ADAPTATION OF AIRPORT INFRASTRUCTURE FOR OPERATION OF ICE-HYBRID AND FUEL-CELL AIRCRAFT

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ABSTRACT

In not-so-distant future, hybrid-electric aircraft are expected to enter the market and revolutionise the segment of local and regional flights. Hybrid-electric aircraft, either as a combination of internal combustion engine (ICE) and battery (ICE-hybrid) or fuel-cell hydrogen and battery (fuel-cell hybrid), will contribute to reduction of the negative environmental impact of aviation while reducing the dependence on fossil fuels. Their introduction will require adaptation of airport ground infrastructure as existing airport ground infrastructure is not suited for hybrid aircraft operations i.e. either is non-existing, insufficient, or inappropriate. A feasibility study aiming to assess the technical aspects of the needed ground airport infrastructure for fast charging of ICE-hybrid and refuelling of fuel-cell hydrogen hybrid aircraft is thoroughly explored and presented in this article. Two study cases, within the MAHEPA project were developed to estimate technical requirements for the relatively novel ground infrastructure needs at airports. The first study refers to multiple charging issues of ICE-hybrid aircraft, while the second study refers to refuelling of fuel-cell hydrogen hybrid aircraft. Since the charging technology for hybrid electric vehicles is already available in automotive industry and is transferable to aviation industry, initial investment is expected to be lower than the investment for fuel-cell hybrid aircraft. The article thoroughly examines various technical aspects of necessary adaptation of airport infrastructure in order to enable smooth operation of ICE-hybrid and fuel cell hybrid aircraft.

Keywords: MAHEPA, hybrid aircraft, ICE-hybrid, fuel-cell hybrid, ground airport infrastructure, airport, aviation

INTRODUCTION

Air traffic causes several negative impacts on the environment such as toxic gas, greenhouse gas and noise emissions. In order to reduce increasing pressure of aviation on the environment, the aviation industry has committed itself to certain targets such as: improving fuel efficiency for 1.5 % per year, achieving net carbon growth by 2020 and reducing global net aviation emissions for 50 % by 2050 (IATA, 2019). Efforts to mitigate the negative environmental impact of aviation have led to a variety of emission mitigation measures such as the introduction of alternative aviation fuels, fuel efficiency improvements (e.g. new design with lightweight composites) and operational measures (e.g. more efficient flight procedures) (Dray, Evans , & Schäfer, 2010; Hassan, et al., 2015; ICAO, 2016; Owen , Lee , & Lim, 2010; Schilling , Rötger, & Wicke, 2016). Momentarily, the aviation industry is strongly inclined to reduce its dependence on fossil fuels through introduction of Sustainable Aviation Fuels (SAF), which are mainly produced of sustainable feedstocks (e.g. waste oils, agricultural residues or non-fossil CO_2) (SkyNRG, 2020). Since SAF feedstock and thus the production of sustainable fuels is limited, the interest in substantial fuel efficiency improvements based on radically new propulsion technologies and designs, stills remains high (IATA, 2019). While all of the beforementioned mitigation measures contribute to reducing aviation emissions and have the potential to improve fuel efficiency up to 30 % by around 2030, more radical improvements will be needed after 2030, if we want to significantly reduce fuel consumption and carbon emissions (IATA, 2019). In this respect, further emission reductions could be achieved through revolutionary technologies, such as new aircraft configurations, new designs and propulsion systems, which include fully electric, ICE-hybrid or fuel cell hydrogen aircraft (Marksel, et al., 2019).

On average every 15 to 20 years aircraft are replaced by new generation of conventional aircraft, with improved average fuel efficiency up to 15 %. Hybrid-electric propulsion can achieve 40 % to 80 % of fuel savings, while fully electric propulsion up to 100 %. In addition, the hybrid-electric powered aircraft with blended wing body can achieve CO_2 emission reductions up to 40 %. Taking into account today available renewable energy sources for electricity, the electric aircraft, could completely eliminate CO_2 emissions compared to conventional aircraft (IATA, 2019). The German Aerospace Center (DLR) studies have revealed that the hybrid-electric aircraft could replace 60 % to 70 % of all conventional regional aircraft (Clean energy wire, 2018). Hybrid-electric propulsion technologies are attractive for the new airline business models because of their several advantages, such as low or no emissions, reduced noise, and low operating costs. Some question, their potential market penetration, because of consequently needed extensive adaptation of the pending airport infrastructure, remain open (Marksel, et al., 2019). The challenges do not arise only at the aircraft level, (e.g. such as the availability and standardization of batteries/hydrogen fuel-cells with sufficient energy density for regional flights), but also at the airport infrastructure level. The main challenges can be, for example, accessibility of ground services and new maintenance procedures, the need for high-power electricity supply and hydrogen supply, which would require several adaptation of the airport infrastructure (IATA, 2019).

The preliminary assessment, carried out in the MAHEPA project (Modular approach to hybrid-electric propulsion architecture), provides valuable understanding of how the existing airport infrastructure should be upgraded in order to enable the operation of hybrid-electric and hydrogen aircraft (Marksel, et al., 2019).

THE REASONS BEHIND APPLYING THE HYBRID TECHNOLOGY IN AVIATION

Conventional aircraft powered by an internal combustion engine (ICE) running on kerosene, emit exhaust gases and particles, such as carbon dioxide (CO_2), water vapor, hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur oxides (SO_X), lead, and black carbon. These gases and particles have not only a negative impact on environment by causing smog, acid rain, the greenhouse effect etc.., but also on human health. Especially, in high concentrations they can cause poisoning, lung, liver, and heart disease and even cancer. Aviation is responsible for about 3 % of total EU greenhouse gas emissions and more than 2 % of global greenhouse gas emissions. Without action to reduce emissions, global annual emissions could increase by over 300 % by 2050 (European Commission, 2020).

One way to minimise the high levels of pollution and negative environmental impact of conventional aviation is to introduce cleaner aircraft propulsion technologies, that can partially or fully reduce the above-mentioned local toxic gas emissions, global greenhouse gas emissions and noise. The all- electric aircraft powered entirely by batteries has many advantages such as no local gas emissions and significant noise reduction. If the battery is powered by renewable sources, it has a significant impact on reduction of global CO_2 emissions. The serial ICE-hybrid aircraft, such as the Panthera hybrid aircraft developed in the MAHEPA project, is powered by an electric engine, fed by an ICE generator or battery which enables the electric take-off and landing. (Gaspari, 2018).Such a propulsion system enables the ICE-hybrid reduction of emissions in the vicinity of airports, while at the same time maintaining good flight characteristics of conventional aircraft, such as relatively low weight and long flight range (Righetti, Falger, Steffen, & Perkon, 2017). The fuel-cell hybrid aircraft developed within the MAHEPA project, such as Hy4, is similar in design to the serial ICE-hybrid aircraft, while the main generator consists of fuel-cells powered by gaseous hydrogen. The fuel-cell hybrid aircraft causes no local emissions, reduces noise and global CO_2 emissions when hydrogen is produced from renewable resources (Flade, 2018).

Although all-electric aircraft are more environmentally friendly than conventional aircraft powered by fossil fuels, their main disadvantage is higher weight load. Another disadvantage of all-electric aircraft is significantly shorter flight range compared to conventional and hybrid-electric aircraft. Currently, the hybrid-electric aircraft concept represents the best compromise between efficiency and flight range in field of light aircraft. The current limitations of battery technology are still too big to allow long-haul flights (HYPSTAIR project, 2019). This is successfully solved by a hybrid-electric propulsion technology, that allows a combination of conventional and electric propulsion, or in the case of FC hydrogen, a combination of hydrogen powered fuel- cell and batteries.

Due to the quiet, short take-off and landing capabilities with zero or low gas emissions, ICE-hybrid and fuel-cell hybrid aircraft can be used on today underutilised airports located in urban areas, in the vicinity of city centres. Revitalisation of existing underutilised airports is a great potential for new air transport routes and services. Additionally, there is also a possibility of replacing existing conventional aircraft in the categories 1-to-8-seater, 9-to-19-seater, and 20-to-70-seater, with cleaner aircraft ICE-hybrid and fuel cell hybrid aircraft. By scaling up new hybrid technologies to a larger aircraft, a greater reductions in emissions can be achieved, thereby supporting the aviation industry's efforts for environment (Marksel, et al., 2019). For introduction of ICE-hybrid and fuel cell hybrid aircraft, an assessment of necessary airport ground infrastructure is needed to enable their operation.

CASE STUDIES

Two case studies were carried out to assess the necessary adaptations in the airport's ground infrastructure. The first study refers to infrastructure needed for multiple charging of ICE- hybrid, while the second study refers to infrastructure for refueling of fuel-cell hydrogen hybrid. Both studies were based on the technology roadmap for ICE-hybrid and fuel cell hydrogen aircraft (IATA, 2019), and were limited to the smaller aircraft. Smaller aircraft, such as 9-to-19-seat and 20-to-70-seat ICE-hybrid or fuel cell hydrogen hybrid aircraft, are expected to enter the market earlier than the larger aircraft (e.g. 200-seat and more), so the replacement is expected to happen sooner in small size aircraft category than in large size category of aircraft.

The existing small passenger aircraft transport volume assessment for Europe is based on the OAG demo-database for 2017. The results show that there were 150 airports in Europe with regular scheduled flights of conventional 9-19-seater aircraft and 484 airports with regular scheduled flights of conventional 20-70-seater aircraft. As can be seen from the Table 1, there were many airports with less than 1 flight per day, but they were also significant share of airports (49 % in case of 9-19-seater and 63,4 % in case of 20-70-seater) operating more than 1 and in some case even more than 50 flights per day.

Table 1: Average number of daily flights

No. of daily flights (in average for 2017)	No. of airports with scheduled flights	
	9-19-seater	20-70-seater
Less than 1	76	177
1 – 2	33	84
2 – 3	27	66
3 – 4	6	35
4 – 5	2	22
5 – 6	1	17
6 – 7	2	16
7 – 8	1	9
8 – 9	1	6
9 – 10	1	7
10 – 15	-	22
15 – 20	-	7
20 – 30	-	9
30 – 50	-	5
More than 50	-	2
TOTAL	150	**484**

Source: OAG demo database, 2017.

As can be seen from the Table 2, the above mentioned aircraft fly different distances, (with 9-19-seater aircraft the most frequent flight distance is between 301 and 500 km, while 20-70-seater aircraft mainly fly distances between 101 and 300 km).

Table 2: Number of seats of aircraft by flight distance

9-19-seater aircraft		20-70-seater aircraft	
Flight distance [km]	Total seats	Flight distance [km]	Total seats
2 – 50	168,599	19 – 100	1,275,466
51 – 100	135,493	**101 – 300**	**12,751,554**
101 – 200	351,491	301 – 500	11,253,337
201 – 300	283,913	501 – 700	4,450,470
301 – 500	**371,915**	701 – 1,000	2,702,282
> 500	119,728	1,001 – 2,000	1,678,100
Sum	1,431,139	> 2,000	44,372

Source: OAG demo database, 2017.

The traffic volume and distance of existing conventional aircraft have been extrapolated in order to correctly estimate the necessary adoptions of airport's ground infrastructure, provided that this segment of air market would be replaced by the ICE-hybrid and fuel-cell hydrogen aircraft (Marksel, et al., 2019).

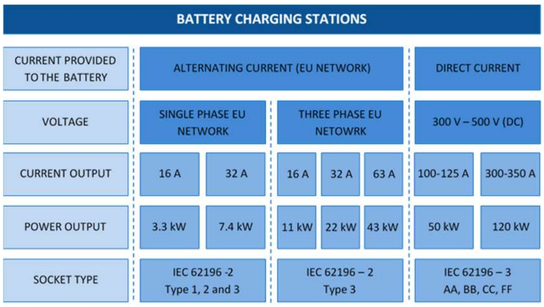
ASSESMENT OF AIRPORT GROUND INFRASTRUCTURE FOR HYBRID-ELETRIC AICRAFT

The airport's infrastructure for charging the batteries of ICE-hybrid aircraft requires adequate electricity system, the battery charging stations and optional battery swapping equipment. Although the possibility of battery swapping is very interesting approach to eliminate the time needed for recharging the batteries this was not taken into consideration based on the experiences in the automotive industry (e.g. different types of batteries and swapping methods, the question of responsibility for failures/accidents). With only slight changes, technology and standardization defined by an International Electro Technical Commission (standard name is IEC 62196), for land vehicles, can be fully used for aviation purposes as well. According to standard IEC 62196, a vehicle battery can be charged in one of the following modes:

- Mode 1: Battery is charged through a regular electric socket with a regular cable.
- Mode 2: Like mode 1, but with added protection device, mounted on a socket or cable.
- Mode 3: Charging through a charging station, which is directly connected to the electrical grid and provides alternating current (AC) to the battery.
- Mode 4: Charging through the charging station, which is directly connected to the electrical grid and provides direct current (DC) to the battery.

Only modes 3 and 4 should be considered, as they provide sufficient voltage, current output and power output to charge a hybrid-electric aircraft considered in the study.

Feasible combinations of charging stations are presented in Figure 1. The possibilities are either to use alternating current or direct current with different voltage, current and power output.



BATTERY CHARGING STATIONS							
CURRENT PROVIDED TO THE BATTERY	ALTERNATING CURRENT (EU NETWORK)					DIRECT CURRENT	
VOLTAGE	SINGLE PHASE EU NETWORK		THREE PHASE EU NETOWRK			300 V – 500 V (DC)	
CURRENT OUTPUT	16 A	32 A	16 A	32 A	63 A	100-125 A	300-350 A
POWER OUTPUT	3.3 kW	7.4 kW	11 kW	22 kW	43 kW	50 kW	120 kW
SOCKET TYPE	IEC 62196 -2 Type 1, 2 and 3		IEC 62196 – 2 Type 3			IEC 62196 – 3 AA, BB, CC, FF	

Source: (Marksel, et al., 2019)

Figure 1: Configurations of charging stations at airport

In case of charging through AC the charging station should be installed and connected to an electric grid network through a single-phase or a three-phase connection. In the case, where several charging stations must be connected to the grid, a transformer may be required. A charging station and a battery in the vehicle (or aircraft in our case) are then connected by a cable, which can be usually detached from both charging station and the vehicle (aircraft). In this case the charging station provides an AC and an AC / DC converter must be installed in the aircraft. For the charging station, connected to the EU grid (voltage difference of 230 V) the maximal power output can be 14 kW in the case of a single-phase connection and 44 kW in the case of a three-phase connection.

The DC charging station must be connected to the electrical network via a dedicated transformer. If several DC charging stations are installed at the same place, they can all be connected through the same transformer to the electrical grid. DC charging stations usually have cable attached and provide direct current directly to the battery management system (BMS), so that installation of AC / DC converter in an aircraft is not required. Current DC charging stations can provide up to 120 kW power, with voltage difference ranging from 300 V to 500 V and maximal current ranging from 300 A to 350 A.

For installation of charging stations, either DC or AC, several procedures and operation are needed, such as:

- Consent form authorities to build charging stations at airport premises.
- Preceding operations, such as excavation for cable ducting and pipe laying, foundation of the base for the charging station, installation of (freely standing) electric measuring boxes, connection to the transformer (no processing in the transformer), road crossing, unproblematic crossing of the electric cable with the water supply system, etc.
- In case that the electricity system does not provide sufficient power, the modification or installation of new transformer with sufficient power is required. A transformer can supply four to five DC charging stations.

To provide fast charging of ICE-hybrid aircraft, several aspects need to be taken in account, such as:

- A good battery condition with low internal resistance that allows fast charging.
- A moderate temperature (above 5°C) for performing fast charging.
- Fast charging should be applied only in the first charging phase (up to 70 % of SoC (State of Charge).
- Charging rate of 1 C (i.e. empty battery would be fully charged in one hour) should not be exceeded in the second phase of charging.
- When charging is completed, Li-ion batteries should be disconnected from the charging source.

The charging capacity estimation carried out in the study, considered the full landing and take-off cycle (LTO) of aircraft with lithium-ion batteries at technology level 2019 and with specific power (i.e. 2 kW/kg) and specific energy (i.e. 100 Wh/kg). The battery under consideration generates enough energy to enable fully electric take-offs and landings of ICE-hybrid aircraft. A battery of a 19-seat ICE-hybrid aircraft would have a capacity of 50 – 100 kWh, while the battery capacity of a 70-seat ICE-hybrid aircraft would be between 180 – 360 kWh.

As seen from Table 3, the charging time of 19- and 70-seat aircraft depend on the capacity of charging station.

Table 3: Charging time of a 19-seater and 70-seater aircraft with different charging stations

Power of the charging station [kW]	Charging time of a 19-seater aircraft [h]	Charging time of 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**

Source: (Marksel, et al., 2019)

The minimum time to fully charge the battery would be one hour. In order to achieve fast turnaround times (e.g. 20 minutes), one or two (depending on battery capacity) 120 kW charging stations would be required to charge a 19-seater aircraft simultaneously, whereas up to eight 120 kW charging stations would be required for a 70-seater aircraft. In both cases the batteries should be charged up to 80 % SoC to prolong battery life.

Taking into consideration charging time (Table 3) and average daily number of flights (Table 1), the single alternating current (AC) three-phase station with a charging capacity of 43 kW would be sufficient for charging a 19-seater ICE-hybrid aircraft at almost all airports. Moreover, a 43 kW AC charging station would also cover the needs for charging a 70-seater ICE-hybrid at 66 % of airports. At majority of airports (88 %), a 120-kW direct current (DC) charging station would be required to charge a 70-seat ICE-hybrid aircraft. The airport with the largest number of flights (i.e. Tromsø in Norway), accounting with more than 9 flights per day with 9-20 seat aircraft and almost 60-flights per day with 21-70 seat aircraft (OAG, 2017), would need up to 8 DC charging stations with 120 kW capacity or three times as many AC charging stations with 43 kW capacity to ensure multiple fast charging.

ASSESMENT OF AIRPORT GROUND INFRASTRUCTURE FOR FUELL-CELL HYDROGEN AICRAFT

The airport infrastructure and operations required for operation of fuel cell hybrid aircraft consist of operations and infrastructure necessary to enable hydrogen production, hydrogen transport, hydrogen liquefaction or hydrogen compression and to provide hydrogen refueling points. Various production methods exist for separating hydrogen from the elements to which it is naturally bound (e.g. oxygen and carbon). Recently, more and more attention has been paid to production of hydrogen from cleaner sources, such as electrolysis based on renewable energy, which might become an economically viable option in the future (Amy & Kunycky, 2019). Currently, steam reforming is still the most cost-effective method of producing hydrogen from either methane or other light hydrocarbons such as oil. It is therefore not surprising that steam reforming is today widely used especially in the chemical industry and is therefore considered in our case study.

Airport can be supplied with the required quantities of hydrogen by road (truck delivery) or rail, by pipelines or by on-site production, when bigger quantities are required (Yang & Odgen, 2007), (Amy & Kunycky, 2019).

In case of hydrogen delivery by tube truck trailer, hydrogen is compressed at the production site and transported to the local consumer site by the tube trailer trucks. It is assumed that the full trailer is dropped at the delivery site and that the empty trailer is picked up afterwards. The highest cost component of the hydrogen tube truck delivery scenario are the operating and maintenance costs of the truck, including drivers' labor cost. Therefore, transport distance has the greatest effect on the hydrogen delivery costs by the tube trailer 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) (Yang & Odgen, 2007).

In the case of delivery by cryogenic truck trailer, hydrogen is liquefied at the production site and transported to the consumer by cryogenic truck trailer. In such a case it is assumed that trailers are not left at consumers' site and that in each trip the truck empties its entire load and that the minimal capacity of hydrogen (H_2), used at the consumption site, is 30 tons per day. The largest cost component, if using cryogenic truck delivery scenario, is liquefaction (80 % - 95 % of all costs), therefore the overall costs of liquid hydrogen delivery, strongly depends on hydrogen flow and is almost independent on the driven distance (Yang & Odgen, 2007).

In the case of delivery by pipeline, hydrogen is first pre-compressed at the production site and then delivered to the consumer by pipeline. Depending upon the purpose of use, hydrogen can be further compressed at consumer's site as well. In this scenario, the most important cost component is the pipeline capital cost. Therefore, the overall costs depend both on the hydrogen flow rates and distance (Yang & Odgen, 2007).

One of the options for delivery of hydrogen, beside pipeline delivery, is also on-site production of hydrogen at airport. Because of the reasons mentioned before, most likely, the steam reforming method for producing hydrogen would prevail (Marksel, et al., 2019). There are some studies that consider the onsite production of hydrogen by using electrolyse in the future, as the case of Los Angeles airport (Amy & Kunycky, 2019) for short (i.e. 380 km) and long-haul (i.e. 3,985 km) flights. The theoretical study concluded that the cost of on-site production of hydrogen would result in twice higher fuel cost (i.e. hydrogen), if compared to existing jet fuel (i.e. kerosene).

Hydrogen can be stored as gas inside underground caverns, as a compressed supercritical fluid, as a liquid in a cryogenic tank, in materials based on H_2, as a slush hydrogen (solid state) in cryogenic tanks as cold-compressed or cryo-compressed hydrogen. Storage of gaseous hydrogen typically employs high-pressure spherical or cylindrical tanks with pressure ratings as high as 30 MPa, but low-pressure spherical tanks with large diameters are also used. Liquid hydrogen storage vessels are low pressure but have high capital costs because of the insulation required to prevent boil-off. Small vessels can be quite expensive, the economy of scale savings are not significant except with extra-large volumes (Howden, 2019).

ASSESMENT OF GROUND INFRASTRUCTURE FOR REFULING FUELL-CELL AICRAFT WITH LIQUID HYDROGEN

Due to its low density, hydrogen, as a gas, has at normal temperature and pressure, large volume. Therefore, it is unpractical for storage and transportation purposes. Hydrogen is usually used in a compressed or liquefied form. Hydrogen liquefies at temperatures lower than 20 K. Most often used liquefaction methods are Linde's cycle or Claude's cycle. If hydrogen is liquefied too quickly, after liquefaction, transition from ortho- to para-hydrogen will cause considerable release of energy and consequential boil-off. Therefore, special catalysers are used to fasten the ortho- to para-hydrogen conversion and liquefaction (Timmerhaus & Mendelssohn, 2007).

All aircraft are not going to change to liquid hydrogen (LH_2) overnight, therefore must airport, during the transition period, be able to handle both LH_2 as well as kerosene aircraft. Most large airports have onsite kerosene fuel storage tanks. Similar tanks will need to be built to store LH_2, below 25 K (e.g. kelvin). The easiest solution would be to subsequently deliver the fuel to the aircraft via a well-insulated refuelling truck. Special care must also be taken for airport vehicles servicing LH_2 powered aircraft (Van Zon, 2018).

Hydrogen refueling point which are defined with standard ISO/PASS 15594 outlines various services that the airport should enable for fueling of fuel cell hybrid aircraft, such as:

- Normal refueling during aircrafts' turnaround between two flights (a cold system fueling).
- De-fueling due to planned maintenance activities and troubleshooting.
- First refueling of new aircraft or refueling an aircraft after maintenance and troubleshooting (warm system refueling).
- Boil-off management due to overnight parking, long-time overhauls, or failure cases.

For minimal requirements, hydrogen can be pursued from hydrogen production facilities and transported to the airport. In this case, no stationary storage of the fuel at airport is needed or recommended – fuelling should take place directly from movable storage, in which hydrogen was transported to the airport (e.g. truck). At the aircraft interface refuelling point, the temperature of the liquid hydrogen should be 20 K or lower. The pressure should be higher than 700 kPa to achieve acceptable fuelling times (20 min). A refuelling coupling unit for a small aircraft, defined as Type I in ISO/PASS 15594, can be manual and must include a refuelling hose, a refuelling connector, and safety monitoring equipment. A refuelling connector, together with the attached part of refuelling hose, cannot exceed 10 kg (or preferably 7 kg). Connector should have a diameter of 30 mm to meet the requirements of the connectors used for road vehicles. A system should include a filter for filtering particles larger than 5 micrometres. Filter should be detachable and cleanable. The safety equipment should include also monitoring equipment powered by batteries that would measure pressure, temperature, flow rate, filling level of the tank, hydrogen leak, valve position and a transportable detector of hydrogen concentration and heat.

In our case study, the liquid form of hydrogen was considered, because it enables a lower load weight of aircraft, better aerodynamics, and lower consumption in comparison to compressed gaseous hydrogen. Since hydrogen fuel cell aircraft with 19- and 70-seats are not yet available on the market (i.e for an accurate calculation we would need aircraft shape and tank size), the feasible assumption of the potential aircraft fuel consumption was assessed, assuming that their energy consumption is similar or slightly lower than the consumption of the conventional aircraft. Although hydrogen burned in fuel cells has a better energy efficiency than kerosene in conventional combustion engine, the overall fuel consumption of hydrogen fuel-cell aircraft increases due to the higher weight of the aircraft (e.g. larger aircraft surfaces and tanks). Therefore, we shall consider, for our estimation that the energy consumption level of fuel-cell hydrogen aircraft is similar to conventional one. Based on these assumptions, we can conclude that a 19-seat aircraft would need approximately 200 kg of hydrogen for a flight over 500 km, while a 70-seat aircraft would need approximately 700 kg of hydrogen for the same range (Marksel, et al., 2019).

According to average number of flights (Table 1) and assuming that 96 % of airports operating with 19-seater aircraft and 50 % of airports operating with 70-seater aircraft would need less than 1 ton of hydrogen per day. The busiest airport in Europe with flights operated by 19-seater and 70-seater aircraft (i.e. Tromsø airport) would need around 44 tons of hydrogen per day. In our case, because of relatively small quantities of liquid hydrogen required, delivery by a cryogenic truck is preferable scenario for supplying hydrogen to airports as on-site production and liquification which should take place at the airport. Additional reason for liquid hydrogen is the fact that compared to pressure gas vessels, a higher amount of hydrogen can be carried out with a LH_2 trailer, as the density of liquid hydrogen is higher than that of gaseous hydrogen. Over longer distances it is usually more cost-effective to transport hydrogen in a liquid form, since a liquid hydrogen tank can substantially hold more hydrogen than a pressurized gas tank. Hydrogen is loaded into insulated cryogenic tanks for transportation of liquid hydrogen. LH_2 trailers have a range of approximately 4 000 km. Although there are some down back of transportation of the liquid hydrogen. During the transport of the hydrogen to its destination, the cryogenic hydrogen heats up, causing the pressure in the container to rise. However, if considering the financial part, the cost of liquid tank truck delivery is still much lower as in case of tube trailer (i.e. about 10 % of the tube trailer delivery) (Dillich, 2012). Therefore, as a main mode of delivery in case of small quantities of liquid hydrogen necessary for fuel-cell hydrogen aircraft, the delivery by cryogenic truck and direct fueling from truck would prevail.

FINAL REMARKS

In the coming years it is expected that a wide range of hybrid-electric aircraft from single-seater ultralights, micro-feeder aircraft to regional airliners will be entering into existing air transport markets., New markets for commercial flights are expected to emerge too. As hybrid propulsion technologies are novel, several aspects of technical, as well as, economic assessment of the ground infrastructure needed for their operation is still largely unexplored. There is no doubt that ground infrastructure at airports will have to be adopted for the operation of ICE-hybrid and fuel-cell hybrid aircraft.

Sufficient number and capacity of charging stations supported by adequate power network will need to be available at the airports for multiple fast charging of ICE-hybrid aircraft airports. Depending on to the average daily flights and charging times, a single AC three-phase station with a capacity of 43 kW, would be sufficient at the most of airports to meet the needs for recharging the 19-seat ICE-hybrid aircraft. At 66% of airports a single 43 kw, AC station would be sufficient to charge 70-seat ICE-hybrid aircraft. Majority of airports, a 120-kW DC charging station would require charging 70-seat ICE-hybrid aircraft. At the busiest airport Tromsø in Norway with more than 9 flights per day with 9-20 seat aircraft and almost 60-flights per day with 21-70 seat aircraft (OAG, 2017), up to 8 DC charging stations with 120 kW capacity or three times as many AC charging stations with 43 kW capacity would be required to ensure multiple fast charging.

In the case of fuel cell hybrid aircraft, the main challenge will be in the field of hydrogen supply. One option for required bigger quantities is local production, the other is establishment of reliable hydrogen delivery (transport) system. While the technology for electric charging of ground vehicles is already developed in automotive industry and largely transferable to ICE-hybrid aircraft, the technology for fuel cell hydrogen aircraft is relatively immature, resulting in high initial investments. The level of investment required in airport infrastructure varies greatly between ICE-hybrid and fuel cell hybrid aircraft. Several airport adoptions and modifications will be necessary to provide airports with necessary amounts of hydrogen. There are many open questions about hydrogen production, transport, liquefaction or compression, storage, and refueling point/station at airports. The latter will have to meet several legal and technical requirements due to flammability of hydrogen to achieve the required level of safety. Regarding the hydrogen delivery scenarios, it can be concluded that delivery of a compressed gas by truck is an optimal solution for short distances and small quantities of hydrogen. Delivery by a cryogenic truck is optimal for long distances and low hydrogen flow rates, while delivery by pipeline is optimal for high hydrogen flow rates and long distances. The case study revealed that less than 1 ton of liquid hydrogen per day would be required at 96% of airports with 19-seat aircraft and 50% of airports with 70-seat aircraft, provided the existing frequency of daily flights and average estimated aircraft hydrogen consumption is taken into account. The busiest airport, Tromsø, would need about 44 tons of hydrogen per day. Accordingly, due to high cost of liquefaction in case on-site production, which is economically justifiable only in case of high quantities of needed hydrogen, in our case where the quantities are relatively small, delivery by cryogenic truck has proven to be the preferred option for delivering liquid hydrogen to the airport.

In summary, although the study was limited to the smaller aircraft (i.e. aircraft with 19- and 70-seats), hybrid technology and in particular hydrogen is much more suited for use in larger aircraft (i.e. aircraft with 200 or more seats). As hydrogen technology will evolve over the coming decades, its application to larger aircraft will be technologically and economically more feasible, so there is no doubt that such studies will need to be extend also to the large aircraft segment.

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