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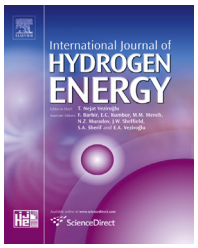

Greening commercial air transportation by using liquid hydrogen (LH_2) as a fuel

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ABSTRACT

Global commercial air transportation has grown over the past two decades at a rather stable annual rate of 4.5–5% in the passenger and 6% in the cargo segment. Such developments have contributed to globalization of the economy and overall social welfare while at the same time increased impacts on the environment and society in terms of fuel consumption from non-renewable sources and related emissions of GHG (Green House Gases), land use, congestion, and local noise. In particular, further growth of emissions of GHG driven by growth of air transportation demand could contribute to global warming and consequent climate change.

This paper, as an update of the author's previous research, investigates the potential of LH_2 (Liquid Hydrogen) as a breakthrough solution for greening commercial air transportation. This includes analyzing the main sources of emissions of GHG, their impacts, mitigating measures and their effects – all considered under the conditions of using (conventional) jet A fuel – kerosene – as a derivative of crude oil. Then the characteristics LH_2 as an alternative fuel and its effects on the emissions of GHG (particularly CO_2) are considered, the latter by using dedicated models and their scenario-based application to the long-term future development of the international commercial air transportation. The results indicate that the gradual replacement of the jet A (conventional) with a LH_2-fuelled (cryogenic) aircraft fleet could result in total cumulative emissions of GHG (CO_2) stabilizing and then reducing to and below the specified target level, despite further continuous growth of air transportation demand. Thus, greening of commercial air transportation could be achieved in the long-term future.

Introduction

Rising awareness of the transportation sector's contribution to emissions of GHG (Green House Gases) and consequently global warming has come increasingly under focus over the past two decades. The same applies to commercial air transportation. The main reason for considering more deeply only commercial air transportation in the given context lies in its continuous and rather fast growth on the global scale

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requiring increased fuel consumption and related emissions of GHG spreading both locally and globally, thus contributing to global warming and climate change. Consequently, some myths about these impacts of commercial air transportation have emerged, including the following [25]:

- It has been excluded from the Kyoto Protocol and thus almost nothing has been done to mitigate fuel consumption and related emissions of GHG;
- It is a major source of emissions of GHG;
- It is the most air polluting transport mode;
- It is exempted from the fuel and other emission taxes; and
- Its growth is unsustainable.

The first myth is only partially true since domestic (national) air transportation has been included in the Kyoto Protocol, while international air transportation has not.

The second myth is untrue since commercial air transportation contributes to only about 2–3% of the total manmade emissions of GHG. The transport sector contributes to about 20% of the total manmade emissions of GHG, to which the commercial air transportation contributes about 12%.

The third myth is also incorrect, particularly when considering improvements in the fuel efficiency of most contemporary medium- and long-haul aircraft in relative terms (i.e., quantity of fuel consumption per passenger kilometer). This has improved over the past two decades by about 1–2% per year.

The fourth myth is partially true, but one should always bear in mind that commercial air transportation is already the most highly taxed transport mode without any subsidies, and fully covers the costs of infrastructure use.

The last myth is only true if considering the cumulative emissions of GHG and related external costs due to their permanent accumulation over time. However, if the costs of these emissions are counterbalanced with the overall social-economic benefits gained from commercial air transportation, this myth is certainly untrue [3].

This paper particularly elaborates in more detail some aspects of the second and fourth myth and discusses the potential of alternative fuel – LH_2 (Liquid Hydrogen) as a prospective (breakthrough) solution for mitigating emissions of GHG, i.e., greening of commercial air transportation while enabling its unconstrained long-term growth.

In addition to this introductory section, the paper consists of seven other sections. Section development of commercial air transportation describes the current and future prospective development of commercial air transportation. Section characteristics and impacts of GHG (green house gases) emitted by commercial air transportation describes the characteristics of particular GHG emitted by commercial air transportation and their prospective impacts on global warming and consequently climate change. Section some measures for mitigating emissions of GHG from commercial air transportation analyses some mitigating measures for reducing fuel consumption and related emissions of GHG by commercial air transportation. Section LH2 as a breakthrough solution for mitigating emissions of GHG by commercial air transportation describes the characteristics of LH_2 as an alternative fuel, its logistics supply chain(s), and the characteristics of cryogenic aircraft. Section models of a "carbon-neutral" air transportation system presents the models for analyzing the effects of the proposed breakthrough solution – partially using LH_2 instead of jet A/kerosene fuel – on mitigating emissions of GHG, i.e., greening, in the long-term. Section application of the models illustrates an application of the proposed models, while the last section summaries some conclusions.

Development of commercial air transportation

The annual global demand for air transportation has increased from 0.5 trillion RPK (Revenue Passenger Kilometers) in 1971 to about 5.145 trillion RPKs in 2011, despite the temporal impacts of global crises [31]. These include the two oil crises in 1973 and 1979, the Gulf crisis in 1991, the Asian crisis in 1998, the terrorist attacks on the US in 2001, SARS in 2003, and the global financial crisis in 2008. Some long-term forecasts of the future long-term development of commercial air transportation have been carried out by different international air transport organizations (IATA – International Air Transport Association, ICAO – International Civil Aviation Organization, ACI – Airport Council International), and the two main manufacturers of commercial aircraft Boeing and Airbus. An illustration of these forecasts in terms of the average annual growth rates of international airpassenger demand between particular global regions is given in Table 1.

As can be seen, the growth rates of international air passenger demand during the observed period are expected to be positive and higher between Asia and both Europe and North America than between North America and Europe. Consequently, the total global air transportation demand is expected to grow at an annual rate of 5% over next two decades. This implies growth to about 10.545 [2] and 11.4 trillion RPKs [7,8] by 2025/26, or up to about 13.256 trillion RPKs by 2030/31 [31]. In addition, the number of air passengers is expected to grow at an annual rate of 4.5%, which will result in their total number of about 6.8 billion in 2025/26 [7,8]. However, some estimates by ACI (Airport Council International) indicate that the number of passengers at airports will increase from about 4.4 billion in 2007 to about 12.3 billion in 2031 [1,50]. In addition, air cargo demand will grow at an average annual rate of 5.8% over the same period, i.e. from about 200 billion RTKs in 2006 to about 650 billion RTKs in 2025/26 [7,51].

The above-mentioned growth of commercial air transportation demand is expected to be primarily driven by global GDP (Gross Domestic Product) with an average annual rate of

Table 1 – Forecasted growth rates in international commercial air transportation (Period 2008–2027) [22]

Organization /Routes	EU–North America	Asia Pacific–Europe	Asia Pacific–North America
Boeing	4.7	5.2	5.6
Airbus	4.8	5.9	5.8
ICAO	4.5	5.8	6.0
Average 1990–2007	**3.6**	**6.2**	**3.4**