D10.1: Ground infrastructure investment plan
July, 2019

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EXECUTIVE SUMMARY

With air traffic increasing constantly, also the pressure on environment is rising. One way to avoid high pollution and negative impact of conventional aviation on environment is by introducing new aircraft propulsion technologies, which could partially or fully reduce stated local toxic gas emissions, global greenhouse gas emissions and/or noise. To address this issue, MAHEPA project explored several electric and hybrid-electric propulsion technologies that could be appealing for a new paradigm of transport services and business models, such as a pure electric battery driven aircraft, an internal combustion engine (ICE) hybrid aircraft and a fuel-cell (FC) hybrid aircraft. To enable a wider implementation of an ICE-hybrid and a fuel-cell hybrid aircraft for passenger and freight transport, novel investments in ground infrastructure has been considered.

Ground infrastructure for ICE-hybrid aircraft will need to include battery charging stations and optionally battery swapping equipment. Similar technology that applies for ground vehicles can be used for aircraft charging stations as well, with only slight modifications (e.g. cable length). To meet the needs for charging 19-seater and 70-seater ICE-hybrid aircraft, most airports would need only one three-phase or direct current charging station, where the total infrastructure costs should not exceed 200 000 EUR. For a hybrid-electric 19-seater (with battery capacity of 50-100 kWh) and 70-seater aircraft (with battery capacity of 180 - 360 kWh), 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, while taking into consideration charging times and an average number of daily flights in airports. Moreover, charging station of 43 kW would cover all needs for charging a 70-seater aircraft in 66 % of airports that operate with such aircraft. Similar, one 120 kW charging station would cover needs of 88 % of airports, which operate with the 70-seater aircraft. The airport with the largest number of flights would need from 4 to 8 charging stations with 120 kW power output or three times as many charging stations with 43 kW power output to provide enough electricity for their hybrid-electric fleet.

Ground infrastructure at airports for fuel-cell hybrid aircraft is considered on delivery of liquefied hydrogen. The most feasible solution for the small airports would be to buy liquid hydrogen from their producers and deliver it to the airport with cryogenic trucks. Presuming that the energy efficiency of a hybrid fuel-cell aircraft is similar to the conventional aircraft, a 19-seater aircraft would then need approximately 200 kg of hydrogen for 500 km range flight, resulting in production and truck delivery cost of around 2.500 EUR. The 70-seater aircraft would need approximately 700 kg of hydrogen for the same range, resulting in higher cost of around 8.500 EUR. If all regional aircraft would be swapped for hybrid fuel-cell aircraft, 90 % of airports would need less than 10 tons of hydrogen on a daily basis to fuel them (resulting in cost of around 120. 000 EUR). Evermore, 80 % 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 (around 12.000 EUR per day). On the other hand, the airport with the most regional daily flights (such as Tromsø airport, Norwegian) would need around 40 tons of hydrogen per day (or almost half a million euro for hydrogen and transport costs). Therefore the production and delivery cost
for liquid hydrogen are assumed to be between 2.500 EUR and half a million euro, largely depended on the size of the aircraft, distance travelled and frequency of flights.
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### Abbreviations

<table>
<thead>
<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ACRE</td>
<td>Advisory Council for Aeronautical Research</td>
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<tr>
<td>AEO</td>
<td>Annual Energy Outlook</td>
</tr>
<tr>
<td>BMS</td>
<td>Battery Management System</td>
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<tr>
<td>CH₂</td>
<td>Compressed hydrogen</td>
</tr>
<tr>
<td>CIS</td>
<td>Commonwealth of Independent States</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
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<tr>
<td>DE</td>
<td>Germany</td>
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<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Center)</td>
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<tr>
<td>DoD</td>
<td>Depth of Discharge</td>
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<tr>
<td>EBAA</td>
<td>European Business Aviation Association</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>EUR</td>
<td>Euro</td>
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<tr>
<td>EW</td>
<td>Empty weight</td>
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<tr>
<td>FC</td>
<td>Fuel-cell</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<tr>
<td>H₂O</td>
<td>Water (vapour)</td>
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<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>HYPSTAIR</td>
<td>Development and validation of hybrid propulsion system components and sub-systems for electrical aircraft</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
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<td>IEC</td>
<td>International Electrotechnical Commission</td>
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<tr>
<td>L/D</td>
<td>Lift-to-drag ratio</td>
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<tr>
<td>LH₂</td>
<td>Liquid hydrogen</td>
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<tr>
<td>Li</td>
<td>Lithium</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>LiFePO 4</td>
<td>Lithium iron phosphate battery</td>
</tr>
<tr>
<td>LTO</td>
<td>Landing and take-off (cycle)</td>
</tr>
<tr>
<td>MAHEPA</td>
<td>Modular Approach to Hybrid-Electric Propulsion Architecture</td>
</tr>
<tr>
<td>MTOW</td>
<td>Maximum take-off weight</td>
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<tr>
<td>N₂O</td>
<td>Nitrous Oxide</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NCA</td>
<td>Lithium Aluminum batteries</td>
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<tr>
<td>NG</td>
<td>Natural Gas</td>
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<tr>
<td>NMC</td>
<td>Lithium Nickel Manganese Cobalt Oxide batteries</td>
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<tr>
<td>NOx</td>
<td>Nitrogen Oxides</td>
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<tr>
<td>OAG</td>
<td>Official Aviation Guide</td>
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<tr>
<td>P</td>
<td>Portugal</td>
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<tr>
<td>PMCD</td>
<td>Power Management Control and Delivery</td>
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<tr>
<td>RO</td>
<td>Romania</td>
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<tr>
<td>RoC</td>
<td>Rate of climb</td>
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<tr>
<td>RPK</td>
<td>Revenue Passenger Kilometre</td>
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<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
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<tr>
<td>SMR</td>
<td>Steam methane reforming</td>
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<tr>
<td>SoC</td>
<td>State of charge</td>
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<tr>
<td>SOₓ</td>
<td>Sulphur oxides</td>
</tr>
<tr>
<td>TP</td>
<td>Transformer</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>USD</td>
<td>United States Dollar</td>
</tr>
<tr>
<td>US</td>
<td>United States of America</td>
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</table>
Airbus: an aircraft manufacturer.

Airliner: a passenger aircraft.

Battery cell: a closed chemical unit that produces electric current.

Battery pack: a system of connected battery cells.

Boeing: an aircraft manufacturer.

Boil-off: the vaporization of a liquid with boiling point lower than that of the environment in which it is stored.

Bombardier: an aircraft manufacturer.

Capacity: an amount of energy stored in a batter.

Ceiling: maximal height at which an aircraft can fly.

Charging speed rate or C-rate: a time needed to fully charge a battery (in hours).

Charter: a holiday or leisure carrier charter flight / an unscheduled flight that is not part of a regular airline routing. With a charter flight you rent the entire aircraft so the departure/arrival locations and times can be determined based on user preferences.

Climb: a flight phase from the moment aircraft leaves the ground until it reaches the set altitude.

Commuter: a small aircraft that generally connects a small regional airport to a main airport.

Conventional aircraft: a traditional aircraft that operates using conventional fossil fuel.

Cruise: the phase of an aircrafts' flight that occurs when the aircraft levels to a set altitude after a climb and before it begins to descent.

Cruise speed: an optimal speed of an aircraft during cruise with minimal fuel consumption.

Cryogenic tank: a thermally isolated vessel used for storage of liquids at very low temperature.

Descent: a flight phase where aircraft lowers its altitude, between cruise and landing.

Depth of discharge (hereinafter: DoD) is an alternate method to indicate a battery's state of charge (hereinafter: SoC). The DoD is the complement of SoC: as one increases, the other decreases. While the SoC units are percent points (0 % = empty; 100 % = full), DoD can use Ah units (e.g.: 0 = full, 50 Ah = empty) or percent points (100 % = empty; 0 % = full). As a battery may have higher capacity than its nominal rating, it is possible for the DoD value to exceed the full value.

Efficiency (of powertrain): an energy output divided by energy input of powertrain.

Electric aircraft: an aircraft powered by electric motors. Electricity may be supplied through a variety of methods including batteries, ground power cables, solar cells, ultra-capacitors, fuel-cells and power beaming.
**Embraer**: aircraft manufacturer.

**Empty weight** (of aircraft): a weight of an aircraft without fuel, payload (passengers and cargo) and crew.

**Energy density**: an amount of energy stored in a given system per unit mass.

**Fuel-cell hybrid aircraft**: an aircraft with a similar design as serial ICE hybrid aircraft, whereas the generator is replaced with fuel-cells powered by hydrogen.

**Generator**: a unit that transforms mechanical or chemical energy into electrical energy.

**Hy4**: a four-seater hydrogen fuel-cell driven aircraft, manufactured by H2FLY.

**Hydrogen dispenser**: a unit used for fuelling vehicle or aircraft with a hydrogen.

**ICE hybrid aircraft**: an aircraft, powered by ICE powertrain or by electro-motor, charged from a battery.

**Jet aircraft**: an aircraft powered by a jet engine - a combustion engine that provides thrust by discharging a fast-moving jet of exhausted gas.

**Landing**: a flight phase, when aircraft decelerates after it touches the ground.

**Maximum take-off mass**: the maximum weight of an aircraft, at which the pilot is allowed to attempt for take-off.

**Micro-feeder**: a 19-seater regional airliner, which could connect small, grass airstrips airports with regional and international airports.

**Narrow-body aircraft or single-aisle aircraft**: an airliner arranged along a single aisle permitting up to 6-abreast seating in a cabin below 4 meters of width.

**On-demand flight**: a non-scheduled flight for passengers, freight or mail (short notice). The on-demand flights refer to air taxiing, commercial business aviation or other on-demand revenue flights (excluding charters).

**Ortho hydrogen**: hydrogen composed of molecules that have spins facing in same direction.

**Panthera**: a four-seater aircraft, manufactured by Pipistrel d. o. o.

**Para hydrogen**: hydrogen composed of molecules that have spins facing in opposite directions.

**Parallel ICE-hybrid aircraft**: an aircraft, where power is provided by an ICE powertrain or by an electro-motor, charged from a battery.

**PMCD module**: an interface between power supplying components (fuel cells, battery) and a motor in a hybrid aircraft.

**Powertrain**: a main component, which generates power and thrust, and enables a vehicle (or aircraft) movement.

**Pure electric battery driven aircraft**: an aircraft with energy provided by a battery, which drives an electro-motor that rotates a propeller.
Regional airliner: a feeder liner is a small airliner that is designed to fly up to 100 passengers on short-haul flights, usually feeding larger carriers’ airline hubs from small markets.

Serial ICE-hybrid aircraft: an aircraft with a power provided by an electric motor that is powered by a power generating unit (e.g. generator and ICE) or by batteries.

Single phase connection: a connection to electrical grid, where alternating current is supplied through a single wire.

Specific energy of a battery: an amount of electric energy stored in per unit mass of a battery.

Specific power of battery: a power output divided by its mass.

State of charge: SoC indicates the charged amount of the battery: 0 % = empty; 100 % = full.

Take-off: a flight phase from the moment an aircraft starts to accelerate to the moment it leaves the ground.

Taxiing: a flight phase when aircraft moves on ground to change location.

Three-phase connection: a connection to electrical grid, where alternating current (AC) is supplied through all three wires.

Transformer: an electrical device that increases or decreases the alternating voltages.

Turboprop airliner: an aircraft, powered by a turboprop engine - a combustion engine, that provides thrust by rotating a propeller.

Volumetric energy density: an amount of energy stored in a given system per unit volume or mass.

Wide-body airliner: a larger airliner usually configured with multiple aisles and a fuselage diameter of more than 5 meters allowing at least 7-abreast seating and often more travel classes.
1 INTRODUCTION

The document outlines the necessary ground infrastructure investments at airports to enable fast charging and refuelling of ICE-hybrid and fuel-cell (hereinafter FC) hybrid aircraft, while considering economic and regulatory aspects as well. In this scope the research was done on existing propulsion system in aviation, with emphasis on the MAHEPA hybrid propulsion system, as to understand technical characteristics and their impact on environment (Chapter 1). In Chapter 2 the preliminary market assessment for air travels will be analysed, focusing on potential markets, where researched hybrid propulsion technologies could be implemented in the future business models. To understand the future potential markets, trends of air passengers were studied in Europe and worldwide, with a special emphasis on regional and on-demand flights, where the implementation of 19-seater and 70-seater hybrid aircraft would be most plausible. Based on a market study and technological improvements, envisioned by partners, several development scenarios for future market entry of hybrid technologies will be outlined in Chapter 3, providing better understanding when and to which extent the necessary ground infrastructure will have to follow to enable the use of hybrid aircraft for transport services.

Following the research on hybrid technology and aviation market, the ground infrastructure requirements for fast charging of hybrid electric aircraft will be defined in Chapter 4. Focus will also be given on batteries, their types and characteristics for use in aviation, while underlining main procedures that should be followed to ensure their long-life cycle. The charging modes and charging stations used in automotive industry have been applied to aviation industry, specifying necessary charging times, procedures, standards and costs, related to implementation of charging stations and supporting necessary infrastructure at airports. The assessment of ground infrastructure based on a case study Milano-Bresso will be done by project partners from Politecnico di Milano (hereinafter POLIMI), who will also provide potential scenarios that could be used in case of a hybrid-electric fleet. Two options will be considered in this case. The first one will focus on only swapping the batteries, while the second option will focus on swapping and electric charging the batteries.

Alongside, the standard infrastructure for hydrogen supply will be outlined in Chapter 5, with special emphasis regarding issues on how to deliver hydrogen to the airports, while concerning hydrogen chemical, technical and price characteristics. Taking all characteristics into account, a study on refuelling requirements and standardizations for use of hydrogen at airports will be conducted. Based on preliminary assessment of potential markets for hybrid aircraft and the necessary charging and refuelling requirements, conclusions will sum up necessary ground infrastructure at airports to enable operation of hybrid fleet in the future, based on specific assumptions and predictions.

Chapter 6 will provide general conclusions and recommendation for novel investments in ground infrastructure at airports to enable wider implementation of ICE-hybrid and FC-hybrid for passenger and freight transport.
2 APPLYING HYBRID TECHNOLOGY IN AVIATION

With air traffic increasing constantly, also the pressure on environment is rising. Using alternative fuels is becoming a necessity in European commission endeavours for clean and safe environment. In EU vision on protecting the environment and the energy supply, the key is in the technologies that will allow reduction of carbon dioxide (CO\textsubscript{2}), toxic gas emission (HC, CO and NO\textsubscript{x}) and noise. 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).

Conventional aircraft are powered by internal combustion engine (ICE) that emits gases and particles, such as carbon dioxide (CO\textsubscript{2}), water vapour, hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO\textsubscript{x}), Sulphur oxides (SO\textsubscript{x}), lead, and black carbon. Carbon dioxide and water vapour are normal combustion by-products, while carbon monoxide and hydrocarbons are products of an incomplete combustion. On the other hand, nitrogen oxides are produced by nitrogen, bonded with oxygen at high temperatures and high pressures. Carbon monoxide is a toxic gas that is bonded 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\textsubscript{x} (including nitrous oxide (N\textsubscript{2}O)) also have a significant greenhouse effect. Carbon dioxide is not toxic, but it’s a major greenhouse gas. Therefore, HC, CO and NO\textsubscript{x} can be considered as local pollutants and their concentrations should be regulated in the vicinity of airports, while CO\textsubscript{2} and NO\textsubscript{x} (including N\textsubscript{2}O) should be considered as global pollutants and contributors to greenhouse effect. One way of avoiding high pollutions and negative impact of conventional aviation on environment is by introducing new aircraft propulsion technologies, which can partially or fully reduce previously stated local toxic gas emissions, global greenhouse gas emissions and/or noise. To address this issue, MAHEPA project explored several hybrid-electric propulsion technologies, which could be appealing for a new paradigm of transport services and business models, such as pure electric battery driven aircraft, ICE-hybrid aircraft and FC-hybrid aircraft.

In a pure electric battery driven aircraft the energy is provided by a battery that drives an electro-motor rotating the propeller, as it is shown in Figure 1. 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\textsubscript{2} emissions, if the electricity would be produced from a renewable source with a low CO\textsubscript{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.

More information on:

- battery driven Panthera can be found in section 2.1.1,
- specific energy of a fuel and its role in defining the aircraft flight characteristics in section 2.2,
– different ranges of electric aircraft in section 2.2.1.

**Figure 1: A scheme of a pure electric battery driven aircraft powertrain**

*Source: Author.*

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. 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 CO₂ 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-powertrain or by an electro-motor, charged from a battery, as shown in Figure 2. A dedicated mechanical system switches between two modes, an ICE or electro-motor. The battery should be designed in a way to provide enough power and energy for take-off and the first miles of a climb (see section 2.2.2 for further explanation).

**Figure 2: A scheme of a power train of a parallel ICE hybrid aircraft**

*Source: Author.*

In a **serial ICE hybrid aircraft**, the propeller is driven only by an electric motor, powered by a generator or by batteries, as shown in Figure 3. 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 energy – and 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 powertrain. A serial ICE-hybrid aircraft Panthera, developed in projects HYPSTAIR – Development and validation of hybrid propulsion system components and sub-systems for electrical aircraft (1) and MAHEPA – Modular Approach to Hybrid Electric Propulsion Architecture (2), is described in section 2.1.1.

A fuel-cell hybrid aircraft is designed similar as a serial ICE-hybrid aircraft with fuel-cells, powered by hydrogen as generator (Figure 4). 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 CO₂ 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. Nevertheless, weight and technical characteristics of a fuel-cell aircraft should be similar to a convectional ICE-aircraft, as discussed in section 2.2.3.
Due to quiet, short take-off and landing capabilities with zero or low gas emissions, we assume that above mentioned aircraft can be used in the vicinity of city centres and revitalize existing under-exploited airports and therefore present a great potential for new flight connections and services. By scaling existing hybrid technologies to a larger aircraft, a greater reduction of emissions can be achieved, which supports endeavours for a cleaner and safer environment. With propulsion components developed within the MAHEPA project, it is possible to build a larger hybrid-electric aircraft, for example a 19-seater or 70-seater, and offer a new commercial transport service, the “micro-feeder”, which could connect small, grass airstrip airports with regional and international airports or offer a flexible and rapid alternative to existing means of transport (2).

2.1 MAHEPA PROPULSION SYSTEM

2.1.1 PURE ELECTRIC AIRCRAFT PANTHERA

Panthera was designed to be equipped with three types of propulsion packages - the conventional, hybrid and pure electric. Technical characteristics of each type can be seen in Table 1 (3). The pure-electric version of Panthera has a 200-kW powertrain and, as an experimental aircraft, aims to demonstrate the ability to cover 400 km (215 miles) quietly, efficiently, with absolutely zero emissions and for a fraction of cost. The platform is open and ready to accept future generations of battery technologies, which will increase the operating range (4) of such aircraft.

Table 1: Technical Data Sheet of Panthera aircraft

<table>
<thead>
<tr>
<th></th>
<th>Exp</th>
<th>Exp &amp; cert</th>
<th>Hybrid exp</th>
<th>Electro exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Utility (+4.4 g, -1.76 g)</td>
<td>Utility (+4.4 g, -1.76 g)</td>
<td>Utility (+4.4 g, -1.76 g)</td>
<td>Utility (+4.4 g, -1.76 g)</td>
</tr>
<tr>
<td>Power plant</td>
<td>Lycoming IO-390</td>
<td>Lycoming IO-540V</td>
<td>Hybrid 200 kW take-off power</td>
<td>Electric 200 kW take-off power</td>
</tr>
<tr>
<td>Rated power</td>
<td>210 HP</td>
<td>260 HP</td>
<td>200 kW (150 kW continuous) Maximum cruise power 100 kW</td>
<td>200 kW (150 kW continuous)</td>
</tr>
</tbody>
</table>

*Source: Panthera aircraft, 2019.*
2.1.2 HYBRID PANTHERA AIRCRAFT

The development of an ICE-hybrid powertrain had already started within the project HYPSTAIR (1) and now continues in project MAHEPA (2). The Panthera is a 4-seater aircraft with a hybrid drive, where a gas turbine supplies power to the electric motor in combination with a small battery so that it can take off on electric power. The propulsion concept consists of a serial hybrid-electric architecture, where propeller is driven by an electric motor, powered by a conventional turbocharged ICE and combined with an electrical generator and a battery system, which consists of two parallel battery packs. In case of a failure to the ICE or the battery system, the powertrain still has the ability to provide enough power for a safe flight and landing. Moreover, to increase the reliability of the entire system, redundant double inverter and electric motor designs were developed. As seen from Figure 5, the mechanical power coming from the ICE (Rotax 915) is converted into alternating current (hereinafter AC) electric power with a generator. The AC electric power is then transformed into a DC electric power with a dual inverter system. The DC electric power coming from the ICE is then connected with the DC power, coming from the battery with a DC-link. Power must now be transformed into the AC domain again with two redundant inverters that feed two different electric motors. This way, even if one DC-AC inverter or motor fails, the system is still capable of providing half power, allowing the aircraft to continue a safe flight (5).

![Figure 5: MAHEPA serial ICE hybrid drivetrain architecture](source: MAHEPA project, 2019)

The powertrain is designed to have a maximum take-off power of 300 kW and a maximum continuous power of 150 kW. The total weight of the powertrain, including the battery system, is expected to be around 370 kg.

An early stage design of hybrid Panthera performance show that due to all-electric take-off capability the aircraft can guarantee markedly lower noise footprint in this flight phase. The cruise speed is lower at low altitudes compared to standard Lycoming four- and six-cylinder engines due to less powerful ICE installed, but the speed penalty is greatly reduced when cruising at high altitudes, where the turbo-
normalized Rotax engine matches the performance of the four-cylinder Lycoming IO-390 engine. In addition, the aircraft fuel consumption is estimated to be lower or in the worst case equal to the standard aircraft motorization (6).

2.1.3 HY4 AIRCRAFT

The development of the hydrogen fuel-cell hybrid started within the Antares H3 project (7), where performance and reliability of fuel cell/battery hybrid were demonstrated in long term-flight tests of a manned motor glider. The project Hy4 later successfully realized a fuel cell/battery-hybrid driven high-aspect ratio long endurance of a four-seater aircraft. The research continues within the project MAHEPA, where existing components will be converted to a different arrangement, also capable of redundancy and in-flight battery recharge. The MAHEPA drivetrain will improve the previous installation in several important areas (improved redundancy and reliability, power, range, etc.).

The Hy4 is the world’s first four-seater passenger aircraft, powered solely by a hydrogen fuel cell system and electric propulsion. The Hy4’s drivetrain consists of a hydrogen storage unit, a low-temperature hydrogen fuel cell and a high-performance battery. The fuel cell converts energy of a hydrogen fuel directly into electrical energy. The only waste product in the process is the clean water. The electric motor uses the power, generated to propel the aircraft. If the hydrogen, required for the fuel cell, is generated via electrolysis using power from a renewable energy source, then Hy4 can fly without generating any emissions at all (8).

Figure 6: A MAHEPA serial FC-hybrid drivetrain architecture

Source: MAHEPA project, 2019.
with an optional freewheeling clutch. The freewheeling capability allows disconnecting the motor in case of any failures that require one of the motors to be stopped. To maintain recuperation capabilities a ground-adjustable locking mechanism will be optionally implemented. The motors are supplied with power from the DC-links. The PMCD (Power Management Control and Delivery) module routes power to the DC-links from both, the battery and the fuel-cell system. The fuel cell and the battery are then connected to the PMCD module (9).

The Hy4 has a very efficient airframe with enough volume to incorporate large fuel cell systems and pressure tanks without adding pods or similar. The dual fuselage configuration allows for up to four seats, while the central nacelle allows for fuel cells and drivetrain to be packed closely together for very high efficiency purposes. Combined with the high aspect-ratio and efficient design of the aircraft, comparatively low power is required for flight, especially in cruise. Combined with the comparatively high efficiency of fuel cells in the range of 50 %, an overall drivetrain efficiency of about 44 % can be achieved, without considering cooling and avionics. The aircraft requires approximately 30 kW of power during cruise and 62 – 85 kW for take-off or propulsion, making it ideal for this application (8).

The Hy4 has a motor output of 80 kW, an approximate maximum speed of 200 km/h and a cruising speed of 145 km/h. With regards to the speed, altitude and load, it can achieve ranges from 750 to 1 500 km. The most striking feature of the Hy4 is its twin fuselages, each with space for two passengers. The maximum weight of Hy4 aircraft is 1 500 kg (8).

### 2.2 FUEL EFFICIENCY

Fuel accounts for approximately one third of aircraft operating costs, creating an incentive for airlines to manage their fuel consumption through technological and operational improvements (10). As aviation fuel consumption linearly depends on the weight of an aircraft and fuel represents an important amount of an aircraft total mass, energy density of fuel plays an important role. Table 2 shows energy density of kerosene, hydrogen and batteries.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Energy density [kWh/kg]</th>
<th>Power plant efficiency (%)</th>
<th>Eff. energy density [kWh/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>12</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>Batteries</td>
<td>0.1 - 0.25</td>
<td>&gt; 90</td>
<td>0.1 – 0.25</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>33</td>
<td>55 - 60</td>
<td>18 - 20</td>
</tr>
</tbody>
</table>


As seen from the Table 2, batteries have very low energy density and can therefore be considered (at the moment) as an energy source only for light aircraft and/or short ranges of flights. On the other hand, energy density of hydrogen is larger compared to kerosene, making hydrogen very appealing type of
fuel for aircraft. Nevertheless, hydrogen has a very low mass density (Table 3) and can therefore be used only in a compressed or liquefied form. Unfortunately, for sustaining hydrogen in such a form it needs to be stored in special hydrogen tanks. Consequently, such tanks are heavy; therefore, they are effectively lowering the energy density of a total hydrogen system (fuel + tank) (11,12).

Table 3: Volumetric energy densities of hydrogen

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Eff. energy density [kWh/kg]</th>
<th>Mass density [kg/m³]</th>
<th>Eff. volumetric energy density [kWh/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>4</td>
<td>800</td>
<td>3.1</td>
</tr>
<tr>
<td>Compressed hydrogen (700 bar)</td>
<td>13 - 20</td>
<td>40</td>
<td>0.64</td>
</tr>
<tr>
<td>Liquid hydrogen</td>
<td>13 - 20</td>
<td>71</td>
<td>1.14</td>
</tr>
</tbody>
</table>


2.2.1 PURE ELECTRIC BATTERY DRIVEN AIRCRAFT

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 7, three different payloads of empty weight of a battery driven electric aircraft are considered:

- green area denotes 0.5 ton of aircraft payload (approx. 6 passengers),
- blue area denotes 2 ton of aircraft payload (approx. 19 passengers) and
- Orange area denotes 7 ton 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 7 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 7 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.
From the above stated data it can be concluded that by batteries, which hold the best energy density, an aircraft can reach ranges up to 200 - 300 km with a 0.5 ton payload, before the mass of the aircraft starts to grow steeply, while for aircraft with 2 ton and 7 ton payload, the battery is not a good solution, even when it comes to short ranges. More information on the subject can be found in Prapotnik Brdnik et al. (2019) (13).

### 2.2.2 AN ICE-HYBRID AIRCRAFT

In the case of an all-electric aircraft the battery energy determines the range of aircraft, whereas in the case of a hybrid-electric aircraft, alongside the batteries, also fossil fuels are used, which allow a substantial increase of range. In a fuel-powered hybrid aircraft, the battery is used during take-off and partly the climb and afterwards a classical ICE system takes over. The battery is partially refilled during decline, giving the aircraft the ability to use that energy for taxiing. The main goal of a fuel-powered hybrid aircraft is therefore to provide clean, noise and pollutant reduced operation in the vicinity of airports. These aircraft have no problems with short ranges as they can achieve similar ranges as ICE aircraft.

A fuel-powered hybrid aircraft has to provide 150 – 300 kW during take-off and climb per ton of aircraft’s mass to have a similar performance as convectional ICE aircraft. In a parallel fuel-powered aircraft this means that such power should solely come from the battery, where batteries with high specific power have to be used. Unfortunately, such batteries also have low energy densities, meaning that energy would be provided for only a short part of the climb, during which an aircraft would fly on zero emissions. In a serial fuel-powered aircraft, power can be provided by both, a generator and a battery, meaning that some adaptations between specific power and specific energy of batteries have to be made. Therefore, the battery of the same mass could provide an energy for a longer period of time, even
though it would not fly completely zero-emission during that time. More information on the topic can be found in Prapotnik Brdnik et al (2019) (13).

2.2.3 A FUEL-CELL HYBRID AIRCRAFT

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 (14). Therefore, an energy density of the whole system (hydrogen and tank) is less favourable, 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 8. Figure 8 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 8: Hydrogen energy density in dependence of stored mass of hydrogen

Source: Author.
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 (15), 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.

2.3 AN ESTIMATION OF GAS EMISSIONS FOR REGIONAL AIRLINERS IN EU

Aviation is the fastest-growing source of greenhouse gas emissions. Besides CO₂, a conventional aircraft emits particles and gases, such as hydrocarbons, carbon monoxide, nitrogen oxides, sulphur oxides, lead, and black carbon, which interact among themselves and with the atmosphere. Various technologies were and are currently designed to reduce the environmental impact, including MAHEPA, which is addressing potential emission reduction by discovering hybrid technologies for 19- and 70-seater aircraft. However, to better understand the potential emission reduction it is necessary to estimate emissions, caused by current regional airliners.

An estimation of gas emissions is calculated based on measuring HC, CO and NOₓ emissions caused by regional airliners in EU during typical LTO (landing and take-off) cycle. A typical LTO cycle is divided into four phases: take-off, ascent, approach and idle (taxiing). The take-off phase involves acceleration of aircraft along the runway and on average lasts about t₁ = 42 s. The ascent lasts from the moment, when aircraft is airborne, until it reaches an altitude of 1 000 m and lasts in average t₂ = 132 s. Landing procedure (approach) lasts from the moment an aircraft is at 1 000 m until it lands and decelerates on ground; it lasts approximately t₃ = 240 s. The idle phase (taxi-in and taxi-out) includes movements of an aircraft on ground to and away from the runway; it lasts around t₄ = 1 560 s. The total emissions of an aircraft are then calculated as:

\[ E₁ = ΣE_{im}t_mW_{f6m}, \]

Where \( E_{im} \) denotes an emission index at \( m^{th} \) phase, \( t_m \) average time duration of a \( m^{th} \) phase and \( W_{f6m} \) the fuel flow during \( m^{th} \) phase. The data on emission indexes and fuel flows are taken from ICAO Aircraft Engine Emission Databank. As the database does not include data for all engines, first a weighted average, based on an actual number of flights, was calculated only for flights, where engine emission data were available. The average emissions were then multiplied by a total number of flights.

Regional airliners in EU have carried 1 043 136 943 air passengers in 2017 (Eurostat, 2017) (16). An analysis on three main aircraft categories by numbers of seats showed that the largest number of flights was performed in category of 20- to 71-seaters, as expected according to OAG demo database (17). Based on the statistical data of flights and data on emission indexes and fuel flows, we can make a
preliminary estimation of potential emissions caused by existing airliners (Table 4), while also considering the projected growth of air transport and the growth of emissions, caused by conventional (existing) aircraft (Table 5).

Table 4: Gas emissions of regional airliners in EU for 2017

<table>
<thead>
<tr>
<th>Aircraft seats</th>
<th>No. of flights</th>
<th>No. of passengers</th>
<th>%*</th>
<th>Weighted average (g)</th>
<th>Weighted average (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HC</td>
<td>CO</td>
</tr>
<tr>
<td>1 – 8</td>
<td>84 326</td>
<td>674 608</td>
<td>0.06</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>9 – 19</td>
<td>79 887</td>
<td>1 517 853</td>
<td>0.15</td>
<td>115.4</td>
<td>2 504.2</td>
</tr>
<tr>
<td>20 – 71</td>
<td>676 577</td>
<td>48 036 967</td>
<td>4.61</td>
<td>93.3</td>
<td>2 672.8</td>
</tr>
<tr>
<td>EU sum</td>
<td>1 043 136 943</td>
<td></td>
<td></td>
<td>Sum</td>
<td>72.4</td>
</tr>
</tbody>
</table>


If the number of projected passengers in EU for the year 2035 is calculated to 1 737 638 000 (+3.7 % per year), considering the share of passengers travelling in each category of aircraft’s size (while taking in account weighted averages of emissions), we can see the rise of emission in all size categories of aircraft from 2017 to 2035 (Table 5).

Table 5: A prognosis on gas emissions of regional airliners in EU for 2035

<table>
<thead>
<tr>
<th>Aircraft seats</th>
<th>No. of flights*</th>
<th>No. of passengers*</th>
<th>%*</th>
<th>Weighted average (g)</th>
<th>Weighted average for 2035 (t)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HC</td>
<td>CO</td>
</tr>
<tr>
<td>1 – 8</td>
<td>130 323</td>
<td>1 042 583</td>
<td>0.06</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>9 – 19</td>
<td>137 182</td>
<td>2 606 457</td>
<td>0.15</td>
<td>115.4</td>
<td>2 504.2</td>
</tr>
<tr>
<td>20 – 71</td>
<td>1 128 241</td>
<td>80 105 112</td>
<td>4.61</td>
<td>93.3</td>
<td>2 672.8</td>
</tr>
<tr>
<td>EU sum</td>
<td>1 737 638 000</td>
<td></td>
<td></td>
<td>Sum</td>
<td>121.1</td>
</tr>
</tbody>
</table>


Geographical locations and the size of the pollution in 2017 (only for NOx (similar is for HC, CO) can be seen on Figure 9.
Figure 9: NO\textsubscript{x} pollution at EU airports in 2017

*Source: Author.*
3 A PRELIMINARY MARKET ASSESMENT AND TRENDS

According to the International Civil Aviation Organization (ICAO) (18), the classification of the commercial air passenger transport can be articulated into scheduled and non-scheduled flights. Scheduled flights are defined as flights performed according to a published timetable, or as regular flights that can be determined in a recognizably systematic series. In either case, they are open to direct booking by public. Non-scheduled flights on the other hand do not operate according to published schedule and are sold individually according to given demand. Non-scheduled flights can be further divided to charter and on-demand flights, latter including air-taxi, commercial business aviation and other similar services.

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. Due to the difference in mechanism, turboprop engines can provide less thrust than jet engines, but on the other hand, use fuel more efficiently. Consequently, turboprop aircraft fly at lower attitudes and with lower speeds than regional jets; they are more suited for shorter ranges.

In our preliminary market study, we have considered the trends in three main segments of scheduled flights (1-to-8-seater, 9-to-19-seater and 20-to-70-seater aircraft), based on OAG demo database for 2017) (17). In the business segment, based on EBAA study (19), we focused on turboprop and small jets aircraft, as they are the most appropriate segments and types of aircraft for our study. The assessment of potential volume of new transport services will help us better understand ground infrastructure, required at airports, for operation of hybrid aircraft (as explained more thoroughly in Chapter 5 and Chapter 6).

3.1 A TREND ANALYSIS

The number of air passengers carried worldwide, grew by 6.3 % to a record 3 979 billion in 2017, continuing the recovery trend since the global financial crisis in 2008/2009. Looking forward, global air travel, measured in Revenue Passenger Kilometres (RPKs), has a growth forecast between 4.5 % p.a. (Airbus) and 4.8 % p.a. (Boeing) over the next 20 years (to 2035). The fastest growth rates of around 6 % p.a. are expected in the emerging economies of Asia-Pacific, Middle East, Africa and Latin America. A more mature European market is forecasted to grow at 3.7 % p.a., while North America is predicted to grow between 2.9 % p.a. (Airbus) and 3.1 % p.a. (Boeing) (20).

Regarding European airports, five are ranked within top 30 in carried passengers. Those are London Heathrow, Paris Charles de Gaulle, Frankfurt Main, Amsterdam Schiphol and Madrid Barajas airport. Like at the US airports, growth has been low at European airports after 2006, due to several restrictions caused by terrorist threats. However, as the Eurozone economies picked up in 2015, all five airports recorded a higher year-to-year growth in 2015, compared to their 10-year average annual growth rates (20).
Europe’s air travel market remained strong in 2015 despite significant economic uncertainties. Europe’s GDP grew by 1.9 % in 2015 and according to forecasts, it is projected to grow by 1.8 % p.a., to 2035. Along with the trend, observed in recent years, especially low-cost carriers continued to expand their route networks between EU and non-EU European countries, which strongly supported the dominance of this flow sector and the 33 % rise since 2010.

A share of each business model on domestic and intra-regional flights in the period from 2007 to 2017 can be seen on Figure 10. The world fleet will more than double over the next two decades and around 37 400 (46 640 according to Flight Global (21)) aircraft will be required to operate over the next 20 years. Most of them – 28 420 (76 %) (65 % according to FlightGlobal) are in the segment of small aircraft with up to 230 seats and a range up to 3 000 nautical miles (NM) (22). For the purpose of this research, regional / commuter and charter / leisure flights are considered as the most interesting segments.

Figure 10 shows quite a large growth in almost all regions (Asia/Pacific, Europe and especially in Commonwealth of Independent States CIS and Africa) in those segments in the period from 2007 to 2017. A small decrease can be seen in Latin America and Middle East and a stagnation in North America.

Table 6 and Table 7 show the number of seats, offered for regional / commuter and charter / leisure flights. The trends from 2007 until 2017 have been calculated according to OAG and Airbus GMF2018. Defined business models were based on 2017 operations and projections until 2035 and 2050, respectively.
Table 6: Trends for regional / commuter flights

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007</td>
<td>2017</td>
<td>2035</td>
</tr>
<tr>
<td>Asia/Pacific</td>
<td>405.8</td>
<td>1 244.7</td>
<td>307 %</td>
</tr>
<tr>
<td>North America</td>
<td>19.6</td>
<td>19.6</td>
<td>-</td>
</tr>
<tr>
<td>Europe</td>
<td>44.1</td>
<td>102.6</td>
<td>233 %</td>
</tr>
<tr>
<td>Latin America</td>
<td>125.6</td>
<td>197.3</td>
<td>157 %</td>
</tr>
<tr>
<td>Middle East</td>
<td>43.1</td>
<td>98.0</td>
<td>227 %</td>
</tr>
<tr>
<td>CIS</td>
<td>3.4</td>
<td>17.1</td>
<td>503 %</td>
</tr>
<tr>
<td>Africa</td>
<td>3.2</td>
<td>10.6</td>
<td>331 %</td>
</tr>
</tbody>
</table>

* an approximate number from OAG, Airbus GMF2018-2037; a – 6 % p.a., b – 2.9 % p.a., c – 3.7 % p.a.


There were 2 375 net commercial aircraft orders in 2015, which is down 30 % on the previous years’ orders. **Narrow-body airliners represented close to two-thirds of total orders**, although orders for these types of aircraft were sharply reduced in previous years (Figure 11) (20).

Table 7: Trends for charter / leisure flights

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007</td>
<td>2017</td>
<td>2035</td>
</tr>
<tr>
<td>Asia/Pacific</td>
<td>45.1</td>
<td>90.2</td>
<td>200 %</td>
</tr>
<tr>
<td>North America</td>
<td>29.4</td>
<td>29.4</td>
<td>-</td>
</tr>
<tr>
<td>Europe</td>
<td>29.4</td>
<td>44.6</td>
<td>152 %</td>
</tr>
<tr>
<td>Latin America</td>
<td>2.1</td>
<td>3.9</td>
<td>186 %</td>
</tr>
<tr>
<td>Middle East</td>
<td>1.6</td>
<td>4.3</td>
<td>269 %</td>
</tr>
<tr>
<td>CIS</td>
<td>0.5</td>
<td>2.9</td>
<td>580 %</td>
</tr>
<tr>
<td>Africa</td>
<td>1.5</td>
<td>5.7</td>
<td>380 %</td>
</tr>
</tbody>
</table>

* an approximate number from OAG, Airbus GMF2018-2037; a – 6 % p.a., b – 2.9 % p.a., c – 3.7 % p.a.;

Source: Author.

Looking forward, growth in air travel demand is expected to result in delivery of approximately 33 070 (Airbus forecast) and 37 340 (Boeing forecast) new commercial jet aircraft (excluding regional jets) during years 2016 and 2035. Airbus and Boeing broadly agree on the level of demand for a wide-body aircraft, but Boeing sees greater demand in a narrow-body aircraft, and only one-third in a very large aircraft (Figure 12).
In a smaller sized segment, turboprop market is expected to be worth more than € 56 billion in deliveries, led by the 70-seat sector with potential for a larger 90±seat size from the late 2020s. According to Flight Global (21), a hybrid-electric airliner could be the next power-plant direction for this market. A sector with regional jets will be worth more than € 104 billion, led by aircraft of over 90-seats, although 40 % of value will come from 70-76-seaters, serving the North American markets (probably also other regions), which are currently scope-clause constrained.
The Brazilian manufacturer Embraer expects to deliver 14,750 aircraft during the next 20 years, whilst the latest available market forecast by Bombardier projects 12,700 deliveries for the same aircraft types (Figure 13) (21).

### 3.2 SCHEDULED FLIGHTS

#### 3.2.1 NUMBER OF AIRPORTS

Based on an analysis of OAG demo database, a number of airports operating regular flights in 2017 in three size segments of aircraft were considered: a 1-8-seater, a 9-19-seater and a 20-70-seater aircraft (Figure 14).
Figure 14: The number of airports in countries with scheduled aircraft by seat

An analysis shows that 50 airports operate regular flights on a 1-8-seater aircraft, 150 airports operate regular flights on a 9-19-seater aircraft and 484 airports operate regular flights on a 20-70-seater aircraft. Additionally, 18 airports offer regular flights on 1-8-seater and 9-19-seater aircraft, 102 airports offer regular flights on 9-19-seater and 20-70-seater aircraft and 15 airports offer regular flights on all three-size categories of aircraft.

The 15 before mentioned airports are offering regular flights in cities: Bergen, Milan (Orio Al Serio and Linate), Bodo, Brussels, Düsseldorf, Westerland, Magan, Hamburg, Ibiza, Teply Klyuch, Kirkwall, London (Lutton and London City airport), Lulea, Luxembourg, Marseille, Nice, Olbia, Copenhagen and Stuttgart.

### 3.2.2 TYPES OF AIRCRAFT

Certain types of aircraft prevail for each size category (e.g. 1-to-8-seater, 9-to-19-seater, and 20-to-70-seater) as seen from Table 8. In total, aircraft in a category of 20-70-seaters provides the largest number of seats and the most commonly used aircraft types for operating such flights are Aerospatiale/Alenia ATR 72, De Havilland Canada DHC-8-100 Dash 8 / 8Q, etc. In the 1-8-seater category, the most common aircraft are Pilatus Britten, Cessna, Beechcraft, Piper and Embraer Phenom.

#### Table 8: Aircraft type with number of available seats

<table>
<thead>
<tr>
<th>Aircraft category</th>
<th>No. of all seats</th>
<th>Aircraft type*</th>
<th>Seats available (2017)**</th>
<th>%</th>
<th>Total seats</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8-seater</td>
<td>1 – 4</td>
<td>- Pilatus Britten, Cessna, Beechcraft, Piper, Embraer Phenom 300</td>
<td>114 708</td>
<td>0,32</td>
<td>465 711</td>
</tr>
<tr>
<td></td>
<td>5 – 8</td>
<td></td>
<td>351 003</td>
<td>0,97</td>
<td></td>
</tr>
<tr>
<td>9-19-seater</td>
<td>9 – 12</td>
<td>- De Havilland Canada DHC-6, LET 410, Pilatus BN-2A/B Islander, British Aerospace Jetstream 32, Fairchild Dornier Do. 228</td>
<td>53 388</td>
<td>0,15</td>
<td>1 431 139</td>
</tr>
<tr>
<td></td>
<td>13 – 15</td>
<td></td>
<td>82 458</td>
<td>0,23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 – 19</td>
<td></td>
<td>1 295 293</td>
<td>3,59</td>
<td></td>
</tr>
<tr>
<td>20-70-seater</td>
<td>20 – 30</td>
<td>- Aerospatiale/Alenia ATR 72, De Havilland Canada DHC-8-100 Dash 8 / 8Q, Aerospatiale/Alenia ATR 42/ ATR 72, Canadair Regional Jet 200, Aerospatiale/Alenia ATR 42-300 / 320</td>
<td>608 749</td>
<td>1,69</td>
<td>34 155 581</td>
</tr>
<tr>
<td></td>
<td>31 – 40</td>
<td></td>
<td>8 193 039</td>
<td>22,73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>41 – 50</td>
<td></td>
<td>11 253 435</td>
<td>31,21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51 – 60</td>
<td></td>
<td>437 386</td>
<td>1,21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>61 – 70</td>
<td></td>
<td>13 662 972</td>
<td>37,90</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>100</td>
<td>36 052 431</td>
</tr>
</tbody>
</table>

*only first 5 most commonly used aircraft are listed; ** derived from OAG demo database

3.2.3 FLIGHT DISTANCE

Mileage analysis, which was based on a various size category of aircraft, outlines the most recurrent distance, covered by a specific aircraft (for 2017). The most covered distance with 1-8-seater is from 2 to 50 km (411 140 seats), where the most covered distances with 9-19-seater are from 301 to 500 km (371 915 seats) and from 101 to 200 km (351 491 seats). The most covered distances with 20-70-seater are from 101 to 300 km (12 751 554 seats) and from 301 to 500 km (11 253 337 seats), as pointed out in the Table 9.

Table 9: Number of seats on aircraft by flight distance

<table>
<thead>
<tr>
<th>Flight distance [km]</th>
<th>Seats</th>
<th>Flight distance [km]</th>
<th>Seats</th>
<th>Flight distance [km]</th>
<th>Seats</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – 50</td>
<td>411 140</td>
<td>2 – 50</td>
<td>168 599</td>
<td>19 – 100</td>
<td>1 275 466</td>
</tr>
<tr>
<td>51 – 100</td>
<td>30 415</td>
<td>51 – 100</td>
<td>135 493</td>
<td>101 – 300</td>
<td>12 751 554</td>
</tr>
<tr>
<td>101 – 200</td>
<td>16 506</td>
<td>101 – 200</td>
<td>351 491</td>
<td>301 – 500</td>
<td>11 253 337</td>
</tr>
<tr>
<td>201 – 300</td>
<td>2 248</td>
<td>201 – 300</td>
<td>283 913</td>
<td>501 – 700</td>
<td>4 450 470</td>
</tr>
<tr>
<td>301 – 500</td>
<td>2 965</td>
<td>301 – 500</td>
<td>371 915</td>
<td>701 – 1000</td>
<td>2 702 282</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>2 437</td>
<td>&gt; 500</td>
<td>119 728</td>
<td>1001 – 2000</td>
<td>1 678 100</td>
</tr>
<tr>
<td>Sum</td>
<td>465 711</td>
<td>Sum</td>
<td>1 431 139</td>
<td>&gt; 2000</td>
<td>44 372</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sum</td>
<td>36 052 431</td>
</tr>
</tbody>
</table>

*Source: OAG demo database, 2017.*

3.2.4 NUMBER OF FLIGHTS

An analysis on the daily number of flights per airport in 2017 shows that on average at least one daily flight is operated by (Table 10):

- 24.0 % of airports with scheduled flights on 1-8-seater aircraft (12 out of 50),
- 75 % of airports with scheduled flights on 9-19-seater aircraft (74 out of 150) and
- 63.4 % of airports with scheduled flights on 20-70-seater aircraft (307 out of 484).
### Table 10: An average number of daily flights

<table>
<thead>
<tr>
<th>No. of daily flights&lt;sup&gt;*&lt;/sup&gt;</th>
<th>1-8-seater</th>
<th>9-19-seater</th>
<th>20-70-seater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 1</td>
<td>38</td>
<td>76</td>
<td>177</td>
</tr>
<tr>
<td>1 – 2</td>
<td>5</td>
<td>33</td>
<td>84</td>
</tr>
<tr>
<td>2 – 3</td>
<td>6</td>
<td>27</td>
<td>66</td>
</tr>
<tr>
<td>3 – 4</td>
<td>-</td>
<td>6</td>
<td>35</td>
</tr>
<tr>
<td>4 – 5</td>
<td>-</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>5 – 6</td>
<td>-</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>6 – 7</td>
<td>1</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>7 – 8</td>
<td>-</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>8 – 9</td>
<td>-</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>9 – 10</td>
<td>-</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>10 – 15</td>
<td>-</td>
<td>-</td>
<td>22</td>
</tr>
<tr>
<td>15 – 20</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>20 – 30</td>
<td>-</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>30 – 50</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>More than 50</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>50</strong></td>
<td><strong>150</strong></td>
<td><strong>484</strong></td>
</tr>
</tbody>
</table>

<sup>*</sup> in average for 2017

*Source: OAG, 2017.*

The average daily flight was calculated by the flight frequencies in 2017, divided by 365 (days per year). Most airports have less than 1 operated daily flight (Table 10).

### 3.3 ON-DEMAND FLIGHTS

Business Aviation in Europe serves 25 280 city or area pairs, not connected by non-stop commercial flights (direct flights), which represent approximately 31 % of total city pairs analysed. Nearly 1 out of 3 connections is not connected by any direct commercial flight, meaning that the connection wouldn’t exist without Business Aviation. The key locations, where business aircraft operate, are Germany, U.K., Switzerland, Italy and France. On regional level, major centres for Business Aviation activities are Paris (Île-de-France), Greater London and Geneva.

According to PrivateFly report (23), the number of based fleets of light jets (26.7 %) and turboprop aircraft (34.2 %) reached up to 2 177. In 2018, there was a 4 % increase of small jets in on-demand flights and a 4 % decrease of small turboprop aircraft in on-demand flights, according to previous year (Figure 15).
According to EBAA report (19) there was a +4.6 % trend from 2016 in this business aviation sector. Business aviation fleet in 31 European countries therefore includes 955 light jets (26.7 %) and 1 222 turboprop aircraft (34.2 %). The rest of the fleet (around 40 %) are heavy- and mid-sized jets. More than 682 city pairs are covered by turboprop and small jets aircraft. As seen from Table 11, 1-to-8-seater aircraft cover more than 40 city pairs (among top 5 city pairs in EU countries), while 9-to-19-seaters cover over 115 city pairs (among top 5 city pairs in EU countries) and 20-to-70-seaters cover 527 city pairs.

Distances from 131 to over 500 km are covered by 1-to-8-seater (up to 2 980 km; e.g. Constanta (RO) – Nurnberg (DE)). Distances up to 7 920 km (e.g. Lisboa (P) – Viracopos (Brazil), which fall under the range from 51,7 up to over 500 km are mainly covered by 9-to-19-seater aircraft, whereas distances from 111 to over 2 000 km are covered by 20-to-70-seater aircraft (up to 3 998 km; e.g. London (UK) – Baku (Azerbaijan)). Most typical aircraft in this business segment are Cessna Citation, Piper, RARE Learjet, Socata TBM, Beechcraft, Bombardier, Piaggio, Pilatus, Embraer, British Aerospace Jetstream and Dassault Falcon.

**Table 11: City pairs with covered distances**

<table>
<thead>
<tr>
<th>Flight distance (km)</th>
<th>1-8-seater* Number of city pairs</th>
<th>9-19-seater* Flight distance (km) Number of city pairs</th>
<th>20-70 seater** Flight distance (km) Number of city pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – 50</td>
<td>0</td>
<td>2 – 50</td>
<td>111 – 300</td>
</tr>
<tr>
<td>51 – 100</td>
<td>0</td>
<td>51 – 100</td>
<td>501 – 700</td>
</tr>
<tr>
<td>101 – 200</td>
<td>7</td>
<td>101 – 200</td>
<td>701 – 1 000</td>
</tr>
<tr>
<td>201 – 300</td>
<td>5</td>
<td>201 – 300</td>
<td>1 001 – 2 000</td>
</tr>
<tr>
<td>301 – 500</td>
<td>12</td>
<td>301 – 500</td>
<td>&gt; 2 000</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>16</td>
<td>&gt; 500</td>
<td>Total</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
<td>Total</td>
<td>115</td>
</tr>
</tbody>
</table>

* only for top 5 city pairs; ** Source: OAG demo database for 2017

The following conclusions can be made about technical, economic and market entry aspect of pure electric, ICE hybrid and fuel-cell aircraft (Figure 16):

- **Pure electric battery driven aircraft** will be technically feasible only for **light aircraft** (1-8-seater aircraft) and **short ranges** (approx. up to 200 km) unless the specific energy of the batteries will significantly improve in following years.

- According to market studies, pure electric battery driven aircraft can be used for **scheduled flights** replacing majority of existing 1-to-8-seater aircraft due to the fact that the majority of 1-to-8-seater aircraft covers distances below 50 km (Table 9).

- According to market studies, pure electric battery driven aircraft cannot be successfully used for business aviation (on-demand flights), as in this air-flight sector in 70% of the cases 1-to-8-seater aircraft connects city pairs with distances over 300 km. Moreover, they do not connect any city pair closer than 100 km (Table 11).

- Pure electric battery driven aircraft present a very appealing option for **flight instructions, sport or hobby use, for touristic flights**, especially around national parks and other restricted or vacation areas due to zero gas pollution and low noise during entire flight.

- The market implementation of pure electric battery driven aircraft will most likely occur around the year 2025.

- **ICE-hybrid aircraft** will be technically feasible for all size categories of aircraft and will probably be economically justifiable for all types of aircraft, especially if considering favourable taxiing and subsidy policy regarding the positive affect on environment (lower emissions, lower noise in comparison to the conventional aircraft).

- With zero gas emissions and low noise during take-off an ICE-hybrid aircraft can achieve same ranges as conventional aircraft and has therefore more advantages on crowded airports and airports near large cities. According to Figure 9, this type of aircraft would be most advantageous in north European region (Scandinavia and Great Britain) and also on airports that charge penalties for gas emissions.

- A propeller driven aircraft, as designed now, has similar flying characteristics as conventional turboprop aircraft. Turboprop aircraft use less fuel on short ranges but are slower than jet aircraft. Therefore, according to market studies, **ICE-hybrid aircraft may not be accepted well in the business flight sector** (on-demand flights). In business flight sector turboprop aircraft are being replaced with jet aircraft indicating that speed is more important than price (Figure 15).

- The fuel driven hybrid is recommended for transition period between convectional and fuel-cell aircraft.

- The market implementation of an ICE-hybrid aircraft will most likely occur around the year 2035.

- In long-term a fuel cell hybrid aircraft could present the only feasible solution.
- As the tank of a fuel-cell hybrid aircraft is larger, the effective energy density of hydrogen-tank system is higher as well, which consequently lowers the level of consumption. Therefore, a fuel-cell aircraft is the most convenient for high payload and/or large ranges. The larger the aircraft, makes the possibility for greater economic return larger as well.

- The production price of fuels (hydrogen and kerosene) will decide between the fuel-cell aircraft and fuel-driven hybrid. A larger transition is not to be expected if the production price of kerosene stays below the production price of hydrogen. For 19- and 70-seater hydrogen driven aircraft, production price of hydrogen can be max. 5 times larger than the price of kerosene, in order to still be more competitive than conventional aircraft. This is not expected to happen before 2037 (nowadays, the production price ratio is 10: 1 in favour of kerosene).

- The market implementation of a fuel-cell aircraft will most likely occur around the year 2040.

Figure 16: Market entry of pure electric and hybrid-electric aircraft (8-, 19- and 70-seater aircraft)

*Source: Author.*
5 FAST-CHARGING OF MULTIPLE HYBRID ELECTRIC AIRCRAFT

5.1 A STANDARD SET OF GROUND INFRASTRUCTURE FOR PARALLEL-FAST CHARGING

5.1.1 BATTERIES

The main characteristics of a battery pack are its capacity, defining the amount of energy the system can store and power that defines the time in which the stored energy can be provided. Each battery pack is composed of several battery cells that can be connected in parallel or series, offering different voltage possibilities and maximal current settings. The capacity and the power of the system depends on the number of used battery cells and the characteristics of the cells. By adding more battery cells to the system, both capacity and power could be increased up to the desired value, at least theoretically. The quality of the battery pack is therefore defined by the quality of battery cells in the pack. Many different types of battery cells are available worldwide, but for the purpose of our research only lithium-ion cells will be discussed. Lithium-ion batteries have large specific energies compared to other batteries. The technology in development is quite mature, and they are also used in electric vehicles. Therefore, the implementation on aircraft would be the easiest one, as the technology already exists for automotive industry and can as such be more or less directly used at airports with only minor adjustments.

![Figure 17: Specific energies and specific powers for different battery types](image)

*Source: Kampker et al, 2018.*
When choosing the most suitable battery cells, the following characteristics should be considered:

- **Specific energy.** An energy that battery can give on a unit mass. It is usually measured in W/kg. Typically, Li-ion batteries have specific energies around 100 - 200 Wh/kg. As energy consumption of an aircraft linearly increases with its mass, specific energy and specific power of the batteries are very important factors and must be as large as possible.

- **Specific power.** The power that batteries can deliver on a unit mass. Unfortunately, Li-ion batteries with higher specific energies have lower specific power ratio and vice versa.

- **Lifecycle.** All batteries age with time and with the number of charging/discharging cycles. Their usage enables the rise of internal resistance and the fall of battery capacity. The most important factor in ageing of Li-ion batteries is the fall of capacity. A long battery lifecycle does not depend only on the type of battery, but also on its usage. The battery lifecycle is measured in number of fully charged/discharged cycles.

- **Safety.** All Li-ion batteries are safe to use if handled properly. Hazards may occur due to manufacturing error (very rarely) or due to improper usage. The latter involves exposure to heat and vibrations or charging batteries below 0°C.

### 5.1.1.2 BATTERY TYPES

Battery characteristics for different types of Li-ion batteries are summarized in Table 12. From the given characteristics it can be concluded that the most appropriate batteries for the aircraft are the Li-Nickel Manganese (NMC) and NCA (Li-Aluminium) batteries due to high specific energies or LFP (Li-Phosphate) due to high specific power. These types of batteries are also most commonly used in electric cars.

**Table 12: Types and specifications of Li-ion batteries**

<table>
<thead>
<tr>
<th>Type</th>
<th>Li-Cobalt</th>
<th>Li-Manganese</th>
<th>Li-Nickel Manganese</th>
<th>Li-Phosphate</th>
<th>Li-Aluminium</th>
<th>Li-Titanate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry Abbreviation</td>
<td>LiCo2</td>
<td>LiMn2O4</td>
<td>LiNiMnCo2O2</td>
<td>LiFePO4</td>
<td>LiNiCoAlO2</td>
<td>Li2TiO3</td>
</tr>
<tr>
<td>Lifecycle</td>
<td>500 – 1 000</td>
<td>300 – 700</td>
<td>1 000 – 2 000</td>
<td>1 000 – 2 000</td>
<td>3 000 – 7 000</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>Safety</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>****</td>
</tr>
<tr>
<td>Specific power</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
</tbody>
</table>

* the higher is the number of stars, the better are the battery characteristics.

*Source: Battery University, 2019.*
5.1.1.3 CHARGING PROCEDURE AND LIFE CYCLE

Lithium-ion batteries charge in two phases (Figure 18). In the first phase, constant current is applied to
the battery, while voltage across the battery cells slightly rises. When voltage increases its maximal value,
the second phase begins, and the current is starting to decrease. When current reaches the value low
enough, the current is terminated, and the battery is fully charged (100 % state of the charge (SoC)).
The speed battery charging is usually measured with C-rates. Battery charging at 1C rate means that
the empty battery would be fully charged in one hour, while 2C rate means that an empty battery would be
fully charged in half an hour. Note that the C-rate is a relative measure. Two battery packs, one with a
larger capacity and the other with a lower capacity, charging at the same C-rate, will be fully charged at
the same time with regard that the battery pack with the larger capacity has to be charged at a higher
power in order to achieve that.

![Figure 18: Battery charging times](Source: Battery University, 2019)

To prolong battery life following recommendations should be taken into the account:

- **State of charge.** Li-ion batteries will last longer if not fully charged. High voltage across the
  battery cell is stressful for batteries.

- **Depth of charge.** Battery lives longer if it is only partially charged/discharged. Also, charging
  the battery between 20 % and 70 % SoC is better that charging it between 50 % and 100 % SoC.

- **Charging speed rate.** Charging the battery at speeds higher than designed will shorten the life
  of a battery, especially in the second phase of charging. Lithium-ion batteries should not be
  charged at speed rates higher than 1C. The exception is LTO batteries that can be charged with
charging speed rates above 30°C. This means that battery packs with higher capacity could be charged at higher power.

- **Temperature.** All Li-ion batteries can operate at temperature range from -20°C to 60°C, but can be charged at the temperature range from 0°C to 45°C. Li-ion batteries should never be charged below 0°C as this will cause severe damage to the battery and compromise its safety usage (such batteries may unexpectedly explode during use). Fast charging cannot be performed at temperatures below 5°C. Charging the battery at high temperatures shortens its lifetime (especially with full charging). If a battery is charged at higher temperatures (above room temperature), it will not charge to its full capacity.

- **Storage.** Lithium-ion batteries should be stored charged (best at 40% SoC) and at cool temperatures, as high temperatures fasten self-discharge rate. If an empty lithium-ion battery is stored for a long time, due to self-discharge, the voltage across the cell can drop below 2.5 V, then the battery will fall in a “sleep mode” and as such cannot normally recharge before special treatment (boosting). If voltage across the cell drops below 2.0 V for a couple of weeks, such battery must be disposed due to safety reasons.

### 5.1.2 AN ELECTRIC CHARGING STATION

Charging of land vehicles is standardized by an International Electro Technical Commission and defined in IEC 62196. In US, another standard, SAE J1772, applies. Standardization of connectors differs in Japan, US, Europe and China. With only slight changes, technology and standardization, defined 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:

1. Battery is charged through a regular electric socket with a regular cable.
2. Like mode 1, but with added protection device, mounted on a socket or cable.
3. Charging through a charging station, which is directly connected to the electrical grid and provides alternating current (AC) to the battery.
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 when charging an aircraft. Feasible combinations of charging stations are presented in Figure 19. The possibilities are either to use alternating current or direct current with different voltage, current and power output.
5.1.2.1 CHARGING THROUGH AN AC CHARGING STATION

In case of charging through AC (Figure 20), the charging station should be installed and connected to an electric grid network through a single-phase or a three-phase connection. In a case, where several charging stations have to 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.

Figure 19: Probable configurations of charging stations
Source: Author.

<table>
<thead>
<tr>
<th>CURRENT PROVIDED TO THE BATTERY</th>
<th>ALTERNATING CURRENT (EU NETWORK)</th>
<th>DIRECT CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOLTAGE</td>
<td>SINGLE PHASE EU NETWORK</td>
<td>THREE PHASE EU NETOWRK</td>
</tr>
<tr>
<td>CURRENT OUTPUT</td>
<td>16 A</td>
<td>16 A</td>
</tr>
<tr>
<td></td>
<td>32 A</td>
<td>32 A</td>
</tr>
<tr>
<td>POWER OUTPUT</td>
<td>3.3 kW</td>
<td>11 kW</td>
</tr>
<tr>
<td></td>
<td>7.4 kW</td>
<td>22 kW</td>
</tr>
<tr>
<td>SOCKET TYPE</td>
<td>IEC 62196 - 2 Type 1, 2 and 3</td>
<td>IEC 62196 – 2 Type 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IEC 62196 – 3 AA, BB, CC, FF</td>
</tr>
</tbody>
</table>

300 V – 500 V (DC)
100-125 A  300-350 A
50 kW  120 kW
3.3 kW  7.4 kW
11 kW  22 kW  43 kW
43 kW

Figure 20: Battery charging through AC charging station
Source: Author.
Maximal allowed current in the cable is 63 A but charging stations providing lower current are also available on the market. For the charging station, connected to the EU grid (voltage difference of 230 V) this means that 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. Power output is obtained by multiplying current output by 230 V for a single-phase connection. In case of a three-phase connection power output is obtained by tripling that value.

5.1.2.2 CHARGING THROUGH A DC CHARGING STATION

The DC charging station (Figure 21) must be connected to the electrical network via a dedicated transformer. If several DC charging stations have to be 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.

![Figure 21: Battery charging through a DC charging station](Source: Author.)

5.1.2.3 CONNECTORS

Standard IEC 62191-1 describes the communication protocol between the charging station and the battery, defines general requirements and testing for socket-outlets, plugs, connectors, inlets and other charging equipment. One of the signals, sent through the cable, checks if the charging station and the battery are properly connected. Also, a battery, depending on its type and status, sends a signal to the charger, thus defining the maximal charging current that can be sent from the charging station to the battery. Standards IEC 62196-2 and IEC 62196-3 define plug and socket designs for AC chargers and DC chargers, respectively. Optional plug designs and their characteristics are presented in Error! Reference source not found. and Figure 23 (26).
### Plug and Socket Types for AC Charging, as Defined in IEC 62196-2

<table>
<thead>
<tr>
<th>TYPE</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTERNATIVE NAME</td>
<td>YAZAKI OR J1772</td>
<td>MENNEKES</td>
<td>SCAME</td>
</tr>
<tr>
<td>USAGE</td>
<td>SINGLE PHASE</td>
<td>SINGLE AND THREE PHASE</td>
<td>SINGLE AND THREE PHASE</td>
</tr>
<tr>
<td>MAXIMAL CURRENT (SINGLE PHASE)</td>
<td>32 A or 80 A*</td>
<td>70 A</td>
<td>16 A** or 32 A</td>
</tr>
<tr>
<td>MAXIMAL CURRENT (THREE PHASE)</td>
<td>/</td>
<td>63 A</td>
<td>63 A</td>
</tr>
<tr>
<td>COUNTRY</td>
<td>US, JAPAN</td>
<td>EU</td>
<td>FRANCE, ITALY</td>
</tr>
</tbody>
</table>

* 80 A is allowed in US, where the higher operating current is defined in SAE J1772.
** For plugs without control pilot contacts

**Figure 22: Plug and inlet types for AC charging**

*Source: Author.*

### Plug and Socket Types for DC Charging, as Defined in IEC 62196-3

<table>
<thead>
<tr>
<th>TYPE</th>
<th>AA</th>
<th>BB</th>
<th>CC</th>
<th>FF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTERNATIVE NAME</td>
<td>CHAdeMO</td>
<td>GB/T</td>
<td>CCS1</td>
<td>CCS2</td>
</tr>
<tr>
<td>COUNTRY</td>
<td>JAPAN</td>
<td>CHINA</td>
<td>US</td>
<td>EUROPE</td>
</tr>
</tbody>
</table>

**Figure 23: Plug and inlet types for DC charging**

*Source: Author.*
5.2 CHARGING TIME

Charging time varies according to the battery and the charging station. If a battery can withstand the maximal current that can be sent from a charging station, then the charging time can be simply calculated as

\[
charging \text{ time}\ [h] = \frac{\text{battery capacity}[\text{kWh}]}{\text{charging station power output}[\text{kW}]} \quad (2)
\]

If a battery cannot withstand the maximal allowed current, then the charging time is longer. For most lithium ion batteries, the fastest charging time is one hour (for fully charged battery). So, for example, if a 120-kWh battery is charged on a charging station with a power output of 40 kW, it would fully charge in three hours. If the same battery is charged on a charging station with a power output of 120 kW, it would fully charge in one hour. On the other hand, if a 40-kWh battery would be charged on the same charging station, it would need one hour to fully charge in both cases. Note that this is true only for fully charged batteries. Battery can also be charged with higher speed than 1C rate in case of partial charging (first phase of charging, see 5.1.1.3).

![Battery charging times in dependence of charging station maximal power output](image)

**Figure 24: Battery charging times in dependence of charging station maximal power output**

*Source: Author.*

Approximate battery charging times are presented in Figure 24. Note that real charging times vary according to a specific battery type and battery setup, therefore they may vary from the ones, specified in Figure 24.
5.3 FAST CHARGING REQUIREMENTS

The following requirements have to be considered for fast charging:
- Battery has to be designed for fast charging. All cells have to be in good condition and have a low internal resistance.
- Charging has to be performed at moderate temperatures (above 5°C).
- Fast charging should be applied only in first charging phase (up to 70% of SoC).
- Charging rate of 1C should not be exceeded in the second phase of charging (see 5.1.1.3).
- When charging is completed, Li-ion batteries should be disconnected from the charging source.

5.4 CHARGING STATION INSTALLATION AND OPERATING COSTS

The following procedures have to be performed in order to install a charging station (estimation according to Slovenian market (27)):
- **Documentation.** Required project documentation needed to obtain consent from the authorities vary between different member states. Documentation cost in Slovenia is approx. 1 500 EUR.
- **Preceding operations.** Under these operations fall: excavation for cable ducting and pipe laying, foundation of the base for the charging station, installation of freely standing connection measuring electric boxes, connection to the transformer station (without processing in the transformer), road crossing, implementation of unproblematic crossing of the electric cable with other communal water, etc. Costs may vary from 10 000 EUR to 25 000 EUR.
- If the transformer does not generate enough power, it is necessary to replace it with more powerful one or make modifications to existing one. If the transformer is running on maximum power, a new transformer has to be built. A transformer that can supply four to five DC charging stations costs around 10 000 EUR.
- The price of AC charging stations, connected to the single-phase electrical network, is around 1 000 EUR, AC charging stations connected to the three-phase electrical network cost around 3 000 EUR, while DC charging stations can cost several 10 000 EUR.
5.5 RELEVANT STANDARIZATION

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 62196</td>
<td>Charging of land vehicles in EU</td>
</tr>
<tr>
<td>SAE J1772</td>
<td>Charging of land vehicles in USA</td>
</tr>
<tr>
<td>IEC 62191-1</td>
<td>Charging station and battery</td>
</tr>
<tr>
<td>IEC 62196-2 ; IEC 62196-3</td>
<td>Plug and socket AC/DC</td>
</tr>
<tr>
<td>SIST EN 61851-1:2011</td>
<td>Electric vehicle conductive charging system - Part 1: General requirements</td>
</tr>
<tr>
<td>SIST HD 60364-7-722:2016</td>
<td>Low-voltage electrical installations - Part 7-722: Requirements for special installations or locations - Supply of electric vehicle</td>
</tr>
<tr>
<td>SIST EN ISO 15118-1:2019</td>
<td>Road vehicles - Vehicle to grid communication interface - Part 1: General information and use-case definition</td>
</tr>
<tr>
<td>SIST EN 61851-22:2002</td>
<td>Electric vehicle conductive charging system - Part 22: AC electric vehicle charging station</td>
</tr>
<tr>
<td>SIST EN 62196-1:2015</td>
<td>Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 1: General requirements</td>
</tr>
<tr>
<td>SIST EN 61851-23:2014/AC:2016</td>
<td>Electric vehicle conductive charging system - Part 23: DC electric vehicle charging station</td>
</tr>
<tr>
<td>SIST EN 62196-2:2017</td>
<td>Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 2: Dimensional compatibility and interchangeability requirements for AC pin and contact-tube accessories</td>
</tr>
<tr>
<td>SIST HD 60364-7-722:2019</td>
<td>Low-voltage electrical installations - Part 7-722: Requirements for special installations or locations - Supply of electric vehicle</td>
</tr>
<tr>
<td>SIST EN ISO 15118-1:2019</td>
<td>Road vehicles - Vehicle to grid communication interface - Part 1: General information and use-case definition</td>
</tr>
</tbody>
</table>
5.6 INFRASTRUCTURE RESIZING - A CASE STUDY OF MILAN-BRESSO

An enabling factor for the introduction of an all-electric or hybrid-electric fleet in the air transport system is the setup of a suitable ground infrastructure. The need for an increased electric power supply has to be accounted for in the reconfiguration of an existing airport. Indeed, the price of electric energy would come to represent a more relevant cost. The purchase price of energy is typically a function of time, changing greatly over a daily or weekly period - reaching up to two times and four times the minimum respectively, over these time frames (28). A smart scheduling of recharge activities should be pursued to reduce the energy supply cost. Smart recharge planning is clearly connected with the technological constraints inherent to available on-board systems and ground recharging facilities (29, 30).

In practice, there are two basic alternatives for exploiting battery charging stations. The first is through plug-in recharging station, where the battery is connected to the recharging facility while plugged in the aircraft. The second alternative is a battery swapping station, where the battery is recharged while unplugged from the aircraft.

Plug-in recharging stations are conceptually similar to fuel refilling stations. A major short come, associated with plug-in stations, is the fact that heavier and higher-performing aircraft – e.g. today’s liners – would need larger amounts of battery energy in the order of MWh. 3.5 - 7 MWh for an aircraft with the weight of a B737-800, depending on the mission (31), would in turn translate into an unacceptable recharging time, which is totally incompatible with the usual turnaround of an airliner. The usual 90 kVA power lines and connectors currently deployed to supply aircraft systems on ground could be multiplied to increase power supply, but besides procurement cost for the hardware, this would impact the peak power, required from the grid, which is responsible for part of the energy supply cost, together with the actual energy acquired from the grid. In the Italian energy supply scenario, the cost of allowed peak power is responsible for 20% of the overall electric energy cost for a typical user (28).

An alternative to plug-in is the battery swapping stations, which allow recharging batteries while unplugged from an aircraft. A matching number of unplugged batteries are provided in this case, with a smart schedule of the recharge, which is simultaneously compatible with air operations and minimizes power acquisition cost. Clearly, a larger amount of batteries represents a higher acquisition cost and an increased logistical effort (batteries need to be transported from and to the aircraft, as well as they need to be safely stored after the recharge and before the plug-in). Furthermore, similar to plug-in stations, recharging power is limited for a single swapping station, hence the higher number of simultaneous battery recharges would imply the need for larger amount of swapping stations, with an ensuing higher acquisition cost.

These factors – required energy/power supply, number of plug-in and battery swapping stations, and number of batteries – constitute the main output of a sizing problem, where the schedule of air operations, i.e. number and time frames, is given in the input. From the viewpoint of a ground operator, the reconfiguration of an airfield for operations with all-electric or hybrid-electric aircraft should imply defining this output, in order to grant minimum procurement and operative costs.
A different scenario is represented by airfields, where a single company is simultaneously acting as a ground operator and the owner of a fleet. In some cases, most typically on smaller airfields serving as bases for flying schools, the operations of that fleet make for nearly the total of all air operations. For such scenario, the study of fleet switching to innovative propulsion should account for the procurement cost of a novel aircraft, such as to grant the same operatively level of a conventional fuel-burning fleet, yielding an extended sizing problem, where an optimal number of aircraft is obtained as an output, together with a suitably sized ground infrastructure.

The latter scenario is of great interest today, when the economic profitability of fleet switching to electric propulsion has to be assessed in detail. Lower absolute costs for both procurement and operations, as well as its limited impact on the existing air transport system, make the flying school or aero club case more likely to translate into a real field application.

In this section, a comprehensive original method to face the problem of optimally sizing the ground infrastructure and fleet will be outlined first. An application of that method to the reconfiguration of the Milan-Bresso (LIMB) airport will be presented next. This airport is operated by the company Aero Club Milano, which acts as an airport manager and owns an aircraft fleet, used for instructional, as well as sport flights.

5.6.1 AN ANALYTIC APPROACH TO GROUND INFRASTRUCTURE AND FLEET RECONFIGURATION

The airport infrastructure and aircraft fleet sizing introduced in 5.6 can be modelled analytically as an optimization problem. From an operator standpoint, the optimum represents a balance between the need to grant an assigned operatively level, i.e. a flight schedule, and that of minimizing procurement and operative cost.

In mathematical terms, a suitable cost function \( J \) can be built up based on cost chapters as follows:

\[
J = C_E + C_P + C_{BSS} + C_{PIS} + C_B + C_{AC},
\]

where the components \( C_E \), \( C_P \), \( C_{BSS} \), \( C_{PIS} \), \( C_B \) and \( C_{AC} \) represent the cost of the electric energy, purchased from the grid, the cost of peak power, the procurement cost of the battery swapping stations and of the plug-in recharging stations, of the batteries, and of the aircraft, respectively. Searching for an optimum of the cost function \( J \), some constraints need to be considered, capable of modelling inherent technological limits, as well as mathematically formulating the physics of recharging operations. In order to correctly evaluate the constraints, the dynamics of the infrastructure are integrated over a suitable time frame of length \( T \). The problem is allocated on a discrete time grid, where the length of each time step is \( \tau \).

The cost components and constraining equations will be described in the following subsections, highlighting their respective dependencies.
5.6.1.1 COST COMPONENTS

The cost components in Eq. 3 can be expressed as follows. The cost of the energy supply $C_E$ is bound to the energy amount $E^P(t)$, purchased from the grid over a given period, and to the monetary value per energy unit $\lambda(t)$. Due to the very low frequencies in the evolution of both functions of time (compared to a daytime scale), providing definitions in discrete time is more typical to this type of problem. Therefore, it is possible to write

$$C_E = \sum_{t=0}^{T} \lambda_t E^P_t,$$

where the value of $E^P_t$ represents the energy acquired between the current time instant $t$ and the next one. Concerning Eq. 4, it would be easy to include a negative cost bound to putting energy into the grid. The ability to store energy in spare batteries, which are not on board, may gain the ground operator the chance to resell energy to the grid at times when its value is higher. This aspect was investigated at a theoretical level but is not of the interest for the case of smaller airports, for the absolute gain obtained selling the energy corresponding to the capacity of smaller batteries would be small and would come at the price of a significant system complexity.

Clearly, the value from Eq. 4 is a function of the time frame $T$ considered for the analysis. That value should be taken consistently with the definitions of the other components of $J$, as described through the next equations.

The cost of power can be expressed as

$$C_P = (N_{BSS} P_{BSS} + N_{PIS} P_{PIS}) c_P \frac{N_D}{30},$$

where $N_{BSS}$, $P_{BSS}$, $N_{PIS}$ and $P_{PIS}$ are the number and nominal power of swapping stations and plug-in stations, respectively. The sum between braces represents a nominal peak power, i.e. the power needed in case all battery swapping stations and plug-in stations are working simultaneously. The $c_P$ term represents the cost per unit of peak-power per month, and the value of $\frac{N_D}{30}$ the number of days in the considered analysis ($N_D$) in a month. The value of $N_D$ implicitly defines the limit for the sum in Eq. 3.

The component $C_{BSS}$ represents the procurement cost of the swapping stations, and can be written as

$$C_{BSS} = N_{BSS} c_{BSS} \frac{N_D}{T_{BSS}},$$

where $c_{BSS}$ is the acquisition cost per unit, and $T_{BSS}$ the expected lifespan of the device. Therefore, $\frac{N_D}{T_{BSS}}$ represents the relative extension of the analysis, measured in days, over the expected lifespan of the device. The cost of the unit can be defined based on a technological regression, as a function of $P_{BSS}$.

In a similar way, the cost model for plug-in recharging station can be written as
The cost model for batteries yields

\[ C_B = N_B w_B, \]

where \( w_B \) is the cost per battery. It should be noted that, at a theoretical level, considering a sufficiently long timeframe for the computation of cost, driving the number of total batteries to a minimum would not imply a lower overall battery cost, but only a lower initial procurement cost. A lower number of batteries would imply each of them should sustain more charge and discharge cycles. This would in turn decrease their life, implying more batteries would be needed on the long run, with an ensuing higher overall cost. On the other hand, a higher number of spare batteries would entail a higher initial procurement cost, and their efficient use would be associated in turn to a higher number of swapping stations. In this sense, the \( C_B \) term makes sense only on a time frame sufficiently limited with respect to the battery lifespan.

Finally, the aircraft procurement cost \( C_{AC} \) can be arranged similarly to Eq. 6 and 7, proportional to the number of aircraft \( N_{AC} \) needed for operativity, yielding

\[ C_{AC} = N_{AC} c_{AC} T_{AC}, \]

where \( c_{AC} \) is the aircraft procurement cost per unit, and \( T_{AC} \) the expected lifespan of the aircraft.

---

5.6.1.2 MODEL CONSTRAINTS

The parameters influencing the components of the cost function need to satisfy an array of constraints, which reflect both technological limits and models of the recharging processes.

The state of charge \( SoC_{i,t} \) of the \( i \)-th battery at time index \( t \) should be between a minimum \( SoC^{min} \) and a maximum \( SoC^{max} \), as required by technological limits. This is expressed by Eq. 10,

\[ SoC^{min} < SoC_{i,t} < SoC^{max}. \]

Battery charging can be carried out through swapping or plug-in stations. Battery charging (positive) rate \( P_{bat_{i,t}} \) cannot exceed a technological limit, expressed by a nominal \( P_{bat}^{max} \). This yields

\[
\begin{align*}
0 < P_{bat_{i,t}}^{SS} &< p_{bat_{i,t}}^{SS,max} \zeta_{i,t} \Phi_{i,t} \\
0 < P_{bat_{i,t}}^{PIS} &< p_{bat_{i,t}}^{PIS,max} \zeta_{i,t} \Psi_{i,t} \\
\Phi_{i,t} + \Psi_{i,t} &\leq 1
\end{align*}
\]
A battery can be recharged at any given time only if it is linked to a swapping or a plug-in station. This is returned by the binary variables $\xi_{i,t}$ and $\zeta_{i,t}$ in Eq. 11, which will equal to 1, if the battery is linked to a swapping station or plug-in station device respectively, and null otherwise. Two separate constraining equations are written in case if the battery is linked to either a swapping or a plug-in station. Two further binary variables $\phi_{i,t}$ and $\psi_{i,t}$ are added to exclude simultaneous recharging of the same battery from a BSS and a BRS – their sum is constrained under 1.

A further constraining equation is represented by the energy balance for the $i$-th battery, yielding

$$\text{SoC}_{i,t} = \left( P_{\text{BSS}_{i,t}} + P_{\text{PIS}_{i,t}} \right) \eta_{c} + \text{SoC}_{i,t-1}, \tag{12}$$

where $\eta_{c}$ is the efficiency of the recharging process. The initial value of the state of charge $\text{SoC}_{i,0}$ needs to be assigned. The energy amount, acquired from the grid and corresponding to the recharge power, is

$$E_{t}^{P} = \tau \sum_{i} \left( P_{\text{BSS}_{i,t}} + P_{\text{PIS}_{i,t}} \right), \tag{13}$$

where the sum has to be carried out on the number of active charging devices (battery swapping and plug-in stations). More binary variables and corresponding constraints are deployed at an implementation level to grant consistency when reducing all constraining equations to a linear form.

5.6.1.3 OPTIMIZATION STRUCTURE AND IMPLEMENTATION ASPECTS

The optimization of the cost function in Eq. 3 is carried out, based on preferred operatively data. The flight schedule is assigned over a considered time frame, yielding a number of aircraft that need to be airborne at any collocation point. The number of aircraft, batteries and recharging devices is then steered by the optimizer to yield the minimum cost, as defined by Eq. 3.

Retrieving the expression of $J$ from Eq. 3, it can be now computed as a function of the optimization variables of $E_{t}^{P}, N_{\text{BSS}}, N_{\text{PIS}}, N_{P}$ and $N_{AC}$. Other quantities, appearing in Eq. 4 to 9, namely $\lambda_{t}, P_{\text{BSS}}, P_{\text{PIS}}, c_{P}, c_{\text{BSS}}, T_{\text{BSS}}, c_{\text{PIS}}, T_{\text{PIS}}, c_{\text{BSS}}, w_{B}, c_{AC}$ and $T_{AC}$ can be considered as assigned technological parameters. Further optimization parameters include the binary variables appearing in the constraining Eq. 9, and those required to express all constraints through linear equations. The resulting optimization problem is based on a mix of discrete and non-discrete variables and can be faced via dedicated MIP (mixed-integer programming) solvers.

An analysis on suitably simplified case studies has been carried out to check if the problem is well posed and to validate results, as well as to test the performance of different commercial MIP solvers. The selected solution algorithm is GUROBI, which implements a MILP (mixed-integer linear programming) approach, fully compatible with a linear formulation of the optimal problem.
5.6.2 INFRASTRUCTURE AND FLEET RECONFIGURATION AT MILAN-BRESSO

The introduced procedure can be applied to the analysis of the reconfiguration of the airport base and a fleet of Aero Club Milano (ACM), which operates at Milan-Bresso (LIMB). The Milan-Bresso airfield features a single 1 080 x 30 m asphalt runway, which does not pose limits to terminal operations by any aircraft in the single-engine propeller-driven weight category. The current fleet of ACM is composed of 21 aircraft, mainly single-engine propeller-driven aircraft. In the current analysis it has been hypothesized to switch from the current aircraft models, mainly Cessna C172 and Piper PA-28, to a homogeneous fleet of Pipistrel Panthera Hybrid. The basic features of the aircrafts’ battery are summarized in Table 13.

Table 13: Basic data of Pipistrel Panthera battery

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity</td>
<td>13.8 kWh</td>
</tr>
<tr>
<td>Usable capacity</td>
<td>11 – 12 kWh</td>
</tr>
<tr>
<td>Life @ 75% DOD</td>
<td>800 cycles</td>
</tr>
<tr>
<td>Charging efficiency</td>
<td>93 %</td>
</tr>
<tr>
<td>Charging power</td>
<td>60 kW</td>
</tr>
</tbody>
</table>

*Source: Panthera aircraft, 2019.*

In order to analytically set up the sizing problem, the recharge power values $P_{PIS}$ and $P_{BSS}$ of the ground recharging devices have been defined at the nominal recharge power of the aircraft, i.e. 60 kW. Similarly, the maximum $SoC^{\text{max}}$, the recharge efficiency $\eta_c$ and the unit cost $w_B$ have been defined based on the data in Table 13. The unit cost of the recharging devices $c_{BSS}$ and $c_{BRS}$ has been fixed at 39.8 k€, based on a technological-statistical regression, for the considered recharge power of 60 kW (32).

5.6.2.1 SIMPLIFIED SIZING PROBLEM

The sizing problem has been carried out at first for a simplified scenario, where only battery swapping stations have been considered for recharging. This yields a simplification in the formulation of the cost function and constraints. The traffic data in input had been taken from the actual operations of the ACM on a given Saturday in October 2017. This month is associated to the most intense flying activity, due to the good weather and shrinking daylight time. It has been selected based on a worst-case, conservative approach for the sizing.
The sizing analysis has been carried out considering a time frame of a single day, and on the corresponding week. The considered discretization time $\tau$ is 15 minutes. The top plots in Figure 25 and Figure 26 are displaying the results in terms of electric energy need over time, compared to the supply cost of energy in Italy, and based on historical data (orange line). The results for one-day and one-week cases are shown in the left and right plots, respectively.

In the bottom plots, the battery requirement is reported, bounded to the assumed schedule of operations. It is possible to note, how the optimal recharge strategy takes advantage of the low energy price during the night hours to recharge the first set of batteries. The remaining recharge operations are carried out conditionally, soon after the beginning of flight operations during daylight hours. This is more advantageous than having a larger number of batteries charged ahead of their respective time of use. After use, batteries are not charged until a lower power procurement price is reached, i.e. after daylight hours.
Table 14 compares sizing results for the one-day and one-week cases. As expected, the number of batteries and swapping stations is the same, as Saturday corresponds to the busiest day of the week. The number of aircraft needed to cover the operative requirements is lower than the current fleet of ACM. This is due to the fact that the investigated scenario does not account for redundancy, required in real operations to mitigate the effect of prolonged unavailability of some aircraft resulting from maintenance and faults, nor it considers that some aircraft with specific instrumentation are indeed required for specific missions, like IFR training, but are generally far less used than the rest in the current ACM fleet.

Table 14: Comparison of sizing results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>One-day sizing</th>
<th>One-week sizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of batteries ($N_B$)</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Number of chargers ($N_{BSS}$)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of aircraft ($N_{AC}$)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Recharged batteries</td>
<td>39</td>
<td>136</td>
</tr>
<tr>
<td>Overall energy requirement [kWh]</td>
<td>410</td>
<td>1 430</td>
</tr>
<tr>
<td>Peak power [kW]</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Power losses [MJ]</td>
<td>103</td>
<td>361</td>
</tr>
</tbody>
</table>

Source: Author.
5.6.2.2 A COMPLETE SIZING PROBLEM

In a more complete scenario, both swapping stations and plug-in stations are considered. For the case of Milan-Bresso, no substantial difference in the output of the design procedure has been highlighted in this case. The recharge time by a plug-in is compatible with the average 15-minute turnaround time for ACM operations, thus the adoption of a plug-in or swapping stations bears a similar impact on operatively. Figure 27 and Figure 28 highlight the similarity of the sizing solutions in the respective cases, with both plug-in and swapping stations (Figure 27) and with plug-in stations only (Figure 28). Both work well with the scenario from Figure 25, where only swapping stations are considered.

![Figure 27: Comparison of sizing solutions (BSS only).](image)

*Source: Author.*

The breakdown of optimal cost corresponding to a sizing solution, where both plug-in and swapping stations are considered, is shown in Figure 29 and Figure 30. The latter plot presents the cost components due to power, as well as procurement of recharging devices and batteries, magnified with respect to the former plot. Figure 29 is dominated by aircraft and energy procurement cost. The columns refer to sizing solutions with different battery unit cost parameter \( w_B \).
As previously reported, a change in this quantity has an indirect effect on the number of charging devices. From the lower plots in Figure 29 and Figure 30, moving leftwards column by column, it is possible to check that under a certain $w_B$ the solution changes to a higher number of rechargers, which greatly increase the recharging ability of the ground infrastructure, and consequently yield a lower number of required batteries.
Figure 30: Cost breakdown for different values of $w_p$ with detailed view on smaller cost components

Source: Author.
5.7 AN ASSESSMENT OF GROUND INFRASTRUCTURE FOR MULTIPLE FAST-CHARGING OF HYBRID-ELECTRIC AIRCRAFT

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

- Batteries for hybrid electric aircraft will be designed in a way to allow zero emissions in the entire LTO cycle, meaning that the battery has to generate enough power for all-electric take-off and landing.
- Specific power and specific energy of batteries are assumed to be at today's level.
- A battery with a high specific power has to be used to meet above stated assumptions. Our prediction model will assume that the aircraft will be equipped with batteries, which have a specific power of 2 kW/kg and a specific energy of 100 Wh/kg.
- A battery has to provide power of 150 – 300 kW per ton of aircraft mass (see 5.1.1).
- The assessment of required ground infrastructure covers charging 19- and 70-seater aircraft, considering the average number of daily flights at airports.

Consideration all above assumptions, a 19-seater aircraft will therefore be equipped with a battery, holding the 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 shown in the Table 15.

Table 15: Charging times of a 19-seater and 70-seater aircraft with different charging stations

<table>
<thead>
<tr>
<th>Power of the charging station [kW]</th>
<th>Charging time of a 19-seater aircraft [h]</th>
<th>Charging time of a 70-seater aircraft [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>15 – 30</td>
<td>55 – 110</td>
</tr>
<tr>
<td>7.4</td>
<td>7 – 14</td>
<td>24 – 48</td>
</tr>
<tr>
<td>11</td>
<td>5 – 9</td>
<td>16 – 33</td>
</tr>
<tr>
<td>22</td>
<td>2 – 5</td>
<td>8 – 16</td>
</tr>
<tr>
<td>43</td>
<td>1 – 2</td>
<td>4 – 8</td>
</tr>
<tr>
<td>50</td>
<td>1 – 2</td>
<td>4 – 7</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>1.5 – 3</td>
</tr>
</tbody>
</table>

Source: Author.

According to charging times, defined in Table 15 and average number of daily flights at airports, presented in the Table 10 (while not considering any limitations on turnaround rates), a single three-
A phase station with charging power of 43 kW would fit the needs of charging a 19-aircraft in all airports. Moreover, a 43 kW charging station would cover all the 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 the needs of 88% of airports that operate with the 70-seater aircraft. The airport with the largest number of flights (TOS) would need 4 to 8 charging stations with 120 kW power output or three times as many charging stations with 43 kW power output. Therefore, an 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 the number of aircraft is predicted to double by 2035, by that time, one 43 kW charging station would cover the needs for charging a 70-seater aircraft in 50% of airports and for charging a 19-seater aircraft in all airports, while one 120 kW charging station would cover charging needs for 70-seater aircraft in 75% of airports.

Nevertheless, battery charging is a long lasting procedure and the minimal time to fully charge the battery would be one hour. To achieve fast turn-around rates (20 minutes), one or two (depends on the battery capacity) 120 kW charging stations would be needed to charge a 19-seater aircraft simultaneously. In that case, batteries could be maximally charged up to 80% SoC (state of charge). Similar, for a 70-seater aircraft 4 to 8 120 kW charging stations would be needed to charge the batteries up to 80% SoC.

Another option would be a battery swapping method. For ground vehicles, a battery swap method was not a probable option 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 depend on how the battery is handled. In case of a possible accident it is therefore hard to define who should take the responsibility. In air transport similar problems arise but to lesser extent. From today's point of view, it is therefore hard to predict if battery swap method or direct charging method would prevail. However, from the battery lifespans given in Table 12, it can be noted that in an aircraft making at least one flight per day, would have to change battery once in three years (in the best case scenario once in five years) unless the battery production technology would advance in improving battery lifespan.
6 A STANDARD SET OF GROUND INFRASTRUCTURE AND OPERATIONS FOR HYDROGEN SUPPLY

6.1 HYDROGEN CHARACTERISTICS

6.1.1 GENERAL CHEMICAL AND PHYSICAL CHARACTERISTICS

Hydrogen is the lightest and most abundant element in the universe. Nevertheless, in can be rarely found on Earth in a free form as a hydrogen molecule H₂. Therefore, it has to be produced from compounds rich with hydrogen, like water or methane. As a gas, hydrogen is odourless, colourless, tasteless, non-corrosive, non-toxic and highly flammable. It changes into liquid at temperatures below 20 K. As a liquid, it is, similar to water, non-corrosive and colourless, with the light blue tint. Due to a small size of its molecule, it has a very low density and a tendency to rise and to defuse quickly, also through solids. Some metals, exposed to hydrogen, can loose on ductility due to penetration of hydrogen atoms into their lattice structure, a phenomenon known as hydrogen embrittlement, or even degradation, if exposed to hydrogen at high pressure and temperatures (hydrogen attack). If released in an atmosphere, hydrogen would rise to the upper atmosphere, where it would oxidize to water, react with pollutants or escape the Earth and not cause any environmental concerns. If released in a closed space, it would rise and accumulate on ceiling.

Table 16: Relevant physical and chemical properties of hydrogen

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point</td>
<td>32.938 K</td>
</tr>
<tr>
<td>Temperature at a critical point</td>
<td>1.2858 MPa</td>
</tr>
<tr>
<td>Pressure at a critical point</td>
<td>0.071 g/cm³</td>
</tr>
<tr>
<td>Density of liquid hydrogen at a boiling point</td>
<td>33 kWh/kg</td>
</tr>
<tr>
<td>Energy density</td>
<td>4 % vol.</td>
</tr>
<tr>
<td>Concentration at lower explosive limit</td>
<td>77 % vol.</td>
</tr>
<tr>
<td>Concentration at upper explosive limit</td>
<td>585°C</td>
</tr>
<tr>
<td>Auto ignition temperature</td>
<td>0.02 MJ</td>
</tr>
<tr>
<td>Minimum ignition energy</td>
<td>346 cm/s</td>
</tr>
</tbody>
</table>

Source: Author

Heat capacity of hydrogen is similar to those of other gases, while its thermal conductivity is significantly higher. Hydrogen has also a very low ignition energy and a very broad range between lower and upper explosive limit, meaning that it can burn in broad varieties of concentration mixtures with air. Relevant hydrogen physical and chemical characteristics are presented in the Table 16.
Hydrogen is mostly used in chemical industry, but hydrogen as a fuel has great future possibilities. As a fuel, hydrogen can produce heat energy through combustion or electrical energy through fuel cells. Using hydrogen in a fuel cell has several advantages over ICE:

- **Better efficiency.** Fuel cells reach efficiencies of 40 - 60% compared to combustion power plants, which reach efficiencies of approx. 30%.
- **Low noise.** Fuel cells and electro-motors produce less noise than combustion engines.
- **Lesser emissions.** Hydrogen combustion cells emit NOx gasses and water, while fuel cells emit only water.
- **Power to weight ratio of electric engines is greater than of combustion engines.**
- Fuel cells can be easily combined with batteries.

### 6.1.2 USING HYDROGEN FOR AIRCRAFT FUELING

Due to previously stated reasons and the following recommendations of ISO/PASS 15594, airports would need hydrogen in a liquefied form for fuelling. Based on following recommendations and explanations, stated in ISO 14687-2 and ISO/PASS 15594, hydrogen has to fulfill demands, listed in Table 17. Temperature of the liquid hydrogen should be 20 K or lower and pressure should be equal of higher than 700 kPa to achieve acceptable fuelling times (20 min) (ISO/PASS 15594).

**Table 17: Purity demands for hydrogen at airports**

<table>
<thead>
<tr>
<th>Form</th>
<th>Liquid hydrogen, type II, grade D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity</td>
<td>&gt; 99.9999% (volume fraction)</td>
</tr>
<tr>
<td>Para-hydrogen</td>
<td>&gt; 95% (minimum mole fraction)</td>
</tr>
<tr>
<td></td>
<td>&lt; 100 μmol/mol</td>
</tr>
<tr>
<td>Total gasses</td>
<td>&lt; 0.00002% (volume fraction)</td>
</tr>
<tr>
<td>O₂ content</td>
<td>&lt; 0.00002% (volume fraction)</td>
</tr>
<tr>
<td>N₂ content</td>
<td>&lt; 0.00005% (volume fraction)</td>
</tr>
<tr>
<td>H₂O content</td>
<td>&lt; 0.000001% (volume fraction)</td>
</tr>
<tr>
<td>C₅H₉ content</td>
<td>&lt; 0.000001% (volume fraction)</td>
</tr>
<tr>
<td>CO content</td>
<td>&lt; 0.000001% (volume fraction)</td>
</tr>
<tr>
<td>CO₂ content</td>
<td>&lt; 0.000001% (volume fraction)</td>
</tr>
<tr>
<td>Total Sulphur compounds</td>
<td>&lt; 0.004 μmol/mol</td>
</tr>
<tr>
<td>HCHO content</td>
<td>&lt; 0.01 μmol/mol</td>
</tr>
<tr>
<td>HCOOH content</td>
<td>&lt; 0.2 μmol/mol</td>
</tr>
<tr>
<td>NH₃</td>
<td>&lt; 0.1 μmol/mol</td>
</tr>
<tr>
<td>Total halogenated compounds</td>
<td>&lt; 0.05 μmol/mol</td>
</tr>
<tr>
<td>Particles diameter</td>
<td>&lt; 5μm</td>
</tr>
<tr>
<td>Maximum particles concentration</td>
<td>1μg/l in normal conditions</td>
</tr>
</tbody>
</table>
The transition to hydrogen as an aviation fuel will be influenced by factors, such as the future cost of liquid hydrogen, advances in hydrogen technologies, potential long-term international restrictions on aircraft emissions and the cost of kerosene. Although sharing the infrastructure with other transport modes could reduce cost for aviation section (33).

6.2 HYDROGEN SUPPLY CHAIN

The standard set of ground infrastructure and operations for hydrogen supply consists of (Figure 31):

- **Hydrogen production.** There are many ways of producing hydrogen, each yielding to a very different cost scheme. The steam methane reforming (SMR) of natural gas (hereinafter NG) prevails as the most widely used in the industry, being currently the cheapest way for producing hydrogen. A technology for bioorganic production of hydrogen (by algae) is still under development.

- **Hydrogen transport.** Hydrogen can be transported to airports in a liquefied form by road (trailers), rail, and water or by pipelines in gaseous form.

- **Hydrogen liquefaction or hydrogen compression.** Due to its low density, hydrogen has a large volume as a gas at normal temperature and pressure and is therefore unpractical for storage and transportation purposes. Therefore, hydrogen is usually used in a compressed or liquefied form. Hydrogen liquefies at temperatures lower than 20 K, while different liquefaction methods can be used like Linde’s cycle or Claude’s cycle.

- **Hydrogen storage.** Hydrogen can be stored as gas inside underground caverns, as a compressed supercritical fluid, as a liquid in a cryogenic tank, in materials based H₂ storage systems, as a slush hydrogen (solid state) in cryogenic tanks as cold-compressed or cryo-compressed hydrogen. The most feasible scenario for supplying hydrogen to airports is with a movable cryogenic storage (cryogenic truck).

- **Hydrogen refuelling point.** Hydrogen refuelling point is defined in ISO/PASS 15594 and will be described in detail in the following section.
HYDROGEN PRODUCTION

Hydrogen is mostly produced from methane (68 %), 16 % from oil, 11 % from coal and only 5 % with electrolysis. There are many ways of producing hydrogen, yet only one production method prevails as the most widely used in the industry. This is the steam methane reforming of natural gas. Since this technology is mature, we can conclude that the variations of hydrogen production costs are largely dependent on the price of the NG. Hydrogen can be produced in the following ways:

- **Steam reforming.** This is the most common and cheapest way for producing hydrogen. Hydrogen is produced from methane and water vapour through chemical reaction. Instead of methane, other light hydrocarbons like oil can be used. More information on steam reforming and similar processes can be found in ISO 16110: Hydrogen generators using fuel processing technologies.
- **Partial oxidation.** Process can produce hydrogen from heavy (long-chain) hydrocarbons like coal or heavy fuel oil using oxygen (O₂) as an oxidant. This method is more expensive than steam reforming, but it can produce hydrogen from other ingredients.

- **Auto-thermal reforming.** A combination of steam reforming and partial oxidation. It is more expensive than steam reforming and therefore not commonly used.

- **Gasification.** A method for producing fuel gases from coal. It uses both water and oxygen as an oxidant.

- **Electrolysis.** A process, where hydrogen is produced from water and electricity. The method is simple but rarely used due to economic reasons (price of electricity). More information on electrolysis can be found in ISO 16110: Hydrogen generators using fuel processing technologies.

- **Biogenic production.** Produces hydrogen from biomass, like wood or straw and other bio-fuels (e.g. bio-methane, bioethanol, vegetable oils, biodiesel, etc.). Hydrogen can be produced thermochemical (with a process similar to gasification) or biochemically (using a certain type of bacteria). Biogenic production is a new method and is therefore partly still in an experimental stage.

For the time being, the most economic hydrogen production method would be a steam reforming. Today, hydrogen can be produced from 10 EUR/kg, while liquefaction may add additional 1 - 2 EUR/kg, so the net price for liquid hydrogen should be around 11 - 12 EUR/kg. Nevertheless, note that hydrogen production costs strongly depend on price of natural gas and electricity and may therefore change in the future.

### 6.2.2 THE PRICE OF HYDROGEN
Currently, the hydrogen production in Europe is led by a few large industrial actors, which play a key role in establishing a market price internally. In general, we may describe the commercial transaction as a bilateral hydrogen transaction between two industries, defined by a high price elasticity, and portrayed by different parameters. Firstly, the inexistence of a global price database leading the market to a lack of traceable information. Additionally, prices depend on buyers’ location, which defines how hydrogen will be delivered (in a liquid or gaseous form), thereby transport and distribution of hydrogen is especially important, when hydrogen is produced in large scale, to get it from centralized production sites to points of use. Moreover, the purity levels play an important role since higher purity levels imply higher costs of hydrogen. Thus, having a reliable market price is extremely challenging, nevertheless, it is known that prices vary from 10 €/kg to 60 €/kg (34). Finally, encompassing these factors, a more reliable approach to forecast hydrogen price in the industry is by analysing its production cost (35).

Information on different cost ranges for the same technology in several industries was compiled and conducted by the Department of Energy of The United States (36). The report proposes 5 different scenarios (considering different NG prices), which were modelled by a tool, called H2A6. The main results of these simulations are shown in the Figure 33. The first scenario uses Annual Energy Outlook (AEO) 2009 prices for industrial NG as a production feedstock (light blue), while the second scenario uses the same principle but uses AEO 2012 prices instead (orange). Then, the report conveys a sensitivity analysis by setting up three flat prices 2 USD/MMBtu (Million Metric British thermal units) (dark blue), 3 USD/MMBtu (yellow) and 4 USD/MMBtu (grey).

![Figure 33: Hydrogen from SMR Cost Evolution Sensitivity Analysis](source: Hinicio, 2019; Data from US Department of Energy, 2019.)

### 6.2.3 COMPRESSION AND LIQUEFACTION OF HYDROGEN

Due to its low density, hydrogen has, as a gas at normal temperature and pressure, a large volume and is unpractical for storage and transportation. Therefore, hydrogen is usually compressed or liquefied. Hydrogen liquefies at temperatures lower than 20 K. Most commonly used liquefaction methods are Linde’s cycle or Claude’s cycle. Namely, two types of H₂ molecules are known: para-hydrogen and ortho-
hydrogen. Considering ortho- to para-hydrogen conversion, special care has to be taken in the process. At normal temperature and pressure, ¾ of all molecules are in the form of ortho-hydrogen and ¼ in a form of para-hydrogen. In a liquid form, where temperatures drop below 20 K, most of hydrogen (99.8 %) is in a para-hydrogen form. The transition from ortho-hydrogen to para-hydrogen occurs very slow (can last several days) and releases energy. Therefore, 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.

**Compressor** can be either reciprocating or centrifugal. Reciprocating compressors are most commonly used for hydrogen applications, but centrifugal compressors are also an option. Reciprocating compressors cost about 50 % more than a comparable centrifugal compressor but have higher efficiencies (37). Compressor costs are based on the amount of work done by the compressor, which depend on the inlet pressure, outlet pressure, and flow rate. Larger compressors are quite cheaper on a unit basis compared to smaller ones. The capital cost ($C_X$) of compressors and liquefiers depend on compressor/liquefier size and can be estimated with the equation (38):

$$C_X = C_0 \left(\frac{S_X}{S_0}\right)^y$$

where parameters $C_0$, $S_0$ and $y$ are defined in the Table 18, while $S_X$ denotes the size of compressor (in kW) and liquefier (in kg of liquefied hydrogen per day). To compress 1 kg of hydrogen or 2 – 3 % of hydrogen energy content 0.7 - 1.9 kWh of energy is used, while liquefaction requires 11 kWh/kg or 33 % on base energy content.

**Table 18: Estimated costs and energy inputs of compression and liquefaction**

<table>
<thead>
<tr>
<th></th>
<th>Compressor</th>
<th>Liquefier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base size ($S_0$)</td>
<td>10 kW</td>
<td>30 000 kg/day</td>
</tr>
<tr>
<td>Base capital cost ($C_0$)</td>
<td>13 500 EUR</td>
<td>36 000 000 EUR</td>
</tr>
<tr>
<td>Scaling factor ($y$)</td>
<td>0.579</td>
<td></td>
</tr>
<tr>
<td>Operation and maintenance cost (fraction of capital cost)</td>
<td>4 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Energy use</td>
<td>0.7 - 1.0 kWh/kg</td>
<td>11 kWh/kg</td>
</tr>
</tbody>
</table>

*Source: Linde, 2019; Protium Innovations LCC, 2015.*
6.2.4 HYDROGEN TRANSPORT

Hydrogen is most commonly transported by trucks or via a pipeline system. Other possibilities of delivery are by train or ship, but they are not analysed in detail in this study (due to a similar approach).

6.2.4.1 TRANSPORT BY TRUCK

Hydrogen can be transported either in a gaseous form with tube trailer or in a liquid form with cryogenic truck (Figure 35 and Figure 36). If there is no direct delivery from truck to aircraft, storage and dispenser are also needed for fuelling (Figure 35). Compared to pressure gas vessels, a higher amount of hydrogen can be carried out with a LH\textsubscript{2} trailer, as the density of liquid hydrogen is higher than that of gaseous hydrogen. At a density of 70.8 kg/m\textsuperscript{3}, around 3 500 kg of liquid hydrogen or almost 40 000 Nm\textsuperscript{3} can be carried at a loading volume of 50 m\textsuperscript{3}. 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\textsubscript{2} trailers have a range of approximately 4 000 km. While transporting the hydrogen to its final destination, the cryogenic hydrogen heats up, causing the pressure in the container to rise. Similar to lorry transport, LH\textsubscript{2} can also be transported by ship or by rail, given that suitable waterways, railway lines and loading terminals are available (41).
The cost of liquid tank truck delivery is about 10% of tube trailer delivery ($0.16/\text{kg} \text{ vs. } 1.82/\text{kg}) (35). Tube trailer investment costs and energy efficiencies are more sensitive to the delivery distance than those of road tankers. An example of needed equipment for tube trailer delivery is shown in Figure 35 (42).

Figure 35: Hydrogen delivery by truck

Source: Author.

Figure 36: Gaseous hydrogen delivery by tube trailer (left) and liquid hydrogen delivery by cryogenic truck (right)

6.2.4.2 TRANSPORT BY PIPELINE

If hydrogen is being delivered continuously by pipeline (Figure 37), little, if any hydrogen storage may be required, and it would not make sense to liquefy the hydrogen and then deliver it to a pipeline as a gas. In pipelines with large variations in flow, hydrogen may need to be stored to meet the peak demand. The method of storage in that case would depend on the stored quantity and the storage time. Piping systems are usually several km long, in some cases even hundreds. Due to a great length of these piping systems, and therefore a great volume, even a slight change in the pipeline system operating pressure can result in a large change of amount of gas, contained within the piping network. By making small changes in operating pressure, the pipeline can be used to handle fluctuations in supply and demand, avoiding the cost of onsite storage (43). Typical specifications for hydrogen pipeline systems are:

- pipe size: 10 cm – 30 cm,
- minimum depth of a pipeline: 90 – 120 cm,
- operating pressure: between 24 – 130 bar,
- most current system is constructed using steel and carbon steel pipes with corrosion protective coatings (mild strength steel – API 5L X42 or X52 and ISO 13847),
- extensive use of automated excess flow valves.

The cost of a H\textsubscript{2} pipeline installation is very dependent on the location (state, rural, street, etc.). As seen from Figure 38, the initial capital investment into pipelines vary from 270 000 € to 810 000 € per km (44). The cost of compression, storage and dispensing is to be between 1.72 €/kg and 2.41 €/kg, with a likely cost of 2.06 €/kg of hydrogen for a pipeline station.

![Figure 37: Hydrogen pipelines](source: Isacc, 2019)
Although hydrogen pipeline transport is technologically mature and the transport costs are similar to those of natural gas, most of the hydrogen is produced in the place of demand, with an industrial production facility every 80 to 160 km. In EU, the most developed pipeline supply is in Belgium (613 km), followed by Germany (376 km), France (303 km) and Netherlands (237 km). A similar pipeline supply and infrastructure could be set in place for transportation of hydrogen to airports. Innovative solutions are emerging, which could allow faster transport of larger capacities of hydrogen. The new technology allows hydrogen to be stored in a solid state inside a chemical, called sodium borohydride, which is much denser than liquid hydrogen (45). The great sustainable aspect shows that when extracting the hydrogen to refuel an aircraft, the chemical returns back to borax, and the compound, from which it is originally produced. As a result, it is fully recyclable and can therefore be reused for further transport of hydrogen (46).

### ON-SITE PRODUCTION

One of the options, beside truck or pipeline delivery, is also on-site production of hydrogen at airport site, whereas as mentioned before, most likely the steam reforming method for producing hydrogen from natural gas would prevail, as it is widely used in chemical industry (as seen on Figure 39). The prices vary from 10 €/kg to 60 €/kg and the variations of hydrogen production cost are largely dependent on the price of NG.
6.2.5 HYDROGEN STORAGE

Hydrogen can be stored in one of the following ways:

- As a gas inside underground caverns.
- As a compressed supercritical fluid at room temperature and pressure up to 70 MPa in a tank, made of carbon fiber or other composite materials. Hydrogen has a volumetric energy density of 4.8 MJ/l (1.33 kWh/l) at pressure 70 MPa, while it has a volumetric energy density of 2.9 MJ/l (0.81 kWh/l) at pressure 35 MPa. Requirements for physical storage of hydrogen can be found in ISO 19881.
- As a liquid at normal pressure in a cryogenic tank. Liquid hydrogen has a volumetric energy density of 8.5 MJ/l (2.36 kWh/l). Cryogenic tanks are made of multiple layers with vacuum or special isolation materials in between the layers and a small vent that releases hydrogen in the atmosphere, when the pressure in a tank increases over the limit due to a boil off. If hydrogen is stored in a liquid form, losses due to a boil-off have to be taken into consideration.
- Inside materials in materials based H2 storage systems. The most common method is a hydride storage, where hydrogen is absorbed inside metallic lattice of metals like palladium, magnesium or aluminium, but also other possibilities are known or tested. This kind of storage is still in an experimental phase and is nowadays commercially not competitive with physical storage.
- As a slush hydrogen (solid state) in a cryogenic tank. Due to economic reasons, slush hydrogen is rarely used.
- As cold-compressed or cryo-compressed hydrogen, where hydrogen is both compressed and cooled. This method is still in an experimental stage but can reach relatively high volumetric energy densities (similar to slush hydrogen).

Above-ground 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. Capital costs for such storage vary between 26 and 172 €/kg of hydrogen. In many cases, small tanks are rented by the gas supplier for a couple thousand dollars a month.

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, and the economy of scale savings are not significant except with large volumes. There is also a reduction in hydrogen losses with larger vessels because of the lower surface area per unit volume at the larger sizes (48). Perlite insulated tanks cost less than Mylar wrapped tanks, but still provide good insulating properties (49). The costs for liquid hydrogen storage vary between 27 and 610 €/kg (7.13 - 280 €/lb).

Because not all aircraft are going to change to LH$_2$ overnight it must be kept in mind that during the transition period an airport must 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. 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 (33).

![Figure 40: Hydrogen liquid storage](source: FSEC, 2019.)
6.2.6 HYDROGEN MANUFACTURERS IN EUROPE

According to preliminary market analysis of existing hydrogen manufacturers in Europe, we noticed actual feasible possibilities to provide hydrogen for aviation sector, when necessary. We can compare geographical position of hydrogen manufacturers and airports that operate flights with 9-19-seater aircraft (Figure 41). We identified several nearby manufacturers, who could supply airports with necessary hydrogen supply in the central Europe (such as western part of Germany, Belgium, Luxemburg, Switzerland, Netherlands, northern part of Italy, etc.). However, in northern parts of Norway, Sweden and United Kingdom we noticed several airports operating above mentioned flights, but they have no nearby hydrogen suppliers. Several EU countries, such as Austria, Czech Republic, Hungary, Slovakia, southern part of Italy, western part of Germany, and Spain have several hydrogen producers, but no nearby airport that would operate flights with 9-19-seater aircraft. Countries such as Slovenia, Croatia, Montenegro, Bulgaria, Romania, and Ukraine have few daily flights operating with 9-19 aircraft, but no hydrogen manufacturer nearby.

Considering the airports in EU, operating flights with 20-70-seater aircraft, the geographical dispersion is very similar (Figure 42). Central Europe has a large amount of hydrogen suppliers, which cannot be said for Eastern Europe (Belarus, Bulgaria, Czech Republic, Hungary, Poland, Moldova, Romania, Russia, Slovakia, Ukraine. The biggest producers of hydrogen in Europe are: Air Liquide, Air products, Linde, Messer and Praxair.
Figure 41: Hydrogen producers in Europe vs. airports operating with 9-19-seater aircraft

Source: Author.
Figure 42: Hydrogen producers in Europe vs. airports operating with 20-70-seater aircraft

Source: Author.
6.2.7 REQUIREMENTS FOR HYDROGEN REFUELING

Airports should be able to provide following services for the hydrogen fuelled aircraft:

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

Due to safety reasons, all above stated procedures have to be performed in open space, free from flammable and combustible objects (e.g. trees) and restricted only to personnel preforming the fuelling or de-fuelling operations. Aircraft, storage and connecting pipeline have to be properly grounded and bounded before an operation of fuelling or de-fuelling starts. During warm system de-fuelling or refuelling, a fuel tank has to be purged with inert gas (helium or nitrogen) to prevent mixing hydrogen with air. More details on how to perform stated procedures can be found in ISO/PASS 15594: 2004 Airport hydrogen fuelling facility operations.

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), as shown on Figure 43. 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).

![Figure 43: An example of aircraft fuel system layout](https://example.com/fig43)

Source: ISO/PASS 15994.

A refuelling coupling unit for a small aircraft, defined as Type I in ISO/PASS 15594, can be manual and has to 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 a monitoring equipment,
powered by batteries that would measure pressure, temperature, flow rate, filling level of the tank, hydrogen leak and valve position and a transportable detector of hydrogen concentration and heat. For minimal requirements, boil-off hydrogen can be directly released safely (open environment). Nevertheless, an equipment for re-catching of hydrogen should be preferred for economical and safety reasons.

6.3 RELEVANT STANDARDIZATION

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 16110</td>
<td>Hydrogen generators using fuel processing technologies</td>
</tr>
<tr>
<td>ISO/PASS 15594: 2004</td>
<td>Airport hydrogen fuelling facility operations</td>
</tr>
<tr>
<td>ISO 19881: 2018</td>
<td>Gaseous hydrogen - Land vehicle fuel containers</td>
</tr>
<tr>
<td>ISO 13847:2013</td>
<td>Petroleum and natural gas industries - Pipeline transportation systems - Welding of pipelines</td>
</tr>
<tr>
<td>ISO/TR 15916:2015</td>
<td>Basic considerations for the safety of hydrogen systems</td>
</tr>
<tr>
<td>ISO 13984:1999</td>
<td>Liquid hydrogen - Land vehicle fuelling system interface</td>
</tr>
</tbody>
</table>

6.4 AN ASSESSMENT OF GROUND INFRASTRUCTURE FOR HYDROGEN SUPPLY

A study from C. Young and J. Ogden (38) considers different hydrogen delivery scenarios for USA. Although the analysis is considering equipment and transport costs characteristically adjusted for USA market in 2007, the obtained conclusions can be generalized to todays’ EU market as well. A study considers three different delivery scenarios: delivery by gas truck, delivery by cryogenic truck and delivery by pipeline.

In the first scenario (delivery by gas truck), hydrogen is compressed at a 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 afterwards. The largest cost component in the gas truck delivery scenario are the operating and maintenance costs of the truck, 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 the second scenario (delivery by cryogenic truck), hydrogen is liquefied at the production site and transported to the consumer by cryogenic truck. A study assumes 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 the liquefier, used at the production site, is 30 tons of H₂ 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 distance.

In the third scenario (delivery by pipeline), hydrogen is first pre-compressed at the production site and then delivered to the consumer by pipeline. With regards to the 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 hydrogen flow rates and distance.

Figure 44 presents an optimal hydrogen transmissions scenarios and minimal transmission costs for different hydrogen flow rates and transport distances. It can be concluded that delivery of a compressed gas by truck is an optimal solution for short distances and low hydrogen quantities. Delivery by a cryogenic truck is optimal for large distances and low hydrogen flow rates, while the delivery by a pipeline is optimal for high hydrogen flow rates and large distances.

![Figure 44: Optimal hydrogen transmission scenarios and minimal hydrogen transmission costs depending of hydrogen flow rates and transport distances.](image)

Nevertheless, above mentioned study assumes that the end user does not differentiate between gaseous and liquid hydrogen. However, as explained in section 2.2.3, aircraft should be fuelled by hydrogen in liquefied form for two reasons. First, an effective specific energy of hydrogen and tank system is higher for liquid hydrogen compared to gaseous hydrogen. Therefore, an aircraft flying on liquid hydrogen is lighter than 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, leading to better aerodynamic properties and therefore even lower consumption. To assess the hydrogen transmission economy, aircraft efficiency consumption has to be considered in the analysis as well. Unfortunately, an exact energy efficiency of a hybrid fuel-cell aircraft is still unknown as it largely depends on the design of an aircraft.

Under the present conditions, where the energy efficiency of a hybrid fuel-cell aircraft is similar to the conventional aircraft (according to section 2.2.3 this is a feasible assumption for 19- and 70-seater aircraft), we can conclude that a 19-seater aircraft would need approximately 200 kg of hydrogen for 500 km range flight, while a 70-seater aircraft would need approximately 700 kg of hydrogen for the same range.

According to the Table 10, if all regional aircraft in EU would be swapped for hybrid fuel-cell aircraft, 90 % of airports would need less than 10 tons of hydrogen daily 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 ton of hydrogen per day. On the other hand, an airport with the most regional daily flights in Europe (i.e. Tromsø airport, Norwegian) would need around 40 tons of hydrogen per day. Nevertheless, it should be taken into account that hydrogen is even more appealing fuel for large aircraft (see 2.2.3) and therefore, one should not limit on assumption that only regional aircraft would fly on hydrogen. In that case, a daily consumption at large airport hubs could be even much larger.
7 CONCLUSION

Hybrid-electric propulsion technologies are appealing for a new paradigm of transport services and business models with their many advantages, such as low or almost zero emissions, reduced noise and low operating costs. However, several questions, such as their market application and with that the adoption of necessary ground infrastructure, remain open. In the upcoming years, a wide range of hybrid-electric aircraft from single-seater ultralights, micro-feeder aircraft to regional airliners will be produced and will enter the existing markets, while in some cases also create new markets for commercial flights. As the hybrid propulsion technologies are novel and currently not widely used in commercial sense, also economic assessment of necessary ground infrastructure is novel for their operation. With no doubt, the ground infrastructure at airports will have to be adopted or newly developed to enable operation of ICE-hybrid and fuel-cell hybrid aircraft, while also concerning operational, financial and regulatory aspects.

Ground infrastructure required for charging batteries of ICE-hybrid aircraft at airports will need to include battery charging stations and optionally battery swapping equipment. For charging stations same technology can be used as for ground vehicles charging, with only slight modifications (e.g. cable length).

For a hybrid-electric 19-seater (with battery capacity of 50-100 kWh) and 70-seater aircraft (with battery capacity of 180 - 360 kWh), 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, while taking into consideration charging times and an average number of daily flights in airports. Moreover, charging station of 43 kW would cover all needs for charging a 70-seater aircraft in 66 % of airports that operate with such aircraft. Similar, one 120 kW charging station would cover needs of 88 % of airports, which operate with the 70-seater aircraft. The airport with the largest number of flights would need from 4 to 8 charging stations with 120 kW power output or three times as many charging stations with 43 kW power output to provide enough electricity for their hybrid-electric fleet.

For the majority of airports investment cost would be between 15 000 EUR and 50 000 EUR, while for the airport with the most frequent number of flights, the infrastructure cost might raise up to around 200 000 EUR. The main obstacle in that case present slow charging times of batteries (one C-rate, at which battery can be fully charged in one hour). For faster turn-around rates, battery swapping mechanism should be considered, although it arises other obstacles (different types of batteries should be kept in stock, determination of responsibility in case of accidents, etc.).

As the number of aircraft is predicted to double by 2035, by that time one 43 kW charging station would have to cover the needs of charging a 70-seater aircraft in 50 % of airports and a 19-seater aircraft in all airports. One 120 kW charging station would have to cover charging needs for 70-seater aircraft in 75 % of airports. For the future implementation it will be important to standardize equipment and procedures, which will be used in aviation. As seen from experience in automotive industry, several standards were developed for sockets and cables with less efforts to unify them. In
aviation the lessons learned from automotive industry could encourage aviation industry to choose a
different approach and follow the same standards worldwide.

The standard set of ground infrastructure at airports for fuel-cell hybrid aircraft will very much
depend on the type of hydrogen delivery. A study on delivery options, such as delivery by truck,
pipeline and onsite production revealed that the choice of delivery depends on the needed quantities
of hydrogen. Therefore, for small airports the most feasible solution would be to buy liquid hydrogen
from liquid hydrogen producers and deliver it to the airport by cryogenic trucks. If airport needs
smaller amount of hydrogen, one truck can serve several airports in one delivery trip. Depending on
needs, airport can fuel aircraft directly from truck on imply a small cryogenic storage for liquid
hydrogen on site. For large airports, and if fuel-cell aircraft becomes widely spread, it could be feasible
to build a hydrogen production plant in the vicinity of an airport. A refuelling station for fuelling small
aircraft at airports is simpler than a refuelling station for ground vehicles and has to include a refuelling
hose, a refuelling connector, and safety monitoring equipment. Although several safety precautions
have to be considered when handling hydrogen. The safety equipment should measure pressure,
temperature, and flow rate, filling level of the tank, hydrogen leak, valve position and heat.

Presuming that the energy efficiency of a hybrid fuel-cell aircraft is similar to the conventional aircraft,
a 19-seater aircraft would then need approximately 200 kg of hydrogen for 500 km range flight, and a
70-seater aircraft would need approximately 700 kg of hydrogen for the same range. If all regional
aircraft would be swapped for hybrid fuel-cell aircraft, 90 % of airports would need less than 10 tons
of hydrogen on a daily basis 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 ton of hydrogen per day.
On the other hand, the airport with the most regional daily flights (such as Tromsø airport, Norwegian)
would need around 40 tons of hydrogen per day. Considering the delivery scenario and mention
necessary amounts of hydrogen (while considering the production cost of liquid hydrogen 12 EUR/kg
and delivery cost of 0.16 EUR/kg) the cost of hydrogen and its delivery would be between 2.500 EUR
to up to almost half a million euro, largely depended on the size of the aircraft, distance travelled and
frequency of flights.

Regarding the timeline of potential development scenarios (presented below), we can predict the
market entry of a pure electric battery driven aircraft up to 8-seater by 2025. The pure electric aircraft
will be most likely used for flight instructions, touristic flights, sport or hobby usage, etc. The ICE-hybrid
is feasible for all size categories of aircraft, so it opens vast possibilities for its use in commercial or
non-commercial flights. However, due to its flying characteristics, most likely it will not be an
economically feasible option for business flight sector, which is less sensitive on price and more on
time (i.e. time is money). Based on our assumption, the ICE-hybrid should enter the market by 2035
as one of hybrid propulsion systems, which could ease the transition to fuel-cell aircraft. The fuel-cell
hybrid aircraft could present a feasible long-term solution, where production prices of hydrogen will
play a major role in the market implementation. According to hydrogen price predictions and
technological development we can expect their market entry around 2040. Concurrent with hybrid
propulsion technological development and trends in air travel demand, the necessary ground
infrastructure at airports will need to be built, adopted or developed, as a prerequisite for
implementation of hybrid aircraft into the transport system.
The MAHEPA ground infrastructure investment plan provides an operational, financial and regulatory aspects of hybrid aircraft operations at airports. It presents a very first serious attempt for economic assessment of relatively novel investments needed in ground infrastructure to enable charging and refuelling of hybrid aircraft. The conclusions and recommendation deriving from MAHEPA ground infrastructure investment plan will help outlining the strategy for a wider implementation of hybrid aircraft and the most plausible business models.
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