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Review

Assessing the Sustainability of Liquid Hydrogen for Future Hypersonic Aerospace Flight

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Abstract: This study explored the applications of liquid hydrogen (LH_2) in aerospace projects, followed by an investigation into the efficiency of ramjets, scramjets, and turbojets for hypersonic flight and the impact of grey, blue, and green hydrogen as an alternative to JP-7 and JP-8 (kerosene fuel). The advantage of LH_2 as a propellant in the space sector has emerged from the relatively high energy density of hydrogen per unit volume, enabling it to store more energy compared to conventional fuels. Hydrogen also has the potential to decarbonise space flight as combustion of LH_2 fuel produces zero carbon emissions. However, hydrogen is commonly found in hydrocarbons and water and thus it needs to be extracted from these molecular compounds before use. Only by considering the entire lifecycle of LH_2 including the production phase can its sustainability be understood. The results of this study compared the predicted Life Cycle Assessment (LCA) emissions of the production of LH_2 using grey, blue, and green hydrogen for 2030 with conventional fuel (JP-7 and JP-8) and revealed that the total carbon emissions over the lifecycle of LH_2 were greater than kerosene-derived fuels.

Keywords: LH_2; JP-7; JP-8; ramjet; scramjet; hypersonic; sustainability

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1. Introduction

Throughout the world, fossil fuels are used in abundance and produced in huge quantities, however, there is a current dispute on whether fossil fuels should be used indefinitely [1]. There are currently three major issues with the continued use of fossil fuels: finite energy production, depletion of fossil resources, and the release of harmful gases to the environment [2]. The availability of fossil fuels is diminishing; however, the rate of fossil fuel usage is increasing. As a result, it is predicted that fossil fuels will have been permanently exhausted by the end of this century [3].

One of the biggest challenges raised by fossil fuel consumption is pollution [4]. The combustion of fossil fuels contributes to global warming and the contamination of the planet with greenhouse gases (GHG), such as carbon dioxide (CO_2). Additionally, pollutants such as carbon monoxide (CO), particulate matter, nitrous oxide (NO_x), unburnt hydrocarbons (UHC) and sulphur dioxide (SO_x), are all released during the combustion of fossil fuels [1,4]. As a result, replacing fossil fuels with clean and potentially limitless fuels such as liquid hydrogen (LH_2) will address these issues [4,5].

Long-range passenger transport, reusable space vehicles, and cruise missiles for space purposes are among the areas where current high-speed aerospace technology is being expanded. [6,7]. Currently, interest from private companies and international governments has resulted in several proposed aircraft capable of meeting hypersonic speeds that could have a role in passenger flights and access to space [8]. The private space industry has grown significantly over the last decade with the expansion of companies such as SpaceX in Los Angeles, California, Virgin Galactic in Mojave, California, and Blue Origin in Kent, Washington [9]. Current trends suggest in the future, the number of private spaceflight launches will continue to grow, and this will amplify the negative environmental impact of rocketry and space travel, thus necessitating more extensive research into the environmental impacts of hypersonic spaceflight [10].

Szirosack and Smith identified that propulsion systems are the most critical factor limiting sustained, efficient access to space [11]. The two engine categories capable of providing hypersonic flights, speeds above Mach 5, are rockets and jets. Rockets facilitated the first unmanned and manned hypersonic test flights, while jets have only recently succeeded in attaining hypersonic flight with the development of scramjet technology [1]. Rockets provide the greatest range of speeds compared to other propulsion systems and are capable of functioning in the absence of oxygen, however, oxidisers must be transported onboard. This increases the overall weight and complexity, lowers safety and reduces specific impulse (I_{sp}). I_{sp} is the thrust-generating efficiency of an engine and measures the amount of thrust generated per unit of fuel or fuel-oxidiser mixture injected per second. The conventional method of gaining access to space is to use rockets with external tanks of fuel and oxidiser, requiring the storage and transport of oxidisers such as liquid oxygen, nitric acid, and liquid fluorine, which increases the weight of the vessel [12,13].

As well as rockets, air-breathing engines have also been used to achieve hypersonic flight, such as conventional turbojets, ramjets and scramjets. Turbojet propulsion systems are limited to Mach 3 (Ma), three times the speed of sound, due to elevated temperatures and pressures [1]. Ramjet propulsion systems are employed for supersonic flight with speeds ranging from Mach 3 to 5. Scramjets are an appealing preference for hypersonic flight, achieving speeds between Mach 5 and 15, the classification of different propulsion systems with their respective speed limits is shown in Figure 1 below. In comparison to other air-breathing engines, scramjets are lighter in weight and are more cost-effective due to the absence of an oxidiser tank, compressors, and turbines. As a result, scramjets can be smaller, lighter, and quicker. A considerable limitation of scramjets is that they are unable to provide thrust at speeds lower than Mach 5–6, hence the rocket booster required by the X-43 [14].

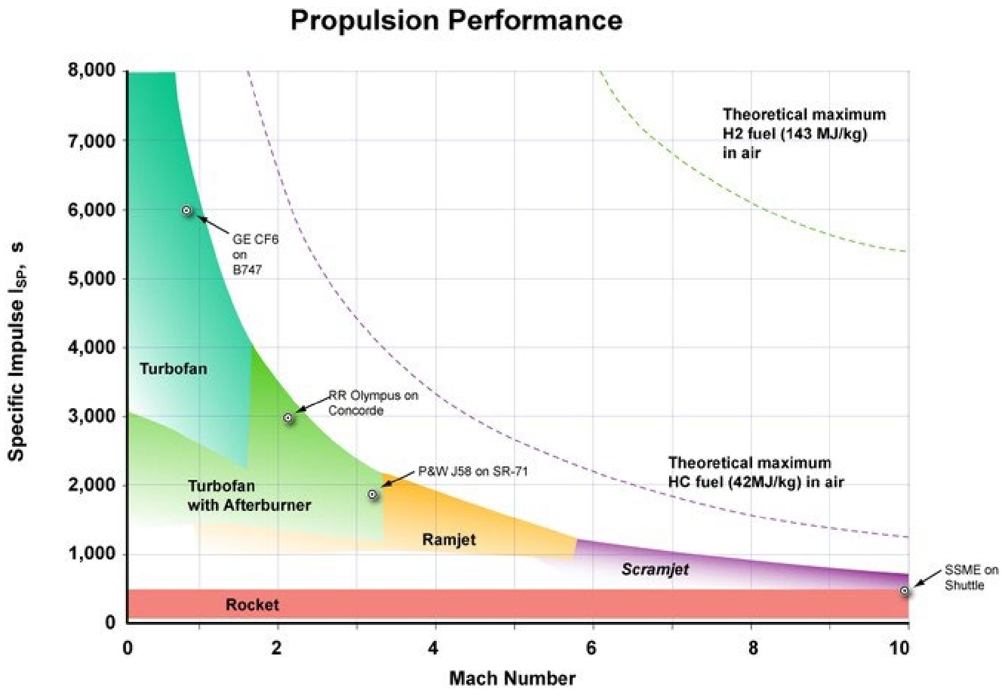

Figure 1. Specific impulse of different engines [1].

Traditionally, space planes and rockets equipped for hypersonic flight utilised a range of liquid fuels, including kerosene derivatives, alcohols, hydrazine, and LH_2. LH_2 is the only potential fuel used for combustion in scramjet engines due to its wide flammability limits, high diffusivity, and minimum ignition energy [15].

The sustainability of LH_2 as an aviation fuel in hypersonic vehicle applications has been previously investigated [1,5,8,15]. However, there are limited studies that have considered the production methods of hydrogen to analyse the sustainability of the fuel for hypersonic flight. Section 2 of the report provides a review of the different propulsion systems and an introduction to the common type of fuels used in space applications, as well as up-to-date international developments centred on proposals for hypersonic aircraft that use LH_2 as fuel. Section 3 investigates the sustainability of LH_2 in hypersonic propulsion systems using green, blue, and grey hydrogen as a method of hydrogen production. While also comparing this to the sustainability of conventional fuels (JP-7 and JP-8) by examining the GHG emissions associated with combustion and fuel production. Analysis in this study is limited to hypersonic flight vehicles due to the growing interest and development plans for future hypersonic projects at various research facilities [9]. Section 4 provides a conclusion to the study by identifying the key points of analysis and highlighting future work.

2. Materials and Methods

This study started by reviewing the classifications of propulsion systems and the common fuels used in space applications. The second part of the study analysed the fuel emissions of JP7 and JP8 and compare these figures to an LCA of green, blue, and grey hydrogen for hypersonic flights; supersonic and ultrasonic flight vehicles are not considered in the analysis due to the scope of this study. Finally, the results and findings shall be discussed to determine the sustainability of these fuels and the effectiveness of scramjet propulsion systems.

2.1. Propulsion Systems

LH_2 has a role in airbreathing propulsion systems for hypersonic vehicles, which combust liquid fuels to generate necessary thrust. With the growing interest in hypersonic flight, there has been considerable research into scramjet propulsion systems [8]. Currently, kerosene-derived JP-7, JP-8 and LH_2 are the only viable fuels for these systems; decarbonising LH_2 would nullify any emissions and result in sustainable hypersonic flight [5].

To understand scramjets, it is first essential to understand ramjets which, unlike traditional turbojets are limited to around Mach 3.5 by the extreme temperatures pushing the thermal limits of the turbine blades. Ramjets contain no compressor and rely upon the speed of the aircraft, travelling at supersonic speed, to compress the air inside the engine and cause the vehicle to accelerate to hypersonic speed. As the freestream air enters the inlet, it is compressed and reduced to a subsonic speed. In the combustor, fuel is injected directly into the compressed air and combusts due to the elevated temperature. This combustion and the geometry of the nozzle accelerate the exhaust fumes to generate thrust. Scramjets operate on the same principle as ramjets but rather than decelerating the freestream air to subsonic speeds, an acceptable supersonic speed is maintained, thus allowing the engine to achieve hypersonic speeds [16].

2.2. Kerosene

Kerosene is a hydrocarbon oil produced via the distillation of petroleum. JP-7 and JP-8 are kerosene bases-fuels that are commonly used in hypersonic flight [16]. The high density of JP-7 reduces onboard fuel storage requirements and enables it to be used as both a lubricant and a fuel [16]. JP-7 is designed with trace sulphur, nitrogen, and oxygen impurities, and utilises many of the crude oil by-products used to make pesticides [17]. A toxicological profile on JP-7 expresses the adverse impacts of the fuel entering the environment upon manufacture or incomplete in-flight combustion, describing how it can contaminate water sources and the atmosphere when released. JP-8 has a lower flashpoint but contains additives to improve lubrication [17].

Favoured for its thermal stability and high flash point, JP-7 was used by the Boeing X-51, which heated the fuel via heat exchangers before combustion in its scramjet engine. JP-8 is deemed significant for its regular use in the B-52 turbojet engines [18–21]. Table 1 illustrates the application of kerosene and other fuels as propellants in previous hypersonic vehicles.

Table 1. Details of Hypersonic Vehicles [18–21].

Vehicle	Flight Date/s (Expected)	Max Powered Speed (Mach)	Max Altitude (km)	Propulsion Systems	Fuel/s (Oxidizer)
X-15	1967	5.89	108	Liquid-propellant rocket	Ethanol, (liquid oxygen (LO_x))
Space Shuttle	1977–2011	22.16	620	Liquid-propellant rockets, solid-fuel rocket boosters	LH2, Aluminium powder, (LO_x, ammonium perchlorate)
Boeing X-37	2010–2020	22.71	805	Liquid-propellant rocket booster	Rocket-grade kerosene, LO_x
X-43	2004	9.90	33.5	Turbojet, solid-fuel rocket booster, scramjet	JP-8, Hydroxyl-terminated polybutadiene (HTPB) solid fuel, (ammonium perchlorate), hydrogen
Boeing X-51 wave rider	2010–2013	5.18	21	Turbojet, solid-fuel rocket booster, scramjet	JP-8, solid rocket propellant, JP-7

2.3. Application of LH_2

LH_2 is environmentally advantageous to kerosene-derived fuels regarding combustion as it does not release CO_2 or CO. The production of hydrogen can be decarbonised with the use of Carbon Capture and Storage (CCS), which is a process of capturing CO_2 before it is released into the atmosphere and storing it underground [22]. It can also be decarbonized by the process of Polymer Electrolyte Membrane electrolysis (PEM) with the use of electricity produced from renewable sources, this process involves the splitting of water via an electrochemical process into H_2 and O_2 on either side of a solid polymer [22]. The hydrogen produced from these methods is known as blue and green hydrogen, respectively, which have the potential to replace Steam Methane Reforming (SMR) and coal gasification as a low-carbon source of hydrogen, also known as grey hydrogen [22].

The development of hypersonic space vehicles requires efficient propulsion systems capable of travelling at speeds above Mach 5. Previous projects include NASA's Hyper-X program which was established to introduce newly developed air-breathing propulsion systems utilized for hypersonic vehicles [23]. Specifically, the X-43A scramjet fuelled by hydrogen was assessed and successfully launched in March 2004 to achieve a velocity of Mach 7 for 10 s [24].

Another series of experiments conducted by the University of Queensland using the test craft, Hyshot, investigated the use of hydrogen fuel in a scramjet. The project aimed to analyse the viability of maintained supersonic combustion under realistic flight conditions and to refer to similar shock tunnel experiments when comparing the findings of observed flights [25]. A two-stage Terrier-Orion Mk70 rocket was employed by HyShot to enhance the empty Orion motor and the payload to an elevation of about 330 km, after which the vehicle was accelerated while the spent motor and its associated cargo fell back to Earth. The characterization of the trajectory was such that between 23 and 35 km, the Mach number of the flight was 7.6.

Similarly, the European Commission initiated the LAPCAT project [25] to study several hypersonic vehicle designs, which led to a vehicle that could facilitate a 4-hour flight time to travel approximately 20,000 km. There is ongoing research into the possibility of developing the Synergetic Air-Breathing Rocket Engine (SABRE) as part of hypersonic transport vehicles that could reach speeds as high as Mach 25. The system combines a rocket engine fuelled with LH_2 with a conventional air-breathing jet engine into a single unit (utilized for speeds less than Mach 5). The Japan Aerospace Exploration Agency (JAXA) is considering the development of a hypersonic vehicle that consists of a single cryogenically precooled turbojet engine powered by hydrogen that would launch at speeds of Mach 5 from take-off [26,27].

At present, the German Aerospace Centre's DLR and MTU Aero Engines are investigating ultra-low-emission engine upgrades using 600 kW electric propulsion systems powered by LH_2 fuel cells to replace two conventional turbojet engines. The program is set to commence in 2025, representing the development of a new range of more efficient and environmentally friendly aircraft propulsion systems than conventional kerosene-fuelled turbojet engines [28].

3. Results and Discussion

3.1. Fuel Efficiency with Regards to Emissions

The combustion of hydrocarbon fuels, particularly at high altitudes, is known to cause a multitude of environmentally adverse effects via the release of GHG emissions. NO_x emissions are produced in mass quantities by hypersonic engines because of their high combustion temperature (which corresponds to the engine pressure ratio (PR) rather than carbon content of the fuel used [16]. As such, all fuels are capable of producing NO_x emissions via the reaction between nitrogen and oxygen in air at high temperatures (see Equation (1)) [29,30]. NO_x emissions can contribute to global warming and cooling by causing a rise in ozone (O_3) and a decrease in methane, respectively [16]. Figure 2 depicts the effects of the engine PR on NO_x production and suggests that regardless of fuel, propulsion systems providing higher Mach numbers create greater quantities of nitric oxide [28,30]. In this sense, the application of LH_2 as a hypersonic aviation fuel will not present environmental benefits, rather, the higher combustion temperature and pressure ratio associated with hypersonic propulsion systems will cause more in-flight nitric oxide emissions.

$$N_2 + O \rightarrow NO + N \tag{1}$$

Equation (2), adapted from Farokhi, assumes perfect combustion to estimate CO_2 emissions from JP-8 based on molar masses. The 12:23 carbon-to-hydrogen ratio is stated by Farokhi as an average composition of the various hydrocarbons present in the fuel [29].

$$C_{12}H_{23} + n(O_2 + 3.76N_2) \rightarrow 12CO_2 + \text{m}H_2O + \cdots \tag{2}$$

where n represents the number of moles of dry air reacted and m corresponds to the number of moles of water vapour produced [30]. The equation suggests the conversion of 1 mol of JP-8 to 12 mol of CO_2, leading to the following mass ratio:

$$\frac{mass_{CO_2}}{mass_{Fuel}} \frac{12(12+32)}{12(12)+23(1)} \cong 3.16$$

Although simplified, this ratio indicates that burning 1 kg of JP-8 fuel emits approximately 3.16 kg of CO_2. This method of emissions calculation was compared to another, described by Nojoumi et al., which similarly balanced chemical equations to derive CO_2 emissions by mass [16]. This approach was adopted to obtain the CO_2 emissions values in Table 2.

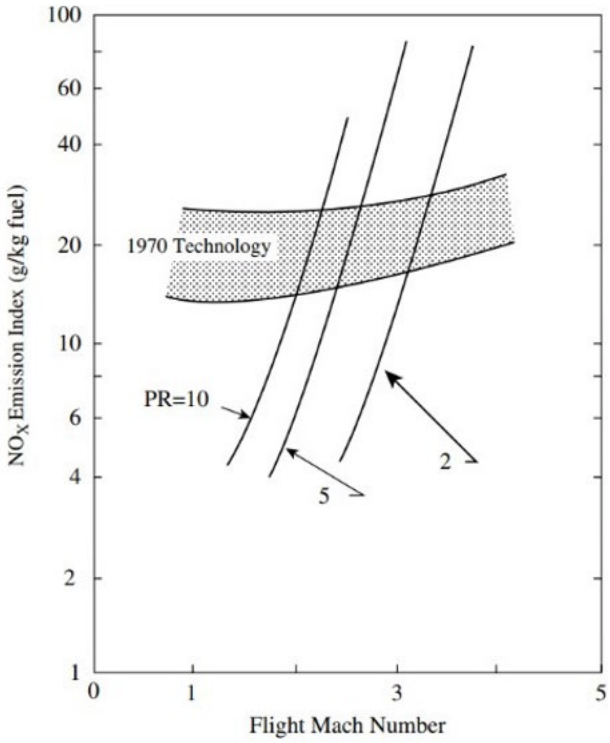

Figure 2. The impact of flight Mach number on NO_x emissions considering different pressure ratios (PR) [31].

Using the sulphur contents of JP-7 and JP-8 outlined in their respective toxicological reports (0.1 and 0.12% of total mass [17,32]), a similar approach was taken to estimate SO_2 emissions from hydrocarbon fuels. These calculations lead to the CO_2 and SO_2 emissions estimations displayed in Table 2.

Table 2. Carbon intensity of hydrocarbon [33–36].

Fuel	Average Composition	Density (kg/m^3)	Lower Heating Value, h_{pr} (kJ/kg)	Flashpoint (°C)	kgCO_2 Emissions per kg Fuel Burnt	kgSO_2 Emissions per kg Fuel Burnt
JP-7	$C_{12}H_{25}$	779–806	43,500	60	3.15	0.00020
JP-8	$C_{12}H_{23}$	800	43,190	38	3.19	0.00024

This method of quantification of CO_2 emissions is based purely on the principle of balancing molar masses from fuel hydrocarbon compositions and does not examine the effects of aircraft flight pattern, weight, or engine operation. However, a numerical study of pollutant emissions from subsonic and hypersonic aircraft by Fusaro identified that there was little divergence in emissions between subsonic and super/hypersonic combustion scenarios [37].

Several studies have identified that most CO_2 emissions from kerosene result from its combustion inside aircraft or rocket engines. A study by S. Howe identified that kerosene-derived jet fuels produce approximately 99% of all life cycle carbon emissions during combustion. Therefore, the figures for kgCO_2 emitted per kg of fuel burnt for JP-7 and JP-8 are assumed to be generally representative of the fuel lifecycle [38].

LH_2 has many properties that make it a suitable fuel for hypersonic flight. The high-low flashpoint (hpr) and rapid ignition time of LH_2 and its wide flammability range mean dry air, with a hydrogen content between 4 and 74%, can be ignited [15]. No CO_2 or SO_x emissions are released when combusting hydrogen, but NO_x is still produced, as explained above. Previous research has identified that 57% of the climatic impact of aviation is a result of contrails, these are condensation trails from aircraft engines that are responsible for capturing and absorbing heat that would otherwise escape into space, and therefore, would constitute a major effect on global warming [39].

The Hydrogen Council published an LCA in 2021 detailing CO_2 emissions from the three different forms of hydrogen production and various sources of energy based on predicted 2030 values. [40] Figure 3 displays a graphical illustration of the GHG emissions released by grey, blue, and green hydrogen production from a range of energy sources, varying by location and distance travelled. The units are the kg of CO_2 released for every kg of H_2 produced. The study assumes a 90% effectiveness at capturing CO_2 from CCS, level with target CCS efficiencies [41]. This analysis is specific to locations and considers that the average emissions vary by producer, nation, and distance.

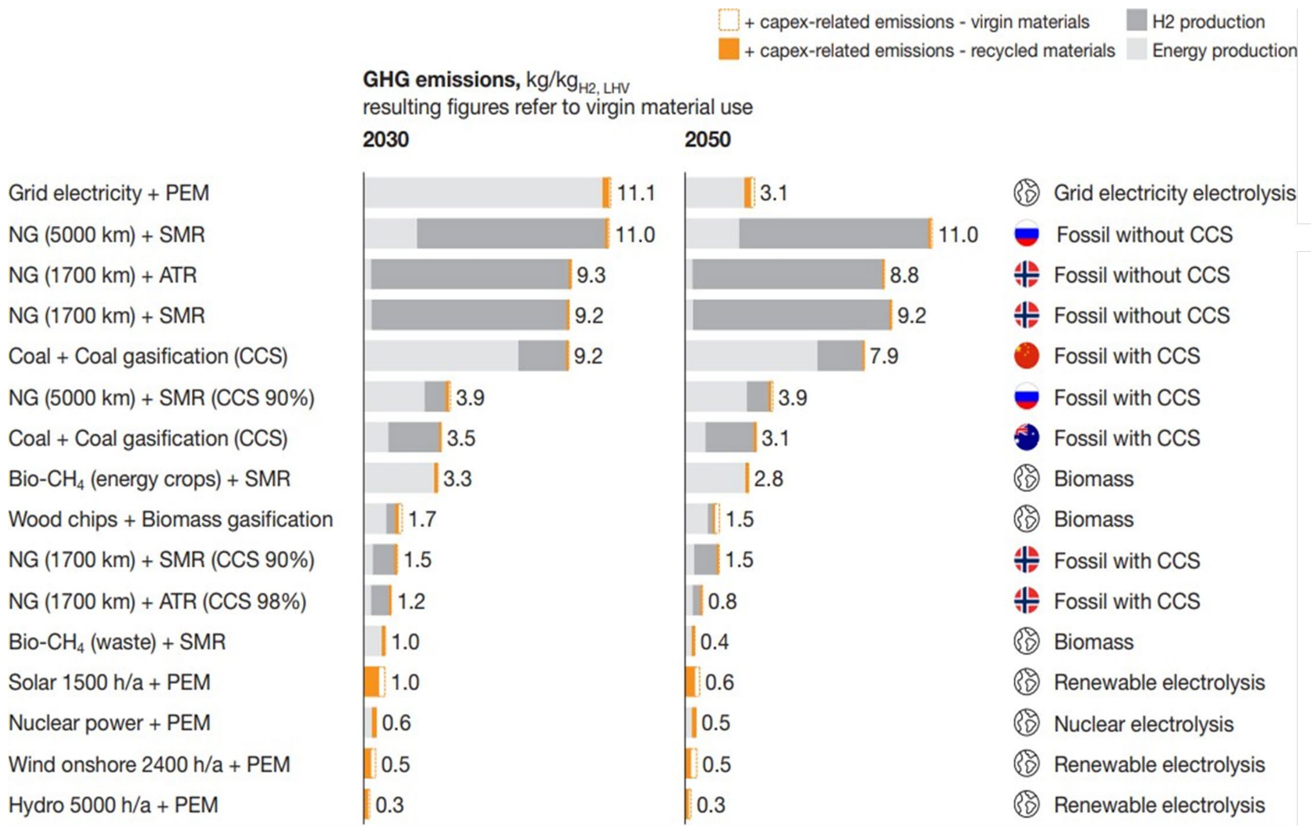

Figure 3. LCA of predicted emissions from blue, green and grey hydrogen production in 2030 [40].

Figure 3 displays the projected GHG emissions for 2030 and 2050 of the LCA assessment of green, blue, and grey hydrogen. Green hydrogen is represented by 'Renewable Electrolysis', blue hydrogen is represented by 'Fossil with CCS', and grey hydrogen is represented by 'Fossil without CCS' in the figure below. It can be revealed that PEM electrolysis with electricity produced from low carbon sources of energy releases the least amount of CO_2 per kg of H_2, between, 0.3 and 1.0 kg. Conversely, the form of hydrogen production with the greatest carbon emissions is PEM electrolysis with the use of grid electricity in 2030, which releases 11.1 kg of CO_2 per kg of H_2.

This is because this study uses the predicted average carbon intensity of the global electricity grid in 2030, based upon predictions from IRENA's 'Renewable Energy Roadmap' [42]. The use of electrolysis in 2030 produces more CO_2 than any form of blue or grey hydrogen production measured by that study, as coal gasification includes CCS. The average carbon intensity of global electricity grids is 220 gCO_2e/kWh, assuming that 68% of electricity is produced by renewable energy by 2030. Figure 3 displays that by 2050 CO_2 emissions from PEM electrolysis will significantly decrease to 3.1 kg CO_2 per kg H_2. If LH_2 is to be a sustainable fuel source for hypersonic flight hydrogen sourced from renewable sources of electricity should be prioritised.

The environmental advantages of LH_2 over kerosene derived fuels are dependent upon the GHG emissions released during the production of hydrogen and the upstream emissions from hydrogen processing. In total, 96% of hydrogen is produced with the use of fossil fuels, hydrogen derived from this source is known as grey hydrogen. The most common production methods of hydrogen are Steam Methane Reforming (SMR) and Autothermal Reforming/Partial Oxidation (ATR), SMR produces carbon monoxide and hydrogen by heating methane from natural gas using steam, and the subsequent products are then used as a fuel or in organic synthesis [43]. On the other hand, ATR produces syngas (composed of hydrogen, carbon monoxide, and carbon dioxide) via an exothermic reaction that combines oxygen and carbon dioxide or steam with methane from natural gas. The methane is partially oxidised during the process, which takes place in a single chamber. Unlike SMR, ATR uses/requires oxygen in the steam-methane reforming process [44]. With the use of natural gas, 48% of total hydrogen production is currently from SMR and ATR [22,45], and 38% of hydrogen production is sourced from coal gasification, illustrating that currently, there is extraordinarily little progress toward decarbonising hydrogen production, which is necessary if LH_2 is to be a sustainable fuel for hypersonic flight.

Dependent upon the sources of energy used for electrolysis, "green hydrogen" may be comparatively worse for the environment than "blue hydrogen" which uses CCS to reduce carbon emissions throughout its lifecycle. For example, Figure 3 displays that SMR with anaerobically produced biomethane produces 3.3 kg of CO_2 per kg of green H_2 produced, while SMR with natural gas and CCS at 90% efficiency produce 1.5 kg of CO_2 per kg of H_2.

The LCA also identifies the mass of CO_2 emitted per kg of H_2 produced from processes where the fuel is shipped over distances greater than 5000 and 1500 km, respectively; providing a useful comparison of emissions depending upon the producer and the distance travelled.

Table 3 displays the variation in carbon emissions per hydrogen production type based on the LCA produced in 2021 by the Hydrogen Council [40]. The sustainability of LH_2 for hypersonic travel is, therefore, dependent upon the method of its production and Figure 3 displays that no form of production is carbon neutral, owing to the emissions released from obtaining materials. LH_2 can be used as a low-carbon fuel when produced with electrolysis from onshore wind, hydroelectric, solar and nuclear sources of energy. However, the upstream emissions of obtaining LH_2 for hypersonic flight also need to be considered, to identify the total carbon emissions released during its lifecycle.

Table 3. Emission from different methods of hydrogen production.

2030 Emissions by Type of Hydrogen Production (kg CO_2/kg H_2)	
Green Hydrogen	0.3–3.3
Blue Hydrogen	1.2–9.2
Grey Hydrogen	9.2–11.1

Upstream emissions of LH_2 refer to any process that produces GHG emissions beyond the production of hydrogen. This refers to liquefaction and transportation and both processes can be decarbonised to produce sustainable LH_2. The process of producing LH_2 is known as liquefaction and is achieved through simple refrigeration cycles such as the Claude Linde-Hampson. This involves compressing hydrogen gas and cooling the product with the use of a refrigerant, often liquid nitrogen, this can be decarbonised with the use of electricity produced from renewable energy [46].

To decarbonise LH_2 transportation, there are several options available. Currently, LH_2 is transported cryogenically in tankers over land. These tankers are usually fuelled with diesel or petroleum but continued progress towards electrified Heavy Goods Vehicles (HGV) and hydrogen-fuelled HGVs could result in carbon-neutral transportation of LH_2 [47,48].

3.2. Fuel Efficiency with Regards to Engine Efficiency

Figure 1 illustrates the specific impulses of the various engines, all of which generally exhibit lower I_{sp} values at higher speeds as their optimal speeds are surpassed, except for rockets which, although capable of functioning across the entire Mach range, offer the lowest specific impulses. This is indicated by the constant, thick bar at the bottom of the graph and is due to the requirement of rockets to house an onboard oxidiser.

Ramjets are most efficient around the Mach 3 mark, after which, disassociation causes efficiency to drop off [49]. Numerous challenges are presented when running scramjets at hypersonic speeds, such as maintaining efficient combustion when the air passing through the engine is extremely pressurised and contained in the combustor for only a few milliseconds. Though little is known about scramjet efficiencies because of the technology's immaturity, the efficiency of mixing fuel with the supersonic airflow is fundamental. Therefore, burner efficiency is a function of combustor length, which improves along the length of the combustor [29].

Improving the efficiency of the propulsion systems can improve the overall sustainability of the propellant. This is because increasing the efficiency of the system will increase the thrust per unit of fuel and therefore less fuel is utilised which contributes to a reduction in the total emissions from the vehicle. The combustion efficiency depends on the dissociation of the combustion products in the chamber, which can be quantified using water production. The combustor inlet temperature of scramjets leads to such elevated temperatures within the combustion chamber that causes dissociation of the main products. This influences the performance, lowering the thrust or specific impulse.

The following are some of the qualities that make hydrogen capable of achieving high combustion efficiencies, hydrogen has a wide flammability range and may be ignited by a variety of fuel-air combinations. Hydrogen may function on a "lean" combination, which indicates that the quantity of fuel required for combustion with a given amount of air is less. This constitutes a better fuel efficiency and a lower end combustion temperature, which minimises the number of pollutants produced in the exhaust, such as NO_x. Another quality is that hydrogen has a higher auto-ignition temperature than hydrocarbons, allowing for larger compression ratios in a hydrogen engine. A higher compression ratio results in higher combustion efficiencies due to less energy loss [49,50].

3.3. Limitations

To use sustainably produced LH_2 in hypersonic vehicles further steps must be taken to establish a hydrogen economy with sustainable transportation and green hydrogen production.

The limitation of LH_2 as fuel for hypersonic flight is that 96% of H_2 is produced with hydrocarbons, resulting in a greater carbon footprint than JP-7 and JP-8. Transportation of LH_2 involves fossil fuel driven Heavy Goods Vehicles (HGVs) and the storage of LH_2 is a further limitation because it must be kept at 0.35 K, which requires specialist containers [48].

LH_2 fuel produced for hypersonic vehicles is sourced from fossil fuels and the current supply pathway involves diesel-driven HGVs and a liquefaction process powered by grid electricity [48]. For LH_2 to be a sustainable fuel for a hypersonic flight the ideal goal is to develop a functioning hydrogen economy. This energy scenario is where hydrogen production, liquefaction, storage and transportation are decarbonised as hydrogen usage becomes more mainstream. At a minimum, the emissions from the production and upstream processes of LH_2 rocket fuel must be decarbonised to replace JP-7 as a sustainable fuel for hypersonic flight.

4. Conclusions

In this paper, the sustainability of LH_2 in scramjets was analysed by comparing the total carbon emissions in the lifecycle of green, blue, and grey hydrogen against conventional kerosene fuel. Initially, an insight into the applications of these fuels in previous and ongoing hypersonic vehicles was reviewed. The following conclusions are drawn from the above discussions:

- Table 2 reveals that the combustion emissions of JP-7 and JP-8 are 3.15 and 3.19 kg of CO_2, respectively. Based on the predicted LCA emissions of grey, blue, and green hydrogen in 2030 highlighted in Figure 2, and the combustion emissions computed in Table 2, an LCA assessment of LH2 was performed. It revealed that SMR with anaerobically produced biomethane produced 3.3 kg of CO_2 per kg of green H_2 produced, while SMR with natural gas and CCS at 90% efficiency produced 1.5 kg of CO_2 per kg of H_2. This confirms that the lifecycle emissions of green hydrogen produce more CO_2 compared to kerosene fuel, as indicated in Table 3.
- Hypersonic flight is likely to produce more NO_x emissions than super or subsonic vehicles because of the greater temperatures reached in the combustion chamber.
- Scramjet technology remains in its infancy. Extensive performance data on the combustion efficiencies and data on the empirical GHG emissions of hypersonic tests are necessary for future work in order to better quantify the sustainability of hypersonic vehicles using different types of fuel.

This paper only considered the LCA of LH_2 when assessing its sustainability compared to other types of jet fuel, future studies could expand further by including an LCA of different types of jet fuel and comparing the findings to LH_2. Moreover, to evaluate the sustainability of other potential alternative fuels to kerosene, such as methane fuel. This paper investigated the sustainability of LH_2 with relation to hypersonic flight vehicles only, future studies could also investigate the sustainability of different propulsion systems and assess the environmental impact of vehicles with different Mach speeds, and conclude which are more environmentally friendly.

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