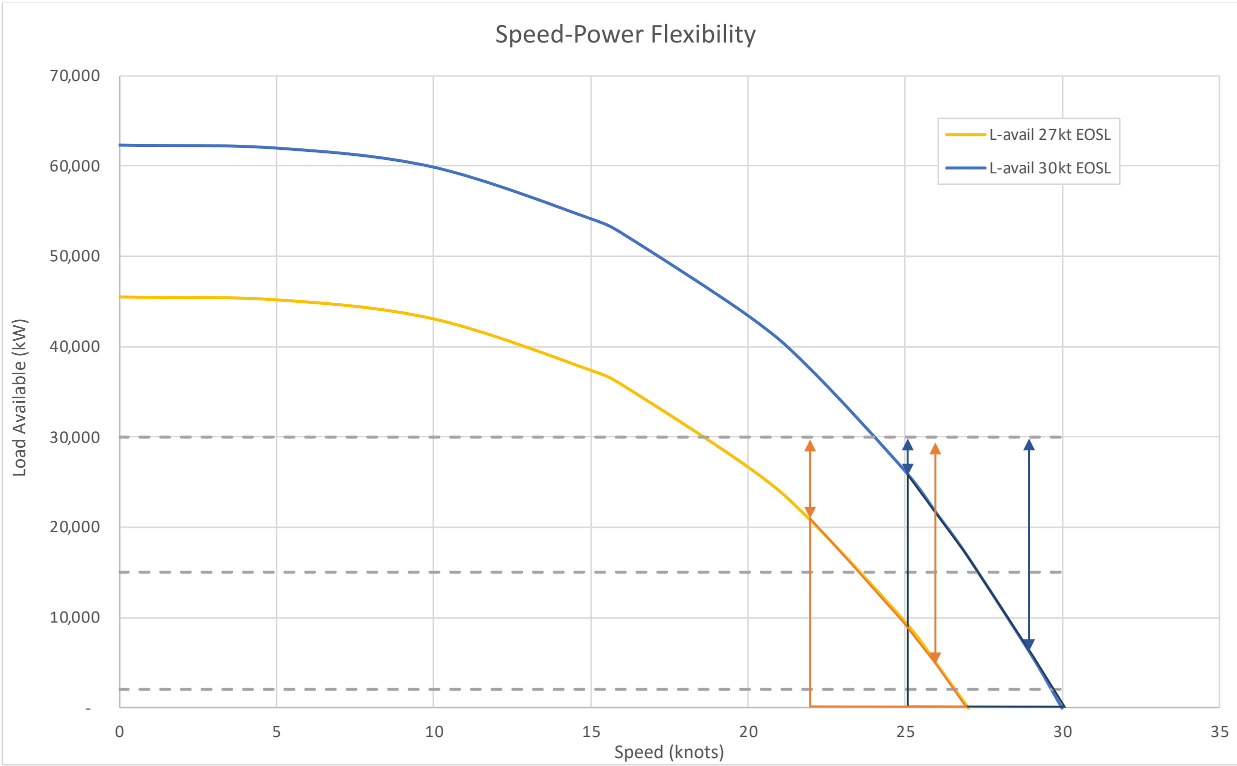

Figure 11: Flexible Power – Load Available at Speed

The debitable power flexibility metrics for each of the eight conditions are plotted in Figure 12 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.

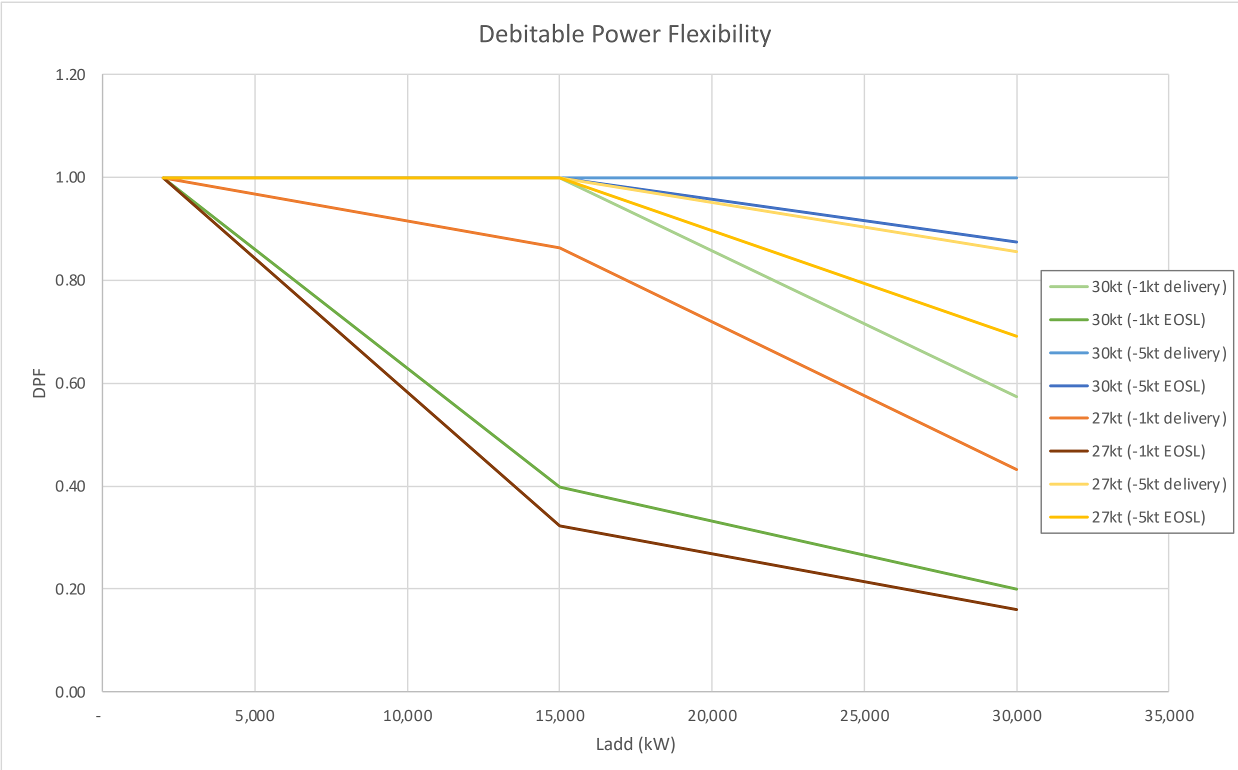

Figure 12: Debitable Power Flexibility versus Load Available for example speed delta cases

6.2 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 8. 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 bounded 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 17 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 17: 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 (ESRDC, Ship Concept Alternatives, 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 of the flexibility of each zone (DST_{zone}): the sum of the flexibility of each 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 in Section 6.2.1.

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

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

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 18 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. Section 6.2.1 provides a case study comparing a split ring and a zonal distribution system architecture at different stages of the design specification process, and different points in the platform's service life. Section 6.5 will elaborate on the use of real options to differentiate between the value of installing capacity upfront vice designing in the ability to upgrade the system in the future once the perturbations have been realized.

Table 18. 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 HTS 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 (PEBB) - Integrated Power Node Centers (IPNC)	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.

6.2.1 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 distribution system 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 19, 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, which are provided in Appendix A ; 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].

Table 19: 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 13, 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 20.

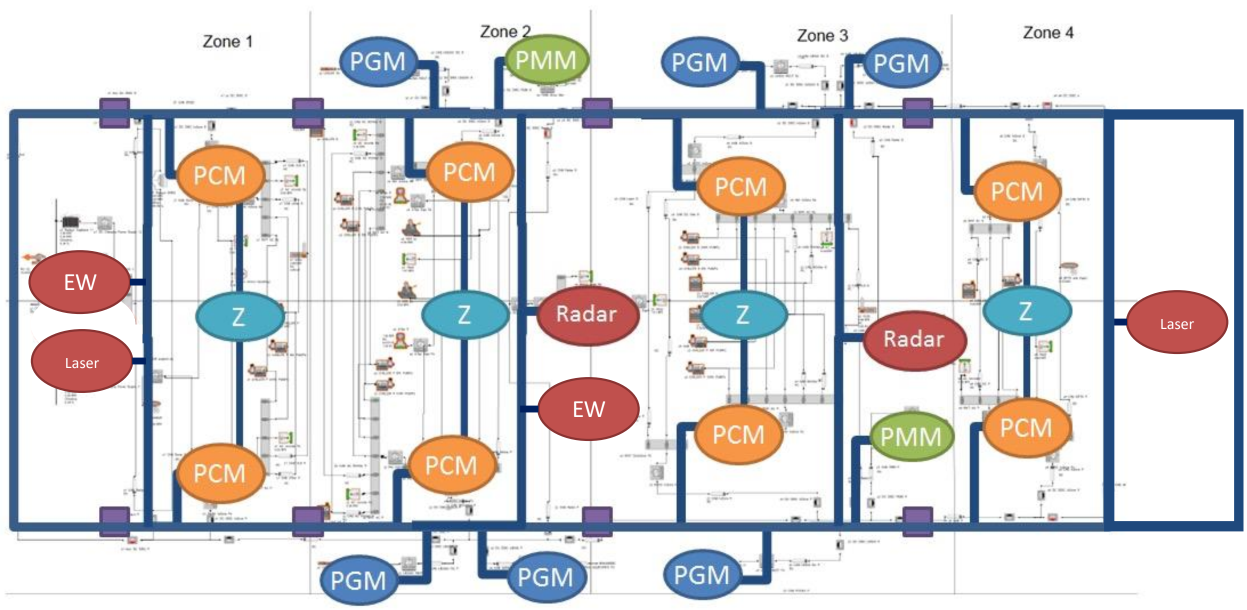

Figure 13: Conventional Split Ring Bus Distribution Architecture Topology. Based on (Smart, et al., 2017).

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 20. The average of the four zones scores determined a total power distribution system flexibility score ($PDSF$) of 0.31.

With the PCM converter and inverter ratings specified for the ESRDC concept, all four zones are able to accommodate the maximum MVAC/MVDC and LVAC load combinations, given the duplicate sets of converters for the port and starboard buses for redundancy. If the analyses were conducted assuming that only a single set of PCMs were engaged at any time in each zone, zone 4 would be unable to accommodate the maximum loading conditions within these voltage categories and score a 0 for these N conditions; all other zones can handle the maximum rating in these conditions with one set of converters.

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 20: 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 (ESRDC, 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 21 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 21, 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.

Table 21: 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
DST_{zone}	1.0	0.65	0.59	0.33

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 14. 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 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).

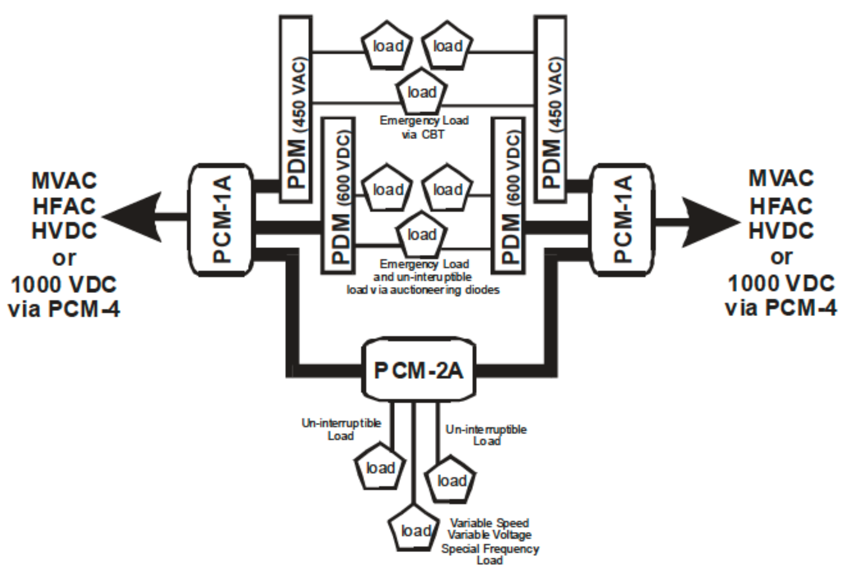

Figure 14: NGIPS Roadmap "Potential Future IFTP" In-Zone Topology (Doerry, 2007)

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. Section 6.5 will discuss the method for designing in "Real Options," requiring flexible design preparations with the objective of reducing upfront cost and risk associated with uncertainty of future load demands. 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 22 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, as shown in Table 23, the total PDSF score improves to 0.85.

Table 22: Zonal IFTP Base Model Distribution Capacity by Zone

	Zone 1 (kW)	Zone 2 (kW)	Zone 3 (kW)	Zone 4 (kW)
PCM-X	0	2,000	3,500	0
PCM-1A	3,000	3,000	3,000	3,000
PCM-2A	2,500	2,500	2,500	2,500
DST_{zone}	0.03	0.16	0.32	0.03

Table 23: Zonal IFTP Block Future Distribution Capacity by Zone

	Zone 1 (kW)	Zone 2 (kW)	Zone 3 (kW)	Zone 4 (kW)	Total DST Capacity (kW)
PCM-X	6,875	6,875	6,875	6,875	27,500
PCM-1A	4,000	4,000	4,000	4,000	16,000
PCM-2A	2,500	2,500	2,500	2,500	10,000
DST_{zone}	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 15. 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 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.

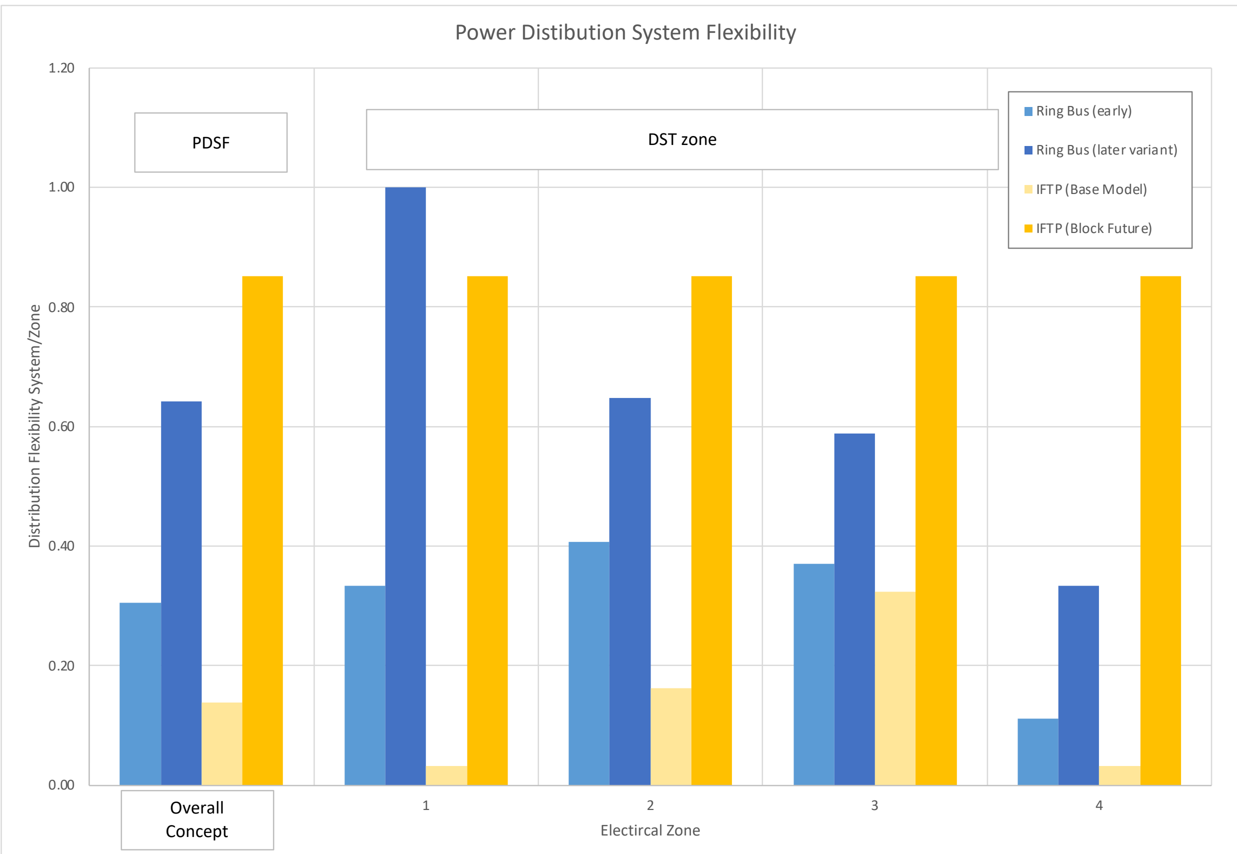

Figure 15: Power Distribution System Flexibility (PDSF) and individual zone (DSTzone) scores

6.3 Energy Storage

Energy storage system (ESS) flexibility provides the ability to respond to perturbations with unique load demands or constraints within the operational view of the power and energy system. The Naval Power Systems Technology Development Roadmap (McCoy & Kuseian, 2013) identifies the need for energy storage to address "pulse power support for advanced weapons and sensors, load leveling, emergency power, and generator transient support and fuel savings initiatives." These mission demands, including laser weapons and advanced radar systems, pose new challenges for the P&E system in terms of the power loading profiles, requirements for steady power cleanliness, and quality of service. Within the logical system view, the energy storage system focuses on power capacity and power quality perturbations that impact requirements upstream of the energy storage in the energy flow between supply and demand loads. Energy storage may be located within the primary or secondary power distribution system, depending on the intended operational use and balanced against the system integration and cost impacts.

Energy Storage System Flexibility (ESSF) metric. Like the distribution flexibility in a zone, ESS flexibility ($ESSF$) is determined by assessing the energy storage system's ability to satisfy each load scenario (S), equation (5). If the ESS has the maximum power rating and total energy capacity to service the load scenario, (S_j) will be scored as a 1; otherwise, if it is unable to satisfy the total energy required, it will receive a 0. The set of load scenarios can be generated as a combination of individual element demands, such as the full set permutation, variations in element peak-shaving assumptions, bounds of uncertainty from stochastic modeling, or by informed CONOPS requirements. The sum of the scores from the assessment of the individual load profile scenario assessments is then divided by the total number of scenarios (S_{tot}) to provide a measure of total platform energy storage flexibility.

$$ESSF = \frac{S_1+S_2+\cdots+S_j}{S_{tot}} \qquad (5)$$

Power profiles for high-energy loads and changes in the propulsion and power generation system operating requirements can be modeled as an expansion of the evaluation load sets developed for the distributable power flexibility. In addition to the load types and magnitudes used in Section 6.2, the operational scenarios for assessing ESS flexibility require a load profile to define the load behavior, such a stochastic or pulse load, over a set duration. Table 24 provides example load profiles for elements requiring ESS service, based on the models proposed by MIT Sea Grant (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023). Compared to the distributable power evaluation sets, the load profiles have been expanded beyond the focus of a single zone to consider a whole-ship configuration, including a scenario requiring energy storage for propulsion and ship service load backup, referred to as the spinning reserve. The assumptions for these load profile power and energy demands, including the peak-shaving approach, will be discussed in detail in Case 4, Section 6.3.1. Additional load profiles can be generated to account for variations in mission loads through stochastic modeling, such as the method defined by (Stevens, Opilia, Cramer, & Zivi, 2015).

Table 24: Example load profiles for potential future operational scenarios requiring energy storage flexibility

Element	Operational Behavior Type	Operating Duration (s)	Power - Peak (kW)	Steady Bus Load (kW)	Peak Shaving Load (kW)	ESS Energy Demand Max (kWh)
Radar	Continuous, Stochastic	4200	1000	727.5	272.5	0.06
Laser	Intermittent, Stochastic	1800	1200	200	1000	92.3
Electronic Warfare (EW)	Continuous, Stochastic	4200	1500	950.3	549.7	0.79
Spinning Reserve	Continuous, Deterministic	300	2000	0	*NA*	238

ESS recharging is considered within the definition of each individual operational scenario demand based on the energy demands of the element(s) over time, and the determination of power able to be drawn from the ship's power distribution system. Balancing the performance of ESS flexibility within the desired scenarios against the cost of acquisition and shipboard integration for a set of design alternatives will inform the decision to pursue a dedicated (point of use) or integrated energy storage solution. This metric can be used to assess the flexibility of both dedicated and integrated energy storage architectures.

6.3.1 Case 4: Energy Storage System Flexibility Metric

This case study evaluates the energy storage flexibility of a notional Energy Storage System design space. One hundred and twenty-five individual ESS architectures, listed in Appendix B are defined based on their draw from the ship's power distribution bus, their energy capacity, and maximum power rating. The design space is generated as the full set of combinations of the discrete parameters defined in Table 25.

Table 25: Notional Energy Storage System Design Space Bounding Parameters

	Bus Capacity (kW)	Energy Storage Capacity (kWh)	Peak ESS Power (kW)
1	200	1	1,000
2	2,000	10	1,600
3	3,250	100	2,200
4	4,500	250	3,000
5	5,000	300	3,200

The operational scenarios used to evaluate the design space are based on the element load profiles established by (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023), and do not reflect actual Navy systems' performance. Columns two through six of Table 26 define the five operational scenarios related to the mission profiles of three element load types and a spinning reserve for ship's power backup. Two element loads, the Radar and Electronic Warfare elements, are assumed to operate in a "peak-shaving" profile, where the average power demand over the operating profile is drawn directly from the ship's power distribution bus and the ESS is responsible for demand fluctuations above and below this average. When the actual demand exceeds the distribution bus supply, the ESS discharges the requisite energy delta, and when the demand is below the bus supply, the ESS utilizes the load delta to recharge. The third element, the Laser weapon, relies solely on the ESS for energy supply throughout its active operating time, with a constant draw of 200 kW from the bus to cover the standby condition between firings. The "combination" scenario accounts for operating the three individual element load types simultaneously. The three elements and their combination scenario are modeled stochastically in MATLAB, 7.1Appendix C , for a seventy-minute operating period, as defined by (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023). A final scenario, the "spinning reserve", is modeled separately. For this case, a ten-run simulation was run for each scenario to provide a sense of the impact from the stochastic variability, with the output power and energy profiles as depicted in Appendix C Table 26 provides the average power and energy characteristics of each individual element simulation and the system-level attributes including the total number of elements of each type. For the combination scenario, the maximum ratings of the individual elements included were adjusted to match the required number of elements included.

Table 26: Case 4 Operational Scenarios for Energy Storage Flexibility

Element:	Radar	Laser	Electronic Warfare (EW)	Spinning Reserve	Combination
Number of Elements within the System	3	1	2	*NA*	6 (included)
Modeled Operational Behavior	Continuous, Stochastic Noise on Sinusoidal Base	Intermittent, Stochastic Pulse Length and Occurrence	Continuous, Stochastic	Continuous, Deterministic	Combined, Stochastic
CONOPS Scenario Duration (s)	4200	1800	4200	300	4200
Individual Element Attributes					
Peak Power - Single Element **(kW)**	1000	1200	1500	2000	7200
Steady Bus Load – Single Element **(kW)**	727.5	200	950.3	0	4352.4
Peak Shaving Power – Single Element **(kW)**	272.5	1000	549.7	*NA*	2847.6
ESS Energy Demand Max – Single Element **(kWh)**	0.06	92.3	0.79	*NA*	*NA*
System Level Attributes – All Elements Included					
Total Bus Load – All Elements **(kW)**	2182.5	200.0	1900.6	0	4352.4
ESS Max Power – All Elements **(kW)**	817.5	1000	1099.4	2000	2847.6
Total ESS Energy – All Elements **(kWh)**	0.18	92.3	1.58	238	99.5

- Radar Mission Load: Modeled as a sine wave with a maximum power of 1000 kW, Figure 16. The operating profile runs continuously over the seventy-minute mission duration, with stochastic variability added as “noise” at each time step. The Radar demands on the ESS are based on the peak-shaving assumption, with the ESS responsible for supplying the difference between the operational Radar power demand and the bus supplied power. Energy is the power over time, calculated at each time step in the profile. The maximum energy is found from the running sum of energy demands at each time step. While the determination of bus power as the average of the radar demands would theoretically lead to an even amount of energy charged and discharged, the stochastic noise modeling provides opportunity for energy demands to accumulate beyond the maximum of one sinusoidal discharge cycle.

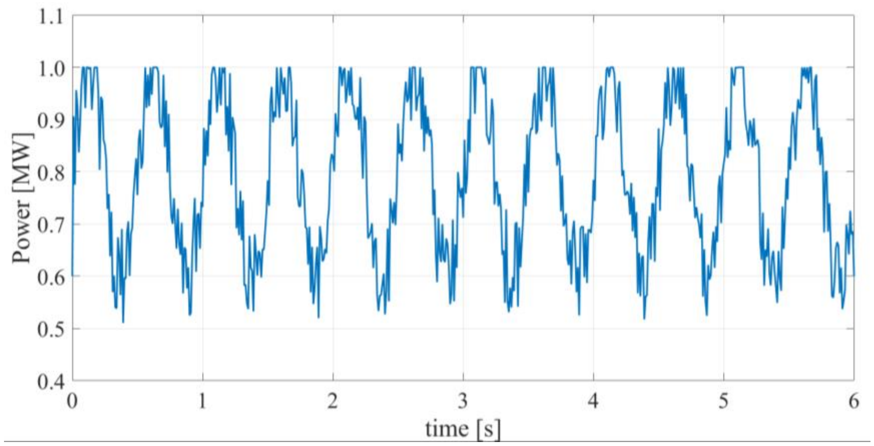

Figure 16: Radar power profile (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023)

- Electronic Warfare Mission Load: Modeled as a random instantaneous load between a maximum power of 1,500 kW and minimum power of 400 kW, Figure 17. The operating profile runs continuously over the seventy-minute mission duration, with stochastic variability incorporated into the operational EW power demand at each time step. EW demands on the ESS maintain the same assumptions for peak-shaving and the determination of the maximum energy demand as in the Radar profile.

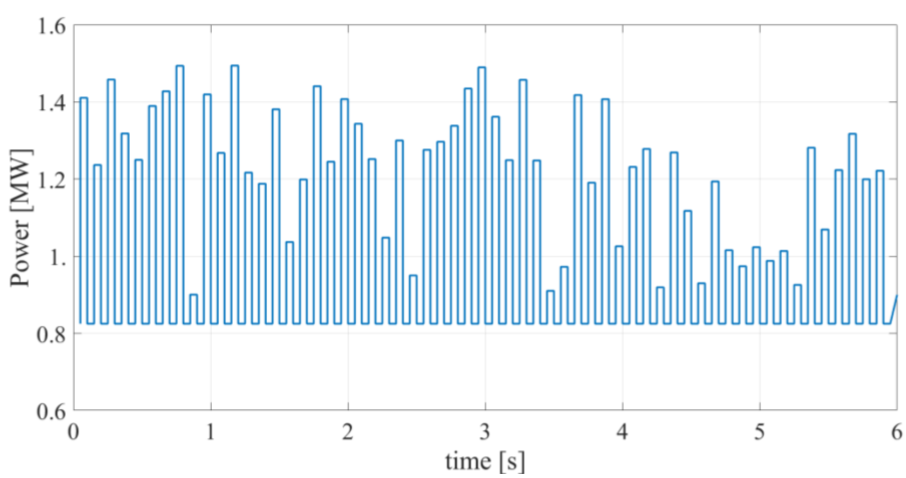

Figure 17: Electronic Warfare system power profile (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023)

- Laser Weapon Mission Load: Modeled as an intermittent load profile in which the firing state draws the maximum power demand of 1,200 kW and the non-firing state maintains 200 kW of standby power drawn from the power distribution bus, Figure 18. The Laser weapon scenario incorporates stochastic variability within the determination of time spent firing or in standby, with a maximum beam duration of six seconds and a maximum time between lasing of 30 seconds. The scenario accounts for thirty minutes of active lasing, consisting of firing and standby states, followed by forty minutes of ESS recharging. As the laser draws almost entirely from the ESS over the thirty-minute lasing period, the maximum energy demand for each run is dependent on the stochastic model of firing durations.

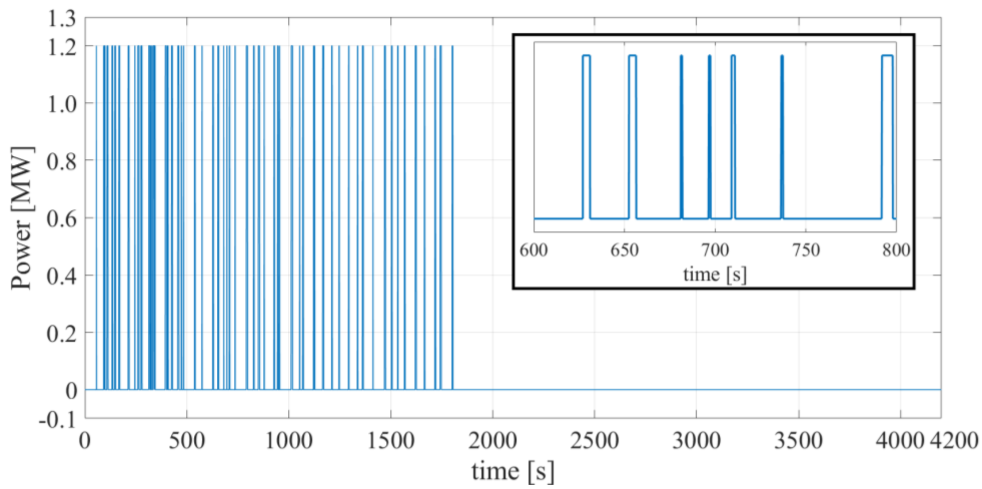

Figure 18: Laser Weapon power profile over a 70-minute operating time. Insert of 200-second period. (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023)

- Combination Mission Load: Modeled as the combination of stochastic load demands from the three Radar, two EW, and one Laser weapon elements. Maximum energy demand is determined by taking the running sum of energy demands at each of the lowest level time steps.

- Spinning Reserve: ESS energy capacity is required to provide 2 MW of continuous power for at least five minutes of ship operations, as assumed for the ship concept presented by (Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023).

Each of the 125 ESS concepts was evaluated for Energy Storage Flexibility ($ESSF$) as measured against the five operational scenarios. Table 27 identifies the number of concepts with sufficient power and energy required to satisfy each scenario. Eight concepts are able to satisfy all five operational scenarios. The average $ESSF$ score across the design space was 0.41 and the median score was a 0.40. The design space was generated based on the range of system-level demands across each element evaluation. Total bus capacity power demands ranged from 200 kW to 4.4 MW, energy storage capacity demands ranged from 817 kW to 2.8 MW, and total ESS energy required ranged from 0.18 to 100 kWh. The 125-concept design space includes architectures that are sized with system cost and affordability in mind to provide options that are "right-sized" for any given scenario requirement.

Table 27: ESS Design Space Flexibility Results for 125 Total Concepts

	3x Radars	1x Laser Weapon	2x EW	Spinning Reserve	Combination	All Scenarios Passed
Number of Passing Concepts	75	75	64	30	12	8
Fail due to Bus Capacity	50	0	25	0	75	*NA*
Fail due to Energy Capacity	0	50	25	75	50	*NA*
Fail due to Max Power Rating	0	0	25	50	75	*NA*

6.4 Interface Control

Interface control is essential for establishing system integration requirements for future equipment installation within the broader system-of-systems architecture. Proper identification of interface requirements, considering the physical, logical, and operational requirements for a particular system, will improve system flexibility by minimizing the cascading effects of unknown future system changes. There are two types of commonly employed interface requirement documents:

- Interface Control Document: formal means of establishing, defining, and controlling interfaces. Documents detailed interface design information between systems and sub-systems for the platform.
- Installation Control Drawing: provides shipboard installation data for future equipment, such as mission system elements. These documents and drawings define and support the engineering, installation, and construction of the platform.

For a mission system, an Installation Control Document can be written to establish the maximum physical characteristics, or "not to exceed" values, such as SWAP-C size restrictions, location, and required services from the power and energy, and auxiliaries systems. In these cases, the Installation Control Document augments the requirements for power generation system capacity, and the size of the distribution and conversion system within each zone.

Interface Control Documents for other ship preparations, such as compartment reservations, define the physical and logical requirements of a reserved space within the ship. These documents are often associated with a modularity approach, where the physical space and connectivity of a module are defined within the ship to accommodate any theoretical future system that meets those interface requirements. This approach pre-determines the location of future load demands and routes the required distributed systems services and utilities where needed.

Specifically for the power and energy system, Interface Control Documents may be written to enable Real Options for future upgrades to the P&E system itself. Within the P&E system boundary, future requirements may drive the need for additional power generation, integrated energy storage, and/or expanded distribution element capabilities. Section 6.5 further defines Real Options Analysis and provides an example related to options and preparations for future upgrades to the power distribution system as future unknown loads are realized.

6.5 Real Options Analysis

Real Options Analysis (ROA) is a method of employing flexibility in design to maximize the expected value of a system while minimizing the upfront cost of procurement and lifecycle cost of operation and sustainment (O&S). It enables the designer to evaluate the uncertainty inherent in a systems-engineering problem and develop a design or plan that maximizes value at a given time in the system's lifecycle, such as at the time of initial delivery, while maintaining the ability to adapt to the future unknown requirements. Said another way, Real Options enable the design or project to be ready to change, by including accommodations (preparations) for flexibility. This enables the system to maintain value over its lifecycle, versus becoming obsolete in the face of new requirements.

Real Options Analysis uses the financial evaluation of Net Present Value (NPV) to determine the value of real assets, such as a construction project or alternative investment opportunities, along with a design decision model to account for the manager's role in determining when to take action implementing design preparations over the system's lifecycle. Where NPV utilizes deterministic assumptions about cost and profit variables, ROA models the uncertainty within the evaluation scenario and looks for the opportunity to use it to the system's advantage. (Page J. , 2012)

NPV analysis converts all cash flows throughout the system's life to a common basis in present time to obtain a single comparable value. This includes all lifecycle cost and initial upfront investment or construction costs, as well as any future profits generated by the system in operation or financial opportunity. As shown in equation (6), the NPV of a future cash flow (V_t) is determined by applying a discount rate (r) and accounting for the time between the present and future periods for all cashflows. The discount rate is a value applied to reflect the difference in the value of money at the present time versus the value of the same amount of money in the future. This enables the decision maker to recognize the cost or benefit impact of future investments in terms of efforts spent now. In this type of assessment, the value of money at present is greater than the same amount in the future. In financial terms, the discount rate represents the opportunity cost of capital, or the potential return on investment based on all the other opportunities available to the investor, and is typically set as an industry standard. The project model that produces a naval power and energy system is subject to discount rate requirements set by the Office of Management and Budget (OMB) under the Executive Office of the President. In 2022 the discount rate was determined to be 0.5% for a 30-

plus-year investment (OMB Circular A-94 Guideliness and Discount Rates for Benefit-Cost Analysis of Federal Programs, 2022).

$$NPV = \frac{V_t}{(1+r)^t} \qquad (6)$$

Ship design and acquisition is an investment in a form of real assets that are not expected to generate a profit by the standard execution of a NPV analysis. In order to balance the present cost against system value in the ROA evaluation model, a measure of performance (MOP) is required. For the analysis of the power and energy system, any of the flexibility metrics presented in the sections above are valid MOPs, depending on the scenario of interest. The NPV and MOP are modeled simultaneously in an evaluation scenario that accounts for the costs occurred and the change in variables impacting the performance metric over time, such as on an annual basis throughout the expected service life of the system. The value of the Real Options Analysis comes from the inclusion of uncertainty within the evaluation scenario. Uncertainty can be implemented by determining the potential perturbations on the system, such as the exercise demonstrated in Section 5.2, establishing the minimum and maximum bounds and likeliness of uncertainty parameters, and linking impacts to the NPV and MOP variables.

Once the uncertainty parameters are linked, the designer can identify Real Options or preparations in design, needed to minimize the risk identified in the base case uncertainty analysis and provide cost effective options to maximize system performance. The decision model is then developed to establish governing logic for when action is to be taken to implement an option in response to the realization of uncertainty.

6.5.1 Case 5: Real Options Analysis of a Future Integrated Power System

This case study demonstrates the use of Real Options Analysis of a flexible power distribution architecture. A base case and two Real Options alternatives of a notional naval surface combatant are evaluated with the intent to maximize the platform mission capability while minimizing the upfront cost of procurement and lifecycle cost of O&S throughout an expected 40-year service life. The ROA evaluates the electrical power distribution system for a zonal IFTP concept, a variant of the architecture identified in Case 3 which includes a notional energy storage module (ESM).

Evaluation Scenario:

Based on the combinations of missions performed, operating speeds, and other equipment configurations, the power distribution system will experience a wide range of loading conditions. Typically, the distribution system (as well as power generation system) is sized based on the most stressing condition to ensure adequate capacity and performance across all conditions. This system model evaluates performance and cost based on the most stressful scenario: propulsion demand (from PMM) for sustained speed plus the maximum margined electrical load (from PLM). The maximum margined electrical load includes the mission operation demand. While this scenario requires the highest load demand on the electrical distribution system, it only accounts for approximately 12% of the ship's time at sea for the current Navy's surface combatant fleet of Arleigh Burke class destroyers, as demonstrated in Figure 19 (Anderson, 2013).

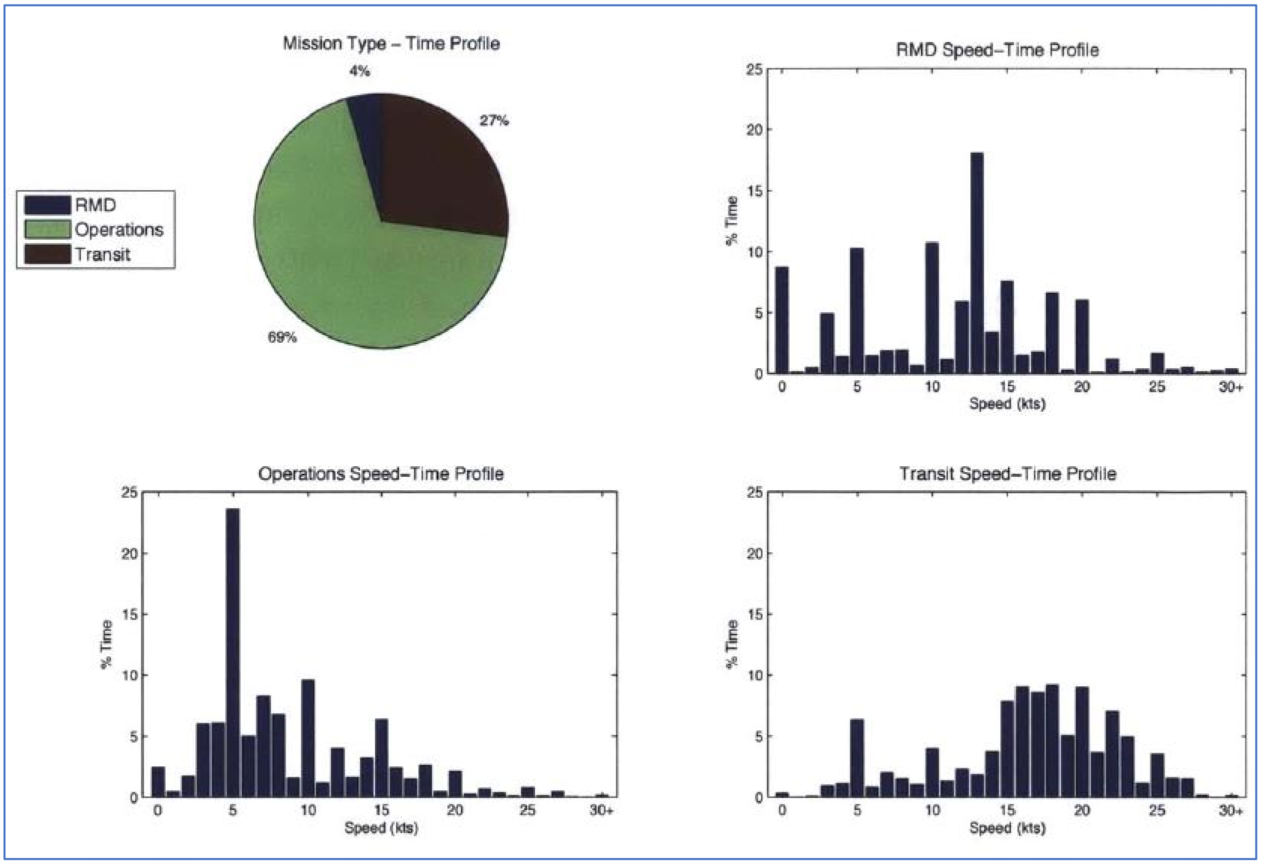

Figure 19: DDG-51 Mission Type-Time Operating Profile (Anderson, 2013)

The system CONOPS, modeled as the annual operating conditions of the concept, is based on the combination of Anderson's (2013) mission-speed time profile in Figure 19, and the set of PMM plus PLM loads in Table 28. It is assumed that based on the ship service and mission system load demands, and the inherent capability of the IPS architecture, that the mission operation speed is allowed to degrade over the service life of the ship, in order to debit propulsion power for shipboard load demands if needed.

Table 28: CONOPS Condition-Loading Profile

	Hours %	PMM (MW)	PLM (MW)
Mission Low Speed	0.57	15	20.16 (base) / Stochastic future load uncertainty
Mission High Speed	0.12	60	20.16 (base) / Stochastic future load uncertainty
Transit	0.27	18	3
Restricted Maneuvering Doctrine (RMD)	0.4	5	3

To define the operational scenario at system delivery (year 0), the initial maximum margined electrical load is assumed to be 18.8 MW, based on an 85% efficiency factor applied to the maximum distribution capacity of the current DDG 51 class destroyers, plus a subset of mission system equipment loads from the ESRDC ship concept (Smart, et al., 2017), as shown in Table 29. A 20% service life allowance is applied to the non-mission-system loads, assuming a 40-year service life, yielding an EOSL maximum margined electrical load of 20.16 MW, which is used to size the in-zone PCMs. Load growth is assumed to be realized in 4-year increments; thus, in year 4 load demand is 18.94 MW, in year 8 load demand is 19.07 MW, and so forth.

Table 29: ESRDC 10,000 ton Ship Concept Mission System Battle Power Condition (Smart, et al., 2017)

Maximum Margined Electrical Load at Year 0	(MW)
Non-mission system load	6.8
Armament	
Active Denial System	2.4
Command and Surveillance	
Multi-Function Phased-Array Radar	5
Integrated Topside (InTop), including Surface Electronic Warfare Improvement Program (SEWIP) and communications	4
Hull Mounted Sonar, Towed-Array Sonar	0.45
Total Ship Computing Environment (Integrated weapons, sensor, machinery and navigation control systems)	0.15
Vehicles	
Helicopter/UAV	0
Small Boats/USV	0
Total	**18.8**

Base Architecture:

The base architecture consists of the following modules:

- **Propulsion Motor Module (PMM)**: 2x 36 Permanent Magnet Motors.
- **Power Generation Module (PGM)**: 2x Rolls Royce MT-30 Large Gas Turbine Generators, rated at 36 MW each, and 2x Rolls Royce MT-5 Secondary Gas Turbine Generators, each rated at 5 MW, for a total of 82 MW of installed power generation.
- **Power Load Module (PLM)**: propulsion and mission load demands, as identified in the evaluation scenario, plus unknown future loads as identified below, in the Uncertainties section.
- **Power Distribution Module (PDM)**: primarily electric cabling, sized to support the maximum distribution capacity. This capacity is held constant in the base project model at 20.16 MW, based on the PLM max margined electric load. This assumption is based on the difficulty in resizing ship cabling once integrated, requiring wholesale removal and replacement, and the complexity in modeling less significant cabling modifications between in zone electrical loads.

- **Energy Storage Module (ESM)**: lithium-ion-based energy storage module, sized for the specific mission load profile.
- **Power Control Module (PCON)**: assumed to be designed alongside the base model with preparations to support the maximum system capability, not modeled in this case.
- **Power Conversion Module (PCM)**: based on the modified Zonal IFTP concepts in Case 3, where the PCM-1A is primarily a power converter, with a power rating of 1MW. The PCM-2A receives power from the PCM-1A and functions as an Integrated Power Node Center (IPNC), to provide a variety of low voltage output power types (Doerry, 2008). The PCM-2A is a transformer-rectifier and is assumed to have a rating up to 500kW. In addition to the NGIPS-based PCMs, the case model utilizes a notional PCM-X and an ESM converter to account for unknown future mission system demands. The PCM-X is assumed to have a 500kW rating and the ESM interface is assumed to have a 500kW charger converter for every 1MW of mission load output.

  The number of PCM-1As and PCM-2As required per zone is based on the maximum margined electrical load at the end of the ship's service life (including 20% SLA), assuming the ability to distribute a quarter of the total load in any given zone. It is then assumed that a completely redundant set of PCMs are required in each zone. PCM-Xs and the ESM interface are sized directly for the mission load required, with no redundancy or required service life allowance.

  Table 30 identifies the PCM rating assumptions, as well as the cost and volumetric criteria for the ROA decision model. The cost for each PCM is notional and does not represent Navy system actuals. The lithium-ion ESM is assumed to cost \$345/kWh, based on National Renewable Energy Laboratory's (NREL) 2021 'Cost Projections for Utility-Scale Battery Storage' (Cole, Frazier, & Augustine, 2021)

Table 30: PCM Assumptions

	Function	Rating	Cost	Volume (m3)
PCM-1A	Converter	1000 kW	\$ 1,200,000	40
PCM-2A	Transformer-Rectifier	500 kW	\$ 340,000	18
PCM-X	Converter/Transformer	500 kW	\$ 1,200,000	12
ESM interface	Converter	500 kW	\$1,200,000 + \$345/kWh	450 kWhr/m3

- **Ship Integration Interface**: like the PDM sizing assumption, the volumetric capacity of the ship concept dedicated to the power distribution system is sized for the maximum distribution capacity, reflected in the number and type of PCMs required, and held constant. Any future PLM requiring electrical distribution system support can only be enabled if sufficient ship compartmentation (volume) is provided for the necessary PCM equipment.

Performance:

The performance of the power distribution system in this model is represented in terms of Flexible Power Capacity (FPC, equation 1). FPC is calculated for each time step (year) and the overall measure of performance for power flexibility is taken as a weighted average of the existing conditions in years 1-40. The weighting is based on a notional temporal prioritization, where mid-system-life flexibility is prioritized over the beginning and end of service life. In this case, the desire to increase operational performance over the second half of system life is higher than immediately after system delivery (requires taking new mission system asset offline) and at end of service life (limited operational value based on hull life).

The amount of distributable power capacity is based on the number of power conversion modules of each type and the upfront PDM capacity. In this model, the distributable power demand is initially based on the standard Navy design practice of Service Life Allowance. The base case PCM and PDM architecture is sized to meet a deterministic prediction of the end of service life condition requirements, based on the SLA demand projection, such that the Flexible Power Capacity performance metric is a near-zero positive value. When uncertainty is introduced within the ROA model, the performance value will reflect the impacts from the magnitude of change in the actual demands and when in the system lifecycle they are realized.

NPV:

Net Present Value is calculated in this model based on Basic Construction Cost (BCC) and Operation and Sustainment cost. BCC includes the material, labor and overhead cost associated with purchase, construction, installation, and activation of the ship. In this model, the BCC cost relationship was developed using the 'MIT 2N Ship Cost Model' (2016), with inputs from the ESRDC ship concept (Smart, et al., 2017) as a surrogate platform and the cost of electrical distribution system modules as defined in the base architecture. To determine the impact of implementation of Real Options, the BCC cost model was adjusted to identify the cost of additional arrangeable ship volume and the cost of required PDM equipment.

Table 31: Cost Parameters

Cost Parameter	Value
BCC ($M)	$1.003+(Cost PCMs)+(Cost ESM)+(Cost Vol)+(Cost PDM)
Cost of volume ($M/m3)	$0.031
Cost of PDM ($M)	((delta MW)/0.85PF/13800V)/800A*$250/ft*775ft
O&S Cost ($M)	$200+($3)*(3000Hrs)/(6.8*(Fuel Consumption Rate)/1000)

The O&S cost accounts for the annual costs of personnel, operations, maintenance, energy, replenishment, and support activities. This model has isolated the impact of annual energy associated with the ability of the power distribution system architecture to meet the required PMM and PLM power load demands. This requires characterization of the power distribution system interface with the PGM, including fuel consumption and generator lineup. Specifically, the fuel consumption rate is dependent on PLM plus PMM load demands, the selection of generator lineup, and the generator efficiency in such operating conditions. At each annual timestep, the fuel consumption rate is determined by pairing the appropriate PGM lineup, Table 32, in each operating condition defined in the CONOPS, Table 28. The fuel consumption rate is further adjusted to account for the notional PGM efficiency based on generator load level, Figure 20 (Smart, et al., 2017).

Table 32: Power Generation Lineups

PGM Lineups	MW online	Fuel Consumption (lton/hr)
MT5	5	1.36
2x MT5	10	2.73
MT5 + MT30	41	8.70
2xMT5 + MT30	46	10.06
2x MT30	72	14.67
MT5 + 2x MT30	77	16.03
2xMT5 + 2xMT30	82	17.39

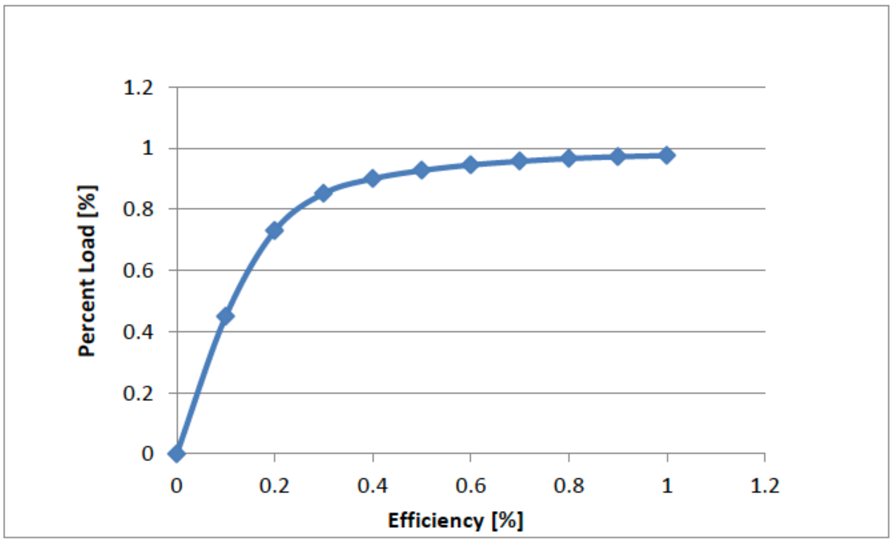

Figure 20: Notional generator efficiency as a function of power level (Smart, et al., 2017)

Uncertainties:

Within the evaluation scenario, any number of perturbations may impact the measure of performance and NPV. For this case, the primary source of uncertainty was modeled based on the long-term perturbation for “changes in the mission system load,” with the sub-type of “increased load demand,” as identified in Table 4. To account for variation in future mission system loads, a probability distribution function was developed from a combination of potential high-energy weapons and sensors, as identified by ESRDC (Smart, et al., 2017). To simulate a normal ship deployment, maintenance, and upgrade cycle, the system model assumes that mission system upgrades occur in a stepwise manner vice continuously year over year. Therefore, the probability that a mission system load increase is realized in any given year was modeled as a 10% likelihood.

In addition to the large electrical load demand fluctuations from the mission system itself, secondary uncertainty parameters for the perturbation sub-type “new load types (pulse loads, ramp rates)” were included in the model to account for the portion of future mission system loads requiring energy storage, and sub-type “secondary impacts realized in the auxiliary systems” to account for the efficiency of the future mission system loads. These secondary uncertainty parameters account for the impact of the ship service distribution system related to auxiliary and support equipment, such as the thermal management and controls equipment. The uncertainty inputs factors are shown in Table 33.

Table 33: Mission system load uncertainty input factors

Uncertainty Variables	
Schedule Upgrade Probability	10%
Realized Demand (Mission Load)	LOGNORMAL PDF
Mission System Load Efficiency	30-70%
Portion of new Mission Load Requiring ESM	0-100%
Probability Distribution	
Log-Normal Distribution	
mean	1.34
Standard deviation	1.7

Excel Decision Model:

Given that the Mission System Load is the highest source of uncertainty, a decision model was developed to account for variability in electrical load demands from the mission system elements and the required auxiliary equipment, to ensure distribution system performance over the 40-year platform service life. The decision model was also required to minimize the impact of NPV cost required to provide performance power flexibility.

In the base model, the expected mission system load was determined to be 12 MW, serviced by 24 dedicated 500kW PCM-Xs. The standard Navy 20% electrical power SLA was applied to the sizing of Primary and Secondary power distribution elements, PCM-1As and PCM 2As, but no design consideration was included for mission system elements requiring dedicated PCM-X utility. Within the standard practice, the ability to add the needed capability in the future would rely on a combination of separate SLA categories for ship displacement, KG, and arrangeable area, such that dedicated PCM-Xs may be added. Once these other non-electrical system specific SLA capacities are consumed, the standard base approach would require a one-for-one removal of existing equipment to be replaced by the new desired element or demand load.

The excel decision model was built to support the evaluation of Real Options which account for the mission system load uncertainty and provide cost effective means of increasing mission system load capability in the future. Decision criteria within the model are structured around the identified uncertainties: schedule of mission system load increase, magnitude of mission system load increase, efficiency of new load, and load type. If the conditions to satisfy the identified decision criteria are realized, a design flexibility option can be implemented.

Table 34: Decision Criteria

Mission System Load Uncertainty Source	Uncertainty Characterization	Decision Criteria	System Impact
Schedule of Upgrade Occurrence	10% chance in any given year	New mission system load demand	Number and type of PCMs, and ESM
Load Magnitude	Log-Normal PDF	Mission system load increases	Number and type of PCMs, and ESM
Load Efficiency	30%-70%	Auxiliary support equipment required	Number of PCM-1A and PCM-2A
Load Type	0%-100% of new load requiring ESM	Energy storage module is required	kWh of ESM capacity and number of charging converters

The flexibility options (Real Options) evaluated in this model include the options to install additional PCM-X, PCM-1A, PCM-2A, ESM Charging Converters, and ESM battery modules. The preparations required to enable these options are the provision of dedicated electrical distribution system compartmentation (volume) within the ship, the initially oversized maximum rating of the PDM, and the capability of the IPS to debit PMM power for mission system load demand. The capacity limitations for flexibility options are based on these preparations and demonstrated in Table 35.

Table 35: Flexibility Option Capacity Limitations

Capacity Type	Flexibility Limit	Value
Max PLM Power (MW)	Minimize dedicated PMM Power required	72 MW (with minimum PMM requirement of 10 MW)
Volume (m3)	Arrangeable space allocated to electrical distribution at ship delivery	50% increase from base
Max PDM Rating (MW)	Amount/sizing of cable (etc.) installed at ship delivery	72 MW (a 350% increase over baseline demand)

Base Case (With and Without Uncertainty):

The base case is a deterministic model representing the standard Navy design approach where the propulsion, ship service and mission system loads are defined for the initial system delivery condition, and all desired future growth is accounted for with a standard 20% SLA. In this way, the power distribution system is designed for the appropriate amount of PCMs, PDM, and in this case no accommodations for ESM. The performance and cost NPV outcomes of the base case assume the outcome is exactly as predicted and demonstrate a cost-effective means for providing the required performance. However, the end outcome 40 years into the future is not so easily predictable and is at risk of influence from uncertainty.

The static base case was developed as the initial project model, without uncertainty, to provide the deterministic analysis of a notional power distribution system. It was used to investigate the direct linkages between input variables, model assumptions and constants, and derived parameters. It assumes that the power distribution system for an IPS electric ship designed for a 40-year service life is based on propulsion power required for sustained speed, plus the ship service power and mission system load requirements as described in the Evaluation Scenario. The deterministic result is a system with performance value Flexibility Power Capacity FPC = 0.055 at a NPV cost of $9.07B. Of this $9.07B, BCC is responsible for $1.07B, and $71M of BCC is associated with the distribution system (roughly 7%).

Table 36: Fixed Input Parameters

Demand projections	
Demand in year 1 (MW) (max margined power)	8
40 Year Power Demand Growth	20%
Projected Mission X Load (MW)	12.0
Future ESM Load (kWh)	0
Cost Parameters	
Basic Construction Costs ($M)	$1.003+(Cost PCMs)+(Cost ESM)+(Cost Vol)+(Cost PDM)
Cost of added ship area ($/m3)	$0.031
Cost delta of added cable ($M)	((delta MW)/0.85PF/13800V)/800A*$250/ft*775ft
O&S Cost ($M)	200+($3)*(3000Hrs)/(6.8*(Fuel Consumption Rate)/1000)
Performance Parameters	
Propulsion Power (Sustained Speed 30kt) (MW)	60
Total installed power (MW)	82
Architecture Type	IPS
Bus	MVAC
DST Compartmentation (m3)	2,165
PCM1 – (kW DC:DC)	1000
PCM2 – (kW AC:DC)	500
PCMX –kW	500
Energy Storage Module kW	500
PDM (cable, junction, other) rating (MW)	20.16
NPV	
Time horizon (years)	40
Discount rate	0.5%

The base case modeled with uncertainty supports a stochastic analysis of power distribution system value. The primary and two secondary uncertainty parameters identified in the Uncertainties section, above, reveal the risk inherent in the static-deterministic model. Figure 21 shows the cumulative distribution function (CDF) for Flexible Power Capacity, given uncertainty in future mission system loads, and Figure 22 shows the associated NPV. In each cumulative distribution function, the red line demonstrates the deterministic case. In both evaluation aspects, the static case falls within the favorable region of the likely outcomes, at the right-hand side of the CDF curve. The large portion of area under the curve left of the deterministic line represents uncertainty structured as risk. Said another way, if the deterministic case is used to design the power distribution system, there is a strong chance that the system will have insufficient capacity.

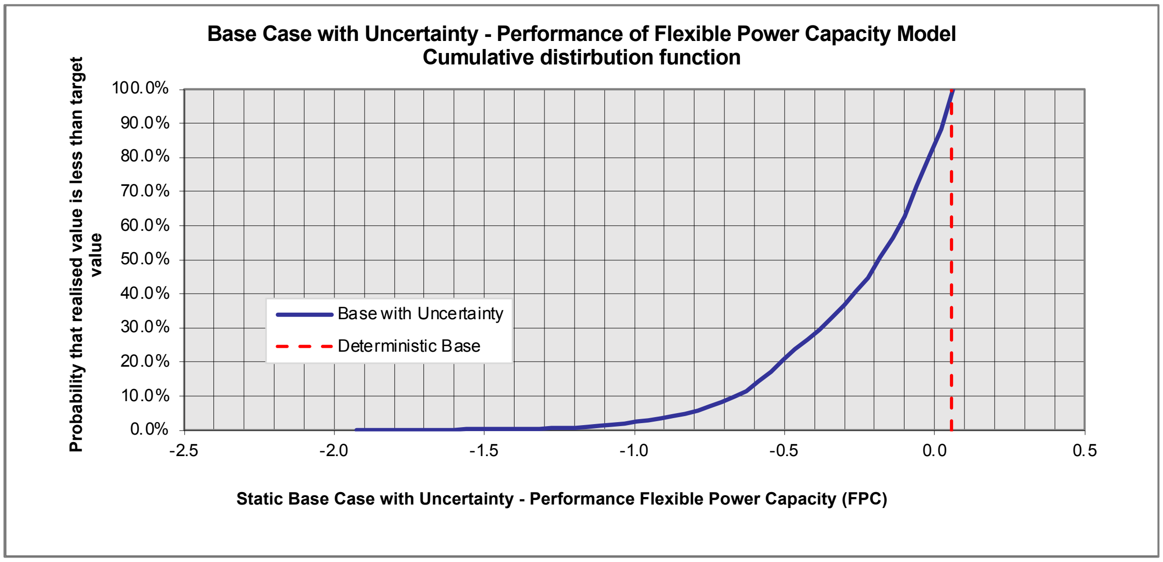

Figure 21: Performance – Flexible Power Capacity (FPC) CDF for base case with uncertainty

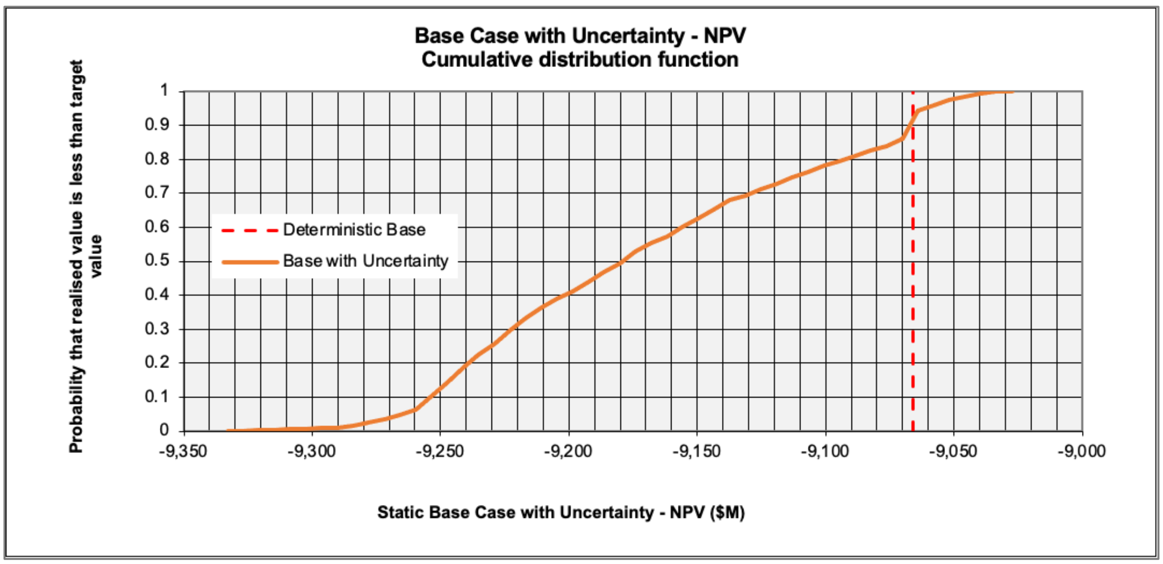

Figure 22: Net present value CDF for power distribution system base case with uncertainty

Real Options:

To minimize the risk identified in the base case uncertainty analysis and provide cost effective options to increase electrical distribution system performance, an evaluation of flexible design options was conducted. Focusing on the mission system load uncertainty, a Real Options model was developed to identify preparations required to enable future electrical distribution system capacity growth, while minimizing impact to NPV cost.

In the Real Options case, the ship platform includes flexibility preparations at initial delivery to provide additional, unused volume dedicated to electrical distribution system growth and up-rated power distribution modules, including cabling sized for a larger future electrical load than the initial mission condition PLM load. The cost of including these upfront preparations is accounted for in the basic construction cost in year zero. Otherwise, at initial system delivery, the number and type of PCMs are the same as in the base case.

As in the base case with uncertainty, the mission system load uncertainty sources are modeled to demonstrate the variability in power distribution load demand, and its associated impact on the derived parameters. However, unlike in the base case, the Real Options case with flexibility is enabled by the decision model to determine the timing, magnitude, and variety of additional PCM and ESM module capacity to be added to the system.

The decision model evaluates the actual electrical load demand against the capacity over the previous 4 periods to determine if available flexibility options should be realized. The decision to expand the system by adding PCMs and ESMs is dependent on the remaining capacity of initial preparations: volume, Power Distribution Module capacity, and Power Generation Module capacity able to be debited from propulsion. Two Real Option cases are presented below to evaluate the impact of decision module variable for capacity expansion rate. Real Option 1 is intended to provide sufficient power capacity as demand increases, while minimizing the cost impact by only installing the number of desired PCMs and ESMs to match the current demand. Real Option 2 is intended to maximize the performance value of the system by anticipating the mission load increase trend and utilizing the selected ship availability to install additional capacity (two times the current demand load increase). In both cases, the capacity limits were held constant as shown in Table 35. The performance and NPV cumulative distribution functions for these Real Options cases, compared to the base case, are shown below in Figure 23 and Figure 24.

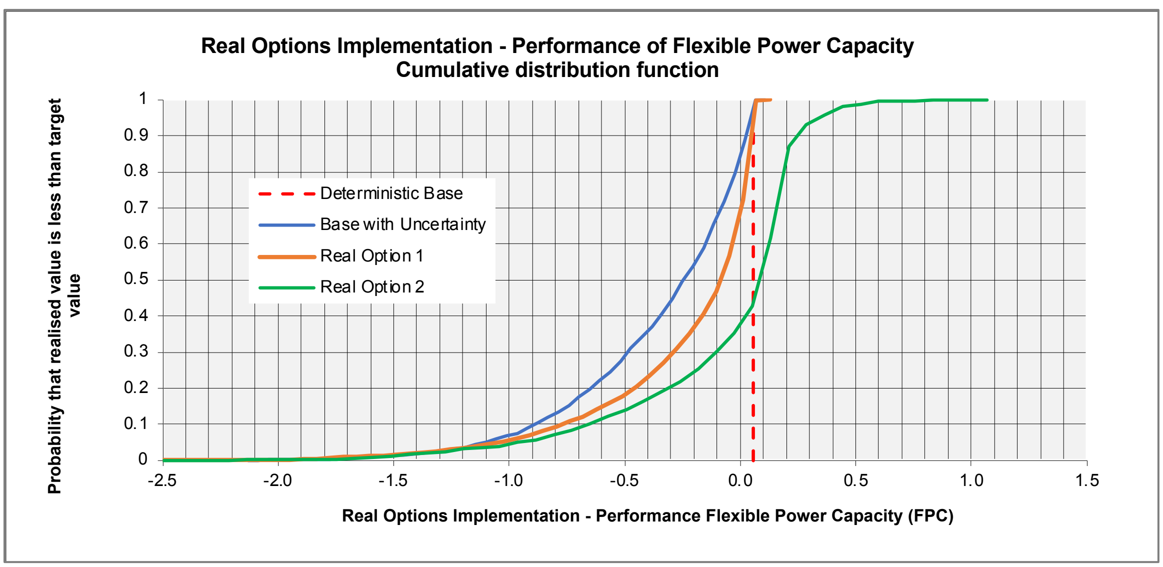

Figure 23: Performance – Flexible Power Capacity (FPC) CDF for Real Options

The performance model cumulative distribution function demonstrates the maximum FPC value achievable by each architecture. The deterministic base case shows the reference point for the initial architecture assuming no uncertainty for future mission system load growth beyond the planned 20% SLA. The base case with uncertainty demonstrates that the likelihood of underperformance and loss of system value is significant. The real options cases utilize preparations in design to enable the decision maker to respond to uncertainty when it is realized and minimize the likelihood of underperformance. This is represented by the "shift" of the CDF curve to the right, and the increase in maximum FPC beyond the deterministic case.

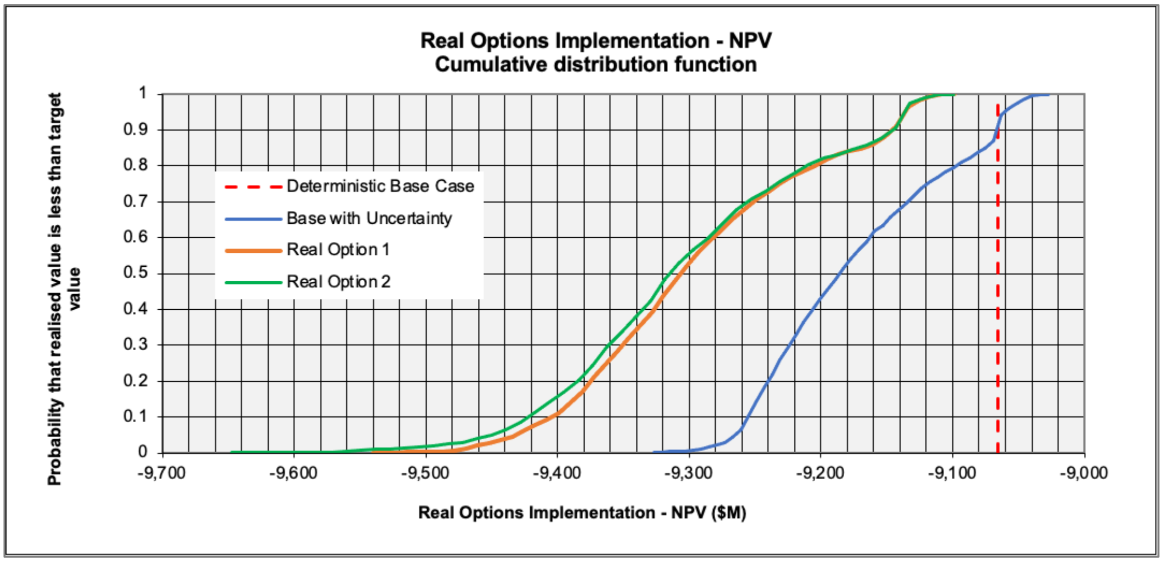

Figure 24: Net present value CDF for power distribution system Real Options

The NPV model cumulative distribution function demonstrates the potential lifecycle cost of each architecture, compared to the deterministic base case. The static base case is shown as a lower cost option, however, we know from the performance model that it is unlikely to provide sufficient system value over time as perturbations in load requirements are realized, as represented by the base case with uncertainty. The real options cases require additional upfront acquisition cost to include preparations in design that enable the decision maker to respond to future uncertainty. It is significant to note that while the NPV reflects the total lifecycle cost, the cost of preparations for Real Option Case 2 is only $70M (6.5%) greater than the BCC of the base case. While this is a relatively small contribution to the overall NPV cost, which is greater than $9B, the power distribution system itself is only 6.7% of the total ship BCC.

Discussion:

This Real Options Analysis model demonstrates the value of flexible design options in terms of Flexible Power Capacity performance and NPV. Designing the distribution architecture to accommodate modular power conversion modules of various voltage and capacity, enables the option to add PCMs and ESMs as future unknown mission system load demands increase, and decision model criteria are met. The preparations required to enable these options are the provision of dedicated electrical distribution system compartmentation (volume) within the ship, the initially oversized maximum rating of the PDM, and the capability of the IPS to debit PMM power for mission system load demand. The capacity limitations for flexibility options are based on these preparations. Within a design space exploration activity, variations in these preparation variables and the modeling of additional uncertainty parameters will give the designer insight into the feasibility and dominance of power and energy system architecture alternatives.

Results from the two Real Options cases suggest that both flexible architectures will improve system performance over the base case, with Real Option 2 providing a 65% improvement over the base case, and positive power flexibility to accommodate future high-energy mission system loads. While the distribution system does not generate profit to counter the upfront cost and annual expenditures identified in the NPV analysis, the project results demonstrated feasibility to achieve the desired performance capability with a 6.5% increase in initial capital expenditure and a 1.4% increase over the system lifetime. These results demonstrate the ability to achieve significant system performance improvement at relatively low system cost through the implementation of flexible design options.

7 Conclusions

This thesis presents a framework for decomposing ility-based requirements into metrics for identifying a dominant architecture within an early-stage design tradespace. Ilities are defined as emergent systems properties that impact a 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 defines the system's purpose, but rather, are attributes used to measure the system's ability to respond to change. Research from a robust literature review of system of systems ilities, their relationships, and methods for differentiating between preferred solutions within a design tradespace was used to develop a hierarchy of "ility" relationships for the naval power and energy system.

The framework for design space exploration 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 perturbation is a mechanism or influence on the system that necessitates change. This thesis focuses on the framework application for the design of the multidisciplinary naval power and energy system, responsible for the energy flows across the mechanical, electrical, thermal, and signals domains.

For a given ility of interest, a comprehensive set of potential perturbations impacting the emergent system property is to be identified and linked to preparations in design. The design space of feasible solutions should be populated with options that satisfy the functional and the ility requirements, based on the initial identification of design preparations. These preparations can be decomposed into their base attributes within the physical, logical, and operational views of the system. Finally, design metrics for measuring system value under the influence of change caused by the given perturbation can be generated by linking independent and dependent variables to identified system attributes.

This thesis implements the framework to develop 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. Four case studies were conducted to develop metrics for Flexible Power Capacity, Debitable Power Flexibility, Distributable Power Flexibility, and Energy Storage Flexibility. A fifth case presents the application of Real Options Analysis for balancing system performance and cost to "right size" the P&E system at initial delivery with the inclusion of preparations in the design to react to future uncertainty.

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. This work is intended to present a repeatable process for developing metrics that can be integrated within early-stage design tools for creating and evaluating the naval power and energy system. The application of traditional and novel metric determination methods, and the implementation within design tools such as Smart Ship System Design (S3D), will enable system architects to rapidly assess a larger number of potential solutions and quickly characterize the cost versus capability tradeoffs of discrete architectural features.

The views expressed herein are the personal opinions of the author and are not necessarily the official views of the Department of Defense or any military department thereof.

7.1 Future Work

This research has identified several opportunities for follow-on actions in the development of standard ility-based design requirements and further application of the design framework. A deeper dive of the Department of Defense requirements and acquisition process may identify a means for directly linking ilities to threshold and objective capability requirements and bring greater attention to their value within the requirement-setting and programmatic decision-making communities.

The design framework should be implemented further within other technical domains, outside of the power and energy system, and in application of additional non-functional requirements, to better understand trends in design space exploration and the relationships between ilities of interest.

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, including interface to the Rapid Ship Design Environment (RSDE).

Lastly, the Navy has the opportunity to implement this design framework, including the P&E system flexibility metrics, within the current design and acquisition program for the next generation large surface combatant, DDG(X).

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Appendix A   Zone Load Evaluation Set Options

Element	Base Load MVAC (kW)	Base Load LVAC (kW)	Energy Magazine (kW)	Laser (kW)	Processing Equipment (kW)	Missile Launcher (kW)	Radar (kW)	EW (kW)	Sonar (kW)
Variant 1	500	1500	0	0	0	0	0	0	0
Variant 2		2000	200	600	200	400	1700	2000	450
Variant 3			1000	1200			3300	4000	
Variant 4			2000						

Permutation of PDSF evaluation load sets

N	PERMUTATIONS
1	500-1500-0-0-0-0-0-0-0
2	500-1500-0-0-0-0-0-0-450
3	500-1500-0-0-0-0-0-2000-0
4	500-1500-0-0-0-0-0-2000-450
5	500-1500-0-0-0-0-0-4000-0
6	500-1500-0-0-0-0-0-4000-450
7	500-1500-0-0-0-0-1700-0-0
8	500-1500-0-0-0-0-1700-0-450
9	500-1500-0-0-0-0-1700-2000-0
10	500-1500-0-0-0-0-1700-2000-450
11	500-1500-0-0-0-0-1700-4000-0
12	500-1500-0-0-0-0-1700-4000-450
13	500-1500-0-0-0-0-3300-0-0
14	500-1500-0-0-0-0-3300-0-450
15	500-1500-0-0-0-0-3300-2000-0
16	500-1500-0-0-0-0-3300-2000-450
17	500-1500-0-0-0-0-3300-4000-0
18	500-1500-0-0-0-0-3300-4000-450
19	500-1500-0-0-0-400-0-0-0
20	500-1500-0-0-0-400-0-0-450
21	500-1500-0-0-0-400-0-2000-0
22	500-1500-0-0-0-400-0-2000-450
23	500-1500-0-0-0-400-0-4000-0
24	500-1500-0-0-0-400-0-4000-450
25	500-1500-0-0-0-400-1700-0-0
26	500-1500-0-0-0-400-1700-0-450
27	500-1500-0-0-0-400-1700-2000-0
28	500-1500-0-0-0-400-1700-2000-450
29	500-1500-0-0-0-400-1700-4000-0
30	500-1500-0-0-0-400-1700-4000-450
31	500-1500-0-0-0-400-3300-0-0
32	500-1500-0-0-0-400-3300-0-450
33	500-1500-0-0-0-400-3300-2000-0
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35	500-1500-0-0-0-400-3300-4000-0
36	500-1500-0-0-0-400-3300-4000-450
37	500-1500-0-0-200-0-0-0-0
38	500-1500-0-0-200-0-0-0-450
39	500-1500-0-0-200-0-0-2000-0
40	500-1500-0-0-200-0-0-2000-450
41	500-1500-0-0-200-0-0-4000-0
42	500-1500-0-0-200-0-0-4000-450
43	500-1500-0-0-200-0-1700-0-0
44	500-1500-0-0-200-0-1700-0-450
45	500-1500-0-0-200-0-1700-2000-0
46	500-1500-0-0-200-0-1700-2000-450
47	500-1500-0-0-200-0-1700-4000-0
48	500-1500-0-0-200-0-1700-4000-450
49	500-1500-0-0-200-0-3300-0-0
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53	500-1500-0-0-200-0-3300-4000-0
54	500-1500-0-0-200-0-3300-4000-450
55	500-1500-0-0-200-400-0-0-0
56	500-1500-0-0-200-400-0-0-450
57	500-1500-0-0-200-400-0-2000-0
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59	500-1500-0-0-200-400-0-4000-0
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70	500-1500-0-0-200-400-3300-2000-450
71	500-1500-0-0-200-400-3300-4000-0
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73	500-1500-0-600-0-0-0-0-0
74	500-1500-0-600-0-0-0-0-450
75	500-1500-0-600-0-0-0-2000-0
76	500-1500-0-600-0-0-0-2000-450
77	500-1500-0-600-0-0-0-4000-0
78	500-1500-0-600-0-0-0-4000-450
79	500-1500-0-600-0-0-1700-0-0
80	500-1500-0-600-0-0-1700-0-450
81	500-1500-0-600-0-0-1700-2000-0
82	500-1500-0-600-0-0-1700-2000-450
83	500-1500-0-600-0-0-1700-4000-0

N	PERMUTATIONS
84	500-1500-0-600-0-0-1700-4000-450
85	500-1500-0-600-0-0-3300-0-0
86	500-1500-0-600-0-0-3300-0-450
87	500-1500-0-600-0-0-3300-2000-0
88	500-1500-0-600-0-0-3300-2000-450
89	500-1500-0-600-0-0-3300-4000-0
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91	500-1500-0-600-0-400-0-0-0
92	500-1500-0-600-0-400-0-0-450
93	500-1500-0-600-0-400-0-2000-0
94	500-1500-0-600-0-400-0-2000-450
95	500-1500-0-600-0-400-0-4000-0
96	500-1500-0-600-0-400-0-4000-450
97	500-1500-0-600-0-400-1700-0-0
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99	500-1500-0-600-0-400-1700-2000-0
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110	500-1500-0-600-200-0-0-0-450
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123	500-1500-0-600-200-0-3300-2000-0
124	500-1500-0-600-200-0-3300-2000-450
125	500-1500-0-600-200-0-3300-4000-0

N	PERMUTATIONS
126	500-1500-0-600-200-0-3300-4000-450
127	500-1500-0-600-200-400-0-0-0
128	500-1500-0-600-200-400-0-0-450
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145	500-1500-0-1200-0-0-0-0-0
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166	500-1500-0-1200-0-400-0-2000-450
167	500-1500-0-1200-0-400-0-4000-0

N	PERMUTATIONS
168	500-1500-0-1200-0-400-0-4000-450
169	500-1500-0-1200-0-400-1700-0-0
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202	500-1500-0-1200-200-400-0-2000-450
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209	500-1500-0-1200-200-400-1700-4000-0

N	PERMUTATIONS
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211	500-1500-0-1200-200-400-3300-0-0
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N	PERMUTATIONS
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N	PERMUTATIONS
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295	500-1500-200-600-0-0-1700-0-0
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N	PERMUTATIONS
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374	500-1500-200-1200-0-0-3300-0-450
375	500-1500-200-1200-0-0-3300-2000-0
376	500-1500-200-1200-0-0-3300-2000-450
377	500-1500-200-1200-0-0-3300-4000-0

N	PERMUTATIONS
378	500-1500-200-1200-0-0-3300-4000-450
379	500-1500-200-1200-0-400-0-0-0
380	500-1500-200-1200-0-400-0-0-450
381	500-1500-200-1200-0-400-0-2000-0
382	500-1500-200-1200-0-400-0-2000-450
383	500-1500-200-1200-0-400-0-4000-0
384	500-1500-200-1200-0-400-0-4000-450
385	500-1500-200-1200-0-400-1700-0-0
386	500-1500-200-1200-0-400-1700-0-450
387	500-1500-200-1200-0-400-1700-2000-0
388	500-1500-200-1200-0-400-1700-2000-450
389	500-1500-200-1200-0-400-1700-4000-0
390	500-1500-200-1200-0-400-1700-4000-450
391	500-1500-200-1200-0-400-3300-0-0
392	500-1500-200-1200-0-400-3300-0-450
393	500-1500-200-1200-0-400-3300-2000-0
394	500-1500-200-1200-0-400-3300-2000-450
395	500-1500-200-1200-0-400-3300-4000-0
396	500-1500-200-1200-0-400-3300-4000-450
397	500-1500-200-1200-200-0-0-0-0
398	500-1500-200-1200-200-0-0-0-450
399	500-1500-200-1200-200-0-0-2000-0
400	500-1500-200-1200-200-0-0-2000-450
401	500-1500-200-1200-200-0-0-4000-0
402	500-1500-200-1200-200-0-0-4000-450
403	500-1500-200-1200-200-0-1700-0-0
404	500-1500-200-1200-200-0-1700-0-450
405	500-1500-200-1200-200-0-1700-2000-0
406	500-1500-200-1200-200-0-1700-2000-450
407	500-1500-200-1200-200-0-1700-4000-0
408	500-1500-200-1200-200-0-1700-4000-450
409	500-1500-200-1200-200-0-3300-0-0
410	500-1500-200-1200-200-0-3300-0-450
411	500-1500-200-1200-200-0-3300-2000-0
412	500-1500-200-1200-200-0-3300-2000-450
413	500-1500-200-1200-200-0-3300-4000-0
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415	500-1500-200-1200-200-400-0-0-0
416	500-1500-200-1200-200-400-0-0-450
417	500-1500-200-1200-200-400-0-2000-0
418	500-1500-200-1200-200-400-0-2000-450
419	500-1500-200-1200-200-400-0-4000-0

N	PERMUTATIONS
420	500-1500-200-1200-200-400-0-4000-450
421	500-1500-200-1200-200-400-1700-0-0
422	500-1500-200-1200-200-400-1700-0-450
423	500-1500-200-1200-200-400-1700-2000-0
424	500-1500-200-1200-200-400-1700-2000-450
425	500-1500-200-1200-200-400-1700-4000-0
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427	500-1500-200-1200-200-400-3300-0-0
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429	500-1500-200-1200-200-400-3300-2000-0
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435	500-1500-1000-0-0-0-0-2000-0
436	500-1500-1000-0-0-0-0-2000-450
437	500-1500-1000-0-0-0-0-4000-0
438	500-1500-1000-0-0-0-0-4000-450
439	500-1500-1000-0-0-0-1700-0-0
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N	PERMUTATIONS
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469	500-1500-1000-0-200-0-0-0-0
470	500-1500-1000-0-200-0-0-0-450
471	500-1500-1000-0-200-0-0-2000-0
472	500-1500-1000-0-200-0-0-2000-450
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480	500-1500-1000-0-200-0-1700-4000-450
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N	PERMUTATIONS
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N	PERMUTATIONS
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587	500-1500-1000-1200-0-0-1700-4000-0

N	PERMUTATIONS
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604	500-1500-1000-1200-0-400-1700-2000-450
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614	500-1500-1000-1200-200-0-0-0-450
615	500-1500-1000-1200-200-0-0-2000-0
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617	500-1500-1000-1200-200-0-0-4000-0
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619	500-1500-1000-1200-200-0-1700-0-0
620	500-1500-1000-1200-200-0-1700-0-450
621	500-1500-1000-1200-200-0-1700-2000-0
622	500-1500-1000-1200-200-0-1700-2000-450
623	500-1500-1000-1200-200-0-1700-4000-0
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625	500-1500-1000-1200-200-0-3300-0-0
626	500-1500-1000-1200-200-0-3300-0-450
627	500-1500-1000-1200-200-0-3300-2000-0
628	500-1500-1000-1200-200-0-3300-2000-450
629	500-1500-1000-1200-200-0-3300-4000-0

N	PERMUTATIONS
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631	500-1500-1000-1200-200-400-0-0-0
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633	500-1500-1000-1200-200-400-0-2000-0
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662	500-1500-2000-0-0-0-3300-0-450
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668	500-1500-2000-0-0-400-0-0-450
669	500-1500-2000-0-0-400-0-2000-0
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671	500-1500-2000-0-0-400-0-4000-0

N	PERMUTATIONS
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700	500-1500-2000-0-200-0-3300-2000-450
701	500-1500-2000-0-200-0-3300-4000-0
702	500-1500-2000-0-200-0-3300-4000-450
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713	500-1500-2000-0-200-400-1700-4000-0

N	PERMUTATIONS
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717	500-1500-2000-0-200-400-3300-2000-0
718	500-1500-2000-0-200-400-3300-2000-450
719	500-1500-2000-0-200-400-3300-4000-0
720	500-1500-2000-0-200-400-3300-4000-450
721	500-1500-2000-600-0-0-0-0-0
722	500-1500-2000-600-0-0-0-0-450
723	500-1500-2000-600-0-0-0-2000-0
724	500-1500-2000-600-0-0-0-2000-450
725	500-1500-2000-600-0-0-0-4000-0
726	500-1500-2000-600-0-0-0-4000-450
727	500-1500-2000-600-0-0-1700-0-0
728	500-1500-2000-600-0-0-1700-0-450
729	500-1500-2000-600-0-0-1700-2000-0
730	500-1500-2000-600-0-0-1700-2000-450
731	500-1500-2000-600-0-0-1700-4000-0
732	500-1500-2000-600-0-0-1700-4000-450
733	500-1500-2000-600-0-0-3300-0-0
734	500-1500-2000-600-0-0-3300-0-450
735	500-1500-2000-600-0-0-3300-2000-0
736	500-1500-2000-600-0-0-3300-2000-450
737	500-1500-2000-600-0-0-3300-4000-0
738	500-1500-2000-600-0-0-3300-4000-450
739	500-1500-2000-600-0-400-0-0-0
740	500-1500-2000-600-0-400-0-0-450
741	500-1500-2000-600-0-400-0-2000-0
742	500-1500-2000-600-0-400-0-2000-450
743	500-1500-2000-600-0-400-0-4000-0
744	500-1500-2000-600-0-400-0-4000-450
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746	500-1500-2000-600-0-400-1700-0-450
747	500-1500-2000-600-0-400-1700-2000-0
748	500-1500-2000-600-0-400-1700-2000-450
749	500-1500-2000-600-0-400-1700-4000-0
750	500-1500-2000-600-0-400-1700-4000-450
751	500-1500-2000-600-0-400-3300-0-0
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755	500-1500-2000-600-0-400-3300-4000-0

N	PERMUTATIONS
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759	500-1500-2000-600-200-0-0-2000-0
760	500-1500-2000-600-200-0-0-2000-450
761	500-1500-2000-600-200-0-0-4000-0
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764	500-1500-2000-600-200-0-1700-0-450
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766	500-1500-2000-600-200-0-1700-2000-450
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769	500-1500-2000-600-200-0-3300-0-0
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815	500-1500-2000-1200-0-400-0-4000-0
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817	500-1500-2000-1200-0-400-1700-0-0
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836	500-1500-2000-1200-200-0-1700-0-450
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849	500-1500-2000-1200-200-400-0-2000-0
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864	500-1500-2000-1200-200-400-3300-4000-450
865	500-2000-0-0-0-0-0-0-0
866	500-2000-0-0-0-0-0-0-450
867	500-2000-0-0-0-0-0-2000-0
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869	500-2000-0-0-0-0-0-4000-0
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886	500-2000-0-0-0-400-0-2000-450
887	500-2000-0-0-0-400-0-4000-0
888	500-2000-0-0-0-400-0-4000-450
889	500-2000-0-0-0-400-1700-0-0
890	500-2000-0-0-0-400-1700-0-450
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892	500-2000-0-0-0-400-1700-2000-450
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898	500-2000-0-0-0-400-3300-2000-450
899	500-2000-0-0-0-400-3300-4000-0
900	500-2000-0-0-0-400-3300-4000-450
901	500-2000-0-0-200-0-0-0-0
902	500-2000-0-0-200-0-0-0-450
903	500-2000-0-0-200-0-0-2000-0
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905	500-2000-0-0-200-0-0-4000-0
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911	500-2000-0-0-200-0-1700-4000-0
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920	500-2000-0-0-200-400-0-0-450
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N	PERMUTATIONS
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928	500-2000-0-0-200-400-1700-2000-450
929	500-2000-0-0-200-400-1700-4000-0
930	500-2000-0-0-200-400-1700-4000-450
931	500-2000-0-0-200-400-3300-0-0
932	500-2000-0-0-200-400-3300-0-450
933	500-2000-0-0-200-400-3300-2000-0
934	500-2000-0-0-200-400-3300-2000-450
935	500-2000-0-0-200-400-3300-4000-0
936	500-2000-0-0-200-400-3300-4000-450
937	500-2000-0-600-0-0-0-0-0
938	500-2000-0-600-0-0-0-0-450
939	500-2000-0-600-0-0-0-2000-0
940	500-2000-0-600-0-0-0-2000-450
941	500-2000-0-600-0-0-0-4000-0
942	500-2000-0-600-0-0-0-4000-450
943	500-2000-0-600-0-0-1700-0-0
944	500-2000-0-600-0-0-1700-0-450
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949	500-2000-0-600-0-0-3300-0-0
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957	500-2000-0-600-0-400-0-2000-0
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959	500-2000-0-600-0-400-0-4000-0
960	500-2000-0-600-0-400-0-4000-450
961	500-2000-0-600-0-400-1700-0-0
962	500-2000-0-600-0-400-1700-0-450
963	500-2000-0-600-0-400-1700-2000-0
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N	PERMUTATIONS
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970	500-2000-0-600-0-400-3300-2000-450
971	500-2000-0-600-0-400-3300-4000-0
972	500-2000-0-600-0-400-3300-4000-450
973	500-2000-0-600-200-0-0-0-0
974	500-2000-0-600-200-0-0-0-450
975	500-2000-0-600-200-0-0-2000-0
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977	500-2000-0-600-200-0-0-4000-0
978	500-2000-0-600-200-0-0-4000-450
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980	500-2000-0-600-200-0-1700-0-450
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1001	500-2000-0-600-200-400-1700-4000-0
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1003	500-2000-0-600-200-400-3300-0-0
1004	500-2000-0-600-200-400-3300-0-450
1005	500-2000-0-600-200-400-3300-2000-0

N	PERMUTATIONS
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1007	500-2000-0-600-200-400-3300-4000-0
1008	500-2000-0-600-200-400-3300-4000-450
1009	500-2000-0-1200-0-0-0-0-0
1010	500-2000-0-1200-0-0-0-0-450
1011	500-2000-0-1200-0-0-0-2000-0
1012	500-2000-0-1200-0-0-0-2000-450
1013	500-2000-0-1200-0-0-0-4000-0
1014	500-2000-0-1200-0-0-0-4000-450
1015	500-2000-0-1200-0-0-1700-0-0
1016	500-2000-0-1200-0-0-1700-0-450
1017	500-2000-0-1200-0-0-1700-2000-0
1018	500-2000-0-1200-0-0-1700-2000-450
1019	500-2000-0-1200-0-0-1700-4000-0
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N	PERMUTATIONS
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1077	500-2000-0-1200-200-400-3300-2000-0
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1085	500-2000-200-0-0-0-0-4000-0

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1091	500-2000-200-0-0-0-1700-4000-0
1092	500-2000-200-0-0-0-1700-4000-450
1093	500-2000-200-0-0-0-3300-0-0
1094	500-2000-200-0-0-0-3300-0-450
1095	500-2000-200-0-0-0-3300-2000-0
1096	500-2000-200-0-0-0-3300-2000-450
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1100	500-2000-200-0-0-400-0-0-450
1101	500-2000-200-0-0-400-0-2000-0
1102	500-2000-200-0-0-400-0-2000-450
1103	500-2000-200-0-0-400-0-4000-0
1104	500-2000-200-0-0-400-0-4000-450
1105	500-2000-200-0-0-400-1700-0-0
1106	500-2000-200-0-0-400-1700-0-450
1107	500-2000-200-0-0-400-1700-2000-0
1108	500-2000-200-0-0-400-1700-2000-450
1109	500-2000-200-0-0-400-1700-4000-0
1110	500-2000-200-0-0-400-1700-4000-450
1111	500-2000-200-0-0-400-3300-0-0
1112	500-2000-200-0-0-400-3300-0-450
1113	500-2000-200-0-0-400-3300-2000-0
1114	500-2000-200-0-0-400-3300-2000-450
1115	500-2000-200-0-0-400-3300-4000-0
1116	500-2000-200-0-0-400-3300-4000-450
1117	500-2000-200-0-200-0-0-0-0
1118	500-2000-200-0-200-0-0-0-450
1119	500-2000-200-0-200-0-0-2000-0
1120	500-2000-200-0-200-0-0-2000-450
1121	500-2000-200-0-200-0-0-4000-0
1122	500-2000-200-0-200-0-0-4000-450
1123	500-2000-200-0-200-0-1700-0-0
1124	500-2000-200-0-200-0-1700-0-450
1125	500-2000-200-0-200-0-1700-2000-0

N	PERMUTATIONS
1126	500-2000-200-0-200-0-1700-2000-450
1127	500-2000-200-0-200-0-1700-4000-0
1128	500-2000-200-0-200-0-1700-4000-450
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1134	500-2000-200-0-200-0-3300-4000-450
1135	500-2000-200-0-200-400-0-0-0
1136	500-2000-200-0-200-400-0-0-450
1137	500-2000-200-0-200-400-0-2000-0
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1139	500-2000-200-0-200-400-0-4000-0
1140	500-2000-200-0-200-400-0-4000-450
1141	500-2000-200-0-200-400-1700-0-0
1142	500-2000-200-0-200-400-1700-0-450
1143	500-2000-200-0-200-400-1700-2000-0
1144	500-2000-200-0-200-400-1700-2000-450
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1152	500-2000-200-0-200-400-3300-4000-450
1153	500-2000-200-600-0-0-0-0-0
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1159	500-2000-200-600-0-0-1700-0-0
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1162	500-2000-200-600-0-0-1700-2000-450
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1165	500-2000-200-600-0-0-3300-0-0

N	PERMUTATIONS
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1167	500-2000-200-600-0-0-3300-2000-0
1168	500-2000-200-600-0-0-3300-2000-450
1169	500-2000-200-600-0-0-3300-4000-0
1170	500-2000-200-600-0-0-3300-4000-450
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1172	500-2000-200-600-0-400-0-0-450
1173	500-2000-200-600-0-400-0-2000-0
1174	500-2000-200-600-0-400-0-2000-450
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1177	500-2000-200-600-0-400-1700-0-0
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1197	500-2000-200-600-200-0-1700-2000-0
1198	500-2000-200-600-200-0-1700-2000-450
1199	500-2000-200-600-200-0-1700-4000-0
1200	500-2000-200-600-200-0-1700-4000-450
1201	500-2000-200-600-200-0-3300-0-0
1202	500-2000-200-600-200-0-3300-0-450
1203	500-2000-200-600-200-0-3300-2000-0
1204	500-2000-200-600-200-0-3300-2000-450
1205	500-2000-200-600-200-0-3300-4000-0

N	PERMUTATIONS
1206	500-2000-200-600-200-0-3300-4000-450
1207	500-2000-200-600-200-400-0-0-0
1208	500-2000-200-600-200-400-0-0-450
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1210	500-2000-200-600-200-400-0-2000-450
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1212	500-2000-200-600-200-400-0-4000-450
1213	500-2000-200-600-200-400-1700-0-0
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1234	500-2000-200-1200-0-0-1700-2000-450
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1252	500-2000-200-1200-0-400-1700-2000-450
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1254	500-2000-200-1200-0-400-1700-4000-450
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1292	500-2000-200-1200-200-400-3300-0-450
1293	500-2000-200-1200-200-400-3300-2000-0
1294	500-2000-200-1200-200-400-3300-2000-450
1295	500-2000-200-1200-200-400-3300-4000-0
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N	PERMUTATIONS
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1362	500-2000-1000-0-200-400-1700-4000-450
1363	500-2000-1000-0-200-400-3300-0-0
1364	500-2000-1000-0-200-400-3300-0-450
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1368	500-2000-1000-0-200-400-3300-4000-450
1369	500-2000-1000-600-0-0-0-0-0
1370	500-2000-1000-600-0-0-0-0-450
1371	500-2000-1000-600-0-0-0-2000-0
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N	PERMUTATIONS
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1445	500-2000-1000-1200-0-0-0-4000-0

N	PERMUTATIONS
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1464	500-2000-1000-1200-0-400-0-4000-450
1465	500-2000-1000-1200-0-400-1700-0-0
1466	500-2000-1000-1200-0-400-1700-0-450
1467	500-2000-1000-1200-0-400-1700-2000-0
1468	500-2000-1000-1200-0-400-1700-2000-450
1469	500-2000-1000-1200-0-400-1700-4000-0
1470	500-2000-1000-1200-0-400-1700-4000-450
1471	500-2000-1000-1200-0-400-3300-0-0
1472	500-2000-1000-1200-0-400-3300-0-450
1473	500-2000-1000-1200-0-400-3300-2000-0
1474	500-2000-1000-1200-0-400-3300-2000-450
1475	500-2000-1000-1200-0-400-3300-4000-0
1476	500-2000-1000-1200-0-400-3300-4000-450
1477	500-2000-1000-1200-200-0-0-0-0
1478	500-2000-1000-1200-200-0-0-0-450
1479	500-2000-1000-1200-200-0-0-2000-0
1480	500-2000-1000-1200-200-0-0-2000-450
1481	500-2000-1000-1200-200-0-0-4000-0
1482	500-2000-1000-1200-200-0-0-4000-450
1483	500-2000-1000-1200-200-0-1700-0-0
1484	500-2000-1000-1200-200-0-1700-0-450
1485	500-2000-1000-1200-200-0-1700-2000-0

N	PERMUTATIONS
1486	500-2000-1000-1200-200-0-1700-2000-450
1487	500-2000-1000-1200-200-0-1700-4000-0
1488	500-2000-1000-1200-200-0-1700-4000-450
1489	500-2000-1000-1200-200-0-3300-0-0
1490	500-2000-1000-1200-200-0-3300-0-450
1491	500-2000-1000-1200-200-0-3300-2000-0
1492	500-2000-1000-1200-200-0-3300-2000-450
1493	500-2000-1000-1200-200-0-3300-4000-0
1494	500-2000-1000-1200-200-0-3300-4000-450
1495	500-2000-1000-1200-200-400-0-0-0
1496	500-2000-1000-1200-200-400-0-0-450
1497	500-2000-1000-1200-200-400-0-2000-0
1498	500-2000-1000-1200-200-400-0-2000-450
1499	500-2000-1000-1200-200-400-0-4000-0
1500	500-2000-1000-1200-200-400-0-4000-450
1501	500-2000-1000-1200-200-400-1700-0-0
1502	500-2000-1000-1200-200-400-1700-0-450
1503	500-2000-1000-1200-200-400-1700-2000-0
1504	500-2000-1000-1200-200-400-1700-2000-450
1505	500-2000-1000-1200-200-400-1700-4000-0
1506	500-2000-1000-1200-200-400-1700-4000-450
1507	500-2000-1000-1200-200-400-3300-0-0
1508	500-2000-1000-1200-200-400-3300-0-450
1509	500-2000-1000-1200-200-400-3300-2000-0
1510	500-2000-1000-1200-200-400-3300-2000-450
1511	500-2000-1000-1200-200-400-3300-4000-0
1512	500-2000-1000-1200-200-400-3300-4000-450
1513	500-2000-2000-0-0-0-0-0-0
1514	500-2000-2000-0-0-0-0-0-450
1515	500-2000-2000-0-0-0-0-2000-0
1516	500-2000-2000-0-0-0-0-2000-450
1517	500-2000-2000-0-0-0-0-4000-0
1518	500-2000-2000-0-0-0-0-4000-450
1519	500-2000-2000-0-0-0-1700-0-0
1520	500-2000-2000-0-0-0-1700-0-450
1521	500-2000-2000-0-0-0-1700-2000-0
1522	500-2000-2000-0-0-0-1700-2000-450
1523	500-2000-2000-0-0-0-1700-4000-0
1524	500-2000-2000-0-0-0-1700-4000-450
1525	500-2000-2000-0-0-0-3300-0-0

N	PERMUTATIONS
1526	500-2000-2000-0-0-0-3300-0-450
1527	500-2000-2000-0-0-0-3300-2000-0
1528	500-2000-2000-0-0-0-3300-2000-450
1529	500-2000-2000-0-0-0-3300-4000-0
1530	500-2000-2000-0-0-0-3300-4000-450
1531	500-2000-2000-0-0-400-0-0-0
1532	500-2000-2000-0-0-400-0-0-450
1533	500-2000-2000-0-0-400-0-2000-0
1534	500-2000-2000-0-0-400-0-2000-450
1535	500-2000-2000-0-0-400-0-4000-0
1536	500-2000-2000-0-0-400-0-4000-450
1537	500-2000-2000-0-0-400-1700-0-0
1538	500-2000-2000-0-0-400-1700-0-450
1539	500-2000-2000-0-0-400-1700-2000-0
1540	500-2000-2000-0-0-400-1700-2000-450
1541	500-2000-2000-0-0-400-1700-4000-0
1542	500-2000-2000-0-0-400-1700-4000-450
1543	500-2000-2000-0-0-400-3300-0-0
1544	500-2000-2000-0-0-400-3300-0-450
1545	500-2000-2000-0-0-400-3300-2000-0
1546	500-2000-2000-0-0-400-3300-2000-450
1547	500-2000-2000-0-0-400-3300-4000-0
1548	500-2000-2000-0-0-400-3300-4000-450
1549	500-2000-2000-0-200-0-0-0-0
1550	500-2000-2000-0-200-0-0-0-450
1551	500-2000-2000-0-200-0-0-2000-0
1552	500-2000-2000-0-200-0-0-2000-450
1553	500-2000-2000-0-200-0-0-4000-0
1554	500-2000-2000-0-200-0-0-4000-450
1555	500-2000-2000-0-200-0-1700-0-0
1556	500-2000-2000-0-200-0-1700-0-450
1557	500-2000-2000-0-200-0-1700-2000-0
1558	500-2000-2000-0-200-0-1700-2000-450
1559	500-2000-2000-0-200-0-1700-4000-0
1560	500-2000-2000-0-200-0-1700-4000-450
1561	500-2000-2000-0-200-0-3300-0-0
1562	500-2000-2000-0-200-0-3300-0-450
1563	500-2000-2000-0-200-0-3300-2000-0
1564	500-2000-2000-0-200-0-3300-2000-450
1565	500-2000-2000-0-200-0-3300-4000-0

N	PERMUTATIONS
1566	500-2000-2000-0-200-0-3300-4000-450
1567	500-2000-2000-0-200-400-0-0-0
1568	500-2000-2000-0-200-400-0-0-450
1569	500-2000-2000-0-200-400-0-2000-0
1570	500-2000-2000-0-200-400-0-2000-450
1571	500-2000-2000-0-200-400-0-4000-0
1572	500-2000-2000-0-200-400-0-4000-450
1573	500-2000-2000-0-200-400-1700-0-0
1574	500-2000-2000-0-200-400-1700-0-450
1575	500-2000-2000-0-200-400-1700-2000-0
1576	500-2000-2000-0-200-400-1700-2000-450
1577	500-2000-2000-0-200-400-1700-4000-0
1578	500-2000-2000-0-200-400-1700-4000-450
1579	500-2000-2000-0-200-400-3300-0-0
1580	500-2000-2000-0-200-400-3300-0-450
1581	500-2000-2000-0-200-400-3300-2000-0
1582	500-2000-2000-0-200-400-3300-2000-450
1583	500-2000-2000-0-200-400-3300-4000-0
1584	500-2000-2000-0-200-400-3300-4000-450
1585	500-2000-2000-600-0-0-0-0-0
1586	500-2000-2000-600-0-0-0-0-450
1587	500-2000-2000-600-0-0-0-2000-0
1588	500-2000-2000-600-0-0-0-2000-450
1589	500-2000-2000-600-0-0-0-4000-0
1590	500-2000-2000-600-0-0-0-4000-450
1591	500-2000-2000-600-0-0-1700-0-0
1592	500-2000-2000-600-0-0-1700-0-450
1593	500-2000-2000-600-0-0-1700-2000-0
1594	500-2000-2000-600-0-0-1700-2000-450
1595	500-2000-2000-600-0-0-1700-4000-0
1596	500-2000-2000-600-0-0-1700-4000-450
1597	500-2000-2000-600-0-0-3300-0-0
1598	500-2000-2000-600-0-0-3300-0-450
1599	500-2000-2000-600-0-0-3300-2000-0
1600	500-2000-2000-600-0-0-3300-2000-450
1601	500-2000-2000-600-0-0-3300-4000-0
1602	500-2000-2000-600-0-0-3300-4000-450
1603	500-2000-2000-600-0-400-0-0-0
1604	500-2000-2000-600-0-400-0-0-450
1605	500-2000-2000-600-0-400-0-2000-0

N	PERMUTATIONS
1606	500-2000-2000-600-0-400-0-2000-450
1607	500-2000-2000-600-0-400-0-4000-0
1608	500-2000-2000-600-0-400-0-4000-450
1609	500-2000-2000-600-0-400-1700-0-0
1610	500-2000-2000-600-0-400-1700-0-450
1611	500-2000-2000-600-0-400-1700-2000-0
1612	500-2000-2000-600-0-400-1700-2000-450
1613	500-2000-2000-600-0-400-1700-4000-0
1614	500-2000-2000-600-0-400-1700-4000-450
1615	500-2000-2000-600-0-400-3300-0-0
1616	500-2000-2000-600-0-400-3300-0-450
1617	500-2000-2000-600-0-400-3300-2000-0
1618	500-2000-2000-600-0-400-3300-2000-450
1619	500-2000-2000-600-0-400-3300-4000-0
1620	500-2000-2000-600-0-400-3300-4000-450
1621	500-2000-2000-600-200-0-0-0-0
1622	500-2000-2000-600-200-0-0-0-450
1623	500-2000-2000-600-200-0-0-2000-0
1624	500-2000-2000-600-200-0-0-2000-450
1625	500-2000-2000-600-200-0-0-4000-0
1626	500-2000-2000-600-200-0-0-4000-450
1627	500-2000-2000-600-200-0-1700-0-0
1628	500-2000-2000-600-200-0-1700-0-450
1629	500-2000-2000-600-200-0-1700-2000-0
1630	500-2000-2000-600-200-0-1700-2000-450
1631	500-2000-2000-600-200-0-1700-4000-0
1632	500-2000-2000-600-200-0-1700-4000-450
1633	500-2000-2000-600-200-0-3300-0-0
1634	500-2000-2000-600-200-0-3300-0-450
1635	500-2000-2000-600-200-0-3300-2000-0
1636	500-2000-2000-600-200-0-3300-2000-450
1637	500-2000-2000-600-200-0-3300-4000-0
1638	500-2000-2000-600-200-0-3300-4000-450
1639	500-2000-2000-600-200-400-0-0-0
1640	500-2000-2000-600-200-400-0-0-450
1641	500-2000-2000-600-200-400-0-2000-0
1642	500-2000-2000-600-200-400-0-2000-450
1643	500-2000-2000-600-200-400-0-4000-0
1644	500-2000-2000-600-200-400-0-4000-450
1645	500-2000-2000-600-200-400-1700-0-0

N	PERMUTATIONS
1646	500-2000-2000-600-200-400-1700-0-450
1647	500-2000-2000-600-200-400-1700-2000-0
1648	500-2000-2000-600-200-400-1700-2000-450
1649	500-2000-2000-600-200-400-1700-4000-0
1650	500-2000-2000-600-200-400-1700-4000-450
1651	500-2000-2000-600-200-400-3300-0-0
1652	500-2000-2000-600-200-400-3300-0-450
1653	500-2000-2000-600-200-400-3300-2000-0
1654	500-2000-2000-600-200-400-3300-2000-450
1655	500-2000-2000-600-200-400-3300-4000-0
1656	500-2000-2000-600-200-400-3300-4000-450
1657	500-2000-2000-1200-0-0-0-0-0
1658	500-2000-2000-1200-0-0-0-0-450
1659	500-2000-2000-1200-0-0-0-2000-0
1660	500-2000-2000-1200-0-0-0-2000-450
1661	500-2000-2000-1200-0-0-0-4000-0
1662	500-2000-2000-1200-0-0-0-4000-450
1663	500-2000-2000-1200-0-0-1700-0-0
1664	500-2000-2000-1200-0-0-1700-0-450
1665	500-2000-2000-1200-0-0-1700-2000-0
1666	500-2000-2000-1200-0-0-1700-2000-450
1667	500-2000-2000-1200-0-0-1700-4000-0
1668	500-2000-2000-1200-0-0-1700-4000-450
1669	500-2000-2000-1200-0-0-3300-0-0
1670	500-2000-2000-1200-0-0-3300-0-450
1671	500-2000-2000-1200-0-0-3300-2000-0
1672	500-2000-2000-1200-0-0-3300-2000-450
1673	500-2000-2000-1200-0-0-3300-4000-0
1674	500-2000-2000-1200-0-0-3300-4000-450
1675	500-2000-2000-1200-0-400-0-0-0
1676	500-2000-2000-1200-0-400-0-0-450
1677	500-2000-2000-1200-0-400-0-2000-0
1678	500-2000-2000-1200-0-400-0-2000-450
1679	500-2000-2000-1200-0-400-0-4000-0
1680	500-2000-2000-1200-0-400-0-4000-450
1681	500-2000-2000-1200-0-400-1700-0-0
1682	500-2000-2000-1200-0-400-1700-0-450
1683	500-2000-2000-1200-0-400-1700-2000-0
1684	500-2000-2000-1200-0-400-1700-2000-450
1685	500-2000-2000-1200-0-400-1700-4000-0

N	PERMUTATIONS
1686	500-2000-2000-1200-0-400-1700-4000-450
1687	500-2000-2000-1200-0-400-3300-0-0
1688	500-2000-2000-1200-0-400-3300-0-450
1689	500-2000-2000-1200-0-400-3300-2000-0
1690	500-2000-2000-1200-0-400-3300-2000-450
1691	500-2000-2000-1200-0-400-3300-4000-0
1692	500-2000-2000-1200-0-400-3300-4000-450
1693	500-2000-2000-1200-200-0-0-0-0
1694	500-2000-2000-1200-200-0-0-0-450
1695	500-2000-2000-1200-200-0-0-2000-0
1696	500-2000-2000-1200-200-0-0-2000-450
1697	500-2000-2000-1200-200-0-0-4000-0
1698	500-2000-2000-1200-200-0-0-4000-450
1699	500-2000-2000-1200-200-0-1700-0-0
1700	500-2000-2000-1200-200-0-1700-0-450
1701	500-2000-2000-1200-200-0-1700-2000-0
1702	500-2000-2000-1200-200-0-1700-2000-450
1703	500-2000-2000-1200-200-0-1700-4000-0
1704	500-2000-2000-1200-200-0-1700-4000-450
1705	500-2000-2000-1200-200-0-3300-0-0
1706	500-2000-2000-1200-200-0-3300-0-450
1707	500-2000-2000-1200-200-0-3300-2000-0
1708	500-2000-2000-1200-200-0-3300-2000-450
1709	500-2000-2000-1200-200-0-3300-4000-0
1710	500-2000-2000-1200-200-0-3300-4000-450
1711	500-2000-2000-1200-200-400-0-0-0
1712	500-2000-2000-1200-200-400-0-0-450
1713	500-2000-2000-1200-200-400-0-2000-0
1714	500-2000-2000-1200-200-400-0-2000-450
1715	500-2000-2000-1200-200-400-0-4000-0
1716	500-2000-2000-1200-200-400-0-4000-450
1717	500-2000-2000-1200-200-400-1700-0-0
1718	500-2000-2000-1200-200-400-1700-0-450
1719	500-2000-2000-1200-200-400-1700-2000-0
1720	500-2000-2000-1200-200-400-1700-2000-450
1721	500-2000-2000-1200-200-400-1700-4000-0
1722	500-2000-2000-1200-200-400-1700-4000-450
1723	500-2000-2000-1200-200-400-3300-0-0
1724	500-2000-2000-1200-200-400-3300-0-450
1725	500-2000-2000-1200-200-400-3300-2000-0

N	PERMUTATIONS
1726	500-2000-2000-1200-200-400-3300-2000-450
1727	500-2000-2000-1200-200-400-3300-4000-0
1728	500-2000-2000-1200-200-400-3300-4000-450

Appendix B Notional Energy Storage System Design Space

Design Alt	Bus Capacity (kW)	Energy Storage Capacity (kWh)	Peak ESS Power (kW)
1	200	1	1,000
2	200	1	1,600
3	200	1	2,200
4	200	1	3,000
5	200	1	3,200
6	200	10	1,000
7	200	10	1,600
8	200	10	2,200
9	200	10	3,000
10	200	10	3,200
11	200	100	1,000
12	200	100	1,600
13	200	100	2,200
14	200	100	3,000
15	200	100	3,200
16	200	250	1,000
17	200	250	1,600
18	200	250	2,200
19	200	250	3,000
20	200	250	3,200
21	200	300	1,000
22	200	300	1,600
23	200	300	2,200
24	200	300	3,000
25	200	300	3,200
26	2000	1	1,000
27	2000	1	1,600
28	2000	1	2,200
29	2000	1	3,000
30	2000	1	3,200
31	2000	10	1,000
32	2000	10	1,600
33	2000	10	2,200
34	2000	10	3,000
35	2000	10	3,200
36	2000	100	1,000
37	2000	100	1,600
38	2000	100	2,200
39	2000	100	3,000
40	2000	100	3,200
41	2000	250	1,000
42	2000	250	1,600
43	2000	250	2,200
44	2000	250	3,000
45	2000	250	3,200
46	2000	300	1,000
47	2000	300	1,600
48	2000	300	2,200
49	2000	300	3,000
50	2000	300	3,200
51	3250	1	1,000
52	3250	1	1,600
53	3250	1	2,200
54	3250	1	3,000
55	3250	1	3,200
56	3250	10	1,000
57	3250	10	1,600
58	3250	10	2,200
59	3250	10	3,000
60	3250	10	3,200
61	3250	100	1,000
62	3250	100	1,600
63	3250	100	2,200
64	3250	100	3,000
65	3250	100	3,200
66	3250	250	1,000
67	3250	250	1,600
68	3250	250	2,200
69	3250	250	3,000
70	3250	250	3,200
71	3250	300	1,000
72	3250	300	1,600
73	3250	300	2,200
74	3250	300	3,000
75	3250	300	3,200
76	4500	1	1,000
77	4500	1	1,600
78	4500	1	2,200
79	4500	1	3,000
80	4500	1	3,200
81	4500	10	1,000
82	4500	10	1,600
83	4500	10	2,200
84	4500	10	3,000
85	4500	10	3,200

86	4500	100	1,000
87	4500	100	1,600
88	4500	100	2,200
89	4500	100	3,000
90	4500	100	3,200
91	4500	250	1,000
92	4500	250	1,600
93	4500	250	2,200
94	4500	250	3,000
95	4500	250	3,200
96	4500	300	1,000
97	4500	300	1,600
98	4500	300	2,200
99	4500	300	3,000
100	4500	300	3,200
101	5000	1	1,000
102	5000	1	1,600
103	5000	1	2,200
104	5000	1	3,000
105	5000	1	3,200
106	5000	10	1,000
107	5000	10	1,600
108	5000	10	2,200
109	5000	10	3,000
110	5000	10	3,200
111	5000	100	1,000
112	5000	100	1,600
113	5000	100	2,200
114	5000	100	3,000
115	5000	100	3,200
116	5000	250	1,000
117	5000	250	1,600
118	5000	250	2,200
119	5000	250	3,000
120	5000	250	3,200
121	5000	300	1,000
122	5000	300	1,600
123	5000	300	2,200
124	5000	300	3,000
125	5000	300	3,200

Appendix C Energy Storage System Flexibility Evaluation MATLAB Code

(Tavagnutti, Chalfant, Chryssostomidis, & Hernandez, 2023)

```
%% Mission Demand Profiles
clear all; clc; close all
%% simulation settings
maxk = 10;      % number of trials

plotOn = 1;       % 1 to show plots, 0 no plots
plotTrials = 1;   % 1 to show comparison bar charts for trials (maximum energy)
plotTrialsMin = 0; % 1 to show comparison bar charts for trials (minimum energy)
runRadar = 1;     % 1 to run sensor, 0 skip
runEW = 1;        % 1 to run EW, 0 to skip
runLaser = 1;     % 1 to run Laser, 0 to skip



% POWER LEVELS AND TIMES
maxPowerRadar_kW = 1000*3;   %max power Radar (peak of sine plus noise) [kW]

maxPowerEW_kW = 1500*2;      %max power EW [kW]
minPowerEW_kW = 400*2;       %min power EW [kW]

maxPowerLaser_kW=1200;     %max power laser when firing [kW]
minPowerLaser_kW=200;      %min power laser when in operational mode but not firing (standby) [kW]
tLaser_off=30;             %laser maximum time off [s]
tLaser_on=6;               %laser maximum time on [s]



% SIMULATION TIME AND TIME STEPS

maxTime = 70*60;        %total time of operational scenario, in seconds
maxTimeLaser = 30*60;   %total time Laser in use, in seconds (laser recharge time = maxTime - maxTimeLaser)
if(maxTimeLaser > maxTime), disp("maxTimeLaser must be less than MaxTime"); return; end

% set and check time steps
timeStepRadar = 0.01;  %s
timeStepMultipleRadar = 1;
if (mod(maxTime,timeStepRadar)) ~= 0, disp("Radar Time Step not evenly divisible into maxTime"); return; end

timeStepEW = 0.05;  %s
timeStepMultipleEW = 5;
if (mod(maxTime,timeStepEW)) ~= 0, disp("EW Time Step not evenly divisible into maxTime"); return; end

timeStepLaser = 1;
```

```
timeStepMultipleLaser = 100;
if (mod(maxTimeLaser,timeStepLaser)) ~= 0, disp("Laser Time Step not evenly divisible into maxTimeLaser"); return; end

%check time step multiples
if (abs(timeStepEW/timeStepMultipleEW - timeStepRadar/timeStepMultipleRadar) > .0000001)
   disp("time step multiples incorrect EW/Radar"); return;
end
if (abs(timeStepEW/timeStepMultipleEW - timeStepLaser/timeStepMultipleLaser) > .0000001)
   disp("time step multiples incorrect EW/Radar"); return;
end

comboTimeStep = min(timeStepLaser,min(timeStepRadar,timeStepEW));

%% Set up for multiple trials

if runRadar
   mxRadar = zeros(maxk,1);
   mnRadar = mxRadar;
   genSetPowerRadar_kW = zeros(maxk,1);
   maxBattPowerRadar_kW = zeros(maxk,1);
end

if runEW
   genSetPowerEW_kW = zeros(maxk,1);
   maxBattPowerEW_kW = zeros(maxk,1);
   mxEW_kW_hr = zeros(maxk,1);
   mnEW_kW_hr = mxEW_kW_hr;
end

if runLaser
   mxLaser_kW_hr = zeros(maxk,1);
   mnLaser_kW_hr = mxLaser_kW_hr;
end


mxCombo_kW_hr = zeros(maxk,1);
mnCombo_kW_hr = mxCombo_kW_hr;


xRadar = timeStepRadar:timeStepRadar:maxTime;
battPowerRadar_kW = zeros(length(xRadar),1);
xEW = timeStepEW:timeStepEW:maxTime;
battPowerEW_kW = zeros(length(xEW),1);
xLaser = timeStepLaser:timeStepLaser:maxTime;
```

```
battPowerLaser_kW = zeros(length(xLaser),1);

for k=1:maxk

    %% Sensor Demand
    % default: assuming sine wave + noise.

    if runRadar

        % underlying sine wave for radar power
        powerRadar = 1/5*sin(4*pi*xRadar) + 0.8;

        % add noise
        noiseHeightRadar = .2;
        noiseRadar = noiseHeightRadar*(-0.5 + rand(1, length(powerRadar)));
        noisyPowerRadar = (powerRadar + noiseRadar)';
        powerProfileRadar_kW = noisyPowerRadar*maxPowerRadar_kW/max(noisyPowerRadar);
        clear noisyPowerRadar noiseRadar;

        genSetPowerRadar_kW(k) = mean(powerProfileRadar_kW);
        battPowerRadar_kW = powerProfileRadar_kW-genSetPowerRadar_kW(k);

        if plotOn
            % figure()
            % plot(xRadar, battPowerRadar_kW)
            % xlim([0,maxTime])
            % xlabel("Time [s]")
            % ylabel("Radar Battery Power [kW]")
            % title ('Radar Battery Power')
            figure()
            plot(xRadar, battPowerRadar_kW)
            xlim([100,115])
            xlabel("Time [s]")
            ylabel("Radar Battery Power [kW]")
            title('Radar Battery Power Snapshot')
        end

        maxBattPowerRadar_kW(k) = max(battPowerRadar_kW(k));
        energyRadar_kW_s = timeStepRadar*battPowerRadar_kW;
        for iter = 2:length(battPowerRadar_kW)
            energyRadar_kW_s(iter) = energyRadar_kW_s(iter-1) + energyRadar_kW_s(iter);
        end

        if plotOn
```

```
        figure()
        plot(xRadar, powerProfileRadar_kW)
        hold on
        plot(xRadar, energyRadar_kW_s)
        hold off
        xlim([0,maxTime])
        legend("Radar Power [kw]", "Radar Energy [kW-s]")
        title ("Radar Power and Energy")
        xlabel("Time [s]")
        ylabel("Power [kW] and Energy [kW-s]")
    end

    mxRadar(k) = max(energyRadar_kW_s)/3600;
    mnRadar(k) = min(energyRadar_kW_s)/3600;
end

%% EW Demand
% default: assuming step functions of regular durations

if runEW
    powerProfileEW_kW = (minPowerEW_kW + (maxPowerEW_kW - minPowerEW_kW)*rand(1, length(xEW)))';

    genSetPowerEW_kW(k) = mean(powerProfileEW_kW);
    battPowerEW_kW = powerProfileEW_kW-genSetPowerEW_kW(k);

    maxBattPowerEW_kW(k) = max(battPowerEW_kW);
    energyEW_kW_s = timeStepEW*battPowerEW_kW;
    for iter = 2:length(battPowerEW_kW)
        energyEW_kW_s(iter) = energyEW_kW_s(iter-1) + energyEW_kW_s(iter);
    end

    mxEW_kW_hr(k) = max(energyEW_kW_s)/3600;
    mnEW_kW_hr(k) = min(energyEW_kW_s)/3600;

    if plotOn
        ministep = .001; %#ok<*UNRCH>
        xa = zeros(1,2*length(xEW));
        xa(1:2:end) = xEW-ministep;
        xa(2:2:end) = xEW;
        xa = [xa(2:end) xa(end) + timeStepEW - ministep];
        ppEW(1:2:length(xa)) = powerProfileEW_kW;
        ppEW(2:2:length(xa)) = powerProfileEW_kW;

        % figure()
```

```
        % plot(xa, ppEW)
        % xlim([0,maxTime])
        % ylim([0,maxPowerEW_kW])
        % xlabel("Time [s]")
        % ylabel("EW Power [kW]")
        % title('EW Power')

        % figure()
        % plot(xa, ppEW-genSetPowerEW_kW)
        % xlim([0,maxTime])
        % xlabel("time (s)")
        % ylabel("EW Battery Power (kW)")
        % title("EW Battery Power")

        figure()
        plot(xa, ppEW-genSetPowerEW_kW)
        xlim([101,105])
        xlabel("time (s)")
        ylabel("EW Battery Power (kW)")
        title("EW Battery Power Snapshot")

        figure()
        plot(xa, ppEW)
        hold on
        plot(xEW, energyEW_kW_s)
        hold off
        xlim([0,maxTime])
        legend("EW Power [kW]", "EW Energy [kW-s]")
        xlabel('Time [s]')
        ylabel("Power [kW] and Energy [kW-s]")
        title('EW Power and Energy')

        clear xa ppEW
    end
end

%% Laser Demand
% assume gen is set to min power laser while laser is in operational mode

if runLaser

    maxStep = maxTimeLaser/timeStepLaser;          %max number of time steps
    onStepMax = floor(tLaser_on/timeStepLaser);    %max number of time steps firing
    offStepMax = floor(tLaser_off/timeStepLaser);  %max number of time steps in standby
```

```
% Loop to create the profile
powerProfileLaser_kW=minPowerLaser_kW*ones(maxStep,1);   % set all time steps to standby power
step_tot=1;
while step_tot<maxStep
   step_tot=step_tot+randi(offStepMax);
   if step_tot>maxStep; break; end
   powerProfileLaser_kW(step_tot:end, 1) = maxPowerLaser_kW;

   step_tot=step_tot+randi(onStepMax);
   if step_tot>maxStep; break; end
   powerProfileLaser_kW(step_tot:end, 1) = minPowerLaser_kW;
end

timeLaserOn(k)= sum(powerProfileLaser_kW(:) == 1200); %add lasing time count

clear onStepMax offStepMax;

maxBatteryEnergyLaser = (maxPowerLaser_kW-minPowerLaser_kW)*length(find(powerProfileLaser_kW>minPowerLaser_kW));
laserRechargeRate_kW = maxBatteryEnergyLaser/((maxTime-maxTimeLaser)/timeStepLaser);

battPowerLaser_kW = -1*laserRechargeRate_kW*ones(maxTime/timeStepLaser,1);
battPowerLaser_kW(1:length(powerProfileLaser_kW)) = powerProfileLaser_kW-minPowerLaser_kW;

energyLaser_kW_s = timeStepLaser*battPowerLaser_kW;
for iter = 2:length(battPowerLaser_kW)
   energyLaser_kW_s(iter) = energyLaser_kW_s(iter-1) + energyLaser_kW_s(iter);
end

mxLaser_kW_hr(k) = max(energyLaser_kW_s)/3600;
mnLaser_kW_hr(k) = min(energyLaser_kW_s)/3600;


if plotOn
   figure()
   x = timeStepLaser:timeStepLaser:maxTimeLaser;
   ministep = .001;
   xa = zeros(1,2*length(x));
   xa(1:2:end) = x-ministep;
   xa(2:2:end) = x;
   xa = [xa(2:end) xa(end) + timeStepLaser - ministep];
   ppLaser_kW(1:2:length(xa)) = powerProfileLaser_kW;
   ppLaser_kW(2:2:length(xa)) = powerProfileLaser_kW;
   yyaxis left
```

```
        plot(xa, ppLaser_kW)
        ylim([0,1700])
        ylabel('Laser Power [kW]')
        yyaxis right
        plot(1:maxTime/timeStepLaser,energyLaser_kW_s)
        ylabel('Laser Energy [kW-s]')
        title("Laser Power and Energy")
        xlabel('Time [s]')
        xlim([0, maxTime])

        figure()
        plot(xa, ppLaser_kW)
        xlim([0,100])
        ylim([0,1700])
        xlabel('time (s)')
        ylabel('Laser Power [kW]')
        title("Laser Power Snapshot")

        figure()
        x = timeStepLaser:timeStepLaser:maxTime;
        plot(x,energyLaser_kW_s/3600)
        xlim([0, maxTime])
        title("Laser Energy")
        xlabel("Time [s]")
        ylabel("Laser Energy [kW-hr]")

        clear ministep xa;

    end
end


%%  Combine

xCombo = comboTimeStep:comboTimeStep:maxTime;

comboRadar = zeros(length(xCombo),1);
for iter = 1:timeStepMultipleRadar
    comboRadar(iter:timeStepMultipleRadar:end,1) = battPowerRadar_kW;
end

%added these 2 lines
comboRadarAvg = ([0;comboRadar]+[comboRadar;0])/2;
comboRadarAvg = comboRadarAvg(1:end-1);
```

```
comboEW = zeros(length(xCombo),1);
for iter = 1:timeStepMultipleEW
    comboEW(iter:timeStepMultipleEW:end,1) = battPowerEW_kW;
end

comboLaser = zeros(length(xCombo),1);
for iter = 1:timeStepMultipleLaser
    comboLaser(iter:timeStepMultipleLaser:end,1) = battPowerLaser_kW;
end

%changed this to include comboRadarAvg instead of comboRadar
comboPower_kW = comboRadarAvg + comboEW + comboLaser;
mxcombopower_kW(k)=max(comboPower_kW);

comboEnergy_kW_s = comboTimeStep*comboPower_kW;
for iter = 2:length(comboPower_kW)
    comboEnergy_kW_s(iter) = comboEnergy_kW_s(iter-1) + comboEnergy_kW_s(iter);
end

mxCombo_kW_hr(k) = max(comboEnergy_kW_s)/3600;
mnCombo_kW_hr(k) = min(comboEnergy_kW_s)/3600;

if plotOn
    figure()
    plot(xCombo, comboPower_kW)
    title("Combined Power Profile")
    xlabel("Time [s]")
    ylabel("Combined Battery Power [kW]")

    figure()
    plot(xCombo, comboPower_kW)
    xlim([0,100])
    title("Combined Power Profile Snapshot")
    xlabel("Time [s]")
    ylabel("Combined Battery Power [kW]")

    figure()
    plot(xCombo, comboPower_kW)
    xlim([200,210])
    title("Combined Power Profile Snapshot 2")
    xlabel("Time [s]")
```

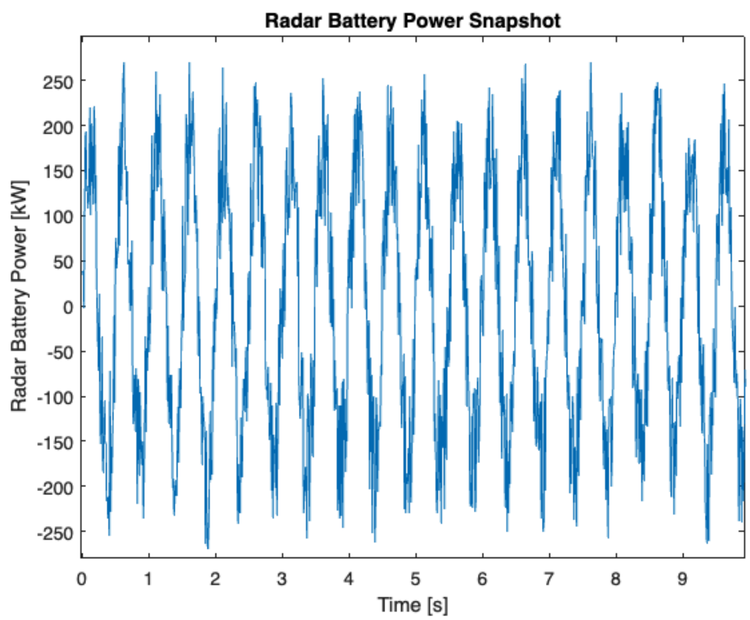
```
        ylabel("Combined Battery Power [kW]")

        figure()
        plot(xCombo, comboPower_kW)
        hold on
        plot(xCombo, comboEnergy_kW_s/3600)
        hold off
        xlim([0,maxTime])
        legend("Power [kW]", 'Energy [kW-hr]')
        xlabel("Time [s]");
        ylabel("Power [kW] and Energy [kW-hr]")
        title('Combined Power and Energy')
    end
end


%% wrap up trial plotting

if plotTrials
    if runRadar
        figure()
        bar(1:maxk,mxRadar)
        xlabel('Trial Number')
        ylabel('Maximum Radar Energy [kW-hr]')
        title("Maximum Radar Energy over Several Trials")
    end

    if runEW
        figure()
        bar(1:maxk, mxEW_kW_hr)
        xlabel('Trial Number')
        ylabel("Max EW Energy [kW-hr]")
        title("Maximum EW Energy over Several Trials")
    end

    if runLaser
        figure()
        bar(1:maxk, mxLaser_kW_hr)
        xlabel('Trial Number')
        ylabel("Max Laser Energy [kW-hr]")
        title("Maximum Laser Energy over Several Trials")
    end

    figure()
```

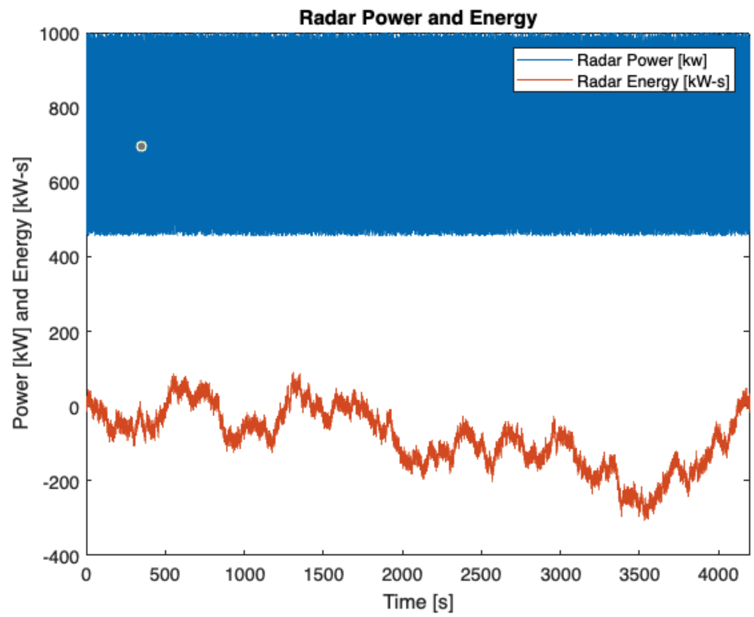
```
  bar(1:maxk, mxCombo_kW_hr)
  xlabel('Trial Number')
  ylabel("Max Combined Energy [kW-hr]")
  title("Maximum Combined Energy over Several Trials")

end

if plotTrialsMin
  if runRadar
    figure()
    bar(1:maxk,mnRadar)
    xlabel('Trial Number')
    ylabel('Minimum Radar Energy [kW-hr]')
    title("Minimum Radar Energy over Several Trials")
  end

  if runEW
    figure()
    bar(1:maxk, mnEW_kW_hr)
    xlabel('Trial Number')
    ylabel("Min EW Energy [kW-hr]")
    title("Minimum EW Energy over Several Trials")
  end

  if runLaser
    figure()
    bar(1:maxk, mnLaser_kW_hr)
    xlabel('Trial Number')
    ylabel("Min Laser Energy [kW-hr]")
    title("Minimum Laser Energy over Several Trials")
  end

  figure()
  bar(1:maxk, mnCombo_kW_hr)
  xlabel('Trial Number')
  ylabel("Min Combined Energy [kW-hr]")
  title("Minimum Combined Energy over Several Trials")
end
```

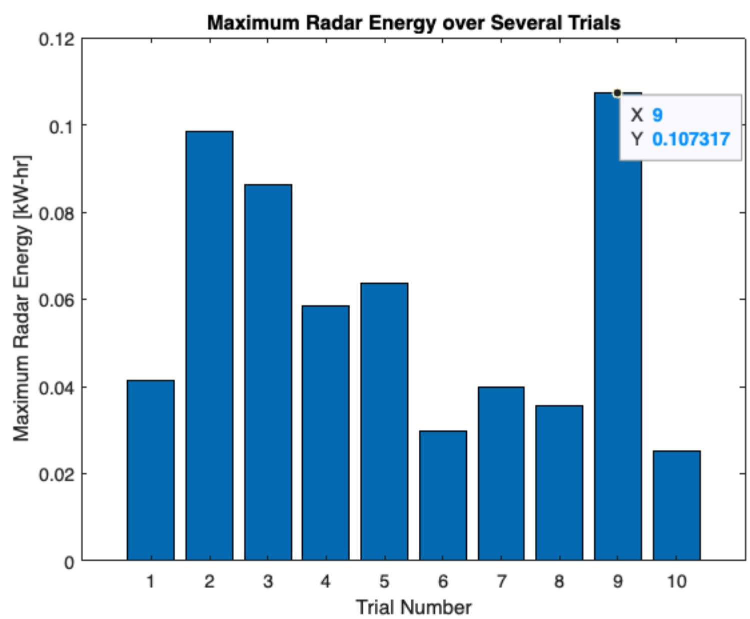
Radar

Peak Power: 1,000 kW
Mission Duration: 4200 seconds

Simulations Run: 10
Mean Power (Bus Power Requirement) (kW):
[727.6 727.5 727.4 727.6 727.6 727.5 727.6 727.6 727.4 727.5]
Max Mission Power, Battery Provided (kW):
[36.0 27.5 -16.0 50.1 145.0 90.4 49.6 117.6 163.1 116.9]
Max Battery Energy (kWh):
[0.04 0.10 0.09 0.06 0.06 0.03 0.04 0.04 0.11 0.03]



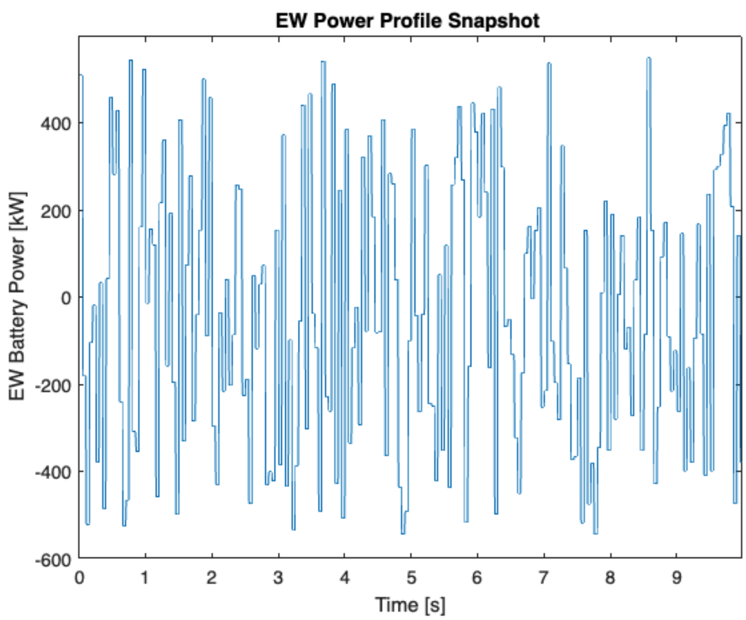

Radar Power and Energy
Radar Power [kw]
Radar Energy [kW-s]
Power [kW] and Energy [kW-s]
1000
800
600
400
200
0
-200
-400
0
500
1000
1500
2000
2500
3000
3500
4000
Time [s]

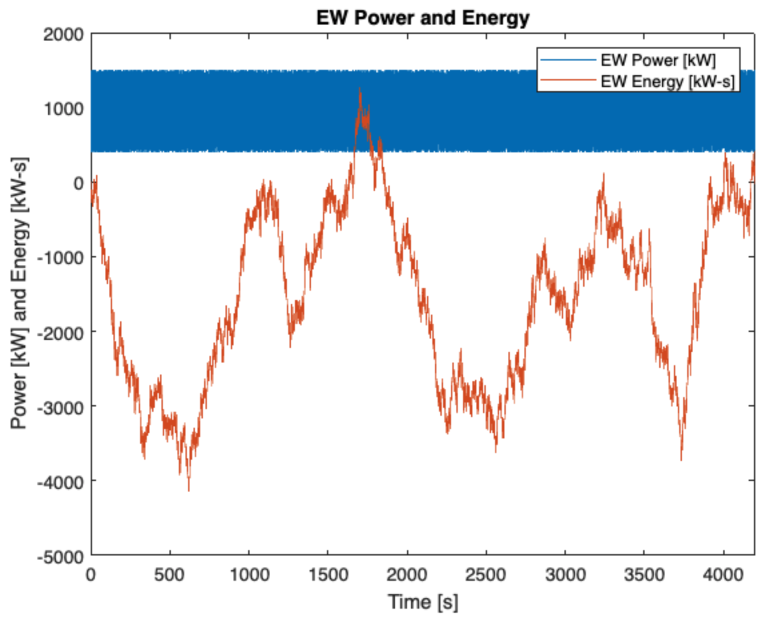

Maximum Radar Energy over Several Trials
Maximum Radar Energy [kW-hr]
0.12
0.1
0.08
0.06
0.04
0.02
0
X 9
Y 0.107317
1
2
3
4
5
6
7
8
9
10
Trial Number

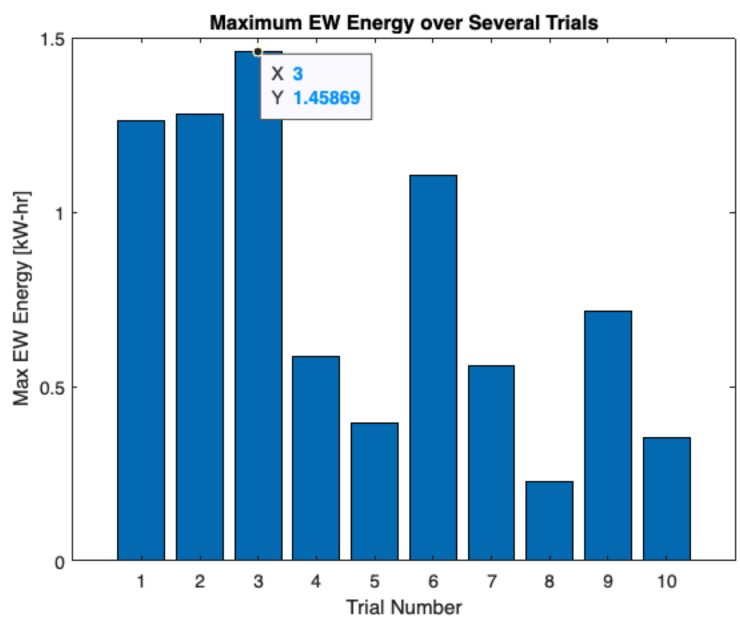
EW

Peak Power: 1,500 kW
Minimum Power: 400 kW
Mission Duration: 4200 seconds

Simulations Run: 10
Mean Power (Bus Power Requirement) (kW):
[950.9 948.4 949.0 949.7 950.1 950.6 951.1 952.5 950.5 950.0]
Max Mission Power, Battery Provided (kW):
[549.1 551.6 551.0 550.3 549.9 549.4 548.9 547.5 549.5 550.0]
Max Battery Energy (kWh):
[1.3 1.3 1.5 0.6 0.4 1.1 0.6 0.2 0.7 0.4]



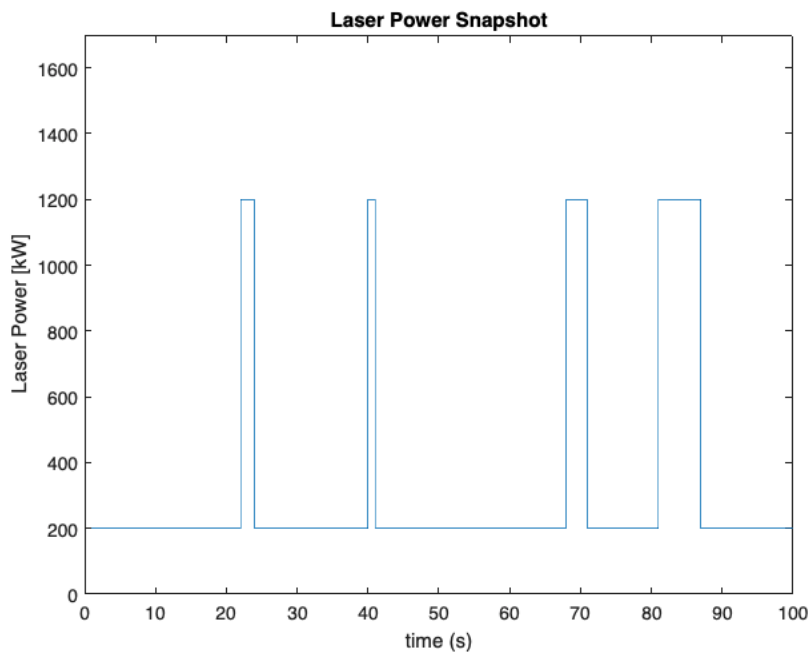

EW Power and Energy
EW Power [kW]
EW Energy [kW-s]
Power [kW] and Energy [kW-s]
2000
1000
0
-1000
-2000
-3000
-4000
-5000
0
500
1000
1500
2000
2500
3000
3500
4000
Time [s]

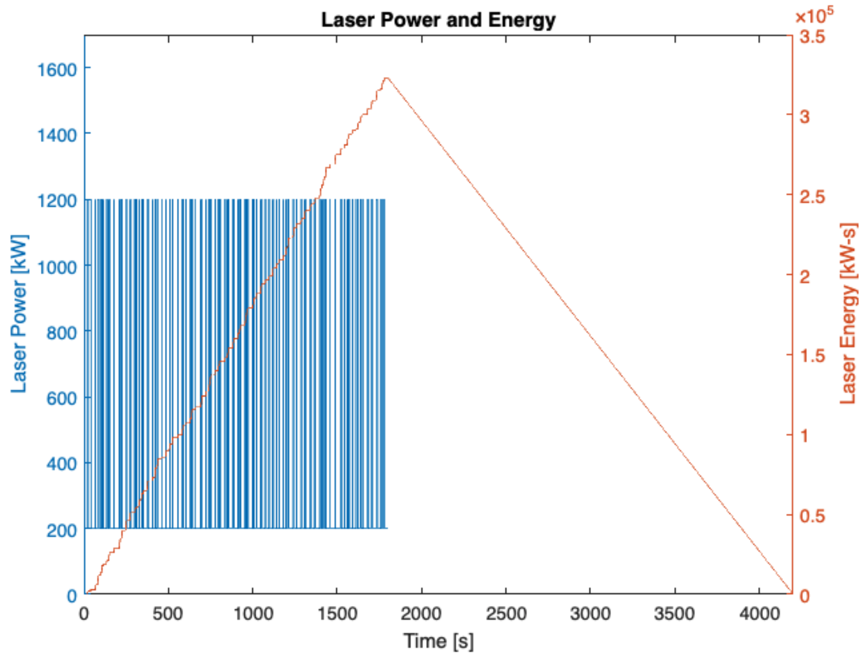

Maximum EW Energy over Several Trials
X 3
Y 1.45869
Max EW Energy [kW-hr]
1.5
1
0.5
0
1
2
3
4
5
6
7
8
9
10
Trial Number

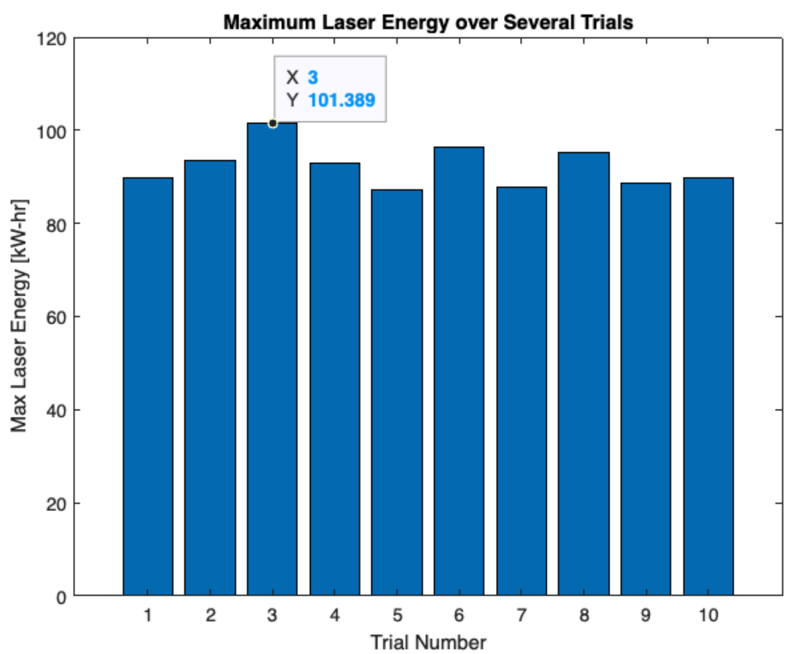
Laser

Peak Power: 1,200 kW
Minimum Power (standby, drawn from bus): 200 kW
Mission Duration: 1800 seconds

Simulations Run: 10
Total Lasing Time (seconds):
[323 337 365 335 314 347 316 343 319 323]
Max Battery Energy (kWh):
[89.7 93.6 101.4 93.1 87.2 96.4 87.8 95.3 88.6 89.7]




Laser Power and Energy
Laser Power [kW]
Laser Energy [kW-s]
×10^5
Time [s]
0
500
1000
1500
2000
2500
3000
3500
4000
200
400
600
800
1000
1200
1400
1600
0.5
1
1.5
2
2.5
3
3.5


Maximum Laser Energy over Several Trials
X 3
Y 101.389
Max Laser Energy [kW-hr]
Trial Number
0
20
40
60
80
100
120
1
2
3
4
5
6
7
8
9
10

Combination

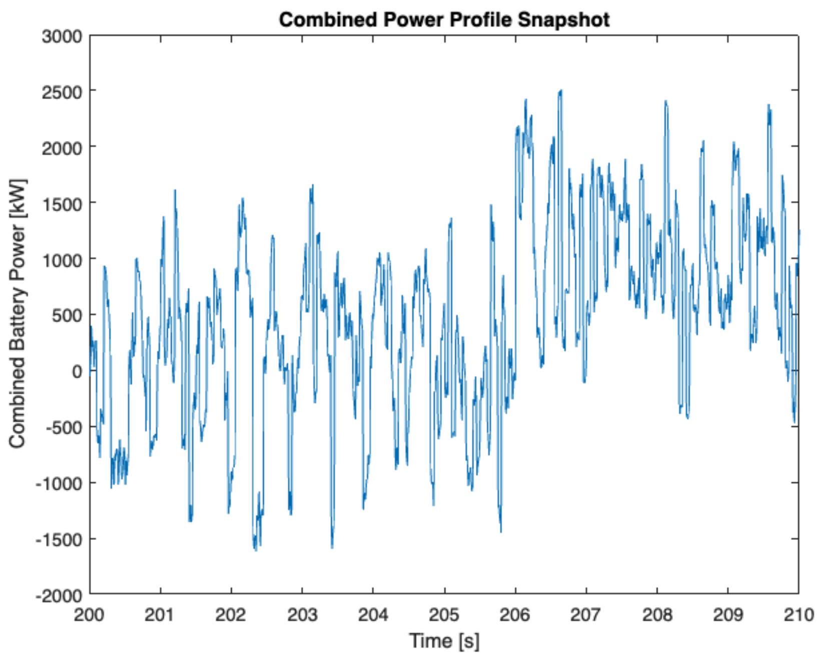
[3x Radar, 2x EW, 1x Laser]
Peak Power: 72,000 kW
Minimum Power: 1,000 kW
Mission Duration: 4200 seconds

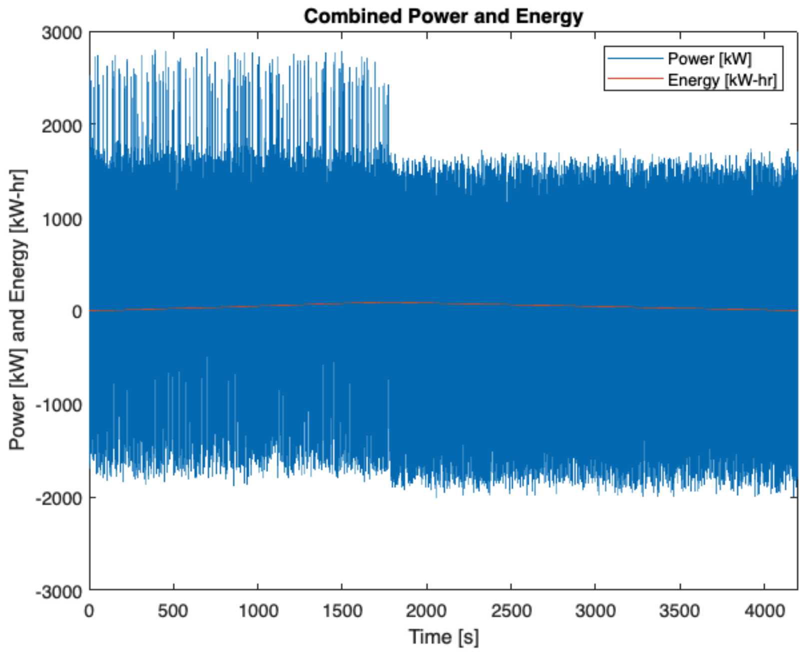
Simulations Run: 10
Max Mission Power, Battery Provided (kW):

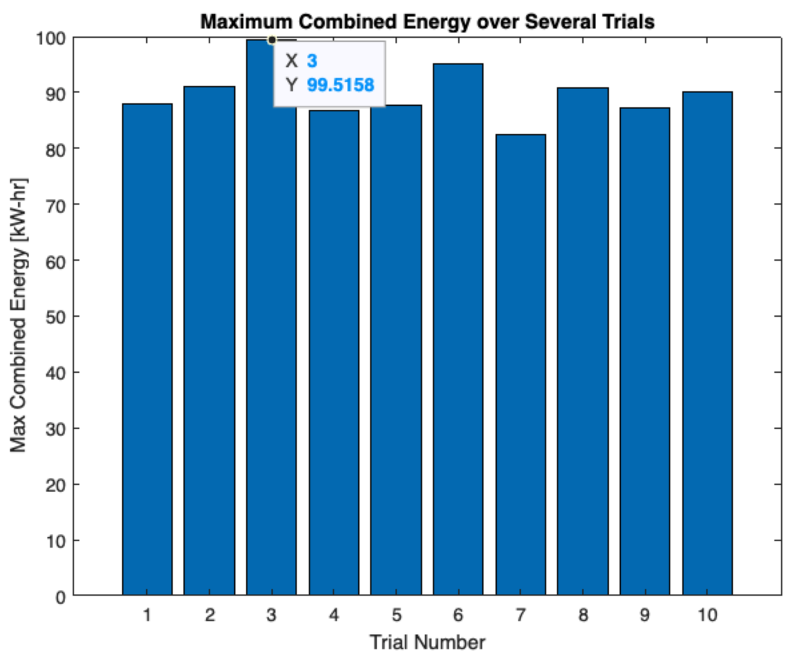
[2846.8 2890.4 2899.2 2870.2 2831.8 2817.1 2830.8 2819.8 2859.5 2809.9]

Max Battery Energy (kWh):

[87.9 91.1 99.5 86.9 87.7 95.1 82.5 90.9 87.3 90.1]




Combined Power and Energy
Power [kW]
Energy [kW-hr]
Power [kW] and Energy [kW-hr]
Time [s]
3000
2000
1000
0
-1000
-2000
-3000
0
500
1000
1500
2000
2500
3000
3500
4000


Maximum Combined Energy over Several Trials
X 3
Y 99.5158
Max Combined Energy [kW-hr]
Trial Number
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10