HYBRID POWER SOURCE FOR THE MILITARY AIRCRAFT FLEET OF THE 2035 ENVIRONMENT

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I am pleased to send you this work entitle "Hybrid Power Source for the military aircraft fleet of the 2035 environment", for the National Academies Powering the U.S. Army of the Future Study, work that has been realized during the period of January and February of 2020 at Purdue university.

Executive Summary

This paper presents a general overview of the military air fleet energy consumption and emphasize the development of hybrid power sources for aircraft. Technologies such as lithium ion batteries and hydrogen fuel cells are still under development to be scaled and used airplanes. However, it is inevitable the introduction of this technologies in a mid- term scenario by the next decade of 2030. The numbers are excellent in paper with high efficiency performance and excellent energy density but the scalability of these technologies is still a challenge. The main idea of this white paper is not proposing a full electric or hydrogen fueled airplanes, instead they should still use hydrocarbons starting with at least 1% of electricity as part of energy power system.

What is a Hybrid Power Source?

A Hybrid Power Source is a combination of technologies to produce power. The possible combinations can be solar and wind energy for power plants, oil and electric engine for cars or even gas turbines integrated with a battery energy storage system.

Hydrogen fuel cell, battery and super capacitor energy system

Several studies and automotive manufacturers have demonstrated how advantageous are hybrid oil-electric cars compared to oil engine vehicles in the last decade. This white paper discusses the advantages and challenges for the implementation of hydrogen fuel cell hybrid electric vehicle for the air military fleet in the environment of 2035. The hydrogen fuel cells have been one of the most promising technologies of the last years, however, scaling that technology is still a challenge because of safety and economics constraints. In Figure 1 can be observed a general scheme of how the powering system of an hybrid plane with fuel cells, batteries and oil and electric engine would look like. However, the design might change depending on the prototype and energy need.

It could be just hydrogen fuel cell and electric engine or just an auxiliary source for the propulsors.

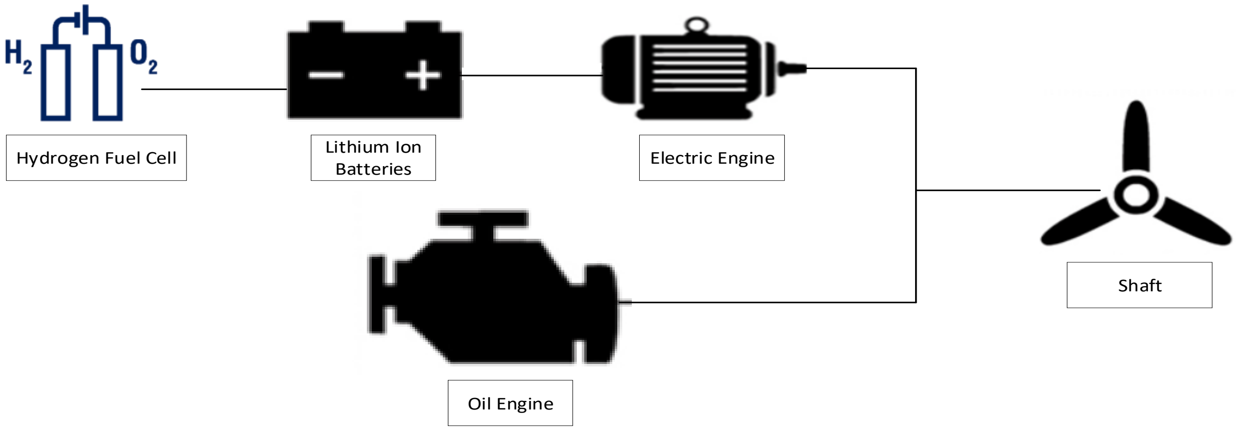

Figure 1. Schematic of a fuel cell hybrid aircraft

A study done by (Fathabadi, 2018) showed that a vehicle constructed of a 90-kW proton exchange membrane fuel cell, a lithium (Li)-on battery of 19.2 kW and a 600 F double layer capacitor could reach an efficiency of 96.2% , providing a maximum speed of 161 km/h. Additionally with one tank of hydrogen with capacity of 5.4 kg/5000 psi the vehicle was able to run for 545km in cruise range velocity. Other experiments and simulations have shown similar results with promising numbers until the date (H, Z, & W, 2008).Given the advancement and developing of this technology it may indicate that the maturity level is in TRL-5 because this technology has been tested in different scenarios with multiple pieces. Some of the advantages of using a hydrogen fuel , battery and supercapacitor system are:

- Higher efficiency because the energy conversion is direct (no combustion) so there is no Carnot Limitation.
- Very short charge and discharge times, from fractions of a second to several minutes if a super capacitor is used.

On the other hand, there are still challenges that need to be solved before implement and scale such technology for multi-domain operations.

- Kerosene (main aircraft fuel) energy density is 40 times higher than batteries. This means that pure electric planes are unlikely by 2035. Kerosene 43MJ/kg, Battery 1MJ/kg.
- Lithium ion batteries can get burned and are physically volatile

General Overview of Energy Consumption in the Military Forces

In United States, the Department of Defense is the largest purchaser of energy. In the fiscal year of 2010 the energy use of the DOD constituted about 80% of the federal government (Schwartz, Blakeley, & O'Rourke, 2012). One of the main fuels is oil and its derivates which is widely used in 500 domestic installation and almost 800 international bases (Vine, 2015). Roughly 75% all of purchases oil goes to operation to maintain and sustain military capabilities, the rest goes to maintain facilities. In

Figure 2 is observed the oil consumption per military branch. Furthermore, it is important to highlight that aircraft represents almost three quarters of oil and petroleum consumption in the military, see

Figure 3. In total, 600 trillion of BTU were used which counted as 15 billion dollars in the FYO 2010 (Office of the Undersecretary of Defense, 2010). That is the total amount of energy consumption of 4 million American houses in a year.

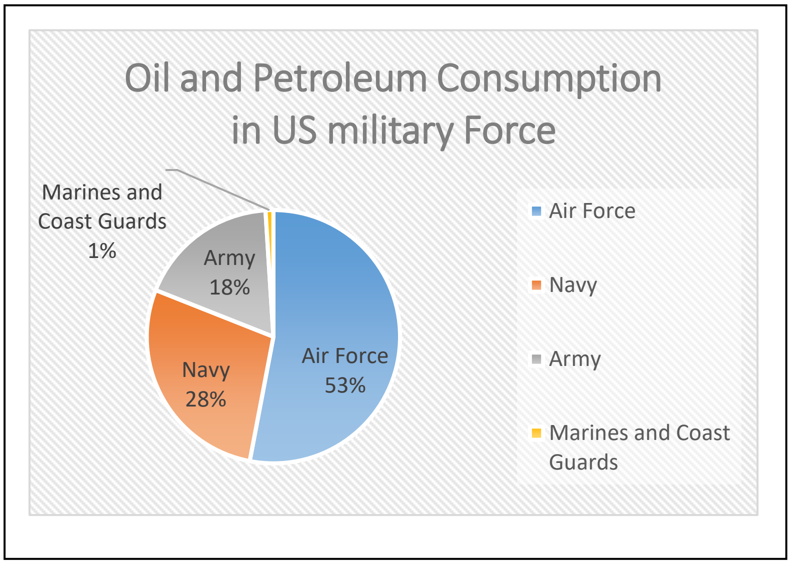

Figure 2. Oil and Petroleum consumption of the military forces.

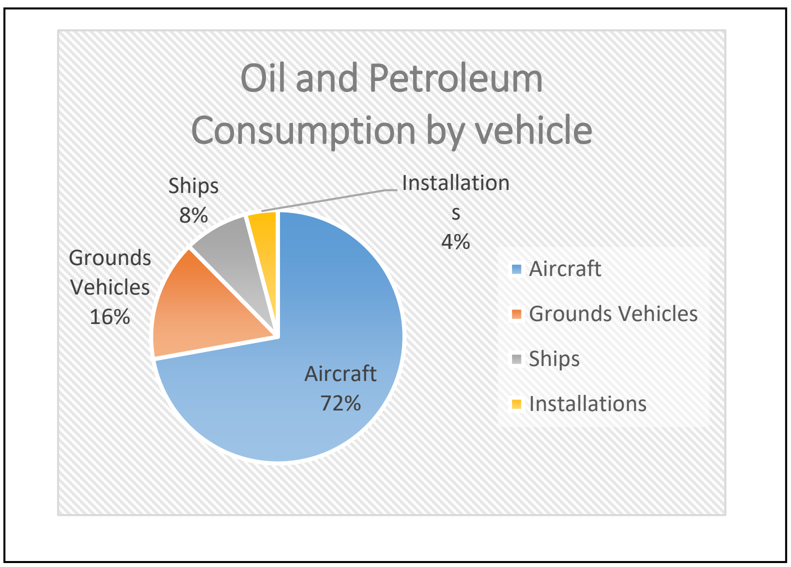

Figure 3. Oil and Petroleum Consumption by vehicle

The installations just account 4% of total oil consumption. That means that moving personnel in exercise such as multidomain operations, tactics or any military operation account for most of the energy consumption in the military forces.   With the highest power requirement in the aircraft fleet.

United States Aircraft Fleet

The military aircraft fleet of United States is composed by a variety of planes such as transport planes, fighters, bombers, unmanned or multipurpose aircrafts. Figure 4 shows the most used type of aircrafts, where the F-16 is found to be one of the most used. Among them there is the T-38, the T-6 and F-15 which are used for training, supersonics velocity practice and other activities.

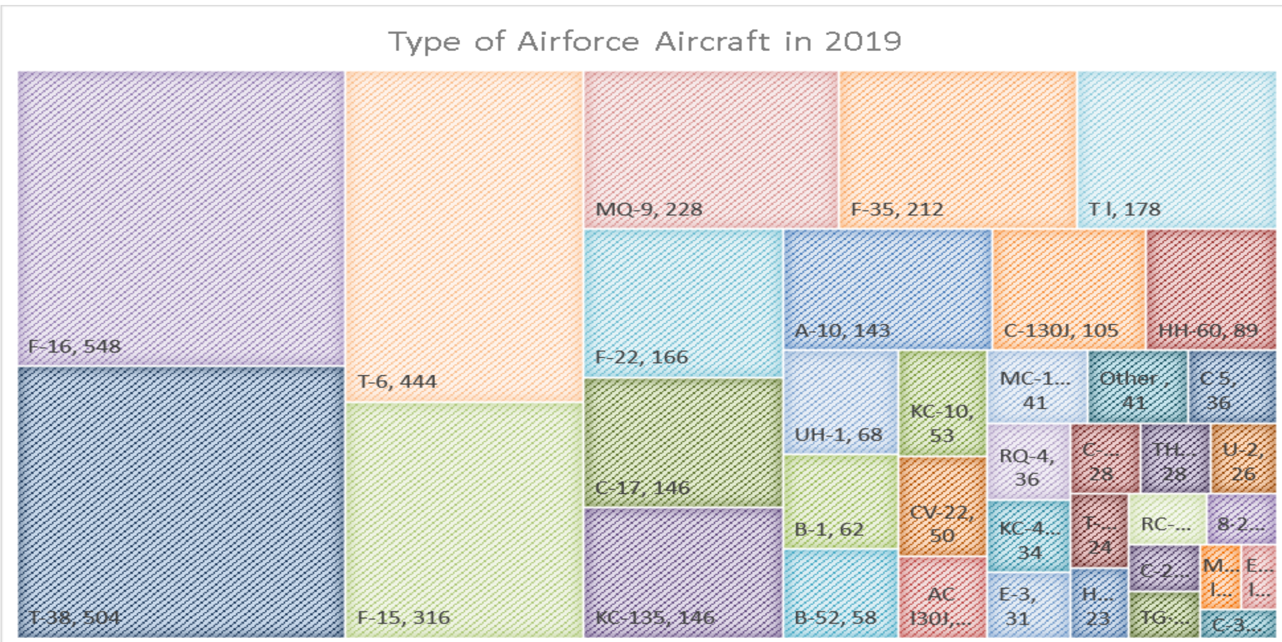

Figure 4. United States aircraft in operation in 2019 (US Air Force , 2019)

Figure 4 shows the matrix of active US aircrafts and it can be useful to understand where should the R&D of military aircraft be oriented for the next decades.

Hybrid Aircrafts and Energy Requirements

Incorporating a battery and an electric engine in a plane implies a radical aircraft propulsion benefit. If electricity is powering the propulsors, then electrical power can move around quite easily. Instead of having one propulsor per wing, you could have multiple electrically driven propulsors, which require less maintenance than a gas turbine (Pickup, 2019) .Indeed, having an electric propulsion dynamize the overall control of aircrafts and can optimize the take-off rather than cruise opening many possibilities in this space. The challenge is how to power the electric engines, either with batteries, hydrogen fuel cells or both together and at the same time not adding too much weight.

The Physics of the Airplane Flight

A plane flies when lift equals the weight of the plane, then when weight is increased the lift has to increase which requires more power. Needing more batteries to deliver more electricity. The following equations intend to look what variables affects airplane flight. Work is force times distance, and power is work divided by time which at the same time is force times the variation of velocity.

$$W = F \times \Delta x$$

$$P = \frac{W}{t} = \frac{F \times \Delta x}{t} = F \times \Delta V$$

When a plane flights on a constant height the force of lift and the force of gravity is balanced. That means the upwards force of lift has to be equal in magnitude to the downward pull for gravity which is the mass of the plane times gravity.

$$F_{grav} = M_{plane} \times g$$

So the power required for lift equals the mass of the plane multiplied by gravity and delta of velocity.

$$P = M_{plane} \times g \times \Delta V$$

Then delta of velocity is the downward velocity of the air that the plane pushes downward. That value depends of the mechanism and physical structure of the plane. The lift an airplane provides is equal to the rate it delivers downward momentum to the air it displaces. That means that the force of gravity must be equal in magnitude to the downward velocity of the deflected air times the rate at which air gets deflected.

$$F_{lift} = M_{plane} \times g = M_{air} \dot{\times}\ \Delta V$$

The mass flow rate of air (A_{sweep}) is equal to the volume of the cylinder that borders the plane times the density of the air which is:

$$M_{air} = \ \rho_{air} \times A_{sweep} \times V_{flight}$$

$$F_{lift} = M_{plane} \times g = \rho_{air} \times A_{sweep} \dot{\times} V_{flight} \ \times \ \Delta V$$

$$\Delta V = \frac{M_{plane} \times g}{\rho_{air} \times A_{sweep} \times V_{flight}}$$

And finally, the power need for lift is given by this equation

$$P = \frac{M_{plane}^2 \times g^2}{\rho_{air} \times A_{sweep} \times V_{flight}}$$

With this equation it can be noticed what variables really impact the energy requirements on the aircraft. As the plane flies faster the power drawn by the engine actually gets smaller and the dragging and lifting force becomes the same which doubles the power requirements. Therefore, at cruising speed, the power demanded by a plane is:

$$\boldsymbol{P = \frac{2 \times M_{plane}^2 \times g^2}{\rho_{air} \times A_{sweep} \times V_{flight}}}$$

The mass is squared and doubled making it a huge and important variable when calculating the amount of power for a plan, it increases the power by 8 times.

What is the power requirement of the most common military aircrafts?

The following equation shows the energy required by a plane, where T is the time of flight and P is the demanded power.

$$E_{battery} = P_{lift} \times T_{flight}$$

Imagine a multi-domain operation that needs at least one F-16, the most used aircraft in the US military forces, flying for 4 hours distance. How much energy does that flight needs? Using the previous equation, the energy needed for this scenario is:

$$E_{battery} = P_{lift} \times 4$$

$$E_{battery} = \frac{2 \times M_{plane}^2 \times g^2}{\rho_{air} \times A_{sweep} \times V_{flight}} \times 4$$

$$E_{battery} = \frac{2 \times (9207)^2 kg \times 9.87^2 \frac{m}{s^2}}{1 \frac{kg}{m^3} \times 47 m^2 \times 986 \frac{km}{h}} \times 4\ h$$

$$E_{battery} = \frac{2 \times (9207)^2 kg \times 9.87^2 \frac{m}{s^2}}{1 \frac{kg}{m^3} \times 47 m^2 \times 273.8 \frac{m}{s}} \times 4\ h$$

$$E_{battery} = 10\ 267\ kWh$$

Since density of batteries can reach about 0.34 kWh/kg then the total weight of batteries is:

$$M_{batteries} = 30\ 198\ kg$$

That is counts as three times the weight of the F-16 which is huge and non-feasible with just batteries. The amount of fuel weight that a plane should have is between 20%-25%, in this case is 300%.   With kerosene this amount changes a lot.

$$M_{kerosene} = 800.26\ kg$$

The mass of kerosene to energize the F-16 is way more feasible to put on a F-16 aircraft. And that is main advantage of this fuel compared to others. It is important to mention that this is just the amount of energy needed in a plane at any given moment in cruiser speed.

What about Hydrogen Fuel Cells, Batteries and Double Layer Capacitors?

The energy density of hydrogen fuel cell in a laboratory is 33.6 kWh/kg (Energy Efficiency and Renewable Energy Office, 2010), but getting hydrogen is complex and expensive. It is produced with large inputs of energy in the process and it also lacks of reasonable storage and transportation system. However, some companies such as ZeroAvia have already made create acceptable prototypes of small planes that can flight with only hydrogen. The energy density they reach was about 0.8 kWh, which is much higher than the best lithium ion batteries (Bogaisky, 2019). In a future scenario with a more efficient system with better hydrogen fuel cells, double layer capacitors and more reliable batteries it can be expected a 1.2 kWh/kg by 2025. Without affecting the weight of military aircrafts this technology can be gradually implemented between a 75% oil and 25% electric weight ratio. In Figure 5 can be observed how much energy can be delivered with the percentage of weight in each technology.

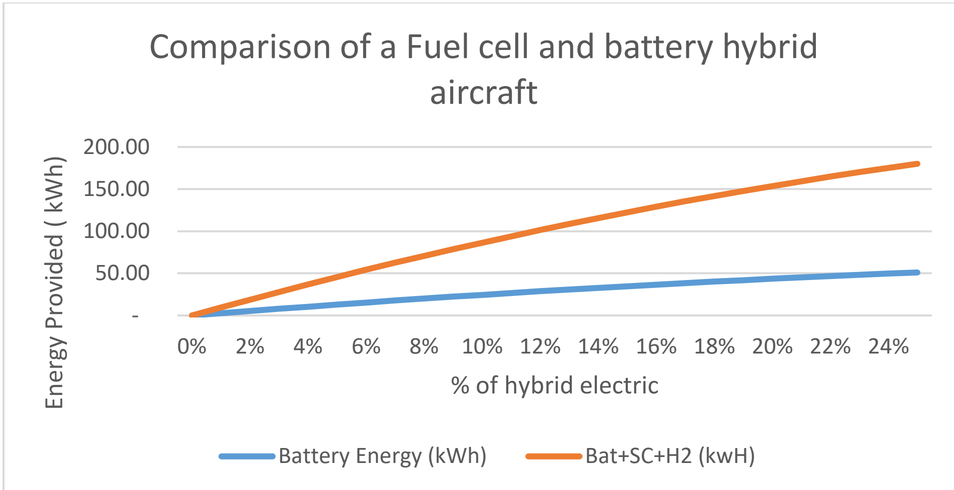

Figure 5. Hybrid Energy Output of hybrid systems

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