What Energy Storage Devices Will Power Aerospace Vehicles of Tomorrow?

Research Support Service

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PRESCOUTER

What energy storage devices will power the aerospace vehicles of tomorrow?

The advent of new more powerful energy storage devices, enabled by advances in materials chemistry, analytics, and dedicated research, is paving the way for new applications in multiple industries. In the Aerospace & Defense sector, the adoption of these technologies is opening up new applications and markets by enabling new designs. Coupled with other emerging technologies like artificial intelligence and autonomous navigation, a proliferation of new vehicle types are starting to fly.

The PreScouter team has provided in this report a highlight of novel state-of-the-art aerospace vehicles currently in development, as well as a snapshot of the different energy storage technologies that will be used to power them. Understanding these new capabilities and the technologies that enabled them can help industry leaders and innovators anticipate a changing landscape and evolve to meet new demands from customers.

Note: *This report is representative of the work output that a standard PreScouter team can generate for clients on a topic over the course of 1 month (2 Intelligence Briefs).*

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Executive Summary

Electric aviation is an emerging area benefiting from the advent of advanced battery technology for energy storage. Though it has garnered less attention than the electrification of ground vehicles, designing more-electric aircrafts (MEA) and all-electric aircrafts (AEA) can help not only to significantly reduce carbon emissions, but will also reduce the size and weight of the aircraft.

Here, as in other sectors, optimizing electric aircrafts necessitates a careful choice of the energy storage system while eyeing a variety of technical factors like energy density, efficiency, cycle life, safety, recyclability, size, weight, and price.

Already, the proliferation of new aircraft designs is being enabled by developments in fuel cells, batteries, and solar panels. To help navigate this emerging sector, this report will serve as a primer on a few of the relevant technologies and designs proliferating around the globe today.

Aerospace vehicles of tomorrow will target the following three main applications:

1. **Passenger transport** with the *Air Taxi* enabling a new type of service
2. **Telecommunications nodes** that will be a key part of the infrastructure enabling the rollout of 5G over the next few years
3. **Surveillance and monitoring applications** for domestic and defense purposes

Executive Summary

With regard to the different **energy storage technologies used in the vehicles of tomorrow** profiled in this Intelligence Brief, fuel cells and lithium-ion batteries are stand-out candidates for energy storage that are currently being used in commercial products.

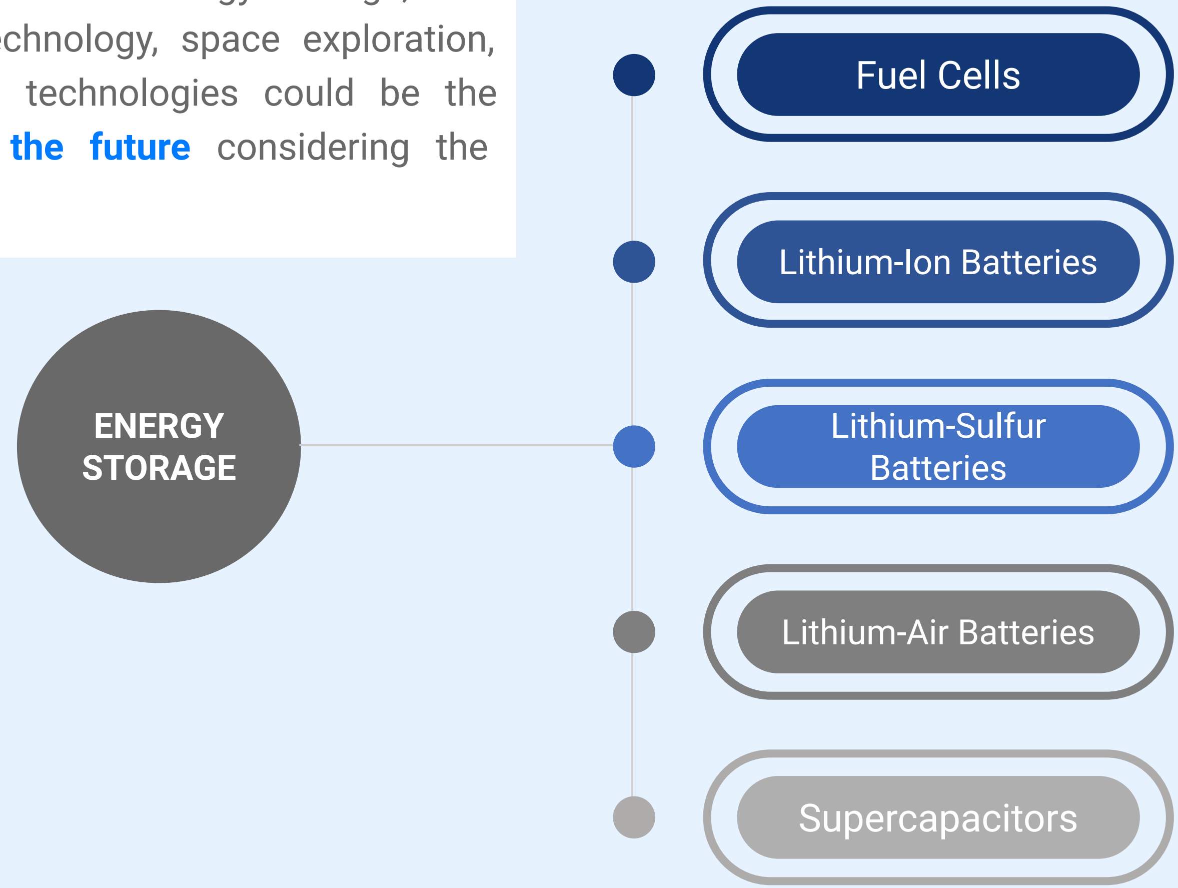
- The hydrogen drone from Project Rachel and Skai's hydrogen-powered flying car both rely on fuel cells
- Thales Alenia Space's Stratobus and Volocity's commercial aerotaxi rely on lithium-ion batteries

For **future energy storage devices** in the aerospace and defense industry, PreScouter concludes the following:

- Li-sulfur, Li-air, and supercapacitor technologies are the most likely to be the next frontier of energy storage in the aerospace and defense sector
- Fuel cell technology is likely to continue growing in importance in the market as advancements in technology focus on improving hydrogen storage

Technologies of the Future in A&D

With increasing demand for renewable energy storage, civil aerial transportation, secured technology, space exploration, and green transportation, these technologies could be the **disruptive storage systems of the future** considering the current advancements in science.



AEROSPACE VEHICLES OF TOMORROW

Section Overview

In the age of the Internet of Things, transportation is undergoing a major generational shift. The transportation industry is witnessing the emergence of new markets that offer different types of autonomous vehicles that can transport people and products in a safer and faster way. Moreover, new innovative vehicles are promising to reduce greenhouse gas emissions.

This, of course, can be achievable by utilizing renewable energy sources (e.g., solar and wind) and by taking advantage of the latest technologies that can help store energy to satisfy the needs of the most sophisticated vehicles.

This section introduces four different **aerospace vehicles of tomorrow**, most of them at different stages of development, that are targeting different segments of the aerospace and defense market.

- **Skai** is an eVTOL 5-passenger air vehicle designed to become a simple air mobility system. Skai relies on the use of hydrogen fuel cells for power, and it offers reliability and safety.
- **The Hydrogen Drone** is the most efficient hydrogen fuel cell powering a multi-rotor unmanned aerial vehicle, with a record time in air (90 minutes with a 5-lb payload).
- **Stratobus** is rejuvenating the idea that airships can become an interesting economic alternative, especially to complement telecommunication technologies and/or work as an Earth observation satellite.
- **VoloCity**, an inspired version of a 2-person aerotaxi, is fully powered by a lithium-ion battery technology.

Company Overview

Alaka'i technologies is an emerging air mobility design and manufacturing company based in Hopkinton, Massachusetts. Founded by Brian Morrison in 2015, the company manufactures and distributes equipment for the aerospace and aviation industry. Alaka'i is the parent company of Skai, which aims to offer a carbon-neutral point-to-point transportation system that is safe, simple, affordable, and comfortable. Alaka'i is positioning itself as the first company to offer point-to-point transportation that is powered using hydrogen.

Energy Storage Used

Skai is completely powered by fuel cells that convert hydrogen into electricity. The hydrogen fuel cells can be 95% reused, and the remaining 5% can be 99% recycled. Hydrogen's energy-to-weight ratio (MJ/kg) is roughly 3 times that of gasoline and more than 200 times that of lithium-ion batteries, making the use of hydrogen ideal for flight. The hydrogen fuel cells enable Skai to fly continuously for up to 4 hours, and with auxiliary tanks it can remain airborne for 10+ hours for specialized applications.

Technical Details

Skai's eVTOL (electric vertical take off and landing) vehicles use a redundant 6X-rotor propulsion system. It holds up to five passengers, including a pilot, with a payload capacity of 1000 lbs. The flying car can reach a speed of up to 118 mph (190 kmh) and is able to fly for over 4 hours within a 400-mile range. It can be refueled in 10 minutes. For safety purposes, the vehicle is fault-tolerant by design; it has a 3X-redundant autopilot system, fly-by-light fiber optics–based controls for electromagnetic interference and lightning protection, and an airframe parachute. The vehicle can be used as an air taxi, personal air vehicle, cargo delivery, and more.

Intellectual Property

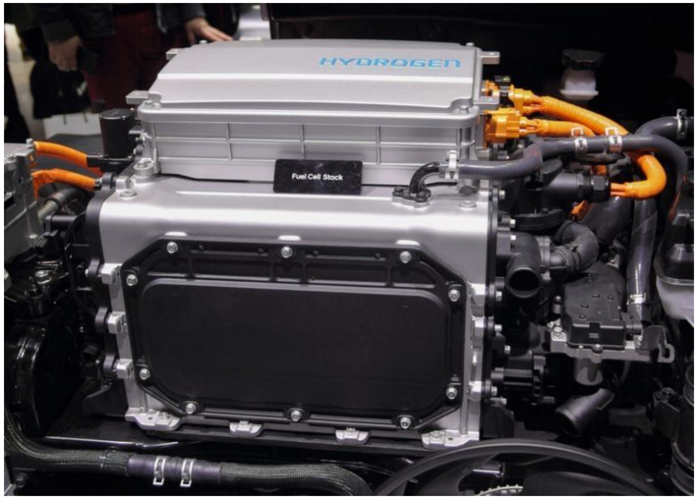
Alaka'i is the owner of three US patents related to methods and systems for the development of a clean-fuel electric multirotor aircraft with full-scale vertical takeoff and landing for personal air transportation and manned or unmanned operation.

References

1. http://assets.ctfassets.net/mv70xbbqomoj/5A22mcCgVXVSBaoIYJr9sP/b7bb8d41208b0a62c1b7eb046e927cb6/FactSheet.pdf
2. https://evtol.news/aircraft/alakai-technologies-skai/
3. https://skai.co/vehicle
4. https://newatlas.com/alakai-skai-brian-morrison-interview/60032/
5. https://www.crunchbase.com/organization/alaka-i#section-overview

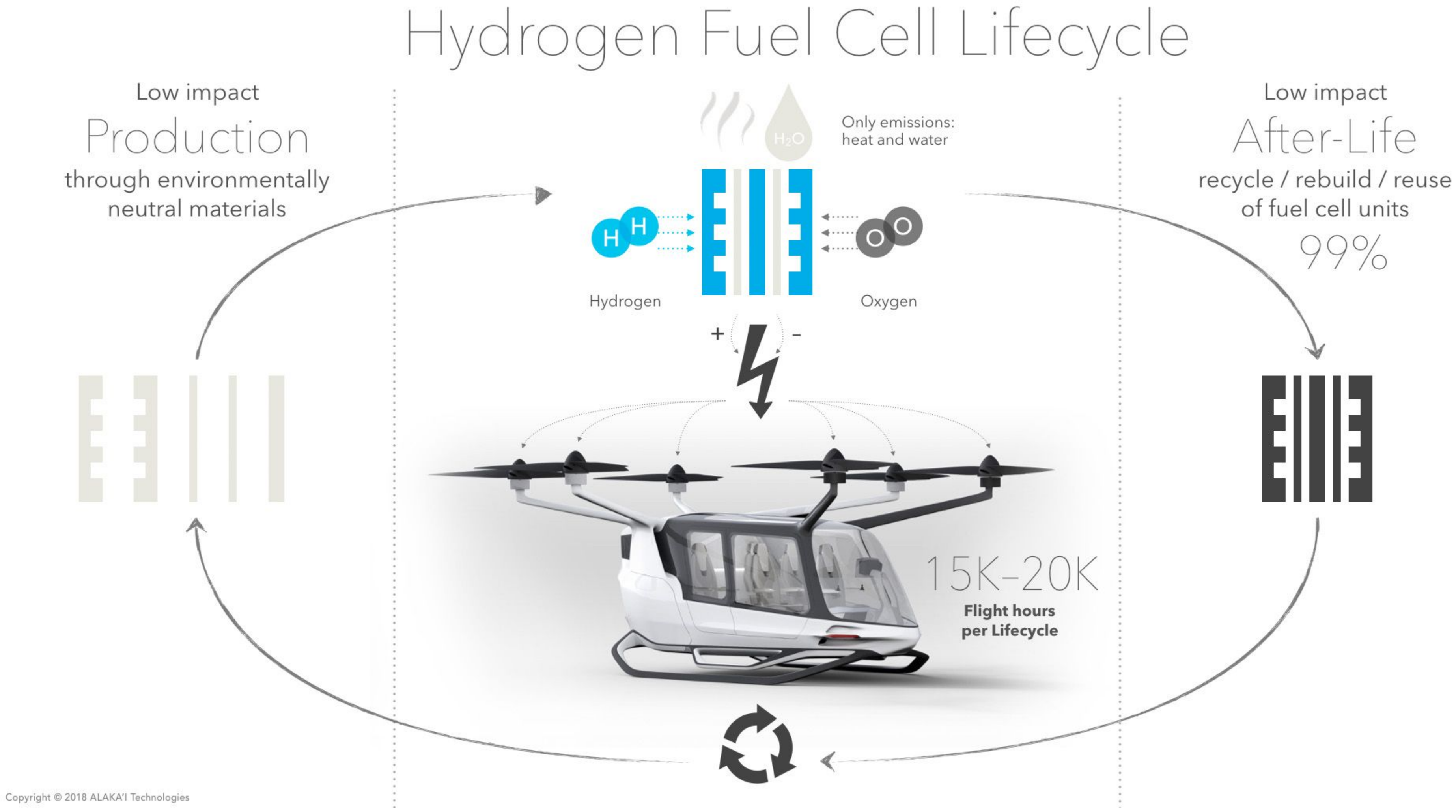
Skai: A Hydrogen-Powered Flying Car

Image of Skai's car. ***Source:*** *[Press Kit (Skai)]*



Fuel Cell Stock in Skai's engine. ***Source:*** *[Cloud Wedge]*

Image of Skai's car. ***Source:*** *Press Kit (Skai)*



***Source:* https://skai.co/hydrogen**

Company Overview

Productiv is a venture engineering company that provides technical, production, and commercial development, forming partnerships with developers and inventors of green technologies. Productiv started its operations in 2011, with headquarters in Coventry, UK. The company is headed by Richard Bruges and currently has 34 employees and total assets of USD 1,388,963.

Technical Details & Energy Storage Used

Productiv is leading Project RACHEL, which aims to develop the first hydrogen fuel cell–powered multi-rotor unmanned aerial vehicle. Current tests of the model drone reported that it has been able to remain in the air for 80 minutes with a 5-kg payload.

The drone is equipped with a multi-rotor engine powered exclusively by hydrogen (~300 bar; at 1 bar hydrogen has approximately 7% of the density of the air) contained in a 6-liter cylinder. It has a 11lbs (5 kg) of payload capacity, and is capable of remaining below 44.1 lbs (20 kg) of maximum take-off mass.

The prototype is testing fuel cell power modules (650 and 800W) that facilitate higher power outputs. The drone can refuel faster and has a prolonged flying time compared to those operated with batteries. The operation is quiet, and it does not vibrate.

PRODUCTIV
DRIVING GREEN TECHNOLOGIES

Applications

Some of the identified applications due to the extended flight time are:

- Filming, TV, and broadcasting
- Agriculture, especially for targeted spraying
- Inspection of infrastructure
- Constant monitoring of open mining areas and activities
- Environmental monitoring
- Emergency services
- Mapping and surveying

Partnerships

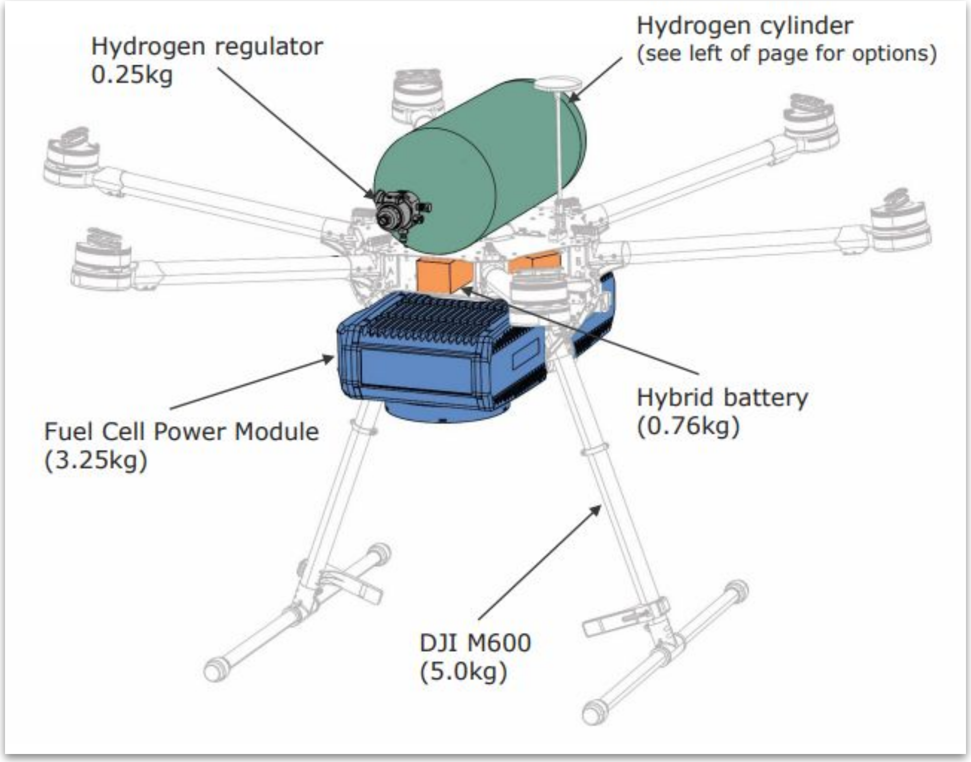
Project RACHEL is supported by Innovative UK, and Productiv has joined forces with the UK's leading UAV filming specialists, BATCAM, and the proton exchange membrane (PEM) fuel cell products company Intelligent Energy. BATCAM is in charge of implementing the visual components that will allow the drone to carry out real-world end-user trials. Intelligent Energy has been in charged of engineering 850W fuel cell power modules. Each company owns the applications and systems that form part of the drone; but it is unclear how this relates to the intellectual property of the UAV itself.

References

1. https://thehydrogendrone.com/
2. http://batcam.tv/case-studies/worlds-first-90mins-flight-time-with-5kg-payload
3. http://www.productivgroup.com/
4. http://www.dronesglobe.com/guide/heavy-lift-drones/
5. https://dronelife.com/2019/04/04/intelligent-energy-productiv-hydrogen-powered-drones/
6. https://www.intelligent-energy.com/uploads/accompanying_files/FC_UAV_intro_Nov_2019_final

Model drone equipped with a 6-L Hydrogen Cylinder. ***Source:*** *Drone Life*

A 800W Fuel Cell Power Module.
Source: *Intelligent Energy*



Fuel cell power module configuration. ***Source:*** *Intelligent Energy*

Company Overview

Thales Alenia Space is a Franco-Italian aerospace manufacturer. It is a joint company between Thales Group (67%) and Leonardo (33%) that was founded in 2007. Its headquarters are located in Cannes, France. The company has 15,000 employees in 58 countries. The earnings before interests and taxes for the first half of 2019 was approximately USD 920 million. Thales Alenia Space leads project Stratobus and has partnered with Airstar Aerospace to build an airship that can be considered a high-altitude pseudo satellite. Airstar Aerospace will be in charge of the design and manufacture of the fully equipped envelope of Stratobus. The airship, which is being designed to fulfill military and civilian roles, will be capable of running a five-year mission, and a prototype is planned for late 2020.

Technical Details

The Stratobus will be powered with solar energy. The airship will complement telecommunication technologies and/or work as an Earth observation satellite. And it will be able to perform duties such as 4G and 5G telecommunication, border surveillance, and real-time weather and environmental monitoring. Stratobus is designed to operate at an altitude of 11.81 miles (19 km) above the jet stream and air traffic, and it does not require a launch vehicle. To remain stationary, the airship must withstand winds of up to 90 km/h.

Energy Storage Used

It will be equipped with 10,764 square feet (1000 square meters) of photovoltaic (PV) cells. The PV cells are flexible, and the modules will weigh less than 800 g/m^2, with a 24% efficiency rate. The PV modules will cover one quarter of the airship surface area, offering a high power output of more than 200 W/m^2 and a large surface area of over 4 m^2. The airship will be equipped with a ring that will allow it to rotate so it will always be exposed to sunlight independently of weather and seasons.

Some of the resultant energy that will power payloads and the electric propulsion systems will be stored in a regenerative fuel cell system (RFCS), which will be composed of an electrolyzer, water, hydrogen and oxygen storage tanks, a fuel cell, and auxiliary components. RFCS technology has a low mass and a corresponding high specific energy that are essential for the Stratobus platform.

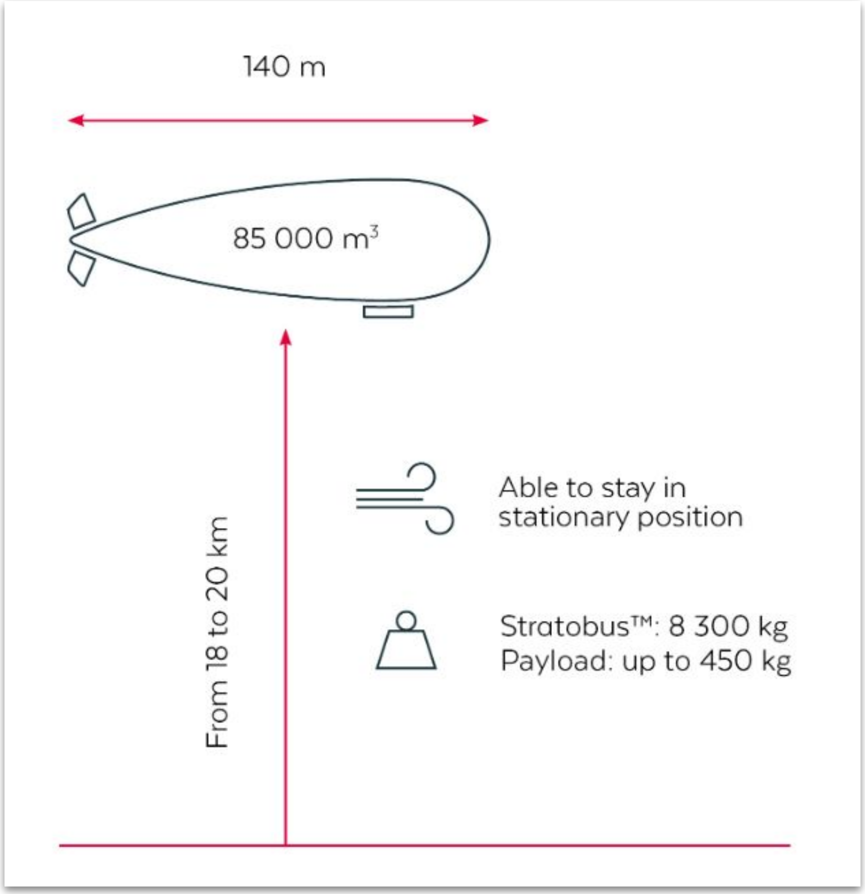
Intellectual Property

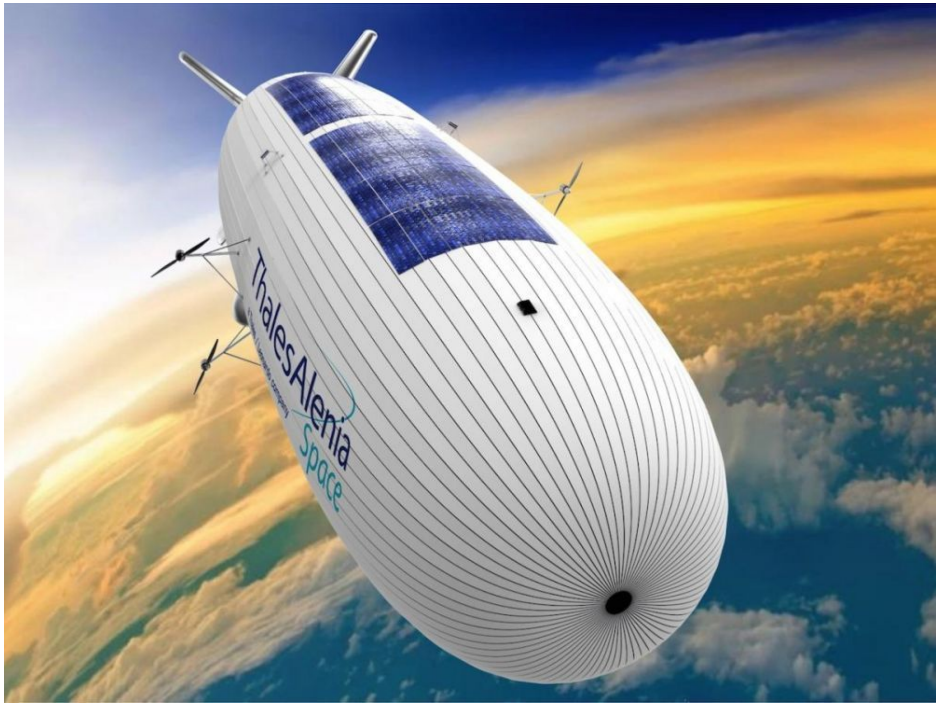
Thales Alenia Space owns the Stratobus trademark. Together with the Centre National d'Etudes Spatiales, France, Thales developed an innovative mechanical flexible solar array architecture using 22-meter-long carbon tape springs. Most of the components on this airship were co-developed with research and development partners worldwide, and the underlying technology is protected by a long list of patents (over 260 registered patents worldwide and 17 registered in the United States).

References

1. http://airstar.aero/en/technologies-for-stratobus/
2. https://www.thalesgroup.com/en

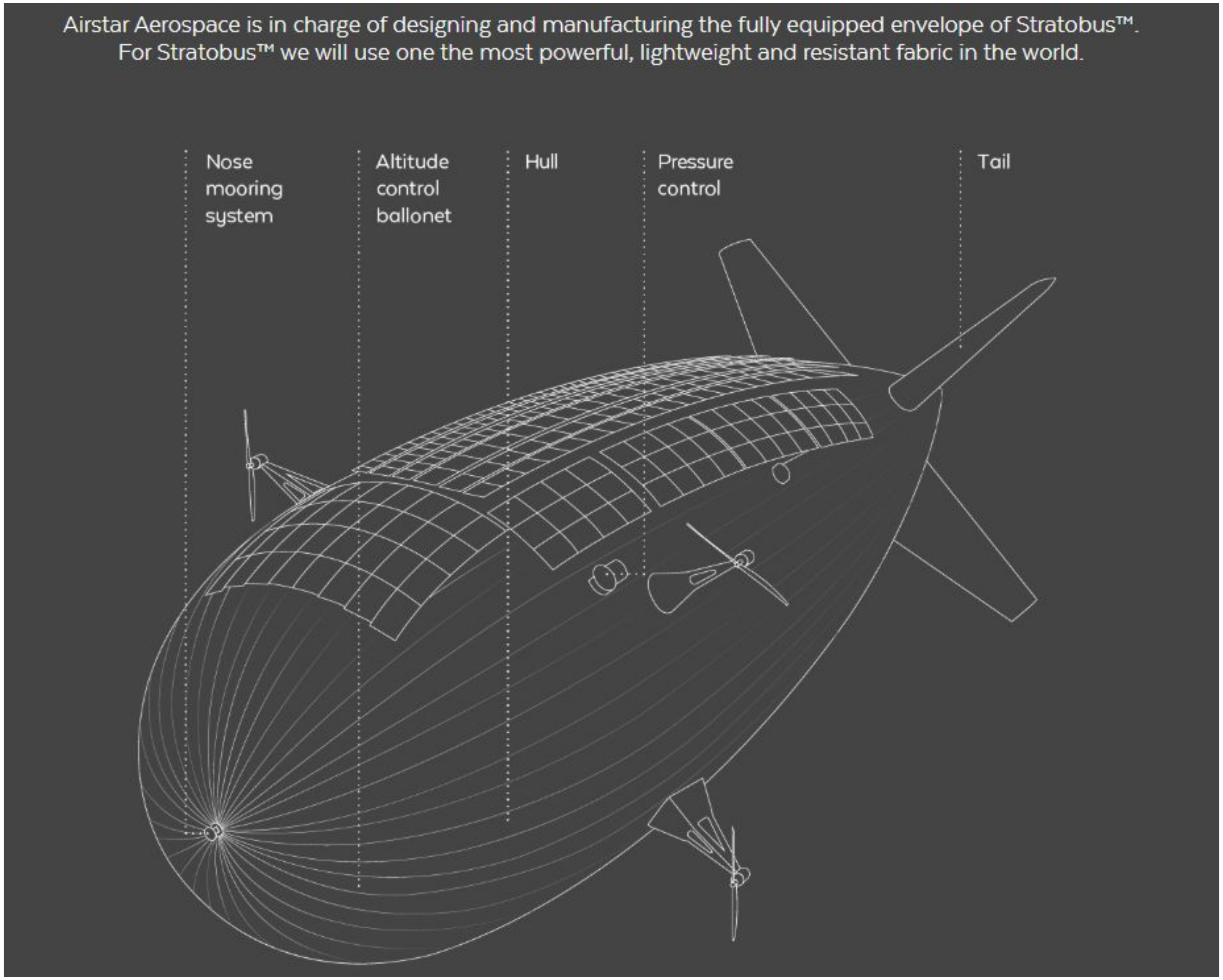
Stratobus: An Autonomous Stratospheric Airship





Artistic representation of Stratobus. ***Source:*** *Thales*.

Stratobus: An Autonomous Stratospheric Airship



The fully equipped envelop of the Stratobus. ***Source:*** *Airstar*

Company Overview

Volocopter GmbH, formerly known as E-Volo GmbH, is a German aircraft maker with headquarters in Bruchsal, Germany. Volocopter is considered to be one of the pioneer companies in the production of electric air taxis. The company was found in 2007 and currently operates with 130 employees. This year, Volocopter announced its partnership with the UK's Skyports to build a prototype station and run trial services in Singapore, Los Angeles, and London. The company has also experienced a USD 55 million investment from Zhejiang Geely Holding Group.

Technical Details

The VoloCity is being advertised as an extremely safe vehicle, with the European Aviation Safety Agency's international certification in place. The vehicle also sets the acoustic standard for air taxis by producing no noise due to their electrically powered rotors. The VoloCity is also 100% electric. It is likely that the project will be completed and commercialized by 2023.

VoloCity can transport two passengers with hand luggage and has a maximum takeoff mass of ~1980 lbs (900 kg) with a payload of ~440 lbs (200 kg). The cruising speed is about 69 mph (110 km/h), with a range of ~22 miles (35 km). The overall height is 2.5 m and the diameter of the rotor rim is 11.3 m, with a diameter of a single motor of about 2.3 m. It has 18 motors that are brushless DC fully electric. The power is supplied by a nine-battery lithium-ion pack. These specifications are calculated approximations that have not been tested in flight.

Energy Storage Used

VoloCity's power is supplied by nine independent lithium-ion batteries. Each battery powers two of the motors. The batteries are set to charge in 120 minutes under standard conditions, but charging time is reduced by ~60% if a municipal power supply is available. One charge can store energy to power flight for about 27 minutes. The aerotaxi can be supplied in a matter of minutes with a newly charged battery shortly after landing and be ready for the next flight.

Intellectual Property

Volocopter is the rights holder of all the technology that enhances the manufacturing of the aerotaxis, heliports, and decking ports that are currently being advertised by the company. This is not limited only to VoloCity but also includes the X2 model.

References

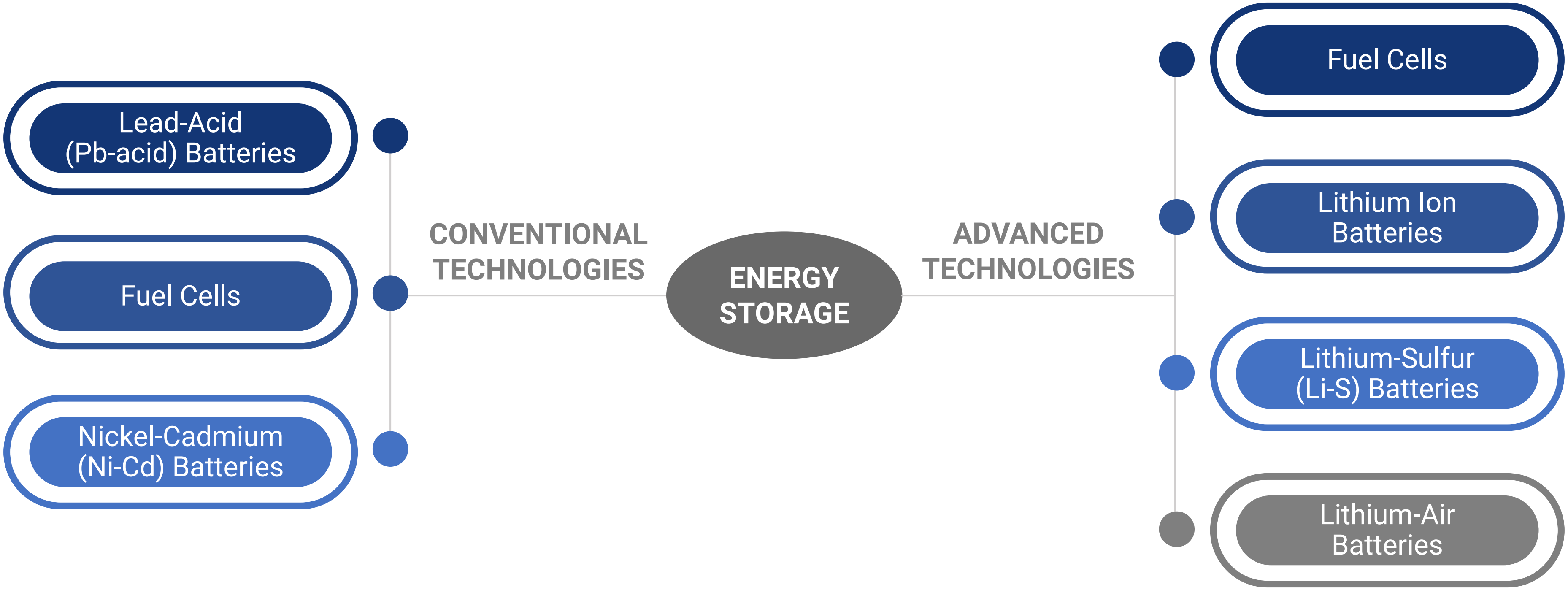
1. https://www.volocopter.com/assets/pdf/20190819_VoloCity_Specs.pdf
2. https://siamagazin.com/the-volocopter-volocity-a-18-rotor-electric-air-taxi-for-two-people/
3. https://press.volocopter.com/index.php/press-releases
4. https://evtol.news/aircraft/volocopter/
5. https://www.owler.com/company/volocopter


Images of the VoloCity, designed by Volocopter supported by Mercedes-Benz Design. ***Source:*** *Volocopter.*

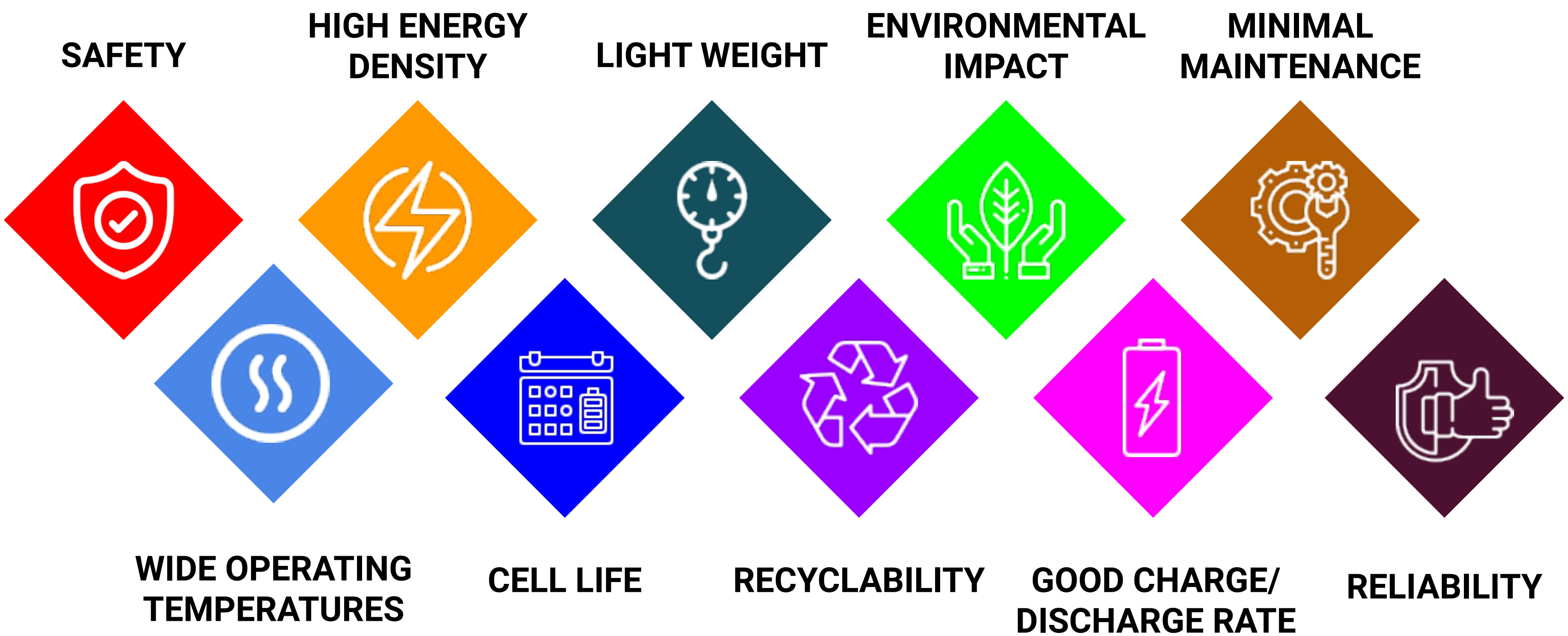
Charging station type for Volocopters. ***Source:*** *Volocopter*.

ENERGY STORAGE TECHNOLOGIES OF USE IN THE A&D INDUSTRY

Key Technologies for Energy Storage



Properties to Consider When Choosing Batteries for Aviation



Notably, the Li-ion battery is the most attractive storage technology based on its high energy density. However, other technologies are being extensively investigated by several companies and research organizations (such as SIEMENS, EAS Batteries, MEGGITT, and NASA). At the same time, the global aerospace energy storage market is steadily growing.

LEAD-ACID (Pb-acid) BATTERIES

On a cost-per-watt basis, Pb-acid batteries are cheap and reliable. The flooded and sealed valve regulated batteries made by Concorde are extensively used in military aircrafts and have a potential future in the commercial aviation industry.

Two Major Types of Lead-Acid Batteries

Spilled or Flooded Lead-Acid Batteries

Two electrodes are usually fixed onto a grid and the electrolyte is flooded into the container holding the electrodes. During the charging process, oxygen is produced at the positive electrode and hydrogen is generated at the negative electrode. Both gases escape from the cell, causing water loss in the cell, therefore requiring periodic maintenance.

- ➢ *Cheap and simple construction*
- ➢ *Uses a microporous membrane as a separator*

Sealed / Valve Regulated Lead-Acid Battery (VRLA)

Absorbent glass mat (AGM) is used as the separator, where the liquid electrolyte is absorbed. This design prevents the leakage of gases and electrolyte from the cell, which is therefore often described as maintenance-free. VRLA batteries are more convenient than the flooded batteries.

- ➢ *The separator can also be of gel electrolyte, where the H_2SO_4 is mixed with silica to form a gel-like material*

Applications of VRLA Batteries

VRLA batteries are widely used in general aviation, small military aircraft, and even helicopters. Some examples are the Pilatus PC-21 military trainer and the Kopter SH09 rotorcraft.

Concorde, a major battery manufacturing company, has a wide range of products, including:

- General aviation batteries
- Turbine-starting batteries
- Emergency batteries
- Military batteries

A general aviation VRLA-type battery (RG 24-9) designed by Concorde Battery Corporation.
Source: Concorde.

Pros & Cons of Lead-Acid Batteries

Advantages of Pb-acid batteries:

- Low cost
- Simple construction
- Minimal maintenance
- Reliable
- Long cell life if stored without electrolyte
- Robust
- Can handle high current
- Recyclable materials (>90% lead can be recovered)

Disadvantages of Pb-acid batteries:

- Low energy density (energy density is approximately 1/3 of Li-ion batteries and approximately 1/2 of nickel-hydrogen batteries)
- Low energy density results in large size and weight to provide high capacity
- Short cycle life (approximately 1/3 of Li-ion batteries)
- Hazard issues from lead, and also overcharging may cause gas evolution and explosion
- Has to be stored in charged condition to prevent electrode sulfation and deterioration

Weight is a major concern for aerospace application. However, Pb-acid batteries are overall a good choice, with ongoing research into new material development by several battery manufacturing companies, such as Concorde, Cella Energy, Saft, Sion Power, and Tadiran Batteries.

Market

The global commercial aircraft battery market is booming, and the lead-acid battery is one of the three major technologies that are used mostly in general aviation, either as a backup or main storage. Although the A&D industry is recently shifting towards Li-ion batteries, general aviation has mostly relied upon lead-acid batteries.

by
2023

The global A&D battery market could reach
$211.8M

Major players in the lead-acid battery market include:

CONCORDE ...the heart of your aircraft
MEGGiTT Securaplane
C&L Aerospace

C&L Aerospace in partnership with Securaplane Technology designed a sealed lead-acid (SLA) battery for the SAAB 340 aircraft.

References

1. https://www.giiresearch.com/report/stv508879-global-aerospace-defense-battery-market-by.html
2. https://advancedpowerproducts.com/products/concorde-aircraft-batteries/
3. https://cla.aero/saab-sla-battery/
4. https://industrynewsstock.com/3124/commercial-aircraft-battery-market-is-booming-worldwide-concorde-battery-cella-energy-saft/

FUEL CELLS

Fuel cells have a long history in the aerospace industry that started initially in space exploration by NASA in the 1970s. Fuel cells are an attractive technology due to excellent energy conversion efficiency.

Fuel Cell Chemistry & Types

A fuel cell (FC) is a device that is capable of converting chemical energy into electricity via an electrochemical reaction. The fuel is H_2 (thus they are often called hydrogen fuel cells), which reacts with O_2 (both are externally supplied) to form water, and free electrons are released in the process. These electrons run through an external circuit to produce electricity.

Fuel cell technology was first used in NASA's Gemini 5 spacecraft in 1965, and it was used in the main electric power system of the Apollo spacecraft and space shuttle due to the high efficiency and power density of the technology.

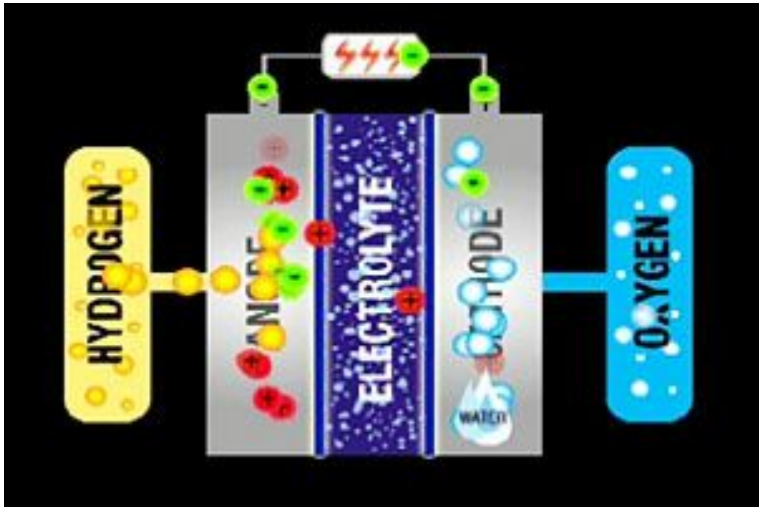


Diagram showing how a fuel cell works.
Source: *NASA*.

Depending on the electrolyte used, there are several types of fuel cells:

- Regenerative Fuel Cell (RFC)
- Proton Exchange Membrane (PEMFC)
- Direct Methanol (DMFC)
- Solid Oxide (SOFC)
- Alkaline (AFC)
- Phosphoric Acid (PAFC)
- Molten Carbonate (MCFC)

Regenerative Fuel Cell (RFC)

Unlike conventional fuel cells, regenerative fuel cells, also called reversible fuel cells, use electricity to electrolyze water while producing H_2 and O_2. In other words, RFCs store supplied energy as gaseous reactants. Hence, an RFC is a fuel cell with an electrolyzer.

Advantages:

One major advantage of a closed RFC is that it could enable the operation of a fuel cell power system **without requiring a new H_2 source infrastructure**.

Limitations:

- Extra price for reversibility
- Use of grid electricity to produce H_2 from water electrolysis, and most of the grid electricity comes from fossil fuel burning

One important aspect is that if renewable energy–based electricity is used, the RFC technology could be of great interest (for example, a solar-powered electrolyzer).

References

1. http://physics.oregonstate.edu/~hetheriw/energy/topics/doc/electrochemistry/fc/fuel_cells_green_power_lanl_p20.pdf
2. https://www.nasa.gov/centers/glenn/technology/fuel_cells.html
3. https://www.hydrogen.energy.gov/pdfs/review18/ia009_jakupca_2018_o.pdf

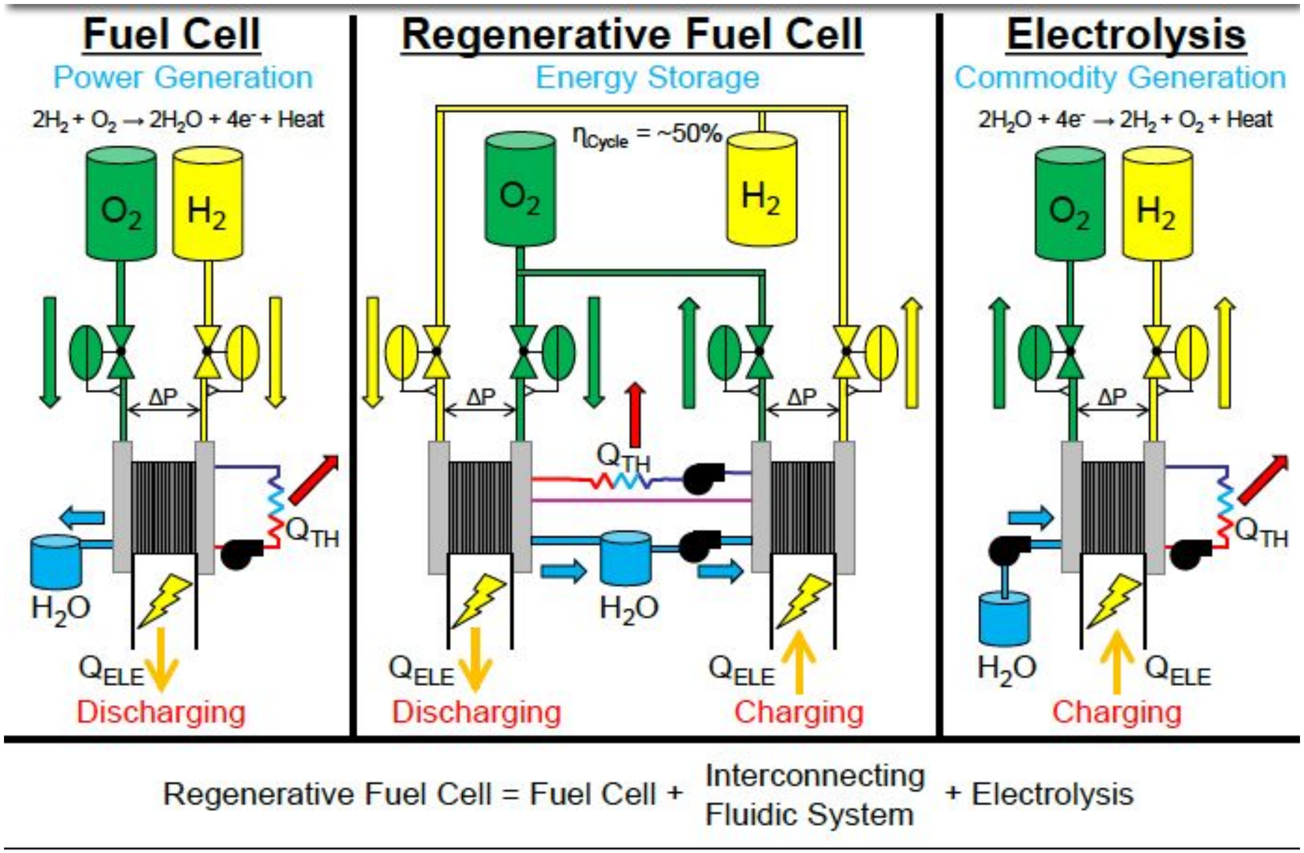
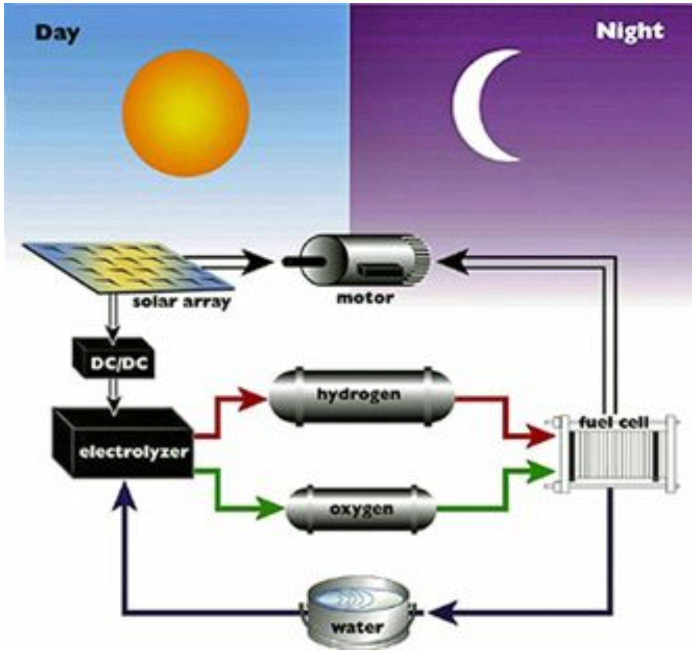


Illustration of FCs and RFCs according to NASA.

Regenerative Fuel Cell (RFC)



NASA's solar-electric Helios prototype using solar PV technology in the daytime and RFC technology at night.

References

1. https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-068-DFRC.html
2. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S2175-91462016000300249

Proton Exchange Membrane Fuel Cell (PEMFC)

PEMFC Specifics

ELECTROLYTE	OPERATING TEMPERATURE
Water-based acidic polymer	Relatively low temperatures (<100°C)

CATALYST	VARIANTS
A platinum-based catalyst is used on both electrodes	High-temperature variants use a mineral acid-based electrolyte and can operate at up to 200°C

FUELLED BY	IDEAL APPLICATION
Generally hydrogen fuelled	Electrical output can be varied, ideal for vehicles

References

1. http://www.fuelcelltoday.com/technologies/pemfc
2. https://hydrogeneurope.eu/fuel-cells

Proton Exchange Membrane Fuel Cell (PEMFC)

Advantages:

- Relatively low temperature operation is useful in the sense that these cells can reach the operating temperature from ambient conditions

Limitations:

- Uses expensive platinum-based electrodes, which raises the cost
- Additional management is required to prevent carbon monoxide poisoning of the platinum metal

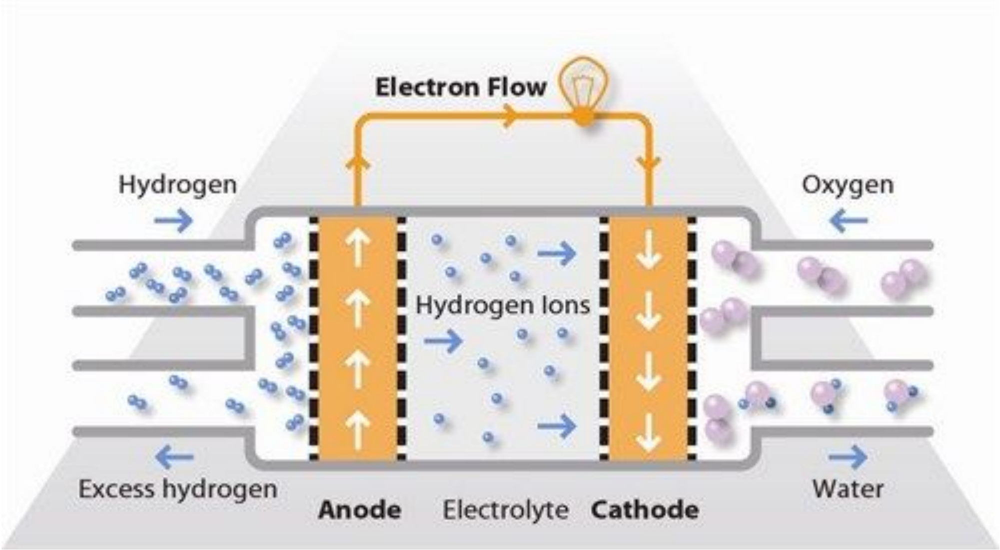


Diagram of how a PEMFC works. ***Source:*** *Fuel Cell Today*.

Direct Methanol Fuel Cell (DMFC)

DMFC Specifics

ELECTROLYTE	OPERATING TEMPERATURE
Polymer membrane (similar to PEMFC)	From 60°C to 130°C

CATALYST	VARIANTS
A platinum-ruthenium catalyst on the anode and a platinum catalyst on the cathode	n/a

FUELLED BY	IDEAL APPLICATION
Catalyst draws hydrogen atoms from liquid methanol (hence the name)	Convenient for portable power applications with outputs generally <250W

References

1. http://www.fuelcelltoday.com/technologies/pemfc
2. https://hydrogeneurope.eu/fuel-cells

Direct Methanol Fuel Cell (DMFC)

Advantages:

- Suitable for mobile electronics and portable power packs
- Since methanol is used, these could be suitable alternatives for PEMFC that require additional hydrogen storage management

Limitations:

- Methanol can pass through the membrane
- Methanol is toxic and flammable and made from nonrenewable sources, which is counterintuitive

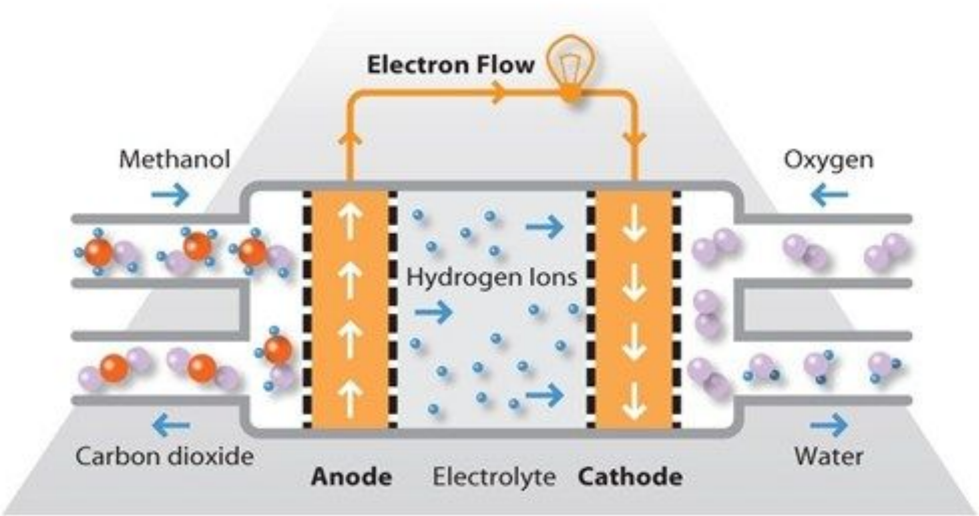


Diagram of how a DMFC works. ***Source:*** *Fuel Cell Today.*

Solid Oxide Fuel Cell (SOFC)

SOFC Specifics

ELECTROLYTE	OPERATING TEMPERATURE
Solid ceramics such as stabilized zirconium oxide	Operates at very high temperatures (800°C - 1000°C)

CATALYST	VARIANTS
A precious-metal catalyst is not necessary	Best run continuously due to the high operating temperature

FUELLED BY	IDEAL APPLICATION
Hydrocarbon fuels such as methane	Stationary power generation

References

1. http://www.fuelcelltoday.com/technologies/pemfc
2. https://www.ukessays.com/essays/engineering/advantages-and-disadvantages-of-solid-oxide-fuel-cells-engineering-essay.php

Solid Oxide Fuel Cell (SOFC)

Advantages:

- Does not require electrolyte loss maintenance and is corrosion free owing to the solid state of the electrolyte
- Expected to have 50-60% fuel-to-electricity efficiency
- Does not require an expensive platinum catalyst and addition CO management.
- High operating temperature makes this suitable for use in heat engine energy recovery devices
- Negligible pollution

Limitations:

- Vulnerable to sulfur, so the use of an adsorbent is required to eliminate sulfur
- Complex fabrication process

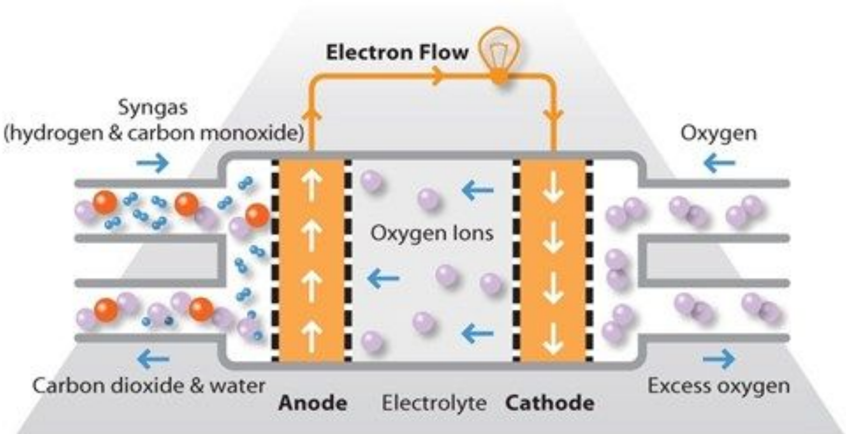


Diagram of how an SOFC works. ***Source:*** *Fuel Cell Today*.

Alkaline Fuel Cell (AFC)

AFC Specifics

ELECTROLYTE	OPERATING TEMPERATURE
Alkaline solution such as potassium hydroxide in water	Typically around 70°C

CATALYST	VARIANTS
Commonly uses a nickel catalyst	n/a

FUELLED BY	IDEAL APPLICATION
Pure hydrogen and oxygen	Space shuttles as power suppliers (2-12 kW with a voltage of 28-32 V). This type was used in NASA's Apollo program

References

1. http://www.fuelcelltoday.com/technologies/pemfc
2. https://www.ukessays.com/essays/engineering/advantages-and-disadvantages-of-solid-oxide-fuel-cells-engineering-essay.php
3. https://www.sciencedirect.com/topics/engineering/alkaline-fuel-cell

Alkaline Fuel Cell (AFC)

Advantages:

- Can use nonprecious catalysts in electrode (nickel anode and activated carbon cathode)
- Operates at a low temperature and atmospheric pressure
- Possesses high electrical efficiency (current FCs can reach 60-70%)
- Fast response and start time

Limitations:

- Sensitive to carbon dioxide present in air
- Alkali has a tendency to corrode the cell component
- Tends to have a relatively large footprint

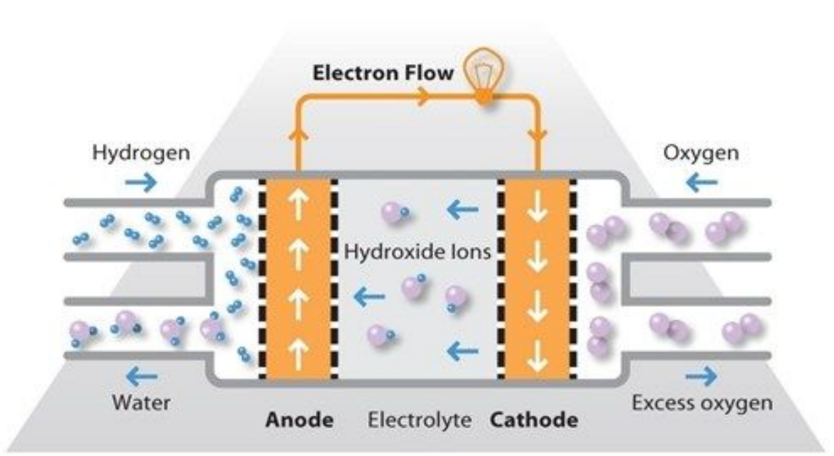


Diagram of how an AFC works. ***Source:*** *Fuel Cell Today.*

Phosphoric Acid Fuel Cell (PAFC)

PAFC Specifics

ELECTROLYTE	OPERATING TEMPERATURE
Liquid phosphoric acid in a bonded silicon-carbide matrix	Around 180°C

CATALYST	IDEAL APPLICATION
A finely dispersed platinum catalyst on carbon	Mostly used in stationary power applications (100 kW to 400 kW)

References

1. http://www.fuelcelltoday.com/technologies/pemfc
2. https://www.sciencedirect.com/topics/engineering/phosphoric-acid-fuel-cell
3. https://hydrogeneurope.eu/fuel-cells
4. https://www.slideshare.net/priyankajaiswal51/fuel-cells-76979271

Phosphoric Acid Fuel Cell (PAFC)

Advantages:

- Good tolerance to impurities such as carbon monoxide

Limitations:

- Limited by long start time and the use of existing non-renewable fuels.
- Less powerful and can not compete with other fuel cells in efficiency.
- Electrical efficiency is relatively low, but overall efficiency can be over 80% if the heat is used.

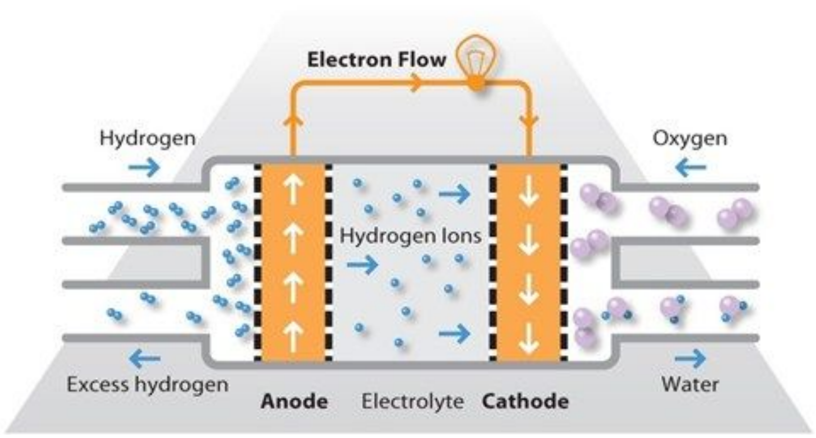


Diagram of how a PAFC works. ***Source:*** *Fuel Cell Today.*

Molten Carbonate Fuel Cell (MCFC)

MCFC Specifics

ELECTROLYTE	**OPERATING TEMPERATURE**
Mixture of molten potassium and lithium carbonate	High temperature (>650°C)
CATALYST	**VARIANTS**
Nickel	n/a
FUELLED BY	**IDEAL APPLICATION**
Natural gas, biogas, syngas, methane, or propane	Natural gas and coal–based power plants for electrical utility, industrial, and military applications

References

1. *http://www.fuelcelltoday.com/technologies/pemfc*
2. *https://hydrogeneurope.eu/fuel-cells*
3. *https://www.sciencedirect.com/topics/engineering/molten-carbonate-fuel-cell*

Molten Carbonate Fuel Cell (MCFC)

Advantages:

- Cheap construction as no expensive catalyst is required due to high temperature operation.
- Also high temperature dramatically improves reaction kinetics at the electrodes
- Decent efficiency of 60-85%
- Less sensitive to CO poisoning
- Can operate on a variety of fuels

Limitations:

- High temperature poses corrosion
- Low power density

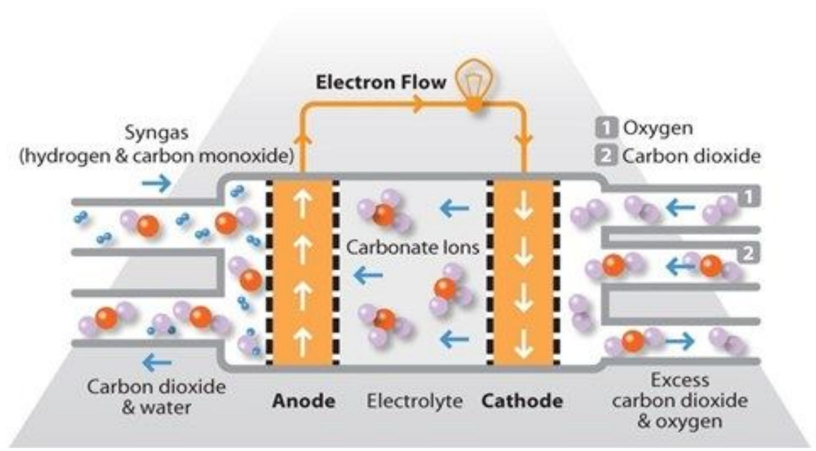


Diagram of how an MCFC works. ***Source:*** *[Fuel Cell Today](#).*

The Applications of Fuel Cells in Aerospace

A review by the US Department of Energy in 2018 summarized the applicable electrochemical chemistries for aerospace applications.

	Low Temperature		Moderate Temperature		High Temperature	
Cell Type	Proton Exchange Membrane (PEM)	Alkaline (AFC)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte	Ionic Polymer Membrane	Anionic Polymer Membrane	KOH in asbestos matrix	Phosphoric Acid in SiC structure	Liquid carbonate in $LiAlO_2$ structure	Anionic Conducting Ceramic
Operating Temperature	10 – 80 ˚ C	20 – 70 ˚ C	70 – 225 ˚ C	200 – 250 ˚ C	~650 ˚ C	600 – 1,000 ˚ C
Charge Carrier	H^+	OH^-	OH^-	H^+	CO_3^{2-}	O^{2-}
Load Slew Rate Capability	Very High (> 1k's $mA/cm^2/s$)	High (~ 1k's $mA/cm^2/s$)	High (~ 1k's $mA/cm^2/s$)	High (~ 1k's $mA/cm^2/s$)	Low to Medium (~100's $mA/cm^2/s$)	Low (~10's $mA/cm^2/s$)
Fuel	Pure H_2		Pure H_2		H_2, CO, Short Hydrocarbons	
Product Water Cavity	Oxygen	Hydrogen	Hydrogen	Oxygen	Hydrogen	

This is a summary presented in the review listing the applicable technologies ***Source:*** *hydrogen.energy.gov*.

The Applications of Fuel Cells in Aerospace

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	Low Temperature		Moderate Temperature		High Temperature	
Cell Type	Proton Exchange Membrane (PEM)	Alkaline (AFC)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Product Water	Liquid Product		Operation defines product water state		Vapor, externally separated	
CO Tolerance	< 2 ppm	< 2 ppm	< 5 ppm	< 50 ppm	Fuel	
Reformer Complexity	Very High	High	High		Minimal	
Aerospace Viability	Promising	TBR (Low TRL)	No longer in production	Not Viable	Not Viable	Promising
Terrestrial Availability	High (Increasing)	Developmental (Increasing)	N/A	Moderate (Stable)	Moderate (Increasing)	High (Increasing)
Terrestrial Markets C = Commercial I = Industrial R = Residential	Transportation, Logistics, Stationary Power (C, I, & R)	Transportation, Logistics (C)	N/A	Stationary Power (C)	Co-generation and Stationary Power (C & I)	Co-generation and Stationary Power (C, I, & R)

This is a summary presented in the review listing the applicable technologies ***Source:*** *hydrogen.energy.gov*.

The Applications of Fuel Cells in Aerospace

A review by the US Department of Energy in 2018 described the potential of fuel cells, and particularly of regenerative fuel cells (RFC) in energy storage application related to space exploration.

	Component	Aerospace TRL Level	Portability of Terrestrial Technology to Aerospace Applications	Remaining Technical Challenge
Electrolyzer Technology	Electrochemistry	9	High	
	Materials	5+	High	High Pressure, Mass
	Seals	5+	High	High Pressure, Mass
	Gas Management	5+	Moderate	High Pressure, Mass
Fuel Cell Technology	Flow Fields	5+	High	
	Bipolar Plates	5+	Moderate	O_2 vs air
	Materials	5+	Moderate	O_2 vs air
	Electrochemistry	5+	Low	O_2 vs air, Performance
	Water Management	5+	Low	Flow Rate, μg

Another summary in the same review showing the technology readiness level (TRL) of fuel cells in aerospace sector

A review by the US Department of Energy in 2018 described the potential of fuel cells, and particularly of regenerative fuel cells (RFC) in energy storage application related to space exploration.

	Component	Aerospace TRL Level	Portability of Terrestrial Technology to Aerospace Applications	Remaining Technical Challenge
Reactant Storage and Management	Fluidic Components	8+	Moderate	O_2 vs air
	Procedures	5	Moderate	O_2 vs air, Performance
	Thermal	8+	Moderate	μg, Vacuum
	Materials	8+	Low	O_2 vs air
	Water Management	5+	Low	O_2 vs air, μg
FC / EZ / RFC System Avionics	Hardware/PCB	8+	High	
	Power Management	8+	High	
	Structure	8+	High	
	Thermal	8+	High	
	Instrumentation	8+	Moderate	

Another summary in the same review showing the technology readiness level (TRL) of fuel cells in aerospace sector

Global Market

The global aircraft fuel cell market will grow by a

CAGR of 6%

between **2017-2021**

The global fuel cell market for **military UAV** applications is growing at a

CAGR of 14%

Major players in the **global aircraft** fuel cell market include:

- ZeroAvia
- Airbus
- Ballard Power Systems
- Boeing
- Hydrogenics
- Nuvera Fuel Cells
- Serenergy

Major players in the **global military UAV** fuel cell market include:

- EnergyOR technology
- Horizon Fuel Cell Technologies
- MicroMultiCopter Aero Technology
- Protonex
- Ultra electronics

References

1. https://www.mdpi.com/1996-1073/10/12/1937/htm
2. https://www.technavio.com/report/global-lithium-sulfur-battery-market-analysis-share-2018

HES Energy Systems is a leading developer and supplier of high-performance ultra-light fuel cells and hydrogen energy storage systems for aerospace, military, and commercial applications. HES has developed an ultra-light electrical energy storage alternative to batteries for long-duration electric-powered flight called Aeropak G. **AEROPAK G can be used to power small-to-medium size commercial UAVs.**

The Aeropak G battery. ***Source:*** *Solar Impulse*.

References

1. http://uavpropulsiontech.com/hes-energy-systems/

Key Players

Hydrogenics is a leading manufacturer of aircraft-grade fuel cells. The first emissions-free planes were designed by scientists at the German Aerospace Center in partnerships with Hydrogenics. The technology developed is HY4, and these plane are driven by hydrogen fuel cells. A low-temperature **PEMFC** operates below 70°C with a power capacity of 21 kWh. This aircraft is operated by the DLR spinoff H2FLY.

The HyPM fuel cells of Hydrogenics are promising FCs for defense, aerospace, and marine applications.

The world's first emission-free, 4-seater electric plane.
Courtesy DLR/Jean-Marie Urlacher.

References

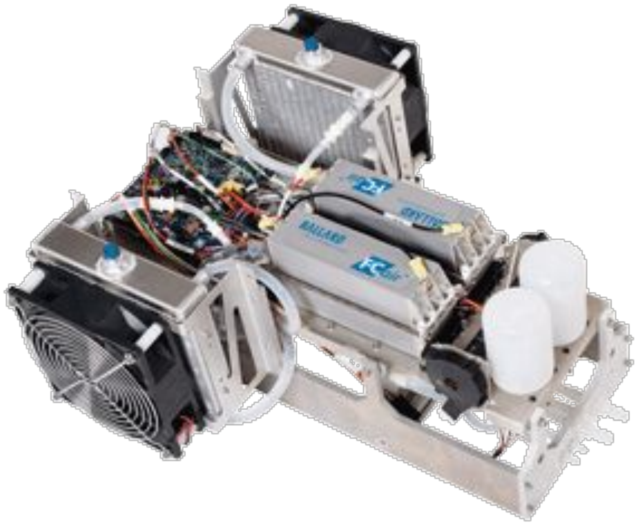
1. https://edition.cnn.com/travel/article/hy4-fuel-cell-plane/index.html
2. https://www.ingenieroemprendedor.com/english/blog/hydrogen-powered-flight/
3. https://www.hydrogenics.com/hydrogen-products-solutions/fuel-cell-power-systems/defence-aerospace-and-security/

Key Players

Ballard is another leading manufacturer of fuel cells for UAVs.

Ballard's FCair provides a complete fuel cell solution for commercial UAVs. In 2018, Ballard signed an MOU with ABB, a technology leader in electrification products, for the development of PEMFC systems for powering **marine applications**.

"Ballard offers 600 and 1,200 watt fuel cell systems appropriate for UAV platforms in the 20 to 55 pound size range."



Ballard's fuel cell for UAVs. ***Source:*** [Ballard]

References

1. https://www.ballard.com/markets/uav
2. https://www.ballard.com/about-ballard/newsroom/news-releases/2018/06/27/ballard-signs-mou-with-abb-for-development-of-fuel-cell-systems-to-power-marine-applications

Key Players

Boeing holds a strong reputation of developing energy storage technologies for civil aviation, defense, and aerospace. In 2016, Boeing delivered a **reversible zero-emission SOFC** energy storage system to the US Navy.

Boeing's reversible solid oxide fuel cell system in operation in Huntington Beach, CA. ***Photo credit:*** *Boeing.*

References

1. https://boeing.mediaroom.com/2016-02-08-Boeing-Delivers-Reversible-Fuel-Cell-based-Energy-Storage-System-to-U-S-Navy

ZeroAvia, in partnership with Intelligent Energy, is running a HyFlyer project to demonstrate H2 fuel cell powertrain technology for aviation. The project is funded £2.7 million (USD 3.3 million) by the UK government. The company claims the flight is the world's largest zero-emission aircraft flying without fossil fuel. **ZeroAvia is planning to deploy zero-emission H2-powered aircrafts by 2022.**

ZeroAvia's HyFlyer powertrain.

References

1. https://www.zeroavia.com/
2. https://www.flightglobal.com/news/articles/uk-backs-hydrogen-fuel-cell-piper-demo-flight-in-ork-461003/
3. https://www.h2-view.com/story/zeroavia-to-deploy-hydrogen-powered-zero-emission-planes-by-2022/

Recent Developments

A project at the University of Illinois is developing a cryogenic H2 fuel cell system, and this project is being backed by NASA.

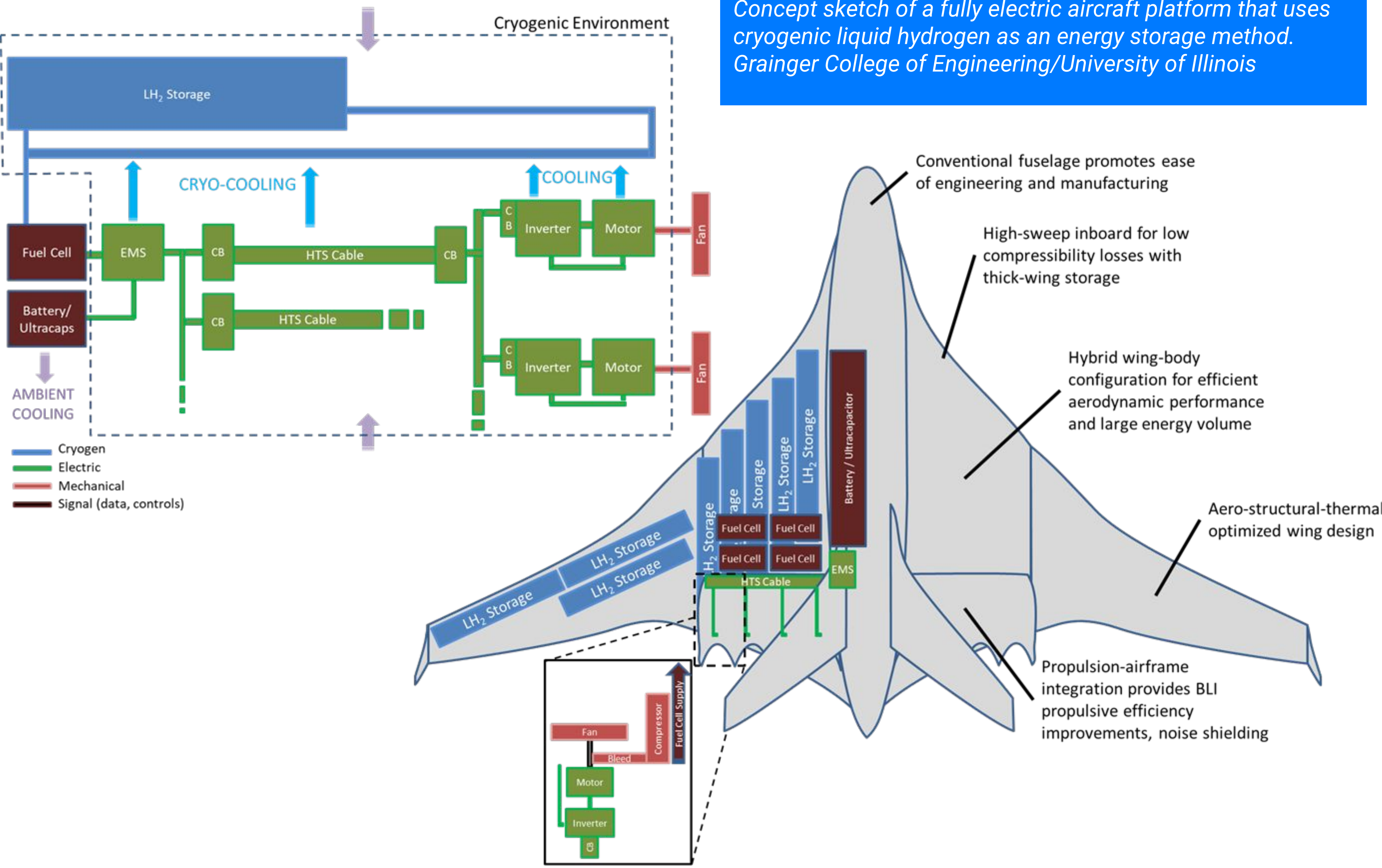
The Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA) will investigate the technology for replacing fossil fuel technologies.

The CHEETA project is a consortium of eight institutions that include the Air Force Research Laboratory, Boeing Research and Technology, General Electric Global Research, Ohio State University, Massachusetts Institute of Technology, the University of Arkansas, the University of Dayton Research Institute, and Rensselaer Polytechnic Institute.

A concept sketch of a fully electric aircraft platform that uses cryogenic liquid hydrogen as an energy storage method is seen in the next slide.

References

1. https://newatlas.com/nasa-cheeta-funding-aircraft-fuel-cell/59725/



Concept sketch of a fully electric aircraft platform that uses cryogenic liquid hydrogen as an energy storage method. Grainger College of Engineering/University of Illinois

Lithium-Ion Batteries (LIB)

The LIB is the fastest growing battery technology, and it is an ideal energy storage system where high energy density and light weight are of prime importance. This makes LIBs highly desirable in the A&D industry.

Lithium-Ion Battery Chemistry

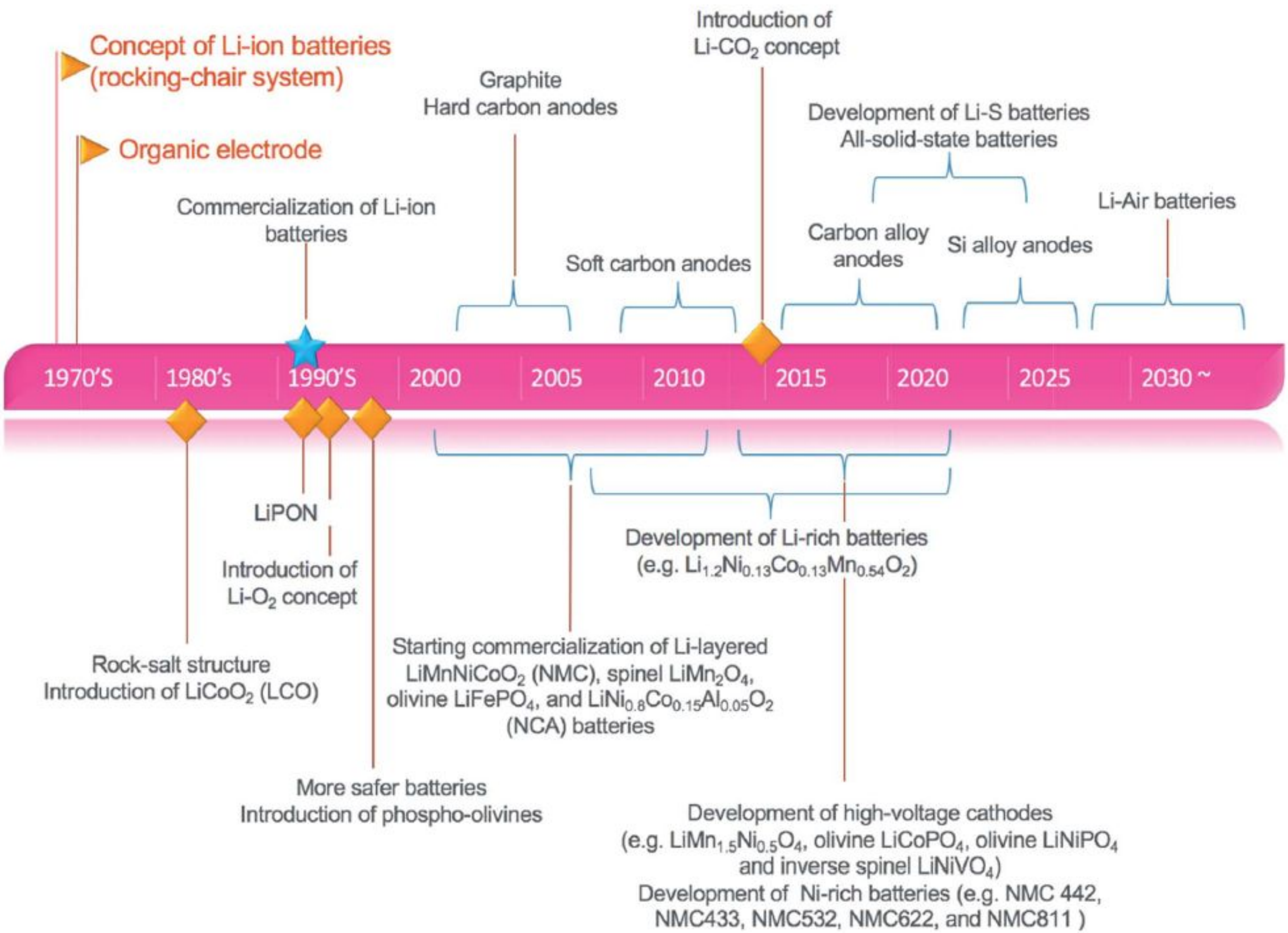
A lithium-ion battery consists of a cathode made of transition metal oxides (such as $LiCoO_4$ and $LiMn_2O_4$, $LiFePO_4$, $LiNiO_2$), where the lithium is intercalated in the oxide structure.

While a free Li atom is reactive and has an inherent tendency to lose one electron, it is stable as an ion (Li^+) in the oxides. The anode is made of graphite sheets that store the Li ions during the charging process.

There is a liquid electrolyte for the transportation of Li ions, and the two electrodes are separated by a microporous membrane that allows only Li ions to pass while preventing electron flow.

When a device is in use (discharge), the Li ions are released from the anode, causing the flow of electrons through the circuit and therefore creating current. The reverse occurs during the battery charging process, when the device is plugged into an electric outlet.

LIB Evolution. ***Source:*** *J. Mater. Chem. A, 2019,7, 2942-2964. DOI: [10.1039/C8TA10513H](10.1039/C8TA10513H)*



Advantages

LIBs have been commercially used since 1991. With the ongoing development of safer and more efficient battery components such as new electrolytes and environmentally benign materials, it could be the future of A&D energy storage.

The advantages are:

- Reliability, durability, and performance
- Lithium is the lightest metal, which enables lighter battery design compared to heavier batteries like Ni-Cd or lead-acid. LIBs are half the mass of Ni-Cd and offer doubly enhanced performance.
- High energy density (currently 150-200 Wh/kg) and high power density (W/kg). Typical energy density is twice that of Ni-Cd batteries.
- LIBs operate nominally at wide temperature ranges (from -40℃ to +60℃), which is desirable when aerospace applications are considered.
- A long shelf life (low discharge rate) and high number of life cycles (500-1000)
- No maintenance required

References

1. https://batteryuniversity.com/learn/archive/whats_the_best_battery

Image showing the LIB BOEING 787 Dreamliner, which has two power systems: auxiliary power unit (APU) and main battery. ***Source:*** *Boeing*.

Limitations

Limitations include:

- **Require protection circuits** for maintaining a safe operating limit. The protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. However, incorporation of a modern integrated battery management system can circumvent this issue.
- **Sensitive to high temperature**. The cathode materials (metal oxides) are thermally unstable at elevated temperatures and releases oxygen, which can trigger thermal runaway and explosion.
- LIBs need to be stored with **at least 40-50% charge** because they suffer from aging, which can cause permanent damage.
- **High cost**, as LIBs are ~40% more expensive than NiCd. Also, cobalt mining is an issue.
- Importantly, larger shipment of LIBs is also a potential **regulatory issue**.

References

1. https://www.electronics-notes.com/articles/electronic_components/battery-technology/li-ion-lithium-ion-advantages-disadvantages.php
2. https://www.cei.washington.edu/education/science-of-solar/battery-technology/
3. https://batteryuniversity.com/learn/archive/whats_the_best_battery
4. https://www.frontiersin.org/articles/10.3389/fenrg.2019.00071/full

Advancements

A technology that can prevent LIBs from explosion and thermal runaway:

- This was designed by a joint operation between KULR Technology and NASA. The technology consists of a thermal runaway shield (TRS) called HYDRA TRS that is integrated with the cell pack. According to KULR Technology, "*HYDRA absorbs heat and shields battery pack cells from entering into thermal runaway propagation*."
- KULR Technologies recently announced that it has secured a patent for this technology

LIBs are still the preferred options for energy storage applications in A&D.

References

1. https://www.globenewswire.com/news-release/2019/01/07/1681416/0/en/KULR-Technology-Secures-Patent-for-Thermal-Runaway-Shield-TRS-Proven-to-Minimize-Risk-of-Fires-and-Explosions-in-Lithium-Ion-Battery-Packs.html
2. *https://www.globenewswire.com/Tracker?data=hlwvwu_7doWJujNRg-cEsbSVbgxQaEzkTKYg8nI279g5_pkykPKRBJHsf4HtVDzbhwkiAF7437Pbp7t-c_sMYNn-yEWDnlSmwTchTS6oxI8HUQpQHTEcD-9IleINXFrf*

Global Market and Key Players

LIBs in A&D are being applied by three types of aircraft makers:

- Commercial and private aircraft makers (such as Boeing, Gulfstream, Cessna)
- Military and defense vehicles, weapons, and satellite developers (the US Air Force and US Navy)
- Government space exploration agencies (NASA, the European Space Agency, the Japanese Aerospace Exploration Agency, the Russian Federal Space Agency, and the Canadian Space Agency)

According to Market Research Engine, the LIB market is expected to exceed more than **USD 92B by 2024 at a CAGR of 16.5%**, and these numbers include consumer electronics, automobile, and aerospace applications.

Leading manufacturers of LIBs are:

- EaglePicher
- RELiON
- Cella Energy
- Saft
- True Blue Power
- Sion Power

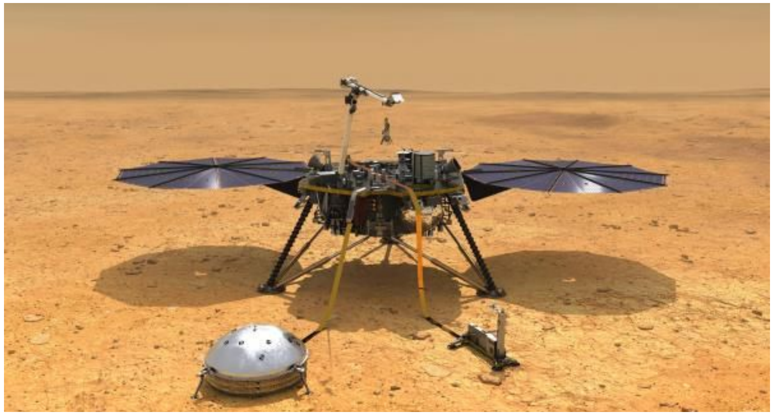


Image of NASA's Insight lander mission to Mars, which is powered by two of EaglePicher's 8-cell, 28 volt, 30 amp-hour batteries. ***Source:*** *EaglePicher*.

References

1. https://www.marketresearchengine.com/lithium-ion-battery-market1

RELiON develops innovative LIBs for aircraft with enhanced safety features. To prevent oxygen generation at the cathode (which is the main cause of fire hazard), they integrated lithium iron phosphate ($LiFePO_4$). This particular battery is 50% lighter than the previous generation and possesses high energy density and superior lifespan.

The image below is a Deep Cycle $LiFePO_4$ battery from RELiON. This technology is used in backup power, marine, RV, and solar applications.

References

1. https://relionbattery.com/products/lithium/application/marine

Key Players

True Blue Power develops innovative LIB technologies for the global aviation and marine industries.

For example, their nanophosphate lithium-ion technology offers stable chemistry, faster charging, consistent output, enhanced safety, excellent cycle life, and superior cost performance.

Images of True Blue Power Li-ion batteries. **Source:** True Blue Power

References

1. https://www.truebluepowerusa.com/nanophosphate-lithium-ion-tech/

Key Players

Saft is another leading battery supplier with a rich history of development in civil aviation, aeronautic applications, and the defense industry. Their Li-ion battery systems comply with the highest standards, including DO-254, DO-178B, and DO-311, and they are adapted to more-electric aircraft (MEA).

Saft has produced close to 700 Li-ion batteries that are currently being used by 13 commercial airlines, including Qatar Airways, Finnair, and Asiana. Li-ion batteries are also in use on close to 200 military aircrafts.

Saft prismatic MP and cylindrical VL rechargeable Li-ion batteries with unrivalled nominal capacities:

- Nominal voltage: 3.6 V - 3.75 V
- Energy density: Up to 385 Wh/l and 180 Wh/kg
- Power range: Up to 1 kW/kg
- Capacity range: 2.6 to 7.0 Ah
- Operating temperature: -20°C to +60°C for charge, -50°C to +60°C for discharge

References

1. https://www.saftbatteries.com/media-resources/our-stories/high-flyer-li-ion
2. https://www.saftbatteries.com/products-solutions/products/mp-vl-batteries-launchers

Sion Power

Sion Power is another major player in LIB development. This picture shows a battery prototype based on Licerion battery technology, which can provide an unparalleled specific energy of 500 Wh/kg, an energy density of 1000 Wh/L, and 450 cycles. This technology can offer:

- Lighter batteries
- High energy density
- Application diversity
- A reliable auxiliary power unit
- Custom design

CEO Tracy Kelley claims that once the commercialization of the prototype is complete, Sion Power can be the next-generation leader in supplying high-efficiency rechargeable LIBs.

*Image of the Licerion high energy density battery based on Li-ion. **Source:** Sion Power.*

References

1. https://sionpower.com/2018/sion-powers-momentum-continues-toward-commercialization-of-its-licerion-lithium-metal-battery/

Future Outlook

Lithium-ion technology has replaced more than 37% of all conventional battery applications and is a **USD 29.86 billion** market. Offering 40–75% weight savings, **lithium-ion technology will soon dominate the aviation and marine industries**. Airbus, Bell Helicopter, Boeing, Leonardo, Lockheed Martin, Northrop Grumman, Robinson Helicopter Company, Sikorsky, and Textron are committed to utilizing this game-changing technology.

Extensive development of lithium-rich cathode materials is currently ongoing due to the promisingly higher theoretical capacity and high operation voltage.

A recent review article in *Frontiers in Energy Research* describes the current challenges and recent progress in the development of safer anode, cathode, and electrolyte materials. The two major aspects that are most important for designing high-efficiency batteries are the design of cheaper as well as greener electrode materials. In this regard, **Li-S and Li-air (Li-O_2) batteries could be the future of aerospace energy storage technology**.

A report by *C&EN* news stated that *"Today's best Li-ion batteries have a specific energy—or energy per unit mass—of around 250 W h/kg, which falls short of the 800 W h/kg scientists say is needed to keep a Boeing 737–sized aircraft in the air for a 1,111 km journey (about the distance from Chicago to New York City)."*

References

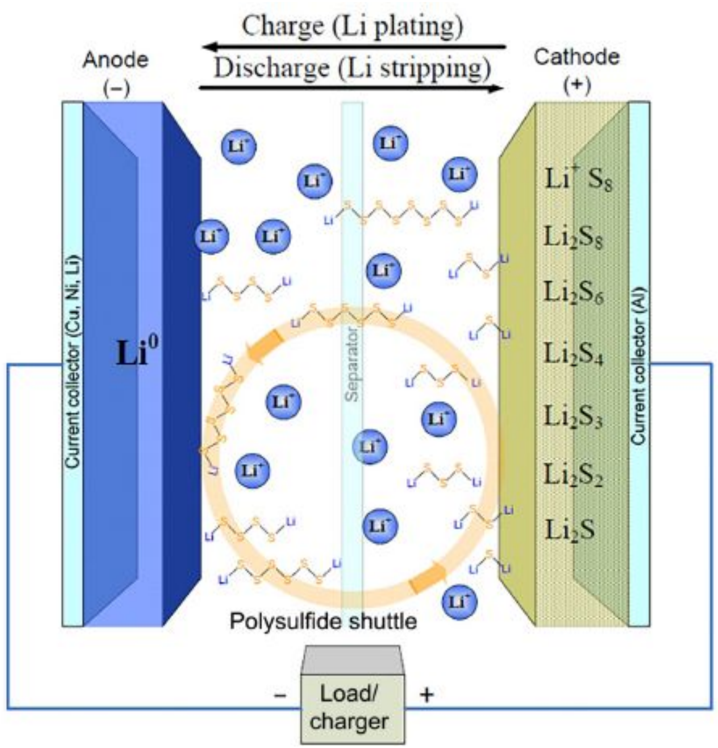
1. https://www.truebluepowerusa.com/pdfs/Brochure_Lithium-ionFAQ_July16.pdf
2. https://cen.acs.org/energy/energy-storage-/Batteries-need-boost-fly-friendly/97/i42
3. https://www.frontiersin.org/articles/10.3389/fenrg.2019.00071/full

Lithium-Sulfur (Li-S) Batteries

Despite the limitations, there has been extensive R&D in producing the Li-S battery due to its recyclability, superior energy density, and nontoxic components.

Technical Description:

- A typical cell consists of a sulfur cathode with a conducting carbon binder, which are coated, on an aluminum current collector. The anode is metallic Li
- There is a separator soaked with liquid organic electrolytes (organic carbonates)
- Discharge process involves Li stripping from the anode and electrochemical reduction of S8 to Li_2S via different polysulfide species formation
- During charging, the resulting Li ions are deposited at the anode (Li plating) as Li metal, and the low-order polysulfide species are oxidized back to S8.



Current usable Li-S battery has reached energy density of 500 Wh/kg.

References

1. https://www.sciencedirect.com/science/article/pii/B9780128163924000025

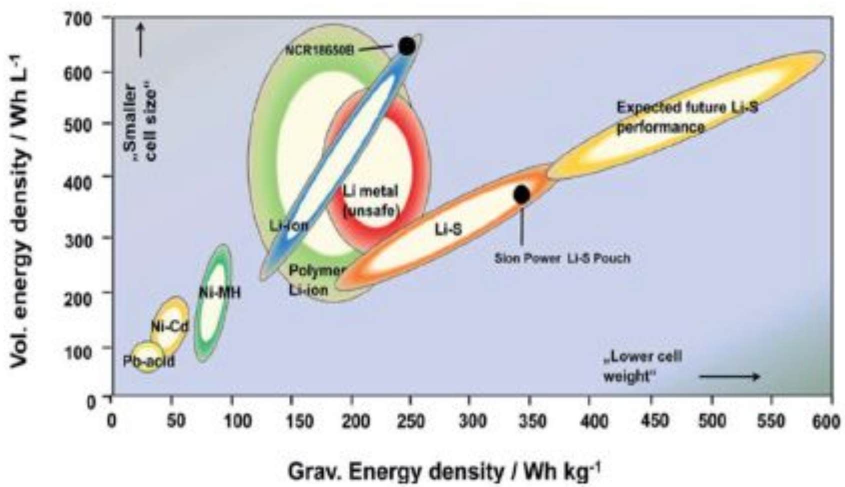
Advantages

Unlike the Co and Ni in LIBs, sulfur is inexpensive, lighter, and environmentally benign. Therefore, Li-S is a competitive technology for the future.

Li-S has superior theoretical capacity of 1675 mA h g^{-1}, which is 5 times more than existing LIB technologies.

It has promisingly high theoretical energy density (~2600 Wh/kg), as shown in the adjacent figure reported in a review article in the *Journal of Materials Chemistry*.

Also, sulfur being a lighter element enables the design of a much smaller battery than an LIB of the same capacity.



References

1. https://pubs.rsc.org/en/content/articlelanding/2018/ta/c8ta01483c#!divAbstract
2. https://www.sciencedirect.com/topics/engineering/li-s-battery
3. https://pubs.rsc.org/en/content/articlelanding/2019/ta/c8ta10513h#!divAbstract

Limitations

The major disadvantages of the Li-S cell are associated with the sulfur cathode, Li anode, electrolyte, and inherent self-discharge.

Polysulfide Shuttle Effect: The discharge process causes formation of various polysulfide (PS, Li_2Sn) species via reduction of elemental S8. These PS species are highly soluble in the electrolyte and can diffuse to the Li anode surface.

During charging, these PSs can either be reduced or react with Li to form short-chain PSs. These short chain PSs diffuse back to the cathode and get oxidized to long-chain PSs.

This parasitic phenomenon results in severe damages such as:

- Low Coulombic efficiency
- Li anode corrosion
- Sulfur loss from cathode via dissolution
- Significant self-discharge of the cell

Cathode Problems: Due to repeated sulfur reduction to PSs, dissolution, and precipitation of the sulfur active material, the cathode degrades over prolonged cycles, with significant volume reduction.

The resulting insoluble PS species (Li_2Sn) accumulate on the cathode upon full discharge. These species are insulators and therefore result in cathode passivation and capacity fading.

Dissolution of active material also results in void formation in the carbon binder, which leads to loss of the porous structure, and the capacity fades.

Limitations

Anode Problems: Apart from Li corrosion due to the shuttle effect, Li metal is highly reactive to the electrolyte.

Also, a research team at PNNL studied the reason behind Li-S cell capacity fading, and they found that the parasitic reaction between electrolyte and PS species with the Li anode lead to the formation of solid-electrolyte interface (SEI) layers, the main cause of capacity fading.

Electrolyte Problems: The ideal electrolyte for Li-S batteries should have the following features:

- High ionic conductivity
- Moderate PS solubility
- Low viscosity
- Wide electrochemical window
- Good chemical stability against Li
- Reliable safety

However, the existing electrolytes cannot fulfill all of these. The prime importance is given to the development of electrolytes that do not dissolve the PS species, and $LiN(SO_2CF_3)_2$ and $LiSO_3CF_3$ appear to be great choices.

References

1. https://pubs.acs.org/doi/abs/10.1021/acs.chemmater.7b00374
2. https://www.sciencedirect.com/science/article/pii/B9781782420903000055
3. http://www.tawaki-battery.com/li-s-batteries/
4. https://pubs.rsc.org/en/content/articlelanding/2015/ee/c5ee01388g#!divAbstract
5. https://www.sciencedirect.com/science/article/pii/B9781782420903000055

Global Market

Despite the limitations, there has been extensive R&D in producing the Li-S battery due to its recyclability, superior energy density, and nontoxic components. In the A&D industry, where weight is a major concern, Li-S battery technology is a supreme choice in the current battery market.

by **2022**

The Li-S battery market size will grow by **$698.8M**

With a CAGR of over **71%**

The US is believed to have the highest growth

48.5% Li-S battery market share

The aviation segment is predicted to attain the highest growth among all other applications.

References

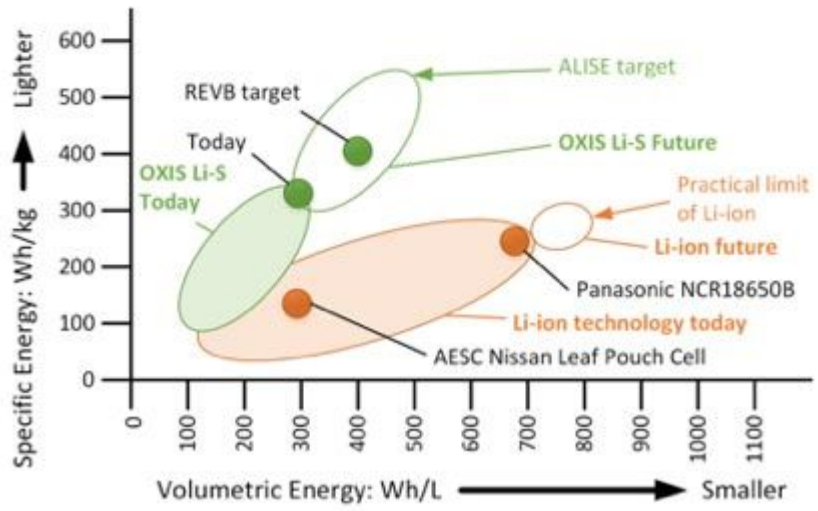
1. https://www.mdpi.com/1996-1073/10/12/1937/htm
2. https://www.technavio.com/report/global-lithium-sulfur-battery-market-analysis-share-2018

Oxis Energy

Oxis Energy is a leading company in the manufacturing of the Li-S battery, with 186 granted patents, 97 patents pending approval, and commercialized cells. Oxis Energy was established in 2000 and is based at Culham Science Centre near Oxford in the UK. They are designing unique Li-S cells while addressing safety and performance fade issues by developing a ceramic passivation layer and a nonflammable liquid electrolyte.

The key features of their technology are:

- Lightweight (50% lighter than LIBs)
- Safe (uses a passivation layer to protect the anode and hgh-flashpoint electrolyte)
- Improved cycle life
- High tolerance level
- Maintenance free
- Cost effective
- Environmentally friendly



Source: *Oxis Energy*.

Oxis cells have successfully passed a series of abuse tests, including short circuit, overcharging, and nail and bullet penetration. Their cells also have 100% depth-of-discharge (DoD) and remain safe during overcharge. The key markets include aviation, defense, aeronautical, and marine.

Key Players

Recent Developments:

- **Oxis**, Hyperdrive Innovation, and the British Antarctic Survey (BAS) have completed the Ultra Low Temperature Battery (ULTB) project, developing an Li-S cell that can operate at -60°C.

"Oxis expects to achieve 500 Wh/kg by early 2020. Our Li-S cells and battery systems are ideally suited for aviation."

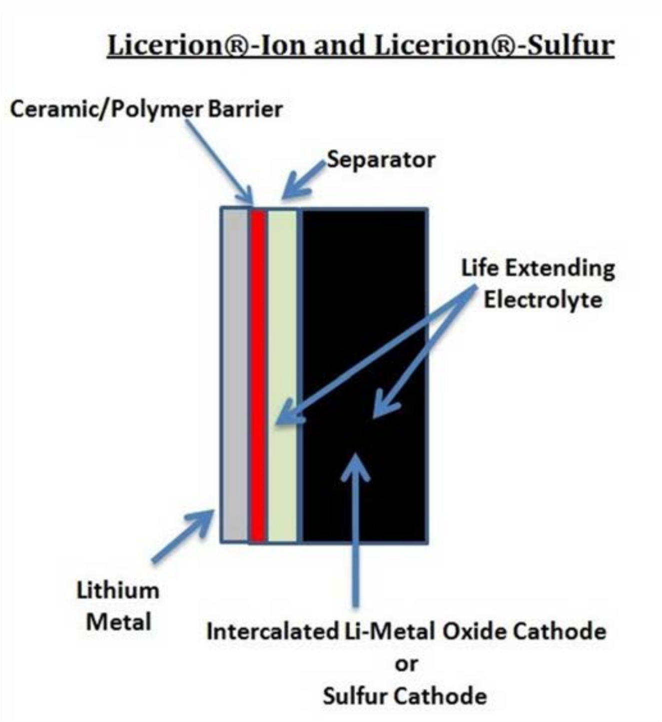
- CEO of Oxis Energy

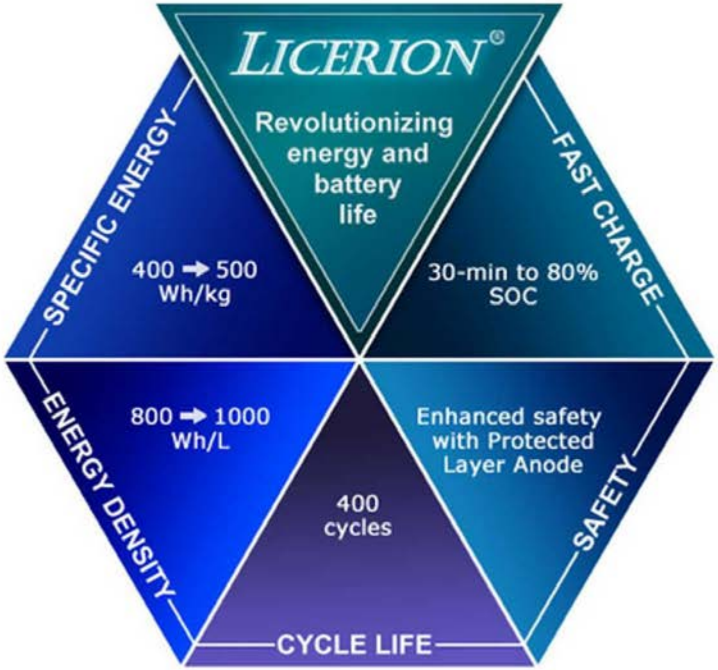
- Oxis is developing ultralight batteries for high-altitude long-endurance (HALE) unmanned aerial vehicle applications. This HALE tech is also suitable for space sectors.
- In collaboration with NASA's Jet Propulsion Laboratory, Oxis is currently developing a 425-Wh/kg cell and also targeting ultralow temperature operation for applications in space.
- Oxis Energy, Steatite, MSubs, and the National Oceanography Centre (NOC) have developed a pressure tolerant Li-S battery that is capable of powering marine autonomous vehicles to depths of over 6,000 metres.
- A recent major collaboration between Oxis Energy and Bye Aerospace is targeting all-electric general aviation aircrafts. The aim of this project is to achieve a 50-100% increase in flight time from a single charge on future Bye Aerospace eFlyers.

References

1. https://oxisenergy.com/battery-that-will-operate-at-minus-80-degrees-in-the-offing/
2. https://oxisenergy.com/applications/
3. https://www.greencarcongress.com/2018/10/20181003-oxis.html
4. https://oxisenergy.com/mission-accomplished-depths-6000-metres/
5. https://byeaerospace.com/bye-aerospace-oxis-energy-begin-collaboration-to-increase-the-endurance-of-future-bye-aerospace-eaircraft/

Although the **Sion Power** is currently focused on the Licerion technology, this company has also achieved Li-S cells with energy densities of up to 400 Wh/kg and 700 Wh/L, while the cycle life remains to be improved.

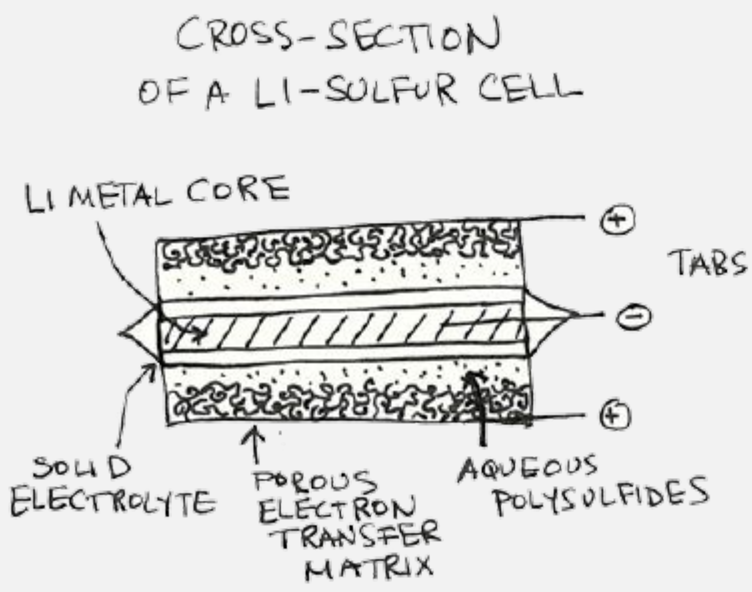




Source: Inside Evs.

Unlike the conventional nonaqueous electrolyte and unprotected Li anode, **PolyPlus**, another leading Li-S battery developer, is working on Li-S cells with a protected lithium electrode (PLE) and inexpensive water-based electrolytes.

They are developing rechargeable Li-S cells with 400 Wh/kg and 600 Wh/L that can cycle over 100 times without potential capacity loss.



Source: *PolyPlus*.

Lithium-Air ($Li-O_2$) Batteries

The concept of the Li-air battery was first introduced in 1996, and it remains an emerging technology. This could be the disruptive technology of the future.

Li-Air Battery Chemistry

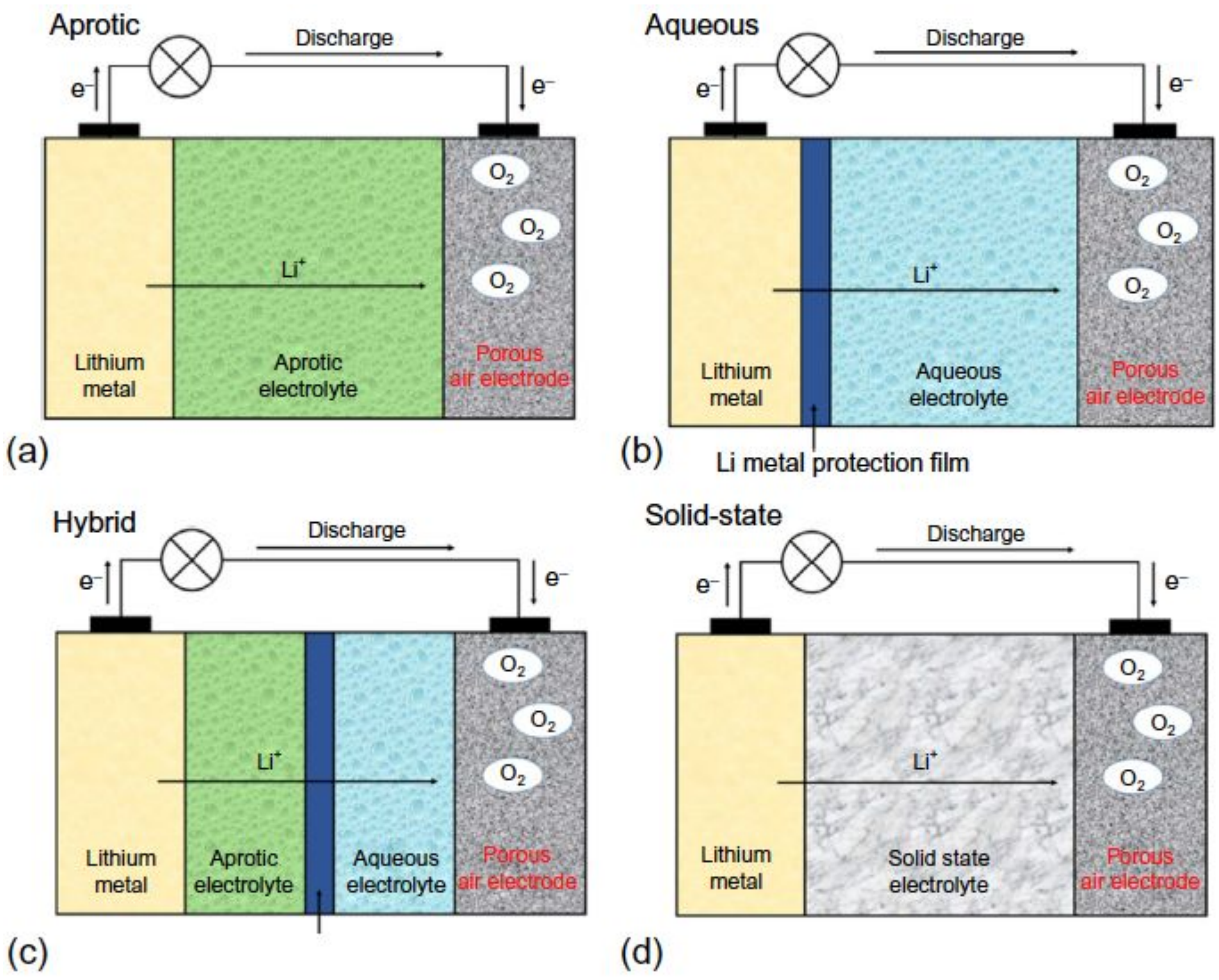
An Li-air cell consists of an anode made of Lithium metal and a cathode made of porous carbon matrix with a catalyst. The electrolyte is either aqueous or nonaqueous. In fact, there are four types of cells, depending on the battery: Li-O_2 aprotic, Li-O_2 aqueous, Li-O_2 mixed, and Li-O_2 all solid.

During discharge, the Li ions travel toward the cathode, where O_2 is reduced and reacts with Li ions to produce Li_2O_2. While charging, the reverse reaction occurs and O_2 is released.

Unlike the other LIBs, where the reacting materials are intercalated into the electrodes, Li-air batteries are open and atmospheric O_2 is used. Therefore, Li-air batteries can provide an extremely high energy density of ~3500 Wh/kg (practical energy density can reach up to 1700 Wh/kg), which makes them a highly attractive energy storage technology.

References

1. https://www.sciencedirect.com/science/article/pii/B978178242013200011X
2. https://pubs.rsc.org/en/content/articlelanding/2019/ta/c8ta10513h#!divAbstract
3. https://www.forbes.com/sites/williampentland/2015/10/31/lithium-air-battery-breakthrough-may-mean-game-over-for-gasoline/#45f2bbb16638
4. https://www.greencarcongress.com/2014/05/20140505-amine.html

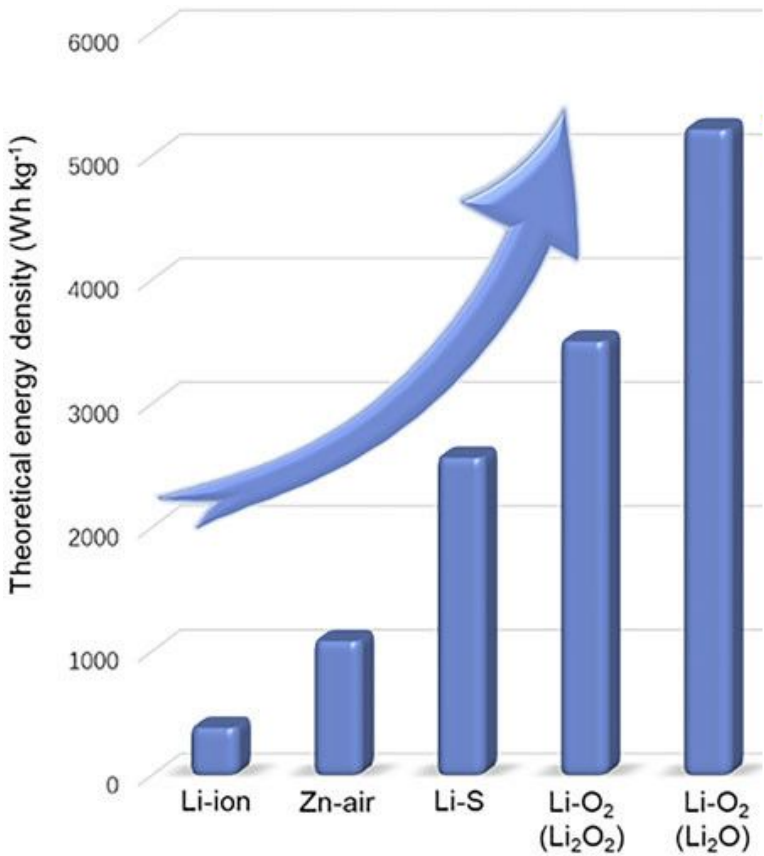


Images of 4 types of $Li\text{-}O_2$ batteries, depending on the electrolyte. The aprotic (nonaqueous) system is most studied. ***Credit:*** *ACS, Lu et al.*

Although Li-air battery development is in its early stages, this technology could be disruptive in the near future:

- As of 2016, Li-air batteries possessed nearly 5-15 times the specific energy and 3 times the power as compared to traditional LIBs.
- $Li-O_2$ batteries have the potential to store over 40 times the charge relative to LIBs of same weight.

Therefore, this technology could offer ultralight batteries with high energy density, which could be highly useful in the aerospace and defense industry.



Theoretical energy densities of different rechargeable batteries showing the extremely high value of $Li-O_2$ batteries. ***Source:*** *APL Materials.*

There are several critical barriers for Li-O_2 batteries to become practical, which are:

- Low energy efficiency
- Short cycle life
- Poor rate capability

The major cause of the shortcomings is associated with the cell components:

- Sluggish O_2 reduction reaction (ORR) at the cathode
- Sluggish reverse reaction-O_2 evolution reaction (OER)
- Slow mass transport
- Li anode degradation due to the half-open cell structure
- Electrolyte limitations due to unwanted discharge product formation

Key requirements for cathode design:

- High catalytic activity (to facilitate OER/ORR)
- High electronic conductivity (to promote fast electrochemical reaction)
- High porosity (to diffuse the discharge product, to promote fast mass transportation, and to have sufficient electrolyte infiltration)

3 types of cathode materials are extensively studied

- **CARBON**
- **PRECIOUS METALS**
- **NON-PRECIOUS METALS**

Challenges

Three types of cathode materials are extensively studied:

- **Carbon-based cathode:** Light weight, low cost, high conductivity, large specific surface area, and tunable pore structure. Poor cycling ability.
- **Precious metal–based cathode:** Expensive and toxic choice but efficient for facilitating ORR and OER. Also effective for reducing charge overpotential. Poor conductivity and aggregation issues.
- **Non-precious metal–based cathode:** Better option that precious metal. Earth-abundant and nontoxic metals are a good choice. Bench scale experiments showed excellent electrochemical performance and long cycle life.

Challenges with anode:

- The half-open configuration of Li-O_2 cell poses additional challenge to the reactive Li metal. The reaction between Li and O_2 reduces the Coulombic efficiency and cycling ability.
- Li dendrite formation
- Unstable solid-electrolyte-interface (SEI) film formation
- Infinite volume change of the anode

However, creating protective films around the anode could solve the issues:

- Stable SEI films by using electrolyte additives (e.g., LiNO3)
- Adding extra membrane is another popular way
- Replacing Li anode with other materials (such as Si)

Challenges

Electrolyte Incompatibility:

Electrolytes react with Li ions to form discharge products that cannot be recycled reversibly, which results in capacity fading. For example, organic carbonate–based solvents with LiPF6 salts are typically used. This forms Li2CO3, which cannot be reduced and therefore causes higher charge overpotential.

Developments

One improvement using sulfoxide-based electrolytes has been documented, such as using a dimethyl sulfoxide (DMSO)–based electrolyte that has low viscosity, low volatility, and high oxygen diffusion.

Ether-based electrolytes are widely used owing to good solubility for Li and O_2, a stable operation voltage window, and a long cycle life.

A research article in *Nature Chemistry* reported that an Li-O_2 battery using an aprotic ether–based electrolyte can operate under capacity levels as high as 5,000 mAh/g of carbon with an average discharge voltage of 2.7 V, leading to a very high theoretical energy density of 13,500 Wh/kg.

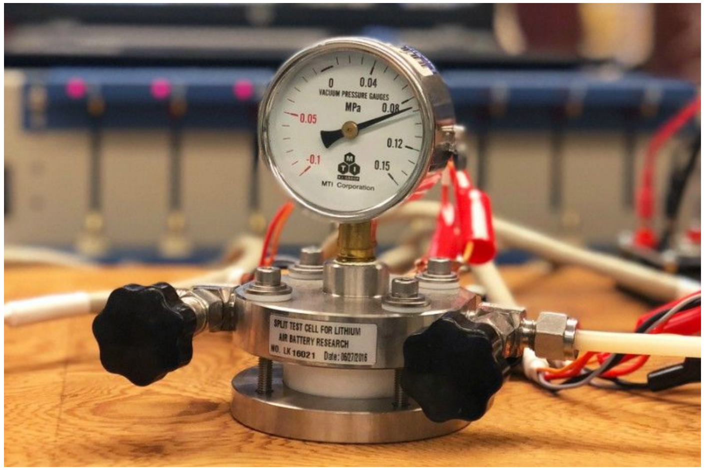
References

1. https://aip.scitation.org/doi/full/10.1063/1.5091444
2. https://www.nature.com/articles/nchem.1376
3. https://slideplayer.com/slide/3452993/

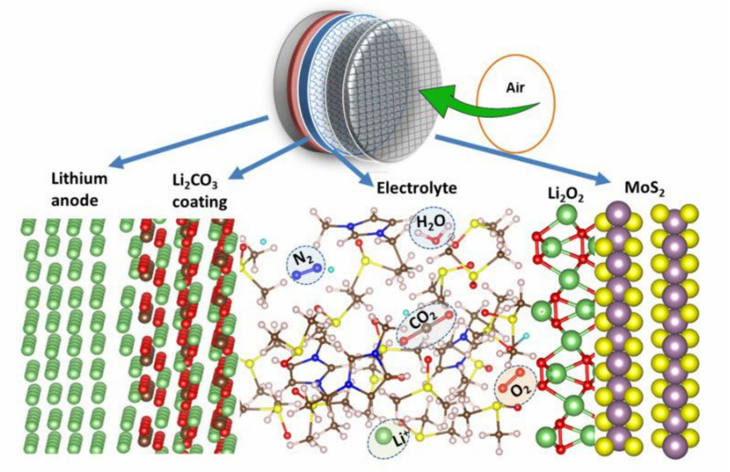
Li-Air: Bench-Scale Development

Salehi-Khojin and fellow researchers at UIC and Argonne National Laboratory have designed an electrochemical cell that works in a natural air environment and still functions after a record-breaking 750 charge/discharge cycles.

The research team at UIC used a cathode coated with molybdenum disulfide. They used a unique hybrid electrolyte composed of ionic liquid and DMSO.



Experimental Li-air battery image. **Photo:** Amin Salehi-Khojin.



Experimental Li-air battery Schematic. **Credit:** UIC and Argonne National Laboratories.

References

1. https://www.techbriefs.com/component/content/article/tb/stories/blog/28772
2. https://today.uic.edu/new-design-produces-true-lithium-air-battery
3. https://www.nature.com/articles/nature25984

Global Market

According to a Mordor Intelligence forecast for 2019-2024, the Li-air battery market is projected to achieve a CAGR of 11%. However, this analysis does not specify any application in A&D industry.

Between

2019-2024

Li-air market is projected to achieve a **CAGR** of

11%

The largest market is North America

The fastest-growing market is Asia

According to research from NASA, a single-aisle 737 class aircraft, even in a hybrid electric configuration, would require a battery specific energy of 1,000 Wh/kg or higher. **Once the Li-air batteries are optimized, they could revolutionize the space exploration and aviation industries.**

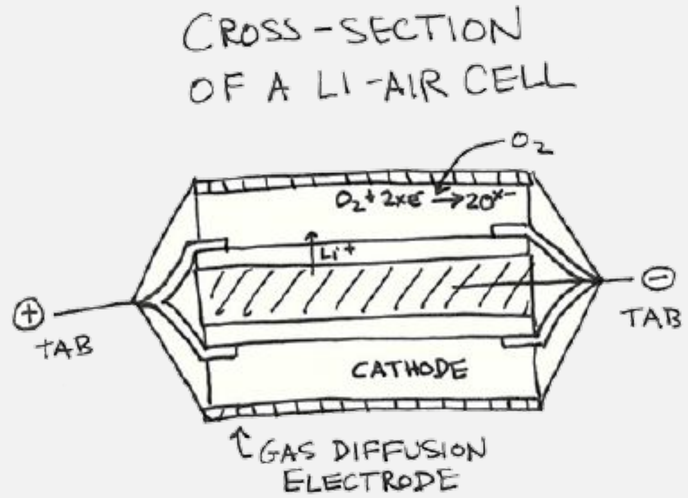
References

1. https://www.mdpi.com/1996-1073/10/12/1937/htm
2. https://www.technavio.com/report/global-lithium-sulfur-battery-market-analysis-share-2018

PolyPlus designed a protected lithium electrode (PLE) technology. They use this PLE with a gas diffusion electrode, aqueous electrolyte, and ambient air.

The key features of their battery are:

- **Ultralightweight:** Cell-level energy density is >800 Wh/kg and pack level delivers >500 Wh/kg
- **Safety:** No toxic chemicals used
- **Long shelf life:** Solid-state PLE prevents parasitic reactions, causing low self-discharge rate with a projected shelf life of >10 years
- **Inexpensive**



Source: *PolyPlus.*

Future Outlook

NASA researchers have built research-quality Li-air battery packs where each pack is a five-cell unit made of a lithium-metal anode, a porous carbon cathode, and an ether-based electrolyte.

A specific energy of about 200 W h/kg (only 5% of the Li-air battery's theoretical maximum) at the cell level has been calculated by the team.

However, John W. Lawson of the NASA Ames Research Center predicted that **once optimized, the battery pack could reach 700–800 W h/kg**, the estimated energy requirement for regional planes.

Source: Visual Capitalist

The team also ran a simulation of a flight profile, including takeoff, cruising, and landing. Model calculations indicated that the **optimized Li-air battery could handle the power requirements for electric aircraft.**

References

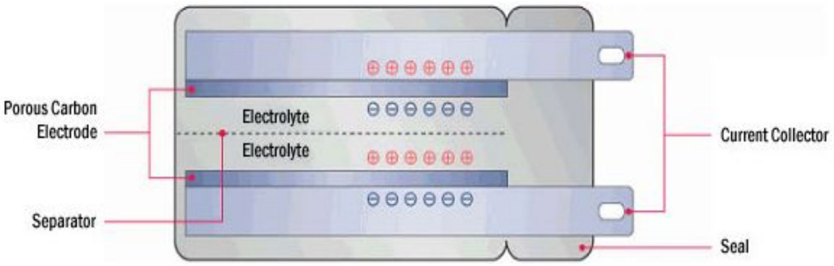
1. https://cen.acs.org/energy/energy-storage-/Batteries-need-boost-fly-friendly/97/i42
2. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140016967.pdf

Supercapacitors/Ultracapacitors

A supercapacitor benefits from high power density and an extended lifetime but suffers from lower energy densities compared to other energy storage technologies.

Supercapacitors (also known as ultracapacitors) consist of two metal plates separated by thin insulator (carbon/paper/plastic). The plates are soaked in electrolytes. When connected to a circuit during charging, opposite charges make a layer, and a double layer is formed. This is why supercapacitors are also called electrical double-layer capacitors (EDLC).

Due to the formation of a voltage gradient, these can store energy. Supercapacitors have a high power density but low energy density compared to batteries. While batteries use chemical reactions, supercapacitors are static electricity. Therefore, their cycle life is theoretically infinite and possess high energy efficiency (95%) and high specific power (6 kW/kg)

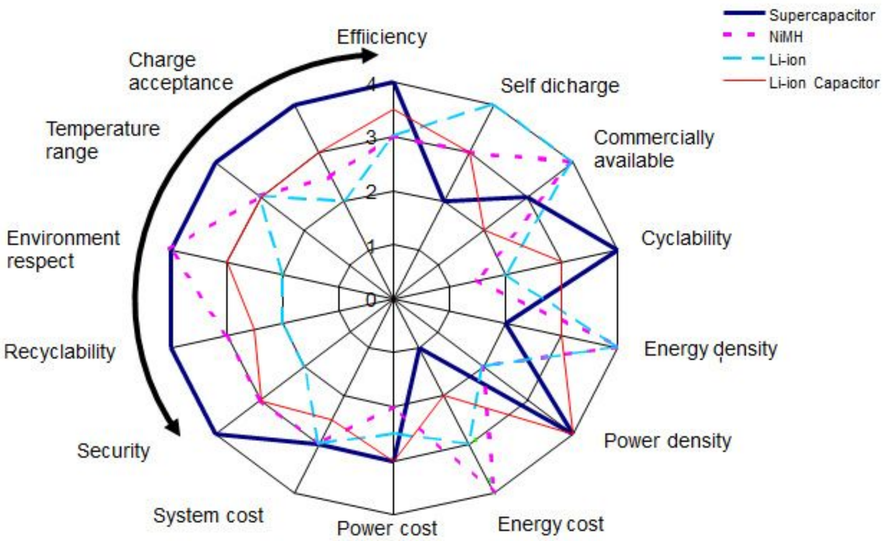


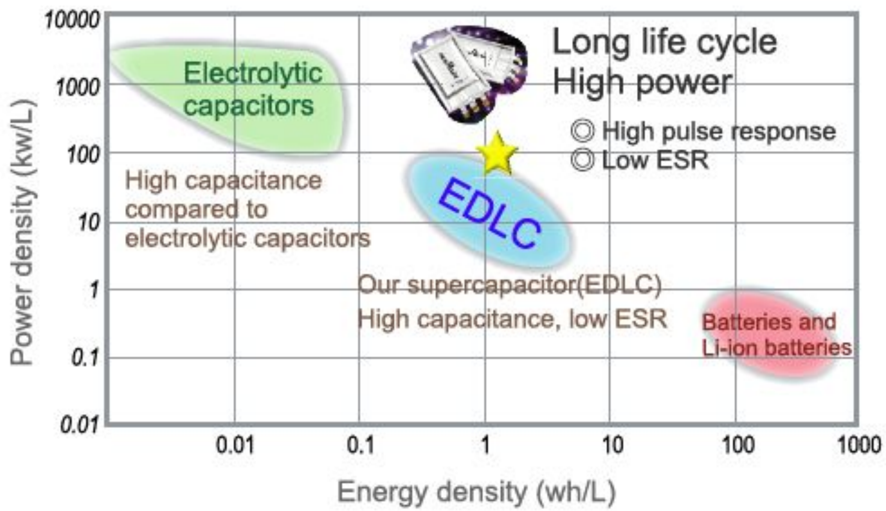
Source: LS MTRON

References

1. https://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor
2. https://www.explainthatstuff.com/how-supercapacitors-work.html
3. https://www.ultracapacitor.co.kr:8001/support/ultracapacitor/introduction

Supercapacitors vs Batteries





Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6V nominal
Specific energy (Wh/kg)	5 (typical)	120–240
Specific power (W/kg)	Up to 10,000	1,000–3,000
Cost per kWh	$10,000 (typical)	$250–$1,000 (large system)
Service life (industrial)	10-15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

Sources: Left image: Passive Components; Right images: Murata.

Advantages & Disadvantages of Supercapacitors

Advantages of Supercapacitors:

- Theoretically unlimited cycle life (over 1 million cycles)
- High power density (up to 100 kW/kg)
- High energy efficiency (95%)
- Charging simplicity, quick charging
- Remarkable capacitance (up to 3000 Farad)
- Safe
- Wide range of operation temperatures (-40^{0}C to +70^{0}C)

Disadvantages of Supercapacitors:

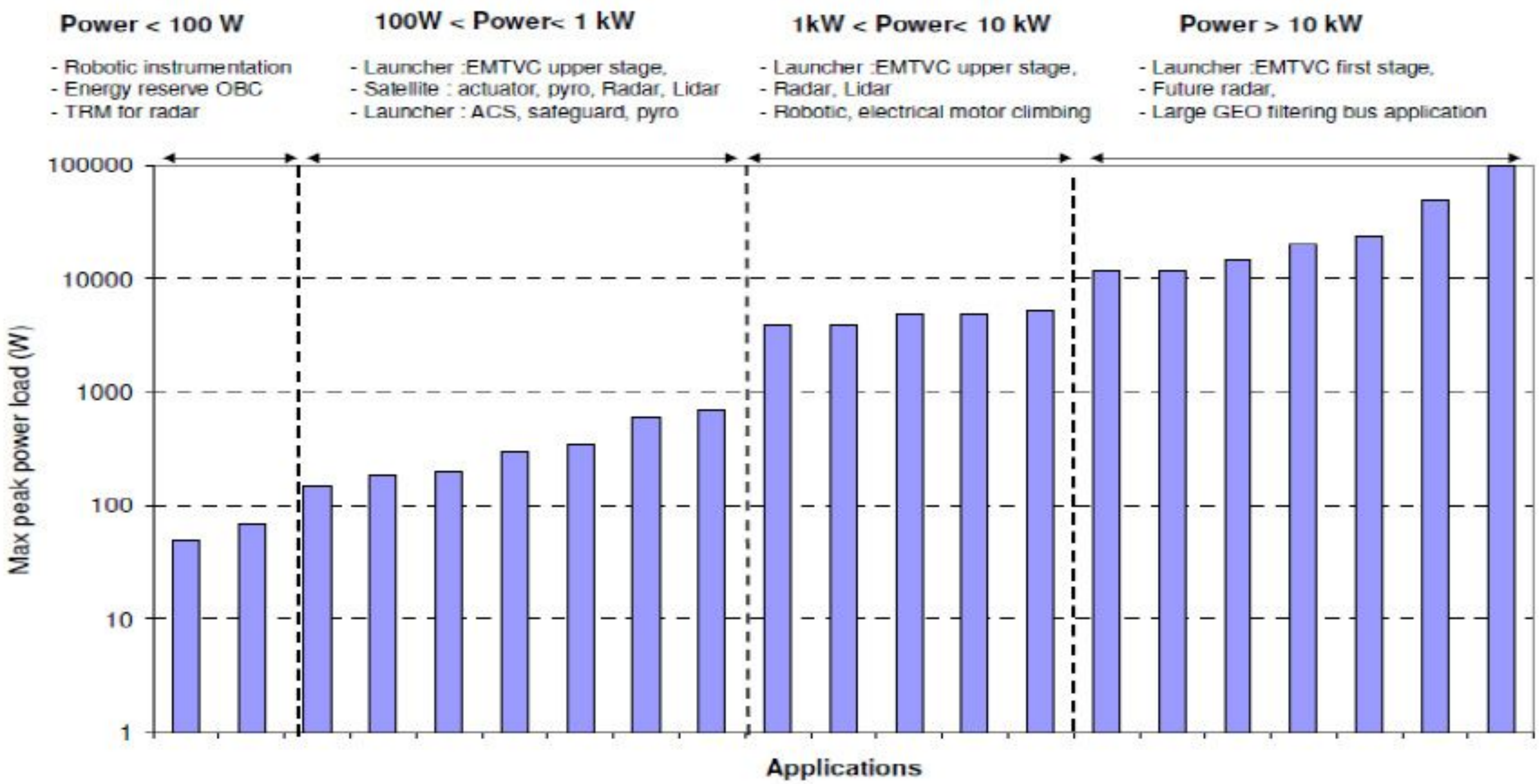
- Low specific energy (6 Wh/kg)
- Low maximum voltage (2-3 V)
- High price (USD 30-100 per Wh)
- High self-discharge

Supercapacitors can fill the gap between batteries and capacitors in space applications.

References

1. https://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor
2. https://www.sciencedirect.com/topics/chemistry/supercapacitors
3. https://passive-components.eu/qualification-of-cots-supercapacitors-for-space-applications/

Applications of Supercapacitors in Space



Commercial off-the-shelf (COTS) supercapacitors may have the required qualifications for application in space.

Source: Passive-Components

Global Market

According to Technavio, the global supercapacitor market is predicted to grow significantly with a CAGR of >21% by 2022. This prediction includes all types of sectors. Future Market Insights predicts it to surpass USD 5.5 billion by 2028.

Between
2017-2022

Global supercapacitor market is projected to achieve a **CAGR** of more than

21%

By
2028

Revenue from the global supercapacitor market is estimated to surpass

$5.5B

Increasing applications in various industrial sectors, such as:

electronics, energy & power, military & defense, and aerospace

Some of the key players include Evans Capacitor, LEAPOOL, FastCap, and LS Mtron

References:

1. https://www.technavio.com/report/global-supercapacitor-market-analysis-share-2018
2. https://www.idtechex.com/en/research-report/supercapacitors-applications-players-markets-2020-2040/661
3. https://www.futuremarketinsights.com/reports/supercapacitors-market

Key Players

EVANS CAPACITOR COMPANY

Evans Capacitor Company manufactures high energy density and high power density capacitors for applications in various sectors including aerospace and defense. They have developed a TDD series hybrid capacitor that has a tantalum anode and ruthenium oxide–coated cathode.

These capacitors combine high capacitance and low ESR in a fully hermetic tantalum package for high reliability defense and aerospace applications where weight and volume are at a premium.

Some features include:

- Low equivalent series resistance (ESR)
- High power density
- Wide temperature range (-55°C to +125°C)

Images of Evans Capacitor TDD series Hybrid Capacitors.
Source: Evanscap.

References:
1. http://mil-embedded.com/eletter-products/evanscaps-energy-dense-supercapacitors-for-military-and-aerospace-applications/
2. https://www.evanscap.com/tdd-series/

Key Players

FASTCAP is a MIT spinout startup and this company is developing ultracapacitors aiming towards space exploration applications.

Their ultracapacitors can store up to 10 times the energy and can achieve 10 times the power density of commercially available products.

Importantly, these are the **only ultracapacitors that can withstand +300ºC and -110ºC**, which is why these are aimed for the space exploration sector in a joint venture with NASA.

Image of FASTCAP's extreme low temperature ultracapacitor. Source: FastCap.

References:
1. https://www.fastcapultracapacitors.com/
2. http://news.mit.edu/2016/new-applications-ultracapacitors-drilling-aerospace-electric-cars-0907
3. https://www.fastcapultracapacitors.com/low-temperature-ultracapacitors

About the Authors

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Managing Director, High Tech / Aerospace & Defense Practice

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Sofiane leads the high-tech, aerospace and defense, and finance verticals at PreScouter. Sofiane earned his BS in Materials Science and Engineering from The University of Illinois at Urbana-Champaign and his PhD in Materials Science and Engineering from the Georgia Institute of Technology, where his research focused on nanotechnology and energy storage. Since graduating from Georgia Tech, he has worked as an emerging technology and business strategy consultant at several firms and for his own clients.

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As a scientist, Jorge aims to study sustainability and development issues that can generate positive changes in the lives of local communities. Jorge finished his Master's degree in Tropical Conservation and Development from the University of Florida and completed his PhD in Biology at Syracuse University. Jorge is based in Canada, where he was, until recently, working for Environment and Climate Change Canada. Jorge has lately become more involved in communicating science to specialized and general audiences, and he still directs most of his efforts to work as an environmental consultant and to teach kids about the need to keep in touch with nature.

About the Authors

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University of Zurich

Professional Summary:

Tufan is currently a postdoctoral researcher at the University of Zurich while working on developing novel synthetic methodologies related to C-H functionalization. He has a PhD in inorganic and organometallic chemistry from Arizona State University, where he developed cheap and environmentally benign catalysts relevant to industrial silicone curing. While two of his PhD projects have been patented, one of his catalysts has been commercialized with Sigma-Aldrich. Tufan's career interest lies in the area of innovative technologies related to renewable energy and water purification. Beyond this, he enjoys communicating scientific facts to broader audiences.

Next Steps

SOME POSSIBILITIES THAT PRESCOUTER CAN OFFER FOR CONTINUATION OF OUR RELATIONSHIP

- COMPETITIVE INTELLIGENCE
- TECHNOLOGY & PATENT LANDSCAPING
- TECHNOLOGY ROADMAPPING
- MARKET RESEARCH & ANALYSIS
- TRENDS MAPPING
- ACQUIRE NON-PUBLIC INFORMATION
- PATENT COMMERCIALIZATION STRATEGY
- DATA ANALYSIS & RECOMMENDATIONS
- REVIEW BEST PRACTICES
- SUPPLIER OUTREACH & ANALYSIS
- CONSULT WITH INDUSTRY SUBJECT MATTER EXPERTS
- INTERVIEWING COMPANIES & EXPERTS

WE CAN ALSO DO THE FOLLOWING

- **CONFERENCE SUPPORT:** Attend conferences of interest on your behalf.
- **WRITING ARTICLES:** Write technical or more public-facing articles on your behalf.
- **WORKING WITH A CONTRACT RESEARCH ORGANIZATION:** Engage with a CRO to build a prototype, test equipment, or any other related research service.

For any requests, we welcome your additional questions and custom-building a solution for you.

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Customized Insights: PreScouter finds and makes sense of technology and market information in order to help you make informed decisions.

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