Reviewing the development of alternative aviation fuels and aircraft propulsion systems

Karna Dahal[a,*], Selma Brynolf[a], Maria Grahn[a], Julia Hansson[a,b] , Mariliis Lehtveer[c]
a) Department of Mechanics and Maritime Sciences, Maritime Environmental Sciences, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden
b) Sustainable Society, Energy, IVL Swedish Environmental Research Institute, Box 530 21, SE-400 14, Gothenburg, Sweden
c) Department of Space, Earth and Environment, Energy Technology, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden
*) corresponding author (karna.dahal@chalmers.se)

Abstract
Alternative aviation fuels such as bio-jet fuels, liquid natural gas (LCH_4), hydrogen (H_2), electro-jet fuels and direct electricity use play an important role in decarbonizing the aviation sector. New aircraft propulsion systems are being developed but low-blending of fuels is possible for some options. It is imperative to understand the technical, environmental and economic performance of the different alternative aviation fuels and the new engine and propulsion technologies for the utilization of these fuels. We have reviewed various literature to map the current status of development on alternative aviation fuels and related aircraft propulsion systems in relation to different perspective such as their cost and technical maturity. There are several challenges related to the design and implementation of the fuels and new propulsion systems. For instance, the volumetric energy content of alternative fuels is lower than the conventional aviation fuels which requires larger fuel storage tanks. Despite the advantageous environmental performance, both the bio-jet and electro-jetfuels are currently not economically competitive. Yet, studies forecast that increased use of alternative aviation fuels is possible after modifications of engines, fuel storage tanks and improvements of the aerodynamics of aircraft and by introducing subsidies and/or carbon taxes on conventional jet fuels.

Keywords: Alternative aviation fuels, aircraft propulsion systems, cost, bio-jetfuels, hydrogen, performance

Introduction
Alternative aviation fuels are low to zero carbon fuels which can reduce greenhouse gas (GHG) emissions and climate impacts significantly. These include bio-jetfuels, liquid natural gas/liquid methane (LCH_4), hydrogen/liquid hydrogen (H_2/LH_2), electro-fuels [produced from electricity, water (H_2O) and carbon-dioxide (CO_2)], and direct electricity use. The compositions of these alternative aviation fuels differ based on their feedstocks and production processes (Zhang et al., 2016). All aviation fuels must pass laboratory, storage and flight tests to get certified before they can be operated in the aircraft (Yilmaz & Atmanli, 2017). The development and commercialization of different bio-jetfuels and synthetic jet fuels is on-going and other possible alternative aviation fuel options such as LH_2 and LCH_4 are being explored. Several airlines have tested bio-jetfuels in some of their aircraft and minor amounts of bio-jetfuels are being used in low blending with fossil jet kerosene at present (Wang & Tao, 2016; IRENA, 2017). In parallel, there is a growing interest for production and testing of electro-fuels (Zhu, 2019). Electro-fuels are primarily produced via electrolysis of H_2O followed by different synthesis processes combining H_2 and captured carbon. These include electro-methane (e-CH_4), electro-methanol (e-CH_3OH) and electro-n-octane (electro-nC_8H_{18}) (Goldmann et al., 2018).

Some alternative aviation fuels cannot be adapted into the existing aircraft engines which run on fossil jet kerosene (Zhang et al., 2016). Thus, new aircraft propulsion systems are being studied and developed to operate on alternative aviation fuels. This is also the case for all electric and hybrid electric propulsion systems which can significantly reduce both the CO_2 and non-CO_2 emissions from aviation sector (Bogaert, 2015; Voskuijl et al., 2018; Schäfer et al., 2019). It is imperative to understand the technical, environmental and economic performance of the alternative aviation fuels and the new engine and propulsion technologies for the utilization of these fuels. Thus, we review various literature to map the current status of development on all the above-mentioned alternative aviation fuels and related aircraft propulsion systems in relation to their cost and technical maturity.

Methodology and reviewed literature

We reviewed 89 different publications published between 2005-2019 for a systematic assessment of alternative aviation fuels and related propulsion systems including electric and hybrid propulsions for future aircraft. The number of scientific publications focusing on alternative aviation fuels and propulsion systems has increased by a factor of five since 2005. To conduct the cost analysis, we reviewed minimum jet fuel selling price (MJFSP) of 12 different alternative aviation pathways including production cost of electro-jetfuel and H_2 from 26 different literatures (Figure 1). MJFSP is the minimum price a costumer has to pay for purchasing the jet fuel so that a zero-equity net present value (NPV) is achieved with certain % of return rate (Seber et al., 2014; de Jong et al., 2015). The electro-jetfuel production cost was estimated 'well-to-tank' cost from renewable resources (Schmidt et al., 2018) and H_2 production cost was estimated from different pathways such as electrolysis, hydrolysis of biomass and steam methane reforming (SMR) of natural gas (Gupta et al. , 2010; Starik et al., 2018). We compared them with the MJFSPs of other alternative aviation fuel pathways. All obtained cost values were first converted to the same units (USD/GJ) and then made equivalent to 2019 cost with the consumer price index (CPI-U) data to make them comparable to each other. The cost for LH_2 and LCH_4 were purchasing price in the market and we assumed them as the MJFSPs.

Technical maturity of the alternative fuels and propulsion systems

At the moment, only some biofuels with certain percentage (10-50%) of blending options with fossil jet kerosene have been certified by the American Society of Testing and Materials (ASTM) for the use in aircraft operation. Considering Technology Readiness Level (TRL) and Fuel Readiness Level (FRL), only Hydroprocessed Esters and Fatty Acids (HEFA) fuel and pathway is commercially ready (Table 1). In addition to the listed fuels in Table 1, both the H_2 and LH_2 as well as LCH_4 have not been certified for the use in aviation.

Table 1: Current status of reviewed alternative aviation fuels (Staples et al., 2014; Atsonios et al., 2015; Mupondwa et al., 2016; Schmidt et al., 2016, 2018; Neuling & Kaltschmitt, 2018; Santos et al., 2018; Wei et al., 2019; Ruzmien, 2020)

Process	Energy efficiency*	Certified level of blending (%)	Technology Readiness Level (TRL)	Fuel Readiness Level (FRL)
Fischer-Tropsch – Synthetic Paraffinic Kerosene/Aromatic (FT-SPK/FT-SPK/A)	0.40-0.53	50	6-7	7
Hydroprocessed Esters and Fatty Acids – Synthetic Paraffinic Kerosene (HEFA-SPK)	0.71-0.77	50	9	9
Direct sugar to hydrocarbons (DSCH) or Hydroprocessing of fermented sugars-Synthetic Iso-Paraffinic kerosene (HFS-SIP)	0.50	10	7-9	8
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	0.91	50	6-7	8
Co-processing	N/A	5	7-8	6-7
Catalytic Hydrothermolysis Jet fuel (CHJ)/Hydrothermal Liquefaction (CHJ/HTL)	0.58-0.89	50	4-6	6
Hydroprocessed Depolymerized Cellulosic Jet (HDCJ)	0.36	Under certification	-	6
Aqueous phase processing/reforming (APP/APR)	0.32	Under certification	-	6
Advanced Fermentation/Fermentation	0.31-0.34	No certification	Under demonstration	-
Mixed alcohol synthesis (MAS)	0.40-0.44	No certification	Proposed technology	-
Pyrolysis	0.6-0.8	No certification	Under development	-
Electro-jet [Power to liquids (PtL)]	0.38-0.63	No certification	5-8	-
Electro-jet [Biomass to liquids (BtL)]	0.38-0.63	No certification	5-9	-
*Energy efficiency: The ratio of energy output (upgraded jet fuel) and the total energy input (process energy input and feedstock energy input) (Tzanetis et al., 2017) or thermal efficiency of a refinery.				

Likewise, propulsion systems for different alternative aviation fuels and hybrid as well as all electric aircraft are being studied (Felder et al., 2017; Schäfer et al., 2018). Current state of the art of battery pack specific energy is just 200-250 Wh/kg which needs to reach around 800-1200 Wh/Kg for a regional electric aircraft (Schäfer et al., 2018). Fuel cells are also not in operation in commercial aircraft system yet (Taghavi et al., 2014). It is suggested that H_2 fuel cells can save up to 70% weight compared to battery-electric propulsion (Satyapal, 2017).

Economic performance

Diverse MJFSPs of alternative jet fuels have been estimated in various literature (Figure 1). Overall, Catalytic Hydrothermolysis/Hydrothermal liquefaction (CH/HTL), Pyrolysis, Alcohol-to-Jet (ATJ) and Fischer-Tropsch (FT) Synthetic processes offer the lowest possible MJFSPs while Hydroprocessed Esters and Fatty Acids (HEFA), Hydroprocessed Depolymerized Cellulosic Jet (HDCJ), Advanced Fermentation (AF) and Direct sugar to hydrocarbons (DSCH) pathways offer highest MJFSPs (Figure 1). HEFA fuels are generally less expensive but if produced from microalgae, they become expensive (Tao et al., 2017; Klein-Marcuschamer et al., 2013). The bio-jet fuel MJFSPs from wheat grain, willow, wheat straws, forestry residues and manure have shown lower cost than other feedstocks included in the reviewed literature.

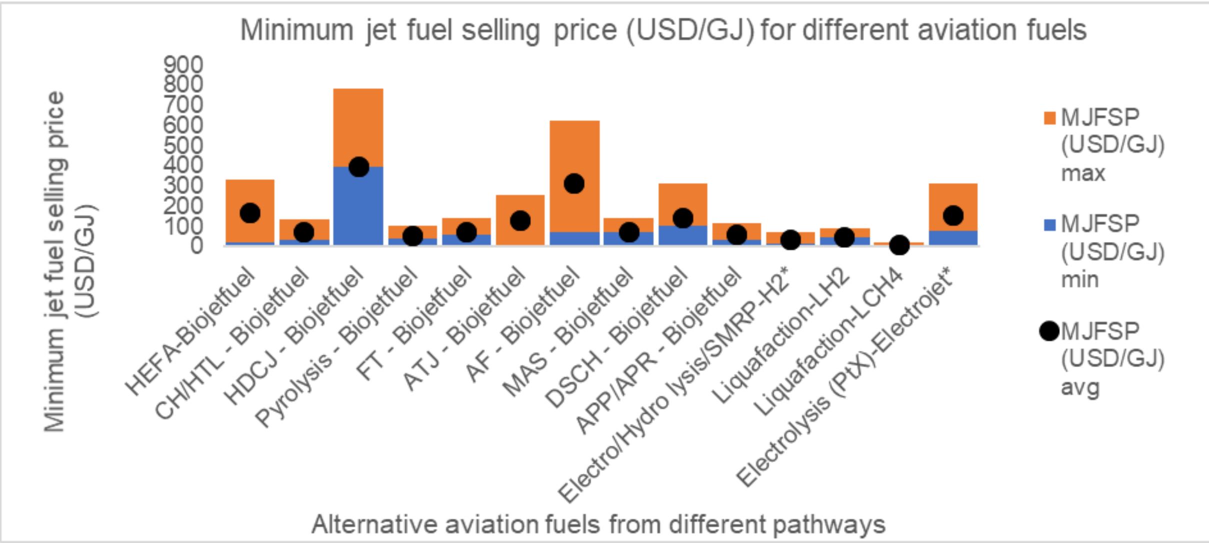

Figure 1: Minimum jet fuel selling price of different aviation fuel pathways (*production cost)

Both the LH_2 and LCH_4 are less expensive than the most bio-jet fuels but LH_2 is more expensive than LCH_4. H_2 production cost is the second smallest among all pathways but their production cost values are contradictory in different literatures as H_2 is produced/utilized in various chemical/fuel production processes. On the other hand, production cost for electro-jet fuel pathway is higher than the MJFSPs of most bio-jet fuel pathways. The average energy based MJFSPs (USD/GJ) of most pathways are 3-22 times higher than the fossil Jet fuel (Jet A-1) purchasing price (17.7 USD/GJ) at the moment (Platts, 2019).

Challenges and opportunities

Deployment of alternative fuels in aircraft engines is challenging at the moment. For instance, the volumetric energy content of alternative aviation fuels (specially LH_2 and LCH_4) are much lower than the fossil jet fuels which requires larger fuel storage tanks (Khandelwal et al., 2013; Rory et al., 2015). Similarly, some alternative aviation fuels have low flame stability and low combustion efficiencies which obstruct easy work in the existing engines (Zhang et al., 2016; Malins, 2017). Supply of some alternative aviation fuels at airports via existing pipelines is not appropriate due to low production volume of such fuels and leftover impurities in the pipes

(Herzig et al., 2017). Lack of suitable fuel storage tanks at airports is also problematic. Similarly, the main challenge of battery-electric aviation is the limited onboard energy storage capacity in batteries (Gnadt et al., 2018). To improve the high specific energy of the battery is material-intensive which increases the weight of batteries and propulsion energy requirement (Hoelzen et al., 2018). The sole use of fuel cells cannot provide enough power required for take-off and hence combustion turbines may be required. Modification of engines and aerodynamic are challenging for new fuel types. The design and construction of tanks for cryogenic liquid storage and controlling the effects of strong thermal stresses in the structural parts are also challenging (Sziroczak et al., 2016).

However, some of the challenges can be resolved by implementing spherical tanks with increased thermal insulation, accommodating reduced surface to volume ratio, and fixing fuel tanks on the top of the fuselage to reduce wing areas (Blakey et al., 2011; Khandelwal et al., 2013; Zhang et al., 2016). Similarly, H_2 and NH_3 can be burnt with oxygen and fuel-air ratio can be altered to mix fuel enough and reduce NO_x emissions (Khandelwal et al., 2013; Goldman et al., 2018). The research and development of suitable new engine types or modification of the combustion chambers are ongoing and will improve the concepts.

Discussion and Conclusion

The results of the literature review show diverse MJFSPs from various pathways primarily due to several factors such as different feedstock, feedstock cost, refinery capital cost, co-product revenues, plant capacity, reactor construction, catalyst used and electricity cost. Bio-jet fuels produced via HEFA, CH/HTL, Pyrolysis, ATJ and FT pathways seem more feasible than other pathways but only HEFA pathway is commercially ready until now. LCH_4 is much cheaper than any other alternative aviation fuels as the market price of the natural gas is relatively low. Similarly, production cost for electro-jet fuel pathway is higher than some bio-jet fuel pathways and 3-6 times higher than fossil jet fuel production (Environment, 2018). However, the average energy based MJFSPs (USD/GJ) of the most pathways are significantly higher than the purchasing price of fossil jet kerosene at the moment. Economic incentives, carbon penalties and other governmental policies are required to further expand the utilization of alternative aviation fuels.

The results also highlight several challenges for the production and implementation of alternative aviation fuels as they possess slightly differing characteristics than fossil jet fuel which limit the performance in the existing engines (Zhang et al., 2016; Malins, 2017). The storage problem is a challenge for all alternative fuels but specifically problematic for H_2 and CH_4 due to their low volumetric energy content. The aircraft using LH_2 or LCH_4 will never be able to fly with the current fuel tanks as the volume limitations prevent the aircraft having enough fuel for take-off, landing and holding (Blakey et al., 2011). Yet, all alternative aviation fuel options have potential to reduce GHG emissions but modifications to engines, fuel storage tanks and aerodynamic systems are required. The research results also show hybrid propulsion systems are more feasible than all electric aircraft in near term.

Acknowledgement

We gratefully acknowledge financial support from the Swedish Energy Agency and the Swedish Knowledge Centre for Renewable Transportation Fuels (f3) [project carried out within the collaborative research program Renewable transportation fuels and systems program (Samverkansprogrammet Förnybara drivmedel och system) “Project no. P48357-1”].

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