\subsection{Thermal Management Considerations}

\subsubsection{Changes of Thermal Management Systems for Alternative Energy Sources}

The thermal management system (TMS) of an airplane which utilizes alternative energy sources can be much different from the one that is in an airplane with conventional jet fuel. The TMS in a conventional jet-fuel airplane includes environmental control system (ECS), anti-icing system, electronics cooling, and passive cooling mechanism by ram air or engine fan air~\cite{shithesis2021, clark2022design}. Such systems are used to ensure proper temperature and pressure for pilots, crews, passengers, cargo, equipment, as well as preventing icing conditions. However, for an airplane with alternative energy sources, new heat loads or new heat sinks may be introduced, leading to new required functionalities of the TMS. For example, hybrid electric propulsion systems will add new generators or electric motors to the propulsion system, which can be significant heat loads with even lower temperature (low-quality heat) considering the amount of required propulsive power and the operational temperature. Specific thermal management mechanism needs to be designed to handle such heat loads, since the existing TMS is not capable of handling such low-quality heat effectively. In addition, the energy sources themselves can be heat loads too, such as batteries, because heat is generated during both the discharging and charging processes. These may come in the form of direct air cooling\cite{}, conjugate cooling\cite{}, liquid immersion cooling \cite{}, phase-change material cooling\cite{}, or cold plates\cite{}. On the other hand, alternative energy sources such as cryogenic fuels (liquid hydrogen, liquid natural gas, etc) may be used as new heat sinks too, which can mitigate the heating problem but need new TMS designs to utilize its cooling potential. Thus, proper design changes of the TMS are needed to enable the new functionalities to handle new thermal management challenges.

To solve these emerging thermal management issues caused by utilizing alternative energy sources, one solution is to use existing TMS with new cooling/heating interfaces to the new heat loads. For example, the conventional ECS is used for battery cooling after cooling the cabin~\cite{perullo2020, shi4, shi2022finalized}. Upsizing the conventional TMS to reach higher cooling/heating capability is also an alternative solution compared to using the existing ones. For other cases, novel TMS designs will be needed. However, it is impossible to enumerate all feasible candidate TMS solutions for a given set of thermal management requirements. By noting that all TMS designs follow the basic heat transfer physics, and most of the TMSs are fundamentally heat pumps, Shi~\cite{shi2021tms, shithesis2021} came up with a behavior-based methodology to systematically generate candidate TMS architectures. Heat transfer behaviors are used to guide the TMS architecture space exploration, and a machine learning-based method is used to filter out infeasible designs. Such method has shown that novel configurations can be generated to handle new thermal management needs, with consideration of new types of heat sinks.

\subsubsection{Capturing Impacts of Thermal Management System Changes}

As shown in previous work by Chakraborty~\cite{ChakrabortyJoA2016Arch} and Shi~\cite{shi2018ECS, shi2018mission}, subsystems influence the airplane-level performance mainly through four ways: 1) change of weight; 2) change of zero-lift drag; 3) extraction of engine bleed power; and 4) extraction of engine shaft-power. Such impacts will further influence both the aerodynamic performance and propulsion performance of the airplane, and then further lead to differences in fuel burn or energy consumption for missions. Such impacts are illustrated in Fig.~\ref{fig:subsystemeffect}~\cite{shi2018mission}. For thermal management systems for alternative energy sources, similar concept still applies. Adding new components for the new TMS functions will add weights. Using ram air as a heat sink will increase the zero-lift drag. Ram air is also only an effective means of cooling when the aircraft reaches high speeds to facilitate sufficient heat transfer – at lower speeds, a puller fan may be required*.* Heat pumps or pumping the cooling/heating fluid requires power. However, this power might not only come from the propulsion system, and it can come from the energy pack as well. Therefore, the updated impacts can be shown by Fig.~\ref{fig:Tmseffect}.

\begin{figure}[!h]

\centering

\includegraphics[width=0.4\textwidth]{Figures/SubsystemEffects}

\caption{Impacts of subsystems on airplane and mission-level performances~\cite{shi2018mission}}

\label{fig:subsystemeffect}

\end{figure}

\begin{figure}[!h]

\centering

\includegraphics[width=0.6\textwidth]{Figures/TMSeffects.png}

\caption{Impacts of thermal management systems with alternative energy sources}

\label{fig:Tmseffect}

\end{figure}

\subsection{Impacts of Regulations On Energy Pack Weight Sizing Constraints}

Many aviation regulations regarding safety have originated and evolved over decades of learnings from safety incidents. The lack of historical data on aircraft with electrified propulsion systems poses not only a problem for sizing (as discussed in section \ref{sec:oewdiscussion}), but for regulators as well. While the same problem may have existed at the beginning of the jet age, the challenge is that the electrified aviation market may grow much quicker, and regulators need to quickly develop methods to manage reliability and fault mechanism uncertainties. For the alternative aircraft designer, the complexity of the potential fault paths and the accommodations will have an impact on weight to establish sufficient fault tolerance for the safety continuum requirements. While this paper is primarily focused on all-electric (battery or fuel cell) powertrains, this is one of the potentially interesting practical attributes of hybrid electric aircraft. Some of the key opportunities with hybrid electric are to 1) meet all reserve fuel requirements with liquid fuel with a delivered energy density factor of at least 20x lithium battery system reserves, and 2) fault accommodation potentially being met by a liquid fuel powerplant technology with decades of system safety history to reduce uncertainty.

It should be noted that not only performance requirements (e.g., payload, range, fuel consumption, etc.) influence on the alternative energy pack weight constraints, but the fuel jettison-related regulations also have great impacts.Based 14 CFR Part 25~\cite{part25}, ``A fuel jettisoning system must be installed on each airplane unless it is shown that the airplane meets the climb requirements of §§ 25.119 and 25.121(d) at maximum takeoff weight, less the actual or computed weight of fuel necessary for a 15-minute flight comprised of a takeoff, go-around, and landing at the airport of departure with the airplane configuration, speed, power, and thrust the same as that used in meeting the applicable takeoff, approach, and landing climb performance requirements of this part.(§§ 25.1001)'' §§ 25.119 and and 25.121(d) refer to Landing climb: All-engines-operating condition and Approach regulations. When battery is used as the alternative energy source of the airplane, special attentions should be paid to these regulations because it would be natural to assume that the "fuel" or energy storage cannot be jettisoned. To ensure the corresponding compliance without having a jettison system, the low-speed aerodynamic performance needs to be analyzed if high credibility is desired. However, most existing publicly available conceptual design approach/tools do not have the capability to do such low-speed aerodynamic analysis, or more specifically, to generate the drag polar associated with low-speed configuration. Therefore, there is a need to add such capability to address the alternative energy pack sizing challenge.

\subsection{Practical Considerations for Conceptual Design}

\subsubsection{Electrified Subsystem Requirements}

Aircraft requirements flow down to the electrified subsystem requirements and reflect, at the highest L0 requirements level, the stakeholder mission for the aircraft. For the user stakeholder, the passengers buying tickets or shipping cargo, it is usually a matter of convenience and cost. Convenience attributes include availability from location to location, travel time, and other elements of logistical complexity. What is the price for different levels of convenience? For the provider stakeholder, including the airline operator and aircraft OEM, the primary measures are usually return on investment and scale of revenue.

While these L0 requirements seem abstract to the detailed electrified subsystem requirements, they are not, as will be described for some key electrified subsystems. The SAE Standard AIR 8678, \textit{Architecture Examples for Electrified Propulsion Aircraft}, presents an organized and generalized decomposition of subsystem elements that may be present in electrified propulsion aircraft and the other subsystems that they typically interact with, shown in Figure \ref{fig:sae8678} \cite{saestandard}. The following are practical implications for some of these key subsystems beyond the basic technical metrics of weight and efficiency:

\begin{figure} []

\centering

\includegraphics[width = 0.5\textwidth, trim = {5cm 9cm 7cm 5cm}]{Figures/sae STd.pdf}

\caption{SAE Standard Air 8678 \cite{saestandard}.}

\label{fig:sae8678}

\end{figure}

\subsubsection{Energy Storage Systems (ESS)}

While an ESS in an electrified propulsion aircraft can be based on several different technologies, the focus of this section will be on lithium-ion battery technology that used in most e-aircraft developments today. The most basic attributes of interest are as usual weight, or when normalized, gravimetric energy density (Wh/kg), and efficiency (\%). For an ESS which is the energy source, the efficiency is the percentage of energy delivered divided by the energy stored.

Beyond weight and efficiency, other key attributes include usable energy, cycle life, and installed cost. The usable energy is typically defined as the percentage of stored energy in a new pack that can be used in normal operation at the end of life when the pack is replaced. If there exists high energy density battery technology but the usable energy fraction is relatively small, then the net value of the technology may be a wash or even worse that more matured lithium battery technologies. One way to capture this is to define the usable gravimetric density, still in Wh/kg, but where the Wh is only end of life usable fraction of the ESS total stored Whs. In this way, different technologies can be compared on a more level field. The next two attributes, cycle life and cost, are coupled from a practical stakeholder requirement perspective. Consider one technology that is capable of 1000 cycles before replacement and costs \$100/kWh installed new, and then a second battery technology capable of 2000 cycles but at a cost of \$200/kWh installed new. If the cost of initial installation and maintenance replacements for these two solutions is calculated, the net lifecycle cost is the same to first order. In utility power projects, they are typically evaluated on a levelized cost of energy basis. The same can be done here. Both of these technologies have a basic levelized cost of \$0.10/kWh.cycle, and within limits can be traded off evenly when designing an e-aircraft with a focus on other attributes such as inherent thermal runaway fault tolerance.

\begin{comment}

The aviation industry is increasingly interested in advancing electrified flight via battery systems. This can be attributed to growing interest in reducing tailpipe emissions and the advances in battery technology that have seen energy densities increase tenfold over the past decade [1]. Over the years, there has been a notable adoption of battery-electric systems in airplanes, with various battery types being utilized, including Nickel-Cadmium (Ni-Cd) [2], Sealed Lead-Acid [3], and Li-Ion batteries [4], each possessing distinct capacities. However, significant challenges prevent the widespread adoption of batteries as the primary energy carrier. While battery-electric aircraft demonstrate superior end-to-end efficiency compared to Brayton-cycle engines, the specific energy of battery systems remains a significant limitation [5]. Various metrics such as energy density, power density, cyclability, safety, and abuse tolerance are generally employed to evaluate the performance of battery cells. Numerous efforts such as ARPA-E’s Propel 1K [6] are underway to improve these performance metrics. Successful improvements in these areas have the potential to profoundly impact the development of large-scale energy systems and contribute to the reduction of aviation-induced emissions. Nevertheless, sectors such as urban air mobility (UAM), regional air travel, and the short-range aviation market can already benefit from the implementation of electrified propulsion architectures. Before diving into a universal metric for accessing different batteries as a feasible energy carry, an overview of the potential cell chemistries is first provided.

Battery Cell Chemistries

Lithium-ion (Li-ion) batteries are extensively used in various industries due to their superior properties when compared to other battery types. Being the third lightest element, the use of lithium allows us to pack as many charged particles as possible per unit volume for the same weight of battery. This results in a significantly higher energy density and a long cycle life compared to lead-acid batteries, and low memory effects compared to Ni-Cd [7]. Nevertheless, when comparing the Li-ion battery performance with jet fuel, which has high gravimetric and volumetric energy densities of 12,000 Wh/kg and 9,600 Wh/L, the current state-of-the-art lithium-ion technology is able to achieve energy densities around 300 Wh/kg and 1,000 Wh/L [8,9]. A Li-ion battery cell is made up of several components, including a cathode anode (negative electrode), separator (porous membrane to isolate the electrodes), and liquid electrolyte. When the battery is being charged, lithium ions move from the cathode to the anode through the electrolyte. An electrochemical reaction generates battery energy, which is converted from chemical energy to electrical energy. Conversely, when the battery is being discharged, the lithium ions move back to the cathode. The separator acts as a physical barrier between the electrodes, but it's porous enough to facilitate the exchange of lithium ions between them through the electrolyte. The energy storage capacity of a lithium-ion battery depends on its charge acceptance and potential, which are associated with the crystalline structure and Gibbs free energy of the active material. Current areas of research involve the use of intercalation electrodes and conversion electrodes.

The most common cathode materials include Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide LMO, Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminum oxides (NCA), and Lithium Manganese Oxide (NMC). Of these NCA and NMC show the most precise due to their high specific capacity, at 200 mAh/g, moderate-to-high specific power, and high cycle and calendar life, with 1000-1500 cycles [10,11]. However, they have similar thermal stability to LCO batteries. Has a higher cycle life of 1000-2000 cycles compared to NCA [12]. For the cathode, the proportions of nickel, manganese, and cobalt can be adjusted to achieve the desired performance characteristics. Nickel increases lithium extraction capacity and specific energy, while manganese improves power capability and thermal stability. Cobalt increases structural stability and cyclability. That said, the rapid improvement of cells and seen intercalation ability of the cathode and graphite-based anode are both approaching their upper limits theoretical limits meaning a flatting of potential specific energy densities at the cell level.

One variant of Li-ion batteries is those whose electrolytes are not liquid, but rather solid. These cells, termed solid-state batteries, offer advantages in weight, as a thin layer can be coupled with high-energy cathodes, as well as safety since the likelihood of mechanical failure of the solid electrolyte film is less [13]. One current drawback of these cells however is the small temperature range for peak performance – too low a temperature inhibits the electrothermal processes that lead to the movement of charged particles. [13]. Lithium-silicon batteries are another emerging class of cells that show promise. Instead of using the conventional graphitic carbon anode, Silicon is utilized due to its high-performance metrics. Li-Si batteries can reach specific capacities as high as 460 mAh/g [14] at a relatively lost cost due to the high availability of raw silica in nature. However, when compared to commercial battery types, Lithium-silicon batteries suffer from limited cyclability [15]. Lithium-sulfur batteries have also significantly improved over the past decades. Among the advantages of such chemistry, the most important is a high theoretical specific capacity (1675 mAh/g) [16], energy density (2600 Wh/kg) [16], low cost due to the high abundance of raw material in nature as well as being the byproduct of many oil and gas refineries [16]. However, some challenges are intrinsically limiting the development of Li-S batteries, such as non-monotonic discharge curves and high voltage hysteresis which can pose a challenge when developing battery management systems. Additionally, during cycling, volume changes up to 80\% and exerts pressure on the cathode integrity with rapid loss of active materials [17]. Furthermore, intermediate reaction products (polysulfides) dissolve in the electrolyte and shuttle between the anode and cathode during the charging process, resulting in extraneous reactions in the electrodes, reducing the Coulombic efficiency [18]

Finally, we have metal-air batteries, which include Magnesium-air (Mg-air), Lithium-air (Li-air), Zinc-air (Zn-air), and Aluminum-air (Al-air). Despite the challenges of practical issues surrounding poor rechargeability, manufacturability and scale, and effective capturing air and extracting oxygen at high altitudes, estimated energy densities, determined to be between 42-58\% of the theoretical energy density, fall between 3500 Whkg-1 [19]. Moreover, the use of Zinc offers the benefit of reducing cost as it is high abundance. This earth metal also possesses low equilibrium potential, environmental benignity, a flat discharge voltage, and a long shelf-life.

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Battery System Integration

Popular cylindrical 18650 lithium-ion cell: The cylindrical cell design offers a long life, is economical but is heavy and has low packaging density due to space cavities

The two most common lithium-ion battery formats are the jelly-rolled cylindrical cells and the prismatic pouch cells. While the former provides durability at the expense of low packaging density, the latter is characterized by a large surface area that is ideal for cooling, but requires a heavy protective case, adding a significant amount of weight to the overall battery pack. Additionally, lithium pouch-based designs have shown a promising energy density of about 711 Wh/kg. Lithium–ion batteries can be further classified based on the chemical composition of the cathode \cite{clarke\_lithiumion\_2021}.

How

Challenges

Discharge changes over time

Energy systms require thermal menegment – ther eis a sweet spot

Thermal management

Battery Management System (BMS): The BMS is responsible for the safe and reliable operation of a battery system

Fault detection

Heaviness of batter ypack

Powe electronic electromagnetic interference

Voltages above XX ft cause arging

Battery Degradation

For a given cell, removable energy and capacity can vary depending on rate, temperature,

and state of health (SOH), while power capability can vary by mode (charge/discharge),

state of charge (SOC), temperature, and SOH. SOC is an estimate of the ratio of charge

stored in the battery, and SOH is an estimate of the ratio of performance remaining in the

battery; generally, charge can be restored but performance cannot. For a given cell, SOH

depends both on cycling and calendar aging, the former depending on the characteristics

and frequency of discharge/charge cycles and the latter depending on storage conditions,

primarily duration, SOC, and temperature [44]. Cyclability is a qualitative measure of

the cell’s tolerance for high-rate charge and discharge and for wide-ranging SOC and

temperature. The SOH is also impacted by instances of abuse and tolerance for abuse.

Mechanical abuse includes vibration, impact, penetration, and water immersion; thermal

abuse includes operation at extreme temperatures, high and low; and electrical abuse includes elevated rates, short circuit, over-charge, and over-discharge.