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AN OUTLINE OF ALTERNATIVE AVIATION FUELS FROM SUSTAINABLE RESOURCES

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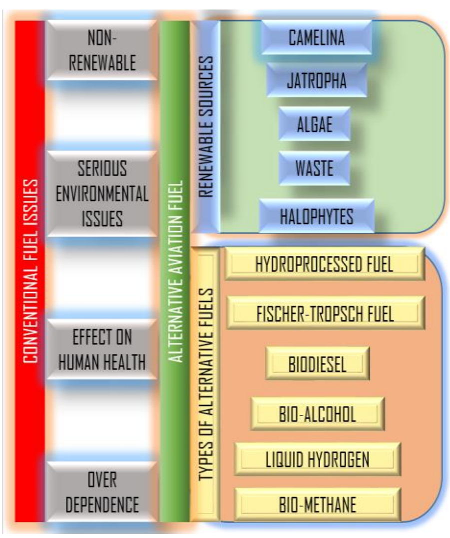
Graphical abstract



Abstract

The depletion of fossil fuels and their market inequality have led to the popularity of biofuels. Biofuels are a renewable energy source which can be a promising solution to the environmental issues created by fossil fuels. The emission of greenhouse gases and fluctuating prices of fossil fuels have put pressure on developing countries and small economic nations. Thus, one of the main concerns is the production of bio jet fuel from renewable resources, with a relatively low greenhouse gas life cycle and sustainability with affordable prices. Therefore, it is imperative to introduce and produce alternative aviation fuels generated from sustainable resources, specifically biofuels. In this study, we have reviewed alternative aviation fuels and their sources. We have also outlined the selection criteria for alternative aviation fuels along with discussing the sources that can be potentially used as fuel for the aviation industry.

Keywords: Alternative aviation fuel, greenhouse emission, renewable energy

Abstrak

Kekurangan bahan api fosil dan ketidaktentuan harga pasaran telah membawa kepada penggunaan bahan api bio. Bahan api bio merupakan sumber tenaga boleh diperbaharui dan mampu menyelesaikan masalah alam sekitar yang terhasil daripada pembakaran bahan api fosil. Pembebasan gas rumah hijau dan ketidaktentuan harga bahan api fosil telah memberi tekanan kepada negara membangun dan negara berekonomi kecil. Oleh itu, penghasilan bahan api daripada sumber boleh diperbaharui, kitaran hayat gas rumah hijau yang rendah dan kemampanan harga yang berpatutan amatlah penting. Justeru, adalah penting untuk memperkenalkan dan menghasilkan bahan api penerbangan alternatif yang dijana daripada sumber yang mampan, khususnya bahan api bio. Dalam kajian ini, kami telah mengkaji bahan api penerbangan alternatif dan sumbernya. Kami juga telah menggariskan kriteria pemilihan bahan api penerbangan alternatif serta membincangkan sumber yang berpotensi untuk digunakan sebagai bahan api bagi industri penerbangan.

Kata kunci: Bahan api penerbangan alternatif, penghasilan gas rumah hijau, tenaga diperbaharui

1.0 INTRODUCTION

The aviation industry has been growing drastically to support travel and transportation purposes either domestically or internationally. 60 million passengers are expected in 2030 which shows a double increment compared to the year 2016 [1]. Consequently, the demand for conventional aviation fuel has increased significantly causing fuel depletion and over-dependency on fossil fuels. In addition, International Civil Aviation Organizations (ICAO) are establishing stringent procedures for the emission certification of conventional fuels, which will certainly prioritise the role of biofuel for future concerns [2]. However, the selection of biofuels must consider the availability of the feedstocks and challenges during the development process. Table 1 shows the different generations of biofuels, the feedstocks, limitations and advantages of each fuel generation. The first generation of biofuel is made from vegetable oil, sugar cane cereals, and sugarcane starch to produce biodiesel and ethanol [3]. Due to limited availability and the competition of the feedstock with food supply, the second generation of biofuel was proposed. The second generation of biofuels is made from non-competing feedstock with food supplies such as jatropha, plant waste and bagasse. The sources are converted into HEFA and FT processed fuel [4]. The energy source of the feedstock in the third generation category is algae. The fourth-generation fuels are motivated toward carbon capture and storage technologies that will make the world carbon negative, thus contribute to the innovation in biofuel processing technology.

The purpose of this paper is to discuss various types of alternative fuels from different sustainable resources and processing techniques for aviation applications. The structure of the article is as follows. The first section presents the important properties needed in jet fuel. The second section presents the chemical process involved in developing the jet fuel. The third section discusses various types of potential feedstocks available and the type of alternative fuels are presented in the final section.

1.1 Biojet Fuel Selection Criteria

The characteristic feature of alternative aviation fuels depends on aircraft types and missions. The biofuel must be able to provide adequate combustion efficiency, adequate stability performance, smooth operation, quick and easy ignition even under adverse condition, adequate combustion intensity, low pressure loss, satisfactory outlet temperature distribution, produce combustion products which does not engine components, and reedom from harmful deposits. Those requirements can be achieved by having good physical and chemical properties. Besides fuel properties other important requirement for fuel selection consists of energy supply, energy density to boost the engine efficiency, minimum weight to avoid extra load during flight, and occupancy for the limitless supply [7]. These criterias are important to ensure the aircraft could complete every missions successfully. The volumetric energy density (MJ/lt) and mass-energy density (MJ/kg) play a key role in engine performance [8].

Table 1 Comparison of Fuel Generation [2,5,6].

Fuel Features	Petroleum Refinery	1st Generation Fuel	2nd Generation Fuel	3rd Generation Fuel	4th Generation Fuel
Feedstock	Crude Petroleum	Vegetable Oil, plants, sugar cane by-products, Corn etc.	Non-Food, Plant waste biomass, bagasse, algae, Jatropha etc.	Algae	Genetically modified algae, Electrofuels
Products	CNG, LPG, Diesel, Petrol, Kerosene and Jet Fuel	Biodiesel, Corn Ethanol, Sugar Alcohol.	Hydro processed oil, Biofuel, FT oil, Bio alcohols.	Bio-ethanol	Vehicular fuels
Limitations	Reserve Depletion, Greenhouse emissions, Overall high costing	Limited Feedstock, Blended fuels	Research still going on.	The limited variant of carbon contrail fuels	Competitive production is uncertain and requires fundamental breakthroughs
Advantages	Research evaluation scale, easily available, sustainable.	No greenhouse emission, low cost, social concern.	No effect on food crops, advanced technology, no greenhouse emission.	No effect on food crops, advanced technology, no greenhouse emission.	using non-arable land

Figure 1 compares the contents of mass-energy density and volumetric energy density for different kinds of fuel. It can be seen that liquid hydrogen is the best energy source in both cases [9]. Methanol has the lowest volumetric energy density and sustainability, but it has a lightweight and less volume thus easy to carry. However, the fuel produces lower performance compared to other fuels [10]. Liquid hydrogen gas (LH_2) shows high energy density but it has low volume density so its storage is complicated and highly flammable which requires intensive safety precautions [9]. However, lower greenhouse gases emitted by the fuel become an advantage towards the implementation of the fuel in aircraft engine.

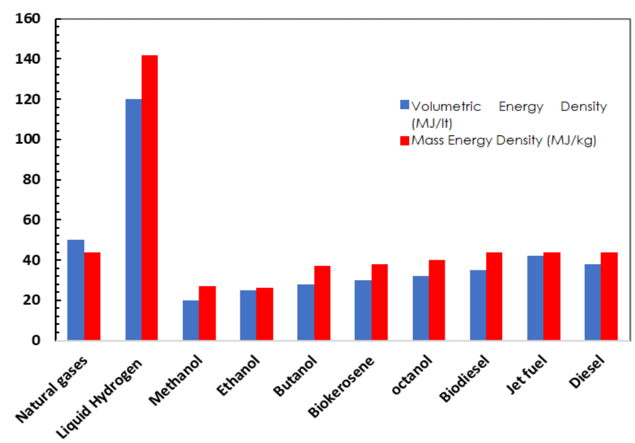


Figure 1 Energy Potentials of Processed Fuels [8]

Liquefied natural gases (LNG) are easily available, clean and cheapest [8]. The heating effect of the fuel is better than kerosene thus improving thermodynamic performance, but carrying the fuel is complicated [11]. Kerosene, gasoline, and diesel have approximately equal mass and volumetric energy densities but have different characteristic features. The overall performance of liquid natural gases is a better option for aviation fuel. Despite fossil fuels, alternative fuels become the next generation's possible source of energy, along with several limitations [10]. The main aspect to focus on alternative fuel is combustion reliability, safety, and availability to replace the current jet fuels [12]. Therefore, a standard of bio-derived jet fuel properties standard (ASTMD 7566) has been established as a benchmark to comply with the requirement. The standard properties of bio-derived jet fuel as in ASTM D7566 are shown in Table 2.

Table 2 Properties of Biojet Fuel (ASTM D7566) [13]

Features for Jet Fuel	Bio Processed Jet fuel
Flash Point	Min 38 ^{0}C
Density at 15 ^{0}C	775-840 kg/m3
Freezing Point	-40 to -47 ^{0}C
Viscosity at -20 ^{0}C	Max 8
Acidity	Max 0.1 mgKOH/g
Net Heat of Combustion	Min 42.8 MJ/kg

2.0 TYPE OF RENEWABLE SOURCES FOR BIOJET FUELS

Jet fuels are generated from different varieties of renewable sources such as sugar or starch, plants, animal fatty oil and other types of biomasses. The research mostly has been done on plant oil, and animal fat oil by using hydro-processing technology. Hydro-treated biofuels eliminate the chemical bond of oxygen and formed an appropriate component of jet fuel. Hydro-treated jet fuels and synthetic paraffinic kerosene jet fuels have approximately the same type of molecular formation, which can be considered an option for alternative fuels.

2.1 Camelina

Camelina can be found mainly in the United States particularly in its northwest region. Camelina grows well in hot temperate and requires less time to grow compared to other plants. Commercial airlines such as Japan Airlines, and KLM Royal Dutch Airlines have tested an isoparaffin-rich jet fuel made from camelina. As of now, all test findings show that the hydrotreated renewable jet fuel (HRJ) made from camelina complies with strict engine fuel and performance requirements and produces lower emissions into the environment, thus becoming a viable feedstock for biofuels manufacturing [15].

2.2 Jatropha

Jatropha is an inedible oil that can be cultivated on waste or insignificant land. Jatropha does not compete with other grain crops. Jatropha plant is resistive as well as lesser input of water. It can grow in any atmospheric condition and grows faster than other yields. Jatropha plants can survive approximately 40 years in minimum water availability [16]. The residue after oil extraction cannot use as food. The residue consists of a high amount of sodium and phosphorous thus it can be used in organic compost. Jatropha can be found in Africa and some parts of Asia [17]. The growth and extraction of the fuel rely on location, maintenance and the variations of the seed.

2.3 Algae

Algae is the most significant potential feedstock due to several factors: rapid growth, does not compete with other agricultural plants, requiring less water to grow compared to other crops, and ability to produce 2–20 times more oil per acre than top oil seed crops [18]. The special chemical reaction such as pyrolysis of microalgae resulted in a generation of products such as olefins, syngas and alkanes. Bio-oils produced from algae have less oxygen, and rich hydrocarbons and possess high heating point than bio-oils synthesized from other biomass [19]. Algae is rich in lipid and has the maximum rate of carbon dioxide absorption, which fulfilled the criteria for the attraction towards alternative fuel generation [20]. Algae also have a high growth rate as compared to Camelina. Algae use minimum land, sunlight, carbon dioxide, and wastewater to grow [21]. The lipid output from algae is more than 25 times the yield per unit area [22].

2.4 Wastes

There are many sources of waste suitable for biofuel generation such as animal waste, different food waste, plant or tree waste, industrial waste, cultivation residue and other waste from the waste-collecting corporation [23,24]. The variety of waste has a different procedures to process for biofuels and possible pathways. Waste processing is cheaper and available in bulk for biofuel generation [25]. The advantage of bio-waste is capable to generate energy without any harmful residue. Nowadays, waste management is very common and full of opportunities for alternative fuels or energy science [25]. Waste and sewages of metropolitan cities possess a high content of lipid that becomes a huge source of alternative fuel generation.

2.5 Halophytes

Halophytes are a salt promising grass that grows in saline-rich water [26]. The roots are in contact with saline water like in saline deserts and mangrove swamps [27]. These plants are not dependent on a saline atmosphere but capable to survive in rich saline content. There are different types of Halophytes such as aqua-halines, terrestro-halines and Aero-halines [28]. Some of the halophytes were analyzed for potential biofuel. *Salicornia Bigelovii* is one of the halophytes which successfully converted into bioethanol [29]. It can survive in a rough atmosphere and does not compete with the other regular food plants. The depletion of other water plants is going through the decades. So, halophytes cultivation is the best option for biofuels. The noticeable facts about halophytes are the supportive features of biofuels. The oil is extracted from the seed and the lignocellulosic biomass of halophytes [27]. Table 3 summarises the different sources of renewable energy sources.

Table 3 Different sources of biojet fuel [10,12,14].

Renewable Bulk sources	Examples
Plant oil sources	algae, camelina, jatropha, oil seeds Yields of Soybean, Palm FFB, Rapeseed, Jatropha seed, Used Cooking Oil
Animal fats	tallow
Biomass	Lignocellulosic, woody, sugars, starches, animal waste
Other plant waste	Leaves and other composites

3.0 PROCESSES OF DEVELOPING BIO-JET FUELS

Fisher-Tropsch process (FT) and Hydroprocessed esters and fatty acids (HEFA) are chemical processes available to develop bio-jet fuels [30]. FT is a process in which biomass is first gasified to provide synthesis gas, which is then utilised in the traditional FT reaction to make liquid fuels. A combination of hydrocarbons with carbon numbers 9 to 15 can be found in the biojet fuel that can be produced from the FT reaction. The creation of syngas, must have precise characteristics (most notably a high carbon and hydrogen content) and be free of tar, chlorine, and sulphur to be useful for FT synthesis [31]. The feedstock of the FT fuels mostly relies on specific working conditions. Power to liquid (PtL) FTs fuels used in the industrial application by generating syngas by using the electrochemical procedure from CO_2 which is captured from the air, is briefly shown in Figure 2.

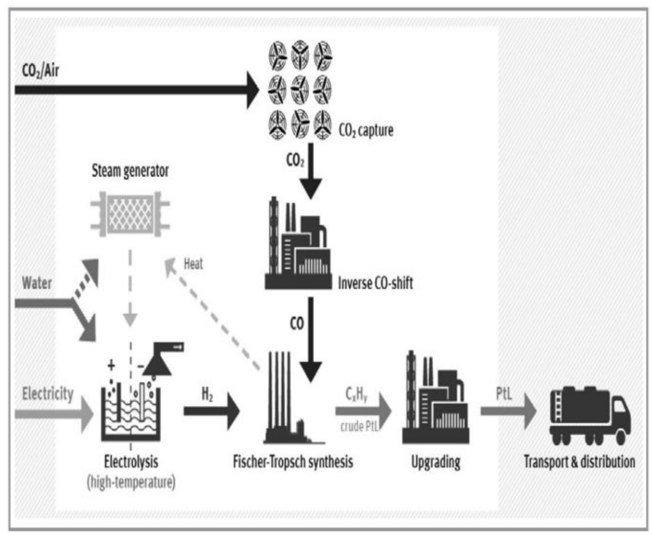


Figure 2 Fischer-Tropsch pathway to produce fuels [12]

The paraffin content in the fuel generated from this process is almost similar to the number of paraffin available in FT fuels. The fuel is frequently named synthetic paraffin kerosene or SPK [32]. The amount of aromatic content of this fuel is minimal. Hydro-processed ester and fatty acids (HEFA) are one of the effective chemical processes in generating paraffinic liquids fuel. Figure 3 depicts a summary of the procedure involved in producing of HEFA type of fuel. The process begins with hydro-deoxygenation of the feedstocks. In this process, the oxygen molecules are removed from the feedstock in the presence of hydrogen (H_2). The deoxygenated fuel is transferred to an isomerization unit (for hydro-cracking and hydro-isomerisation processes) to produce paraffinic liquids which have a straight carbon chain. After being isomerized, the hydrocarbon product is chilled with cooling water before being transported to a separation tower, where excess hydrogen, carbon dioxide, and mixed paraffin gases are removed from the liquid products. The hydrogen and paraffin gases that are extracted from the carbon dioxide are then returned to the hydrotreater. Product storage tank farms receive the liquid goods after being divided into streams for liquid petroleum gases (LPG), naphtha, jet fuel, and diesel. Water waste is removed from the product stream and treated.

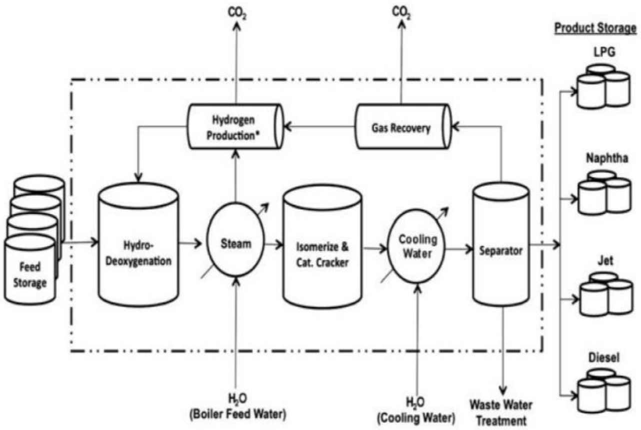


Figure 3 A HEFA pathway to produce fuels [33]

Table 4 lists some of the successful demonstration flights conducted by various airlines. 35% of the flight tests listed in the table used biojet fuel produced using HEFA process. The biofuel was tested as a "drop-in" or blend fuel in one of the aircraft engines. The post-flight data analysis observed no issues during the flight tests. The performance of the engine during the flight tests was similar to the performance of the engine during the ground test. These flight tests indicate the capability of biojet fuel produced by different sources to be used in aircraft engines [10].

Table 4 Commercial Flights using biojet fuel [34]

Raw Materials	Airlines	Aircrafts
Camelina	US Navy, AeroMaxico, Iberia, Royal Dutch Airlines KLM, US Air Force, Boeing, Honeywell	Gulfstream G150, G280, G550, F/A18, 'Green Hornet', MH-60S 'seahawk', Boeing 747 8F
Jatropha	Air New Zealand, TAM Airlines, Interjet Airlines, Lufthansa, Finnair	Boeing 747-400; Airbus 320, 321, A319
Algae	Continental Airlines, EADS, US Navy, United Airlines	Boeing 737, Diamond DA42, MH-60S Seahawk
Used cooking oil	KLM, Finnair, Thomson Airways, AirFrance, Alaska Airlines, Thai Airways, Lufthansa, Etihad Airways, Lan Airlines, Ana Airlines, Scandinavian Airlines, Norwegian Air Shuttle, Hainan Airline, Dragon Air	Boeing 737, 747 777, 300ER, 787; Airbus 330, 320, 321, A319, Aerovodochody L29 Delfin, Bombardier Q400,

4.0 TYPE OF ALTERNATIVE FUELS

Alternative fuels can be generated from different biomass sources. The alternative fuels should produce less emission of hazardous gases or greenhouse gasses, have plenty of sources, availability, compatibility, suitability, sustainability, and minimum residue burning.

4.1 Hydro-Processed Renewable Jet Fuels (HRJ)

Hydro-processed renewable jet fuels (HRJ) developed from HEFA are generated from various sources such as vegetable oils, grease, animal lipids, and algae. Some of the HRJ is made from most of the specific forms of water and propane [35]. The key feature of HRJ is the minimal emission of hazardous gasses and health concern microparticles. There are some other advantages such as a high cetane number makes it more efficient and effective on fuel ignition in the engine. Thermal stability can also have considered a key feature of ideal jet fuel. The minimum tailpipe emission and no aromatic, as well as Sulphur content, should be negligible. HRJs have convenient and stable storage to prevent other waste growth to spoil [36]. These fuels have a positive approach to use in conventional high-altitude aircraft and do not require any alteration in engines. The results are more promising than other regular fuels even though no residue is left so there is no option for corrosion. HRJs have no content of Sulphur that is resulted in viscosity reduction. The other part of the HRJs is blending with other fuels to increase the cetane number for better ignition performance. Lufthansa air has used hydro-processed ester and fatty acids fuel in their aircraft engine [37].

4.2 Fischer-Tropsch Fuels

Fischer-Tropsch (FT) process-based fuels have remarkable features that attracted researchers for decades [38]. Hydrocarbon fuels are developed based on a catalytic transformation of syngas which was used in a huge range of biomass feedstock [39]. Synthesis of syngas and further treatment by using thermal technology proceed to FTs fuels [40]. The conversion of biogas to liquid fuel is called the biomass to liquid process. Earlier, FT process is to produce gasoline and diesel. Nowadays, this technology is used to convert biomass and cultivation waste into hydrocarbons [41]. FTs fuels have advantages in terms of octane number, negligible emission, no particle residue and minimum Sulphur content [38]. In comparison to the other fuels, FTs technology can produce more fuels without any distributed setup and fuel quality but the process is expensive. With all key features, there is some limitation, low viscosity due to the absence of Sulphur and low fuel economy. The ASTM international standard has tested and verified to appropriate and sustainable for aviation fuels [42].

4.3 Biodiesel

Biodiesel is a type of fuel that is processed from natural oil and animal fats to generate alkyl esters of fatty acid [43]. Figure 4 described the conversion process of biodiesel from vegetable oil (VO), esterification and transesterification techniques used in the presence of methanol, converted into crude biodiesel. The conversion of VO in crude form process through washing and drying for the final output in biodiesel. The blending of biodiesel with diesel fuel resulted in a highly efficient fuel due to engine efficiency improvement, low fuel consumption and fewer emissions compared to 100% diesel fuel [44]. Biodiesel has less content Sulphur, has no water content and no additive content like aroma amalgam thus can be considered as no toxic content fuel. However, a limitation in biodiesel properties does not adequate for aviation fuels [45]. Biodiesel does not fulfil the energy content criteria in comparison to aviation jet fuel. The stability of biodiesel storage is complicated because it is biodegradable and resulted in the unwanted biological problem [46]. Additionally, biodiesel also does not an appropriate option for an aircraft due to the high peak freezing point.

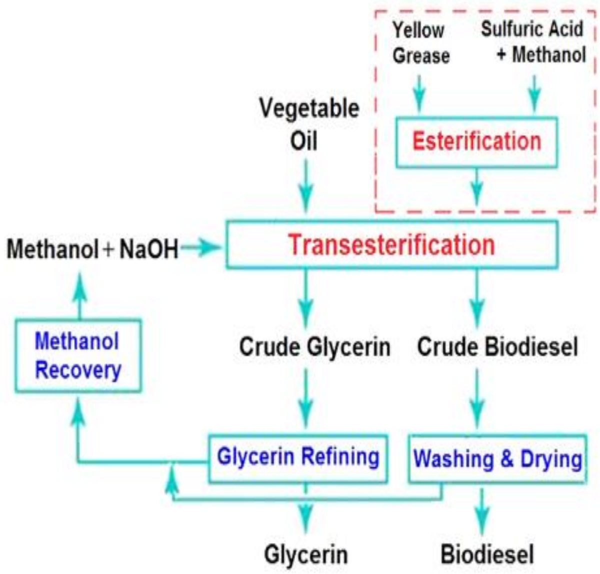


Figure 4 Flow Chart of biodiesel production from used vegetable oil [47]

4.4 Bio Alcohols

Bio-alcohol is the fermented form of catalytic formation of biogas [48]. Ethanol does not compatible with aircraft fuel due to its high volatility in nature. However, it has a very low flash point that helps to ignite faster and has low energy density. The storage of ethanol needs specific arrangements and proper transportation. The issues of ethanol regarding safety are challenging at a higher altitude of aircraft. Alcohol is not favourable in composition with other regular fuels due to low fuel characteristic features [49].

4.5 Liquid Biohydrogen

Hydrogen is a highly volatile fuel for jet engines and other aviation transport [50]. The liquid hydrogen is the stable form for aviation transport. Biohydrogen is suitable to be used for aviation. Biohydrogen is processed from biomass feedstock such as algae [51]. The processing of biomass succeeded with heat treatment and some chemical formulation to convert it into fuel. Liquid hydrogen is comparatively highly efficient due to its high energy density [52]. The storage of liquid hydrogen is large and complex due to its volatile and highly flammable [53]. In addition, biohydrogen has clean ignition without residue and omits less greenhouse emissions making it preferable along with limitations. However, using liquid hydrogen fuel requires a new engine design due to fuel ignition and safety compatibility. Along with the use of liquid hydrogen to blend with biodiesel is can ignite at low density due to low heating value [54]. Even though an example of a closed-loop application setup of hydrogen production and its utilization to generate electrical energy by using water source conversion with electrolyzer, solar plant, ionizer, liquefier in a consolidated form is shown in Figure 5.

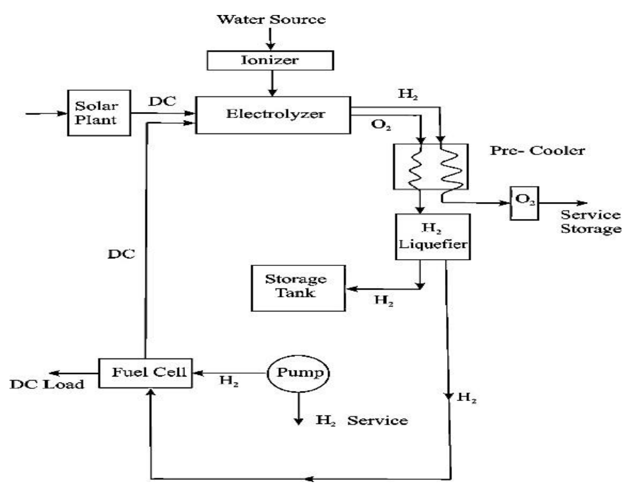


Figure 5 Production layout of Liquid Hydrogen [55]

4.6 Biomethane

Biomethane is a renewable and sustainable natural gas formed by the decomposition of organic matter. The anaerobic decomposition of animal dead bodies, plants, trees, manure, and other waste formed the biomethane [56]. Liquid methane is used in cryogenic air vehicles [50]. The use of biomethane or liquid methane requires modification in the engine or redesign of the structure and thus do not favour the commercialization of biomethane as a fuel [26]. The emission of methane gas also does not match the criteria of greenhouse measures.

Table 5 highlights the physical properties of various alternative fuels compared to JP-8. Methanol's freezing point has a near result, but its energy density and specific energy have a large gap. The characteristics of HRJ and SPK fuels are promising as an alternative for aviation sectors.

Table 5 Physical properties of different types of aviation fuels [2,34,57–59]

Fuels	Method	JP-8	Biodiesel	SPK (FT jet and HRJ)	Biokerosene	Methanol	HRJ fuel
Freezing Point	D7153	-51°C	-8°C	-48°C	-10-15°C	-54°C	-40°C
Specific Energy (MJ/kg)	D3338	43.2	37.3	43.28	33.8	20	
Energy Density (MJ/L)	D3338	34.5	33	43.40	29.5	15.9	43.22
CO_2 emission	D5291	0.8	76	0.76	0.86	0.79	0.53
Test Programme		AAFEX Engine/RR corporation	P & W Canada	Japan Airlines/Air New Zealand/Continental Airbus	KLM/Air France	RR corporation/ Research facility engines	Japan Airlines/ Air New Zealand/KLM / Air France

5.0 CONCLUSION

Manufacturers and aviation researchers are now focusing on efficient, available and sustainable alternative fuels. Certification organization is looking forward to market-scale production and appreciate alternative fuels to take in mainstream fuel list. Mass production of biofuels can affect water, food resources, ecosystem, biodiversity, and land. The fuel processing technologies have been proposed and studied to solve the complication of production procedure, distribution, storage, and sustainability. These all researches roam around the minimization of effective production processing costs. The future expectation from jet fuels should not compete with food and fuel needs. Greenhouse jet fuel emissions must be negligible and particulate-free for the environment. The fuel must be sustainable and available at a cheaper cost. The enhancement in fuel production technology can be possible with new technologies. The use of additives and catalysts can show better results in terms of more volumetric outcomes. The existing engines required the same specifications of fuel, but the blending of conventional fuel with biofuel made them more environmentally friendly and sustainable in the long run. Blending fuels can be a successful alternative fuel source since it consistently produces positive outcomes towards commercially affordable, sustainable, available and minimum change to the system for fuel replacement. The investment and participation of government, industries and other related organizations can create a huge opportunity for researchers or job seekers to maintain the production sustainability of jet fuels.

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