PROJECT SOURCE TO SOAR

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Abstract

Project Source to Soar proposes to utilize a small modular reactor (SMR) and lithium-air batteries to meet aviation industry sustainability goals through a life cycle with lessened climate impact. These two technologies will be adapted by having SMR technology as the source of electricity generation of the aircraft and lithium-air battery technology being the intermediate storage on the aircraft for propulsion use. Market changes over the coming decades will facilitate this implementation, with feasibility dependent on changing aircraft design to accommodate battery usage. A catalyst to this transition is aided by the current battery electric vehicle (BEV) adoption rate in the worldwide automotive industry. Given this choice for propulsion and energy generation, this paper provides a realistic and tangent technology pathway from current technology development and socio-economic needs.

A review of previous life cycle assessments was conducted to estimate impacts from the proposed life cycle. Technology readiness was assessed to foresee changes in industry and manufacturing capability. Safety advantages and risks were outlined to direct focus to potential hazards and outline benefits. Economic, political, and social implications were considered in order to understand the environment in which the life cycle would be implemented. Climate impacts of the proposed energy sourcing were found to be approximately 46.22 grams CO_2 eq/kWh, representing a 84.9% decrease in production impacts when compared to conventional jet fuel.

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1. Introduction

Project Source to Soar presents an innovative solution that addresses one of the most critical issues facing the aviation industry today: the release of harmful emissions from aircraft due to the reliance on conventional jet fuels. As a submission to NASA's Gateways to Blue Skies: Clean Aviation Energy Competition, this paper combines battery electric vehicles (BEVs) and small modular reactor (SMR) technology. The paper's purpose is the application of lithium-air batteries on electric planes and an on-ground sustainable electricity generation system to power these commercial aircraft, aligning with a shared vision of low-emission air travel by the 2050s. Initially, aircraft design and energy system integration into commercial flights is considered with respect to the 2050s aviation landscape. Analysis was completed on the entire lifecycle of the proposed energy source, with considerations to the environment, safety, and the technological and manufacturing readiness of the system.

2. Energy Source Selection and Feasibility

2.1. Future Landscape

By the 2050s, the aviation industry will shift to favor more sustainable fueling options and aircraft design. The gap between rising oil demand and stagnant production in the coming decades will force alternative supply chains to emerge to replace needed energy across all sectors [1]. Among these alternate sourcing methods, electric will become an attractive end-goal choice for aviation due to its high efficiency in energy transfer from battery to the engine, as opposed to conventional jet fuel [2]. Aircraft capable of integrating this design into a commercial product still faces many hurdles, but small aircraft such as NASA's X-57 prototype show a proof-of-concept for an electric motor system [3, 4, 5]. In order to store this energy, battery systems capable of an energy density similar to conventional jet fuel would be needed. One such system in development is lithium-air, which has a high potential density that is suitable for this application. The battery itself would not produce emissions during flight, however, these impacts are offset by electricity production and battery manufacturing, which must be analyzed against current aviation energy.

Production of electricity for aviation could take many forms as the global grid moves to more renewable sources [6]. One option for low carbon generation is SMR technology. In opposition to current facilities in place, SMRs represent a new viability for nuclear due to their greatly-increased manufacturability and deployability [7]. Current viable designs such as NuScale's iPWR (integral pressurized water reactor) modules are based upon established Generation III+ nuclear technologies. Other designs have been popularized through potential increases in fuel and cost efficiency, such as Terrestrial Energy's IMSR (integral molten salt reactor), based upon experimental Generation IV technologies with lessened operator experience [44]. Changes in commercial aircraft design to show the feasibility of this concept, as well as an assessment of impacts and safety of the proposed lifecycle are outlined in the following sections.

2.2. Aircraft Design

The proposed aircraft concept is based on utilizing electric storage technology with a lithium-air chemistry to achieve a higher power density. The concept will use a design similar to Tesla 4680 Tabless Structural Battery packs. These battery packs are arguably the most advanced on the open-market based on performance, ease of manufacturing, and vehicle integration. This technology provides a pathway to integrate the batteries into the cabin floor of the aircraft to expand overall energy capability and save weight [Fig. 2]. This transforms portions of the cabin floor into additional room for energy storage that can support light cargo and passengers while maintaining structural integrity. With the battery pack being the floor of the cabin, the seats would be bolted to the battery pack, similar to Tesla's Model Y vehicle [9, 8]. This design feature allows the battery pack to run the entire length of the fuselage, making the batteries load bearing. The overall goal is to enable lithium-air batteries to work by modifying current aircraft while speculating a specialized electric aircraft design in the future.

Fig. 1. Tesla 4680 structural battery pack with seats pre-attached for final assembly [8].

The total weight of the energy storage is estimated to be 16.17 metric tonnes located in the fuselage of the aircraft where jet fuel is normally stored [Appx. B.1]. These calculations are based on replacing the weight of the maximum jet fuel. This weight is similar to the maximum fuel weight of 20.5 metric tonnes the Boeing 737-700 can carry, based on the density of Jet A and a maximum fuel capacity of 26,020 L [10]. This provides a feasible range for the integration of the battery pack without exceeding weight limits. The difference between the current Jet A weight limit and our structural battery weight can be neglected by assuming that aircraft redesign can accommodate more battery weight by removing jet-propulsion systems. The comparison to the Boeing 737-700 and our theoretical BEV plane is only used to prove feasibility. By incorporating the battery packs into the structure of the aircraft, the design aims to achieve improved energy efficiency and save cargo space based on good judgment.

2.3. Aircraft Power

The proposed aircraft design utilizes li-air battery chemistry with a high theoretical energy density, which could potentially offer significant advantages for aircraft propulsion. To derive the battery pack density for a theoretical structural 4680 li-air battery pack, the weight of the cylindrical 4680 battery cells was first determined through data from Munro & Associates, Inc. [9]. The Wh/kg energy density provided by li-air technology research was then applied to the weight of just the 4680 battery cells to calculate the usable energy capacity of the theoretical li-air 4680 structural battery pack [Appx. B.1]. Energy capacities were based on the total number of battery packs that could be installed in the aircraft, as determined through the available surface area of the fuselage.

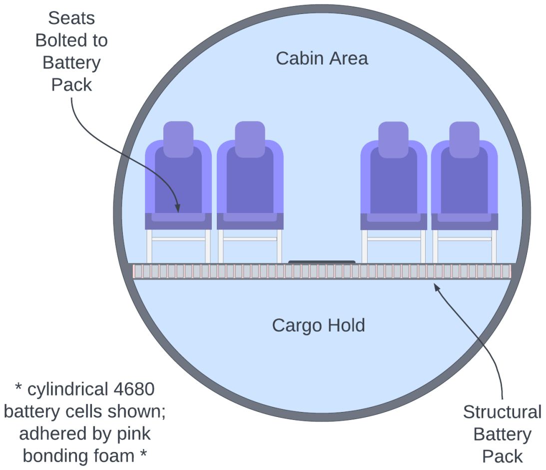

Fig. 2. Cross sectional fuselage view showing structural battery pack.

One major issue that has arisen from utilizing li-air technology on cylindrical cells is the need for oxygen flow through the batteries. Concept of pressurizing li-air batteries within a sealed tank for viability has been discussed in academia [60], but would result in a non-structural application. To allow the structural application, a design change to the current Tesla 4680 battery pack would be needed. Appx. C Fig. C1. shows the addition of tubes/manifolds with the accommodation of a variable valve for desired pressure release of oxygen. The feasibility of this design change is small in judgment but still is a design assumption. The addition of oxygen tanks and other pneumatic apparatus would be needed, but details of integration are out-of-scope for this report. By utilizing compressed oxygen storage, the issue of the aircraft becoming heavier during flight is eliminated since the oxygen remains in a closed loop system on the aircraft. The flight time of the aircraft would depend on several factors, including the weight of the aircraft, the altitude at which it is flying, and the power required to maintain flight. The following calculations are considering several key assumptions: the aerodynamics of the aircraft does not change in the transition from turbofan engines to electric propulsion, the li-air batteries carry all required oxygen on board in lightweight carbon composite oxygen tanks and therefore do not gain mass over time, and the aircraft is flying at MTOW to simulate maximum payload and flight time [10]. An additional assumption was that electric propulsion (propellers) could reach the same flight speed as the turbofan engines, which may prove unrealistic. This can be avoided with different electric propulsion methods, or reducing flight speed; despite this, the energy ratios in comparing the percentage of energy of the jet fuel imparted in propelling the aircraft can be compared to the percentage of energy the li-air batteries could impart in propelling the aircraft.

With these assumptions in mind, for a flight time of two hours the theoretical 4680 li-air battery pack requires an energy density of 3340 Wh/kg at the pack level, providing 51 mWh in battery capacity [Appx. D]. This can be compared to the 4680 lithium ion pack density of 276 Wh/kg to show that 4680 li-air battery packs would be 12 times denser than 4680 lithium packs [9]. This pack energy density includes the mass of the battery cell and of the surrounding 4680 pack. For reference, the maximum theoretical energy density of the battery cell is 5200 Wh/kg, which results in a 4680 pack density of 3614 Wh/kg [11, Appx. B.1, Appx. B.2]. Thus, since the required energy density is lower than the theoretical density, this battery design is shown to be plausible.

These flight times were based on the current maximum range of 6,255 km and a cruise speed of 828 km/h, up to 7.5 hours including landing and takeoff [10, Appx. D]. Then, using a ratio of the usable energy contained in the batteries in proportion to the usable energy contained in jet fuel to find the maximum range and thus flight time of the electric aircraft [10, Appx. B.2]. The usable energy in the jet fuel was accounting for an average overall engine efficiency of 50% [63]. The average propeller was assumed to be 90%, motor efficiency to be 95%, usable state-of-charge of 94.4%, and battery efficiency to be 80% using platinum/gold catalysts [13, 14, 11]. This overall electric efficiency from storage to propulsion is 64.3% [Appx. D]. The battery capacity would determine the maximum flight time of the aircraft, needing to be carefully balanced with the weight and power requirements of the aircraft for optimal performance. The 3340 Wh/kg energy density required for a 2 hour flight may be further reduced as battery efficiency improves, aircraft design adapts to structural battery pack design to minimize weight, and as reducing cargo or passenger payload. The table below presents the low estimate of the current battery cell, the theoretical estimate of lithium air, and the required energy density for a 2 hour flight.

Table 1. Theoretical Aircraft Energy Storage Metrics.

	Li-Air Cylindrical Cell Density	Theoretical 4680 Structural Pack Density	Total Theoretical Usable Energy Storage	Aircraft Range	Flight Time
Low Estimate	2,210 Wh/kg	1536 Wh/kg	23.45 mWh	803 km	0.97 hours
Theoretical Estimate	3500 Wh/kg	2433 Wh/kg	37.14 mWh	1,272 km	1.54 hours
Required Estimate	4805 Wh/kg	3340 Wh/kg	48.2 mWh	1747 km	2.11 hours

*Usable energy storage was calculated by using 94.4% usable State-of-Charge on total theoretical energy storage

*Calculations are located in Appendix B

3. Life Cycle

3.1. Scope

In order to assess the potential production and delivery of the proposed energy source in the coming decades, a review of life cycle analyses (LCA) was conducted. Climate impacts, expressed as CO_2 eq, were analyzed in order to evaluate its feasibility as a low-emission source of aviation energy. Safety was assessed in order to identify hazard hotspots and improve implementation. The currently available technology and supply chains were assessed through technology readiness levels (TRLs) to identify needed improvements. A flow diagram outlining system boundaries (source-to-flight) can be seen in Fig. 3.

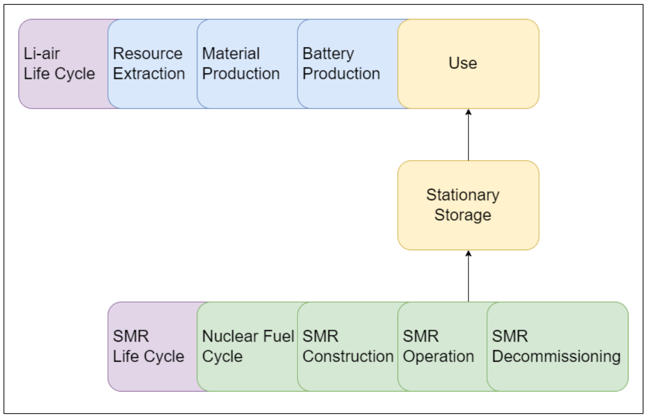

Fig. 3. Life cycle system boundaries.

3.2. Small Modular Reactor and Energy Transfer

As the source of energy for electric aircraft, SMRs will be the primary component in the delivery of clean aircraft propulsion. Since the submission of the initial proposal, the team has looked further into the viability of differing SMR technologies and the available information on such reactors. In addition, energy transfer and storage has been considered within the lifecycle. Near-term deployment will consist of reactors based upon established technologies such as the previously mentioned NuScale LWR modules. Due to a lack of operator and industry experience with Generation IV reactors, their lifecycle is not as heavily studied in this paper, instead utilized as a point of reference for technology development.

Existing LCAs on the Nuscale module [23] and Westinghouse W-SMR iPWR [24] serve as the basis of the proposed lifecycle and potential climate impacts. The utilization of the SMR within this scope was split into four main stages: nuclear fuel cycle, construction, operation, and decommissioning. The uranium-based nuclear fuel cycle consists of mining, milling, conversion, enrichment, and fabrication. The main methods of mining include in-situ, open-pit, and underground. Although in-situ has been evaluated to have higher environmental impacts, its lower cost makes it less likely to be dethroned as the most-used method unless new technologies arise [16, 17, 18]. Thus, the current mining method makeup was considered for this study. After extraction, uranium must be milled in order to purify the ore into U_3O_8 “yellowcake” through the use of a leaching agent, leaving behind mail tailings containing heavy metals and radium [19]. Conversion occurs at a dedicated plant, where yellowcake is reacted with fluorine to produce UF_6, which is cooled from gas to solid and shipped to an enrichment plant [20]. Enrichment occurs

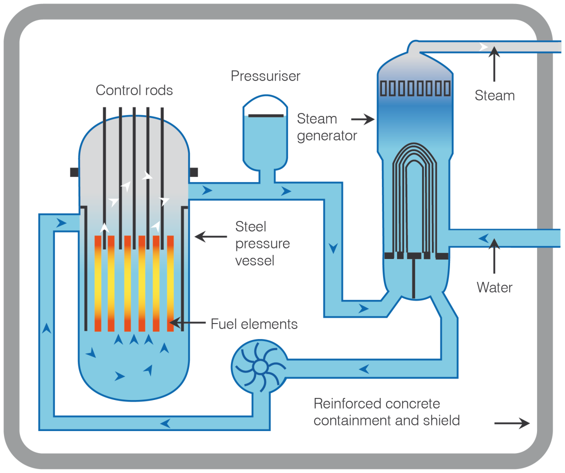

Fig. 4. Pressurized water reactor operating principle [48].

through the gas centrifuge, allowing heavier isotopes to move to the outside of a spinning cylinder through several cycles [21]. Solid UF_6 is vaporized in a fuel fabrication facility, which is then treated to produce UO_2 powder. This powder is pressed into pellets and constructed into fuel assemblies [22].

As SMRs are an emerging technology, impacts for construction, operation, and decommissioning are based upon available information on future installations and extrapolations of current facilities. SMR iPWR models are premised as scaled-down versions of nuclear reactors that have been in service for decades [44]. In short, existing PWRs and SMRs based on this technology utilize a pressurized water loop that is heated due to the fission reaction within the core. This water transfers its heat to a steam generator, which in turn produces steam and turns a turbine. This action generates electricity, which can then be transmitted to an airport energy storage system [49]. SMR modules often differ from traditional facilities by integrating these components into a single vessel [44].

Energy transmission losses from generation to a given airport are estimated to be 5% based on an United States average [45]. In contrast to batteries utilized by aircraft, stationary energy storage is not limited by mass constraints. This gives opportunity for less dense and conventional battery technologies, such as lithium ion, which have shown to have promising impacts when compared to other lithium battery chemistries. Lithium-ion efficiency is assumed to be 90% overall [46].

3.3. Li-Air Battery Application

The utilization of the li-air battery within this scope was split into three main stages: resource extraction, material production, and battery production. Inventory steps were based on previously conducted LCAs and literature on li-air battery technology [25, 26, 27]. Due to the highly novel nature of this technology, the exact makeup and thus impacts of such a device are speculative based on research-scale models. Three LCAs on li-air battery technology were identified, with one being utilized in climate impact estimation due to its utilization of tanks for pure oxygen feed and integration of battery management systems (BMS) similar to those proposed here [26].

While each study represents a different methodology for the manufacturing of cells, a basic life cycle can be overviewed. Batteries are assembled through the manufacturing of a TEGDME (Tetraethylene glycol dimethyl ether) electrolyte and lithium metal anode in combination with a porous cathode. For a future scenario, these batteries may be assembled in a similar manner to modern lithium-ion batteries, through the stacking of components in a pouch and the injection of the electrolyte. Alternatively, they are considered as constructed similarly to Tesla 4680 Tabless Structural Battery packs, with assumed similar impacts in construction and implementation impacts to pack construction in the LCA utilized due to a lack of data on the former. Following the battery manufacturing, they may be charged and utilized for aircraft energy.

The introduction of water-stable, solid electrolyte-protected lithium electrodes [58] addresses numerous challenges and opens up possibilities for the advancement of both aqueous and nonaqueous Li-Air batteries, boasting unparalleled energy densities. The choice between aqueous, nonaqueous and solid-state batteries depends on the specific application and requirements, all with advantages and disadvantages. The team compared the developments between the types of Li-Air batteries, and nonaqueous batteries are superior choice in use in an aircraft. Primarily, they have a higher energy density after discharging. During discharge, lithium ions are oxidized at the anode, releasing electrons and creating lithium cations. These cations then travel through the electrolyte and react with oxygen from the air at the cathode, forming lithium peroxide and generating electrical energy [58, 59]. Nonaqueous electrolytes also have a wider electrochemical stability window, allowing for the use of more diverse electrode materials and potentially higher voltages. This can result in better overall battery performance. One drawback of the use of these batteries is the necessity of pure oxygen (O_2): “air contains carbon dioxide and water vapor. Water will penetrate into the battery from the air electrode to the lithium electrode, which leads to serious oxidation of the Li anode, and CO2 will gradually react with Li_2O_2 to form Li_2CO_3, which can only be decomposed at a high potential during the charge process. These side reactions considerably reduce the efficiency and decrease the cycle life” [60]. Additionally if Li-Air battery technology develops so non aqueous could function with normal air, theoretically CO_2 and H_2O can be removed on the plane from inlet flow, which would reduce overall mass required. However, the team foresees there always being significant byproducts in the presence of air, which would make the battery less effective after recharge cycles. Thus, the team specifically incorporated lightweight carbon composite pure oxygen tanks into the design to eliminate the need for changing weights from using additional air, additional equipment that would be required to remove the CO_2 and H_2O, and most byproducts.

4. Impact and Readiness Assessment

4.1. Climate Impact

In order to assess climate impacts across the proposed life cycle, CO_2 eq emissions can be accounted for as a baseline unit of contribution towards manmade climate change. The functional unit utilized in this analysis was 1 kWh of energy delivered, to standardize impacts across all phases of the life cycle, as well as to aid in comparison. Existing literature was considered for a basis of potential climate impact, as seen in Table 2, which was averaged to find a total estimated impact. As the scope of this paper ends at flight, the use phase of the batteries was not considered, including potential end of life and recycling phases of materials. A comparison to conventional Jet A aircraft fuel as assessed by Kolosz et al. [28] was conducted in order to evaluate the proposed lifecycle as an effective tool in reducing climate impacts.

Table 2. Studies utilized in the estimation of climate impacts of aircraft energy delivery.

Scope	Impact (g CO_2 eq/kWh)	Reference
Small Modular Reactor		
Twelve 60 MWe Nuscale modules	4.55 (5.32)	[23]
Westinghouse 225 MWe W-SMR	9.1 (10.6)	[24]
Airport Storage		
Lithium stationary storage	20.4	[46]
Li-air Battery		
Li-air modeled for electric vehicle integration	149 (15.2)	[26]
Averaged Total	46.22	

Due to an overall efficiency of 85.5% for energy transfer from electricity generation to li-air battery charging, impacts from SMR use are increased to compensate to show a levelized delivery impact. Impacts from li-air battery usage were adjusted to reflect carbon composite (carbon fibre reinforced plastic, injection moulded, modeled in Ecoinvest 3.8) utilized in oxygen tank construction to replace aluminum originally used in the study. Original impacts per kilometer traveled were also adjusted to reflect kWh impacts, as well as long term li-air technology goals reflected in literature and in previous feasibility analysis outlined in this paper [25]. Adjusted values used to calculate total impacts are shown in parenthesis in Table 2. Jet A was found to have a climate impact of 48.55 g CO_2 eq/kWh for production and 306.86 g CO_2 eq/kWh including combustion, representing a potential decrease of 84.9% of lifecycle climate impacts per energy functional unit delivered to the aircraft. This differential may even be higher by incorporating impacts of non-CO_2 combustion compounds, increasing jet fuel climate impacts by as much as 2.47 times [28].

4.2. Safety

At the forefront of most SMR designs is the emphasis on safety. Integrated SMRs such as the modules in development by NuScale and Westinghouse will utilize passive safety systems in order to comply with regulatory requirements and increase their overall safety margin. This will include systems that act without the need for outside energy to stimulate them, such as gravity-driven coolant injection [50]. In addition, PWR designs allow for lowered risk as they are based on established technologies with known potential risks and mitigations.

In the production and fabrication of nuclear fuel for SMR use, utmost precaution is imperative. For the mining, milling, and purification of uranium, reducing operational risk is the main concern. To accomplish this, there must be precise ventilation of dust to reduce inhalation of alpha/gamma particles, limited worker exposure to radiated areas, frequent equipment inspection, and attention to the surrounding environment, as water/air quality and waste products may threaten public safety [34].

Battery technology is developing to increase energy density and decrease flammability. li-air batteries have low toxicity, but present problems in some aspects of electrical safety [29] A challenging issue for non-aqueous lithium air batteries is dendrite formation and growth during the charging process [61]. These dendrite formations can cause the electrode to short circuit [32] or have a compressive shock [33]. If the battery cell is shorted in this manner, “the electrolyte may start to decompose by exothermic reactions if the temperature reaches above a certain threshold, causing thermal runaway with potential health and safety hazards” [33]. To avoid this outcome, researchers have been developing several solutions: “lowering the yield stress of a solid metal electrode, using semi-solid electrodes that consist of co-existing solid and liquid alkali metal pages, and introducing a wetting interfacial liquid film between the electroactive metal and solid electrolyte” [30].

li-air batteries also raise safety concerns due to their reaction and interaction with the required oxygen supply. Electrolysis of Li-Air batteries when exposed to regular air can produce byproductions [29] that may be reactive. To avoid this, our concept includes non-aqueous batteries in a closed-loop pure oxygen system. This eliminates the chance of CO_2, H_2O and other molecules from reacting with the lithium. One drawback of pure O_2 is its susceptibility to fire, however, the team proposes a purging system with gaseous inert nitrogen. A rapid flush of nitrogen will flush out the oxygen quickly, resulting in a halt of battery discharge, cooling , and potentially eliminating any internal fires.

Despite the challenges facing the development of proper safety within li-air batteries, the team foresees that the aviation industry will be able to adapt these safety components. Additionally, implementing safety measures to improve battery calibration and management will be crucial to the success of the proposed energy life cycle. Decades of battery management technology innovations have validated this project’s ambitions in a safe manner.

4.3. Economic Considerations

Numerous studies have been conducted on the economic feasibility of SMR technology, with values varying greatly for the cost of electricity production. Current studies show a lower totalized capital investment cost per kWe produced for PWR SMRs ($3465 - $5470 kWe) when compared to large nuclear reactors ($5587 - $9855 kWe) [53]. The lack of a standardized methodology in calculating these costs with respect to SMRs makes comparisons difficult, if not impossible. Levelized costs of energy have been estimated for SMRs to be in the range of Due to economies of scale, the actual cost of electricity will vary depending on the number of modules installed at a given site, generally increasing with decreasing capacity. However, advancements in the supply chain and mass manufacturing may work to offset this effect [52, 53, 54]. Costs not encompassed by traditional economic analyses can also be explored in order to justify SMR deployment.for use.

Currently, nuclear facilities must integrate emergency planning zones (EPZs) into the operational costs of the plant. These zones represent 10 and 50-mile radii where protective actions must be taken in the event of an accident, such as evacuations. Due to the lowered capacity of SMRs, it was found that EPZ expenditures could be reduced by up to $50 million over 40 years by shrinking the required zone around the facility down to 5 miles due to lowered exposure risks [51]. In addition to improved safety implications, lowered exposure risks can effectively lead to a decreased cost of electricity from an SMR by simplifying regulatory necessities. Regardless of distance from a given airport, the SMR could be located at a distance within current regulation (dependent on country of deployment) and still be a viable energy source.

4.4. Socio-Political Considerations

The political landscape surrounding SMRs is characterized by public perception, international collaboration, policy frameworks, and regulatory considerations. Governments should prioritize these aspects and take proactive measures to foster the development and deployment of SMRs for a sustainable and low-carbon energy future. Recent accidents such as Cheronobyl and Fukushima have worked to deteriorate public trust in nuclear technology, contrary to its actual safety record being better than conventional power generation methods such as coal and natural gas [55]. Surveys within the United States show an increase in support (up to 51% from 49% three years ago), though down from 62% in 2010 [56]. Despite these public setbacks, numerous countries are still currently heavily pursuing SMR technology [53]. Governments should prioritize public engagement efforts to educate and inform the public about the benefits and safety measures associated with SMRs. Transparency, open dialogue, and addressing concerns can help build trust and mitigate opposition.

Additionally, governments need to develop comprehensive regulations that address safety, waste management, and licensing processes for SMRs. Streamlining regulatory processes and ensuring international harmonization can facilitate the deployment of SMRs and boost investor confidence. The nuclear waste potential from SMRs is heavily debated, with the sentiment often being that their usage would decrease the overall waste stream. However, recent studies have shown that they may increase this waste stream by up to 35 times, largely due to the smaller scale of the reactor and increased neutron leakage [57].

Public opinion surrounding BEVs can vary significantly, however, the environmental benefits as well the introduction of electric automobiles and other vehicles already making strides on the market will help people adapt to electric aircraft. The structural integration of the batteries into the floor of an airplane may discourage some about its safety. However, ample education, transparency, and detailed safety measures will be implemented to ensure good relations with the public.

4.5. Technology and Manufacturing Readiness Level

The team employed NASA's Technology Readiness Level system [38], as seen in Appendix C.1, to fully evaluate each component and how the technology will develop by 2050. It is expected that all aspects of the proposed energy source will be operational and ready for public use.

Table 3. Current and Projected 2050 Technology and Supply Chain Readiness Levels.

Component	Current TRL	Predicted 2050 TRL	Supply Chain Readiness 2050 TRL	Justification
li-air Battery Chemistry	3	8 / 9	5	Despite the early level of development, the predicted theoretical energy density and the steady improvements in battery technology indicate the maturity of the product by 2050.
Small Modular Reactor - iPWR	8	9	7	SMRs have been produced and extensively tested, and are now in the commissioning process [39].
Small Modular Reactor - ISMR	3	7	5	Integral molten salt reactors MSR design is becoming more popular due to several key advantages. Multiple concepts designs by different companies are in development [57].
Stationary Lithium Storage	9	9	9	Stationary electricity storage is already readily available. Advanced battery chemistry is not needed since a stationary location does not have weight requirements. [62]
Battery Management System	7	9	8	BMSs have been improved upon for the past few decades due to the mobile electronics market. Although Li-air chemistry may require a redesign.
4680 Cylindrical Battery Cells	7	9	9	Due to the increased manufacturing of automotive BEVs, the cylindrical battery cell manufacturing industry has matured globally.
Electric Passenger Airplane	5	9	3	Medium-fidelity prototypes of electric aircraft are being developed and tested as of 2022 [40].

The main advancement essential to the success of the concept will be the readiness of li-air batteries. Currently, li-air batteries are a proven concept (TRL 3), with many laboratories confirming theoretical energy densities and their potential to be vital in the development of electric power. Multiple research teams have focused on improving performance, with Japan's National Institute of Materials (NIMS) and Softbank Corp. creating a li-air prototype with an energy density of over 500 Wh/kg [41]. Besides advancements in energy density, li-air requires further research to expand the number of rechargeable cycles, decrease safety risks, and improve supply chain readiness. These developments along with the public need for improved battery technology led the team to predict that li-air will be qualified for commercial flight. Overall, researchers need to ensure that the battery stays stable for a reasonable amount of recharge cycles and that the energy density can sustain an average cross-country flight.

Additionally, a proper battery management system and structural battery packs are estimated to be ready by 2050. Currently, Tesla designed the most advanced battery packs based on performance and manufacturing readiness. Electric automobile research augmented the maturity of the 4680 Cylindrical Battery Cells, and further social and economic drive for electric vehicles and aircraft will ensure that this component will be operational by 2050. A fully mature battery management system is also projected to be TRL 9 by 2050. Further research of li-air battery chemistry may require adjustments to the current system, however, the team is confident this can be accomplished by 2050.

Small modular reactors are under development in 19 countries and the first SMR units are in operation in China and Russia [42]. SMRs are in their final configuration, they are fully tested and analyzed for their intended operational use. Recently in the United States, the US Nuclear Regulatory Commission (NRC) issued a final rule certifying NuScale's small modular reactor (SMR) design for use [42]. These established Generation III+ nuclear technologies serve as the foundation for viable designs like NuScale's iPWR modules. Moreover, other designs have garnered interest due to their potential to enhance fuel and cost efficiency.Though the technology is nearly mature, modifications are needed in the supply chain, law, and public opinion to be implemented as an energy source [39]. Additionally, IMSR (integral molten salt reactor) was considered as a potential SMR that could produce sufficient amounts of energy. While progress has been made in terms of design and feasibility studies, the IMSR technology still faces various technical challenges and regulatory hurdles that need to be addressed for its full-scale deployment. These challenges include materials compatibility, corrosion, radiation damage, and the development (TRL 3) of efficient fuel processing and recycling methods [57]. If integral molten salt reactors were able to develop in time by 2050, the supply chain would be more capable due to thorium being more abundant and the excess of nuclear waste that could be used to start the reaction.

Fig. 5. Tecnam's P-Volt electric aircraft [43].

Even with all other components ready by 2050, significant changes to the aircraft itself will be necessary to implement batteries on a plane, particularly a commercial plane. Currently, prototypes for light electric aircraft have been designed and tested. Despite not having the projected energy capacity of the li-air battery, numerous organizations and companies are innovating mainly lithium-ion powered aircraft [40]. As battery technology improves, the viability of these designs will grow exponentially. Despite being relatively low in terms of readiness for both the technology's maturity and the supply chain, the push for sustainable aviation along with advancements in the other components indicate that electric aircraft should be feasible by 2050.

5. Conclusion

The proposed energy life cycle integrating SMR and li-air technology will drastically decrease airborne emissions by commercial aircraft and provide a pathway to energy production with lesser impact than conventional jet fuel. Changes in the aviation landscape in the coming decades will facilitate this transition to sustainable energy sources, and proposed changes to aircraft design will allow for the use of battery technology on most commercial flights. These advancements will allow electric aircraft to have more flexibility in aerodynamic design and propeller placement, higher energy efficiencies, and reduced complexity; unlocking potential breakthroughs for future aircraft design. Essential technologies outlined will have sufficient readiness for an entrance into the 2050s aviation market, with a focus on safety necessary for implementation. Future work should include harmonized analyses on SMR and battery economics and life cycle impacts beyond those pertaining to climate, which will become easier as more facilities come online and studies become less speculative.

Appendices

Appendix A: References

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Appendix B: Aircraft Power Calculations

1.
$$\textbf{Theoretical Quantity of 4680 Structural Battery Packs on Plane [1]} = \frac{((\text{ Fuselage Length } \mathbf{x} \text{ Fuselage Width }) + \text{ Wing Area })}{(\text{ Battery Pack Length } \mathbf{x} \text{ Battery Pack Width })}$$

$$\textbf{[units]} = \frac{(([\text{m}] \;\mathbf{x}\; [\text{m}]) + [\text{m\^{}2}])}{([\text{m}] \;\mathbf{x}\; [\text{m}])}$$

2.
$$\textbf{Theoretical 4680 Structural Plane Battery Pack Weight} = \text{Theoretical Quantity of 4680 Structural Battery Packs on Plane [1]} \;\mathbf{x}\; \left(\text{Li-Ion 4680 Battery Pack weight} - \text{Penthouse Weight} \right)$$

$$\textbf{[kg] (sum)} = [\text{units}] \;\mathbf{x}\; \left([\text{kg}] - [\text{kg}] \right)$$

3.
$$\textbf{Single Li-Air 4680 Battery Pack Total Energy Capacity [3]} = \text{Weight of 4680 Cells In Battery Pack} \;\mathbf{x}\; \text{Li-Air Chemistry Energy Density}$$

$$\textbf{[kWh]} = [\text{kg}] \;\mathbf{x}\; [\text{kWh/kg}]$$

4.
$$\textbf{4680 Li-Air Structural Plane Battery Pack Total Usable Energy Capacity} = \text{Single Li-Air 4680 Battery Pack Total Energy Capacity [3]} \;\mathbf{x}\; \text{Theoretical Quantity of 4680 Structural Battery Packs on Plane [1]} \;\mathbf{x}\; \text{Li-Ion 4680 Usable Capacity Percentage}$$

$$\textbf{[kWh] (sum)} = [\text{kWh}] \;\mathbf{x}\; [\text{units}] \;\mathbf{x}\; [\%]$$

* To view calculated numbers and full datasheet, visit tinyurl.com/bdcuer5k

Fig. B1. Calculations determining the usable energy capacity provided by batteries.

5.

Usable Jet Fuel Energy in Aircraft [5]	=	(	Jet Fuel Energy Density	**x**	Mass of Jet Fuel in Aircraft	)	**x**	Turbofan Propulsive Efficiency
124,896 kWh	=	(	9.6 kWh/L	x	26,020 L	)	x	50%

6.

	Usable Battery Energy for Propulsion [6]	=	4680 Li-Air Structural Plane Battery Pack Total Usable Energy Capacity [4]	**x**	Aircraft Prop Efficiency	**x**	Electric Motor Efficiency	**x**	Battery Discharge Efficiency
Cell Density: 2,210 wh/kg Pack Density: 1,536 wh/kg	16,040 kWh	=	23,450 kWh	x	90%	x	95%	x	80%
Cell Density: 3,500 wh/kg Pack Density: 2,433 wh/kg	25,404 kWh	=	37,140 kWh	x	90%	x	95%	x	80%
Cell Density: 4,805 wh/kg Pack Density: 3,340 wh/kg	34,884 kWh	=	51,000 kWh	x	90%	x	95%	x	80%

7.

	Range of Theoretical Electric Aircraft [7]	=		**x**	Range of Jet Aircraft
			$\left(\frac{\text{Usable Battery Energy for Propulsion [6]}}{\text{Usable Jet Fuel Energy in Aircraft [5]}}\right)$		
Cell Density: 2,210 wh/kg Pack Density: 1,536 wh/kg	803 km	=	$\left(\frac{\text{1,6040 kWh}}{\text{124,896 kWh}}\right)$	x	6255 km
Cell Density: 3,500 wh/kg Pack Density: 2,433 wh/kg	1,272 km	=	$\left(\frac{\text{25,404 kWh}}{\text{124,896 kWh}}\right)$	x	6255 km
Cell Density: 4,805 wh/kg Pack Density: 3,340 wh/kg	1,747 km	=	$\left(\frac{\text{34,884 kWh}}{\text{124,896 kWh}}\right)$	x	6255 km

8.

	Flight time of Theoretical Electric Aircraft	=	$\frac{\textbf{Range of Theoretical Electric Aircraft [7]}}{\textbf{Aircraft Cruising Speed}}$
Cell Density: 2,210 wh/kg Pack Density: 1,536 wh/kg	0.97 hrs	=	$\frac{\text{803 km}}{\text{828 km/h}}$
Cell Density: 3,500 wh/kg Pack Density: 2,433 wh/kg	1.54 hrs	=	$\frac{\text{1,272 km}}{\text{828 km/h}}$
Cell Density: 4,805 wh/kg Pack Density: 3,340 wh/kg	2.11 hrs	=	$\frac{\text{1,747 km}}{\text{828 km/h}}$

Fig. B2. Calculations for flight times of the proposed electric aircraft.

Appendix C: Additional Figures

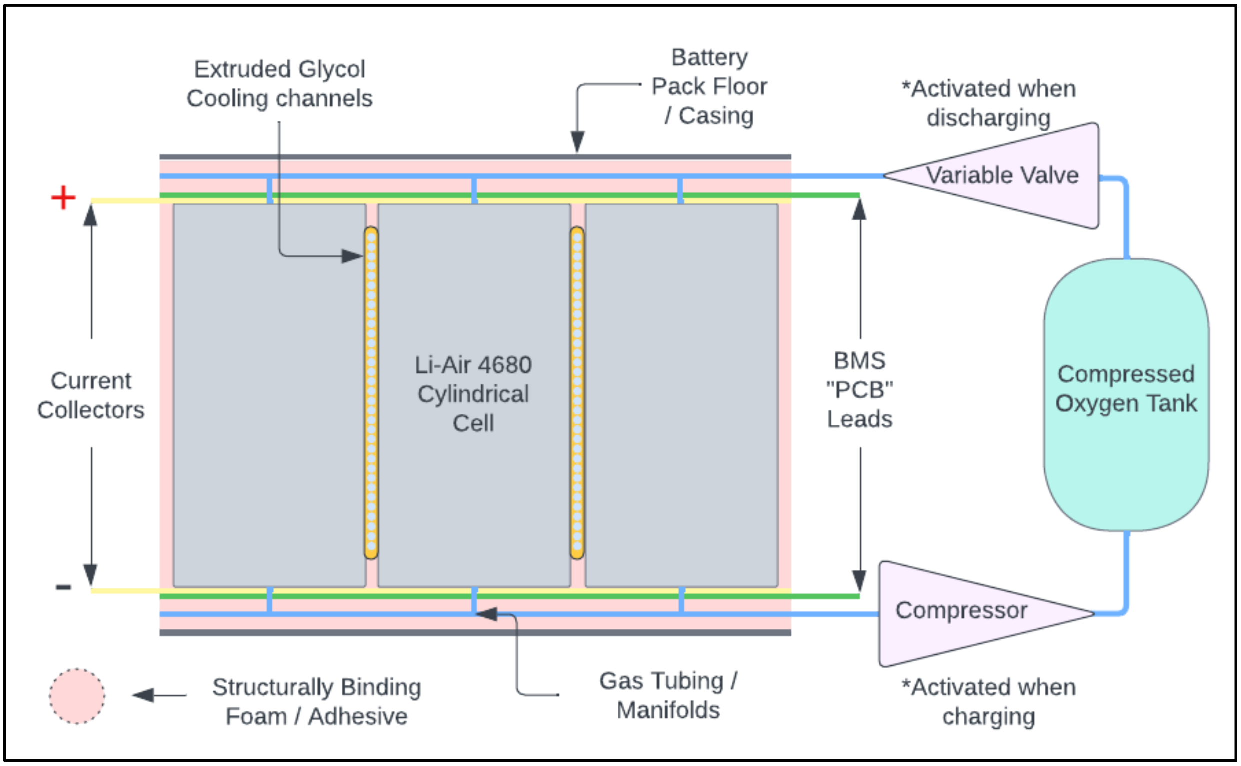

Fig C1. Modified Tesla 4680 Structural Battery Pack for li-air Chemistry

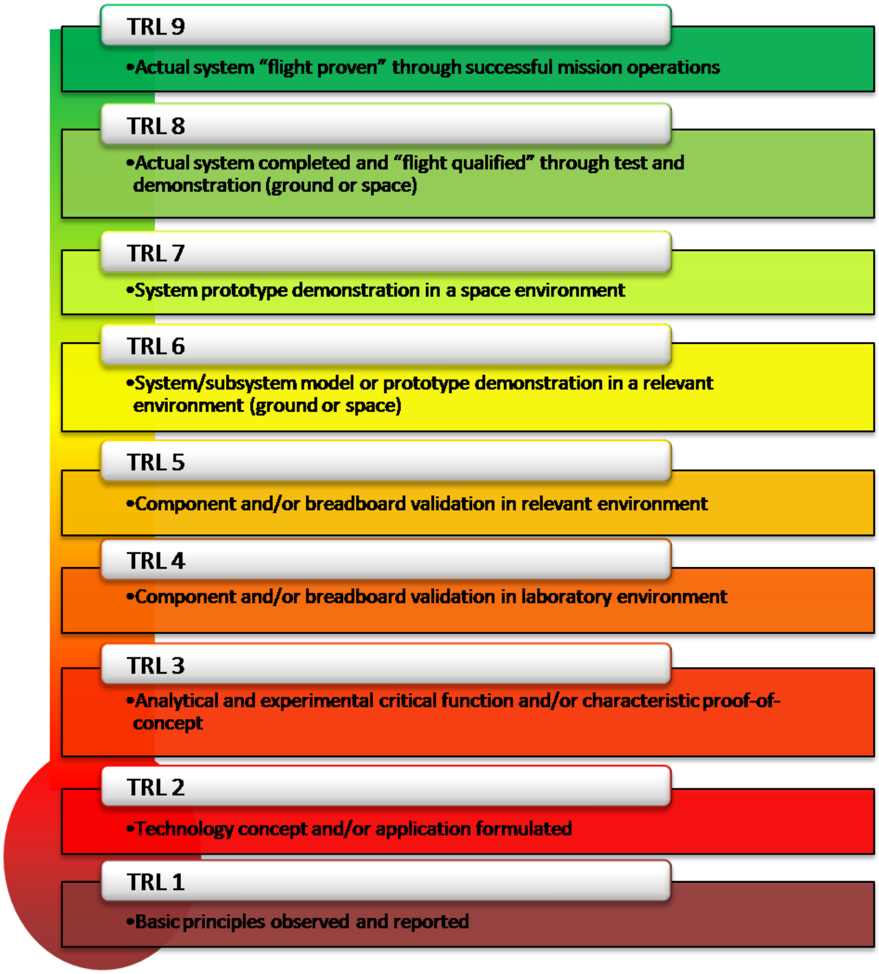

Fig C2. NASA's official Technology readiness Levels Chart (TRLs), based on a scale from 1 to 9 [37].

Appendix D: Aircraft Power MATLAB Calculations

```matlab
%% Electric Efficiencies
nprop=0.9; %for cruise at high speed 80-90% max
%Motor efficiency
m_e=0.95;
%Battery efficiency
b_eh=0.8; %higher end, goal
usable=0.944;
totale_e=nprop*m_e*b_e;
totale_eh=nprop*m_e*b_eh*usable;
%% Aircraft Properties
%Operating Empty Weight
empty_mass=38410; %kg
% Maximum landing weight (lower than takeoff)
max_landing_mass=58050; %kg
%% Turbofan Efficiencies
% %Turbofan cruise mach
% mach=0.82;
% cruise_speed_km=828; %km/hr
% % Boeing 737-700 specific cruise
%% Electric Weight
%Weight of flooring replaced by structural packs
%Flooring is roughly 3000kg, assuming 2/3rds can be replaced by battery
%packs
saved_mass=2000;
% Max Weight the Li-Air Batteries can have
% Assumes the difference between turbofan engines weight and motor and
propller weight are
% negligent
Max_emass = max_landing_mass-empty_mass;
%% Flight Time
Jet_max_fuel=248.8; %mWh
% Turbfan overall propulsive efficiency
turbo_e=0.5; %high end %
Jet_energy=Jet_max_fuel*turbo_e;
% Burns 250mWh of fuel to reach this
%2nd Assumption, B737-700 Currently flies at 850km/h, Max payload 6255 km
Jet_time=6255/828;
%Goal is 2 hr flight (45 mins to taxi, wait to land, etc?)
e_time=2;
energy_needed=(e_time/Jet_time)*(Jet_energy/totale_eh)*1e6; %in wh
%% Oxygen mass
%O2 ratio in kg per kg pack (25% from tank, 35% from O2)
O2_ratio=0.6;
Cell_mass=294; %kg per pack
Pack_mass=423; %kg per pack
```

```
O2_amount=O2_ratio*(Cell_mass/Pack_mass); %amount of O2 kg applied only to cell mass
%% Required energy density
g_mass=(Max_emass+saved_mass)/(1+O2_amount);;
g_mass_and_ox=g_mass*O2_amount+g_mass;
e_time=2;
energy_needed=(e_time/Jet_time)*(Jet_energy/totale_eh)*1e6;
g_pack=energy_needed/g_mass;
%% Plot Energy Required vs Flight Time
times=linspace(0,10);
a=Jet_energy/Jet_time; %mwh per hr
JetA1=a*times;
b=energy_needed/e_time/1e6; %mwh per hr
LiAir1=b.*times;
plot(times,JetA1,times,LiAir1)
title('Energy Required vs Flight Duration')
xlabel('Flight Duration (hours)')
ylabel('Power Required (mwh)')
legend('Lithium Air Batteries','Jet A Fuel')
%% Currently not sure how to plot, just has good data points for maximum energy storage
JetA_density=12000; %wh/kg
JetA_mass=20500;
Jet_energy=Jet_max_fuel*turbo_e %mWh
Li_Air_mass=g_mass_and_ox;
Li_Air_energy=energy_needed/1e6 %mWh
Li_density=270; %wh/kg
Li_mass=Max_emass;
Li_energy=Li_density*Li_mass*(totale_eh*0.9/0.8)/1e6 %mWh
```