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ANALYSIS AND PERSPECTIVES OF SUSTAINABLE HYDROGEN GENERATION AT AIRPORTS FOR ON-SITE ENERGY PRODUCTION AND CONSUMPTION IN AIRCRAFT

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Abstract. *Hydrogen-powered aircraft emerge as a promising alternative for reducing carbon dioxide emissions in the atmosphere, given the need to diversify the energy matrix. These aircraft can reduce gas emissions by 50% to 99% when compared to kerosene-powered ones. Currently, technological options available for integrating hydrogen into aviation include hydrogen gas turbines, hydrogen fuel cells, and hybrid hydrogen power systems. Hydrogen fuel cells can operate more efficiently than combustion engines and have the potential to convert the chemical energy of fuel into electrical energy with efficiency levels of up to 70%. The use of hydrogen as a fuel gas is noticeable due to its ability to considerably reduce polluting emissions, characterizing it as a clean energy source, since the only byproduct resulting from its combustion is water. Although hydrogen production through water electrolysis is an established practice, entails a high energy consumption associated. Thus, efforts toward a sustainable production of this element deserve attention. In this context, the use of aluminum and its reaction with sodium hydroxide and water to form sodium aluminate and hydrogen emerges as a viable method for generating this gas. It is relevant to highlight that this technology differs from electrolysis, as it does not require the addition of energy to the system, since the reaction is highly exothermic. Additionally, production costs can be further reduced due to the possibility of using recyclable aluminum waste as a raw material. Among the critical components hindering the implementation of hydrogen use as a fuel, one can mention the lack of refueling stations, high production costs, and supply network, storage, and transportation. In the context of the challenges presented, this article aims to present an analysis and future prospects for the feasibility of implementing an on-site sustainable hydrogen generation system, from metallic aluminum waste, to supply aircraft and energy consumption stations at airports. These are locations where significant volumes of aluminum are discarded due to service activities, such as food courts, aircraft maintenance stations, and waste disposal. Our current research efforts aim at investigating the viability of such a system as an efficient solution for medium- and high-traffic airports.*

Keywords: *sustainable hydrogen, hydrogen aircraft, renewable energy*

1. INTRODUCTION

The phenomenon of global warming and energy crises have been increasingly manifesting over the last century, without a definitive solution being found to mitigate the adverse impacts of these phenomena on the planet (Mazloomi et al., 2012). It has been established that the burning of fossil fuels is the main cause of the increase in carbon dioxide in the atmosphere, which drives the pollution process. According to data from the International Energy Agency (IEA), global consumption of fossil fuels is astronomical, with more than 89 million barrels per day (Degirmenci et al., 2023). This figure justifies the high demand for energy that the globalized world currently requires, mainly due to modern varieties of transportation, such as automobiles, freight transport, and air transport. These sectors are the primary contributors to climate change, accounting for 27% of greenhouse gas emissions (Milner et al., 2019), considering that the aviation industry contributes approximately 12% of the carbon dioxide emissions from the transport sector (Postorino et al., 2014), as one of the main factors is that aircraft emit gases and particles directly proportional to the amount of fuel burned in the upper troposphere and lower stratosphere (Degirmenci et al., 2023).

In light of these statistics, it becomes urgent to seek alternative fuels to decarbonize the planet. Thus, the incentive for sustainable fuel production for transportation is particularly driven by aviation, given the forecast that air transport will triple by 2050 compared to the beginning of this century, in addition to the stringent quality requirements in this sector (Pipitone et al., 2023). The high demand for air transport is justified by the fact that aircraft are essential vehicles for daily life, being the only ones capable of transporting people and goods around the world in a single day. In 2016, aviation drove $2.7 trillion in economic activity and supported 65.5 million jobs, representing 3.6% of the global gross domestic product (GDP) (Adler et al., 2023).

Given this relevance, the impact of aviation on climate change is motivating a renewed interest in hydrogen-powered aircraft, aiming for a fully renewable production free from fossil fuel dependence. Hydrogen is a versatile energy carrier with distinctive characteristics such as global availability, safety, high energy content per unit mass, and low pollution rates (S. Yigit et al., 1997). Hydrogen also enables innovative technologies like fuel cells; however, handling and storing hydrogen is a challenge, especially in liquid form (Adler et al., 2023). Due to its abundance, hydrogen can be obtained by water dissociation through various techniques employing renewable resources, among them, a renewable hydrogen production method is electrolysis, which is considered the most predominant (Bolt et al., 2020).

However, an alternative hydrogen production method involves using aluminum to extract the hydrogen molecule from the water molecule (Taher et al., 2023), suggesting an attractive concept for developing a sustainable local hydrogen generation system from aluminum metal waste. Intended to provide energy for aircraft and facilities, this method is favorable for hydrogen generation at airports because it allows local gas production, promotes the recycling process, and facilitates aluminum procurement, given that, according to the International Civil Aviation Organization (ICAO), there is waste disposal at airports resulting from the activities of public areas and airport administrative offices, retail tenants, and terminal concessions, aircraft and airline offices, and cargo operations.

2. HYDROGEN

Hydrogen has played a fundamental role in the energy industry since the mid-20th century, a period when its application became predominant in the oil refining process. Moreover, more than 200 years ago, hydrogen was used to power the first internal combustion engines (International Energy Agency, 2019). The various uses of hydrogen, ranging from transportation to power generation, highlight its potential as a transformative energy vector (Habib et al., 2024). This is because the element possesses the highest specific energy among all fuels, meaning that 1 gram of hydrogen contains the same energy as 2.8 grams of gasoline. When liquefied by cooling, this low molar mass fuel occupies 700 times less volume than when in its gaseous state. Additionally, its density is significantly lower than that of air, being 14.4 times lower (0.08967 kg/m³ compared to 1.2928 kg/m³), and when it combusts, the reaction product is only water (Nicolay et al., 2021).

Hydrogen can be stored in various forms, such as compressed gas, liquid, or in chemical compounds, providing an effective solution to mitigate the intermittency of renewable energy sources, such as solar and wind (Jeje et al., 2024). Moreover, it offers versatility as it can be used in fuel cells. However, due to the high annual demand for hydrogen in its pure form, which reaches approximately 70 million tons (MtH2/year), about 6% of the global natural gas consumption and 2% of the world's coal consumption are directed towards hydrogen production (International Energy Agency, 2019). This underscores the urgent need to develop hydrogen production sources that do not rely on fossil fuels. Otherwise, the beneficial properties of this element are counterbalanced by the continued environmental impact and toxic gas emissions into the atmosphere.

Due to its abundance in nature, hydrogen can be obtained in various ways, such as in water, biomass, and fossil fuels, which has enabled the development of numerous production processes and techniques (Bakenne et al., 2016). Water electrolysis is widely used to break the water molecule. This process involves dissociating water into hydrogen and oxygen through a series of successive chemical reactions (Vincent et al., 2017). The thermal energy required for this process can be supplied by renewable sources, such as solar power plants or nuclear power (Xiao et al., 2012). Since thereare various forms of primary energy sources for hydrogen generation, each process can be distinguished by different colors. In the case of water electrolysis, hydrogen is characterized as green hydrogen because its sources are renewable (Figueiredo et al., 2023). The color coding system aims to help consumers understand more clearly the environmental impact of energy use. Additionally, it provides governments with a mechanism for implementing taxes on the energy sources used (Jeje et al., 2024). An alternative method for sustainable hydrogen production involves using aluminum to extract the hydrogen molecule from the water molecule. This hydrogen production method is also notable for its low cost and abundance, as aluminum represents 8.1% of the Earth's crust. This element is one of the most economical metals worldwide, being priced at $2.36 per kilogram. Additionally, it has considerable potential for recycling and extraction from waste (Bolt et al., 2020).

2.1 Hydrogen in the aviation industry

Since the mid-1950s, the use of hydrogen in aviation has been the subject of study and experimentation. A notable example is NASA's 1955 project, which adapted a B-57 "Canberra" (Figure 1) to operate with an engine powered by liquid hydrogen (LH2) pressurized by helium (Winter, 1990). In this model, the liquid hydrogen was stored in a tank at the wingtip and converted to vapor through a heat exchanger that used air to transform the hydrogen, which was then conducted in gaseous form to the engine's combustion chamber (Maniaci, 2008). Over the years, the use of hydrogen in the aviation industry has become progressively more relevant due to its potential as an energy source for aircraft and the demand in air traffic. This interest stems from the fact that hydrogen-powered aircraft have a significant capacity to operate without carbon emissions, substantially contributing to mitigating climate change and promoting environmental sustainability (Adler et al., 2023). Driven by climate change concerns, governments, particularly in Europe, have been prompted to establish stricter regulations for the commercial aviation industry and fund international programs to assess the benefits of hydrogen-powered aircraft. Faced with the prospect of stricter standards, major aerospace corporations such as Airbus, CFM International, Pratt & Whitney, and Rolls-Royce have announced initiatives focused on developing hydrogen-based projects (Adler et al., 2024).

The importance of replacing kerosene with hydrogen as a fuel lies in the fact that, in addition to carbon emissions, the climatic impact of aviation is intensified by other effects resulting from these emissions. Depending on flight altitude and surrounding atmospheric conditions, exhaust products such as nitrogen oxides (NOx) and the combination of soot particles and water vapor can cause the formation of contrails (artificially induced clouds) and ozone, both of which are detrimental to the climate (Hoelzen et al., 2022). A study conducted by Nojoumi et al. (2009) analyzes the difference in environmental impact between hydrogen-powered aircraft and those fueled by kerosene, considering greenhouse gas emissions and other polluting substances. Evaluating flights from Toronto to Montreal and Calgary to London, the studydemonstrates that hydrogen has a significantly reduced emissions inventory, highlighting it as an environmentally favorable alternative.

Ensuring the future of hydrogen-powered aviation involves considering numerous factors under investigation. It is necessary to adopt innovative designs for aircraft, implement systematic changes in aircraft manufacturing and operation, optimize engine performance, review weight metrics, develop air traffic management strategies, and promote safety advancements (Rondinelli et al., 2014). Adler et al. (2024) emphasize that the challenges associated with implementing hydrogen in the aviation industry involve the intrinsic properties of this element and also state that hydrogen, being a gas at ambient temperature and pressure, has a very low density to be adequately stored in aircraft. Thus, although compression to high pressures or liquefaction by cooling to 20 K are the most viable hydrogen storage options to achieve practical energy densities, hydrogen tanks have significant weight, requiring technical adaptations in the aerodynamic parameters of the design to avoid efficiency loss. Additionally, operational costs related to the use of hydrogen as fuel, including the need to maintain extremely low temperatures or high pressures are considerably high.

However, the aerospace company Airbus, committed to overcoming the challenges associated with using hydrogen in its aircraft, has unveiled three innovative concepts for the first zero-emission commercial aircraft, promising operation by 2035 (AIRBUS, 2020). The designs presented by the company include a turbofan (100 - 200 passengers) powered by a gas engine with the possibility of operating with hydrogen through combustion, the turboprop (100 passengers) also powered by hydrogen combustion in gas engines, and finally, the blended-wing body design (200 passengers), which has a concept similar to the turbofan but with wings that merge with the main body of the aircraft, offering various options for hydrogen storage and distribution. The volumetric requirements of hydrogen, associated with the need for tanks with a low surface area to volume ratio, imply that the fuel cannot be stored in the wing box in the same way kerosene fuel is currently stored (Adler et al., 2024), highlighting the importance of the concepts presented by Airbus. Another aerospace company that stands out in this scenario is Embraer, which in 2021 announced a new family of concept aircraft developed to achieve the goal of zero carbon emissions by 2050, one of which is powered by hydrogen electric propulsion through a fuel cell, with electric motors mounted at the rear of the aircraft (EMBRAER, 2021).

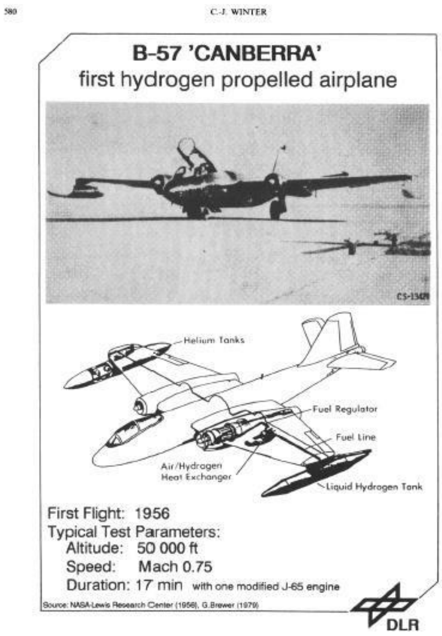

Figure 1. B-57 Canberra: first hydrogen propelled airplane (Winter, 1990)

3. AIRPORT INFRASTRUCTURE AND OPERATIONS

It is evident that airports will need to evolve to accommodate regular operations of hydrogen-powered aircraft, ensuring the appropriate infrastructure for their maintenance and support (Rondinelli et al., 2014). Alongside the B-57 bomber project in 1956, the first physical hydrogen supply chain network to fuel an airport was developed. Gaseous hydrogen was transported to a central liquefaction facility via trailers, where it was converted to its liquid form at a hydrogen liquefaction unit installed by Air Products at the airport (Degirmenci et al., 2023). Another example is a study conducted by NASA - The Boeing Company analyzing O'Hare International Airport, evaluating the airport's infrastructure and the safety, operational, technical, and economic aspects for supplying liquid hydrogen to aircraft. In the study, the hydrogen supply network involved transporting hydrogen to the airport via the GH2 pipeline, liquefying hydrogen at an on-site liquefaction facility, and transporting LH2 to an on-site storage facility, with an expenditure of approximately $469 million on ground fuel. Viable options for transporting liquid hydrogen at airports include vacuum-jacketed pipelines, tank trucks, and rail tank cars (Brewer, 1991).

It has been identified that hydrogen infrastructure at airports is a serious barrier (Daggett et al., 2006). In addition to a high degree of risk, the transportation and storage of cryogenic liquid hydrogen present technical and operational challenges crucial for optimizing the economic efficiency of the entire process (Brewer, 1991). For hydrogen fuel to be commercially viable, it is essential that various airports are prepared to integrate LH2 refueling systems. This requires a well-coordinated logistics and supply chain, including the need for an on-site hydrogen production facility or the implementation of infrastructure capable of safely storing LH2 reserves at airports (Rondinelli et al., 2014). In addition to emissions of toxic gases from industrial processes, transportation, and air traffic, airports are significant emission points, contributing 30 million tons, or 5%, of the total pollution generated by the aviation industry (Rondinelli et al., 2014). The factors justifying these statistics include aircraft, passengers, cargo, and ground vehicle movements (Janic, 2010).

Therefore, it is crucial to recognize that the infrastructure needed to support hydrogen-powered aircraft at airports extends beyond the aircraft refueling system. The implementation of airport service vehicles, such as baggage carts powered by fuel cells, plays a crucial role in reducing emissions at airports. Examples of this integration are already observed in airports in Denmark (Degirmenci et al., 2023). The efficiency and effectiveness of airport operations can be significantly enhanced through a well-structured logistics chain and the adoption of sustainable technologies that encompass not only aircraft refueling but also the support of the entire airport operation. In a published report (Airport Surface Access Strategy, 2022) as part of its Sustainable Development Goals, Gatwick Airport in England has started using hydrogen-powered electric vehicles. In 2019, the airport inaugurated a hydrogen station, with production carried out through electrolysis using renewable energy. After 2020, the Sustainable Development Goals (SDGs) were intensified due to the Covid-19 pandemic (Degirmenci et al., 2023), with increased focus on hydrogen aviation. This is because the United Nations established 17 SDGs in 2015, with SDG 3.9 and SDG 7 supporting the use of hydrogen in the aviation industry for a sustainable airport.

4. SUSTAINABLE LOCAL HYDROGEN PRODUCTION

4.1 Sustainable Hydrogen Generation: Hydrogen Reactor and Trailer

The Sustainable Energy Research and Development Center (NPDEAS) at the Federal University of Paraná (UFPR), linked to the Department of Mechanical Engineering and the Graduate Program in Mechanical Engineering, developed in parallel with the ROTA 2030 Project – UFPR/FUNDEP/RENAULT S.A, an extended autonomy solution for electric vehicles using hydrogen and fuel cells. The project combines theoretical, numerical and experimental activities to optimize hydrogen production and reduce equipment weight, technical and economic reviews of the process.

The first objective of the Project ROTA 2030 - UFPR/FUNDEP/RENAULT S.A. was the development of an 18-liter pilot-scale hydrogen reactor (Fig. 2a). A mathematical model was created by Taher et al. (2023) to accurately describe hydrogen production from aluminum scrap (Fig. 2c), considering mass balance, energy, and the kinetics of the chemical reaction for hydrogen generation from aluminum (Al) waste and sodium hydroxide (NaOH). The author states that the proposed model successfully matched the experimental data. The reactor operates in batch mode and, according to Bolt et al. (2020), the balanced chemical reaction for hydrogen generation in the presence of sodium hydroxide is described in Equation (1):

$$2Al + 2NaOH + 2H_2O \rightarrow Na_2Al_2O_4 + 3H_2 \tag{1}$$

After achieving this objective, the next step was to design a complete system capable of generating hydrogen under both stationary and moving conditions. To this end, an automotive trailer (Figure 2b) was used to install all necessary equipment for the process, from the chemical reaction of hydrogen production to the feeding of a fuel cell. This setup included not only the reactor but also elements such as a storage cylinder, booster, thermocouples, pressure gauges, and a proton exchange membrane fuel cell (PEMFC) with a power output of 5 kW (Raimundo et al., 2023).

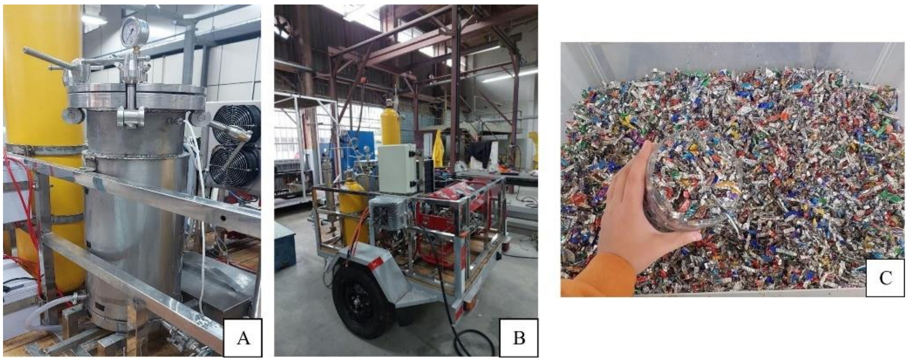

Figure 2: A) Hydrogen Reactor; B) Trailer with the Complete System and C) Aluminum Scrap

An exergetic analysis of the system was conducted, considering the energy balance for the cooling system, compressor, amplifier, and battery, including heat and work calculations for each component. Raimundo et al. (2023) report that hydrogen production from water using the proposed system, with residual aluminum, resulted in an exergetic cost of only $0.15 per kWh, a value obtained at the storage cylinder outlet and equivalent to the excess hydrogen not consumed at the PEMFC output. Additionally, the exergetic cost of electricity generated by the PEMFC was calculated as $0.19 per kWh. The authors conclude that hydrogen production using residual aluminum showed potential for large-scale application, demonstrating an economically promising exergetic cost of hydrogen production with potential for optimization, and producing high-purity hydrogen. Preliminary experiments revealed the production of 21.16 g of sustainable hydrogen with an efficiency of 83.68% in this system. These results are not detailed in this work as they represent initial data from the characterization of this system.

4.2 Perspectives of the Sustainable Hydrogen Generation System at Airports

The distribution of hydrogen at airports involves supplying this fuel to utilization sites, including ground support vehicles, auxiliary power systems, and aircraft (Degirmenci et al., 2023). According to airport traffic data released by the International Airports Council (ACI World), the Hartsfield-Jackson Atlanta International Airport was the busiest in the world in 2023, with 104,653,451 passengers. Following in the rankings are the Dubai and Dallas/Fort Worth Airports. ACI World also reported that the total global passenger traffic in 2023 was approximately 8.7 billion. In contrast, the Afonso Pena Airport, for instance, is not ranked among the twenty busiest in the world according to ACI World's data, as it is a small airport. However, a study conducted by the Integrated Center for Technology and Professional Education - SENAI/CIC estimated that at the beginning of this century, the Afonso Pena Airport saw a passenger movement of 2,509,117 per year. In the same SENAI/CIC study, waste management at the Afonso Pena Airport was conducted, concluding that sources such as aircraft, restaurants, stores, lobbies, industrial areas, and parking lots generate 10,804 kg of aluminum annually. Therefore, according to projections that air transport will triple by 2050 compared to early-century levels (Pipitone et al., 2023), the amount of waste generated, which was already significant, will also increase.

This suggests the feasibility of using a significant amount of aluminum waste for large-scale implementation of the vehicular trailer from the ROTA 2030 Project - UFPR/FUNDEP/RENAULT S.A., helping to mitigate challenges related to the production, storage, and transportation of hydrogen at airports and fostering sustainable alternatives for using this fuel. On a pilot scale, the size characterized in the project, it is possible to aid in extending the autonomy of various ground vehicles used at airports or fuel cell-powered aircraft. Aircraft designed to use liquid hydrogen can also be supported by this system, as it produces the gas on-site and can be transferred to pipeline systems and liquefaction stations quickly, eliminating the transportation cost obstacle of gas over long distances to fueling sites.

In the 1970s, NASA investigated various methods for supplying hydrogen to airports for civil aviation use, analyzing trucks, trailers, and pipelines for hydrogen in gaseous or liquid form. This study concluded that the most economical delivery mode is transporting hydrogen by pipelines in gaseous form and liquefying it as close to the airport as possible (Degirmenci et al., 2023). It is noteworthy that the system proposed by the project was designed to produce hydrogen both in stationary and mobile conditions, echoing the possibility of aiding in the direct refueling of fuel cell-powered fuels and reservoirs destined for gas liquefaction and subsequently, transportation to tanks in aircraft. Additionally, the system developed in the vehicular trailer eliminates the intermittency associated with renewable energy sources such as solar and wind, as hydrogen production is initiated instantly when aluminum waste and sodium hydroxide react in the reactor, meeting the constant fuel supply needs of airports (Evans et al., 2009). Aircraft concepts are being developed byseveral aerospace companies, including some mentioned in this work, such as Airbus and Embraer. These companies are evaluating different designs for aircraft that use hydrogen fuel with varying capacities. Therefore, the large-scale implementation of this system contributes to the demand for vehicle refueling, potentially increasing their autonomy, including in route connection strategies.

5. CONCLUSION

The objective of this article was to offer an analysis and perspectives of a sustainable local hydrogen generation system at an airport, aiming to overcome the challenges involved in the infrastructure of these locations to achieve greater ease in hydrogen transportation and storage, improving the efficiency of this process and fostering the hydrogen aviation industry. It can be observed that hydrogen-powered aircraft and infrastructure models have been developing over the years. This evidences that hydrogen is gaining increasing prominence in the industry, mainly due to global warming, which currently demands urgent changes for the decarbonization of the planet. The proposed system to refuel aircraft and ground vehicles with hydrogen was found in the literature and, despite being a pilot project characterized on a small scale, it brings positive perspectives for investment and development on a larger scale. The adopted technologies allow this system to produce hydrogen without intermittencies, with a high degree of purity, and assume various positions within an airport. Moreover, it enables the reuse of waste, considering the large volume of passenger movement. Although there are many regulations to be established and incentives to be incorporated into public policies, the use of this sustainable hydrogen generation system at airports demonstrates the possibility of producing the fuel of the future, allied to relevant environmental issues.

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