2022-09

BATTERY USAGE IN THE FUTURE FLEET

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Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/71135

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE REPORT

BATTERY USAGE IN THE FUTURE FLEET

by

Sean G. Auld, Daniel V. Camp, Paul Kylander,
Nathan Vey, and Jerald J. Willis

September 2022

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2022	**3. REPORT TYPE AND DATES COVERED** Systems Engineering Capstone Report

4. TITLE AND SUBTITLE
BATTERY USAGE IN THE FUTURE FLEET

5. FUNDING NUMBERS

6. AUTHOR(S) Sean G. Auld, Daniel V. Camp, Paul Kylander, Nathan Vey, and Jerald J. Willis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

This research effort examined the current advanced battery requirement (baseline) and projects anticipated battery requirements for the operating force in 2035 and 2045. The research is conducted using a mission engineering perspective to determine the battery requirements. The analysis includes battery chemistry, energy density, charge/discharge rate, safety concerns, and the like, of the battery. In this research the following questions are answered: What is the current advanced battery requirement (baseline)? What is the projection for batteries required by the operating force by 2035? What is the projection for batteries required by the operating force by 2045? Upon completion of the research, the team was able to definitively determine that there will be a role for Li-ion batteries within the fleet of Navy vessels. That role will, however, be limited to running specific subsystems or equipment and will not replace the ship generators. This will remain true until the energy density of battery technology even begins to approach that of petrochemicals, which we believe is many years away if possible.

14. SUBJECT TERMS
battery, batteries, Li-ion, energy storage, naval batteries, future fleet, future battery use, naval architects, naval applicability, energy generation, storage trade space, shipboard battery analysis

15. NUMBER OF PAGES
81

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Nathan Vey, and Jerald J. Willis

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2022

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This research effort examined the current advanced battery requirement (baseline) and projects anticipated battery requirements for the operating force in 2035 and 2045. The research is conducted using a mission engineering perspective to determine the battery requirements. The analysis includes battery chemistry, energy density, charge/discharge rate, safety concerns, and the like, of the battery. In this research the following questions are answered: What is the current advanced battery requirement (baseline)? What is the projection for batteries required by the operating force by 2035? What is the projection for batteries required by the operating force by 2045? Upon completion of the research, the team was able to definitively determine that there will be a role for Li-ion batteries within the fleet of Navy vessels. That role will, however, be limited to running specific subsystems or equipment and will not replace the ship generators. This will remain true until the energy density of battery technology even begins to approach that of petrochemicals, which we believe is many years away if possible.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	alternating current
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
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
USS	United States Ship
UUV	unmanned underwater vehicle
WIC	Warfare Innovation Continuum
XLUUV	extra-large UUV

EXECUTIVE SUMMARY

As part of their Energy Storage Strategy, the Department of Navy (DON) are developing mid- and long-term plans for the electrification of its fleet of ships. Driving this strategy is the need to provide energy solutions for power-hungry modernized mission equipment, advanced weapons systems, and the multitude of manned and unmanned vehicles that are operated from Navy vessels. Electrification initiatives include the employment of batteries and more specifically Lithium-Ion (Li-ion) batteries, which have been shown to provide the best size, weight, and power characteristics to meet stored energy requirements. The research team completed four primary tasks on behalf of the DON to determine the Li-ion battery requirements in the years 2030 and 2045. The tasks were as follows:

1. Identify the use of batteries on board the current Navy fleet
2. Discuss the future fleet structure
3. Conduct a trade space analysis between energy storage and energy generation
4. Predict the use of future batteries in the years 2030 and 2045

The research and findings of these tasks will enable the DON to develop and implement plans and programs that meet their electrification objectives. Using open-source resources, the research team, completed all tasks and captured the detailed results in this capstone report.

The proliferation of Li-ion batteries is due to their size, weight, and power advantages but is also due to their improved energy density over lead acid alternatives. Energy density is the amount of energy stored in each system or region of space per unit volume or mass (Golnik 2003). The greater the energy density the more effective the system. Another advantage of Li-ion is its life expectancy. Li-ion batteries tend to last 15–20 years versus other battery types that last only 5–7 years (Turcheniuk et al. 2018).

A primary concern with Li-ion technology is the risk of fire. Although very unlikely, Li-ion batteries can fail resulting in overheating, explosion, release of toxic gasses, or in extreme circumstances thermal runaway where an unrecoverable exothermic chain reaction takes place. 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 best fire suppression results a foam extinguisher with CO2, dry chemical, powdered graphite, copper powder, or soda (sodium carbonate) should be utilized.

The methodology for Task 1 was to examine both maritime and air vehicles within the Navy. Within the maritime category the research team focused on surface and subsurface vehicles that are launched from a vessel. All small, medium, and large unmanned surface vehicles (USVs) were found to be petroleum based with no Li-ion batteries included in their configuration. Conversely, small, medium, large, and extra-large unmanned underwater vehicles (UUVs) are or will be equipped with a variety of Li-ion batteries based on their individual power requirements (L3Harris Technologies, Inc. n.d.; Janes 2021; General Dynamics Mission Systems, Inc. n.d.; Hydroid n.d.; Teledyne Brown Engineering 2021; Mizokami 2019). Within the manned air domain, only the F-35 and CH-53K have Li-ion batteries installed and neither platform uses them for primary power (NS Energy Staff Writer 2013; Concorde Battery Corporation n.d.). In the unmanned air domain only the RQ-11 and RQ-20 were found to have Li-ion batteries (Coba 2010). In summary, there is some evidence of Li-ion battery use in both maritime and air vehicles, however, there is extensive use of Li-ion batteries in subsurface vessels.

Task 2 examines the Navy future fleet structure and potential uses for batteries for that future force. Leveraging the Annual Long-Range Plan for Construction of Naval Vessels for Fiscal Year 2023 (Office of the Chief of Naval Operations) and the Warfare Innovation Continuum (WIC) Workshop: Hybrid Force 2045 September 2021 After Action Report (Englehorn 2021), the research team was able to predict the number of operational vessels in 2030 and 2045. With that prediction in hand the team then examined technologies that would be appropriate for battery power. Although there are many possibilities, two technologies were identified as being well suited for battery power: high energy laser (HEL) and the integrated power systems (IPS). Given the emergence and exponential rise in technology demonstrations of HEL systems we foresee the integration of one or more systems onto the larger Navy vessels driving the need for battery technology. The Navy is also in the process of developing IPS technologies, which add energy storage capabilities as part of an overarching power management approach (PEO Ships 2019). Using generators to charge banks of Li-ion batteries is one viable option to improve the overall power management strategy. Given the growth in the number of ships and the incorporation of emerging technologies being integrated onto the Navy fleet we see a large growth in the use of batteries.

In Task 3, the research team looked at the trade between energy storage and energy generation. The key distinction between generators and batteries is that the energy generated by a generator is either used or it is lost versus a battery that can store energy and supply it when needed. The primary challenge with replacing generators with batteries is because the volumetric energy density of gasoline is 20 times greater than that of a Li-ion battery (Schlachter 2012; Vehicle Technologies Office 2022). Given this fact, it seems unlikely that Li-ion batteries will be able to replace generators any time soon although as was identified in Task 2, specific applications such as HELs (High Energy Laser) and IPSs (Integrated Power System) would include batteries in some capacity.

The final task of predicting battery use in the years 2030 and 2045 focused on deployable vehicles and permanently installed systems. In the case of deployable vehicles, significant increases in Li-ion use are predicted as seen in 0. The battery usage of permanently installed systems is more difficult to predict, however, based on the promise of IPES (Integrated Power and Energy System) architectures and HEL weapons, the research team expects that future ships will make use of large, on-board batteries, though the exact size will likely be determined through a comprehensive analysis that is outside of the scope of this research.

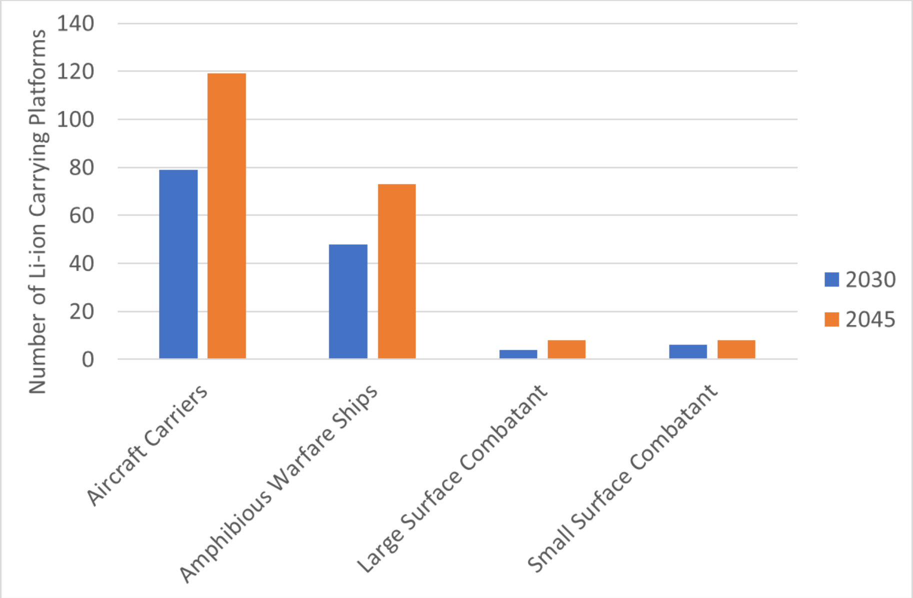

Figure 1. Projected Number of Platforms with Li-ion Batteries

Upon completion of the research the team was able to definitively determine that there will be a role for Li-ion batteries within the fleet of Navy vessels. That role will, however, be limited to running specific subsystems or equipment and will not replace the ship generators. This will remain true until the energy density of battery technology even begins to approach that of petrochemicals, which we believe is many years away if possible.

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ACKNOWLEDGMENTS

The team would like to thank the Naval Postgraduate School for developing and promoting a positive learning environment that is centered on the Department of Defense, the faculty members of the Systems Engineering Department for encouraging individual growth and sharing a wealth of knowledge, and all the staff behind the scenes. A special thanks goes to those who helped us through our capstone project: our project sponsor who set forth a challenge, Mr. Cayle Bradley; our advisors who kept us on track and answered our questions, Dr. Douglas Van Bossuyt, LCDR Ross Eldred, and Mr. Jonathan Lussier; our writing coach who helped ensure we wrote what we wanted to say, Dr. Kate Egerton; and our education technician who made sure we never missed a deadline, Ms. Heather Hahn. The most important thank you goes to our families and friends who supported us throughout our educational journey at the NPS.

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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 on the existing Navy fleet and to aid in figuring out what future battery requirements will be 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 expects that Li-ion batteries will continue to be the battery technology needed to support future systems. This research is meant to inform the Navy of the current state of Li-ion battery usage and to supply enough substantiation to request and secure more resources to appropriately equip the Navy fleet for the years 2030 and 2045.

B. BACKGROUND

The Department of Navy (DON) is seeking help in what has been termed the Energy Storage Strategy to support the electrification of its fleet. The Navy is pushing 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 DON from fully realizing 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 Navy's theory 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 2030 and in 2045 to start the planning and resourcing of those power sources. The Navy N9 Warfare Systems office started this project with the Naval

Postgraduate School (NPS) in October 2021 when they asked the research team to complete research to inform the Navy on the use of batteries aboard its fleet of vessels. The N9 and NPS research team agreed to four research tasks in key areas.

Task 1 was to perform an open-source literature review in the domain of battery technology with an emphasis on naval operational applications. The research team completed this task prior to the capstone group's involvement. The capstone group came onboard at the start of task two. The first task for the capstone team was to identify existing battery systems being employed in the current Navy operational fleet. Completion of Task 2 provides the Navy and the research team with a good starting point from which to scope and bound the larger battery problem. Research into the distinct types of battery technologies, understanding the benefits that Li-ion technology provides, discussion of the safety aspects of Li-ion, and an overview of battery metrics will establish a common baseline for the research team and the Navy. Task 2 establishes a baseline to determine future power requirements. Leveraging what is found in task two, task three then delves into the future fleet structure and the emerging technologies that will require the use of battery technology. Multiple technology papers and briefings discuss the future application of directed energy weapons (DEWs), unmanned aerial vehicles, unmanned surface vessels, unmanned subsurface vessels among many other future capabilities that are targeted for integration onto the Navy fleet. Many of these systems will require power to operate and determining those details will help define the battery requirements for those systems.

The next two tasks build on one another by first examining the trade space with Li-ion battery technology and then using those findings to make predictions on future battery use in the 2030 and 2045 timeframes. To complete the trade space analysis, the research team investigated the trade between energy generation and energy storage. With the trade space task completed, the final task was for the research team to make predictions on future battery use in the short and long term. Specifically, the team assessed the power needs of the future capabilities that are projected to be integrated onto the Navy fleet, and determined the batteries required to support future capabilities. Those were compared with what is anticipated to be available from a Li-ion battery standpoint, which was then translated into the overall battery requirements for the Navy fleet. Researching and gaining knowledge into the appropriate chemistry, examining the battery industry to determine the rate of growth in power output over time, and looking at the projections of future size, weight and power of modern batteries will facilitate the completion of the final task. This final task and the corresponding recommendations will provide the sponsors with a projection of what the battery needs of the future Navy are.

The Navy N9 Warfare Systems office has recognized the need and value of integrating Li-ion batteries onboard the Navy's fleet of vessels. A series of challenges from fire safety, platform integration and battery size, weight, and power present significant issues with realizing that objective. The research being performed on behalf of the Navy intends to explore those aspects of Li-ion technology and its employment on military vehicles. This research will also provide the Navy with the information they need to request and secure appropriate resources to equip the Navy with Li-ion batteries in the 2030 and 2045 timeframes.

This capstone report uses the "manuscript option"' (O'Halloran 2017). The format of this capstone is: Chapter I provides a broad overview and motivation and contextualizes the research; Chapter II is the journal manuscript that has been submitted to the *Naval Engineers Journal* for peer review; Chapter III explains the Shipboard Battery Analysis Tool that was developed to support the research; and Chapter IV is a summary of the capstone report and suggestions for future work.

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II. JOURNAL MANUSCRIPT

This chapter provides a journal manuscript that the capstone team prepared for submission to the *Naval Engineers Journal* for peer review. The submission to the *Naval Engineers Journal* will be Daniel Camp, Nathan Vey, Paul Kylander, Sean Auld, Jerald Willis, Jonathan Lussier, Ross Eldred, and Douglas L. Van Bossuyt, "Li-ion and the Electrification of the Fleet." Copyright does not apply in the United States because all authors are federal government employees to the submitted manuscript but may apply internationally.

A. INTRODUCTION

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 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—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 past few decades due to their performance advantages. Li-ion batteries, while having many advantages, also present an increased amount of risk that requires specialized monitoring equipment to predict and prevent battery 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, usage, storage, and as necessary conducts test events culminating in certification for use aboard Navy vessels.

Naval technology has witnessed significant changing tides of innovation over the last several hundred years to traverse vast distances at increased 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, even when it meant assuming 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 paper is to assist the Navy and Naval engineers in identifying the resources required to procure and integrate Li-ion batteries into the Navy fleet in the 2030 and 2045 timeframe. These requirements were determined by performing an assessment of the technology that will be integrated aboard Navy vessels at those key years, and then determining the corresponding power requirements. One of the foundational assumptions of this paper is that Li-ion batteries will be the battery chemistry employed by future Navy systems.

B. BACKGROUND

Prior to discussing the research results contained within this paper it is important to inform readers on several aspects of battery technology. To that end, a review of battery types and the factors that go into selecting a battery solution will be discussed. Following that, a review of battery metrics will be performed. There are several key metrics that battery developers take into consideration and need to trade off 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 if the battery is a primary or secondary power source, if 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 as 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 are 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.

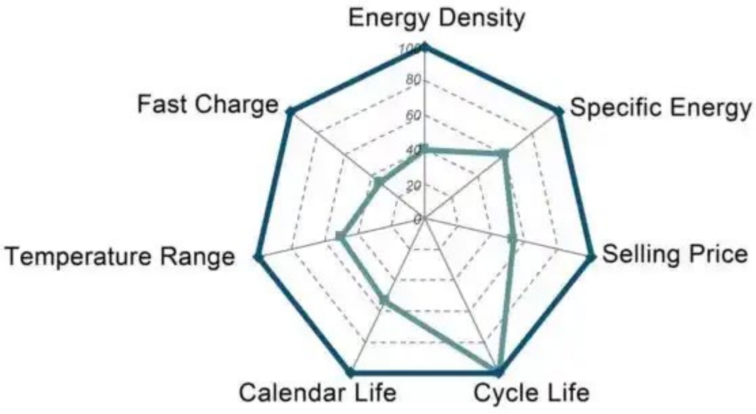


Figure 1. Battery Metrics. Source: Argonne National Laboratory (n.d.).

The two most common ways of measuring capacity are in Ampere Hours (Ah) or in 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 they have a much higher energy density for longer battery life in a lighter configuration. For example, Cummings Newsroom compares the energy density between

Li-ion and lead acid batteries: “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 the current trends with batteries, lead-acid batteries will soon be phased out for the more energy efficient and environmentally friendly Li-ion alternative. With Li-ion chemistries being able to accept a faster rate of charge current, this means they can charge much faster than batteries made with lead acid and provide improved energy efficiencies over other battery chemistries. Li-ion batteries 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 in older battery technologies. Li-ion batteries have a much longer life than traditional batteries as they do not lose permanent storage capacity during continued usage. 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 make-up of Li-ion batteries and how they work.

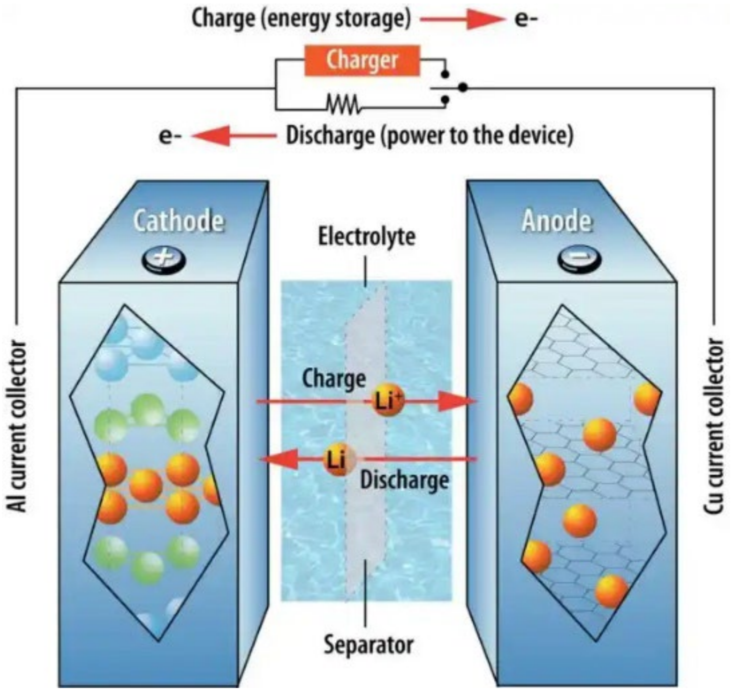


Figure 2. How a Lithium-ion Battery Works. Source: Argonne National Laboratory (2010).

Li-ion batteries do not have toxic cadmium in them, making it 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 leads users to often prefer them over other battery chemistries. Li-ion batteries offer a higher energy output in shorter amounts of time and therefore create a higher performing battery at a reduced cost. Li-ion batteries also have a better life expectancy of 15–20 years when compared to other battery types that typically have a life expectancy of 5–7 years (Kostiantyn Turcheniuk et al. 2018).

Li-ion batteries are considered safe, but they do require specific engineering and special safety precautions to prevent fires. Safety is one of the largest downsides to Li-ion batteries, particularly as the batteries age. Li-ion safety concerns revolve around their tendency to overheat and ability to be damaged at high voltages. In the case of using Li-ion batteries for shipboard energy storage, the large amount of energy present in one location gives rise to concerns of explosion, gas hazards, and in case(s) of battery module failure. Proper fire suppression, ventilation, and gas detection systems are critical in reducing the risk of fire and injury to sailors. The main reason Li-ion batteries are unsafe is because they are sensitive to elevated temperatures and are known to be flammable when not used properly.

Li-ion batteries become unsafe when they are operated outside the designed safe zone. The safe zone for Li-ion batteries is between 10° and 55°C (50°–131° F). One of the key differences between a Li-ion battery fire and traditional fires is that a Li-ion battery fire does not need oxygen to burn because the fire is created from a chemical reaction. 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 not able 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 even better 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, vent location, etc.; a generalized formula is proposed that predicts the computational fluid dynamics (CFD) model outputs and can give the recommended ACH for a given compartment (Gully et al. 2019).

During failure, a Li-ion battery produces gases in a process called off-gassing. 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, certain sensors, such as the Nexceris Li-ion Tamer placed within the battery module, can detect off-gas, 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).

The chances of a Li-ion battery catching fire are considered rare, although it is important to note that fire prevention and avoidance is a key factor in mitigating the safety risk associated with Li-ion batteries. Fire mitigation can be done by following the proper procedures regarding storage, usage, and maintenance. Li-ion batteries should be properly spaced and ventilated when stored. They 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 evaluates and compares the effectiveness of multiple fire suppression systems. While no “Silver Bullet” solution is 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, shows 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.

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. METHODOLOGY

(1) Problem Decomposition

The focus of this paper is on 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, and supply and transport ships are not included in this paper although they all have potential for a Li-ion footprint. The authors' focus is to approach the research in this paper in such a manner that both the scope of the research was manageable and to address the portion of the Navy most likely to be affected by the rising adoption of Li-ion batteries.

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:

1. Existing Battery Systems Aboard Operational Systems
2. Future Fleet Structure
3. Trade Space of Energy Generation vs. Storage
4. Predictions for Future Battery Use

This section will explore each of these research areas in more detail.

(2) Existing Battery Systems Aboard Operational Systems

In this research area the authors identify Li-ion battery systems being used aboard the existing Navy 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.

(3) Future Fleet Structure

Work in this research area focuses on developing predictions for future battery use in the mid-term and far-term—2030 and 2045, respectively. This includes considering vehicles and subsystems that are not currently battery powered but could be in the mid or far term. Work is also presented that predicts overall Navy force structure. This combination of systems that could use batteries and number of systems gives a basis for prediction of battery use in the future Navy.

(4) Trade Space of Energy Generation vs. Storage

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

(5) Predictions for Future Battery Use

This task develops predictions for future battery use across the fleet in the mid- and far-terms based upon the future fleet structure and the trade space analysis.

(6) Timeframes

An important aspect of this research is to consider the Li-ion issue in the near, mid, and far term. The near term is focused on systems that are either currently fielded or nearly fielded. For the mid and far terms, the authors selected 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).

(7) Data Collection Techniques

The authors 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.

D. ANALYSIS

1. Existing Batteries

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 have batteries and the specific parameters of those batteries.

A. Onboard 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 considered a focus for this section of the research. Discussion of surface and subsurface capabilities are further delineated by manned and unmanned categories.

DON continues to explore the potential for maritime unmanned surface vehicles (USVs), also referred to 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 as the Mine Countermeasures (MCM) as a small (SUSV), Sea Hunter as the medium (MUSV), and Overlord as the large USV (LUSV). The USVs outlined by PEO USC use petroleum-based fuels with no indication of lithium or significant battery usage (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 retrieve vehicles. Lastly, extra-large UUVs (XLUUV) are pier launched and designed for long distance, long duration mission sets.

SUUVs associated with this category require a small amount of energy to achieve mission endurance times 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. Indications are that the Bluefin Sand-Shark were discontinued; however, as this SUUV potentially is part of the Naval inventory and to ensure a thorough accounting, the Bluefin Sand-Shark have 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 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 underwater winged 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 differing support structures to launch and recover. The Snakehead requires heavy equipment and is compliant with ship payload handling system(s) 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).

b. Air Systems

There are few examples of Li-ion batteries on aircraft in service in the Navy today. In terms of manned aircraft, the only two platforms the authors found the use of Li-ion batteries on 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.).

For unmanned aircraft, the only two 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 pack 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 hobbyist RC aircraft, the authors assume a voltage of 22.2 V (Hacker Motor USA 2017), making the total battery capacity approximately 544 Wh.

c. Summary of Existing Batteries

The preceding section shows that the current fleet has some reliance on Li-ion batteries, but most manned air systems and unmanned surface vehicles do not use Li-ion batteries. Of note is that currently, there seem to be more unmanned systems that make use of Li-ion batteries than manned systems. Also, worth pointing out is that most systems that have Li-ion batteries are new systems. Additionally, all unmanned underwater vehicles leverage Li-ion batteries for propulsion and on-board 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 this study due to the high variability in the quantities onboard a ship and a lack of available data.

2. Future Fleet Structure

This area of research focuses on predicting how the Navy could use batteries in the future. This consists of gathering information to try to estimate the shape of the future fleet. There are several aspects of the future fleet that are relevant to this research: the type and number of vessels, the future power-hungry technologies likely to be onboard future vessels that could affect the need for or usage of ship-wide batteries, and the number of deployable vehicles aboard ships that could contain batteries themselves.

To better focus the problem, the authors use two distinct future timeframes: mid-term and far-term. Based on the information of future naval warfare and future Navy 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 Warfare Innovation Continuum (WIC) Workshop: Hybrid Force 2045 September 2021 After Action Report (Englehorn 2021), the authors use 2030 for the mid-term and 2045 for the far-term.

a. Types and numbers of ships

The U.S. Navy adheres to a Naval Instruction titled, "General Guidance for the Classification of Naval Vessels and Battle Force Ship Counting Procedures" for determining its fleet size. Such a policy aids in aggregating numerous purpose-built ships into classes and categories. The Navy's 30-year Shipbuilding Plan uses the same categories with the slight deviation of splitting Surface Combatants into separate groups for small and large ships. With that distinction, 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 Fiscal Year 2023, the plan includes information from prior studies and battle force projections that were submitted in the fiscal year 2022 plan.

In the plan, the Navy submits their projections of each ship category for three key aspects of the fleet: 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. Total inventory and total deliveries are deemed most important for this research since they represent the ships that are most likely to utilize or carry copious amounts of Li-ion batteries.

The Navy submitted three distinct battle force alternatives for the mid- and far-term due to fiscal and environmental uncertainty. To simplify the analysis in this paper, 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)

b. Future technologies

After determining the ships that are likely to make up the future navy, the authors investigate future technologies that may be included on those ships and that may influence future battery usage. Technologies that that are especially power-hungry are explored as those are assumed to be the most likely to impact ship-wide battery usage. Many future technologies are considered but the authors find the two technologies most likely to impact battery usage are high energy laser (HEL) systems and integrated power systems (IPS). Other technologies investigated but not included for several reasons include radar, railgun, high power microwave, and future electronic warfare systems.

HEL weapons are an area of heavy research focus and interest currently 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, or 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 are predicted to be the power of lasers that will be fielded on new ships and that will possibly be retrofit 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 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 could be used as an energy magazine to be able to fire the laser weapon even if the ship's generator cannot provide sufficient on-demand power. This very well could be the case for older ships retrofitted with laser weapons.

IPS systems are also promising technologies and are already fielded on the DDG-1000 (PEO Ships 2019). IPS systems use generators to produce electricity, which is used both to power subsystems that require electricity and to drive electric motors that move the ship. In contrast is the traditional approach, which uses engines mechanically coupled to the drive shaft and turns the propellors or impellors to move the ship as well as using smaller generators to power electrical subsystems. This IPS concept allows for added flexibility and more electrical power available to 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 upcoming ships into an Integrated Power and Energy System (IPES) architecture (Markle 2018). IPES is like IPS but adds advanced controls and energy storage. This enables enhanced flexibility and adaptability to support future capabilities and mission requirements as well as improved ship survivability and efficiency. The energy storage that enables this technology is likely to be a large array of batteries distributed around 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 on newer ships, with IPES architectures not fully matured and fielded until the far term (Hart 2022; Markle 2018).

c. *Number of vehicles*

Most of the Li-ion batteries onboard naval ships are likely to reside within systems that are transported by the ship, but are not necessarily part of the ship itself, 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, this study considered either the published standard complement when available or whichever complement contains the most platforms. For example, an America Class amphibious assault ship can carry a mix 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 systems that Marines may bring onboard with them even though it is known that they are there. 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 usages 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).

d. Summary of Future Fleet Structure

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 utilize 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.

3. Energy Generation vs. Storage Trade Space

This research area focuses on the tradeoffs between generating energy outright and storing some amount of energy to be used by systems on an as-needed basis. Currently most U.S. Navy vessels make use of multiple generators that can generate enough energy to power all the systems on the ship. Often there are enough generators on the ship that the ship can still run at full power even if a single generator is lost. This section explores making use of energy storage, in the form of Li-ion batteries, to store some of the power generated by the ship-board generators so that it can be used later.

The primary advantage of using generators of any kind for power generation is that they can harness the incredibly densely stored energy of various 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 fuel 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 any time soon, 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 otherwise it is wasted. Many generators can be run at various speeds and fuel burn rates to generate more or less power but the speeds and fuel burn rates the generators can operate at tend to be narrow and the efficiency of the generator suffers when running outside its optimal speed. Additionally, it can be challenging to ramp up or ramp down generators quickly enough to meet changing electrical demands of a ship. In practice, generators are typically run at a fixed speed where they operate most efficiently and any power that is not used is lost. This is typically not the case with engines that are being used to move the ship. In many cases those are forced to operate at varying speeds to appropriately control the speed of the ship and are designed to be most efficient when the ship is sailing at its cruise speed.

Using batteries to store energy leads to less power wasted, because the generator can be shut off when it is not in use. Batteries can deliver a diverse range of power. Batteries can deliver remarkably high- and low-levels of energy if the energy demand is within the design of the battery, which can be designed for remarkably high charge and discharge rates. Additionally, batteries can change between various power demands instantaneously without penalty making them especially well-suited for fluctuating power demands such as is required by many electronic warfare systems and directed energy weapons.

Batteries can also be beneficial when used as part of the ship propulsion architecture to capitalize on the benefits of hybrid electric propulsion. Hybrid electric propulsion on ships can yield higher fuel efficiency, like the improved fuel efficiency of hybrid electric cars. This improvement in efficiency can lead to reduced operation and sustainment costs as well as additional range and time on station for certain use cases and implementations.

As discussed in the previous section, the Navy is moving towards IPES architectures to realize the many benefits of electrification. This architecture will use generators in combination with large onboard batteries to power the ship to realize the improvements described in the previous paragraphs. It is important to realize that both energy generation and energy storage have their advantages and disadvantages and that the best solution is a combination of both but depends on the specific use case.

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 fits in the same footprint but can deliver 4 MW of power. Likewise, 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 unclear whether this rapid pace of energy density improvement is sustainable, but at the least, even if the explosive rate of improvement slows, steady more incremental improvements are expected at a minimum.

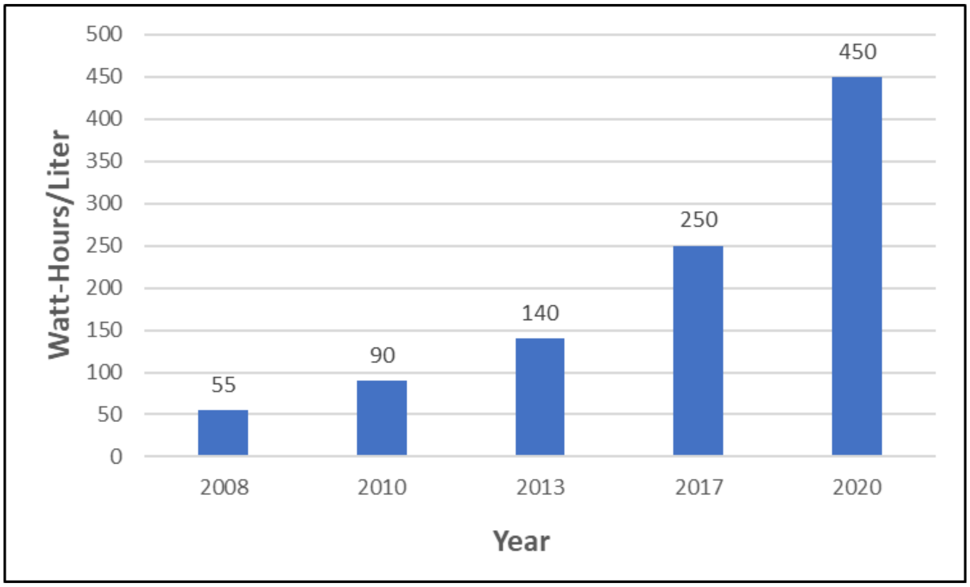


Figure 3. Li-ion Energy Density Increase over Time. Source: Vehicle Technologies Office (2022).

Despite major improvements in recent years, Li-ion batteries are still far behind gasoline in terms of energy density. This along with the space constraints of a ship make it unlikely that batteries will be able to fully power a ship for a long time. 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 true up until the time that the energy density of Li-ion batteries is closer to petrochemical systems.

High energy laser systems are the only technology investigated in this research that may be able to operate mostly on battery power. This is because compared to other systems, HEL systems are not on all or most of the time. In addition, HEL systems require less power as compared to the energy required to run the radar or to move the ship. It is also worth considering that if HEL systems are to be retrofitted onto older ships, then an energy magazine in the form of a battery could help to power the laser then be slowly charged back up by the smaller, older generators found on older ships.

The research in this section highlights that the final decision between power generation and power storage is not simply one or the other. The optimal solution likely includes both, but the challenge is to strike the appropriate balance between the two. As found in the future fleet structure, the Navy is extremely interested in IPS and IPES architectures and research in this area shows why. The specifics of those architectures remain to be seen and it is difficult if not impossible to predict with any accuracy how they will be implemented.

4. Future Battery Use

This section focuses on predicting battery use in the mid-term and far-term. The research has been broken out into two main categories: roll-on/roll-off and permanently installed systems. For the ship wide batteries, too much is still unknown or unavailable in the open-source literature to be able to make accurate predictions, instead this section outlines several of the possible implementations for ship-wide batteries in the mid and far term and discusses impacts and battery sizing considerations.

a. Roll-on / Roll-off systems

Almost all the U.S. Navy systems that were found to have Li-ion batteries in the first research area are roll-on / roll-off systems that are deployable from surface vessels. Using the information found in the Future Fleet Structure task and making some assumptions about the future use of Li-ion batteries of these systems, the authors were able to develop predictions for the quantity and capacity of batteries that could be onboard 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 put into the "Manned Fixed Wing Aircraft" group. Other similar groupings were made such as "Group 1 UAS," "Group 2 UAS," "Group 3 UAS," as well as "Small UUV," and "Medium UUV."

All were grouped and assigned a representative battery size as well as a battery likelihood. The battery size for any group was based on the battery sizes of known systems found in the Existing Battery research area. 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 was set to 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 and 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.

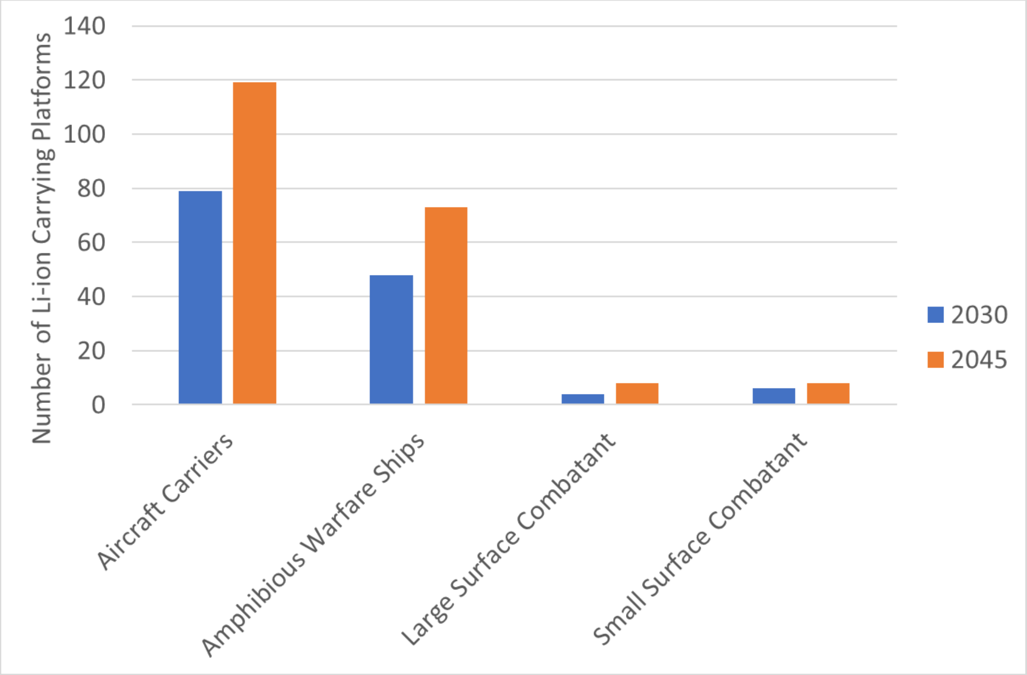


Figure 4. Projected Number of Platforms with Li-ion Batteries Onboard U.S. Navy Ships in 2030 and 2045

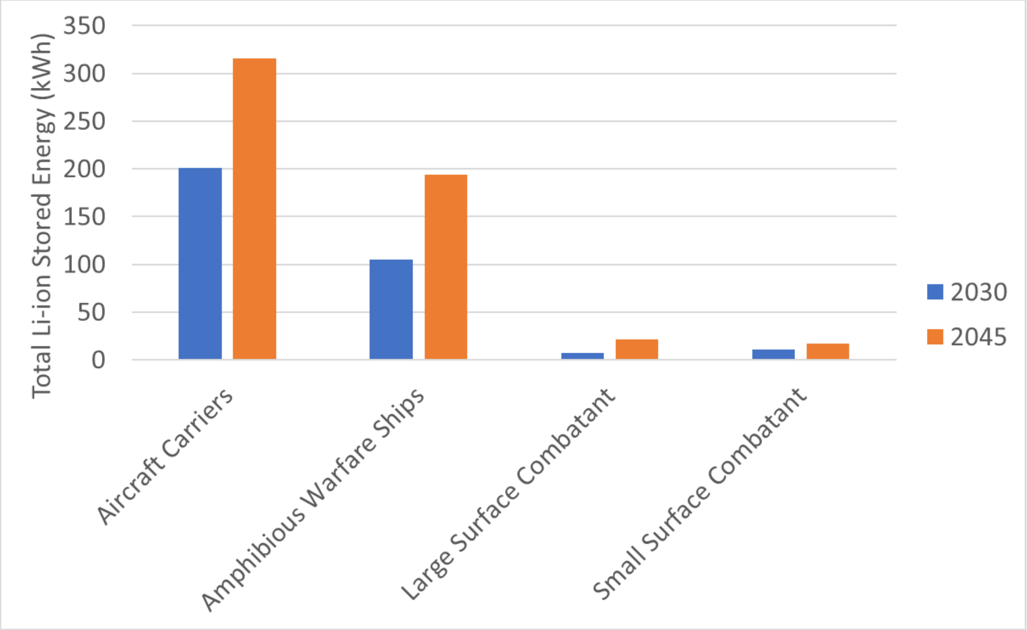


Figure 5. Projection of Li-ion Stored Energy Onboard U.S. Navy Ships in 2030 and 2045

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, the figures highlight that aircraft carriers and amphibious warfare ships are particularly highly effected and with 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 systems with batteries that are launched and recovered from Navy ships as part of their mission, another Navy mission is to transport Army and Marine Corps assets via sea when necessary. This entails moving everything from personnel and their personal gear to major equipment such as armored fighting vehicles and tanks. Since the Army and Marine Corps are investing in the electrification of platforms as is the Navy, these electrified systems are likely to significantly contribute to the stored energy onboard certain ship classes. Therefore, the ability to recharge, safely store and transport varies configurations of equipment and as such is a major concern for the Navy.

The Army and Marine Corps are both heavily investing in electrification, and with staunch support from Congress. It is reasonable to expect that new variants of some roll-on/roll-off platforms will carry Li-ion batteries by 2030, but also that the number will significantly increase by 2045. Despite the contribution of these batteries, further investigation into this area was not conducted in this project to manage project scope.

b. Ship-wide Batteries

The future use of ship-wide batteries is highly dependent on the state of IPS and especially IPES architectures on future ships. In the mid-term, it is expected that fielded ships will have IPS but not yet have IPES. Large ship-wide batteries capable of running the entire ship for any amount of time are unlikely for this reason. It is more likely that certain high power consumption subsystems such as HELs that have been retrofit onto ships and whose existing electrical generation cannot reliably support them will also be retrofitted with a large battery to function as an energy magazine.

Figuring out just how large a battery like this would be is quite difficult and depends greatly on how much energy the ship can produce and how much energy the subsystem uses and how long the subsystem needs to be able to run without needing to be recharged. In terms of the power required to fire any of the HEL systems, the authors assume a power efficiency of 30% based on typical efficiencies of solid-state lasers, which all the current HEL demonstrators are (Michnewich 2018).

Assuming that ships in the mid-term will be deployed with a 150-kW laser, that would lead to a total power draw of 500 kW. Assuming the laser needs to be able to fire for a cumulative duration of one hour before the battery needs to be recharged, and if the ship does not have any excess power to use to charge the battery during that one hour, that would require a 500-kWh battery. Based on an energy density of 450 Wh/L, a 500-kWh battery would be roughly 1.1 m^3 (39.2 ft^3). This volume should easily fit on a ship. However, protecting a battery this large against shipboard fire would be challenging. It is assumed that with current fire suppression technology and careful planning and integration work this challenge could be overcome.

It should be noted that the size of the battery would need to be scaled to what is needed and the space available on the ship. Even a small amount of Li-ion battery storage could enable substantially increased magazine size for future laser systems (Gattozzi et al. 2015). There is a detailed model of a destroyer class ship, which demonstrated that a small volume (0.23 m^3) of Li-ion batteries might enable hundreds of shots with a 125-kW laser while protecting the ship from the strain of a direct pulse load (Sylvester 2014).

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 in the future fleet structure research area, 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, which were discussed in the generation vs. storage trade space research area. This onboard battery will likely be sized based on several factors to include 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 up to a total of 80 MW. Then to account for the larger size and additional technology of the DDG(X), the maximum power requirement estimate used by the authors is increased to an estimated total of 100 MW.

Using this maximum power requirement and assuming a desire to be able to run for 1 hour at full power using battery alone, an estimate of the size of the battery required can be generated. 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.

This is an extremely large amount of space but removing fuel capacity could make sense to fit this battery because of the gains to efficiency or the overall size of the ship could be increased to accommodate. It is also worth noting that while 1 hour of operating time does not sound like much, the ship could operate for far longer than that if it is not using maximum power. This is an oversimplification of the problem, but it is interesting to see the potential size of future batteries.

c. *Summary of Future Battery Use*

Research in this area shows that battery usage in the U.S. Navy and in navies around the world is likely to drastically increase their usage of Li-ion batteries. New naval based systems are being developed and fielded today that make use of Li-ion batteries and the research team expects this trend not only to continue, but also to increase. 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. Also shown in this research is the wide range of benefits that can be realized by navies by making use of large batteries and hybrid electric power architectures. The exact size of batteries that could be used is difficult to predict with certainty, but the advantages of large ship-wide batteries are likely to push many navies to implement them in some way. All of this will have an impact on ship design to make sure that all Li-ion batteries on board are installed in a way that is safe and resistant to battery fires.

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.

Both manned and unmanned aircraft currently use Li-ion batteries, although the usage is not widespread. Open-source research shows only the F-35 and the CH-53K currently use Li-ion batteries across all manned aircraft that are employed onboard Navy ships. For the unmanned aircraft environment, only two aircraft are found with Li-ion batteries: the small, man portable RQ-11 Raven and the RQ-20 Puma. Multiple platforms are found to currently use batteries, but the RQ-11 and RQ-20 are the only ones currently using Li-ion batteries. The number of aircraft could easily exceed ten different systems in just the next few years as the older battery chemistries are exchanged for more efficient Li-ion batteries.

The result of this research indicates that the usage 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. Li-ion batteries are becoming common in many recent technologies and are being used to better enable older technologies, but many of these new systems are just starting to break into the fleet. Energy demands from weapon and sensor systems are growing already, and those demands are expected to continue. Future combat scenarios will likely require short bursts of substantial amounts of power with minimal notice to power sensors and/or directed energy weapons. In those scenarios, there is potential to outstrip the power generation on many ships, thus requiring substantial amounts of stored energy. The number of Li-ion batteries in naval fleets will increase significantly over the next several decades as they are used to store energy for numerous shipboard systems. They will become a key component of the future U.S. Navy.

The world's naval fleets and civilian maritime communities are sure to adopt technological advancements that will directly and indirectly impact how they will operate and store batteries. With the rapid expansion of Li-ion battery usage around the globe the entire maritime community needs to invest time and resources into this area. Naval fleets around the world are showing significant increases in efforts to build the next era of naval fleets with the latest technological advancements. Not only will the technological advancements be seen directly in the naval ships, but they will also be seen indirectly through the systems that operate on the ships and the cargo the ships carry. Naval architects and marine engineers are responsible for designing, overseeing testing, installation, and repair of maritime equipment. Therefore, time and resources investments need to be made for naval architects and marine engineers to fully understand and properly incorporate Li-ion batteries into the naval and maritime fleets in the safest and most effective manner possible.

The analysis presented here demonstrates that not only is the future of the U.S. Navy fleet going to see a significant increase in battery usage and storage requirements due to technological advancements but so is the entire maritime community. The increase in

Li-ion battery usage aboard ships is not a unique problem to the U.S. Navy as we have seen through our research. It directly affects how other countries naval fleets, and the civilian maritime communities will operate their ships with increased Li-ion batteries aboard. On March 1, 2022, a cargo ship, Felicity Ace, sunk 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 though there is still no official report about the cause (Hahn 2022). The Felicity Ace was carrying more than 4,000 vehicles that were on their way to the United States. Luckily all the crew survived, but there will be everlasting ecological impacts because of Felicity Ace's sinking. These impacts must also be considered when naval and maritime experts integrate technologies that use Li-ion batteries. The ecology of the ocean and world are impacted by the sinking of any ship therefore time and resources must be allocated to making sure safety standards are improved and met as the world's maritime fleets are ever changed by technologic advancements in all areas but especially with Li-ion batteries.

F. CONCLUSION

The research conducted for this project has shown that the demand for Li-ion batteries will grow in the coming decades. Naval applications requiring energy storage are rapidly growing, while battery technologies are being developed that are safer and significantly more powerful. As there is an increased focus on unmanned platforms, advanced mission equipment, and directed energy weapons, the requirements for robust energy storage also continue to grow. With the size and scale of planned transformation to the U.S. Navy force structure and implementation of modern innovative technologies requiring substantial amounts of power, the need for battery solutions to accompany these new developments are expected to grow beyond expectations. Energy storage concerns within the U.S. Navy have historically taken a background role in system development, but as electrification of the fleet continues and more systems are built to use energy as a weapon, advanced batteries will present an effective solution to increase efficiency and enable new power intensive technologies.

Significant consideration must be accounted for in terms of the location and access of battery storage for deployable systems and for ship energy storage. Several factors that influence storage locations and access to battery storage. Deployable system battery storage should be close to the deployment location, such as a well or main deck, to enable easy and quick access in critical use scenarios. It is important that fire risks are considered when evaluating storage locations. The U.S. Naval Lithium Battery Safety Program (2015) provides limited guidance on how commercial off-the-shelf (COTS) batteries should be stored.

The roll-on / roll-off platform environment plays a significant role in the U.S. Navy fleet. Even though the roll-on / roll-off platforms were not analyzed in this research, it is important to note that the future of Li-ion batteries in the roll-on-roll-off systems will impact the future U.S. Navy fleet. It is therefore important for the U.S. Navy to invest in future research into Li-ion not only for the U.S. Navy platform environment but also in the roll-on-roll-off platform environment.

Based on this research the authors conclude that Li-ion batteries will dominate the U.S. Navy battery usage in the coming years. Over the next several decades, new Li-ion technologies are likely to be developed and become available on a global scale. Battery usage is expected to surge significantly by the early 2030s in the U.S. Navy and continue to grow from there. The application of Li-ion batteries onto the future U.S. Navy fleet is not an exception, and as such the time and resources spent on what the future battery usage in the U.S. Navy fleet will look is critical to how the U.S. Navy and the United States defends itself and its allies against its adversaries.

III. SHIPBOARD BATTERY ANALYSIS TOOL

This section introduces and describes the tool that was built to assist with this research. Included are screenshots and guides to help users understand how to operate the tool. The final portion of this section includes ideas on how the tool can be adopted for current use or expanded to account for future needs.

A. CONCEPT

It was necessary to organize the data collected for this research, but the data is also likely to change between now and the 2030 and 2045 timeframes that were analyzed. Additional unpublished information not included in the data about their platforms was not included in the data for this research. The team developed a simple but effective software tool to enable the research analysis, but also to aid the Navy in increasing the data fidelity they can use to inform policy and other ship-related decisions regarding the usage of Li-ion batteries in the fleet.

Many different systems engineering, or software development tools would have met the needs for collecting the open-source data used in this study. The requirements laid forth by the team were akin to those used for standard database development, such as capturing batteries associated with various systems or platforms found onboard ships (e.g., manned, and unmanned aircraft and maritime systems) and associating those platforms with specific ships based on a pre-determined timeframe (2030 and 2045 for this study). A paramount requirement was that the Navy N9 would be able to use the tool with standard software available on a regular, unclassified Navy network. Microsoft Excel was selected for the tool for a few reasons. It is readily accessible across the DOD, most of the likely users are familiar with how to use it, and the project team already had expertise in what was needed to implement the concept.

In general, the goal was to associate Li-ion batteries, and their sizes, with the platforms that carry them based on timeframes. Associating those platforms to a specific category and flight of ship to finally determine the 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

There are a multitude of active ships within the Navy, and they all follow common classification by type. The Navy publishes a directive that establishes the means ships will be classified by for the purpose of counting the size of the fleet, also known as the Ship Battle Forces (Secretary of the Navy 2022). The tool developed for this research closely aligns with the Navy's ship counting methodology, although there are some differences. One such difference is that of the general categorization of Surface Combatants. In the Navy's directive, all Surface Combatants are classified together to include all cruisers, destroyers, frigates, and littoral combat ships. However, it was determined early on that it would be worthwhile to split this classification into large- and small-surface combatants; this is also how the Navy submits its long-range ship building plan. Although the research did not specifically examine the submarine and logistics categories, they were included in the development of the tool to assist with potential expansion. There are also several ship classes within each category that mostly represent something equivalent to 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 represent different technology packages onboard ships of the same classes—somewhat equivalent to a minor change in the ship's design. In summary, though there are some exceptions, each ship can be classified by its category, class, and flight.

Standard database design practices were followed when designing the tool to ensure its usability, efficiency, and extensibility. Microsoft Excel is not meant for use as a database, but it is more than capable and recent additions have expanded its ability to work for moderately complex database designs. In line with common practices and to simplify the design in Excel, separate tables were created for ship category (*Lkp_Category*), ship class (*Lkp_Class*), and ship flight (*Lkp_Flights*). Additional tables were created to add timeframes of concern (*Lkp_Timeframe*) and for specific platforms along with their timeframe and battery characteristics (*Lkp_Platforms*). The final data table in the tool was created to associate the platforms with different 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.

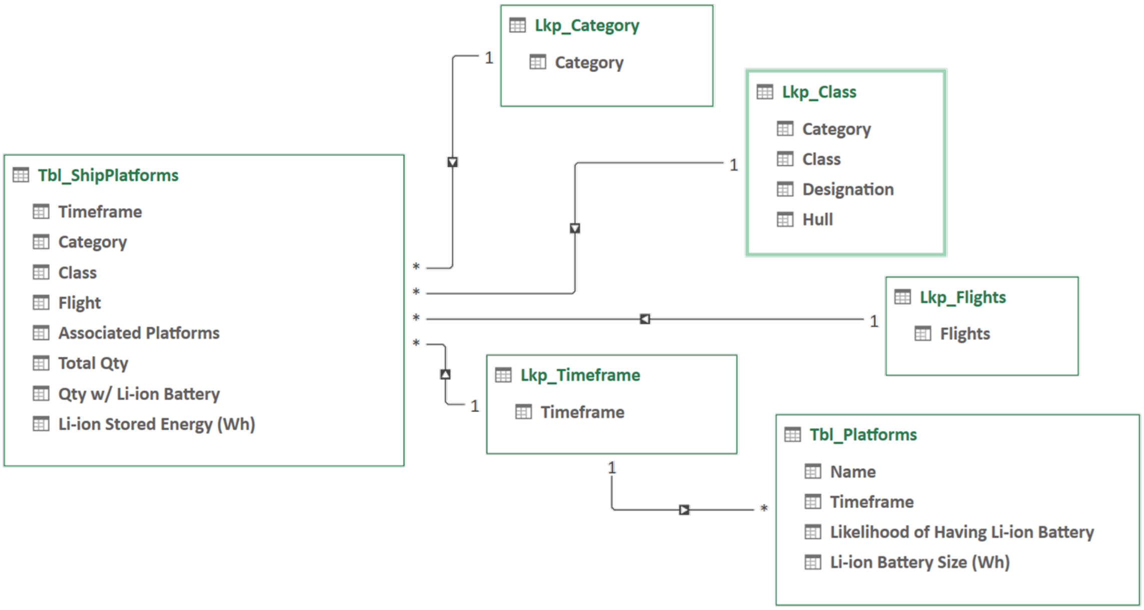


Figure 7. Entity Relation Diagram for the Shipboard Battery Analysis Tool

Three primary user groups were considered in the design of the tool. An admin with moderate to advanced knowledge of how to use 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 was identified to be someone responsible for knowing what Li-ion batteries are, or will be, present on individual platforms or as someone who could identify what platforms are, or will be, present on different ships. The last user group considered was those in the Navy N9 who are responsible for understanding the implications of having

Li-ion batteries onboard ships but may not necessarily have the same detailed knowledge about the topic as a data entry user.

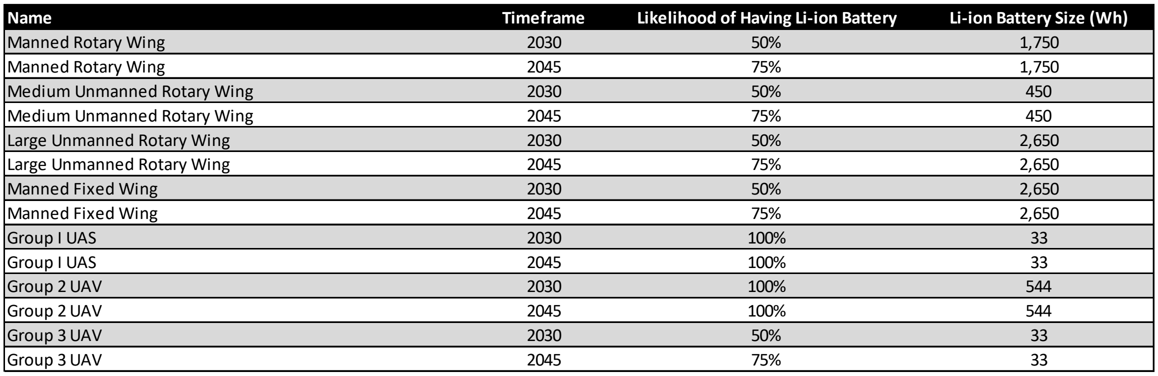
Based on the data and user requirements, the tool was separated into a total of five sheets within the Excel workbook to simplify its usability, two sheets are for admin use only, two are for data entry, and one contains a summary of all data, which can be used and interpreted by any user. Additional details about how to use each element of the tool are provided in the next section.

C. USAGE

Each sheet of the workbook was color-coded according to the user level it was meant to be associated with; black is for admins, blue is for data entry users, and green is for everyone. It is worth noting that the team considered enforcing editing restrictions to ensure data integrity, but it was deemed that the Navy's admin user could implement such security controls according to their own policies rather than for the team to establish them unilaterally. This section will detail each of the sheets within the workbook from admin to data entry, and then to general users.

The two sheets meant for admin control are colored black and are hidden by default. They are rightfully titled, "*Lookups*" and "*Dynamic Lists*" according to their purposes. *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 for 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 Navy decides to look at Li-ion battery usage in new timeframes. *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 as 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 as they may serve as a foundation for Navy decision making with regards to Li-ion batteries, 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—the platform's name, Timeframe—when that data applies, Likelihood of Having Li-ion Battery—percentage (0–100%) of if the platform will have a battery, and Li-ion Battery Size (Wh)—total Li-ion battery capacity of platform in 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 simple 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.

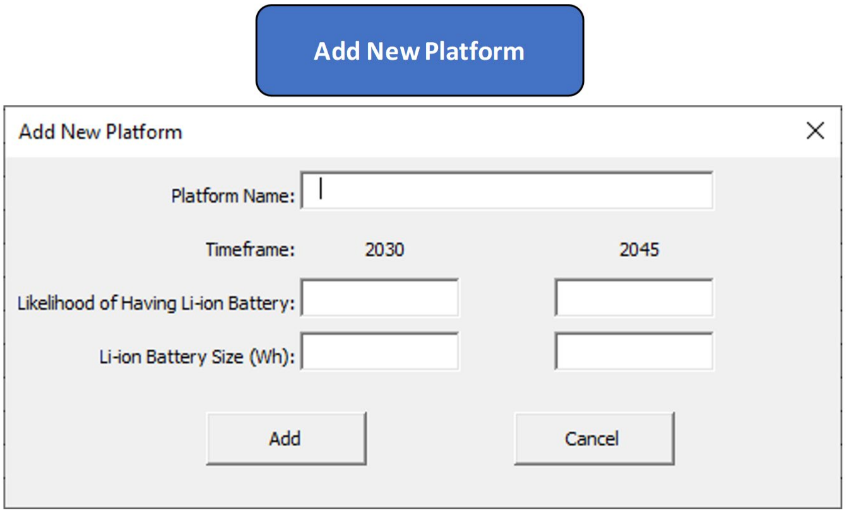
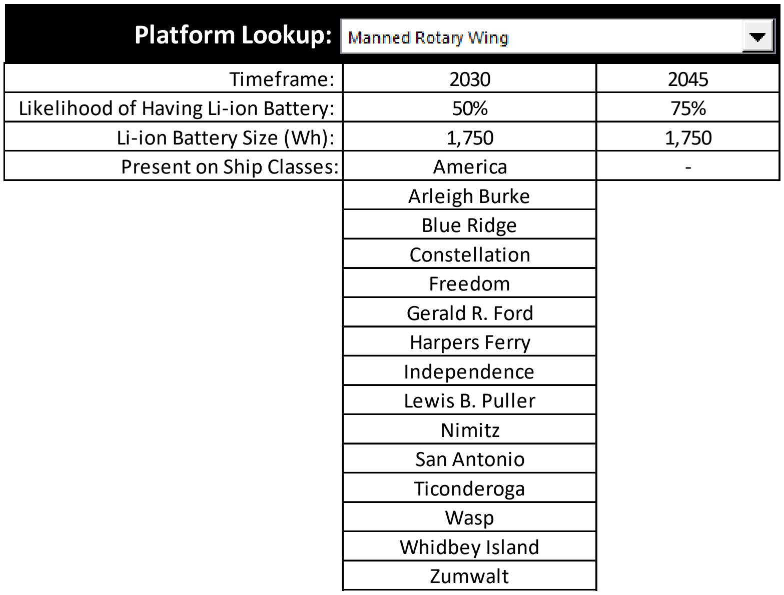


Figure 9. Button and Form to Add New Platform

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.

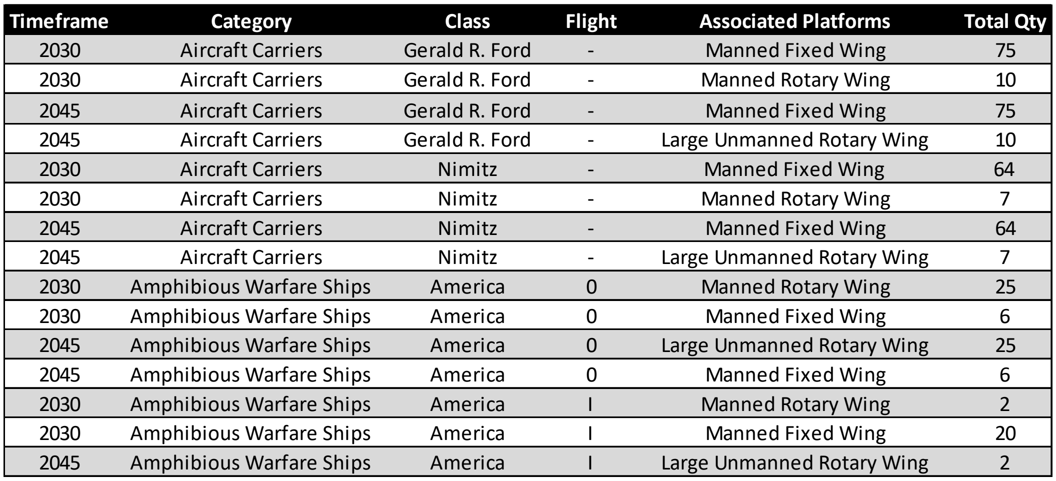


Platform Lookup:	Manned Rotary Wing	
Timeframe:	2030	2045
Likelihood of Having Li-ion Battery:	50%	75%
Li-ion Battery Size (Wh):	1,750	1,750
Present on Ship Classes:	America	-
	Arleigh Burke	
	Blue Ridge	
	Constellation	
	Freedom	
	Gerald R. Ford	
	Harpers Ferry	
	Independence	
	Lewis B. Puller	
	Nimitz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

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

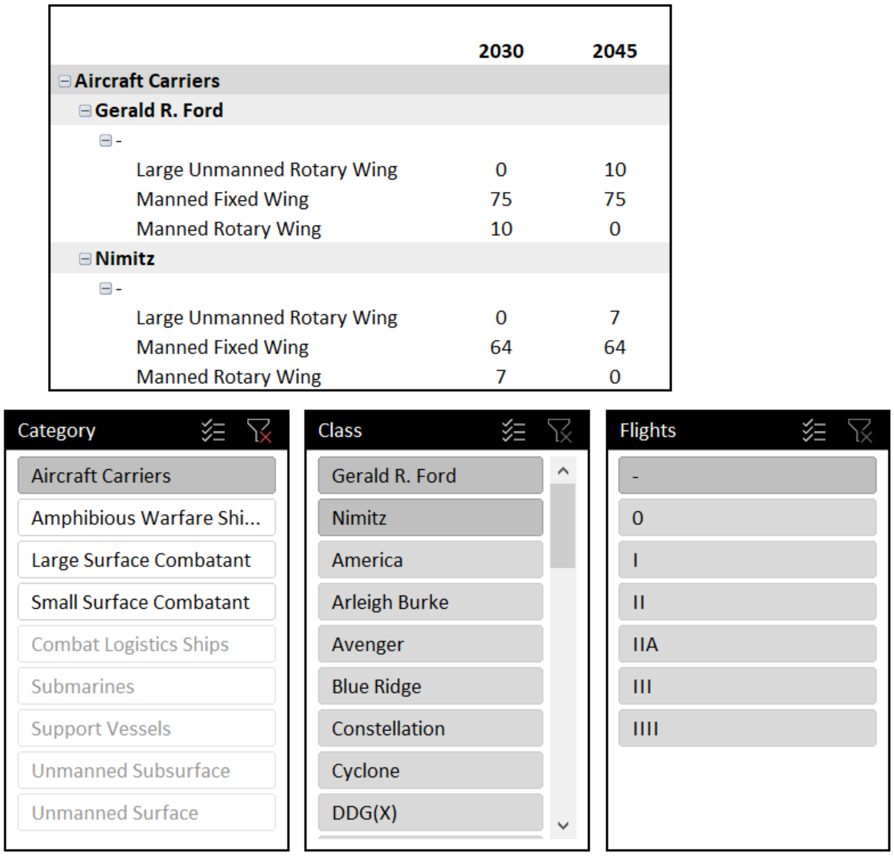
The next sheet meant for data entry is the *Ship–Platforms* sheet, shown in Figure 11 and Figure 12. This sheet is where the user will associate the Li-ion carrying platforms with the ship(s) that may carry them. Most of the necessary data—timeframe; ship category, class, and flight; associated platforms; and quantity of each platform—is fillable via drop-down menus. This sheet seeks to systematically state that there are, or expected to be, X number of platforms carrying X number of batteries onboard a particular type of ship in the specified timeframe.

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). 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 what data 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

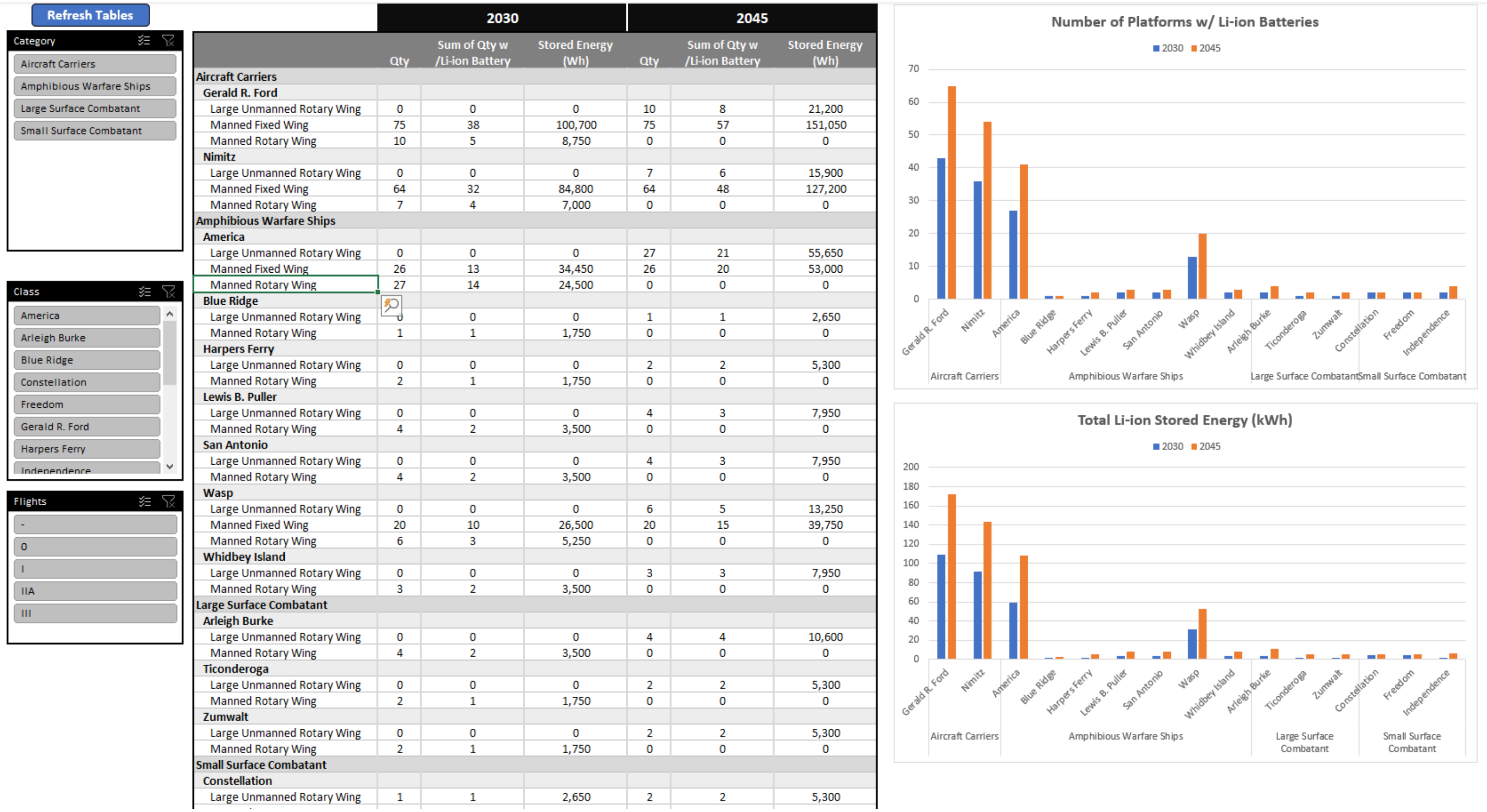
Figure 11. Data Table from Ship–Platforms—Contains all platforms associated with their ships



	2030	2045
Aircraft Carriers		
Gerald R. Ford		
-		
Large Unmanned Rotary Wing	0	10
Manned Fixed Wing	75	75
Manned Rotary Wing	10	0
Nimitz		
-		
Large Unmanned Rotary Wing	0	7
Manned Fixed Wing	64	64
Manned Rotary Wing	7	0

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; it is colored green. Like its title, this sheet is meant as 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 meant to convey the most important aspects of Li-ion batteries being onboard 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 *Summary* 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

This tool sufficiently organized the data necessary for this study, but requires data input from platform and ship experts across the Navy before it should be used to inform any major decisions. This study used open-source data, but more accurate data may alter the trends presented in the summary. As was suggested earlier, there are many other options for implementing a tool like this, even following the same design. This tool was designed as a database and would be better suited for database-oriented applications such as Microsoft Access, SQL, or Mongo DB. However, most of the anticipated users are not likely to be familiar with these databases or have access to them, so Microsoft Excel was used instead. One of these database-specific options should be used if they are available to the Navy.

The team is aware of previous efforts to capture Li-ion usage in the fleet from across the Navy. It is recommended that such efforts be informed by the data elements necessary to populate the current tool as the incorporated metrics are the most salient for consideration in informing Navy-wide decisions regarding the implementation and adoption of Li-ion batteries when considering the risk association to a particular ship. The team also recommends that the Navy extend the tool 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 implementing at the ship level, the Navy may consider implementing tools based on storage or usage location within a ship.

Understanding the general number and capacity of Li-ion batteries onboard a ship is a good starting point, but the fire risk of the batteries is also associated with their proximity to one another (i.e., the aggregate storage matters significantly). Naval engineers should understand the risks associated with Li-ion battery storage and how those risks may affect their designs. However, ships designed before such knowledge are still prevalent in the modern Navy and must be considered. Likewise, future platforms will be brough onboard ships that were not initially designed to carry them. Basic inventory-like tracking of Li-ion batteries onboard ships utilizing a tool like what was developed for this research should be helpful in ship-based risk assessments and in informing broad Naval policies.

IV. PROJECT CONCLUSION

The purpose of this research was to assist the N9 Warfare Systems office in determining the resources required to support the use of Li-ion batteries on the fleet of Navy vessels in the year 2030 and 2045. The research team worked with the N9 Warfare Systems office to develop four tasks to achieve that goal. Those tasks were to determine the use of Li-ion batteries on board the current Navy fleet, examine the future fleet structure and investigate emerging technologies that would use Li-ion batteries, perform a trade space analysis on energy generation versus energy storage onboard Navy ships, and to make recommendations on the future use of Li-ion batteries. The research team successfully accomplished all tasks, which are captured in this report.

Based on the research conducted, there will absolutely be a role that Li-ion battery technology plays in the overall powering of Navy vessels. The energy density of Li-ion batteries when compared to petrochemicals, however, has a long way to progress before it can legitimately be considered as an option to power the propulsion system of a ship. There is a place for Li-ion to power certain mission equipment packages, subsystems or vehicles that are launched from a host vessel. The challenge with predicting the exact number of Li-ion batteries that will be carried on the future force is due to the unknown rate that Li-ion technology will continue to grow. Li-ion has experienced an exponential growth and improvement in energy density since 2008, but the expectation is that this growth will level off at some point in the future.

Another key consideration for having Li-ion batteries onboard naval vessels are the risks associated with thermal run-away and fire. For years, many small, unaccounted Li-ion batteries such as those for personal mobile phones, laptop computers, and battery backups for small electronics have been carried onboard Navy ships while other items such as missiles and sonobuoys have been subjected to formal review processes even though they may carry smaller batteries. Loss of life due to an uncontrolled thermal runaway is 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 goes aboard a ship. The Federal Aviation Administration (FAA) establishes Li-ion limits of 100 Wh and 160 Wh for airline passengers in the United States in 49 CFR 175.10. A similar approach could work for the Navy to determine where to focus resources. Consideration should also be given to the battery's common usage and storage locations onboard due to its proximity to a critical system, which may increase its risk factor even though it is a smaller battery. For example, several small replacement batteries stored near a critical computer system may pose a greater risk than a larger Li-ion battery on a roll-on / roll-off system that has vehicle-specific fire mitigations and is stored in an open area of the ship that also has an ample fire suppression system.

From the completed research it is safe to say that Li-ion battery technology will be a key part of the Navy's fleet of vessels in 2030 and 2045. Continued investment in Li-ion battery technology will ensure the improvement of energy density making Li-ion technology even more viable for integration onto the Navy fleet. Perpetuating the technology and continuing to invest in fire suppression, packaging and handling of Li-ion batteries will also help the Navy incorporate the latest in battery technology without increased risk to the people aboard those ships.

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