Li-ion Batteries and the Electrification of the Fleet

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Abstract

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

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

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[1] NPS

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.

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.

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.

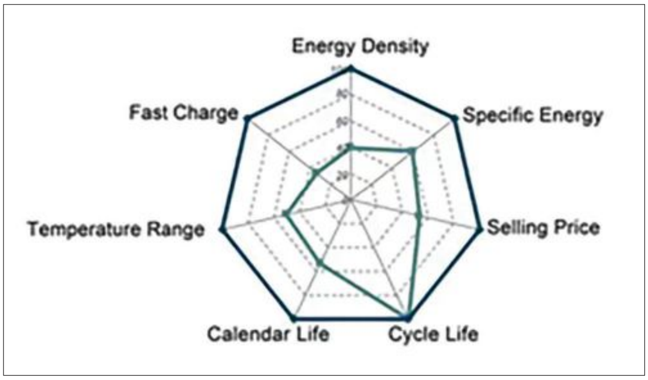

FIGURE 1. Battery Metrics

Source: Argonne National Laboratory (n.d.)

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," 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.

The two most common ways of measuring capacity are in Ampere Hours (Ah) or in Watt Hours (Wh). Wh is identical to Ah with the exception that Wh is the measure of the power a battery can provide over a length of time, whereas 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. Energy density is the amount of energy stored in each system or region of space per unit volume or mass (Golnik, 2003). 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.

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 like older battery technologies do. 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 et al., 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.

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, Dmitry Bondarev, Vinod Singhal & Gleb Yushin 2018).

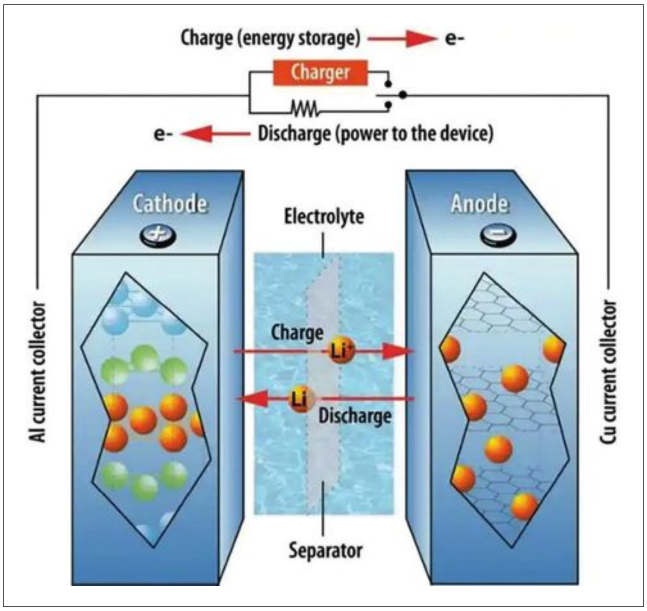

FIGURE 2. How a Lithium-ion Battery Works

Source: Argonne National Laboratory (2010)

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° – 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 & 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 & 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.

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).

Methodology

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.

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.

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.

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.

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.

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).

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.

Analysis

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.

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).

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.

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.

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.

Types and Numbers of Ships

The US 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

	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

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

Note: 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).

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.

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(Lockheed Martin Corporation, 2021; Mizokami, 2020; Peach, 2014).

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).

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; Englehorn, 2021; Naval Sea Systems Command, 2019; Office of the Chief of Naval Operations, 2022; Rosenberg, 2021).

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.

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 US 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 shipboard 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.-a) that can deliver 3 MW of power is being replaced by the new AG9160 (Rolls Royce, n.d.-b) 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 US 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.

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.

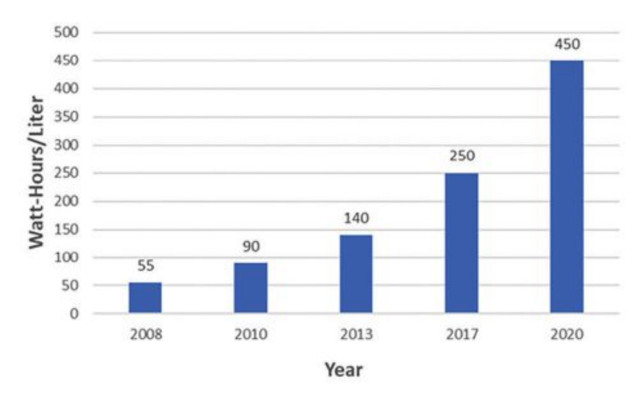

FIGURE 3. Li-ion Energy Density Increase over Time

Source: Vehicle Technologies Office (2022)

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.

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.

Roll-on / Roll-off systems

Almost all the US 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 US 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.

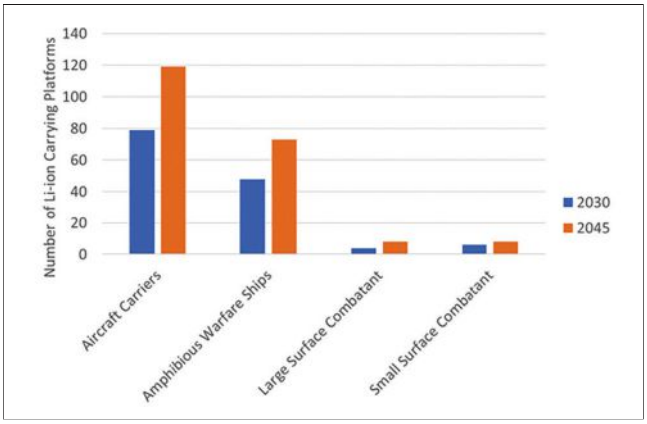

FIGURE 4. Projected Number of Platforms with Li-ion Batteries Onboard U.S. Navy Ships in 2030 and 2045

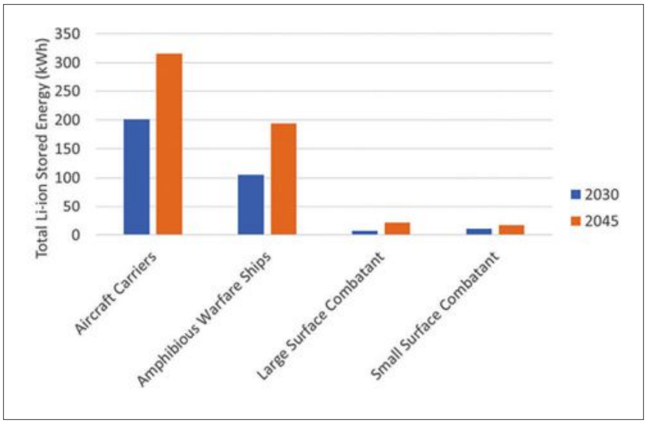

FIGURE 5. Projection of Li-ion Stored Energy Onboard U.S. Navy Ships in 2030 and 2045

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 US 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.

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.

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)particularly for applications requiring back fit of the new systems onto existing platforms with limited electric power generation and cooling capacities. The University of Texas Center for Electromechanics (UT-CEM. 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.

Summary of Future Battery Use

Research in this area shows that battery usage in the US 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.

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 (Duaine 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.

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 2030's 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. NEJ

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