# Life Cycle Assessment of Lithium-Based Batteries for Conceptual Hybrid-Electric Aircraft

João Pedro Vargas Ribeiro
joao.pedro.vargas.ribeiro@ist.utl.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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**Abstract**

Nowadays, the transportation sector faces a considerable challenge regarding its ecological impact and contribution to global warming. A common evaluation approach usually relies only on low carbon emissions during operation and does not account for a life cycle assessment (LCA) of the product and/or its sub-components, e.g. batteries, that may significantly contribute to the ecological mark produced by the final product. In this sense, this dissertation addresses the environmental impact, considering an LCA of lithium-sulphur (using IREC cells) and lithium-oxygen (composed of STABLE cells) batteries for conceptual aircraft design phase application. In a first analysis, it provides insights on the relative contribution of all components of each cell. Comparing both cells, the STABLE cell has a lower overall environmental impact with a carbon footprint of approximately 70.7 % less than the IREC cell. However, its human toxicity impact is 10.1 % superior. Afterwards, considering limitations and future estimates, the battery packs are modelled to suit a wide range of hybrid-electric propulsion system. An assessment is conducted considering extraction of raw material, production, operational processes, and finally recycling, re-use, landfill and other end-of-life (EOL) processes.
**Keywords:** life cycle assessment, hybrid-electric aircraft, lithium-sulphur battery, lithium-oxygen battery.

## 1. Introduction

Since the early 1970s, global warming is a scientifically proven threat with direct consequences for the environment including changes on the average and extreme temperatures, leading to polar cap melting, rising of sea level, catastrophic atmospheric phenomena and irreversible modifications on the ecosystems.

Air transportation has a significant effect on climate change that tends to intensify as it becomes more demanding. According to the 2016 report from the European Aviation Safety Agency (EASA) in collaboration with the European Environment Agency (EEA) and EUROCONTROL, the number of flights in Europe have increased 80 % between 1990 and 2014 and is prospected a 45 % increase until 2035 followed by an increase of the same amplitude in emissions [1]. These emissions include many chemical products most of which consist of $CO_2$, a greenhouse gas known to remain on the atmosphere for about 100 years [2]. About 2007, global aviation contributed with approximately 3.5 to 5.5 % of the annual $CO_2$ emissions, and it is expected an increase from 10 to 15 % by 2050 [3]. Thus, it is acknowledged of most importance to investigate and develop carbon-free alternatives aiming to counteract the actual trends.

On a global scale, many organizations as the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA) and the Advisory Council for Aeronautics Research in Europe (ACARE) are committed in developing advanced technologies, policies and standards that will help to cut-off aviation emissions and noise in order to to reduce the life cycle's environmental impact of aircraft. According to ACARE's Strategic Research and Innovation Agenda (SRIA), aircraft should emit 75 % less $CO_2$, 90 % less $NO_x$ and produce 65 % less noise by 2050 relative to reference data from the year 2000 [4]. NASA has a more optimistic vision, foreseeing by 2025, 80 % fewer $NO_x$ emissions and a 60 % fuel reduction relatively to 2005 [5].

A concept in early stages of research is the use of battery technology as an aircraft propulsive mean, similar to a present-day electric vehicle (EV). The potential of new emerging lithium-based batteries is undeniable, however, the duration of further investigation as well as the advantages of its use for this application remains uncertain. The state-of-art is far below the requirements for most aircraft, as it only suits small aircraft with limited carrying capacity for a short-range mission. Hopefully, in the next few years, aviation will start progressively using more-electric propulsion systems as has happened with the automotive industry.

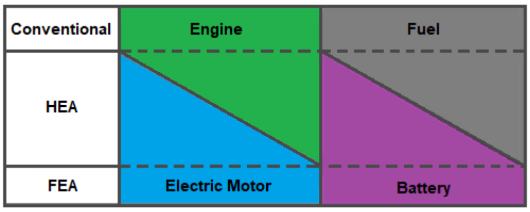


Figure 1: Hybrid-electric series configuration

As illustrated in Figure 1, these may only resort to electrical devices, in the case of a full-electric aircraft (FEA), or a combined system integrating both conventional engine and an electrical source, in the case of a hybrid-electric aircraft (HEA). Several studies agree that there is a limit in aircraft weight and size even if achieving significant improvements in battery technology. Realistically, the use of batteries alongside conventional fuel combustion appears more promising for general aviation (GA) and perhaps regional aircraft with limited capacity. Nevertheless, this is a conceptual study based on a forecast for future lithium-based battery technologies until 2050.

## 2. Background

### 2.1. Alternative Propulsion Systems

The levels of emissions reduction associated with alternative propulsion systems strongly depend on the chosen configuration, component performances, weight and the control strategy. A hybrid-electric system is a combination of both full-electric and conventional systems. It shows potential to integrate commercial aircraft once the energy from the batteries will offset some fuel consumption while being able to fly at conventional airspeeds and over longer distances. Among the studied configurations, the parallel and series are the most referenced in similar studies [6].

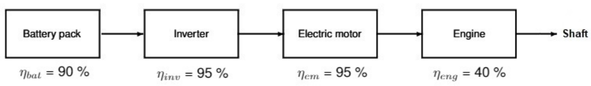


Figure 2: Hybrid-electric series configuration

A series system (See Figure 2) consists of a battery-powered electric motor and an engine both mechanically connected to a shaft that drives a fan, ensuring that each can serve as a propulsive mean. Compared to the parallel system, this configuration requires fewer electrical devices where either the electric motor or engine can be downscaled without a maximum power loss leading to a minimal weight. The overall efficiency of this system is also higher since there are fewer energy losses between components. The main drawback is the complexity of the mechanical coupling as well as the control system significant intricacy once the power flow has to be properly regulated and blended from two different sources. In addition, mid-flight battery charging is only practicable if the electric motor is able to operate as a generator, which is done with the expense of increased weight and complexity due to the additional electronic components required.

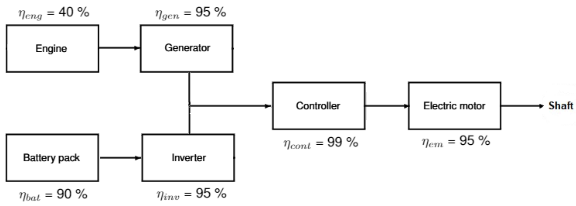


Figure 3: Hybrid-electric parallel configuration

In a parallel system, the electric motor is the only component mechanically coupled to the shaft (See Figure 3). The engine drives a generator which consequently powers a controller that might receive or provide power to the battery system. The total power from both engine and battery is managed to supply the electric motor which in turn transmits it to the shaft. In practice, given that the engine's mechanical energy has to be first converted to electrical energy then passed to the electric motor and converted once again to mechanical energy, the conversion losses between components will be higher. This propulsion system operates in three different modes:

- Exclusive use of the battery's energy capacity to power the electric motor
- The engine produces electricity through a generator that in turn powers the electric motor
- The engine produces electricity through a generator that powers both the battery system and electric motor

Although there are still not enough developments on this topic, in theory it is possible to design architectures based on combinations between the ones above mentioned, as in the case of the series/parallel partial hybrid-electric and turboelectric configurations. These alternative propulsion systems will most probably integrate future aircraft once the ones that are currently already in development are not suitable for most aviation segments.

## 2.2. Battery

Since the most promising battery technologies under investigation will take time to achieve a maturation level enough to meet the energy demand for aircraft propulsion, it is followed a forecast for the decades to come as done by many authors. Even though battery performance tends to progress slowly every year, sometimes big leaps occur as new materials and technologies become available. Therefore, it is quite difficult to accurately predict the state-of-art advancement based on current data. Given that, this study focus on the next generation of lithium-based batteries with the potential to integrate hybrid-electric propulsion systems for each aviation segment.

### 2.2.1 Li-ion

The lithium-ion (Li-ion) battery is widely used for portable electronic devices and, more recently, as traction mean for EVs. Since it started to be manufactured, the specific energy improved from less than 100 W.h/kg for an individual cell to a state-of-art of around 200 W.h/kg for a battery system [7]. However, even if this technology reaches its expected full potential as predicted (350 W.h/kg [6]), the total weight of a HEA will easily exceed the feasibility limit. Thus, the state-of-art of Li-ion batteries is clearly insufficient for this type of application and it is of most importance to investigate new technologies to find a solution towards sustainable development of the aviation industry.

Although these devices are almost fully technologically matured, there is still a small increase each year regarding the cell's specific energy, mainly due to design optimization and manufacturing process improvement. While currently cutting edge, the Li-ion battery is likely to be surpassed by different lithium-based chemistries on the next decades, particularly for high-performance applications.

### 2.2.2 Li-S

The lithium-sulfur (Li-S) battery is seen as the most promising technology to replace the Li-ion battery in several years. First introduced in the late 1960s, currently, almost every global cell developer is investing in Li-S research capability. This rise in interest is explained due to its known high theoretical specific energy of 2570 W.h/kg and specific capacity of 1675 A.h/kg, which comes from the cell's redox reaction with 2.1 V potential [7]. A complete Li-S battery system, however, is expected to reach only between 25 to 33 % of the theoretical value due to the additional component's weight [8]. On this study, it is considered a technological advancement of 1200 W.h/kg with reference to 2030 for Li-S battery systems.

Even though Li-S is experiencing major breakthroughs on a relatively short time period, there are still many aspects to improve such as:

- The sequential reduction of sulphur results in the formation of polysulphides ($Li_2S_x$) of intermediate polarity that can easily dissolve with the electrolyte, leading to anode corrosion, active material loss, low overall efficiency and poor life cycle.
- Polysulphides may also cause parasitic reduction and oxidation of intermediate products on the electrodes which results in a capacity fading.
- The lithium sulphide ($Li_2S$) at the anode tends to form an insoluble coat layer that blocks the lithium electrons transport.
- The low electric conductivity and instability of some reaction agents, including the sulphur and lithium that constitute electrodes, affects the charge rate capability and limit the specific power of the battery.
- The uneven deposition in the lithium anode tends to form a dendritic pattern which may lead to a short-circuit of the cell.

Despite these limitations that need to be overcome, the quality and quantity of research being carried out in the field, suggest that chemistry improvements will occur, as there are many companies set up for industrial mass production transfer. Li-S batteries provide a substantial opportunity for the development of more environmentally friendly HEA propulsion systems.

### 2.2.3 Li-air

The lithium-air (Li-air) is a battery technology still in an early development stage. These cells show a huge potential to power small to large-capacity aircraft in the next decades, given its theoretical specific capacity of 3.86 kA.h/kg and specific energy of 11.43 kW.h/kg, almost matching the fossil fuel specific energy ($\approx$ 12 kW.h/kg). Still, the practical specific energy of a battery system is presumed to be 70 % lower in relation to the theoretical value [7]. Following the same annual growth rate as for Li-S, in 2030, Li-air batteries are expected to reach a technological advancement of 2700 W.h/kg. Further, in 2050, this value is assumed as 8700 W.h/kg. It is clear that there is a certain level of uncertainty, that increases the further the forecast relates.

The working principle of a Li-air cell uses oxygen reaction with the lithium ions to form lithium peroxide ($Li_2O_2$), on the case of a non-aqueous electrolyte, or lithium hydroxide ($LiOH$), on the case of an aqueous electrolyte. There are still many investigations to do about several crucial issues among which stand out:

- Prevent $Li_2O_2$ to deposit on the cathode's surface to avoid damping and blockage of the cell reaction.
- The non-aqueous electrolyte instability to the peroxide radical attachment with high oxygen solubility leads to a low cycling capability.
- Develop a catalyst for $Li_2O_2$ reduction with an improved efficiency.
- Develop a oxygen-selective membrane to remove $H_2O$ and $CO_2$ from ambient air
- Protect the lithium metal anode from the aqueous electrolyte.
- Reduce the weight of the lithium-conducting electrolyte.
- Investigate electrodes with an higher capacity.
- Develop an anion exchange membrane as a separator to deposit the $LiOH$ into the aqueous solution

An important issue has to do with the progressive increase of weight while discharging due to the accumulation of reaction product which may lead to severe weight penalties during an aircraft mission. Considering the early stage of research with respect to this technology, it should be recognised that it will only become feasible on a system-level for this kind of application on a medium to long-term as this progress still depends on many factors.

### 2.3. Electric Motor

The electric motor is an essential component of a hybrid-electric propulsion system. Even though electric motors are known for low specific power of 2 to 10 kW/kg [9], these are highly efficient, compact, light, less expensive and require less maintenance comparing to conventional aircraft engines. Furthermore, since it is relatively easy to transmit power electrically, several electric motors can be stacked in series for distributed propulsion with increased horsepower for a large-capacity HEA. High temperature superconducting (HTS) materials will certainly be important for the optimal performance of electric motors. HTS materials require a cooling system to maintain the conducting wires below their critical temperature for the whole mission.

The HEA design methodology does not include a detailed analysis of the electric motor and subcomponents. Power is estimated as relative to the battery system.

## 3. Implementation

### 3.1. Hybrid-Electric Aircraft Design

Modelling a hybrid-electric propulsion system first starts with the conceptual design of the conventional aircraft. The selection of an aircraft for each segment was based on a market overview taking into account the mission profile, configuration, safety, produced units and available reliable data.

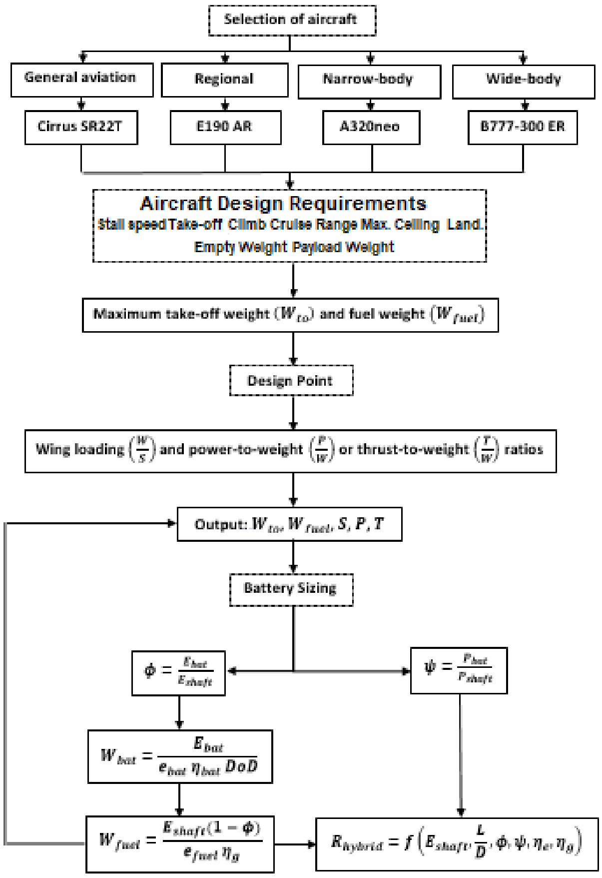


Figure 4: Hybrid-electric aircraft design procedure

Flight requirements were obtained from specification data sheets made available by companies and airports. Several aviation trend tables, aircraft regulation and systems engineering approach were also considered. For this design phase, the parameters obtained are used as a reference, however, are not irrevocable and might undergo changes (See Figure 4). The maximum take-off weight (MTOW) of each HEA is estimated according to:

$$W_{to} = W_{payload} + W_{empty} + W_{fuel} + W_{bat} \quad (1)$$

Fuel ($W_{fuel}$) and battery ($W_{bat}$) weight are responsible for the MTOW deviation from the conventional, however, by design option it might be considered a reduction of the payload weight ($W_{payload}$) so that some HEA will transport fewer passengers given the technological progress of each selected scenario while the operational empty weight ($W_{empty}$) remains constant. Afterwards, a control strategy must be defined for each HEA. A portion of the fuel energy that reaches the shaft ($E_{shaft}$) of each conventional aircraft must be compensated by using electrical energy which will directly influence the total energy capacity of the battery and, consequently, weight. The degree of hybridization of energy ($\phi$) was selected to size the batteries. To obtain an estimate of the hybrid range ($R_{hybrid}$), the degree of hybridization of power ($\psi$) was used along with several factors such as the available shaft energy ($E_{shaft}$), the efficiency of both electrical ($\eta_e$) and conventional ($\eta_g$) power trains and aerodynamic properties of the aircraft.

## 3.2. Life Cycle Assessment

A LCA is a systematic tool to analyse and assess impacts on the environment over the entire life cycle of a product. The standards to perform a LCA are established by the International Organization for Standardization (ISO): ISO 14040:2006 (Environmental management – Life cycle assessment – Principles and framework) and ISO 14044:2006 (Environmental management – Life cycle assessment – Requirements and guidelines) [10].

It is important to emphasize, that a LCA is not decision-making but a decision-supporting tool that is responsible for carrying out a detailed analysis of the environmental impact of products at all stages in their life cycle pointing out exactly what processes or components cause the most impact so these can be analysed and possibly reduced.

### 3.2.1 Goal and Scope

The intended goals of this methodology are to assess the environmental impact of:

- Lithium-based cells from the extraction of raw materials to production.
- Battery systems employing such cells considering the whole life cycle including its operation on a hybrid-electric propulsive system.

For this effect, two types of cells were selected: Li-S cells manufactured by the IREC (Catalonia Institute for Energy Research) laboratories [11] and Li-air cells from the European project STABLE [12].

**Functional Unit**

Generally, a battery LCA uses a variety of functional units depending on the application. Therefore, for the cradle-to-gate analysis of a battery cell the functional unit used is per weight (g) or energy (kW.h). The most adequate functional unit for the cradle-to-grave analysis of a battery system is per flight missions over its lifetime. The battery systems are scaled for an energy capacity given from conceptual design to determine the necessary number of cells and remaining components to suit the aircraft propulsion requirements from the preliminary design within a limit of cycles for the selected control strategies.

**System Boundary**

The system boundaries corresponding to each objective of this study are shown in Figure 5. For the first objective, the LCA is performed using a cradle-to-gate approach to assess the impacts of a single cell from extraction to production. Afterwards, not only a cradle-to-gate but also a cradle-to-grave approach is selected to assess the environmental impact of each battery system, from raw material extraction through production and operation on each selected HEA and, finally, EOL processes.

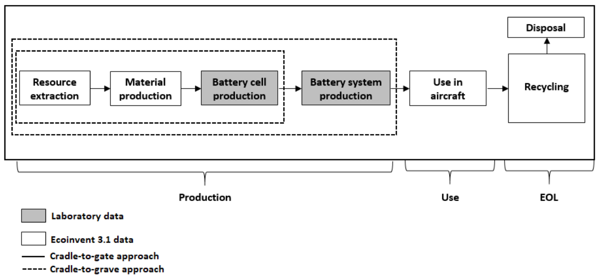


Figure 5: System boundaries of the LCA study

The associated resources and emissions were found from the Ecoinvent 3.1 database and represent global averages.

**Impact Categories**

Eight impact categories (shown in Table 1) are assessed.

| Impact category | Abbreviation | Unit |
|---|---|---|
| Climate Change | CC | $kg\ CO_2-eq$ |
| Ozone Depletion | OD | $kg\ CFC11-eq$ |
| Terrestrial Acidification | TA | $kg\ SO_2-eq$ |
| Freshwater Eutrophication | FE | $kg\ P-eq$ |
| Marine Eutrophication | ME | $kg\ N-eq$ |
| Photochemical Oxidant Formation | POF | $kg\ NMVOC$ |
| Particle Matter Formation | PMF | $kg\ PM10-eq$ |
| Human Toxicity | HT | $kg\ 1.4DB-eq$ |

Table 1: Selected impact categories and respective units

The ReCiPe is a complete impact assessment method covering both the midpoint and endpoint level impacts. Midpoint indicators include all of the above-mentioned impact categories while endpoint encloses them into three categories: damage to human health, damage to ecosystems and damage to resource availability [13]. The ReCiPe Midpoint (H) V1.11 / Europe Recipe H method is used as an indicator approach for evaluating the chosen environmental impact categories. For comparison, the ReCiPe Endpoint (H) V1.11 / Europe Recipe H method is also assessed to corroborate the impact gap between both battery cells.

**Limitations and Assumptions**

Many limitations emerged during this study, most of which were due to the lack of sufficiently detailed data. For instance, the STABLE cell lacked detailed information regarding few element's weight ratios and these were assumed as in similar studies. Some chemical elements were not even included in Ecoinvent 3.1 and were swapped for similar elements while others, were modelled according to each formation reaction. The energy requirements to produce a single cell and a battery system were computed regarding well-known specifications for industrial manufacturing processes used by the automotive industry for Li-ion batteries.

A critical drawback holding back the use of these lithium-based batteries has to do with their capacity fading leading to a limited life cycle. An assumption of $DoD = 80$ %, as in present-day EVs batteries, leads to a total of 2000 cycles.

Another limitation relates to the fact that currently almost no detailed data on battery and module pack. Likewise, little is known about recycling or waste disposal for these devices. Thus, the associated environmental impacts are modelled as from the involved hydrometallurgical recycling processes and treatment processes, including transportation to a scrap yard. Metallic materials and easily separable plastic parts do not come into contact with hazardous materials and, therefore, are up to 80 % recycled. The recycling process of traction batteries has not really started once there are not yet enough of such batteries that have reached the end of their lives.

### 3.2.2 Life Cycle Inventory

**IREC Cell**

The IREC is a Li-S coin cell consisting of a sulphur-carbon composite cathode, a lithium anode and an organic electrolyte. The electrolyte is a gelled-based non-aqueous solvent made of ethylene glycol dimethyl ether (EGDME) mixed with dioxane, lithium hexafluorophosphate and lithium nitrate. Despite its lightness, coin cells are known for a poor cycling performance making it difficult to adapt them to this application. Sadok [13] assessed both cylindrical and coin Li-S cells configurations, modelling the IREC cell as cylindrical for comparison and evaluation. To be able to compare the two battery cells, these were sized up to a certain battery system capacity operational for 2000 cycles. The electrodes, electrolyte, and membrane were scaled up to have the same weight as these same parts on a reference Li-S cylindrical cell but still maintaining the same weight fraction as in the Li-S coin cell. The parts pertaining to the coin cell (gasket, spacer, and spring) were neglected and replaced with electrode connectors and casing.

**STABLE Cell**

The STABLE high-density energy battery cell is an EU project under research and development. This kind of design has attracted the attention of many researchers due to its incomparable lightness. The project achieved a specific energy of 2700 W.h/kg at cell-level operating for 50 cycles with a 66 % charge and discharge efficiency with 20 % cycled capacity share of total capacity. At a system-level, it is estimated a 52 % loss with respect to that specific energy value [13]. The long-term goal is to improve cell performance and manufacturing processes for the commercialization of a complete battery system to occur.

The prototype is an aqueous Li-air cell with a cathode consisting of about 85 % of $Co_3O_4$ nanoparticles. These are manufactured on a semi-industrial scale using flame spray pyrolysis (FSP) and then mixed with multi-walled carbon nanotubes (MWCNT). The binder, which holds the active material particles together and in contact with the cathode connects, is a compound mixture of polyvinylidene difluoride (PVDF) and N-methyl-2-pyrrolidone (NMP). The mixture and the binder are then mixed into slurry and cast on GDL24BC, which consists of a thin electrically conductive copolymer made of acrylonitrile-butadiene-styrene (ABS). The electrolyte is produced by magnetically stirring lithium perchlorate and tetraethylene glycol dimethyl ether (TEGDME). The cell casing was modelled as a housing in polypropylene and a sealing gasket, representing approximately 30 % of the cell's total weight.

**Battery and Module Pack**

The battery pack and module pack are responsible for protecting the cells from damage, prolonging battery life and maintaining the battery at a high-performance state. The module pack enclosures and connects multiple cells securing better electrical management. A battery pack usually consists of a battery management system (BMS), a cooling system (CS) and a packaging (P). Since both battery technologies are still subject to investigation at cell-level, there is almost no available data about these components. Thus, it was used an inventory of a reference Li-S battery pack [14] with more detailed specifications regarding the BMS, cooling system and packaging used on a recent LCA on Li-ion [15] for more accurate results. The battery pack and module pack weights are equivalent to 40 % and 12.5 % of the total cell weight and approximately 25 % and 8 % of the total battery weight, respectively.

**Cell and Battery Assembly**

Energy requirements for cell manufacturing and battery assembly processes can vary widely depending on which share of the assembly steps require the most energy-intensive conditions. Estimations and measurements fluctuate between 0.28 to 111.1 kW.h/kg for serial industrial and laboratory scale cell production, respectively [16]. Since the cells here under study are yet only possible to be manufactured and assembled in laboratory conditions, an estimate of 46.6 kW.h/kg battery is used for the cell assembly required energy [14]. Regarding the second objective of this dissertation, both battery models are set with an average value from 11.3 to 22.8 kW.h/kg found from data for Li-S battery system assembly energy requirements [14], given that no information about Li-air battery systems is yet known.

## 4. Results

### 4.1. Hybrid-Electric Propulsion System Design

As expected, the results for the hybrid-electric version of a SR22T are quite positive. Since this aircraft is already planned to travel in a short-range, in 2030, a HEA-SR22T making use of a 135 kWh ($\phi = 21.5$ %) Li-S battery system charged on ground, consumes less 12 kg of fuel per flight while being able to carry three passengers, as the estimated MTOW increases about 5 % (See Figure 6). In 2050, considering the same mission profile, it might be possible to design a full-electric version of this aircraft. A benefit from reaching this technological maturity is that the aircraft MTOW is diminished by 2 %, which is justified through the enhanced efficiency of the electrical power train. For the aircraft to become entirely independent from combustion, the usable energy capacity of a battery system has to increase about four times when compared to the prediction with respect to 2030, The alternative propulsive system, of which 55 % is determined to be the battery system, weights approximately 12.5 % of the total aircraft weight. Therefore, the total environmental impact of the propulsion system may be reduced exclusively to the battery system plus the additional electrical components as well as the energy consumption during its life cycle.

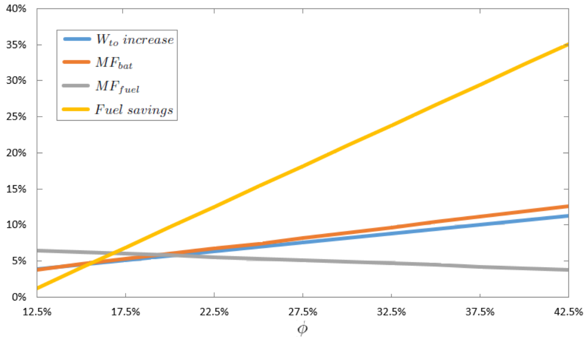


Figure 6: HEA-SR22T design operating with a 1200 W.h/kg Li-S battery with $\phi$ variation

On the other hand, the remaining aircraft operate long-range missions and the technological progress until 2030 will certainly be insufficient to accommodate most of the requirements of a conventional mission. As shown in Figure 7, a HEA-A320 designed to operate within a range of 1057 nm shows an MTOW increase of 8 % in a medium-term. The carrying capacity must be reduced in 66 % relative to the conventional aircraft, i.e., the aircraft is able to transport 68 passengers, while showing 3.6% of fuel savings per mission. Thus, to reduce the required stock of fuel as well as the batteries' energy demand, range was reconsidered to be shorter. Furthermore, the carrying capacity was chosen to ensure that each aircraft remains framed in its respective aviation segment, still to achieve considerable fuel savings. A 23 MW.h Li-air battery system will be required for the hybrid version of an A320neo to transport 125 passengers over an 881.7 nm range while allowing for a total of 12 % of fuel savings per mission. Likewise, the reachable fuel savings per mission might differ from 16 %, for a HEA-E190 using Li-S batteries, to 23.7 % for a HEA-B777 operating with Li-air batteries.

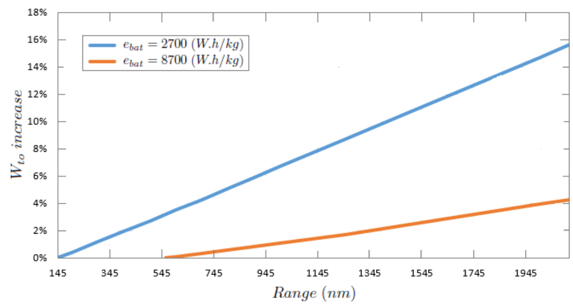


Figure 7: MTOW increase vs range for a HEA-A320 for different $e_{bat}$ ($\phi = 20$ %)

In 2050, as the demand for air transportation will be high, each large-capacity HEA was designed to maintain the reference passenger capacity and range. The propulsive system allows for mid-flight battery charging, thus decreasing the required batteries' energy capacity and, consequently, weight, Plus, the use of electricity is extended to all flight phases with a fixed $\phi$, as considered for the HEA-SR22T. Accordingly, it is estimated that savings of more than 50 % of the fuel consumed relative to the present-day aircraft are to be achieved. Once again, this will only be attainable if this technology matures as suggested.

### 4.2. Life Cycle Impact Assessment and Interpretation for Battery Cell Analysis

The description of the life cycle impact assessment (LCIA) results is intended to highlight major findings that may be accounted for further development of the technology. The environmental impact is quantified and classified in different impact categories using *SimaPro 8.0.4.30.*

Climate change is the most sought-after impact category concerning with diminishing the carbon footprint of air transportation. Figure 8 below shows the effect on climate change of each IREC cell component. The cathode dominates with about 89 % contribution of the total impact followed by the lithium anode and the energy demand to assembly a cell. The remaining components show a lower environmental impact of less than 1 % each. The total impact on climate change for a single IREC cell, since the extraction of raw materials to the production process, is of 180.8 kg of carbon dioxide equivalent.

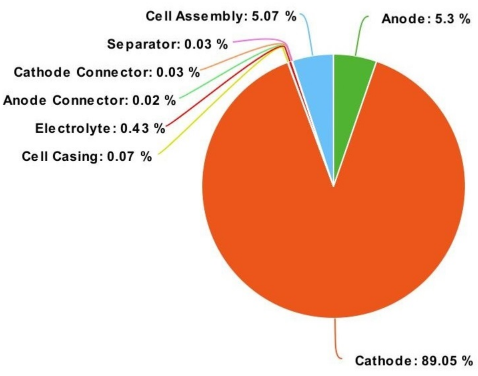


Figure 8: LCIA climate change results for the IREC battery cell categorised by cell part (in-house production)

The IREC cathode is produced in in-house conditions one unit at once, which justifies its tremendously high environmental impact contribution for each cell produced. This analysis proposes a change to an industrial scale production process allowing the energy consumption per cathode to be drastically reduced to 0.55 MJ per gram of cathode. Therefore, climate change impact is expected to be reduced in 88.5 %. Hence, the $CO_2 - eq$ emissions related to cathode production are out-weighted by the assembly process and anode production with a share of 90.6 % of the total impact.

The available data about the STABLE cell data was not detailed enough and did not account for all the production methods, therefore the environmental impact of each component is considered mostly for material production processes from the database. For comparison, it was assumed that the energy demand per gram of cathode for a STABLE cell equals the IREC cell for a considered industrial production process. Comparing a gram of each cell, the STABLE cell is responsible for the emission of 70.7 % less of $CO_2 - eq$, still inducing a human toxicity impact superior by 10.1 %. This is explained due to the copper tab used to produce the anode connector, which is known for its high impact potential on this category (See Figure 9), plus the STABLE cell anode connector has a higher weight ratio. For the same analysis, the endpoint indicators revealed that per each gram of cell produced the IREC is responsible for a total of 4.77 milipoints of impact, while the STABLE causes 52 % less with the highest environmental impact being with respect to resource depletion.

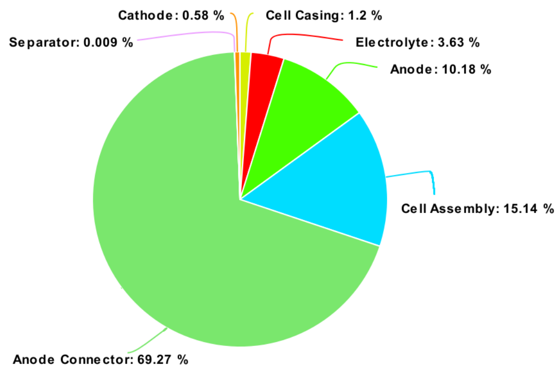


Figure 9: LCIA human toxicity results for the STABLE battery cell categorised by cell part (industrial production)

Additionally, a comparative analysis was performed on the two solvents used in both cells: EGDME on IREC cells and TEGDME in STABLE cells. As shown in Figure 10, using EGDME rather than TEGDME comes out to allow an overall reduction on the environmental impact per gram of solvent. An electrolyte embodying one gram of

EGDME as solvent is accountable for the emission of 2.42 g of $CO_2 - eq$ which represents a reduction of 72 % regarding climate change compared to the same amount of TEGDME. Ozone depletion and marine eutrophication are the impact categories that benefit the most, showing a reduction of around 80 %.

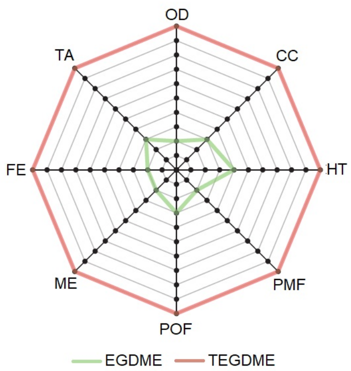


Figure 10: Comparison between results from both electrolyte solvents for each impact category

### 4.3. Life Cycle Impact Assessment and Interpretation for Battery System Analysis

From the production point of view, the environmental impact of both battery system is dominated by the number of cells and assembly energy demand, while the module pack shows a higher impact on freshwater eutrophication and human toxicity, mainly due to the integrated circuit and copper. Considering the overall impacts relative only to the module pack, these materials contribute the most in all the categories. Hence, the STABLE battery system will be responsible for less emissions regarding climate change (76.4 %), ozone depletion (73.3 %), terrestrial acidification (74.6 %), freshwater eutrophication (62.9 %), marine eutrophication (77.1 %), photochemical oxidant formation (74.3 %) and particulate matter formation (74.3 %) and human toxicity (56.8 %) comparing to an IREC battery system with the same energy capacity.

From the cradle-to-grave analysis, however, it is conclusive that electricity once again plays a dominant role as the use phase has the most impactful effect all the categories while recycling, on the other hand, has a less significant impact.

#### 4.3.1 Sensitivity to Electricity Mix

Nowadays, most of the countries electricity mixes still rely significantly on fossil power plants, holding a high average of carbon dioxide emissions. If both battery systems considered are manufactured in Portugal, the production impacts per gram of cell decrease from 39.9 to 36 g of $CO_2 - eq$ for the IREC and from 11.7 to 10.5 g of $CO_2 - eq$ for the STABLE. As the investment for renewable energy power plants increases, most countries target a growing contribution to the future of electricity generation. Although in minority, countries such as Sweden already extended the use of renewable energy and is responsible for a 91.3 % lower climate change environmental impact compared to the global average. From this analysis, it was found that a 135 kW.h IREC battery to be charged in Portugal operating on an aircraft like HEA-SR22T will allow the emission of 30 tons of $CO_2 - eq$ less than the global average, whereas with a 23 MW.h STABLE battery a reduction of 5.1 kilotons of $CO_2 - eq$ is estimated for a large-capacity aircraft such as a HEA-A320 (See Table 2). Comparing the same batteries to be charged in Sweden, means a reduction of 167 tons of $CO_2 - eq$ and 28.3 kilotons of $CO_2 - eq$ for the IREC and STABLE battery operational process, respectively. Thus, it can be concluded that an improved environmental friendliness of an aircraft should be combined with further expansion of renewable energy plants.

| Climate Change ($kg\ CO_2 - eq$) | World Average | Portugal | Sweden |
|---|---|---|---|
| **135 kW.h IREC battery system** | | | |
| **Production** | 1.1E04 | 1.0E04 | 5.9E03 |
| **Use** | 1.83E05 | 1.53E05 | 1.59E04 |
| **23 MW.h STABLE battery system** | | | |
| **Production** | 4.42E05 | 3.98E05 | 1.96E05 |
| **Use** | 3.11E07 | 2.6E07 | 2.71E06 |

Table 2: Electricity mixes climate impact on the production and use phases for different battery systems operating for 2000 cycles

#### 4.3.2 Sensitivity to Specific Energy

Further advancements regarding the specific energy of a battery system lead to a decrease in its overall environmental impact due to the implicit reduction in the material required to produce it. Li-air batteries show more promising results due to its high expected specific energy evolution. Therefore, in 2050 a STABLE battery system production is expected to contribute largely less to climate change (82.6 %), ozone depletion (84.1 %), terrestrial acidification (83.1 %), freshwater eutrophication (76.4 %), marine eutrophication (84.2 %), photochemical oxidant formation (82.2 %), particulate matter formation (82.8 %) and human toxicity (76.2 %) when compared to 2030.

### 5. Conclusions

The potential environmental impact benefits of a hybrid-electric propulsion system for each aviation segment was investigated and presented. Given the lack of detailed research studies on such concepts,there is still much uncertainty on the expected level of technological progress between present-day and 2050. Hopefully, as identified in this dissertation, batteries such as Li-S and Li-air which are presently seen as the most probable upcoming technologies to replace Li-ion given their promising specific energy are expected to reach a maturity level suitable to be integrated into most of the analysed aircraft. Although these hypothetical scenarios dependent on several factors already pointed and the difficulty to make an accurate prediction, the success of such projects may be key to creating a more sustainable future.

Through the LCA several materials and processes have been pinpointed for a higher environmental impact and, ultimately, how these impacts related to battery systems for aircraft propulsion will lower on the case that technology evolves in an expected way. From the cradle-to-grave analysis, it was shown that the process of charging a battery system for an aircraft propulsion system is the main cause of the overall life cycle's environmental impact of each battery system. As most countries still rely on fossil power plants, the investment on renewable energy power plants for the future of electricity generation will be crucial to reduce the life cycle's environmental impact of a battery system. Sweden already successfully managed to reduce its electricity mix carbon footprint in more than 90 % below the global average. Considering a specific energy as high as 8700 W.h/kg, the overall environmental impact of the STABLE battery system production is foreseen to be largely reduced.

## 5.1. Future Work

Based on the findings, there is much future work that can be done here. As more research is done in this field, some of the alternatives suggested by researchers to reduce an aircraft's carbon footprint could be modelled with more precision while others, given their proved difficult practicability, will be discarded. Once only fuel and batteries were considered for this study, a more detailed analysis could be carried out taking into account the remaining components of the propulsive systems to determine their influence on these results. In addition, more sensitivity analyses could be performed on this LCA, some of which could include varying the battery's life cycle or exchange several materials from the most impactful components. In general, as these batteries undergo further investigation and show a better performance, LCA studies with the updated materials and processes could show more realistic results.

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