Boeing Technical Journal

Environmental Impacts of Aerospace Batteries

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Abstract

With an increasing demand to improve the energy efficiency and performance of our products, Boeing also faces a demand to decrease our emissions and environmental footprint. Batteries and energy storage technologies are key enablers to reach these goals. Electrification of vehicles, aircraft, and satellites is pushing the aerospace industry towards improved energy storage systems, but consideration must be given to sustainable and environmental solutions. In this work, the environmental impacts of a variety of primary and secondary battery cell chemistries were evaluated and compared. Traditional chemistries investigated include lead acid, nickel cadmium, and nickel metal hydride, while newer chemistries involved lithium ion, lithium sulfur, lithium air, and lithium zinc. Life cycle assessments were carried out with a focus on resource extraction, manufacturing, use, and end of life revealing greenhouse gasses, water consumption, solid waste, nitrous oxides, and the environmental footprint for each chemistry. It was found that the lithium sulfur chemistry offered the best combination of energy storage and environmental impact.

APU	Auxiliary Power Unit
BoL	Beginning of operational life
DfE	Design for Environment
DoD	Depth of Discharge
EoL	End of life
EPM	Environmental performance measure(s)
GHG	Greenhouse gas (CO_2, CH_4, and N_2O included)
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
ISO	International Organization for Standardization
KOH	Potassium hydroxide
LCA	Life Cycle Assessment
Li-air	Lithium air
Li-ion	Lithium ion
Li-S	Lithium sulfur
MCM	Mixed conductive membrane
NiCd	Nickel cadmium
NiMH	Nickel metal hydride
NOx	Mono-nitrogen oxides (NO and NO2)
ONE	Opportunities for New Experiences
OEW	Operating empty weight
Pb-acid	Lead Acid
TRL	Technology readiness level
Zn-air	Zinc air

I. INTRODUCTION

Boeing utilizes batteries for energy storage platforms throughout the enterprise including use in commercial airplanes, helicopters, and satellites. Understanding the environmental impact differences of these battery chemistries, in addition to potential solutions, involves a holistic life cycle approach to capture various environmental impacts. By evaluating the full product life cycle factors relative to the technical performance, Boeing can prepare for a future of aircraft electrification with guided innovative research efforts.

The purpose of this study is to determine an optimal battery chemistry for the aerospace industry that will provide a combination of superior technical performance and minimal

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environmental impact, ensuring a sustainable and responsible use of energy storage systems within the industry. A commonly used process for evaluating environmental impacts is Life Cycle Assessment (LCA) as described in the International Organization for Standardization (ISO) 14040. The LCA method was used as an analysis tool to quantify material and energy flows of a product system, and the subsequent waste and emissions generated throughout the product's lifecycle. The lifecycle includes four phases including resource extraction, manufacturing, use, and end of life (EoL). Impacts to the environment from wastes and emissions are used to characterize the "footprint" of a product's lifecycle.

The work presented here will go through a literature review of the battery cell chemistries of interest, the methodology of the LCA approach, the LCA results, and a comparison of each LCA metric to determine the optimal aerospace battery.

Please note that competitively sensitive proprietary information was also removed from various portions of the paper before this publication.

II. METHODOLOGY

A. *Literature Review*

Battery technologies of interest in this study included both conventional and advanced chemistries. The conventional battery chemistries included Lead Acid (Pb-acid), Nickel Cadmium (NiCd), and Nickel Metal Hydride (NiMH). These batteries are used throughout the aerospace industry and are well established in other industries. Literature and data regarding the conventional battery chemistries and their respective lifecycles is abundant, and provided the framework for the other batteries considered. The data used in this study represents typical data for each of these batteries. Advanced batteries included Lithium ion (Li-ion), Lithium Sulfur (Li-S), Lithium Air (Li-air), and Zinc Air (Zn-air). These batteries are relatively newer in comparison to the conventional technologies and have promising improved performance. These batteries exist at a range of technology readiness levels (TRLs). Li-ion batteries are already being used in aerospace applications, Li-S is under active research, and secondary Zn or Li-air (metal-air) batteries are very low TRL. Use of Metal-air batteries in the aerospace industry could be considered only speculative. Information regarding these newer chemistries was limited, and theoretical data was used and assumptions were made to complete the evaluation.

A literature survey was conducted to capture relevant inputs to the LCA study. In all cases, information regarding the system level battery were used over information for individual battery cells. Key properties of each chemistry included the materials and relative compositions of each chemistry, the manufacturing process, end of life scenarios, and lastly performance attributes such as specific energy (Wh/kg), discharge cycles, depth of discharge (DoD), charge efficiency.

Lead Acid Batteries

The Pb-acid battery chemistry is an established technology that was invented in 1859 making it the oldest rechargeable battery. The Pb-acid battery can be found in various aerospace applications.

The components of the Pb-acid battery cell include a cathode comprised of lead peroxide, an anode made of sponge lead, electrolyte of sulfuric acid, and a fiberglass separator [1]. The advantages of the Pb-acid battery are its manufacturing simplicity, mature technology, dependable service, low maintenance requirements, and low cost. Additionally, processes have been established to make the Pb-acid battery highly recyclable. It is estimated that 95% of all Pb-acid batteries produced are recycled, and new Pb-acid battery materials range from 60 to 80% recycled content [1]. A drawback of the Pb-acid battery are its low energy density (Wh/L), a critical factor when considering use for aerospace applications.

The majority of the information used for specifying the Pb-acid battery's performance was provided by AllCell Technologies LLC white paper A Comparison of Pb-Acid to Li-ion in Stationary Storage Applications [2]. Additional information was taken from and cross-referenced with a report written by the Argonne National Laboratory titled A Review of Battery Life Cycle Analysis: State of Knowledge and Critical Needs [1].

Nickel Cadmium Batteries

Although the basic chemistry for NiCd batteries has been utilized for some time, there has been continuous development on the electrode, electrolyte, and packaging technologies to enable a wide range of applications. The components of the NiCd battery cell include a cathode comprised of Nickel hydroxyl-oxide, an anode made of metallic cadmium, and an electrolyte of KOH [1].

NiCd cells come in all forms for many applications such as small cylindrical cells for lower power, pocket-plate for high mechanical and electrical abuse, and sintered plate for higher-rate discharge [3]. The flexibility of NiCd batteries is why it is used on many Boeing defense and commercial products with specific power requirements.

Besides the wide range of applications that NiCd batteries have, other advantages include reliability, long battery cell life, low maintenance, long storage life, and a wide range of operating temperatures. When comparing to other cell chemistries, NiCd battery cells have lower cost, but they suffer from low recycle rates [4].

Nickel Metal Hydride Batteries

NiMH batteries are commercially available batteries that are widely used in hybrid vehicles and portable electronics. The NiMH battery originated as the successor to the NiCd battery, and exhibits a higher energy density and specific energy when compared to Pb-acid and NiCd[3]. The components of the NiMH battery cell include a cathode comprised of nickel hydroxyl oxide, an anode of mischmetal (Me) hydrides, electrolyte of Potassium hydroxide (KOH), and a separator of a porous polypropylene membrane [1].

A benefit of the NiMH battery is that environmentally acceptable and recyclable materials are used in the construction [3]. The battery does not contain hazardous materials such as cadmium, mercury, or lead. The batteries are also maintenance free, and are very safe during charging and discharging [3].

NiMH batteries are not historically used as a primary source of power in aircraft applications. However the NiMH cells are used within other aircraft equipment or systems. The batteries are often used to power systems such as the emergency door and floor escape path lighting as well as portable entertainment devices and electronic flight bags [5].

Lithium Ion Batteries

Li-ion batteries provide energy on a vast array of programs across the enterprise. The designs for each of these platforms include either small or large cell formats making up the battery pack. Small cell batteries offer many advantages over large cells, including high reliability, high volume manufacturing, high volumetric efficiency, and reduced likelihood of cell-to-cell thermal runaway propagation [6]. A Li-ion cell comprises a cathode which contains lithium composite oxide materials (LiMnO, $LiCoO_2$, etc.), while the anode is graphite based composite. The electrolyte varies in composition but is commonly a combination of ethylene carbonate [solvent], diethyl carbonate [solvent], and lithium hexaflurophosphate [salt].

Li-ion batteries are sealed cells, requiring no maintenance and the chemistry offers high specific energy and low discharge rates, thus providing an extended cell life cycle [7]. Environmental impacts are minimal in the production of lithium and extraction processes are not energy-intensive [8]. However, recycling standardization is challenging due to the variation in materials within the cathode, anode, and electrolyte used to construct Li-ion batteries, as well as diversity in shapes and sizes.

Li-ion batteries are widely used in consumer electronics, military electronics, aircraft, automotive and spacecraft applications. The diversity of Li-ion cells makes the technology ideal for specialized battery design; however, large hurdles, such as developing large-scale recycling efforts, must be overcome for li-ion to maintain popularity as other technologies emerge.

Lithium Sulfur Batteries

The Li-S battery is capable of revolutionizing the battery industry. With a theoretical energy capacity of 2600 Wh/kg, it has an energy capacity five times higher than Li-ion batteries [8]. The battery is lightweight, inherently safe (doesn't make use of flammable solvents), durable, and maintenance-free. The battery is eco-friendly and has a low cost in comparison to anode and cathode based materials such as graphite and LiCoO2, respectively. For comparison, the cost per capacity ($/kAh) is 110 (LiCoO2) vs. 1.9 (graphite) vs. $1x10^{-3}$ (Sulfur). As with all lithium battery chemistries, there is a risk of combustion if lithium is exposed to the air. The primary weaknesses of the cell chemistry is the formation of lithium dendrites and dissolution of sulfur active materials from the polysulfide shuttle effect, ultimately limiting the charge-discharge cycle life [8]. Many methods are recommended on preventing dendrite formation, but recent work at the University of Southern California claims the use of a mixed conduction membrane (MCM) within a Li-S battery can achieve a cell cycle life comparable to that of the current state of the art Li-ion battery technology [9].

Advancement in this technology is showing the likelihood of the Li-S battery becoming the battery of the future. The current industry leader in Li-S technology is Oxis, who currently produces the rechargeable Li-S Rack Mounted Battery for European consumers. The rack mounted battery has a nominal voltage of 48 V, a rated capacity of 3 kWh with a weight of 25 kg, and a cycle life (80% DoD, 60% BoL) of 1400 cycles [10].

Lithium Air Batteries

Li-air, also called a Li-oxygen battery, is typically designed using a lithium metal anode, a porous carbon cathode, and an electrolyte (typically lithium salt). Metal-air batteries have the highest energy density because the cathode active material (oxygen) is not stored in the battery, but can be accessed from the environment. Currently lithium batteries are the subject of ARPA-E efforts, but are not mass produced commercially. The theoretical capacity of Li-air batteries makes them very attractive for aerospace/automotive applications, however, there are several technical challenges that need to be overcome first including the decomposition of the organic electrolyte at the cathode which drives the low number of charge cycles.

The theoretical capacity of a Li-air battery is 11,457 Wh/kg, however, the current state of the art at the pack level is around 500 Wh/kg which has been achieved by PolyPlus as part of an ARPA-E research contract. One of the major drawbacks of this technology is current Li-air batteries lose 25% of their original capacity after only 50 discharge cycles. This is one of the major technology hurdles for this specific battery chemistry. Charge efficiency with a carbon cathode is only 57% which falls well short of the typical aerospace efficiency of >90%. Use of platinum/gold catalysts can improve this to 73%, however, this is not likely to be a commercial solution due to the cost of platinum and gold.

Zinc Air Batteries

As mentioned earlier, the greatest benefit provided by metal-air batteries is their high energy density, as compared to other battery chemistries. The Zn-air configuration represents a safe, environmentally responsible and potentially inexpensive option for the storage of electrical power. Because of this fact, a recent surge in research efforts has developed in Zn-air battery chemistries for potential usage in both portable (cell phones, laptops) and stationary devices (power grid), as well as electric vehicles.

Zn-air batteries are composed of three main components: a zinc anode, an alkaline electrolyte (KOH), and an air cathode, usually made of a porous and carbonaceous material [12]. In a comparison of theoretical and practical gravimetric energy density (Wh/kg) for various electrochemical energy storage devices, it was found that Zn-Air possesses a practical energy density of 350 Wh/kg, while Li-Air possesses a practical energy density of 1700 Wh/kg [11].

When comparing Zn-air batteries to other metal-air chemistries, there are several potential advantages that can be exploited in the battery manufacturing process. One example is the abundance of zinc metal as a raw material. Currently, zinc is a more readily available and less expensive material to mine than lithium metal. The number of zinc reserves are relatively high around the globe, with countries such as Australia, Canada, China, and the USA being the largest mass producers of zinc metal [13, 14]. This key benefit potentially provides an advantage in the hypothetical expense of the mass production of zinc-air batteries. With respect to the environment, zinc, as a raw metal, is a safer material than lithium and can be fully recycled [13].

B. Life Cycle Assessment Development

This study was conducted utilizing a cradle-to-gate LCA methodology. Using data provided by the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET) database, four key life cycle phases and five impact categories were explored across each battery chemistry. Beginning with resource extraction, this life cycle phase explores the energy and environmental impacts associated with the acquisition of raw materials for each battery chemistry, and processing the materials into useable forms, such as metal ingots. Next, the manufacturing LCA analyzes the energy and environmental impacts associated with converting the required raw materials into the necessary components to construct a functional battery of each discrete chemistry. Use phase LCA then accounts for the total energy, emissions, and waste associated with the operation of each battery chemistry during in-service (work) conditions. Finally, the EoL LCA evaluates the energy, emissions, and water consumption associated with the separation and recycling of each component of the exhausted battery.

Though LCA data is available for many of the established battery chemistries, there is still a critical need for this data to be acquired for many of the novel battery chemistries. Unfortunately, for chemistries such as the lithium -air and zinc-air batteries, life-cycle assessment data simply has yet to be acquired.

Resource Extraction

The resource extraction section LCA was derived using materials production data from the GREET database [15]. The characteristics that were calculated were emissions, solid waste to landfill, total energy, and water consumption.

To calculate the emissions produced during the resource extraction phase of production, each battery was broken down into elemental/material percentages. The material percentages for PbA, NiMH, NiCd, Li-Ion were obtained from the Argonne National Laboratory [1]. The metal-air battery compositions were used from the Journal of Power Sources [16]. The battery percentages were multiplied by the grams per lb of material product and later converted into grams based on the required battery weights for the use case. Carbon dioxide was the largest contributor to emissions followed by Kyoto gases.

The solid waste to landfill statistics regarding resource extraction were calculated using data from the GREET database. To extract the materials needed for production of each of the battery chemistries the total energy in Btu's was calculated for each battery. The final metric that was analyzed for the resource extraction phase of the life cycle analysis was the water consumption used to acquire the resources needed to manufacture the different battery chemistries.

Manufacturing

The manufacturing phase of the LCA takes into account all expenditures necessary to convert commodity materials into battery components and assemble these components into a functional unit. For this LCA, all battery chemistries where sized against the requirements of the GS-YUASA LiCoO2 battery currently used by the 787. The manufacturing emissions per battery chemistry were then determined using the following process: first the total energy of manufacturing (mmBTU) per weight of battery (ton) was determined for each battery's manufacturing process. If more accurate manufacturing energies could not be determined, then the manufacturing energies given in the Argonne report [1] were used. The grams of each pollutant released for manufacturing were then determined by multiplying the total manufacturing energy by the grams of pollutant per mmBTU. This information was pulled from the GREET electrical generation data.

A multitude of references were used to gather the necessary manufacturing energies for the various batteries, and because of the proprietary nature of battery production, numbers for the total energy of production could greatly vary.

Assumptions for the manufacturing phase of each battery are described in the paragraphs below.

The manufacturing phase for the production of the Pb-acid battery was relatively straightforward, the longevity of the battery has created an industry-wide processing standard. Information taken from the Argonne report data was used to establish the total energy of manufacturing. This data was validated with the manufacturing and assembly process found on edgefx [17] and the work done by Rydh and Sanden [18].

Finding data for manufacturing energy consumption of NiCd batteries proved difficult, for this reason the manufacturing energy was taken from the GREET report [1] which references the work done by Rydh and Sanden [18]. For simplicity, the average of the range given in the GREET report was used.

The energy of manufacturing for the NiMH battery was taken from the total energy for production given in the supporting information for Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-in Hybrid and Battery Electric Vehicles [19]. The process for determining emissions for the NiMH chemistry differed on that the processing and energy requirements given in [19] were listed by energy source (i.e., electricity, medium voltage; heat, light fuel oil; heat, natural gas). Here we did not use the general assumption for electricity production but could attribute emissions to the amount of energy derived from each source. Majeau-Bettez et. al. [19] used a top-down methodology to determine the manufacturing energies for each stage of production. This involved taking reported industry overall manufacturing energy requirements and breaking them down using published estimates for processing phase, industrial process modeling, thermodynamic calculations, or use of proxies. The number we report in our LCA neglects the large assumption left process waste heat in [19].

The most recent and best estimates for total manufacturing energy requirements for the production of Lithium ion batteries was based upon Rydh and Sanden [18]. Majeau-Bettez et al [19] expanded upon this work by employing a top-down approach, taking the total manufacturing energies provided by Rydh and Sanden and determining process energies for each manufacturing step. The value for manufacturing energy consumption we reported in our LCA omits the expenditure for waste heat reported in [19].

Li-S battery chemistry is a relatively new battery chemistry which is just now emerging in the market. For this reason there is little manufacturing information available on Li-S batteries. An LCA written specifically for Li-S batteries proved essential to this report. In Life cycle assessment of lithium sulfur battery for electric vehicles the team determined the energy demand of the Li-S manufacturing process through measuring and modeling the energy consumption of battery manufacturing equipment in a 93.2 m^2 pilot scale dry room facility of Johnson Controls Inc. Writers of this report believe at an industrial scale one could see a 51 to 76 percent reduction in energy consumption at the manufacturing stage of Li-S battery production.

Being a relatively new battery chemistry there was little data to go one to determine the energy consumption of the Li-Air manufacturing process. An LCA out of Europe determined the energy requirements for Li-air cell assembly to be 74 MJ/kg battery [20], a number derived from data in The Saft Corporation 2008 annual report. There is no description on how this number was derived, so additional resources for this information should be considered.

Suffering from similar limitations as the Li-air battery, not much information is available or has been identified to determine the energy consumption of the Zn-Air battery manufacturing process. However, due to the similar working principles of the air battery chemistries, it can be assumed that the manufacturing process for these batteries are also similar, outside of the resource extraction and raw materials processing steps. Recognizing this, the Zn-air battery's energy consumption figure is approximately 33% less than the Li-air battery figure. This adjustment was made to account for the relatively high accessibility and cheap material cost of zinc, as it compares to lithium; and the lack of an energy-intensive drying process for the Zn-air battery chemistry, that is a common place process in other battery chemistries. Considering the aforementioned aspects of the manufacturing process of Zn-air batteries, it was determined that an energy requirement of 48.8 MJ/kg is a responsible estimate of the energy consumption need to manufacture a Zn-air battery of the required capacity.

Use Phase

The use phase of the battery cycle was calculated using the 787 APU as a baseline. The total lifetime energy use of the battery (aboard the aircraft) was calculated using the 787 APU battery endurance testing specification which simulates 5 years of battery usage. The total energy expended over the course of the test is 102.5 kAh. For each battery chemistry the total energy use (from the grid) was then calculated by taking the total energy use aboard the aircraft and dividing by the charge efficiency to account for loses. The charge efficiency of batteries is affected greatly by the charge rate. In this case the 1C charge rate was used because the 787 spec requires that the battery be charged to its full capacity in 75 minutes which is close to 1C (the true value of 0.8C is not always readily available). The total energy usage was then used in conjunction with average US electric grid data to compute the pollutant outputs and water usage.

In addition to the energy expenditure while on the aircraft, information about the use of the batteries was needed to feed into the resource extraction, manufacturing and end of life LCA calculations. Specifically the mass of the batteries was needed to calculate the mass of the component elements. To calculate the required mass for each battery, the required battery capacity was derived based on the 787 APU specification. The battery used is Li-ion with a required capacity of 50Ah. Li-ion batteries have a typical maximum DoD of 80% which leads to only 40Ah being usable capacity. The DoD of each other battery chemistry was then used to calculate the required cell capacity to have 40Ah of usable charge. weight of required for a single battery was calculated by taking the product of the specific energy of each battery chemistry, and the calculated capacity. Finally, the number of discharge cycles for each chemistry was used is to determine the number of batteries required to complete the 5 year life cycle. The number of batteries required and the weight of a single battery derive the total lifecycle weight of each battery chemistry.

End of Life

The EoL of each battery was modeled by taking into account three processes: separation of the battery materials, recycling, and landfilling. Total energy required for each battery was calculated using Equation 1.

$$E_{EoL} = W * \left(E_{sep} + f_{rcyl} * E_{rcyl} + \left(1 - f_{rcyl}\right) * E_{landfill}\right) \quad \text{eq.(1)}$$

Where W is the total lifecycle weight of the battery, E_{sep} is the energy required for separation (101.46 BTU/lb) [21], f_{rcyl} is the fraction of recycled material, E_{rcyl} is the energy required for recycling, $E_{landfill}$ is the energy required to transport waste to a landfill (285.89 BTU/lb) [21], and E_{EoL} is the total energy consumed at EoL.

None of the resources indicated that any of the battery materials are incinerated; therefore, this end of life scenario was excluded. Recycling fractions, and energy required for recycling for each battery were taken from literature sources [1, 2, 5, 22, 23, 24]. Emissions and water consumption for this lifecycle phase were assumed to be entirely related to the energy used, and was calculated using E_{EoL}, and emission and water consumption of the 2015 US grid averages for energy production. Finally, solid waste to Landfill was calculated using Equation 2.

$$Solid\ Waste\ to\ Landfill = w * \left(1 - f_{rcyl}\right) \quad \text{eq. (2)}$$

Aircraft Performance Considerations

Differences in battery weight described in the use phase are a critical consideration for aircraft performance. Increased weight results in greater fuel burn, resulting in emissions and upstream fuel production impacts. A 787-8 reference mission was used as a baseline. Information regarding the impacts of a 787-8 was taken from quickLCA, a software tool developed by Boeing to conduct aircraft level LCAs.

Changes in fuel efficiency driven by differences in OEW were also considered, but were found to be negligible given the range of weights used in this study.

III. LIFE CYCLE ASSESSMENT RESULTS

The data used in this study represents typical or theoretical data for each battery type, and the analysis could be adjusted for more specific data if used for trade studies for specific applications if desired.

Table 3.1 shows calculated weights of each battery chemistry needed to complete the performance requirements of the aircraft. Included is both the single battery weight, or the weight that is aboard the aircraft, the number of batteries used over a 5-year period, and the total battery weight, or the weight of all the batteries used in that period.

Table 3.1 Battery Weights

Battery Chemistry	Pb-Acid	Ni-Cd	Ni-MH	Li-ion	Li-S	Li-Air	Zn-Air
Single Battery Weight (lbs)	77.18	86.83	47.19	65.12	6.51		9.30
Number of Batteries per lifecycle	2.86	2.86	2.86	1.00	1.43	40.00	40.00
Total Lifecycle Weight (lb)	220.51	248.08	134.82	65.12	9.30	416.77	372.11

Figure 3.1 shows the total Greenhouse Gas (GHG) Emissions represented in grams of CO_2 equivalents. Lifecycle phases represented are Resource Extraction, Manufacturing, Use and End of Life. Figure 3.3 shows the total lifecycle water consumption of each battery for similar lifecycle phases represented in Figure 3.1

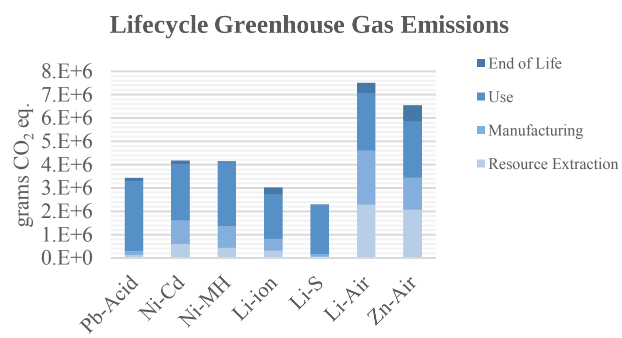

Figure 3.1 Lifecycle Greenhouse Gas Emissions

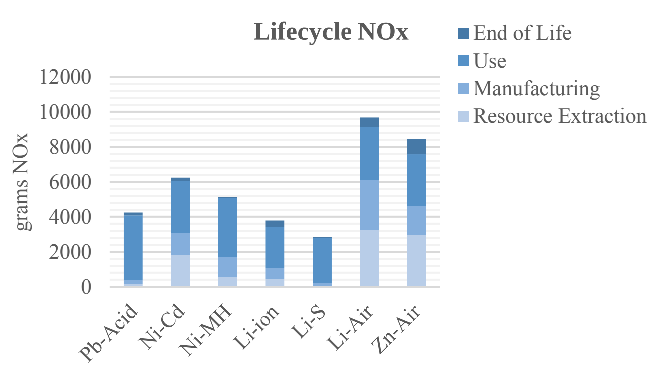

Figure 3.2 Lifecycle NOx

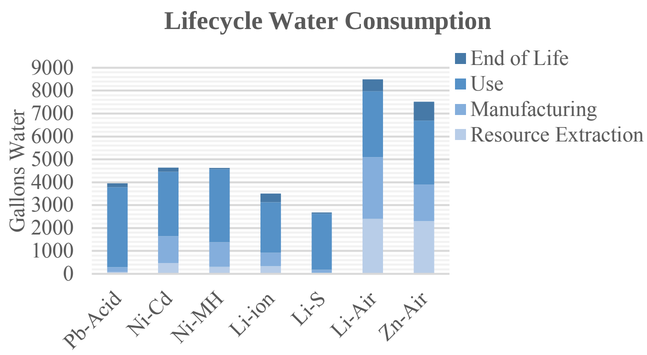

Figure 3.3 Lifecycle Water Consumption

Results for emissions generated and water consumed by each battery follow similar trends in terms of relative performance to other batteries. When excluding impacts to aircraft performance, each of these EPMs are driven by total battery weight. Li-S and Li-Ion consistently outperform other chemistries while Li-Air and Zn-Air perform significantly worse than the other batteries.

Figure 3.4 shows the total lifecycle solid waste to landfill of each battery for similar lifecycle phases represented in Figures 3.1 - 3.3

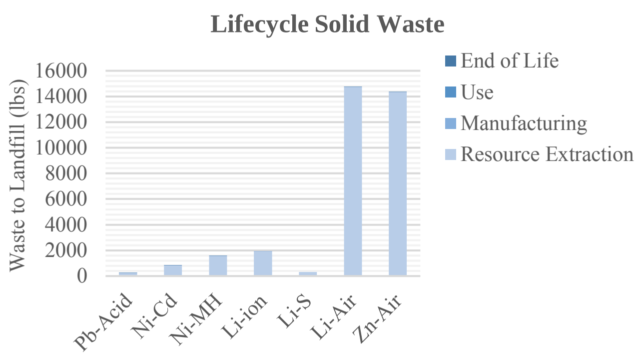

Figure 3.4 Lifecycle Solid Waste

Results of solid waste to landfill are significantly different from the other EPMs. Here, resource extraction dominates over the other lifecycles. Li-S and Li-ion perform the best while Li-Air and Zn-Air perform orders of magnitude worse.

Figure 3.5 shows the lifecycle total energy consumption of each battery chemistry with the same lifecycle phases represented as Figures 3.1 - 3.4 with the exception of the use phase. The use phase is divided into the energy actually used for the aircraft mission, and the energy lost to charge inefficiencies.

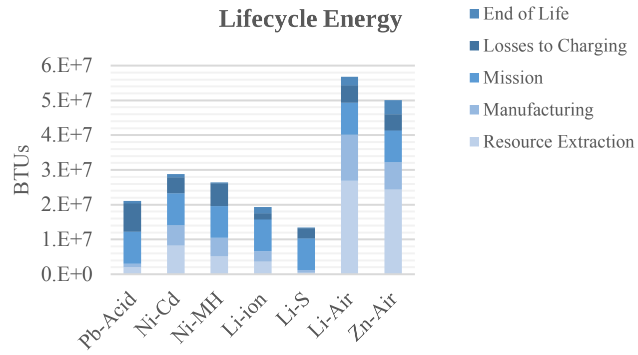

Figure 3.5 Lifecycle Energy

Results of Figure 3.5 demonstrate the dependence on total battery weight similar to the results of Figures 3.1-3.3.

Figure 3.6 shows a radar chart of five battery chemistries. These include Pb-acid, NiCd, NiMH, Li-ion, and Li-S. The metal air batteries are excluded because their values skew the visualization of the graph. Each axis of the radar chart represents a different impact category normalized to the performance of Li-ion. In other words, Li-ion equals unity on every axis. The values for the remaining batteries denote their performance relative to Li-ion. These values show the percentage of potential improvement, or decline, in environmental impacts resulting from replacing the 787 APU battery with each respective chemistry.

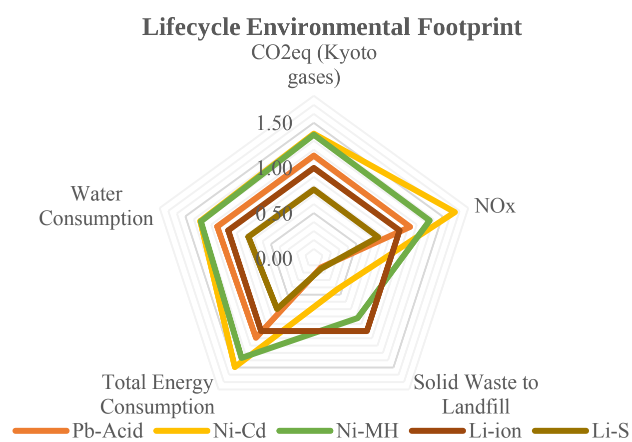

Figure 3.6 Lifecycle Environmental Footprint

The lifecycle energy storage performance of a battery can be characterized by the total energy stored by the battery over its lifetime compared to the total energy consumed by the battery over its lifecycle. Batteries that have a percentage of 50% or greater use more energy to perform the function of the battery (energy storage) than is needed to generate and dispose of the battery. Table 3.2 shows this "Energy-Use" percentage of each respective battery in this study.

Table 3.2 Useful Energy Percentage

Pb-Acid	Ni-Cd	Ni-MH	Li-ion	Li-S	Li-Air	Zn-Air
43.49%	31.79%	34.70%	47.49%	68.06%	16.14%	18.32%

Li-S is the best performing battery by this metric. However, Pb-Acid and Li-ion are both near the 50 percent target. Given the assumptions made and fidelity of the data, they could also be considered high performing. Alternatively, the metal air batteries show very poor performance.

Use phase emissions in this LCA study were calculated assuming the required energy for charging is supplied by the 2015 United States electrical grid. The respective mix of generating sources in 2015 have associated emissions, which are primarily derived from fossil fuels. Because of this, changes in generating sources and electrical grid mixes have a significant impact on the emission of a battery's use phase. Higher penetration of renewable energy sources into the electrical grid will lead to a reduction in lifecycle emission for each battery. To explore the sensitivity a grid mix has on a battery's lifecycle, the percentage of lifecycle carbon emissions resulting from charging and discharging were calculated for each battery chemistry. Table 3.3 shows these percentages. These percentages represent the potential reduction in emissions if each battery were charged with carbon free energyTable 3.3 Potential Emission Reduction from Carbon

Table 3.3 Free Energy Sources

Pb-Acid	Ni-Cd	Ni-MH	Li-ion	Li-S	Li-Air	Zn-Air
87.4%	57.6%	66.0%	62.7%	91.1%	32.9%	36.7%

From the results of Table 3.3, Li-S has the highest potential of emission reduction, followed by Pb-Acid, NiMH and Li-ion, while metal-air batteries have the least potential.

As discussed earlier, the additional weight of each battery implies changes to overall fuel burn during operation of the aircraft. The implication of these performance changes for gwater consumption and total energy consumption are shown in Figures 3.9 and 3.10 respectively.

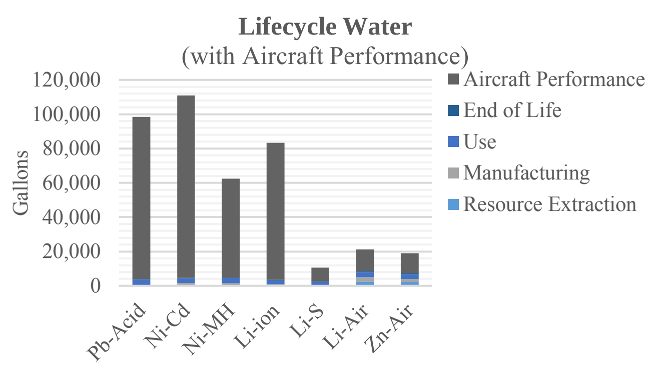

Figure 3.9 Lifecycle Water Consumption

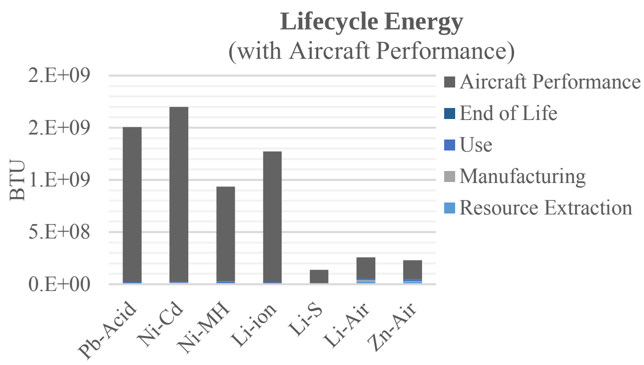

Figure 3.10 Lifecycle Energy

When aircraft performance is considered, each of these four EPMs are driven by the weight of a single battery. Li-S again outperforms all other batteries, while the performance of the two metal air batteries greatly improve. Because additional weight to the aircraft contributes negligibly to solid waste generated during use, the solid waste results remain constant whether considering aircraft performance or not.

IV. DISCUSSION

When taking into account aircraft performance, the results show the energy intensity of materials and manufacturing processes are less significant than the overall technical performance of the battery. This is true for each EPM except solid waste to landfill. In the solid waste to landfill EPM, the high volumes of waste generated by the metal-air batteries are driven by the limited number of discharge cycles, requiring the batteries to be replaced more often.

Recycling measures are a classic method to reduce impacts to resource extraction. Because of the small contribution resource extraction poses to emissions, water and energy, improved end of life scenarios would not significantly improve performance in these EPMs. However, it is evident that recycling measures could greatly reduce the amount of solid waste to landfill for every battery chemistry. The LCA illustrates the extent of this trade. Improving the recycled fraction of the battery will only have a small effect on how much of the final product would be diverted from landfill, but there is a large potential to displace a majority of the waste generated over the batteries lifetime by limiting waste generated from resource extraction.

Finally, the two metrics described in tables 3.2 and 3.3 demonstrate Li-S is the best candidate for sustaining a future of high renewable energy use. This result compliments the findings of the EPMs, and indicate both technical and environmental benefits of utilizing Li-S technologies at Boeing.

When comparing other battery chemistries, Li-ion shows strong technical performance and small environmental impacts in each metric except solid waste to landfill, where it performs the worst. NiMH batteries compete well with Li-ion in each EMP when considering aircraft performance, but suffer in useful energy percentage. Pb-acid battery performs well in useful energy percentage and potential emission reduction, but has poor EPM performance compared to Li-ion. NiCd demonstrates poor performance in each metric except waste to landfill. From this analysis, Li-ion remains the contemporary battery of choice. In addition, it is evident that the biggest potential to reduce Li-ion environmental impact is to increase the recycle rate, and avert waste generation during resource extraction.

V. CONCLUSIONS

This study compared the relative performance of seven aerospace battery chemistries to Boeing's EPMs. In every metric, Li-S batteries outperformed the other battery chemistries assessed in this study. Li-S batteries' low weight overcame perceived shortcomings such as low charge efficiency, poor recyclability and energy intensive manufacturing processes. Not only do Li-S batteries have the lowest environmental impact potential for aerospace, it also promises significant advantages in technical performance. However, the technical maturity of this technology will need to improve further to realize some of the life cycle benefits outlined in this study.

VII. ACKNOWLEDGMENT

The authors would like to acknowledge the ETT ONE program for providing funding and administrative support by means of the Integration Team Focals. These included Nicole Mendoza, Mark R. Mahowald and Daniel A. Charles. The team and project benefited from technical support on behalf of Dwaine Coates, who provided guidance to Boeing specifications and working knowledge of various batteries. Lastly, the project could not have been accomplished without the support of Technical Mentors Marty Bradley and Thomas Barrera. Marty Bradley provided expertise in advanced concepts, commercial airplane energy requirements, and technical writing. Thomas Barrera was pivotal in this paper's conception, and provided expertise in battery technologies across the enterprise, along with critical resources used throughout the literature review. Thomas should be considered a co-author of this paper, but unfortunately is no longer an employee of the Boeing Company.

VIII. REFERENCES

1 Sullivan, J.L., and L. Gaines. "A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs". *Argonne National Laboratory*. October 1, 2010. Accessed April 13, 2017.

2 Albright, Greg, Jake Edie, and Said Al-Hallaj. "A Comparison of Lead Acid to Lithium-Ion in Stationary Storage Applications." March 2012. Accessed April 13, 2017.

3 Thomas Reddy, *Linden's Handbook of Batteries* (New York: McGraw Hill, 2011), 4.

4 Plachy, Jozef. "Cadmium Recycling in the United States 2000". *U.S. Geological Survey Circular 1196-O.* (2003).

5 David Wyatt, Mike Tooley, *Aircraft Electical and Electronic Systems* (New York: Routledge, 2011), 1.

6 K Cox, S Arroyo, L Kang, D Coates, V Dominguez, D Hall, "Optimization of Small Cell Batteries through Mixed Integer Programming and Metaheuristic Algorithms," *2016 NASA Aerospace Battery Workshop*, 2016.

7 L Gaines, "Enabling Future Li-Ion Battery Recycling," *127th Convention + Power Mart Expo*, 2015.

8 Deng, Yelin, Jianyang Li, Xianfeng Gao, and Chris Yuan. "Life Cycle Assessment of Lithium Sulfur Battery for Electric Vehicles." January 21, 2017. Accessed April 13, 2017.

9 Moy, Derek, and S. R. Narayanan. "Mixed Conduction Membranes Suppress the Polysulfide Shuttle in Lithium-Sulfur Batteries." *Journal of The Electrochemical Society 164, no. 4* (January 27, 2017). doi:10.1149/2.0181704jes.

10 "Rechargeable Lithium Sulfur Rack Mounted Battery". Accessed April 18, 2017.

11 Girishkumar, G., McCloskey, B., Luntz, A.C., Swanson, S., Wilcke, W.: "Lithium-air battery: promise and challenges." *J. Phys. Chem. Lett. 1, 2193-2203* (2010)

12 Caramia, V., Bozzini, B.: "Materials science aspects of zinc-air batteries: a review". *Mater Renew Sustain Energy 3:28,* (2014)

13 "Zinc Recycling" I*nternational Zinc Association.* (Accessed March 2017)

14 "Lead and Zinc Statistics". *International Lead and Zinc Group*. (Accessed March 2017)

15 Burnham and Wang. "Development and Applications of GREET 2.7 – The Transportation Vehicle-Cycle Model." *DOE Energy Systems Division, Argonne National Laboratory*, 2006.

16 Gerssen-Gondelach and Faaij. "Performance of batteries for electric vehicles on short and longer term." *Journal of Power Sources*, 2012.

17 Agarwal, Tarun. "Know About the Steps of Battery Manufacturing Process." Accessed April 18, 2017.

18 Rydh, Carl Johan, and Bjorn A. Sanden. "Energy Analysis of Batteries in Photovoltaic Systems. Part I: Performance and Energy Requirements". December 7, 2004. Accessed April 13, 2017.

19 Majeau-Bettez, Guillaume, Troy R. Hawkins, and Anders Hammer Stromman. "Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles." *ACS Publications*. April 20, 2011. Accessed April 18, 2017.

20 Zackrisson, Matt, Kristin Fransson, Jutta Hildenbrand, and Gorazd Lampic. "Life Cycle Assessment of Lithium-air Battery Cells." June 23, 2016. Accessed April 13, 2017.

21 Staudinger, Jeff, Keolenia, Gregory A. "Management of End-of-Life Vehicles (ELVs) in the US", *Center for Sustainable Systems at the University of Michigan*. March 2001,

22 Inderscience Publishers. "How to recycle lithium batteries: Efficient approach to leaching lithium and cobalt from recycled batteries." *ScienceDaily*.

23 "Energy Consumption" *VMZINC*. Accessed March 2017.

24 "QuickLCA." *Product Development Environmental Performance, Boeing Commercial Airplanes*, 2016.

25 Y. Deng et al. Journal of Power Sources 343 (2017) 284e295

26 Wang, J., Li, Y., Sun, X. "Challenges and opportunities of nanostructured materials for aprotic rechargeable lithium-air batteries." *Nano Energy* 2, 443-467 (2013)

27 Jennifer B. Dunn (9), Linda Gaines (9), Jarod C. Kelly (9), and Kevin G. Gallagher (10). "Life Cycle Analysis Summary for Automotive Lithium-Ion Battery Product." *Springer*. January 01, 1970. Accessed April 13, 2017.

IX. BIOGRAPHIES

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Dustin D'Angelo is an MP&P Engineer in the Boeing Research and Technology (BR&T) Assembly and Automation Division located in Charleston, SC. Dustin majored in manufacturing engineering at the Rochester Institute of Technology and graduated with a bachelor's of science in 2010, and a master's of science in 2012. He later completed his Master's in Business Administration in 2016. He started his professional career as a mechanical engineer working as a contractor for the U.S. government at an army facility. Dustin joined Boeing in April, 2015 and supported the qualification and implementation of an automated assembly line in Propulsion South Carolina building 88-53. He is currently supporting the 737 MAX Inlet program with manufacturing and assembly processes, rate enabling equipment, and emergent support.

Dr. Joseph Fernando Gonzalez graduated with a BS in Aerospace Engineering from the University of Illinois at Urbana Champaign (UIUC). In 2011, Joseph later acquired his MS in Aerospace Engineering where his graduate and undergraduate research work focused on crack path selection in microstructurally tailored inhomogeneous polymers. Joseph was later awarded the National Science Foundation Graduate Research Fellowship Program to continue his doctoral studies in the subject matter of 3D characterization and quantification of composites and Li ion battery materials. Joseph started working for the Boeing Company in 2015 at Huntsville, AL as a material processes and physics (MP&P) engineer for Boeing Research and Technology (BR&T) as a part of the Chem Tech group. His work focuses on next generation battery development/characterization, and space launch system (SLS) mechanical and fluids testing.

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