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BEGINNING STEPS OF THE ELECTRIFICATION OF COMMERCIAL PASSENGER AIRCRAFT TRANSPORT

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1. INTRODUCTION

Air passenger transport is rapidly growing. The associated revenue, based on the calculation of passenger kilometres (RPKs), is projected to grow annually, at a rate over of 4%, within the next 20 years. Although the fastest growth rates are expected in regions with emerging economies, such as Pacific Asia, the Middle East, Africa, and Latin America, RPKs in the more mature European market are still expected to grow at rate of 3.7%. Likewise, the world fleet is expected to increase by 25,000 units from 2018 to 2037, leading to the total number of 53,600 aircraft at the end of 2037. On the other hand, main European airports are expected to reach their full capacity by 2030. If airports do not grow to meet the demand, this can lead to significant economical and other deficits. One of the main obstacles preventing the growth of large-airport hubs is the environmental impact of air transport to the local environment. Larger European hubs are already inducing flight restrictions, such as disallowing take-off and landing during night hours or charging fees for gas emissions.

Conventional aircraft are powered by internal combustion engine (ICE) emit gases and particles such as carbon dioxide (CO_2), water vapour, hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_X), sulphur oxides (SO_X), lead, and black carbon. Carbon dioxide and water vapour are normal combustion by-products, while carbon monoxide and hydrocarbons are products of incomplete combustion. Nitrogen oxides, on the other hand, are produced by nitrogen bounding with oxygen at high temperatures and high pressures. Carbon monoxide is a toxic gas that bounds to haemoglobin and therefore reduces its ability to carry oxygen. CO is deadly at high concentrations, while at lower concentration a human body naturally recovers from poisoning in a couple of hours or days (depending on severity of poisoning). Hydrocarbons are major contributors to smog, while prolonged exposure to HC can cause lung and liver diseases as well as cancer. Nitrogen oxides contribute to the formation of smog and acid rain and can cause lung and heart diseases. Furthermore, NO_X (including nitrous oxide (N_2O)) have also a significant greenhouse effect. Carbon dioxide is not toxic, but it's a major greenhouse gas. Therefore, HC, CO and NO_X can be considered as local pollutants and their concentrations should be regulated in the vicinity of airports, while CO_2 and NO_X (including N_2O) should be considered as global pollutants and contributors to greenhouse effect.

As air traffic is constantly increasing so is rising the pressure on environment and use of alternative fuels is becoming necessity in the European commission endeavours for clean and safe environment. In EU vision for protecting the environment and the energy supply, a key is in technologies that will allow reduction of carbon dioxide ($CO_{2,}$) and nitrogen oxides (NO_X), toxic gas emission and noise. the Advisory Council for Aeronautical Research in Europe (ACRE) has set a target to reduce NO_X emissions in air transport by 80% by the end of 2020 and by 90% by the end of 2050. Likewise, the target for noise reduction is 50% by the end of 2020 and 65% by the end of 2050. The European Commission Vision is also shared by International Civil Aviation Organisation (ICAO), International Air Transport Association (IATA) and National Aeronautics and Space Administration (NASA).

One way to avoid high pollutions and negative impact of conventional aviation on environment is by introducing new aircraft propulsion technologies that can partially or fully reduce before mentioned local toxic gas emissions, global greenhouse gas emissions and/or noise. To address this issue, MAHEPA project explored several hybrid-electric propulsion technologies that could be appealing for a new paradigm of transport services and business models, such as pure electric battery driven aircraft, ICE hybrid aircraft and fuel-cell hybrid aircraft. To enable wider implementation of ICE-hybrid and fuel-cell hybrid for passenger and freight transport, novel investments in ground infrastructure for charging at airports will be required as well.

2. NEW AIRCRAFT PROPULSION TECHNOLOGIES

2.1 Electric battery driven aircraft

In a pure electric battery driven aircraft the energy is provided by a battery that drives an electro-motor rotating the propeller. A propeller then gives a thrust to an aircraft. The main advantages of a battery driven aircraft are zero local gas emissions and significant noise reduction. A battery driven aircraft can also present an opportunity for reducing global CO_2 emissions, if the electricity would be produced from a renewable source with a low CO_2 footprint. Nevertheless, a major disadvantage of a battery driven aircraft is a very low specific energy of the battery. Consequently, battery driven aircraft are heavier, consume more energy and may reach significantly shorter ranges.

With pure electric battery driven aircraft, different ranges can be achieved depended upon the aircraft payload and energy density of batters. As seen on Figure 1, three different payloads of empty weight of a battery driven electric aircraft are considered: green area denotes 0.5 tonne of aircraft payload (approx. 6 passengers), - blue area denotes 2 tonne of aircraft payload (approx. 19

passengers), and orange area denotes 7 tonne of aircraft payload (approx. 70 passengers). The top border of each area indicates ranges, reachable by batteries with energy density of 0.25 kWh/kg, while the bottom border indicates ranges reachable by batteries with energy density of 0.1 kWh/kg. Figure 1 assumes that the energy is used only during cruise for overcoming the drag force. To reach a cruise speed of around 500 km/h or to gain 1 km in altitude, an aircraft will use approximately the same amount of energy as for flying 25 km during cruise. As typical turboprop aircraft have a cruise speed between 400 − 600 km/h and a ceiling at around 7,600 m, approximately 200 km should be deduced from the ranges given in Figure 1 for electric aircraft with similar characteristics. In addition, energy must be used for other functions as well, like heating the cabin and passenger section. Likewise, for safety reasons, some additional energy must be kept at reserve, triggering even larger reduction in range. By expanding the wing surface or increasing the aspect ratio, a range of the electric aircraft could be somewhat extended. On the other hand, this would reduce the cruise speed of an aircraft.

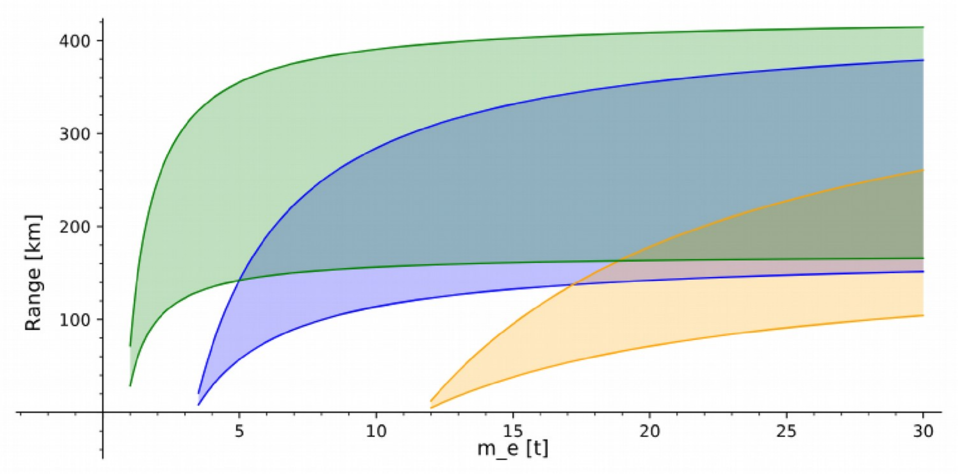

Figure 1: Ranges reachable by electric battery aircraft.

2.2 ICE-hybrid aircraft

In an ICE-hybrid aircraft an energy is provided from a combination of a battery and ICE system. A fuel powered hybrid aircraft is designed to provide an electric take-off and landing, while cruise flight would be performed with an ICE system. During decline, the battery is partially refilled giving the ability of the aircraft to use that energy for taxiing. Fuel-powered hybrid aircraft have to provide 150-300 kW battery power per tonne of aircraft's mass to enable all electric take-off. If batteries with high specific power are used (and consequently lower specific energy), they could provide enough energy for take-off and first kilometres of climb. An advantage of such an aircraft would be a zero local toxic gas emissions and significant noise reduction in the vicinity of airports, while keeping good flight characteristics of convectional aircraft, like low weight and long range. Nevertheless, a fuel powered hybrid aircraft would not contribute to a significant reduction of CO_2 emissions.

Considering the architecture aspects, there are two possible types of fuel powered hybrid aircraft: parallel and serial. In a parallel ICE-hybrid aircraft, propeller is rotated either by an ICE-power train or by an electro-motor, charged from a battery. A dedicated mechanical system switches between two modes, an ICE or electro-motor. In a serial ICE hybrid aircraft, the propeller is driven only by an electric motor, powered by a generator or by batteries. Compared to the parallel ICE hybrid aircraft, serial ICE hybrid aircraft has a few advantages. First, the lack of a mechanical power transfer between the power generating unit (ICE or electro-motor) and the propeller reduces the mechanical complexity and increases the overall system reliability. Second, the electric motor offers increased reliability and reduced maintenance, compared to the ICE-powered engine. Third, a further reduction of noise emissions can be achieved by designing electric motors and corresponding propellers rotating at lower speeds, without the need of weight-inefficient reduction gearboxes that are required by parallel hybrids. Fourth, gaseous emission reduction is not only achieved during the segments of flight, when an aircraft is powered only by battery (e.g. take-off and landing), but also by a possibility to run a fuel-driven power unit (generator) in the most efficient regime, which therefore increases the efficiency of the entire power-train.

2. 3 Fuel-cell hybrid aircraft

A fuel-cell hybrid aircraft is designed similar as a serial ICE-hybrid aircraft with fuel-cells, powered by hydrogen as generator. In a fuel-cell, electric energy is produced from hydrogen, making water the only by-product. Therefore, fuel-cell aircraft does not emit any additional gases beyond water vapour. A low noise, zero local toxic gas emission aircraft, powered by hydrogen, can also reduce CO_2 emissions in case of hydrogen being produced from a low carbon dioxide footprint sources (e.g. electrolysis, electricity produced from renewable resources), compared to a fuel-driven hybrid aircraft. Moreover, hydrogen has a very high specific energy (higher than kerosene). Unfortunately, due to its low mass density, hydrogen must be kept in pressure or cryogenic tanks with high mass.

In an automotive industry hydrogen can be either used in a compressed or a liquefied form. Liquefied hydrogen must be stored in well insulated tanks. An insulated 90-liter tank with a storage capability 6.3 kg of liquid hydrogen has a mass of 40 kg. In case of compressed hydrogen, a 100-liter tank containing 4 kg of hydrogen under 700 MPa pressure has a mass of 50 kg. Therefore, an energy density of the whole system (hydrogen and tank) is less favorable, holding only 2.7 kWh/kg for a liquefied hydrogen and 1.5 kWh/kg for a compressed hydrogen. Fortunately, as a volume of tank grows, mass of the tank grows proportionally with the tanks' surface. As surface-to-volume ratio is greater for larger tanks, an energy density of the system rises with enlargement of a tank volume, as shown in Figure 2. Figure 2 shows an effective energy density of a hydrogen-tank system in dependence of its capacity to liquid hydrogen (blue area, full-line), and compressed hydrogen (green area, dashed-line) for fuel-cell efficiencies between 55 % and 60 %. For comparison, the black line represents an effective energy density of kerosene. Considering the efficiency of turboprop engines and fuel cells the effective energy density of a hydrogen system can reach that of kerosene for tanks containing 20 kg of liquid hydrogen (approx. 300 liters) or tanks containing 150 kg of compressed hydrogen (approx. 2 000 liters). This is an indication that hydrogen is a good fuel choice for aircraft with more payload and/or large ranges.

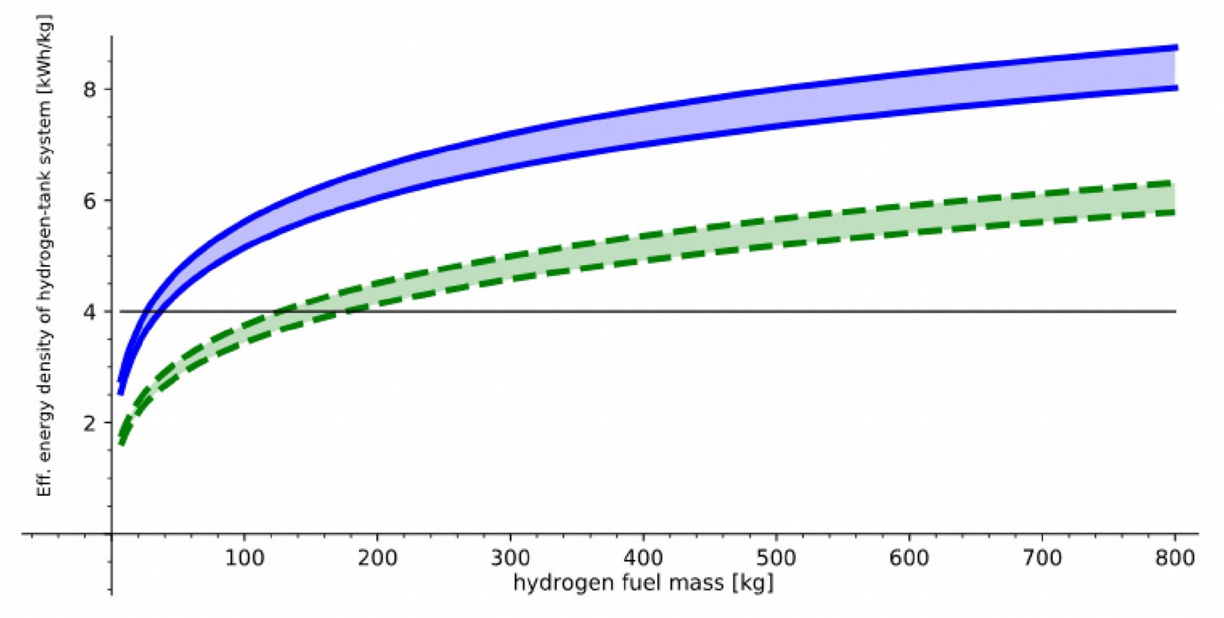

Figure 2: Hydrogen energy density in dependence of stored mass of hydrogen.

On the other hand, the fuel consumption of a fuel-cell hybrid aircraft would increase compared to the convectional aircraft, also due to enlarged surface of tanks. According to Verstraete, this can lead to L/D ratio of a fuel-cell hybrid decreasing from 20 to 17, yielding a 17 % increase in fuel consumption due to higher parasitic drag. By taking this into account it can be concluded that an energy consumption of a 19-seater and 70-seater aircraft could be at least similar, if not even lower than the consumption of a convectional aircraft. The exact consumption can be calculated only if exact shape of the aircraft and tank is known. Nevertheless, by assuming that energy consumption of a fuel-cell hybrid aircraft is the same as the energy consumption of a convectional aircraft, one can predict that a 19-seater aircraft would consume from 50 kg to over 200 kg of hydrogen (depending on range), while a 70-seater aircraft would consume from 200 kg to over 700 kg of hydrogen for the same range.

3. POTENTIAL MARKET

Conventional passenger aircraft are usually classified into three categories: single-aisle (narrow-body), twin-aisle (wide-body), and regional aircraft. Regional aircraft are the smallest type of aircraft, which can typically carry up to 100 passengers. Depending on the engine type, regional aircraft can be further divided into regional jets and turboprops. In turboprop engines, the energy released from combustion is used to rotate a propeller. The propeller then provides the thrust that drives the aircraft. On the other hand, the energy released by combustion in jet engines is used to accelerate exhaust gases backwards, providing the thrust that pushes the aircraft forwards. Due to the difference in mechanism, turboprop engines can provide less thrust than jet engines, but can use fuel more efficiently. Consequently, turboprop aircraft fly at lower attitudes and with lower speeds than regional jets, and are more suited for shorter ranges. As all-electric and hybrid aircraft are also driven by a propeller, their flight performance is very similar to turboprop aircraft. Therefore, it can be assumed that hybrid aircraft could replace turboprop aircraft, but not necessarily jet aircraft. The latter would occur only if the ecological impact prevails over the speed advantages of jet aircraft. According to FlightGlobal, it has been predicted that, in the period from 2018 to 2037, over 45,000 new aircraft will enter the flight service, either as a replacement for old models or due to the increase in passenger aircraft traffic; furthermore, 16% of these aircraft will be used in Europe. Around 4000 of all new aircraft will be regional jets and around 3000 turboprops. Therefore, potentially, around 40% of newly-produced regional aircraft could be exchanged for hybrid aircraft without any loss in flight performance (around 500 being in the EU). Furthermore, the International Civil Aviation Organization (ICAO) divides commercial air passenger transport services into scheduled and non-scheduled flights. Non-scheduled flights can be further divided into charter and on-demand flights, the latter including air-taxi, commercial business aviation, another similar services. All records of scheduled flights are kept in databases, such as Official Airline Guide (OAG). According to OAG demo database (Figure 3), a vast majority of flights using 1–8 seater aircraft were operated over ranges shorter than 50 km. These flights can be efficiently covered with small, electric battery driven aircraft. Furthermore, 9–70 seater aircraft covered ranges up to 500 km, and could therefore be replaced with hybrid aircraft without a considerable loss in flight performance. Nevertheless, apart from scheduled flights, the number of on-demand business flights in EU is constantly growing and can present an important aircraft service potential in the near future. According to the PrivateFly report, the business aviation fleet, servicing on-demand flights in EU in 2017, was comprised of 955 light jets (26.7% of the fleet) and 2177 turboprops (34.2% of the fleet). The rest were heavy and mid-sized jets. Nevertheless, as shown in Figure 4, light jets seem to be replacing turboprop aircraft, leading to a conclusion that, in the on-demand flight sector, speed is treated as more important than cost. Furthermore, unlike scheduled flights, on-demand flights tended to cover higher ranges (above 500 km). Therefore, it is questionable whether hybrid aircraft (based on propeller propulsion) would be a suitable option for covering this section, as well.

Figure 3: Number of passengers for 1–8 (blue), 9–19 (orange), and 20–70 (green) seater aircraft in theEuropean region in 2017.

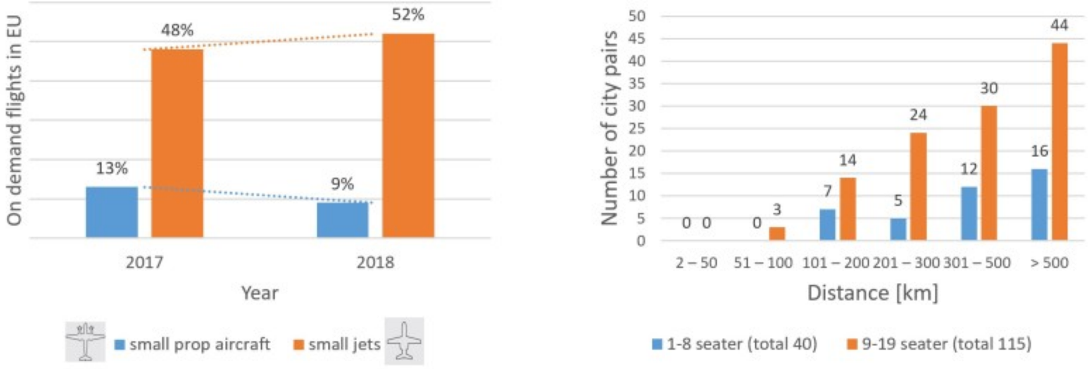

Figure 4: Share in on-demand flights for turboprop (blue) and small jets (orange) for 2017–2018 in the EU. Number of city pairs covered with 1–8 and 9–19 seater aircraft, by distance.

4. GROUND INFRASTRUCTURE REQUIREMENTS

4. 1 Charging station requirements

The assessment of required ground infrastructure and ground handling services at airports for fast multiple charging of hybrid-electric aircraft consist on following assumptions:

- Batteries for hybrid electric aircraft will be designed is such a way to allow for zero emission in the whole landing and take-off (LTO) cycle. This means that the battery has to provide enough power for all-electric take-off and landing.
- Specific power and specific energy of batteries are assumed to be at today's level.
- To satisfy above assumption, a battery with a high specific power have to be used. We will model our prediction on the assumption that the aircraft will be equipped with batteries with a specific power of 2 kW/kg and specific energy of 100 Wh/kg.
- Battery has to provide a power of 150-300 kW per tonne of aircraft mass.
- The ground infrastructure required is assessed for charging 19 and 70 seaters, considering the average number of flights per day on airports.

Taking into account above assumptions, a 19-seater aircraft will therefore be equipped with a battery with capacity of 50 -100 kWh, while the 70-seater aircraft will have the battery capacity of 180-360 kWh. The approximate times needed to charge a 19-seater and 70-seater aircraft are presented in Table 1.

Table 1: The approximate times needed to charge a 19-seater and 70-seater aircraft with different charging stations

Charging station power [kW]	Time to charge a 19-seater aircraft [h]	Time to charge a 70-seater aircraft [h]
3.3	15-30	55-110
7.4	7-14	24-48
11	5-9	16-33
22	2-5	8-16
43	1-2	4-8
50	1-2	4-7
120	1	1.5-3

According to charging times in Table 1, and average number of flights per day on airports, a single three-phase station with charging power of 43 kW would be enough to cover all needs of charging a 19-aircraft in all airports. Moreover, 43 kW charging station would cover all needs for charging a 70-seater aircraft in 2/3 of airports that operate with 70-seater aircraft. Similar, one 120 kW charging station would cover needs of 88% of airports that operate with the 70-seater aircraft. The airport with the largest number of flights (TOS) would need 4-8 charging stations with 120 kW power output or three times as many charging stations with 43 kW power output. Therefore, investment costs for the majority of airports would be between 15,000 EUR and 50,000 EUR, while for the airport with the most frequent number of flights, the infrastructure may cost around 200,000 EUR. As number of aircraft is predicted to double by 2035, by that time, one 43 kW charging station would cover needs for charging a 70-seater aircraft in 50% of airports and for charging a 19-seater aircraft in all airports, while one 120kW charging station would cover charging needs for 70-seater aircraft in 75% of airports.

Nevertheless, it has to be taken into account that battery charging is long lasting procedure and that the minimal time to fully charge the battery would be one hour. To achieve fast turn-around rates (20 minutes), one to two (depends of battery capacity) 120 kW charging stations would be needed to charge a 19-seater aircraft simultaneously. I that case, batteries could be maximally charged up to 80% SoC (state of charge). Similar, for a 70-seater aircraft 4-8 120 kW charging stations would be needed to charge the batteries up to 80% SoC. Another option would be a battery swap method. For ground vehicles, battery swap method was abounded for several reasons. First, different types of vehicles need different types of batteries (one size does not fit all), therefore a vast majority of different types of batteries for every type of vehicle should be kept in storage. Second, safety and battery life depends on how the battery is handled. In the case of accidents, it is therefore hard to define, who should take the responsibility. In air transport, similar problems arise, but to less extend. From today's point of view, it is therefore hard to predict if battery swap method or direct charging method will prevail.

4. 2 Hydrogen requirements

A study done by C. Young and J. Ogden considers different hydrogen delivery scenarios for USA. Although the analysis is done taking into account equipment and transport costs characteristically for USA market in 2007, the obtained conclusions can be generalized to today EU market as well. The study takes into account three different delivery scenarios: delivery by gas truck, delivery by cryogenic truck and delivery by pipeline.

In first scenario (delivery by gas truck), hydrogen is compressed at production site and transported to the local consumer by tube trailer trucks. It is assumed that the full trailer is dropped at the delivery site and that the empty trailer is picked up. The largest cost component in gas truck delivery scenario are the truck operating and maintenance costs, including drivers labour. Therefore, transport distance has the greatest effect on delivery costs and scales linearly with distance, while on the other hand, costs are relatively independent on hydrogen flow rate (amount of hydrogen delivered to the consumer per day).

In second scenario (delivery by cryogenic truck), hydrogen is liquefied at production site and transported to the consumer by cryogenic truck. Study assumes that trailers are not left at consumers site and that in each trip the truck visits empties its entire load, and that the minimal capacity of the liquefier used at the production site is 30 tonnes per of H_2 day. The largest cost component it cryogenic truck delivery scenario is liquefaction (80%-95% of all costs), therefore the overall costs liquid hydrogen delivery strongly depends on hydrogen flow and is almost independent on distance.

In third scenario (delivery by pipeline), hydrogen is first pre-compressed at production site and then delivered to the consumer by pipeline. Depending on usage, hydrogen can be further compressed on consumer's site as well. In this scenario, the far most important cost component is the pipeline capital cost. Therefore, the overall costs depend both of hydrogen flow rates and distance.

Figure 5 presents the optimal hydrogen transmissions scenarios and minimal transmission costs for different hydrogen flow rates and transport distances. It can be concluded that the delivery by of compressed gas by truck is optimal for short distances and low hydrogen quantities; delivery by cryogenic truck is optimal for large distances and low hydrogen flow rates, while delivery by pipeline is optimal for high hydrogen flow rates and large distances.

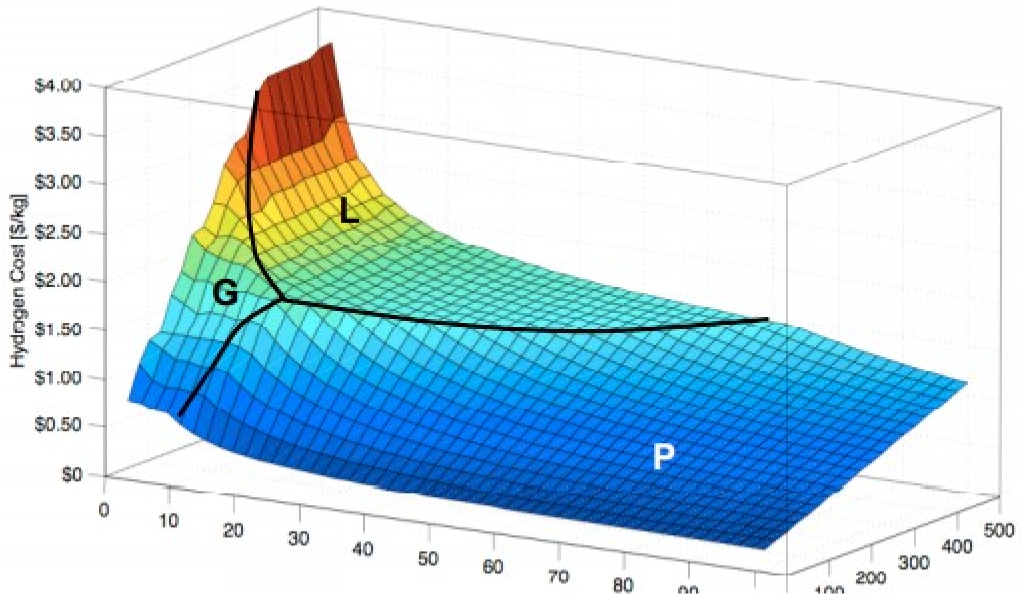

Figure 5: Optimal hydrogen transmission scenarios and minimal hydrogen transmission costs depending of hydrogen flow rates and transport distances.

Nevertheless, above study assumes that the end user does not differentiate between gaseous and liquid hydrogen. Aircraft prefer hydrogen in liquefied form for two reasons. First, effective specific energy of hydrogen and tank system is higher for liquid hydrogen compared to gaseous hydrogen. Therefore, aircraft flying on a liquid hydrogen is lighter as the aircraft using compressed hydrogen. As aircraft consumption is proportional with aircraft mass, aircraft flying on liquid hydrogen consumes less hydrogen. Moreover, cryogenic hydrogen tanks are smaller than compressed hydrogen tanks, which has for a consequence better aerodynamic properties and therefore even lower consumption. To asses the hydrogen transmission economics, aircraft efficiency consumption has to be taken into analysis as well. Unfortunately, exact energy efficiency of a hybrid fuel-cell aircraft is still unknown as it largely depends on aircraft design.

Under premises that the energy efficiency of a hybrid fuel-cell aircraft is similar to the conventional aircraft, we can conclude that a 19-seater aircraft would need approximately 200 kg of hydrogen for 500 km range flight and 70-seater aircraft would need approximately 700 kg of hydrogen for the same range. If all regional aircraft in EU would be exchanged for hybrid fuel-cell aircraft, 90% of airports would need less than 10 tonnes of hydrogen per day to fuel them. Evermore, 80% of airports operating with 19-seater aircraft and 50% of airports operating with 70-seater aircraft would need less than 1 tonne of hydrogen per day. On the other hand, the airport with most regional flights per day in Europe (i.e. Tromsø airport, Norwegian) would need around 40 tonnes of hydrogen (per day). Nevertheless, it should be taken into account that hydrogen is even more appealing fuel for large aircraft and therefore, one should not limit on assumption that only regional aircraft would fly on hydrogen. In that case, a daily consumption on large airport hubs can be even much larger.

6. CONCLUSIONS

It may be concluded that ICE-hybrid aircraft can provide a good solution for the reduction of NO_X, HC, and CO emissions in the vicinity of airports. Hybrid aircraft also produce significantly less noise during take-off and, therefore, contribute to the reduction of noise pollution as well. As an ultralight ICE-hybrid aircraft has already been developed, similar concepts can be used for regional aircraft. ICE-hybrid aircraft could be equipped with batteries large enough to enable all-electric take-off and landing. On the other hand, electric battery driven aircraft could be successfully used, but only for aircraft with up to eight seats and short ranges. Such aircraft could be used for scheduled flights replacing conventional 1–8 seater aircraft, and for services such as panoramic sight-seeing. On the other hand, for services where long ranges with high speeds are expected, such as on-demand flight services, neither electric battery driven electric nor hybrid aircraft of current design could meet the demands. Therefore, it would be convenient to design a hybrid aircraft model that could combine a battery-driven propeller with a jet engine. Moreover, a further development can be expected in optimization of aircraft shape and in the improvement of battery technology. Moreover, neither electric battery driven nor ICE-hybrid aircraft could significantly reduce the overall emissions of the greenhouse gases CO_2 and NO_X. The latter can be reduced by using fuel-cell aircraft, but only if hydrogen could be produced from renewable sources. Evenmore, a fuel-cell aircraft will be economically feasible only when the price of hydrogen fuel (compared to price of kerosene) is competitive enough, which is not the case, at present.

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