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Electrical Energy Storage Strategy to Support Electrification of the Fleet

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

ELECTRICAL ENERGY STORAGE STRATEGY TO SUPPORT ELECTRIFICATION OF THE FLEET

by

Daniel V. Camp, Nathan L. Vey, Paul W. Kylander, Sean G. Auld, Jerald J. Willis, Jonathan F. Lussier, Ross A. Eldred, Douglas L. Van Bossuyt

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14. ABSTRACT

Lithium-ion (Li-ion) batteries have begun to proliferate across the U.S. Navy fleet, commercial shipping, and in many other naval contexts. Naval engineers must account for Li-ion batteries when designing new vessels to ensure safety and adequate integration of the batteries into ship electrical systems. This article examines current Li-ion battery use and predicted battery requirements for the U.S. Navy's operating force in 2035 and 2045 from a mission engineering perspective and surveys battery chemistry, energy density, charge/discharge rate, safety concerns, etc. Projections of future battery requirements for the operating force in 2035 and 2045 are developed which clearly show that several classes of vessels will have significant growth in Li-ion batteries aboard the future fleet. The role of Li-ion batteries, however, will likely be limited to running specific subsystems or equipment and will not replace ship generators. This will remain true until the energy density of battery technology even begins to approach that of petrochemicals, which is many years away if possible. With recent high-profile Li-ion battery fires aboard civilian vessels, this research makes clear that Li-ion batteries will become more prevalent aboard ships over the next 20+ years and that naval engineers must begin accounting for Li-ion batteries now.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	alternating current
AMDR	Air and Missile Defense Radar
AUV	autonomous underwater vehicles
BMS	battery management system
CFD	computational fluid dynamics
COTS	commercial off-the-shelf
DC	direct current
DEW	directed energy weapons
DON	United States Department of Navy
FAA	Federal Aviation Administration
HED	hybrid electric drive
HEL	high energy laser
HELIOS	High-Energy Laser with Integrated Optical-dazzler and Surveillance
IPES	integrated power and energy systems
IPS	integrated power systems
LaWS	Laser Weapon System
LBS	littoral battlespace sensing
LBSP	Lithium Battery Safety Program
Li-ion	lithium-ion
LUUV	large UUV
LWSD	Laser Weapon System Demonstrator
MIL-STD	military standard
MUUV	medium UUV
NAVSEA	Naval Sea Systems Command
Ni-Cd	nickel cadmium
PEO USC	PEO Unmanned Small Combatant
RHIB	Rigid Hull Inflatable Boat
SoC	state of charge
SoH	state of health

SUUV	small UUV
TEM	tactical energy management
UAV	unmanned aerial vehicle
USS	United States Ship
USV	unmanned surface vehicle
UUV	unmanned underwater vehicle
WIC	Warfare Innovation Continuum
XLUUV	extra-large UUV

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I. INTRODUCTION

A. PURPOSE

The design, development, and fielding of new and emerging technologies onto Navy vessels is driving an increase in power requirements. The Deputy Chief of Naval Operations Warfare Systems (N9) office requires research be conducted to assess the current employment of lithium-ion (Li-ion) batteries within the Navy fleet and to aid in determining future battery requirements to power a wide variety of vehicles, weapons, and other subsystems. Li-ion technology has quickly become the power source of choice for systems that have large instantaneous and continuous power needs, and the Navy currently expects that Li-ion battery technology will continue to be needed to support many future systems. This research is intended to inform the Department of the Navy (DON) of the current state of Li-ion battery use and to substantiate requests to secure more resources to appropriately equip the fleet through 2045.

A literature review of naval Li-ion battery uses and possible future capacity requirements was conducted using unclassified sources. This review, provided in the following chapter, can be broadly split into four categories: current lithium battery use cases, future lithium battery use cases, U.S. Navy doctrine driving lithium battery adoption and battery storage considerations. Gaps in publicly available literature were noted in the areas of current use cases and future power requirements, likely due to the sensitive nature of many of the relevant systems. Areas where significant, open-source information exists are reviewed in detail. It is found that lithium batteries are already used in some limited applications in the fleet, and their use will likely grow exponentially in coming decades due to new, power-hungry technology developments.

B. BACKGROUND

The DON is seeking help with the development of an energy storage strategy to support the electrification of the fleet. The Navy is pursuing the electrification of the fleet from unmanned undersea systems to surface ships to tactical systems and everything in between. Many systems rely on stored electrical energy from batteries and other energy storage systems to function during some phases of operation. Current regulations restrict the use of some battery chemistries due to the risk of fire and explosion, which limits the full realization of the benefits of the latest Li-ion battery technology. Many existing ships have batteries that support a wide variety of operational and tactical systems. The assumption is that the modernization of mission equipment, integration of advanced weapons such as directed energy weapons (DEW), and the operation of vehicles from Navy vessels will require the use of advanced battery technology such as Li-ion. N9 Warfare Systems requires an understanding of future battery requirements for the fleet in the 2030 and 2045 timeframes to enhance the planning and resourcing of those power sources. The N9 Warfare Systems office has, therefore, asked the Naval Postgraduate School (NPS) in October 2021 to research the use of batteries in the fleet. Thus, N9 and the NPS research team agreed to four research tasks in key areas.

In Task 1, the faculty research team performed an open-source literature review in the domain of battery technology with an emphasis on naval operational applications. A Systems Engineering capstone team then augmented the faculty research team at the start of Task 2 - the identification of existing battery systems currently employed in the fleet. This task provided a good starting point to scope the remaining research objectives. Furthermore, investigating the distinct types of battery technologies, the benefits that Li-ion technology provides, the safety aspects of Li-ion and various battery metrics helped establish a baseline for the remaining research effort. Leveraging this knowledge, the team then delved into the future fleet structure and the emerging technologies that will require the use of batteries in Task 3, the identification of CONOPS and mission scenarios for future battery uses. Multiple technology literature sources discuss the future application of directed energy weapons (DEWs), unmanned aerial vehicles (UAVs), unmanned surface vehicles (USVs), unmanned underwater vehicles (UUVs) among many other future capabilities targeted for integration with the fleet.

The final two tasks conclude the research effort by first examining the trade space with Li-ion battery technology (Task 4) and then using those findings to predict future battery use in the 2030 and 2045 timeframes (Task 5). During the trade space analysis, the research team investigated the trade-offs of energy generation vs. energy storage. The team then assessed the estimated power needs of the projected future capabilities and determined the corresponding battery requirements to support them. These estimated energy storage requirements were then compared with anticipated battery technology energy storage capabilities, which was then translated into the overall battery procurement requirements for the fleet. Thus, authors' goal is that this final task, along with the corresponding recommendations, will provide the research sponsor with an overall projection of battery technology requirements gaps in the 2030 and 2045 timeframes.

C. METHODOLOGY

1. Problem Decomposition

The focus of this study is battery technology aboard major U.S. Navy surface combatant ships such as carriers (CVNs), destroyers (DDGs) and amphibious assault ships (LHAs and LHDs). Small Navy boats (e.g., patrol boats), submarines, supply and transport ships are not included in this study although they all have potential for a Li-ion footprint. This approach kept the scope of the research manageable while addressing the key aspects of Li-ion adoption and integration most likely to significantly impact Navy planning.

To assess the current use of batteries within the Navy and to predict the future growth of battery use, the authors investigated four research areas:

<u>Current Battery Systems Aboard Operational Platforms:</u>

This area identifies Li-ion battery systems being used in the fleet as well as their use to power other operational and tactical systems operated from the vessels. This includes identifying where batteries are used and gathering any available information on the specifics of the battery such as capacity, voltage, and the use of the battery.

<u>Future Fleet Structure:</u>

This area attempts to predict future battery use in both the mid-term (2030) and far-term (2045). This includes considering vehicles and subsystems that are not currently battery powered but could be in these timeframes. An attempt is also made to predict the overall Navy force structure; thus, the combination of the systems that could use batteries and the total number of systems provides a basis for the prediction of battery use in the future Navy.

Trade Space of Energy Generation vs. Storage:

This area analyzes the tradeoffs between energy generation and energy storage based on the energy requirement derived from the developed future fleet structure. This analysis also identifies strengths and weaknesses of both energy generation and energy storage.

Predictions for Future Battery Use:

This area develops predictions for future battery use across the fleet in the mid and far term based on the future fleet structure and the trade space analysis.

2. Timeframes

An important aspect of this research is the consideration of Li-ion use in the near, mid and far term. The near term is defined as use on systems that are either currently fielded or nearly fielded. Mid and far term is defined as 2030 and 2045, respectively, based on the information available regarding future naval warfare and the future Navy force structure contained within the *Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023* (Office of the Chief of Naval Operations 2022) and the Warfare Innovation Continuum (WIC) Workshop: Hybrid Force 2045 September 2021 After Action Report (Englehorn 2021).

3. Data Collection Techniques

The team searched open-source databases and collections, including open-source publications by the Navy and other government agencies, journal articles, news articles, publicly available product specifications, as well as other online sources.

II. LITERATURE REVIEW

A. OVERVIEW

The DON is steadily electrifying and modernizing its fleet to achieve greater fuel efficiency, provide increased operational flexibility and establish the power infrastructure required for future radar, communications systems, electronic warfare systems, and directed energy weapons (Evans 2016). Many Naval platforms rely on battery-stored electrical energy to function as part of their day-to-day operations, serving as both primary and redundant power sources for a multitude of subsystems, not to mention the numerous batteries contained in the personal electronic devices of thousands of sailors and in the other vehicles and equipment that the vessels may be carrying. As such, Naval ships contain thousands of batteries to support those operations with the expectation that more batteries, and higher capacity batteries, will be required as new capabilities are integrated on board. Reliance on efficient, safe, and effective battery technology such as Li-ion is expected to increase along with this growth in the number of systems being operated as well as their overall demand in power. Li-ion batteries have become the battery of choice over the last several decades due to their performance advantages. Li-ion batteries, however, also present an increased amount of risk that requires specialized monitoring equipment to predict and prevent failure. Without improvements to current monitoring equipment, Li-ion batteries are susceptible to unpredictable catastrophic failures.

Ship and crewmember safety is a key concern for the DON. Given the inherent safety risks associated with Li-based batteries, the DON has a Lithium Battery Safety Program (LBSP) that is designed to assess, evaluate, and minimize risk to personnel and platforms while allowing the use of lithium batteries on ships, aircraft, and submarines. Naval Sea Systems Command (NAVSEA) establishes the policy used for the LBSP to conduct comprehensive reviews of a battery's intended platform, use, storage, and, as necessary, conducts test events culminating in certification for battery use aboard Navy vessels.

The Navy has witnessed many significant advances in technology over two-and-a-half centuries to enable sailing vast distances at ever increasing speeds. From early ships powered by wind, to the advent of steam, and, later, combustion engines, the Navy has continued to strive forward in powering the fleet, often entailing the assumption of additional risks. In the case of batteries, the Navy's appetite to adopt stored energy was introduced onto naval vessels in the late 19th century. Early battery technology involved risks not too dissimilar from today's lithium chemistries; however, the ability to store and manage energy is paramount in addressing expanding ship-wide capabilities ("Ships" 1900; "Storage Batteries" 1899). Unlike the initial adoption of battery power, the sheer scale of modern manufacturing means the introduction period for Li-ion batteries is likely to be exponentially quicker than that of its lead-acid predecessors.

The specific contribution of this study is to assist decision makers with identifying the resources required to procure and integrate Li-ion batteries into the fleet in the 2030 and 2045 timeframes. These requirements are determined by performing an assessment of the technology that is likely to be integrated aboard Navy vessels by those key years, and then estimating the corresponding power requirements.

****One of the foundational assumptions of this research is that Li-ion batteries will be the battery chemistry employed by future Navy systems.****

B. CHARACTERISTICS OF BATTERY TECHNOLOGY

Prior to discussing the research results, it is important to review several aspects of battery technology, including battery types and the factors that go into selecting a battery for a naval technological solution. Following that, a review of battery metrics will be provided. There are several key metrics that battery developers must consider and tradeoffs that must be made when designing new batteries. Given that the focus of this research is Li-ion batteries, a detailed analysis of Li-ion is then conducted highlighting the reasons why Li-ion technology has become the battery of choice to meet stored energy requirements. The final portion of this section then discusses the naval applicability of battery technology.

1. Battery Types

Marine vessels use batteries to power numerous devices in differing environments from cold weather to tropical climates. Climate and power requirements drive the type of battery selected for integration, but many other factors should be considered. Additional points to consider when deciding a battery configuration include whether the battery is a primary or secondary power source, whether it will power a critical system, and if it is used for continuous use or periodic use. The two most common battery chemistries are lead acid and Li-ion; each chemistry has a unique set of attributes that should be considered based on the requirement. Li-ion battery chemistry provides longer discharge and battery life, ranging from 8–10 years, compared to 3–5 years for lead acid.

2. Battery Metrics

Figure 1 depicts the key characteristics of Li-ion batteries and some of the tradeoffs that are considered when determining the appropriate battery design (Sagoff 2020). In addition to those characteristics, other key battery attributes include capacity, voltage, discharge rate, depth of discharge, and volumetric energy density ("Volt, Amps, Amp-Hour, Watt and Watt-Hour: Terminology and Guide" n.d.). For the purposes of this study, the authors have focused primarily on battery capacity and energy density. Capacity is the total amount of energy the battery can hold. Energy density is the capacity of a battery per unit of size or weight, with specific energy density being capacity per unit of weight and volumetric energy density being capacity per unit of size.

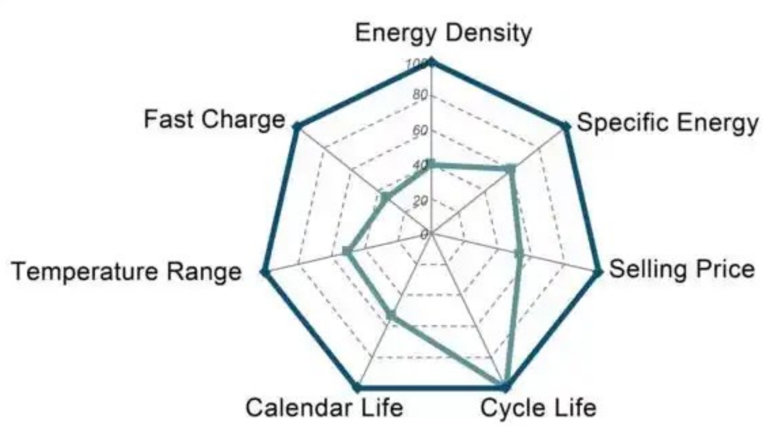


Figure 1. Battery Metrics. Source: Argonne National Laboratory (n.d.).

The two most common ways of measuring capacity are Ampere Hours (Ah) or Watt Hours (Wh). A Wh is identical to an Ah with the exception that a Wh is the measure of the power a battery can provide over a length of time, whereas an Ah is the measure of the current a battery can provide over a length of time. In theory, converting between Ah and Wh is as simple as multiplying the Ah rating by the nominal voltage of the battery. The authors chose to measure battery capacity in Wh due to the importance of energy density to this paper. According to Golnik (2003), "Energy density is the amount of energy stored in each system or region of space per unit volume or mass." This is an important measure because the higher the energy density of a battery, the greater the amount of energy that it has stored ("Energy Density–Energy Education" n.d.). Further, energy density is easier and more reliable to calculate in terms of Wh than Ah. This is because the Ah capacity of a battery is independent of the battery's voltage, which has a direct impact on its weight and size.

3. Li-ion Specifics

There are three main reasons why Li-ion batteries are more likely to prevail for maritime use than other chemistries such as lead acid. Li-ion batteries can charge faster, last longer, and have a much higher energy density for longer battery life in a lighter configuration. Cummings Newsroom compares the energy density between Li-ion and lead acid batteries as follows: "lithium ion achieves an energy density of 125–600+ Wh/L versus 50–90 Wh/L for lead acid batteries" (Cummins Inc. 2019). A Li-ion battery installed on a vehicle and used to power the vehicle for the same distance would take up to 10 times less volume and be substantially lighter than the lead acid (Cummins Inc. 2019). Based on current trends, lead-acid batteries will soon be phased out for the more energy efficient and environmentally friendly Li-ion alternative. Li-ion batteries also provide more stability and are critical for time-sensitive, high-utilization applications, thus resulting in fewer recharge intervals.

Additionally, Li-ion batteries do not contain the "memory effect" as is the case with older battery technologies. Li-ion batteries have a much longer life than traditional batteries as they do not lose permanent storage capacity during continued use. For Li-ion batteries, "State of Charge (SoC) and State of Health (SoH) are important metrics" since they "can help in both battery prognostics and diagnostics for ensuring high reliability and prolonged lifetime" (Sukanya, Suresh, and Rengaswamy 2021). A lead-acid battery can take significantly longer to charge than a Li-ion battery (Cummins Inc. 2019). Lead-acid batteries "can take more than 10 hours" to charge compared to "3 hours to as little as a few minutes" for a Li-ion battery depending on the size. Additionally, Li-ion chemistries can accept a faster rate of current, which results in charging quicker than batteries made with lead acid (Cummins Inc. 2019). Figure 2 depicts the principles of Li-ion battery operation.

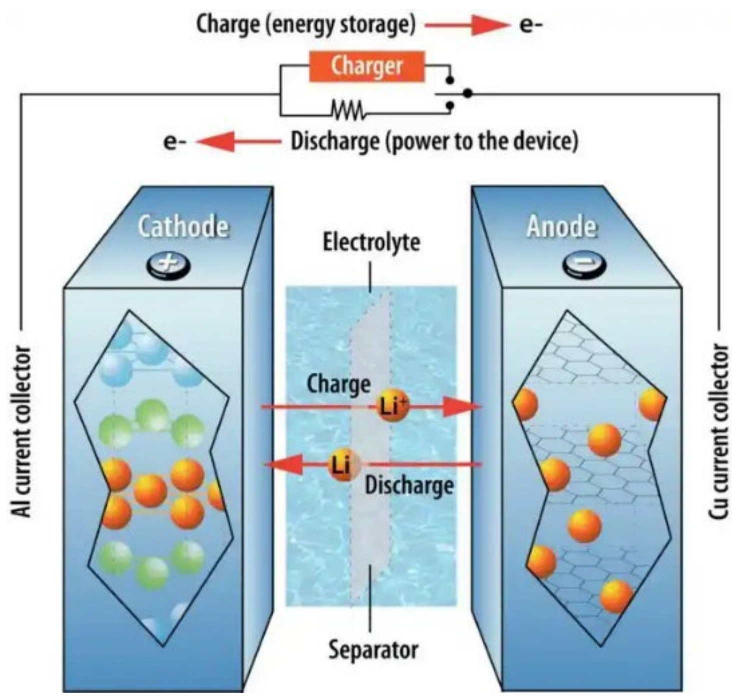


Figure 2. How a Lithium-ion Battery Works. Source: Argonne National Laboratory (2010).

Li-ion batteries do not contain toxic cadmium, making them significantly easier to dispose of than rechargeable Nickle Cadmium (Ni-Cd) batteries. Li-ion batteries can use various materials as electrodes. The typical minimal maintenance of Li-ion batteries often makes them preferable to other battery chemistries. Li-ion batteries offer a higher energy output in shorter amounts of time and also have a greater life expectancy (15–20 years, compared to other battery types that typically have a life expectancy of 5–7 years) (Kostiantyn Turcheniuk et al. 2018).

Li-ion batteries are generally considered safe, but they do require specific engineering and safety precautions to prevent fires. Safety is a chief concern for Li-ion batteries, particularly as the batteries age. These safety risks revolve around their tendency to overheat and their ability to be damaged at high voltages. In the case of Li-ion battery use for shipboard energy storage, the substantial energy concentration in one location leads to increased risk of explosion, fire and toxic gas hazards in the event of a battery module failure. Proper fire suppression, ventilation, and gas detection systems are critical in reducing the risk of fire and injury to sailors.

Li-ion batteries become unsafe when they are operated outside the designed safe temperature zone - between 10° and 55°C (50°–131° F). One key difference between a Li-ion battery fire and a traditional fire is that a Li-ion battery fire does not need oxygen to burn. Thermal runaway is a scenario that can occur with overheating Li-ion batteries and is caused by an exothermic chain reaction creating an uncontrollable self-heating state that is unable to be overcome by the intended cooling process. Yamaki (2014) presents three possible exothermic reactions: (1) chemical electrolyte reduction at the negative electrode, (2) thermal electrolyte decomposition and (3) electrolyte oxidation at the positive electrode. Li-ion batteries have a failure rate of less than 1 in a million and, with a quality Li-ion cell, the failure rate is less than 1 in 10 million.

During a battery module failure, off-gassing presents both explosive and toxin risks. Ventilating the affected areas is a key component of battery safety. While many factors affect the required ventilation in case of battery failure, it has been found that in a room of 25 m^3 the required ventilation might range from 0 air changes per hour (ACH) for a 60 Ah battery to 153 ACH for a 2,000 Ah battery. The ACH will vary depending on vent location and battery size. The required ventilation is highly dependent on many factors like battery size, composition, installed fire suppression systems, room design and vent location. A generalized formula has been proposed that predicts the computational fluid dynamics (CFD) model outputs and can give the recommended ACH for a given compartment (Gully et al. 2019).

Off-gassing begins at the time of failure and continues through the decomposition of the cell. One key new development in early battery fire early warning systems is the detection of released gases prior to thermal runaway. While normal explosive gas sensors and smoke detectors are not sensitive enough to detect off-gassing before thermal runaway, some sensors, such as the Nexceris Li-ion Tamer (placed within the battery module), can detect off-gassing and trigger a shutdown of the cell prior to thermal runaway, thereby avoiding a fire (Cummings and Swartz 2017; Gully et al. 2019). Placement of the sensors within the battery module was found to be a key factor in early warning (Gully et al. 2019). Nexceris claims that a gas sensor, when combined with a conventional battery management system (BMS), can provide more robust early warning by checking for voltage fluctuations once gas has been detected, thus reducing the chance of false positives (Cummings and Swartz 2017).

Fire mitigation can be done by following the proper procedures regarding storage, use, and maintenance. Li-Ion batteries should always be kept in climate-controlled environments where they will not exceed their maximum temperatures and where proper fire suppression, ventilation, and gas detection systems are in place. It is important to inspect Li-ion batteries for damage prior to charging and they should always be charged away from flammable locations and never overcharged. Li-ion batteries are more sensitive to failure the more that they are exposed to improper procedures such as extreme heat and overcharging.

Due to the unique nature of Li-ion battery fires, conventional fire suppression systems do not work well. A 2019 study by DNV-GL evaluated and compared the effectiveness of multiple fire suppression systems. While no "silver bullet" solution was found, a combination of multiple systems, such as direct injection of foam into the battery modules and a high-pressure water mist flooding the affected compartment, showed promise in both suppressing the spread of fire and absorbing heat and toxic gas (Gully et al. 2019). Li-ion batteries are made up of liquid electrolytes that provide a conductive pathway, which is why they are given a Class B fire classification. For the best results, a foam extinguisher with CO2, dry chemical, powdered graphite, copper powder, or soda (sodium carbonate) should be utilized.

On March 1, 2022, a cargo ship, *Felicity Ace*, sank in waters off the Azores due to what is believed to be a battery fire that started in an electric vehicle it was carrying within its cargo hold, though there is was no official determination of the cause at the time of this report (Hahn 2022). The *Felicity Ace* was carrying more than 4,000 vehicles to the United States. Luckily all the crew survived, but there will be lasting ecological impacts because of her sinking.

4. Naval Applicability

The DON Office of Naval and Power Energy Systems Technology Development Roadmap identifies several power initiatives for the future fleet (Naval Sea Systems Command 2019). The roadmap emphasizes the concept of an energy magazine along with integrated power solutions, which acts as a buffer between "legacy MIL-STD-1399 AC interfaces and new highly dynamic, high power DC mission systems." An energy magazine's intended purpose is to augment and or address electrical requirements for current and future solutions of tactical energy management (TEM).

C. CURRENT USE OF LI-ION BATTERIES ON SURFACE SHIPS

The U.S. Navy has been using lithium-based rechargeable battery chemistries for decades in many applications. Despite safety concerns, use of lithium batteries has become increasingly widespread due to the increased performance they can provide over other battery types. In a report on the Navy's lithium battery safety program, Dow gives an example list of applications which require battery use in the Navy (Dow 2010):

Guided missiles
Bombs
Mines
Fuses
Guided projectiles
Torpedoes
Underwater targets
Submarines
Swimmer delivery vehicles
Unmanned underwater vehicles
Unmanned aerial vehicles
Explosive ordnance disposal robots

Medical equipment
Memory backup
Depth charges
Aircraft
Telemetry
Surveillance buoys
Sonobuoys
Sound sources
Acoustic transponders
Field communications
Laser designators
Countermeasures
Night vision
Weapons handling equipment

While this list is extensive, it does not specify which of the above applications are currently implementing lithium batteries, only that some form of energy storage is required.

The following sections will attempt to identify some key uses which currently make up a large portion of aggregate capacity present in the U.S. Navy. The battery applications identified can be grouped into three main categories: aviation, unmanned systems, and utility uses. Weapon applications in which the battery is integrated into the system, such as missiles and torpedoes, are considered outside the scope of this report. While many of the key current use cases have little open-source documentation, the authors will attempt to approximate the overall aggregate capacity they represent.

1. Carrier Operations

Most naval aircraft, such as the Seahawk helicopter, carry only small lead acid batteries for emergency use and engine start (Sikorsky 2010). These batteries are typically small (around 10 AH) and do not share the volatility issues of lithium-ion batteries. The one notable exception is the F-35, which uses lithium batteries for emergency power and engine start (Saft, n.d.; Wiegand 2018). The F-35 has two lithium-ion batteries on board: one smaller battery rated at 28 volts and 900 Watt-hour (Wh) capacity and one larger, rated at 270 volts and 1750 Wh capacity (GE Aviation, n.d.). Current plans call for the Navy to procure a total of 273 F-35Cs, while the Marine Corps is expected to procure 67 F-35Cs and 353 F-35Bs (Gertler 2022). Little information is publicly available about the extent to which the Navy is planning to carry spare F-35 batteries on board. While the batteries do not need to be replaced frequently, it is likely that some number of spares will be carried in case of unexpected failure or damage. Between the two batteries on each aircraft and the number on planed aircraft, aggregate lithium-ion battery capacity bought to the DON by the F-35 system aggregates to 2650 Wh on 693 aircraft, totaling over 1,800,000 Wh of energy.

2. Deployable unmanned systems

In the future, many unmanned systems in naval use may be powered by lithium batteries. Currently, there are very few visible examples of this, in part due to the developmental nature of many unmanned systems, and in part due to the difficultly in certifying a lithium battery for naval use. The Navy has tested several lithium-powered UAV systems (RQ-11, RQ12A, and RQ20) for use at its Air Test and Evaluation Squadron (U.S. Navy, n.d.). It is unclear to what extent these UAV systems are used onboard naval vessels, but as shown by Dow, widespread use of deployable systems which require battery power already exists (Dow 2010).

3. Other Applications

Numerous miscellaneous systems use lithium-ion batteries aboard ships, including power tools, UPS systems for computers, laptops, cell phones, radios and other systems. While no dedicated study could be found for these applications, the aggregate capacity they represent will be estimated in this report.

D. FUTURE USE OF LI-ION BATTERIES FOR SURFACE SHIPS

The Navy is currently undergoing significant transformation to respond to the rapid development of new threats and emerging technologies which have the potential to overwhelm current generation ship defenses. The Navy must invest in technologies that are cost effective and sufficiently flexible to counter threats in this ever-changing battlefield. Certain novel technologies, such as directed energy weapons (DEWs), show substantial promise; however, these systems require power on a level never seen before. While exact specifications were unvailable to the research team, many of these systems require pulse power on the mega-watts or tens of mega-watts level (Beach 2005; Herbst 2013).

1. Generation of Electrical Power

Current surface ship power generation can be broadly split into two categories: power for propulsion and power for electronic systems. In most cases, the power needed to move the ship at speed dwarfs the power needed for electronics. The DDG-51 (Arleigh Burke) flight IIA, for example, is only capable of generating 6 MW of electrical power while its main propulsion system generates around 100 MW to move the ship (Vandroff 2016; GE Aviation, n.d.). Most ships do not have any ability to generate electrical power from propulsion power plants or propel the ship on electrical power alone. Power for electrical systems is generally generated on a just-in-time basis, meaning there is little to no energy storage available. Electrical power generation ranges from 2 MW in smaller surface combatants to over 70 MW in the Zumwalt class, although not all of the Zumwalt's 70 MW is available for electronic systems due to its use of an integrated power system (IPS) (Naval Technology 2020; Inglis 2020). IPS and other combined power systems, like the hybrid electric drive (HED), will be discussed later in this report; their use is not widespread at this time. Power is typically generated by gas turbines for larger vessels and diesel engines in smaller vessels. In most configurations, between two and four generators are used. Per Navy policy, one generator must be kept in reserve for redundancy purposes, therefore a ship's available power is generally what is produced by all but one generator set.

2. Weapon and Sensor System Requirements for Pulsed Power

Directed energy weapons and high-power sensor systems are rapidly growing in both capabilities and power requirements, and they may provide a good response to emerging threats to ship defense. DEWs are a possible effective counter to air threats but are currently limited by shipboard energy generation and storage (O'Rouke 2021a). The DDG-51 flight III ships are being fitted with the AN/SPY-6 Air and Missile Defense Radar (AMDR), and while power generation was increased from a possible 6 MW to 8 MW to accommodate the AMDR system, there is not enough power left over for a DEW system like the 60-150 kilo-watt output (kWo) High Energy Laser and Integrated Optical-dazzler with Surveillance (HELIOS) (O'Rouke 2021a).

3. Planned Power Generation for Future Platforms

Future surface combatant platforms will likely be built with increased power generation. While still at an early design stage, the Navy's requirements for its next generation destroyer include an IPS architecture like that installed in the Zumwalt and increased size, weight, power and cost (SWAP-C) to enable DEWs and sensor systems (O'Rouke 2022). Similarly, the Navy's future frigate program, the FFG-62 Constellation class, will be powered in a combined diesel-electric and gas (CODLAG) configuration and have roughly 8 to 9 MW of power available (O'Rouke 2020; Seapower 2021; Blenkey 2020). The Constellation class is expected to incorporate a small version of the SPY6 radar, the Enterprise Air Surveillance Radar (EASR), but has no directed energy weapons currently planned, although it is noted that SWAP-C will be reserved for a future 150kW laser (O'Rouke 2020). The general trend within Navy ship planning is to move toward more power generation, and IPS and HED systems on larger ships. Little to no energy storage has been planned for ship platforms other than that integrated into specific weapon systems.

4. Potential Use of Batteries to Bridge Energy Storage Capability Gaps

As weapon and sensor energy demands grow, so does the potential to outstrip power generation on many platforms – especially when new systems are retrofitted onto platforms that were not originally designed to support them. Many future combat scenarios require heavy use of sensors and DEWs on short notice for sustained periods or short bursts. One possible use of lithium batteries is to provide large amounts of power with no ramp-up time and enable sustained use of high energy systems. Research done in collaboration with the University of Texas Austin and the Naval Postgraduate School has shown that even a small amount of Li-Ion battery storage could enable substantially increased magazine size for potential laser systems (Gattozzi 2016). In a detailed model of a destroyer, it was found that even a small volume (0.23 m^3) of lithium-ion batteries might enable hundreds of shots with a 125 kWo laser while protecting the ship from the strain of a direct pulse load (Sylvester, 2014). This type of energy storage may become critical as ships such as the Arleigh Burke class destroyers are backfitted with increasingly advanced weapons and radar systems. While the Arleigh Burke flight III destroyers were upgraded to power the AMDR, they do not have power left over for a laser system like HELIOS at the 60-150 kWo level. An energy storage system like that described by Gattozzi and Sylvester could be one possible solution. In addition to providing power to weapons and sensor systems, potential energy storage systems have several potential benefits, such as providing UPS power in emergencies and smoothing shipboard power bus voltage ripples during rapid load changes (Gattozzi 2016).

E. NAVY DOCTRINE AND ITS IMPLICATIONS FOR FUTURE BATTERY STORAGE REQUIREMENTS

Recent developments in hypersonic missiles, unmanned swarms, surface-to-air missiles, and other technological advances by adversarial states have forced the Navy to evolve its doctrine. While many important changes have been made, two are particularly relevant to this study: the development and fielding of unmanned systems of varying types and sizes, and the development of new defensive weapons to protect surface ships. The following sections detail the likely corresponding future increases to aggregate battery capacity.

1. The Shift to a Distributed Force of Smaller, Unmanned Platforms

Many unmanned systems are being developed for surveillance and reconnaissance, logistics and offensive capabilities. The CNO’s 2021 NAVPLAN emphasizes the implementation of unmanned and optionally-manned systems. With a push towards a distributed force of smaller and unmanned platforms, operational energy considerations for these platforms are becoming a critical concern. Additionally, as the world-wide trend towards renewable energy and electrification continues, more and more systems are being built to take advantage of the battery systems brought to economies-of-scale by commercial industries. This has resulted in the propagation of lithium-ion batteries into everything from vacuum cleaners to electric vehicles and grid energy storage installations. Many unmanned systems are designed to leverage the decreased cost, increased performance, and long lifetime that lithium batteries offer over other battery chemistries.

2. Hybrid Force 2045

The Naval Postgraduate School's Naval Warfare Studies Institute (NWSI) holds a warfare innovation workshop each year to advance naval innovation. In 2021, the workshop focused on how emerging technologies might be applied to a global conflict in 2045. In the notional 2045 scenario, it quickly became apparent that unmanned and optionally-manned platforms would be critical in countering near-peer threats. These platforms range from large, unmanned surface vessels (LUSVs) to hand launched drones. The idea of using numerous, expendible platforms in contested areas like the South China Sea has the potential to reduce risk in conflict scenarios substantially. While a carrier strike group (CSG) presents a high-value target to an advisory's missiles, a distributed force of smaller, more diverse and optionally-manned platforms might project the same power and deterrent effect as a CSG while greatly reducing the net risk to high-value targets. In the scenario, the prolific use of unmanned surface platforms and UAVs to provide surveillance and weapons capabilities might rely heavily on lithium batteries to provide power for UAV systems and increase time on station for surface vessels.

3. Directed Energy Weapons for Self-Defense

Development of DEW systems have been ongoing over multiple decades, but some efforts are coming close to fruition, with tests of laser systems aboard ships successfully shooting down UAV targets (O'Rourke 2021a). The Undersecretary of Defense for Research and Engineering has put additional focus on directed energy weapons, identifying directed energy as one of three critical defense-specific technology areas offering new ways to counter diverse and emerging threats (Shyu 2022). The possibility of using DEW for air and missile defense is generating continued investment from the Navy, with the hope that using emerging DEWs for air and missile defense will free-up magazine capacity for additional offensive weapons (Braithwaite 2020). From the CNO's 2021 NAVPLAN:

> Our rivals are relying on their ability to overwhelm our defenses with a massive number of missiles. Therefore, we need fixed and mobile sensors as well as submarines and unmanned platforms to operate inside of an adversary's missile

> defense zone. We also need inexhaustible defensive systems aboard our warships and aircraft. We are allocating more resources to systems that improve defensive strength of the fleet and deliver more offensive firepower. This includes capabilities such as directed energy and electronic warfare systems. We will complete fielding of the high-power directed energy weapons systems our fleet needs to prevail in a near-peer fight before our adversaries achieve the same capability.

China has been observed rapidly ramping up its naval power and modernizing its fleet to compete with US Navy forces. This power growth may embolden them to address the situation with Taiwan militarily (O'Rourke 2021b). A possible conflict with China in the South China Sea could see heavy use of anti-ship cruise missiles (ASCM), anti-ship ballistic missiles (ASBM), and wake homing torpedoes, among other weapon systems. China is also known to be developing drone swarm technology utilizing kamikaze tactics with relatively cheap drones carrying a block of high explosive (Tandon 2021; Trevithick 2021). When these threats are combined, they present a very difficult scenario for conventional surface ship defense. DEWs, coupled with highly effective sensor systems, offer an ideal counter to many missile threats. These systems, however, come with a high cost in power requirements. As explored earlier, the pulsed power requirements of DEWs such as lasers and microwaves are an order of magnitude higher than what current shipboard systems can provide. High power radar systems, such as the AMDR, are also power hungry and can be expected to require increasing power as their capabilities grow.

4. Sample Directed Energy Weapon CONOPS

DEWs – particularly lasers – present a possible defense against many threats to surface ships. They can be used to destroy or disable swarming fast-attack craft / fast in-shore attack craft (FAC/FIAC), UAVs, and ASCMs. Solid state laser weapons are particularly attractive for countering missile threats because they are flexible, with the same laser capable of engaging many types of threats, and the cost per shot being only the cost of fuel necessary to generate the electricity. Each target engaged, however, requires the consumption of significant energy. High energy laser (HEL) systems cannot be connected directed to a ship's electrical bus, as the presence of a high-power pulse load can cause power transients (Michnewich 2018). Depending on the size of the laser system and other electrical loads on a ship, many ships may not be able to power a laser system at all without some form of energy storage. In his thesis, Michnewich provides a hard use case for a 150 kWo laser system defending a ship from swarming FAC, UAV, and ASCM threats. Armor types, environmental effects, target speeds and numbers were considered. In the thesis scenario, a 200 MJ energy storage system would be able to destroy a swarm of 30 FAC/FIAC and 20 UAVs. If the energy storage system chosen is lithium-ion batteries, it would weigh 600kg and take up 0.6 cubic meters of space (Michnewich 2018). Michnewich contends that energy storage systems can greatly increase the magazine depth of some DEW configurations on ships.

F. LI-ION STORAGE CONSIDERATIONS

1. Operational Capability

While mean time between failures (MTBF) varies between battery systems, the volume needed for a lithium-ion battery of a given power is generally correlated to its volumetric energy density. Current-generation electric vehicle (EV) battery cells have a volumetric energy density of around 760 watt-hours per liter (Panasonic n.d.). It should be noted, however, that this number does not account for the volume required for cooling, BMS, and battery structure; it is the energy density of a single cell. Real world energy densities will be lower. One estimate gives a required 0.26 cubic meters of battery cells to power a 125kWo laser for sixty shots of a 6-second duration at a 50% duty cycle (Gattozzi 2015).

2. Logistics

The location and access of battery storage for deployable systems and shipboard energy storage are influenced by many factors. For deployable systems, battery storage should be close to the deployment location, such as a well deck or main deck, to enable easy access in emergencies. Storage locations must also take fire risks into account. The technical document, S9310-AQ-SAF-010, gives limited guidance on how commercial-off-the-shelf (COTS) batteries should be stored, such as in a fireproof container, with less than 1000 Wh aggregate capacity in one place, etc.

For shipboard energy storage, an additional consideration is the proximity to pulsed power loads supported by the battery system. The ability of existing bus systems to handle transferring power from the battery system to a given load is also important. Many designs for shipboard railgun systems include power storage systems at the location of the gun, which reduces the need for routing longer power transfer cables. This solution may negatively impact the ship's center-of-gravity, however, by putting very heavy energy storage systems near the deck, high above the waterline (Beach 2015). Additionally, high voltages can be routed longer distances by using alternating current. The DDG-1000 uses 4160 V-AC for its distribution system, which can move more power safely (Vandroff 2016).

III. ANALYSIS

A. CURRENT NAVAL BATTERY USE

The first research area explored existing batteries aboard Navy ships to understand the Navy's current utilization of batteries. Two major categories of systems were investigated: maritime and air. Research was conducted to understand what systems in these categories use batteries and the specific parameters of those batteries.

1. Maritime Systems

Analysis of maritime systems is divided into surface and subsurface categories. In this context, surface vehicles are loosely defined as vehicles that are deployed from a larger vessel. Naval ships (carriers, surface combatants, etc.) were not found to have any installed batteries and, therefore, are not a focus for this section. Discussion of surface and subsurface capabilities are further categorized as manned and unmanned.

DON continues to explore the potential for maritime unmanned surface vehicles (USVs), known as the "Ghost Fleet." The DON is planning for a large USV Program of Record decision in fiscal year 2023. Rear Adm. Casey Moton, the Program Executive Officer for Unmanned and Small Combatants (PEO USC) and Capt. Pete Small, the unmanned maritime systems Program Manager at PEO USC, spoke at the Association for Unmanned Vehicle Systems International (AUVSI) annual defense conference (Eckstein 2020). Rear Adm. Casey Moton elaborated on planned DON USV vehicles, capabilities, and notional timelines. PEO representatives referred to the capabilities of Mine Countermeasures (MCM) as a small unmanned surface vessel (SUSV), Sea Hunter as the medium unmanned surface vessel (MUSV), and Overlord as the large unmanned surface vessel (LUSV). The USVs outlined by PEO USC use petroleum-based fuels with no indication of significant lithium battery use (Small 2019).

Unmanned underwater vehicles (UUVs) were selected using the PEO USC road map (Small 2019). The unclassified roadmap provides context to the DON's catalog of current capabilities and direction for future UUV platforms. The roadmap identifies 10 vehicles earmarked as current or near-term UUV capabilities. This forward-looking document outlines the proposed evolution of the DON’s UUVs systems and provides a starting point for developing a research baseline.

Maritime subsurface vehicles are categorized as small, medium, large, and extra-large. Small UUVs (SUUV) are typically man-portable and require 1–2 persons. SUUVs weigh 10–50 kg (22–33 lbs.) and require no specialized equipment for deployment and recovery. Medium UUVs (MUUV), due to size and weight (up to 227 kg or 500 lbs.), are crew-served and deployable from a Rigid Hull Inflatable Boat (RHIB) or surface ship. Large category UUVs (LUUV) are launched from surface ships or submarines and weigh between 5,000–10,000 kg (11,000–22,000 lbs.) thus requiring winching and docking equipment to deploy and recover vehicles. Lastly, extra-large UUVs (XLUUV) are pier launched and designed for long range, long duration mission sets.

SUUVs require a small amount of energy to achieve mission endurance between 8 and 14 hrs. Currently in service are the MK 18 Swordfish and the IVER3 580EP UUV (L3Harris Technologies, Inc. n.d.). The MK18 Swordfish leverages the Remus 100 chassis and is powered by up to three internally rechargeable 3.2 Ah Li-ion cells generating 1.5 kw of power (Janes 2021). Li-ion batteries supply the Remus 100 with an estimated system endurance of up to 12 hours (depending on configuration and environmental conditions). IVER3 configuration requires 800 Wh of power, providing an estimated 8–14 hours of system endurance. Both vehicles allow for internal charging and swappable Li-ion batteries. Additionally, the Bluefin Sand-Shark, which may be discontinued, has lithium-polymer battery packs with rated power of approximately 1.5 kWh (General Dynamics Mission Systems, Inc. n.d.).

DON’s proposed catalog of MUUVs consists of several littoral battlespace sensing (LBS) configurations, autonomous unmanned vehicles (LBS-AUV), gliders (LBS-G), and the improved AUV(S) Razorback. Alongside LBS options, DON maintains an inventory of Kingfish and Knifefish UUVs. Built on a REMUS 600 submersible craft, the Razorback, LBS-AUV, and the Kingfish are powered by a 5 kWh Li-ion battery, allowing approximately 24 hrs of run-time (Hydroid n.d.). LBS-G resides on the Slocom G3 glider—a torpedo-shaped vehicle. This winged underwater vehicle can operate for up to 18 months and can be powered by Li-ion batteries (Teledyne Brown Engineering 2021). Although online materials state the glider can use alkaline or Li-ion battery chemistry, the amount of energy required for vehicle operation is not readily available.

The Snakehead and ORCA represent the Navy's large and extra-large UUV categories. Described as long endurance, multi-mission vehicles, each requires specific support structures for launch and recovery. The Snakehead requires heavy equipment and is compliant with shipboard payload handling systems and can be launched/ recovered using a submarine's dry deck shelter. The Orca is limited to deployment from a pier, due to its size, with a length of 15.5 meters and weight of 51 metric tons (Mizokami 2019). Powered by 18 kW of Li-ion battery power and on-board power generation for recharging, the Orca can deploy for months and travel approximately 6,500 nautical miles (Mizokami 2019).

2. Air Systems

There are few examples of Li-ion batteries on aircraft in service in the Navy today. For manned aircraft, the only two platforms the authors found that use Li-ion batteries are the F-35 and the CH-53K. The F-35 uses two Li-ion batteries. The first is a 270 V, 1750 Wh battery to power the aircraft's flight controls in case of engine failure and to start or restart the engine on the ground or in flight (NS Energy Staff Writer 2013). The second is a 28 V, 900 Wh battery, used for emergency power of aircraft electrical systems (NS Energy Staff Writer 2013). The specifics of the Li-ion battery used in the CH-53K could not be found in the open literature, however, the battery manufacturer states that the battery is designed for a high discharge rate for engine start and emergency power and that the battery will be "part of an integrated design with the control software and electronics of the aircraft system" (Concorde Battery Corporation n.d.).

The only two unmanned aircraft found with batteries are the small, man-portable RQ-11 Raven and the RQ-20 Puma. The RQ-11 Raven has a 25.2 V, 4 Ah battery and the RQ-20 Puma has a 24.5 Ah capacity battery (Coba 2010). Voltage information for the RQ-20 Puma battery is not available, but based on similarly-sized hobby RC aircraft, the authors estimate a voltage of 22.2 V (Hacker Motor USA 2017), making the total battery capacity approximately 544 Wh.

B. FUTURE FLEET STRUCTURE

This section investigates how the Navy might implement batteries in the future using estimates of the shape of the future fleet force structure. Relevant aspects of the future fleet include the types and number of ships and the types and numbers of power-hungry technologies deployed aboard them.

1. Types and Numbers of Ships

SECNAVINST 5030.SC, "General Guidance for the Classification of Naval Vessels and Battle Force Ship Counting Procedures," gives top level guidance for determining the size of the fleet. This policy aggregating ships into classes and categories. The Navy's 30-year Shipbuilding Plan also uses these categories, apart from dividing surface combatants into separate groups for small and large ships. Thus, the following seven categories were used as the basis for ship counting in this study:

- Aircraft Carriers
- Large Surface Combatant
- Small Surface Combatant
- Submarines
- Amphibious Warfare Ships
- Combat Logistics Ships
- Support Vessels

As previously noted, unmanned systems are more likely to use Li-ion batteries; however, the study categories do not account for unmanned systems. While the Navy does not specifically include any unmanned system requests in the 30-Year Shipbuilding Plan for FY2023, the plan does include information from prior studies and battle force projections that were submitted in the FY2022 plan. In this plan, the Navy submits their projections of each ship category for three key aspects: 1) total inventory, 2) total retirements, and 3) total deliveries. The total inventory provides an estimate of the total number of all ships in the respective category during that year. The total retirements are the sum of how many ships in the category the Navy expects to decommission during that year. Lastly, the deliveries are a sum of how many new ships of the category the Navy expects to commission during that year.

The Navy submitted three distinct battle force alternatives for the mid- and far-term due to fiscal and environmental uncertainty. To simplify the analysis, the projected inventory and delivery schedules are averaged for the three alternatives. Additionally, total counts for 2023, 2030, and 2045 are used. While inventory amounts for each year can be used as-is, the deliveries for each period are calculated by summing the total deliveries for each category within each time range. For example, the total number of deliveries used for 2030 is comprised of the total number of deliveries from fiscal year 2023 through fiscal year 2030. Delivery estimations are not included for the unmanned systems since they are not included in the formal submission for fiscal year 2023. Table 1 shows the total ship counts that were derived from the 30-Year Shipbuilding Plan for Fiscal Year 2023 and used for this study.

Table 1. U.S. Navy Ship Inventory and Delivery Schedule

	2023	2030		2045	
Platform	Total Inventory	Deliveries	Total Inventory	Deliveries	Total Inventory
Aircraft Carriers	11	2	11	6	10
Large Surface Combatant	88	20	83	28	75
Small Surface Combatant	27	11	28	27	47
Submarines	67	12	58	47	71
Amphibious Warfare Ships	14	10	31	30	49
Combat Logistics Ships	4	12	34	22	49
Support Vessels	28	20	46	15	33

Attack, Ballistic Missile, and Cruise Missile Submarines were aggregated since they were not considered in this study. Adapted from Office of the Chief of Naval Operations (2022)

2. Future Technologies

After estimating the number ships that are likely to comprise the future force, the authors investigated future technologies that may be integrated and influence future battery use. Technologies that are especially power-hungry are emphasized as those are assumed to be the most likely to impact ship-wide battery use. Many future technologies were examined, but the authors found the two technologies most likely to impact battery use are high energy laser (HEL) systems and integrated power systems (IPS). Other technologies investigated but not included in the analysis include radar, railgun, high power microwave, and future electronic warfare systems.

HEL weapons currently are a topic of heavy research interest, with technology demonstrators being installed and tested on fielded vessels such as the 30 kw Laser Weapon System (LaWS) deployed on the USS Ponce (AFSB 15, formerly LPD 15) in 2014, the 150 kW Laser Weapon System Demonstrator (LWSD) deployed on the USS Portland (LPD 27) in 2020, and the 120 kw High-Energy Laser with Integrated Optical-dazzler and Surveillance (HELIOS) deployed on the USS Preble (DDG 88) in 2022 (Peach 2014;

Mizokami 2020; Lockheed Martin Corporation 2021). These latest HEL demonstrators use the same level of power of lasers that are predicted to be fielded on new ships and possibly be retrofitted onto older vessels in the mid-term. This conclusion is supported by the plan to equip the DDG(X) with a 150-kW laser as part of its baseline capabilities (Hart 2022). For the far term, it is expected that ships will be equipped with multiple, higher-power lasers. This prediction is based on the rapid pace of technology development in the field of HEL combined with the DDG(X) future capability plan to field two 600 kW lasers (Hart 2022). Batteries might be used to fire the laser weapon if the ship's generator cannot provide sufficient on-demand power.

IPS systems are promising technologies already fielded on the DDG-1000 (PEO Ships 2019). IPS systems use generators to produce electricity to power subsystems and drive electric motors that move the ship. The traditional approach, in contrast, uses engines mechanically coupled to the driveshaft to turn the propellors or impellors that propel the ship and smaller generators to power electrical subsystems. The IPS concept increases flexibility to power various subsystems when full power is not needed to move the ship.

The Navy already has plans to evolve the IPS architectures in current and future ships into an Integrated Power and Energy System (IPES) architecture (Markle 2018). IPES is similar to IPS, but incorporates advanced controls and energy storage. This enhances support for future capabilities while improving ship survivability and efficiency. The energy storage form that is most likely to enable this technology is a large array of batteries distributed throughout the ship. Based on publicly available briefing packages from the DDG(X) program and the Navy's Electric Ships Office, IPS architectures are likely to be common in the mid-term, especially for newer ships, with IPES architectures not likely to be fielded until the far term (Hart 2022; Markle 2018).

3. Number of Vehicles

Most Li-ion batteries aboard naval ships are likely to reside within systems transported by the ship, but not necessarily part of the organic ship structure, such as aircraft, deployable unmanned systems, or land-based fighting equipment like tanks or armored personnel carriers. Since the actual complement of these platforms depends on the current mission, the authors used the published standard complement, when available, or whichever complement contained the most platforms. For example, an America Class amphibious assault ship can carry a mixture of: F-35B Joint Strike Fighter aircraft, MV-22 Osprey tiltrotor aircraft, CH-53E Sea Stallion helicopters, UH-1Y Huey helicopters, AH-1Z Super Cobra helicopters, and MH-60S Knight Hawk helicopters (Naval Sea Systems Command 2021). The most consistent open sources for this information were found to be Wikipedia and Janes Defense. While neither source is likely to be completely accurate, the known variability in the complements of each individual ship, for each mission, lessens the impact of obtaining official complement data from naval sources.

Information about the general complements of major vehicle platforms for each ship type is widely available. However, less information is available to determine the number of smaller platforms that may be onboard. For example, little information is published about the potential number of packable Raven UAS that Marines may bring onboard even though it is known that they are present. A better understanding of the type and quantity of these systems would improve the results of this research, since it is more common today for these unmanned systems to use Li-ion batteries than it is for larger, full-size vehicle platforms (e.g., manned aircraft). Estimations informed by known uses of systems today, reported test events, and predictions of future use as supported by current Navy concepts are used for the type and quantity of these platforms in this research (Department of the Navy 2021; Rosenberg 2021; Office of the Chief of Naval Operations 2022; Naval Sea Systems Command 2019; Englehorn 2021).

C. ENERGY GENERATION VS. STORAGE TRADE SPACE

This section focuses on the tradeoffs between generating energy outright and storing energy to be used by systems on demand. Currently, most U.S. Navy vessels employ multiple generators that can provide enough energy to power all the systems on the ship. Often, there are enough generators on the ship to allow it to run at full power even if a single generator is lost. This section explores the use of Li-ion batteries to store power generated by the ship-board generators for later use when needed.

The primary advantage of using generators is that they can harness the incredible stored energy density of petrochemicals. The volumetric energy density of gasoline is roughly 9,600 Wh/L (Schlachter 2012). In comparison, the volumetric energy density of a Li-ion battery is around 450 Wh/L (Vehicle Technologies Office 2022). Despite substantial improvements in the energy density of Li-ion batteries in the last 10–15 years, gasoline is still 20 times more energy dense when compared by volume. Gasoline, and other petrochemicals, fare even better against Li-ion batteries when compared on a weight basis. The specific energy density of gasoline is approximately 100 times larger than that of Li-ion batteries (Schlachter 2012). Given this incredible disparity, it is unlikely that petrochemical driven generators will be replaced any time soon for vehicles where space and weight are at a premium and where range and endurance are critical.

Even though it is unlikely that traditional fossil fuel burning generators will be replaced on Navy vessels in the foreseeable future, there are many potential advantages that can be realized by supplementing generators with energy storage. The primary disadvantage of generators is that without any meaningful way to store energy, power must be used as it is generated or it is wasted. Many generators can operate at various speeds and fuel burn rates to generate more or less power but these rates tend to be narrow and the efficiency of the generator suffers when operated outside its optimal speed. Additionally, it can be challenging to ramp up or ramp down generators quickly to meet changing electrical demands. In practice, generators are typically run at a fixed, optimal speed and any power that is not used is lost. This is typically not the case with engines used for propulsion. Typically, these engines are operated at various speeds to appropriately control the speed of the ship and are designed to be maximally efficient when the ship is sailing at its cruise speed.

Using batteries to store energy reduces wasted power, because the generator can be shut off when it is not in use. Batteries can deliver a diverse range of power at remarkably high (and low) energy levels if the demand is within the battery operating limits, which can be designed for very high charge and discharge rates. Additionally, batteries can cycle between various power demands instantaneously, without penalty, making them especially well-suited for fluctuating power demands required by many electronic warfare systems and directed energy weapons. Batteries can also be beneficial when combined with the ship's propulsion architecture to enable hybrid electric propulsion. Hybrid electric propulsion can yield higher fuel efficiency and reduce operation and sustainment costs while extending range and time on station for certain use cases and implementations. Additionally, as previously discussed, the Navy is moving towards IPES architectures to realize the many benefits of electrification. This architecture will combine generators with large onboard batteries to power the ship.

The amount of power that generators can produce has been incrementally improving, and that trend is expected to continue. For example, on the Arleigh Burke Flight III, the Rolls-Royce AG9140 (Rolls Royce n.d.) that can deliver 3 MW of power is being replaced by the new AG9160 (Rolls Royce n.d.) that occupies the same structural footprint but can deliver 4 MW of power. Similarly, Li-ion battery technology has been progressing, with rapid improvements being made to energy density. According to the U.S. Department of Energy, the volumetric energy density of Li-ion batteries has increased from 55 Wh/L in 2008 to 450 Wh/L in 2020, shown in Figure 3 (Vehicle Technologies Office 2022). It is unknown how long this rapid pace of energy density improvement will continue, but incremental improvements are expected to continue.

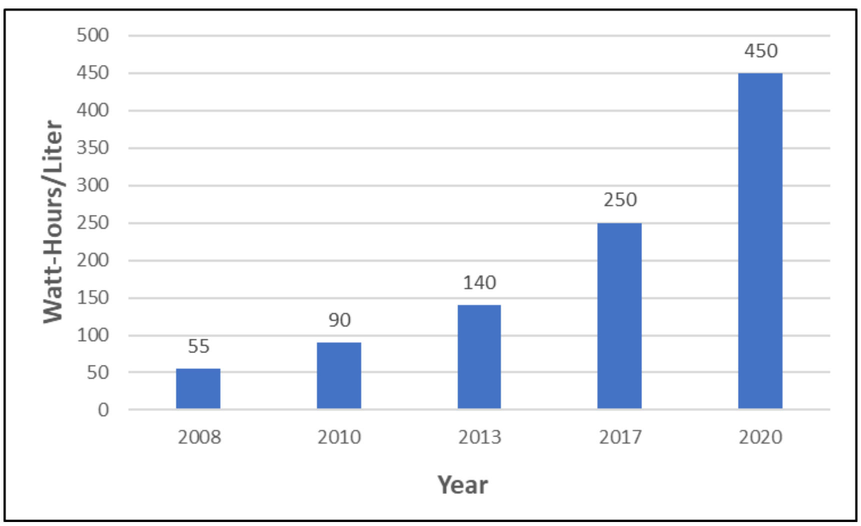


Figure 3. Li-ion Energy Density Increase over Time. Source: Vehicle Technologies Office (2022).

Despite major improvements in recent years, Li-ion batteries are still far behind gasoline in terms of energy density. This, combined with shipboard space constraints, make it unlikely that batteries will be able to fully power a ship in the foreseeable future. All the systems discussed in this paper are critical systems that must have power available when it is required. For these reasons, it is anticipated that ships in the mid- and far-term will be configured with generators or some other petrochemical energy system. This will remain the case until the energy density of Li-ion batteries is comparable to petrochemical systems. High energy laser systems are the only technology identified for this study that may be able to operate primarily on battery power, due largely to the fact that these systems are not on all or most of the time and require less power than that required to operate the radar or propel the ship. It is also worth considering that if HEL systems are retrofitted onto older ships, then a battery could help power the laser and then be slowly recharged by the smaller, older generators found on these platforms.

D. FUTURE BATTERY USE

This section focuses on predicting battery use in the mid-term and far-term. The results are divided into two main categories: roll-on/roll-off and organic (permanently installed) systems. Too little open-source information was available concerning organic batteries to be able to make reasonably-accurate predictions, therefore, this section instead offers several possible implementations for organic batteries in the mid and far term and discusses impacts and battery sizing considerations.

1. Roll-on / Roll-off Systems

Almost all the U.S. Navy systems that were found to have Li-ion batteries in the are roll-on / roll-off systems deployable from surface vessels. Using the information found in the Future Fleet Structure policy and, after making some assumptions about the future integration of Li-ion batteries in these systems, the authors made some predictions for the quantity and capacity of batteries that be deployed aboard future U.S. Navy vessels. To simplify the analysis, similar systems were grouped together. For example, systems such as the F-35 and F/A-18 were categorized into the “Manned Fixed Wing Aircraft” group. Other similar groupings were made such as “Group 1 UAS,” “Group 2 UAS,” etc.

Systems were grouped and assigned a representative battery size and likelihood of having a battery. The battery size each group was based on the battery sizes of known systems found in the previous investigation of current battery systems. The battery likelihood parameter was assigned to approximate the probability that an individual system in any given group would have a Li-ion battery. For example, in the "Manned Fixed Wing Aircraft" group, the main systems are the F-35 and the F/A-18. Currently the F-35 has 2 Li-ion batteries with a total capacity of 2,650 Wh while the F/A-18 has no Li-ion batteries. In the mid-term it is predicted that the U.S. Navy will be using the F-35 and the F-18 in approximately equal numbers. As such, for the Manned Fixed Wing Aircraft Group, for 2030, the Battery Likelihood parameter assigned as 0.5 and the battery size was set to 2,650 Wh. A similar approach was taken to assign battery likelihood and battery size parameters to all the identified groups, both for the mid-term and far-term.

These groups, with their associated battery size and likelihood, were then combined with the approximated ship complement found in the Future Fleet Structure research area. From this information, the authors were able to estimate the number of platforms that had Li-ion batteries and the total capacity of all batteries for both 2030 and 2045. Figure 4 shows the estimated number of platforms that will have Li-ion batteries. Figure 5 shows the total joint capacity of those batteries.

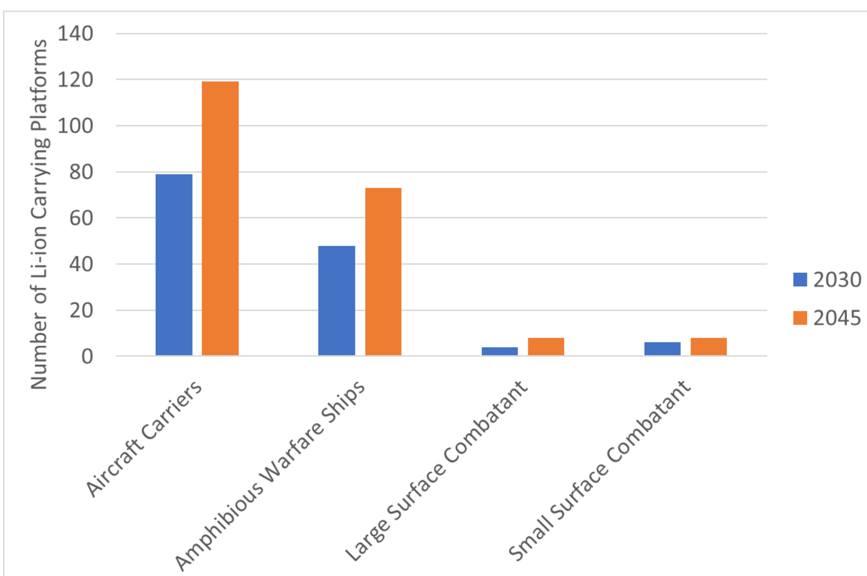


Figure 4. Projected Number of Platforms with Li-ion Batteries Onboard U.S. Navy Ships in 2030 and 2045

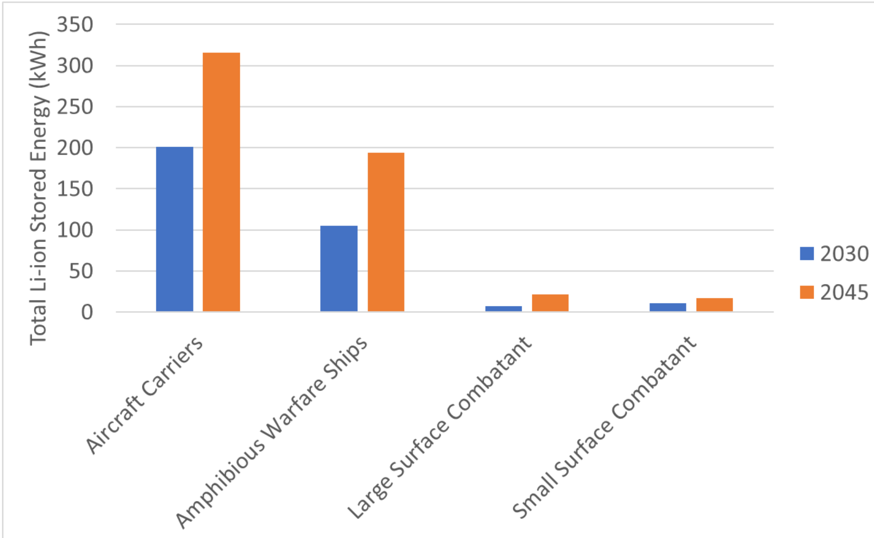


Figure 5. Projection of Li-ion Stored Energy Onboard U.S. Navy Ships in 2030 and 2045

It can be seen in Figure 4 and Figure 5 that both battery quantity and capacity are expected to increase dramatically in the coming years. Additionally, these figures highlight that aircraft carriers and amphibious warfare ships are particularly highly affected. Given the predicted electrification of vehicles in the future, these vessels will likely carry many systems with Li-ion batteries and the total combined capacity of those batteries can be significant.

In addition to the battery-containing systems that are launched and recovered from Navy ships as part of their mission, some naval vessels commonly transport Army and Marine Corps assets. This entails moving everything from personal gear to major equipment such as armored fighting vehicles and tanks. Given that the Army and Marine Corps are also investing in the electrification of platforms, these systems are likely to significantly contribute to the stored energy onboard these ship classes. It is reasonable to expect that new variants of some roll-on/roll-off platforms will carry Li-ion batteries by 2030 and that the number may significantly increase by 2045.

2. Organic Batteries

The future use of organic shipboard battery use is highly dependent on the state of IPS - and especially IPES - architectures on future ships. In the mid-term, it is expected that ships will have IPS but not yet have IPES. Large organic batteries capable of powering the entire ship for any amount of time are unlikely for this reason. It is more likely that certain high power consumption systems, such as HELs, which have been integrated with ships whose existing electrical generation systems cannot reliably support them, will also be retrofitted with a large battery for energy storage. Determining the appropriate size of such a battery is quite difficult and depends greatly on how much energy the ship can produce, how much energy the system uses and how long the system needs to operate before recharging. In terms of the power required to fire a HEL systems, the authors assume an efficiency of 30%, based on the typical efficiencies of solid-state lasers (which all the current HEL demonstrators are) (Michnewich 2018).

A total power draw of 500 kW would be required, assuming that ships in the mid-term will be deployed with a 150-kW laser. Furthermore, assuming the laser needs to be able to fire for a cumulative duration of one hour before the battery needs to be recharged, and assuming the ship has no excess power for charging the battery during that hour, a 500-kWh battery would be required. Based on an energy density of 450 Wh/L, a 500-kWh battery would be roughly 1.1 m^3 (39.2 ft^3) – a volume that would easily fit aboard a ship. With current fire suppression technology and careful planning and integration, the risk of fire should be relatively easily mitigated. Even a small increase in Li-ion battery storage could enable substantially increased capability for future laser systems (Gattozzi et al. 2015).

Ships in the far term are likely to have IPES, which are expected to include large onboard batteries. There is limited information available regarding the specifics of how future ships will use IPES, but as discussed previously, the basic framework will include large generators that generate enough power to drive electric motors to move the ship and to run all the other electric systems onboard. The batteries used on these future ships could be large enough to enable hybrid electric propulsion and benefit from all the advantages it provides, as discussed in the section concerning trade space. This onboard battery will likely be sized based on several factors, including those derived from an analysis of the potential benefits to efficiency, survivability, flexibility, and adaptability. Such a comprehensive analysis is outside the scope of this research, however, it is possible to arrive at a rough order-of-magnitude estimate based on current technology. One battery sizing parameter could be the duration the ship could operate on battery alone at maximum power required. To begin, an estimate of maximum power required is needed.

Using a large surface combatant as an example, the future DDG(X) is expected to be slightly larger than the current DDG 51 class. For ship propulsion, the Arleigh Burke Class destroyer is equipped with four General Electric LM 2500–30 engines, which produce a total of 100,000 horsepower, or about 75 MW of power (Naval Sea Systems Command 2022). In addition to the power required to propel the ship, there are additional electrical loads such as the radar, electronic warfare system, laser weapons, and other systems. To account for these systems, the total power requirement of the ship is increased by an estimated 5 MW for a total of 80 MW. Finally, to account for the larger size and additional technology of the DDG(X), the maximum power requirement estimate is increased to a total of 100 MW.

Using this maximum power requirement, and assuming a desire to be able to operate for 1 hour at full power using battery alone, an estimate of the size of the battery required can be derived. Based on the energy density of Li-ion batteries and pace of improvement shown in Figure 3, a future energy density of 900 Wh/L is used for the calculation. A hypothetical 100 MWh battery with an energy density of 900 Wh/L would occupy about 111 m^3 (4,000 ft^3) of space.

E. DISCUSSION

This research focuses on identifying the U.S Navy's current Li-ion energy storage aboard operational systems and projects the anticipated Li-ion battery requirements for the U.S. Navy operating force in 2030 and 2045. It is known that most ships today do not have any ability to generate electrical power from propulsion power plants or propel ships on electrical power alone. The power for electrical systems is customarily generated on a just-in-time basis, therefore there is little to no energy storage available. However, there are still Li-ion batteries onboard ships today and future ships will need to store substantial amounts of energy for various purposes.

The author's investigation concluded that the fleet has some reliance on Li-ion batteries, but most manned air systems and unmanned surface vehicles do not use Li-ion batteries. Notably, there currently appears to be more unmanned systems that use Li-ion batteries than manned systems. Additionally, all identified unmanned underwater vehicles leverage Li-ion batteries for propulsion and onboard system components. Other categories considered, but not explored, in this research were munitions, land systems, and expendables. These categories are important and include systems with Li-ion batteries that may make their way onto Navy vessels; however, they were not included in the scope of this study due to the lack of available data.

The future fleet structure analysis establishes a baseline understanding of the number of ships expected in the fleet along with the technologies and platforms that reside on them. Emerging ship-based technologies that use substantial amounts of stored energy (e.g., HEL and IPS) are expected to arrive en masse during the increase in ship deliveries between 2030 and 2045. Around the same time, new air and ground platforms are likely to begin replacing those that are present today. The result is a steep increase in the number of Li-ion batteries onboard ships due to the surging demand for stored energy and the efficiency of Li-ion.

The author's investigation of future navy battery use reinforced the likelihood of a dramatic increase in the use of Li-ion battery technology in the coming years. In addition to the electrification of naval based systems, other systems that must be transported on naval vessels are being increasingly electrified, further contributing to the increased prevalence of Li-ion batteries. This chapter also described the wide range of benefits that can be realized by using large batteries and hybrid electric power architectures. Successful integration requires that all Li-ion batteries aboard naval vessels are installed or transported safely.

The research indicates that the use of Li-ion batteries onboard Navy ships today is less than initially anticipated due to a limited number of combat systems that currently use large Li-ion batteries. Energy demands from weapon and sensor systems are growing already, and those demands are expected to continue. Future combat scenarios will likely require short, high-power bursts with minimal notice for both sensors and directed energy weapons. In those scenarios, there is a potential risk of outstripping the power generation capability of many ships, thus requiring substantial stored energy.

IV. SHIPBOARD BATTERY ANALYSIS TOOL

A. CONCEPT

The team developed a simple software tool to support this research effort and a summary is offered here. The authors hope this tool will aid the Navy in increasing the data fidelity used to inform policy regarding the use of Li-ion batteries in the fleet. Many systems engineering or software development products could have met the needs for organizing the open-source data used in this study. The requirements were akin to those used for standard database development, such as capturing batteries associated with various systems or platforms (e.g., manned/unmanned aircraft and maritime systems) and associating those platforms with specific ships based on a pre-determined timeframe (e.g., 2030 and 2045). A key requirement was that the users would be able to use the tool with the typical software available on unclassified Navy networks; thus, Microsoft Excel was selected. In general, the goal was to associate Li-ion batteries, by their sizes, with the platforms that carry them, based on timeframes, and associate those platforms to a specific category of ship to determine the total amount of onboard energy stored in Li-ion batteries. A high-level block diagram for the concept is shown in Figure 6.

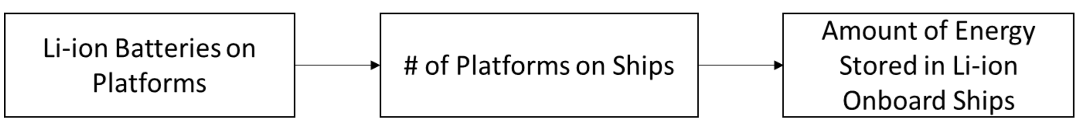


Figure 6. Software Tool Design Block Diagram

B. DESIGN

The tool closely aligns with the Navy's ship counting methodology, as outlined in the Ship Battle Forces document (Secretary of the Navy 2022), although there are some differences. One such difference is the general categorization of surface combatants, where it was determined that it would be worthwhile to split this classification into large- and small-surface combatants as is done in the long-range ship building plan. Although this research did not capture the submarine and logistics ship categories, they were included in the tool to assist with future expansion. There are also several ship classes within each standard category that represent major changes in the ship's design, but not necessarily a major change in its mission. Similarly, there are different ship flights within each class that entail different onboard technology packages. Thus, each ship can be classified by its category, class, and flight.

Standard database design practices were followed when building the tool to ensure its usability, efficiency, and extensibility. While Microsoft Excel is ideal for use as a database, it is more than capable given recent improvements that have expanded its ability to handle moderately complex database designs. Separate tables were created for ship category (*Lkp_Category*), class (*Lkp_Class*) and flight (*Lkp_Flights*). Additional tables were created to add timeframes (*Lkp_Timeframe*) for specific platforms along with their battery characteristics (*Lkp_Platforms*). The final data table associates the platforms with ships (*Tbl_ShipPlatforms*). All tables were developed with consideration for extensibility and usability. Each table was added to the Excel Data Model and "one-to-many" relationships were created between them to establish their connections. An Entity Relation Diagram (ERD) for the tool is shown in Figure 7.

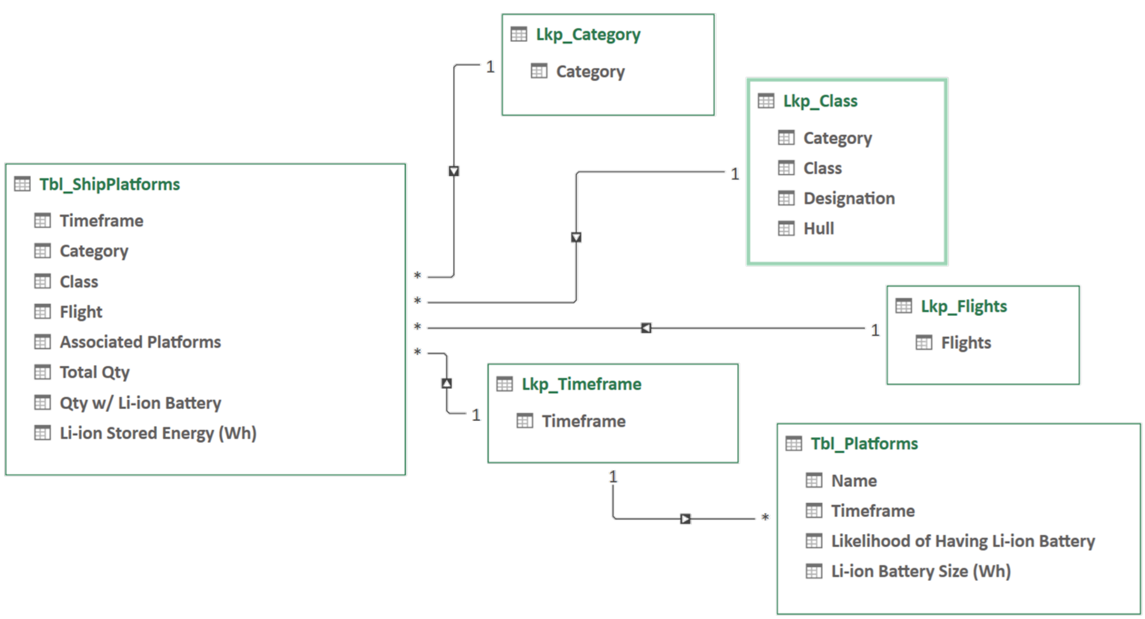


Figure 7. Entity Relation Diagram for the Shipboard Battery Analysis Tool

Three primary user groups were considered in the design of the tool:

- An admin with moderate to advanced knowledge of Excel PivotTables, advanced functions such as FILTER() and UNIQUE(), and with an understanding of spilled ranges was considered for occasional updates to the tool based on changing needs or new ship classes.
- A data entry user, responsible for knowing what Li-ion batteries are, or will be, present on individual platforms or someone who could identify what platforms are, or will be, present on various ships.
- N9 users responsible for understanding the implications of having Li-ion batteries onboard ships but who may not have the same detailed knowledge about the topic as a data entry user.

The tool consists of five sheets within the Excel workbook; two for admin use only, two for data entry, and one containing a summary of all data, to be used and interpreted by any user.

C. USE

Each sheet of the workbook was color-coded by user level - black for admins, blue for data entry users, and green for everyone. Editing restrictions were considered to ensure data integrity, but the team decided that the admin user could implement security controls according to their own policies. The two sheets, *Lookups* and *Dynamic Lists,* are for admin control and are colored black and hidden by default. *Lookups* contain the lists for ship category, class, and flight, along with additional lookups for flight information (used as a lookup itself for *Lkp_Flights*), timeframe, and platforms that may be associated with ships. Some of these tables may require periodic updates when new ship classes or flights are added to the fleet or if the timeframes change. *Dynamic Lists* contains spilled lists that are used for dynamic drop-down choices to ease user data entry on other sheets. It should not require any admin modification, for any reason, since excess blank columns were included to allow for substantial expansion to the admin-controlled lists.

There are two sheets for entering data - *Platforms* and *Ship–Platforms*. Each of the sheet tabs are colored blue for easy identification. These are the most critical sheets in the tool due to their potential impact for decision making, so care must be taken by those entering data. The *Platforms* sheet is meant to be the first stop for data entry as each Li-ion carrying platform must be entered into the tool before it can be associated with a ship. The sheet contains four data elements for each platform; Name, Timeframe, Likelihood of Having Li-ion Battery (0–100%) of if the platform will have a battery at all, and Li-ion Battery Size (Wh), which is the total Li-ion battery capacity of platform in the specified timeframe. Figure 8 shows these elements as they are captured in a table on the *Platforms* sheet.

Name	Timeframe	Likelihood of Having Li-ion Battery	Li-ion Battery Size (Wh)
Manned Rotary Wing	2030	50%	1,750
Manned Rotary Wing	2045	75%	1,750
Medium Unmanned Rotary Wing	2030	50%	450
Medium Unmanned Rotary Wing	2045	75%	450
Large Unmanned Rotary Wing	2030	50%	2,650
Large Unmanned Rotary Wing	2045	75%	2,650
Manned Fixed Wing	2030	50%	2,650
Manned Fixed Wing	2045	75%	2,650
Group I UAS	2030	100%	33
Group I UAS	2045	100%	33
Group 2 UAV	2030	100%	544
Group 2 UAV	2045	100%	544
Group 3 UAV	2030	50%	33
Group 3 UAV	2045	75%	33

Figure 8. List of Previously-Entered Platforms on the *Platforms* Sheet of the Shipboard Battery Analysis Tool

In the macro-enabled version of the tool, a blue button was included; *Add a New Platform*. Once clicked, the user is prompted to complete a form in a pop-up window, see Figure 9, and the new platform will be added to the table.

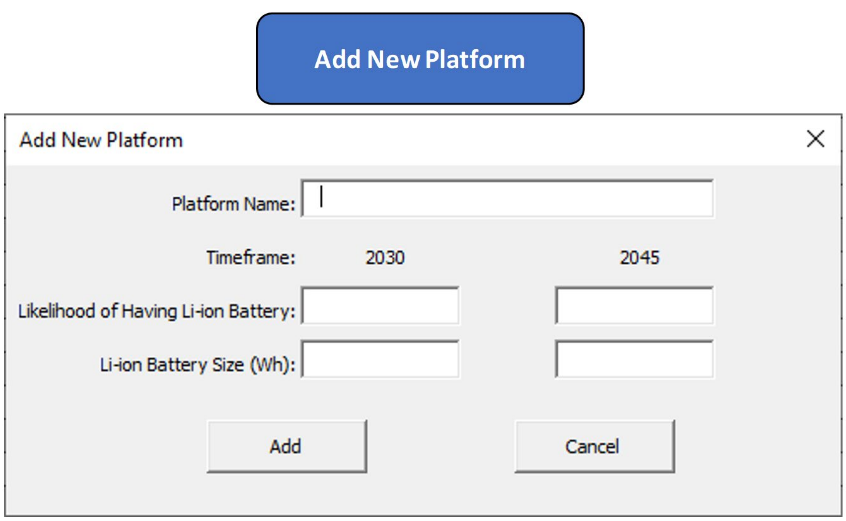


Figure 9. Button and Form to Add New Platform

If the user would simply like to view the current platform information in the tool, the drop-down menu for Platform Lookup can be used to populate a table that contains timeframe-specific information for the platform's Li-ion battery likelihood, associated battery size, and what ships it is currently associated with in the tool. Figure 10 shows the Platform Lookup section of the sheet. This information may be helpful for both data verification and validation.

Platform Lookup:	Manned Rotary Wing	
Timeframe:	2030	2045
Likelihood of Having Li-ion Battery:	50%	75%
Li-ion Battery Size (Wh):	1,750	1,750
Present on Ship Classes:	America	-
	Arleigh Burke	
	Blue Ridge	
	Constellation	
	Freedom	
	Gerald R. Ford	
	Harpers Ferry	
	Independence	
	Lewis B. Puller	
	Nimitz	
	San Antonio	
	Ticonderoga	
	Wasp	
	Whidbey Island	
	Zumwalt	

Figure 10. Platform Lookup Section of the Platforms Sheet of the Shipboard Battery Analysis Tool

The next sheet intended for data entry is *Ship–Platforms*, shown in Figure 11 and Figure 12. In this sheet, the user will associate the Li-ion carrying platforms with the ship(s) that may carry them. Most of the necessary data – timeframe, ship category, class, flight, associated platforms, and quantity of each platform – is fillable via drop-down menus.

Data entry on this table is done via direct entry into the table. However, another blue button, *Add New Platform to Ship*, was included to add a new row easily to the top of the table to accept the new entry. Starting from left to right, new data can be added via the in-cell drop-down menus that are based on pre-existing data in the tool. The only entry that does not have a preset drop-down is the total quantity column (Total Qty). General users should contact the admin user if the desired data is not in the drop-down menu. A PivotTable with slicers for the ship category, class, and flight were all included on the sheet as a quick means to find data that may already be captured in the tool. If a new entry is made, the blue *Refresh Tables* button will update that PivotTable along with all others in the workbook. Note that the tables will not update automatically after new data is entered.

Timeframe	Category	Class	Flight	Associated Platforms	Total Qty
2030	Aircraft Carriers	Gerald R. Ford	-	Manned Fixed Wing	75
2030	Aircraft Carriers	Gerald R. Ford	-	Manned Rotary Wing	10
2045	Aircraft Carriers	Gerald R. Ford	-	Manned Fixed Wing	75
2045	Aircraft Carriers	Gerald R. Ford	-	Large Unmanned Rotary Wing	10
2030	Aircraft Carriers	Nimitz	-	Manned Fixed Wing	64
2030	Aircraft Carriers	Nimitz	-	Manned Rotary Wing	7
2045	Aircraft Carriers	Nimitz	-	Manned Fixed Wing	64
2045	Aircraft Carriers	Nimitz	-	Large Unmanned Rotary Wing	7
2030	Amphibious Warfare Ships	America	0	Manned Rotary Wing	25
2030	Amphibious Warfare Ships	America	0	Manned Fixed Wing	6
2045	Amphibious Warfare Ships	America	0	Large Unmanned Rotary Wing	25
2045	Amphibious Warfare Ships	America	0	Manned Fixed Wing	6
2030	Amphibious Warfare Ships	America	I	Manned Rotary Wing	2
2030	Amphibious Warfare Ships	America	I	Manned Fixed Wing	20
2045	Amphibious Warfare Ships	America	I	Large Unmanned Rotary Wing	2

Figure 11. Data Table from Ship–Platforms contains all platforms associated with their ships

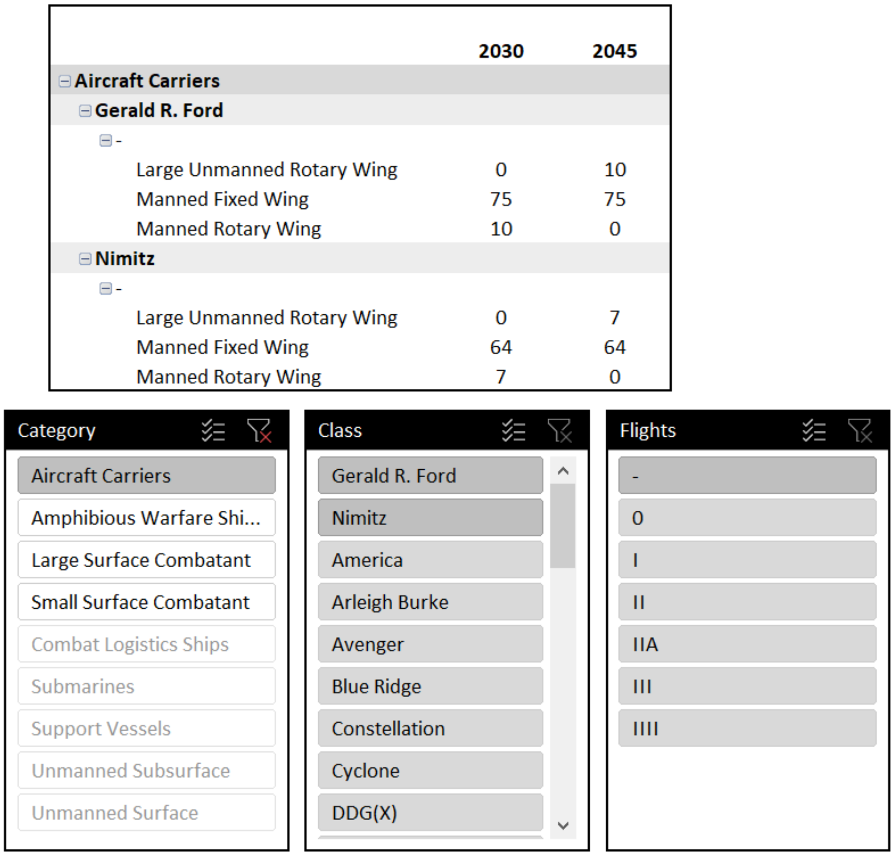
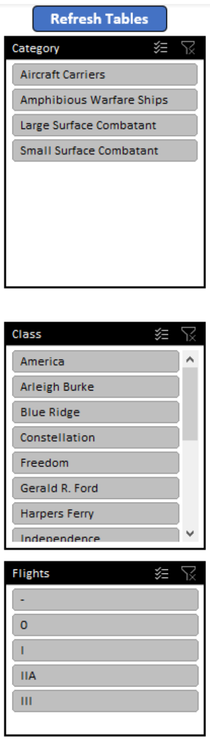
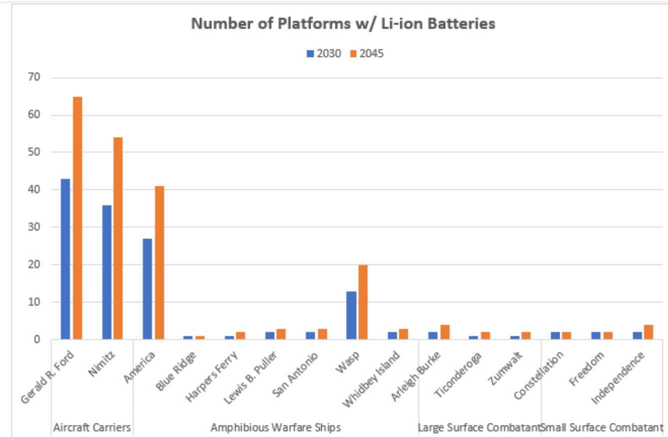


Figure 12. Ship–Platforms PivotTable of Existing Data and Slicers—Currently Filtered to Display only Aircraft Carriers Category

The last sheet of the tool, *Summary,* is meant for all users and is colored green. Like its title, this sheet is intended to be a summary of the rest of the data captured elsewhere in the tool. The sheet offers the user several slicers that can be used to filter the displayed data to only the desired ship(s) of interest. It also presents the Li-ion battery data for the filtered ships in both tabular and graphical forms. The central table and the associated graphs show both the number of Li-ion carrying platforms and the respective amount of energy stored in the Li-ion batteries, presented as Wh. This dashboard-like presentation is intended to convey the most important aspects of Li-ion batteries aboard Navy ships within defined timeframes to help the Navy identify major trends across the fleet. Figure 13 shows an image of the main parts of the S*ummary* sheet of the Shipboard Battery Analysis Tool.



	2030			2045		
	Qty	Sum of Qty w /Li-ion Battery	Stored Energy (Wh)	Qty	Sum of Qty w /Li-ion Battery	Stored Energy (Wh)
Aircraft Carriers						
Gerald R. Ford						
Large Unmanned Rotary Wing	0	0	0	10	8	21,200
Manned Fixed Wing	75	38	100,700	75	57	151,050
Manned Rotary Wing	10	5	8,750	0	0	0
Nimitz						
Large Unmanned Rotary Wing	0	0	0	7	6	15,900
Manned Fixed Wing	64	32	84,800	64	48	127,200
Manned Rotary Wing	7	4	7,000	0	0	0
Amphibious Warfare Ships						
America						
Large Unmanned Rotary Wing	0	0	0	27	21	55,650
Manned Fixed Wing	26	13	34,450	26	20	53,000
Manned Rotary Wing	27	14	24,500	0	0	0
Blue Ridge						
Large Unmanned Rotary Wing	0	0	0	1	1	2,650
Manned Rotary Wing	1	1	1,750	0	0	0
Harpers Ferry						
Large Unmanned Rotary Wing	0	0	0	2	2	5,300
Manned Rotary Wing	2	1	1,750	0	0	0
Lewis B. Puller						
Large Unmanned Rotary Wing	0	0	0	4	3	7,950
Manned Rotary Wing	4	2	3,500	0	0	0
San Antonio						
Large Unmanned Rotary Wing	0	0	0	4	3	7,950
Manned Rotary Wing	4	2	3,500	0	0	0
Wasp						
Large Unmanned Rotary Wing	0	0	0	6	5	13,250
Manned Fixed Wing	20	10	26,500	20	15	39,750
Manned Rotary Wing	6	3	5,250	0	0	0
Whidbey Island						
Large Unmanned Rotary Wing	0	0	0	3	3	7,950
Manned Rotary Wing	3	2	3,500	0	0	0
Large Surface Combatant						
Arleigh Burke						
Large Unmanned Rotary Wing	0	0	0	4	4	10,600
Manned Rotary Wing	4	2	3,500	0	0	0
Ticonderoga						
Large Unmanned Rotary Wing	0	0	0	2	2	5,300
Manned Rotary Wing	2	1	1,750	0	0	0
Zumwalt						
Large Unmanned Rotary Wing	0	0	0	2	2	5,300
Manned Rotary Wing	2	1	1,750	0	0	0
Small Surface Combatant						
Constellation						
Large Unmanned Rotary Wing	1	1	2,650	2	2	5,300



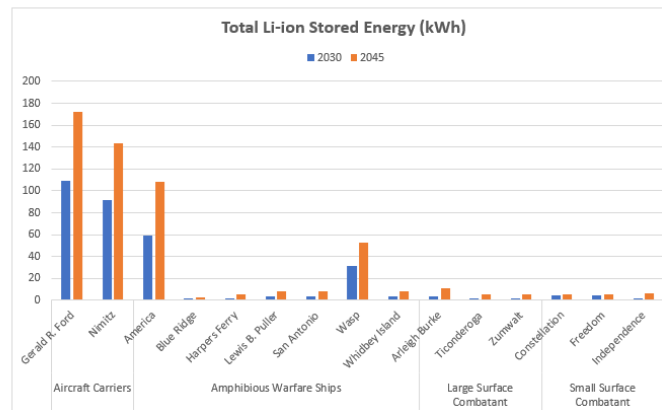


Figure 13. Summary Sheet of the Shipboard Battery Analysis Tool

D. ADOPTION AND EXPANSION

Although the tool developed here sufficiently organized the available data, updated data collected from subject matter experts in the specific technologies using lithium-ion batteries for naval applications should be input before the results are used to inform any major integration decisions. This study used available open-source data, but more accurate or current data may alter the trends presented in the summary. As was suggested previously, there are many other software packages that could be used to build a similar tool, including better database-management options such as Microsoft Access, SQL, or Mongo DB, even following the same design; however, most anticipated users are unlikely to be familiar with or have access to these databases software tools, hence the choice to use Microsoft Excel.

The team is aware of some previous efforts to capture Li-ion use in the fleet. It is recommended that future efforts capture the data elements necessary to populate this tool, as the incorporated metrics are the most salient for informing decisions regarding the implementation and adoption of Li-ion batteries when considering the risks to a particular ship. The team also recommends that the tool be extended to account for individual ships via another lookup table to delegate the platform-to-ship association to each ship's commander. Any ship may contain different platforms based on an assigned mission, so its Li-ion energy storage may vary by mission in addition to varying by the timeframe. If successful in implementation at the ship level, the Navy may consider implementing tools based on storage or use-location onboard a ship.

Understanding the general number and capacity of Li-ion batteries onboard a ship is a good starting point, but the fire risk is also associated with their proximity to one another – aggregate storage is a very significant factor. Naval engineers should understand the risks associated with Li-ion battery storage and how those risks may affect future designs; however, legacy ship designs will remain prevalent in the modern Navy and must be considered. Likewise, future platforms will be brought onboard ships that were not initially designed to carry/service them. Basic inventory-like tracking of Li-ion batteries onboard ships using a tool like such as the one presented may be helpful in platform-based risk assessments as well as informing broad Naval policies.

V. CONCLUSION

The purpose of this research effort was to help the N9 Warfare Systems office determine the resources required to support the integration of Li-ion batteries in the fleet in the 2030 and 2045 timeframes. The research team worked with the office to delineate four tasks to achieve that goal: (1) determine the use of Li-ion batteries in the current Navy fleet from open source information, (2) examine the future fleet structure and investigate emerging technologies that might use Li-ion batteries, (3) perform a trade space analysis for energy generation versus energy storage aboard Navy ships, and (4) develop a means for making recommendations regarding the future use of Li-ion batteries. The results of these tasks are captured in this report.

The research supported the original assumption that Li-ion battery technology will play an increasing role in the electrification of the fleet. The energy density of Li-ion batteries, in contrast to petrochemicals, is a long way from serious consideration as an option for ship propulsion; however, there is a significant role for Li-ion in powering mission-related systems and vehicles from a host vessel. The key challenge with estimating the exact quantity of Li-ion batteries that must be stored on future platforms is the unknown rate of Li-ion technology growth. Li-ion has experienced exponential growth in both general prevalence and improvement to its energy density since 2008, but it is expected that this growth will plateau at some point in the relatively near future.

Key considerations for shipboard Li-ion battery integration include the risks associated with thermal runaway and fire. For years, many small, unaccounted Li-ion batteries, such as those used for personal mobile phones, laptop computers, and battery backups for small electronics, have been carried aboard Navy ships while other Li-ion batteries, such as those used in missiles and sonobuoys, have been subjected to formal review processes even though they may be smaller or less of a fire risk. Loss of life or ship due to an uncontrolled thermal runaway is likely the greatest risk posed by Li-ion batteries, however, it is unrealistic and unnecessary for the Navy to monitor and control every Li-ion battery that finds its way aboard a naval vessel. Consideration should be given to the battery's intended use and storage location, including its proximity to critical systems.

Li-ion is here to stay, and continued investment in Li-ion battery technology will, among other things, support the improvement of its energy density – thus making Li-ion batteries even more applicable for future integration use cases. Continued investment in fire suppression, packaging and handling processes will help the Navy integrate the latest battery technology while minimizing risk to platforms and sailors. Perhaps most importantly, careful planning must be undertaken in future ship designs to account for the space (and other logistic) requirements borne of the ever-increasing demand for lithium-based energy storage. The use of specially-tailored software tools, such as the one provided in this study, may aid in the effectiveness of future designs and deliberate risk planning efforts, and should be regularly updated with the most current data to maximize its utility.

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