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Taking stock of the climate impact of the hydrogen pathways for the aviation sector by 2050

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ABSTRACT

The adoption of hydrogen as a viable alternative for kerosene in the aviation sector has attracted significant attention. However, comprehending the environmental impacts of hydrogen pathways is a complex endeavor that relies on the specific production pathways employed. The aim of this study is to provide a Well-to-Wake analysis by examining the environmental effects six distinct hydrogen production pathways. Moreover, this research provides an estimating of hydrogen leakage and its indirect effects on the atmosphere. To achieve this, besides use the Aviation Integrated Model, an extensive review of numerous articles is incorporated to determine the value of equivalent of carbon dioxide of production pathways. The research predicts that 12.2 Mt, 10.6 Mt, and 7.3 Mt of unburned hydrogen will permeate the atmosphere in 2050 across the high, medium, and low demand scenarios, respectively. The penalty factor, which quantifies the additional environmental impact of hydrogen pathways compared to conventional jet fuel, for electrolysis from renewable resources ranges from −1.37 to −0.02 kg of carbon dioxide equivalent per hectojoule (kg CO_2eq/hJ) in the mid-demand scenario, while renewable thermal water splitting consistently maintains a negative penalty factor, reaching −0.30 kg CO_2eq/hJ by 2050. In contrast, electrolysis from the existing electricity grid's penalty factor is projected to increase dramatically from −1.27 to 12.23 kg CO_2eq/hJ by 2050 under the mid-demand scenario.

1. Introduction

Aviation is crucial to modern society, contributing significantly to the global economy and job market. It accounts for over 80 million jobs and nearly 3.5 % of global Gross Domestic Product (GDP) [1]. The industry is expected to grow substantially, with Revenue Per Kilometer (RPKs) projected to quadruple by 2050, leading to a tripling of energy consumption [2]. However, this growth presents challenges, particularly regarding greenhouse gas (GHG) emissions. Aviation currently contributes 5 % to anthropogenic global warming [3]. Without intervention, the industry may fail to meet climate goals set by the Intergovernmental Panel on Climate Change (IPCC) [4]. The key challenge is to reduce emissions while meeting increasing fuel demands [1], prompting stakeholders to seek sustainable and economical solutions for achieving net-zero emissions by 2050. Over the last decades, innumerable works have been conducted regarding the sustainable aviation concept, and valuable solutions are presented accordingly to tackle this dilemma. Alternative fuels[5] (or specifically biomass-based synthetic fuels[6]), technological and infrastructural developments[7], policy[8] and regulatory [9] implements, and behavioral changes[10] are prevalent cures for addressing this dilemma.

Among the various approaches to achieving sustainable aviation, alternative fuels warrant particular attention due to their potential for significantly reducing greenhouse gas emissions. A systematic analysis of viable fuel options reveals hydrogen as a leading alternative to conventional kerosene, offering unique characteristics that make it particularly suitable for the aviation sector[11]. A comprehensive study was conducted on the application of hydrogen in the aviation sector, identifying multiple challenges and limitations associated with the development of hydrogen-powered aircraft[12]. In addition to examining the technical challenges of hydrogen implementation in aviation, the economic implications of this energy source were also investigated. The results indicate that adopting hydrogen technology could potentially increase the direct operating costs of aircraft [13]. Despite these challenges, integrating hydrogen-powered aircraft into commercial fleets appears more feasible than ever before[14]. However, this transition heavily depends on reducing costs associated with the necessary infrastructure for hydrogen fuel implementation [15] and the challenge of hydrogen supply chains for airports[16]. Consequently, a thorough

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Nomenclature

Latin Symbols

R	Radiative forcing scaling factor $(Wm^{-2}ppb^{-1})$
a	Production rate of species resulting in the indirect forcing (mixing ratio yr^{-1}) per ppb H_2 change at steady-state
CO_2eq	Equivalent of carbon dioxide
H	The time horizon considered.
C	Conversion factor for converting H_2 mixing ratio (ppb) into H_2 mass (kg)
tp	Length of step emission (yr)
D	Ground distance (km)
PL	Payload (kg)
P	Penalty factor (kg CO2eq/J)
W	Fuel weight (kg)

Greek Symbols

α_R	Lifetime of perturbation to species causing the radiative forcing
α_H	H_2 lifetime (combined chemical and deposition lifetime) (yr)
η	Engine performance parameter
ϑ	Engine NO_x emission parameter

Subscripts

t	Aircrfat type
s	Aircrfat class
m	Flight mode
i	Hydrogen production pathway

Acronyms

AGWP	Absolute global warming potential
AIM	Aviation integrated model
BG	Biomass gasification
CAEP	Committee on aviation environmental protection
CCS	Carbon capture and storage
CG	Coal gasification
CI	Carbon intensity
EC	European Commission
EEG	Electrolysis from existing electricity grid
ERE	Electrolysis from renewable resources
EU	European union
GDP	Gross domestic product
GHG	Greenhouse gases
GWP	Global warming potential
ICAO	International civil aviation organization
IPCC	Intergovernmental panel on climate change
JRC	Joint Research Centre
OH	Hydroxyl radical
PEM	Polymer electrolyte membrane
PM	Particulate matter
RPK	Revenue per kilometer
RTS	Renewable thermal water splitting
SMR	Steam methane reforming
TTW	Tank-to-Wake
WTT	Well-to-Tank
WTW	Well-to-Wake

assessment of the environmental impacts of hydrogen adoption in the aviation industry is imperative. This consideration becomes particularly significant when accounting for the fact that the rate of hydrogen emission from infrastructure and distribution systems is comparable to that of methane emissions [17] (Tiny hydrogen molecules can quickly leak into the surrounding environment[18]). A groundbreaking study has examined the life cycle of hydrogen produced via electrolysis using renewable energy sources. The findings unequivocally demonstrate that current aviation emissions are not on a trajectory to meet the objectives outlined in the Paris Agreement [19]. While adopting hydrogen in the aviation industry may reduce greenhouse gas emissions, the potential impact of direct hydrogen emissions into the atmosphere has been largely overlooked. Only Warwick et al. [20] investigated the indirect effects of pure hydrogen emissions on the atmosphere, but their research focused on power generation, not aviation application.

Accordingly, this study examines the impact of emissions of hydrogen pathway throughout the various stages of the hydrogen fuel life cycle, considering it a potential penalty in transitioning from fossil fuels to hydrogen in the aviation sector. The quantity of hydrogen emissions during production was derived from a comprehensive literature review. The greenhouse gas emissions from hydrogen propulsion systems were calculated using the model presented in the Aviation Integrated Model (AIM2015). Additionally, estimates for hydrogen leakage were incorporated into the analysis. Another prominent difference between the current study and Dray et al. [19] work is proving a Well-to-Wake (WTW) analysis for six different hydrogen production pathways, the chosen pathways are diverse in energy sources, technologically feasible across countries, and economically viable. All in all, the leading objectives of the attending study are multi-faceted as follows:

- To provide a systematic review of six different hydrogen production pathways to compare their climate impact objectively.
- To calculate the contribution of hydrogen leakage to the CO_2-equivalent in the aviation sector.
- To propose a penalty factor of different hydrogen pathways.
- To reckon the effectiveness of different hydrogen production pathways in achieving net zero carbon aviation by 2050.

The remainder of this paper is organized as follows: Section 2 reviews the mechanisms by which hydrogen affects the climate. Section 3 outlines the methods, assumptions, and limitations of the study. Section 4 presents the results. Finally, the conclusions are summarized in Section 5.

2. Review of mechanisms by which hydrogen affects climate

The substantial problem considered in the present study as a penalty for using hydrogen fuel in the aviation industry is the possibility of emitting pure hydrogen during production, transportation, and combustion, which is supplementary to emitting conventional GHGs. Figs. 1 and 2 illustrate the distinct hydrogen production pathways and the stages at which pure hydrogen release occurs. When emitted into the atmosphere, hydrogen undergoes oxidation, leading to both direct and indirect impacts on global warming. In the atmosphere, it is estimated that around 70 %-80 % of emitted H_2 is removed by soils through bacterial uptake and diffusion, while 20 %-30 % of escaped hydrogen into the atmosphere is reacted with the hydroxyl radical (OH). The process of hydrogen oxidation in the atmosphere attends to rising concentrations of GHG in both the stratosphere and troposphere [21]. In the troposphere, OH is considered the constitutional sink of methane; when the emitted H_2 is oxidized with OH, the amount of available OH for reacting with methane decreases; this tends to a longer methane's atmospheric lifetime, which accounts for 50 % of hydrogen's total indirect warming effect [22]. Additionally, hydrogen oxidation produces atomic hydrogen, which reacts with O_2 to produce HO_2, which, in turn, after a

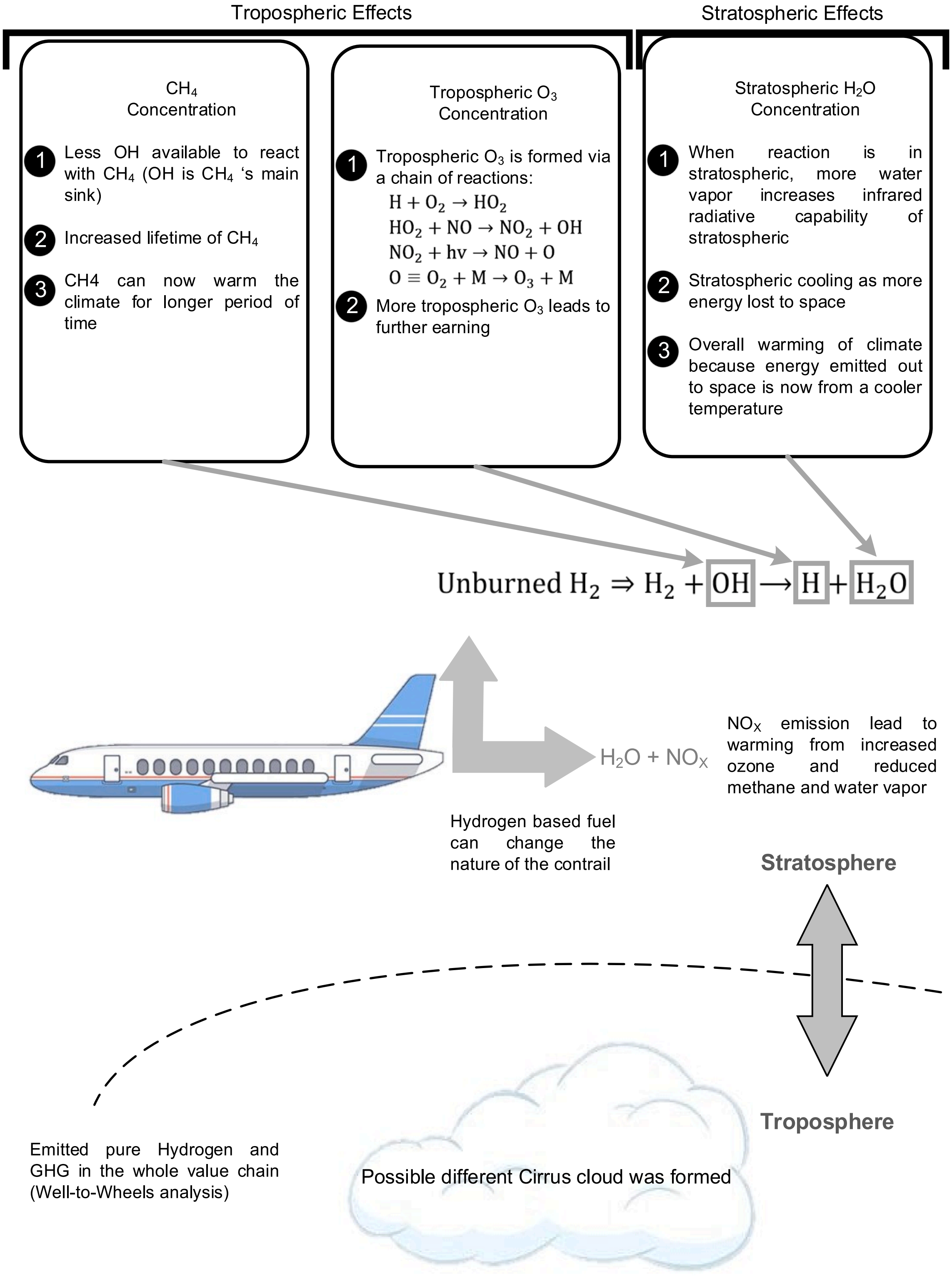


Fig. 1. Consequences of hydrogen oxidation on atmospheric greenhouse gas warming and concentrations.

series of reactions, ultimately tends to produce troposphere ozone that contributes to the 20 % of hydrogen warming impacts [22]. In the stratosphere, hydrogen oxidation increases the concentration of water vapor, enhancing the stratosphere's infrared radiative capacity and leading to stratospheric cooling—a phenomenon that indirectly warms the climate by directing more energy to the atmosphere. This effect contributes nearly 30 % of hydrogen's total climate impacts[18]. Though this stratospheric cooling may increase ozone-destroying reactions due to polar stratospheric clouds, these effects are considered relatively minor[22]. These interactions highlight the complex role of hydrogen in atmospheric warming and underscore the importance of examining hydrogen pathways' contributions to GWP in detail. To quantify these impacts, the methodology in the subsequent section evaluates the global warming potential of hydrogen emissions.

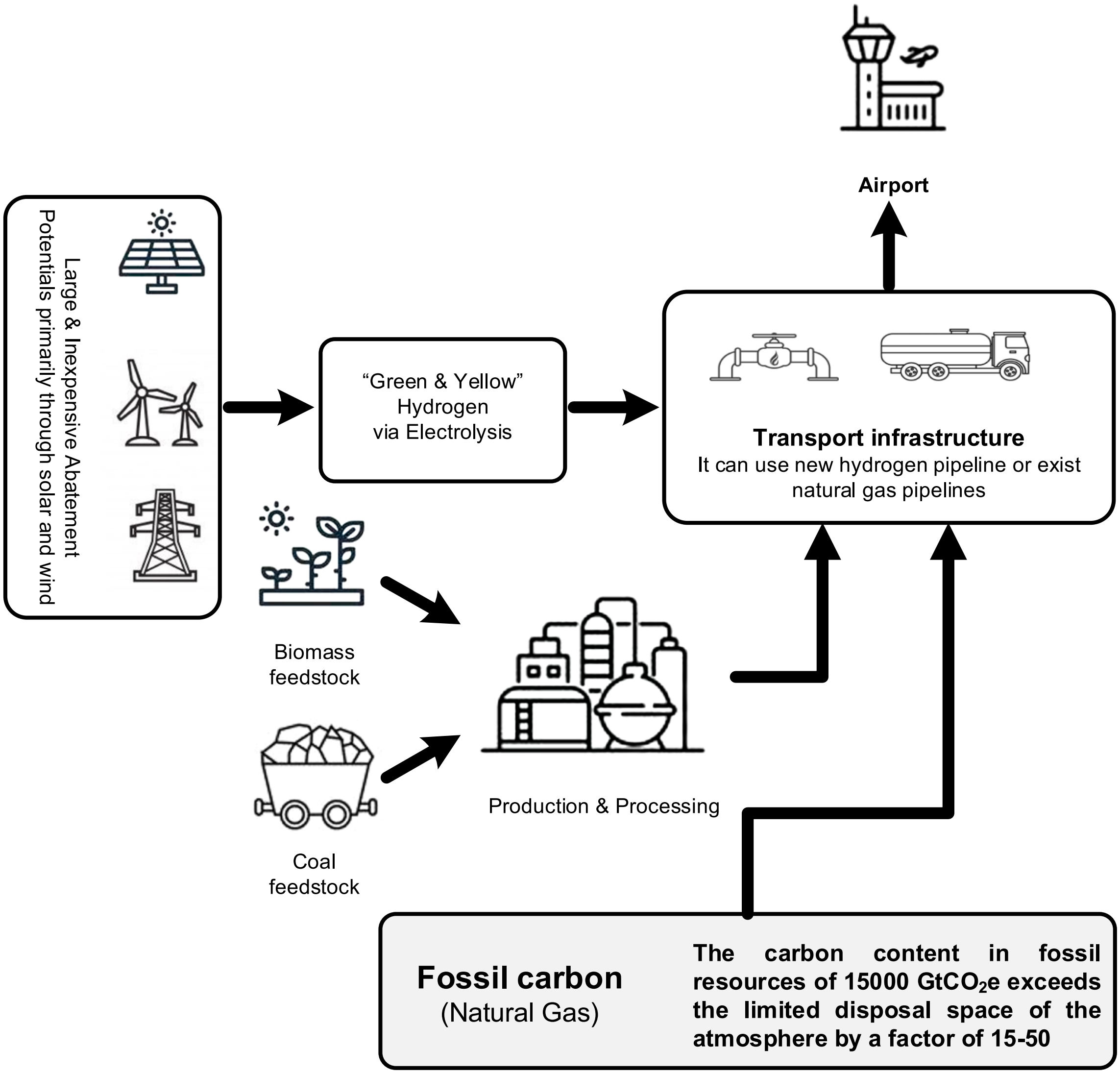


Fig. 2. Layout of the CO_2eq emission cycle in the aviation sector. Hydrogen originates from various pathways in which (renewable) electricity, natural gas, biomass, coal, and renewable thermal can be used via dissimilar technologies to meet energy demands.

3. Methodology

In this study, the analysis consists of five components. First, a comprehensive review is conducted to extract the well-to-tank (WTT) emission factors of different hydrogen production pathways. Second, the emission ratios of pure hydrogen at various stages of the supply chain, as well as the leakage of unburned hydrogen from the combustion chamber in aircraft engines, are estimated based on assumptions and existing literature. Third, the global warming potential (GWP) of hydrogen is calculated using a well-established model[23]. As a core part of the methodology, the emissions from hydrogen- and kerosene-powered aircraft for a single flight are computed based on the class of aircraft. In the final step, the required amount of hydrogen and the associated emissions up to the year 2050 are calculated using the projection method outlined in AIM2015 model[24]. All sub-sections are explained in detail in the following sections.

3.1. *Well-to-tank emission factors of hydrogen production pathways*

The study examines six diverse hydrogen production pathways, encompassing the thermochemical, electrochemical, thermal-electrochemical, and biochemical production families. These pathways have been chosen for several key reasons. First, they utilize a diverse range of energy sources and feedstocks. Second, they are technologically feasible for implementation in various countries. Finally, they are economically viable and reasonably priced. The selected pathways include steam methane reforming (SMR), biomass gasification (BG), coal gasification (CG), electrolysis from the existing grid (EEG), electrolysis from renewable resources (ERE), and renewable thermal water splitting (RTS). The literature review process was conducted systematically, examining articles related to each hydrogen production pathway chronologically. Initially, a comprehensive collection of articles was compiled, followed by a rigorous screening process to identify relevant studies. This thorough literature analysis resulted in the selection of 66 pertinent articles published up to 2023, yielding a total of 154 carbon intensity (CI) values. A complete list of the reviewed papers is provided in the supplementary information. It is worth mentioning that the final WTT emission factors for each hydrogen production pathway are calculated by averaging the factors extracted from all the reviewed studies, providing a representative estimate for each pathway.

3.1.1. *Natural gas reforming*

Gray hydrogen, produced via the SMR method, accounts for over 95 % of hydrogen production in large central plants[25]. The process typically uses Ni-based catalysts in packed-bed reactors due to their cost-effectiveness and high efficiency[26]. The natural gas feedstock undergoes desulfurization, followed by pre-reforming with steam to generate methane and syngas. In the main reactor, methane is then converted into carbon monoxide and hydrogen[27].

3.1.2. *Gasification*

Coal and biomass are key feedstocks in gasification technology, which can significantly reduce emissions when combined with Carbon Capture and Storage (CCS)[28]. Gasification converts carbonaceous materials into syngas, a mixture of carbon monoxide and hydrogen, typically at high temperatures (up to 1400 °C) and pressures (up to 33 bar). The process requires a gasifying agent, such as steam, oxygen, or air, to facilitate the reaction[29].

3.1.3. *Electrolysis*

Electrolysis decomposes water into oxygen and hydrogen and is notable for its scalability, allowing for small-scale implementation. Hydrogen extraction via electrolysis can occur through various methods, including photochemical, biochemical, direct thermochemical, and photoelectrochemical conversions[30]. Common types of electrolysis include polymer electrolyte membrane (PEM) and alkaline electrolysis. The type of energy source used to power the electrolysis process is a critical factor in determining its environmental impact.

3.1.4. *Water splitting*

Water-splitting methods are recognized as highly environmentally sustainable approaches, utilizing high-temperature waste heat from industries, renewable energy sources, and nuclear power plants to produce significant quantities of clean hydrogen[31]. This study focuses specifically on water-splitting processes driven by renewable energy sources.

3.2. *Hydrogen leakage factors*

There is a need to investigate hydrogen emission factors across different stages of the value chain. This section builds on previous research and assumes that 10 % of hydrogen is released into the atmosphere in an unburned form [20]. Additionally, this article assumes a hydrogen leakage rate of 0.31 % in storage tanks at production plants and 0.03 % in airport tanks [17]. It is also worth mentioning that hydrogen leakage during transportation from production tanks to airport tanks is considered negligible. This article does not make a new assumption about the release of pure hydrogen during the production process. Instead, it builds on existing findings from the hydrogen production section, using the results extracted from the articles reviewed in Section 3.1.

3.3. *Determining a hydrogen global warming potential*

In contrast to other species, the radiative forcing of the hydrogen is entirely indirect[18]. As discussed, emitted hydrogen has a sophisticated impact on the atmosphere through chemical reactions. Therefore, this study utilizes the Absolute Global Warming Potential (AGWP) equations developed by Warwick et al., which are based on detailed experiments using chemical-climate modeling for hydrogen [20]. The AGWP equations consider several factors: the radiative forcing caused by the initial chemical disturbance from a step emission (AGWP1), the decay of this chemical disturbance over time (AGWP3), and the remaining chemical effects in the atmosphere after the step emission has ceased (AGWP2). One of the fundamental challenges is choosing the time horizon, due to considering the long-term effects of CO_2, GWP-100 is used in this research in the form of the following formulas:

$$AGWP_1 = Ra\alpha_R\alpha_H C\left[tp-\alpha_R\left(1-exp\left(\frac{-tp}{\alpha_R}\right)\right)-\left(\frac{\alpha_H}{\alpha_H-\alpha_R}\right)\left(\alpha_H\left(1-exp\left(\frac{-tp}{\alpha_H}\right)-\alpha_M\right)\left(1-exp\left(\frac{-tp}{\alpha_R}\right)\right)\right)\right] \tag{1}$$

$$AGWP_2 = \frac{Ra\alpha_R\alpha_M^2 C(1-exp\left(\frac{-tp}{\alpha_R}\right))}{\alpha_H-\alpha_R}\left[\alpha_H\left(exp\left(\frac{-tp}{\alpha_H}\right)-exp\left(\frac{-H}{\alpha_H}\right)\right)-\alpha_M\left(exp\left(\frac{-tp}{\alpha_R}\right)-exp\left(\frac{-H}{\alpha_R}\right)\right)\right] \tag{2}$$

$$AGWP_3 = Ra\alpha_R^2\alpha_H C\left[1-exp\left(\frac{-tp}{\alpha_R}\right)-\left(\frac{\alpha_H}{\alpha_H-\alpha_R}\right)\left(exp\left(\frac{-tp}{\alpha_H}\right)-exp\left(\frac{-tp}{\alpha_R}\right)\right)\right]\left[exp\left(\frac{-tp}{\alpha_R}\right)-exp\left(\frac{-H}{\alpha_R}\right)\right] \tag{3}$$

$$GWP_{H_2} = \frac{AGWP_{H_2}}{AGWP_{CO_2}} \tag{4}$$

In equation (4), the AGWP for CO_2 over a 100-year time horizon is set to 8.95×10^{-14}. The AGWP for H_2 is considered as the sum of AGWP1, AGWP2, and AGWP3. Further information regarding the GWP is provided in the supplementary information file.

3.4. *Emissions modeling for hydrogen and kerosene-powered aircraft*

The research examines various crucial factors in assessing environmental impact, such as fuel usage, emissions of nitrogen oxides (NO_x), carbon dioxide (CO_2) output, and water vapor (H_2O) release. The foundational equations for estimating fuel consumption and emissions are derived from methodologies developed by Dray et al. [32] specifically, the fuel use calculation employs a simple fuel burn rate-based approach. The study accounts for two types of aircraft: kerosene-powered aircraft and hydrogen-powered aircraft. Therefore, for an aircraft of type t, class s, and flight mode m, the fuel use is modeled as:

$$fuel_{tsm} = \eta_{tsm,0} + \eta_{tsm,1}D + \eta_{tsm,2}D.PL + \eta_{tsm,3}D^2 + \eta_{tsm,4}PL + \eta_{tsm,5}D^2.PL \tag{5}$$

In this context, D represents the total ground distance covered by the aircraft, while PL denotes the combined weight of passengers, their luggage, and any additional cargo. The parameters η_{tsm} are determined through estimation processes, with distinct values calculated for various aircraft categories. This model is applicable for climb, cruise, and descent modes and their related η_{tsm} for kerosene aircraft are derived from PIANO-X performance model[33]. Fuel usage and emission levels for other flight modes are computed using standardized consumption rates and emission coefficients tailored to each aircraft model. However, when it comes to hydrogen-powered aircraft, there's a scarcity of reliable data on fuel efficiency across various operational modes. The comparative fuel consumption between hydrogen and traditional kerosene-powered aircraft remains uncertain. Given this limitation, our analysis adopts a simplified approach. The hydrogen aircraft's fuel efficiency during different flight phases is estimated by applying a direct scaling factor to the known consumption patterns of conventional kerosene-based aircraft. This methodology mirrors the approach utilized in the AIM2015 study. The necessity for this scaling technique stems from the current absence of comprehensive, real-world data on how hydrogen-powered aircraft actually consume fuel under varying flight conditions. To model NO_x emissions, an approach similar to fuel consumption modeling is employed. Thus, the NO_x emission formulations for the climb, cruise, and descent phases are as follows:

$$NO_{x\,tsm} = \vartheta_{tsm,0} + \vartheta_{tsm,1}D + \vartheta_{tsm,2}D.PL + \vartheta_{tsm,3}D^2 + \vartheta_{tsm,4}PL + \vartheta_{tsm,5}D^2.PL \tag{6}$$

The values of ϑ_{tsm} are derived from the results of performance modeling analyses. The quantities of CO_2 and H_2O emissions are derived directly from the fuel consumption values in each flight mode. The data on the GWP of each component, along with the coefficients for calculating fuel consumption and NO_x emissions, are provided in the supplementary file. Fig. 3 presents the process of calculating fuel use and emissions.

3.5. Demand modeling

The latest version of the AIM2015 model [32] is employed to forecast aviation demand by considering the effect of the last global shock (COVID-19). The basis of AIM2015 model is modeling the interactions between airlines, airports, passengers, and other stakeholders. The research utilizes three different scenarios—low, medium, and high demand—based on Shared Socioeconomic Pathways 1, 2, and 3, respectively. Fig. 4 depicts the layout of the updated AIM2015 structure; the model consists of four disparate basic modules, including aircraft movement, airport and airline activity, demand and fare, and aircraft performance and cost; a stable solution can emerge by iterating between various modules. The modules are responsible for projecting the in-flight routing of available aircraft, forecasting the resulting airport-level schedules, demand, and delay for aircraft, envisaging the genuine origin–destination passenger need between different cities, choosing the route and airport by the passengers, the technology uptake, fleet composition, costs, and fuel use, respectively (e.g., [24]). It should be noted that hydrogen-powered aircraft are assumed to gradually enter the air fleet starting in 2035[19].

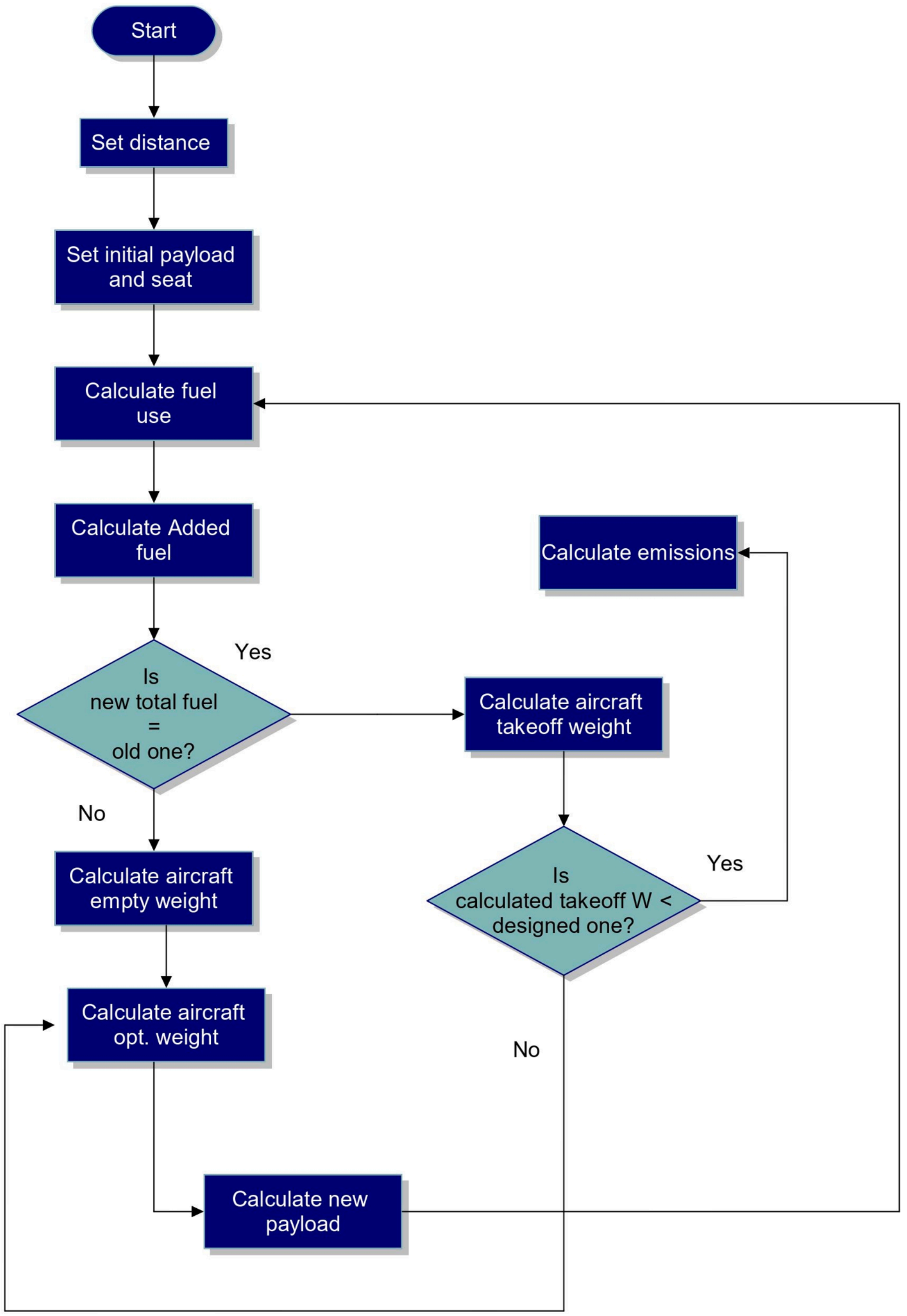


Fig. 3. Simplified flowchart of the environmental modeling process, illustrating the interconnectivity between the six main modules.

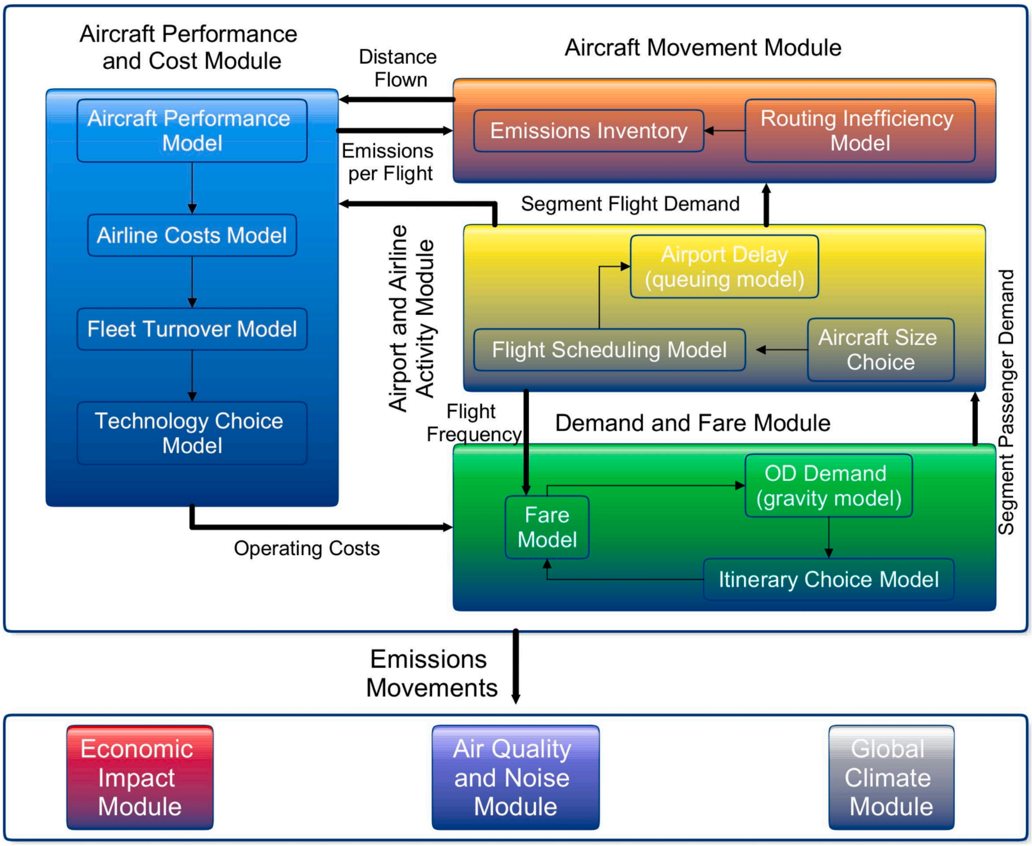


Fig. 4. Layout of the updated AIM2015 model structure. The model consists of seven different modules that include blue: aircraft performance and cost module, orange: aircraft movement module, yellow: airport and airline activity module, green: demand and fare module, gray: global climate module, purple: noise and air quality module, red: economic impact module. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.6. Penalty factor for each pathway

The penalty formula P_i (kg CO_2eq/hJ) is designed to assess the atmospheric impact of various hydrogen production pathways by comparing them to the conventional kerosene-based pathway. It considers the CO_2eq emissions from hydrogen leakage and production and subtracts the CO_2eq emissions associated with the production of kerosene (in the kerosene-only pathway). The result is then normalized by the combined energy of kerosene and hydrogen used in each pathway. This formula helps quantify the relative penalty of each hydrogen production method, allowing for a clear comparison of their environmental impacts compared to traditional jet fuel.

$$P_i = 100\left(\frac{CO_2eq_{H_2,leakage} + CO_2eq_{H_2,production} - CO_2eq_{Jet_A,production}}{E_{Jet_A} + E_{H_2}}\right) \tag{7}$$

3.7. Limitation and assumptions of the work

While this study strives to provide a comprehensive analysis, it is important to acknowledge its inherent limitations. The research is constrained by several factors that may impact the breadth and depth of its conclusions. These constraints articulated as follow:

- Pure hydrogen leakage during the production process is not considered.
- Emissions from transferring hydrogen from production site tanks to airport tanks are omitted, assuming the production site is located near the airport.
- The study does not consider variations in the energy mix over future years or differences between countries.
- The performance coefficients of hydrogen aircraft are calculated by comparing the energy density ratio of kerosene to hydrogen.
- The study does not conduct sensitivity analyses on the different hydrogen production pathways.
- To compute the life cycle emissions of kerosene, the CI produced from extraction, transportation of crude oil, and refinery process is supposed to be equal to 0.6 kg CO2eq/kg kerosene [34].
- In theory, it is assumed that the burning of hydrogen doesn't lead to producing particulate matter (PM); however, the lubrication system could emit a considerable value of PM[35], in this study, PM emission during hydrogen combustion is considered zero.
- It is assumed that hydrogen-powered aircraft will enter the fleet starting in 2035.
- Hydrogen production must exceed the amount used in aviation sector due to hydrogen leakage.

4. Results

This section includes four different subsections titled “Review process,” “Well-to-Wake emissions factor,” “Roles of hydrogen production pathways,” and “Penalty of hydrogen pathway scenarios.” Each subsection is expanded upon herein.

4.1. Review process

It is understood that three production pathways constitute 68 % of the total number of CI values: SMR (24 %), ERE (23 %), and EEG (21 %). Results of this study are slightly different from those of the other research [28]due to examining a broader range of research. Fig. 5

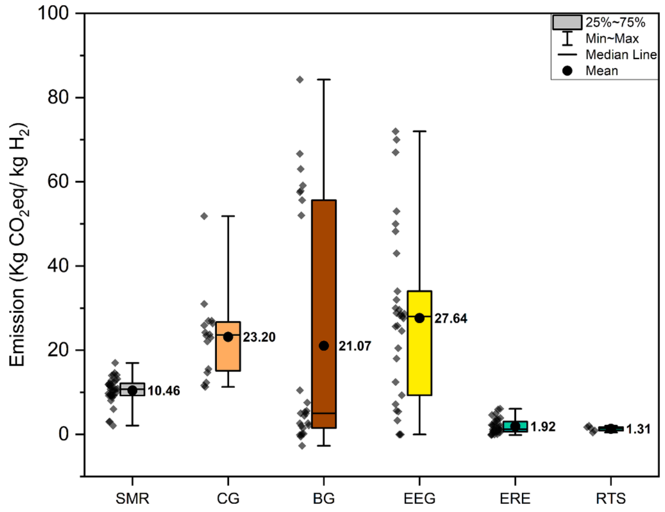


Fig. 5. Summary of the GHG emissions for the main Hydrogen production pathways. The gray, light and dark brown, yellow, green, and jade green colors represent the steam methane reforming (SMR), biomass gasification (BG), coal gasification (CG), electrolysis from existing grid (EEG), electrolysis from renewable resources (ERE), and renewable thermal water splitting (RTS) pathways, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depicts the CI values and pictorial statistics of the six primary hydrogen production pathways. According to Fig. 5, SMR, the most common hydrogen production method, has a CO_2eq between 2 and 17 kg CO_2eq/kg H_2. However, using CCS during the process reduces the amount of CO_2 emission by half. Based on findings, it has an average of 10.46 kg CO_2eq/kg H_2, while its average value equals 13.7 kg CO_2eq/kg H_2 according to the results of [28]. SMR method has been examined without CCS technology; it has been shown that using CCS reduces the CI amount by 60 %. According to the literature review, the CO_2-equivalent emission of coal gasification is demonstrated between 11.3——51.9 kg CO_2eq/kg H_2 with an average of 23.19 kg CO_2eq/kg H_2. Although Busch et al. [28] found that coal gasification has the highest amount of CI, our results ascertain that electrolysis from the existing grid (EEG) has the highest amount of CI, which averages 27.63 kg CO_2eq/kg H_2. Precisely, according to the findings of Busch et al.'s work, [28] biomass gasification has the most diversity, which appears in two different clusters. Eight high values that form one of the clusters are extracted from Reano and Halog [36], analyzing a low-efficiency biomass gasification system using crops. The average amount of CI in biomass gasification is close to coal gasification, equal to 21.065 and 23.19 kg CO_2eq/kg $H_{2,}$ respectively. Two very environmentally friendly pathways with the lowest CI are the electrolysis method of using renewable energy (ERE) and renewable thermal water splitting (RTS), in which the average values of CI are equal to 1.91 and 1.31 kg CO_2eq/kg $H_{2,}$ respectively. Fig. 5 offers the average, minimum, and maximum CO_2eq emissions in distinct hydrogen production pathways. It is clear that EEG has the highest average CO_2eq emission, while the highest CO_2eq emission belongs to BG. It is worth mentioning that all information about the used papers is provided in the supplementary file.

4.2. *Well-to-wake emissions factor*

Table 1 presents the CO_2-equivalent Well-to-Tank (WTT) emissions factor and Tank-to-Wake (TTW) emissions for the middle demand scenario. The results for the high and low-demand scenarios are provided in the supplementary file. It is important to note that only hydrogen leakage is considered for calculating TTW emissions in Table 1.

4.3. *Roles of hydrogen production pathways*

Figs. 6–8 depict the Well-to-Wake (WTW) CO_2-equivalent for the aviation sector between 2000 and 2050 for high, medium, and low demand scenarios. The life cycle of SMR, CG, BG, EEG, ERE, and RTS hydrogen production pathways have been studied; the cycle includes the extraction and transportation of feedstock and the production and combustion of the produced hydrogen. Since in the life cycle of fuel (from extraction to combustion), different species are emitted, for the calculation of CO_2-equivalent, emissions of CO_2, H_2O, NO_x, and particulate matter (PM) must be considered, while, during the hydrogen burn, H_2O and NO_x are the only waste products [37]. It has been determined that 2.6 times more H_2O is produced while burning hydrogen compared to burning of kerosene for the same energy need[38]. In addition, the concentration of H_2O increases during the emission of atomic hydrogen in the stratosphere, which is considered in the indirect effects of hydrogen on the atmosphere. On the other hand, the amount of NO_x emission decreases by 90 %, and this is due to the higher flame temperature in hydrogen fuel compared to conventional fuels. In the Figs. 6-8, the purple dotted line represents the WTW CO_2eq of kerosene fuel, predicted with a specific slope in all three demand scenarios until 2050. The results of the kerosene-only pathway reveal that the value of WTW CO_2eq for high, medium, and low demand is 3666, 3284, and 2373 Mt. As it is clear that the value of WTW CO_2eq for high demand is 1.55 times that of low demand, this shows regardless of other aspects, the low-demand scenario has more potential to meet the goals of the IPCC from an environmental point of view. On the other hand, opting for the

Table 1
Carbon dioxide equivalent related to WTT and hydrogen leakage (TTW) for middle demand scenario.

year	CO_2eq WTT (Mt)						CO_2eq TTW (hydrogen leakage)		
	SMR pathway	CG pathway	BG pathway	EEG pathway	ERE pathway	RTS pathway	Storage of production site (kt)	Storage of airport (kt)	Hydrogen jet engine (Mt)
2036	7.42	16.45	14.94	19.60	1.36	0.93	23.75	2.29	0.76
2037	30.27	67.11	60.96	79.95	5.53	3.79	96.88	9.35	3.11
2038	69.10	153.21	139.17	182.54	12.62	8.65	221.19	21.34	7.11
2039	126.68	280.85	255.12	334.62	23.13	15.87	405.47	39.12	13.04
2040	203.09	450.26	409.00	536.47	37.08	25.44	650.05	62.71	20.90
2041	291.00	645.16	586.04	768.68	53.14	36.44	931.43	89.86	29.94
2042	377.53	836.99	760.29	997.24	68.94	47.28	1208.38	116.58	38.85
2043	466.00	1033.13	938.46	1230.93	85.09	58.36	1491.55	143.90	47.95
2044	558.30	1237.76	1124.34	1474.75	101.95	69.92	1786.99	172.40	57.45
2045	654.39	1450.79	1317.85	1728.56	119.49	81.95	2094.54	202.07	67.34
2046	752.55	1668.42	1515.54	1987.86	137.42	94.25	2408.74	232.38	77.44
2047	853.68	1892.62	1719.19	2254.98	155.88	106.91	2732.42	263.61	87.84
2048	956.58	2120.76	1926.43	2526.81	174.67	119.80	3061.80	295.38	98.43
2049	1065.45	2362.11	2145.66	2814.37	194.55	133.44	3410.24	329.00	109.63
2050	1178.40	2612.53	2373.13	3112.73	215.18	147.58	3771.77	363.88	121.26

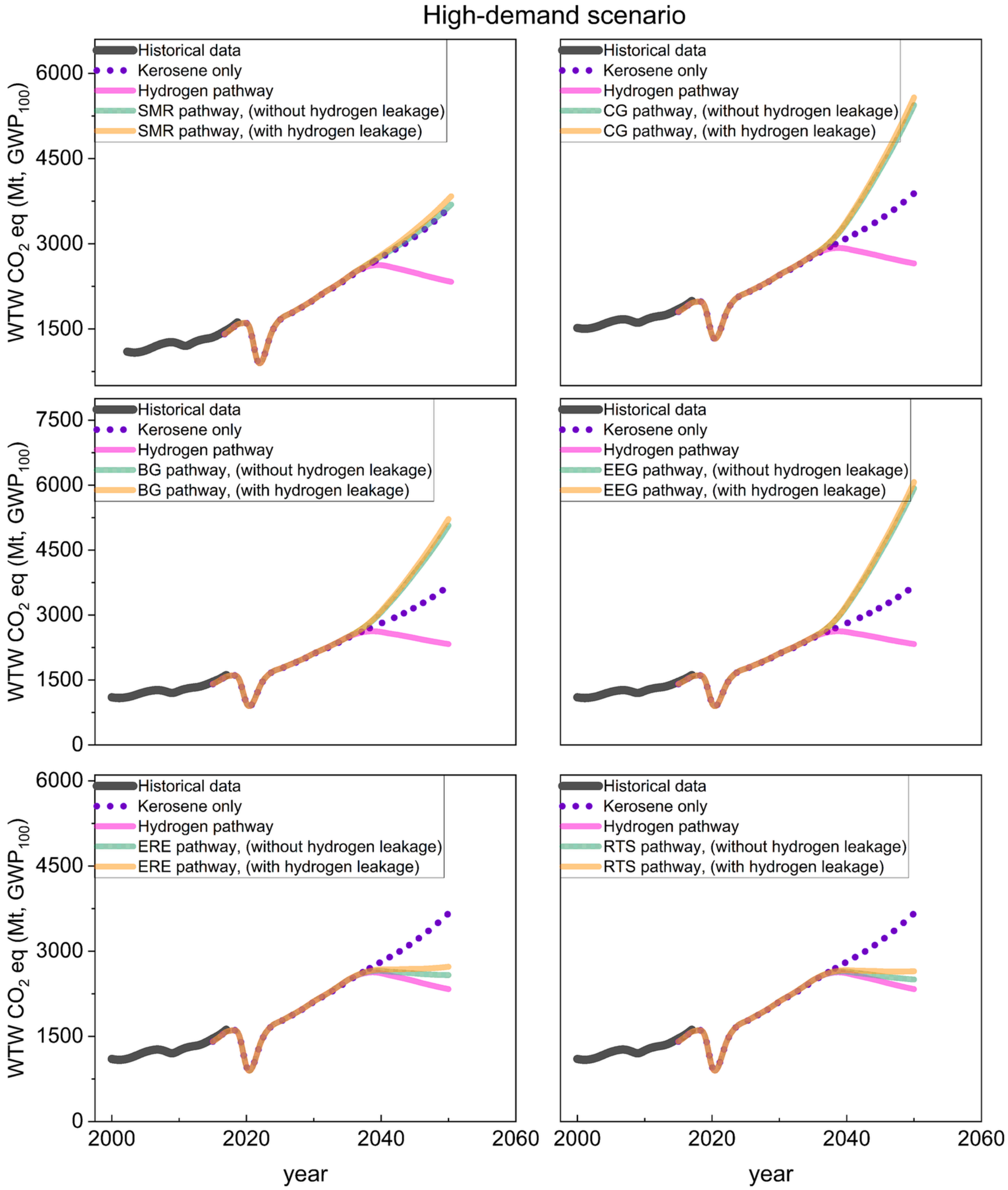


Fig. 6. High-demand scenario calculation of WTW CO$_2$eq of fossil kerosene and hydrogen pathways. The purple dotted line: the kerosene-only pathway, the pink solid line: hydrogen pathway regardless of the method of hydrogen production, the green solid line: WTW of the hydrogen pathway without pure hydrogen emission, and the orange solid line: WTW of the hydrogen pathway with pure hydrogen emission. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

low-demand scenario could cause a severe economic impact on the aviation industry, caused by decreased demand for purchasing tickets and using services. Based on International Civil Aviation Organization (ICAO) [39] forecasts, in the committee on aviation environmental protection (CAEP) technology freezing scenario, the amount of direct carbon dioxide emissions due to fossil fuel burning in 2050 will be about 1550 Mt. This confirms our findings, where our results show that the amount of direct CO$_2$ emissions in high, medium, and low demand scenarios is 2006, 1802, 1313 Mt, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In Figs. 6-8, the pink solid lines represent the CO$_2$eq caused by burning the fuels (not including the life cycle) if hydrogen aircraft enter the worldwide fleet from 2035. The reduction of CO$_2$eq from 2035 can be witnessed in Figs. 6-8. The CO$_2$eq of the hydrogen pathway reduces by 28 % on average compared to the kerosene-only pathway, while the amount of kerosene use has decreased by 53 % on average. This distinction is due to hydrogen-related emissions (more water vapor) without considering pure hydrogen leakage into the atmosphere. The green solid line shows the amount of CO$_2$eq emissions in the hydrogen

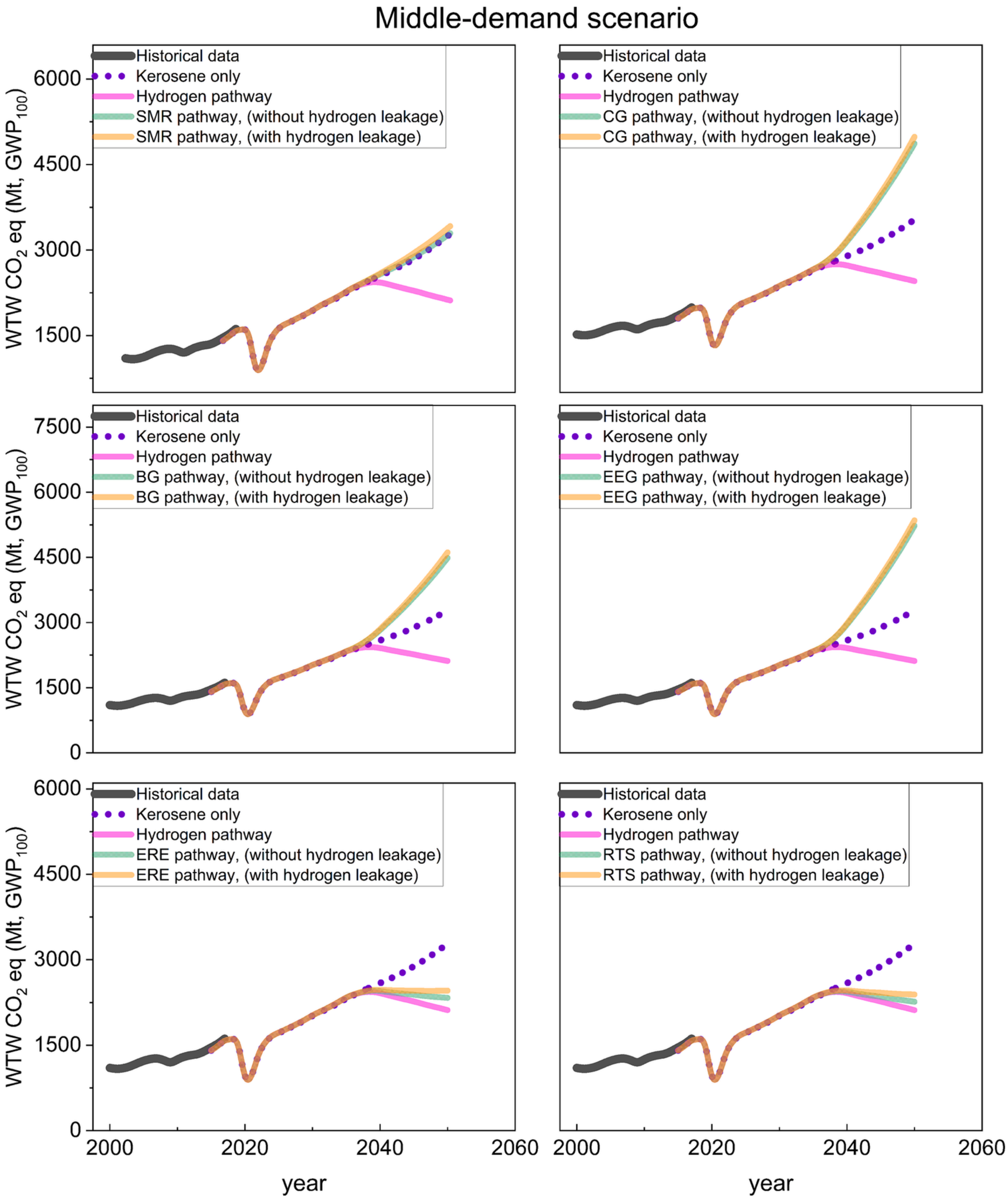


Fig. 7. Middle-demand scenario calculation of WTW CO_2eq of fossil kerosene and hydrogen pathways. The purple dotted line: the kerosene-only pathway, the pink solid line: hydrogen pathway regardless of the method of hydrogen production, the green solid line: WTW of the hydrogen pathway without pure hydrogen emission, and the orange solid line: WTW of the hydrogen pathway with pure hydrogen emission. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pathway using six different technologies without considering the pure hydrogen leakage into the atmosphere. Naturally, the difference between the green and pink lines is related to emissions caused by hydrogen production processes. The increase in WTW CO_2eq produced by the EEG pathway compared to fossil fuel in high, medium, and low demand scenarios is 55 %, 67 %, and 107 %, respectively. Gasification technology (coal and biomass feedstocks) follows the EEG pathway; in the high, medium, and low demand scenarios, the difference between them and the kerosene-only pathway is 38 %, 47 %, and 80 % (coal feedstock) and 31 %, 40 %, and 70 % (biomass feedstock). The ERE and RTS pathways are available, and the results show that their emissions are less than those of the kerosene-only pathway. Although the RTS pathway has the lowest emissions level, this method has limitations, including high cost, land and space requirements, and dependency on weather conditions, which make its widespread use a challenge. When the CO_2eq emissions are examined in the high, medium, and low demand scenarios of the RTS pathway, reductions of 32 %, 30 %, and 28 % respectively can be observed compared to the kerosene-only pathway. In

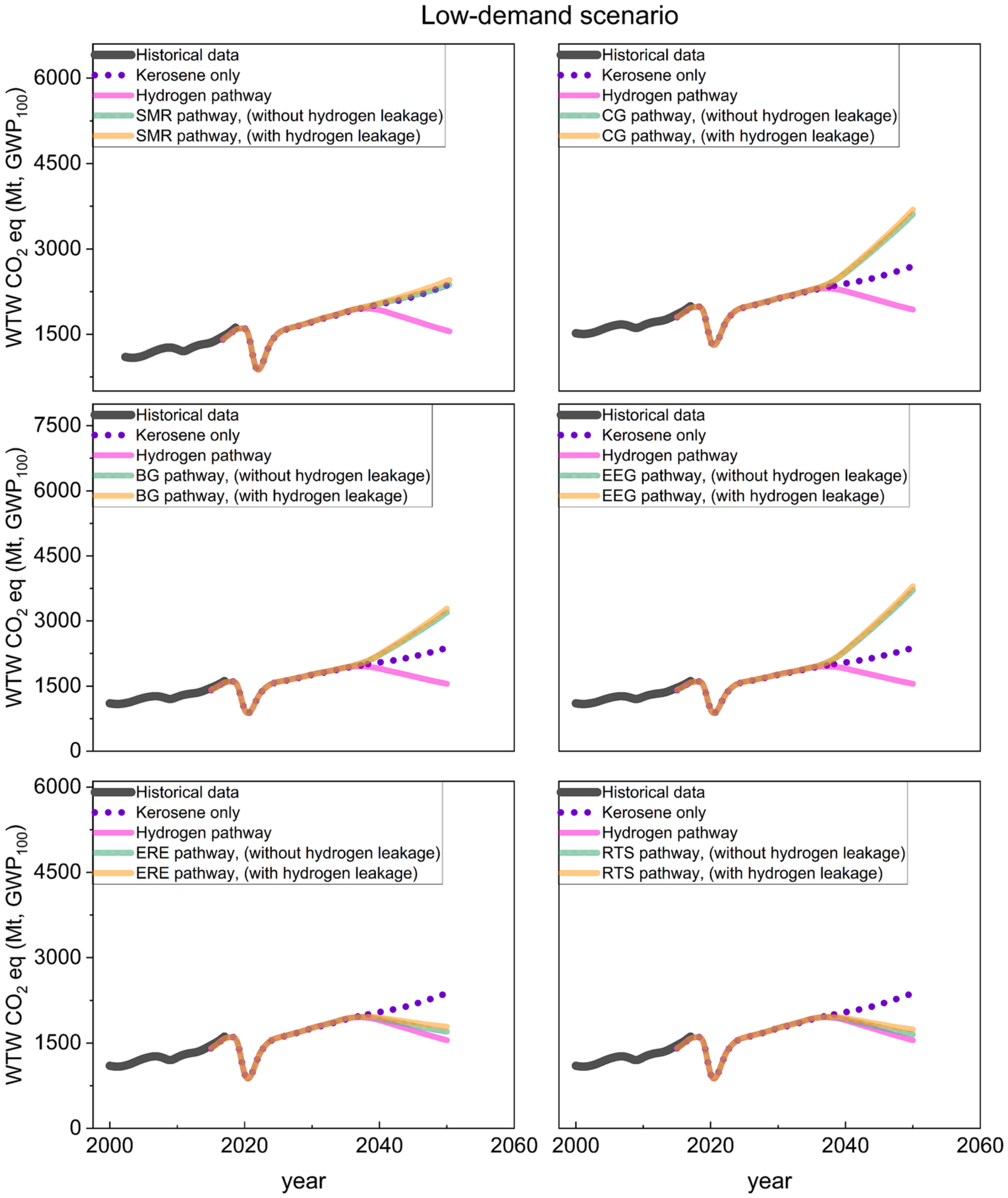


Fig. 8. Low-demand scenario calculation of WTW CO_2eq of fossil kerosene and hydrogen pathways. The purple dotted line: the kerosene-only pathway, the pink solid line: hydrogen pathway regardless of the method of hydrogen production, the green solid line: WTW of the hydrogen pathway without pure hydrogen emission, and the orange solid line: WTW of the hydrogen pathway with pure hydrogen emission. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the case of the ERE pathway, these reductions are found to be 30 %, 28 %, and 24 % respectively. Scrutinizing the pathways of EEG and ERE, while electrolysis is often regarded as an environmentally friendly hydrogen production technology, its sustainability is highly dependent on the electricity source used. Studies, such as the WTT analysis conducted by the Joint Research Centre (JRC) for the European Union, have shown that when grid electricity from non-renewable sources is used, the overall emissions from electrolysis-based pathways can exceed those of other hydrogen production methods[40].

The noteworthy point is that based on the limitations and assumptions of this study and considering the mean of the emission by different pathways, the hydrogen pathway where the SMR technology is employed does not have a particular advantage over using kerosene fuel. The CG, BG and EEG pathways are unbelievably worse than fossil fuels; however, using sustainable residual biomass for BG and adding more renewable energy to the EEG grid could decrease these technologies' worsening conditions. Among these three paths, EEG performs worst, mainly due to the required electricity generation through fossil fuel. To mitigate, the temperature can eventually rise by 75 mK[4] by the year 2050 (a 1.5 ℃ increase criterion). By comparing the results of this research with Dray et al. [19], it seems that based on the limitations and assumptions of this study, the existing scenarios cannot meet the temperature limit. Although the two routes, RTS and ERE pathways, can have multiple advantages, if there is an insistence on using hydrogen aircraft, it is necessary to allocate a more significant portion of the fleet to hydrogen aircraft, which should be assessed from an economic point of view.

For a clearer comparison, Fig. 9 presents the projected CO_2eq emissions (in Mt) across various hydrogen production pathways under high, medium, and low-demand scenarios for the years 2040, 2045, and 2050. This figure highlights the variations in emissions based on differing demand levels and provides a comprehensive view of the environmental impact of each hydrogen production pathway as demand evolves over time. The RTS pathway maintains a sustainable low-emission profile by relying on renewable energy sources and using water as a feedstock, emitting significantly fewer greenhouse gases than fossil fuel-based feedstocks. However, changes in demand across different scenarios can impact the emission rate of the RTS pathway. For example, an increase in demand from low to medium–high levels corresponds to emission rate increases of 37 % and 52 %, respectively. Despite these increases, the RTS pathway still retains a relatively low emission profile compared to other methods for the reasons mentioned earlier. There are limitations to consider. High initial capital costs, geographic constraints, and issues with the intermittency of renewable energy sources—such as variations in the weather for solar-powered RTS systems—can impede widespread adoption. Additionally, RTS technology faces scalability and energy efficiency challenges, with many systems still in the experimental phase and struggling with the energy demands of high-temperature thermal splitting. Despite these obstacles, the RTS pathway remains a promising option in the transition towards low-carbon hydrogen production.

4.4. Penalty of hydrogen pathway scenarios

Based on assumptions (presented in section 3.2), it is predicted that if the decision makers adopt the hydrogen pathway, a significant value of 12.2, 10.6, and 7.3 Mt unburned hydrogen will enter the atmosphere in high, medium, and low demand scenarios in 2050. The Fig. 10 offers a compelling insight into the environmental impacts of various hydrogen production pathways as potential replacements for conventional kerosene in aviation fuel. The analysis spans from 2036 to 2050, covering three demand scenarios: high, low, and mid. Across all scenarios, there is a general upward trend in the penalty factors for most production pathways over time. This indicates that as the timeline approaches 2050, the relative environmental impact of hydrogen production compared to kerosene increases. However, this trend is not uniform across all pathways. SMR starts with negative values in 2036 but steadily increases, becoming positive around 2041–2042. By 2050, it will reach moderate positive values, indicating an increasing penalty over time. Coal gasification and biomass gasification are the two pathways that show the most dramatic increases in penalty factors. Starting from negative values in 2036, they rapidly rise to become the highest penalty factors by 2050. CG consistently shows slightly higher penalties than BG. Electrolysis using Electricity from the Grid pathway exhibits the steepest increase in

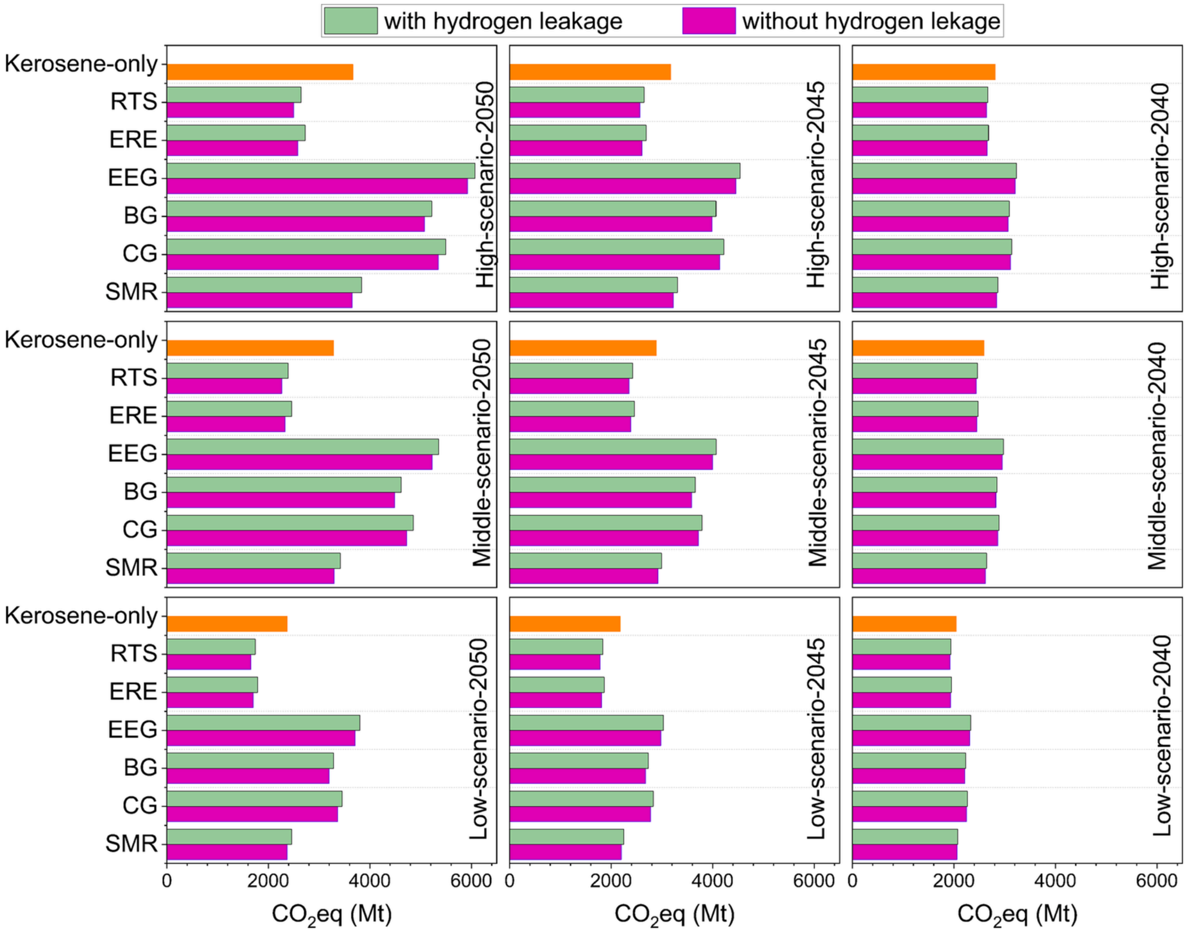
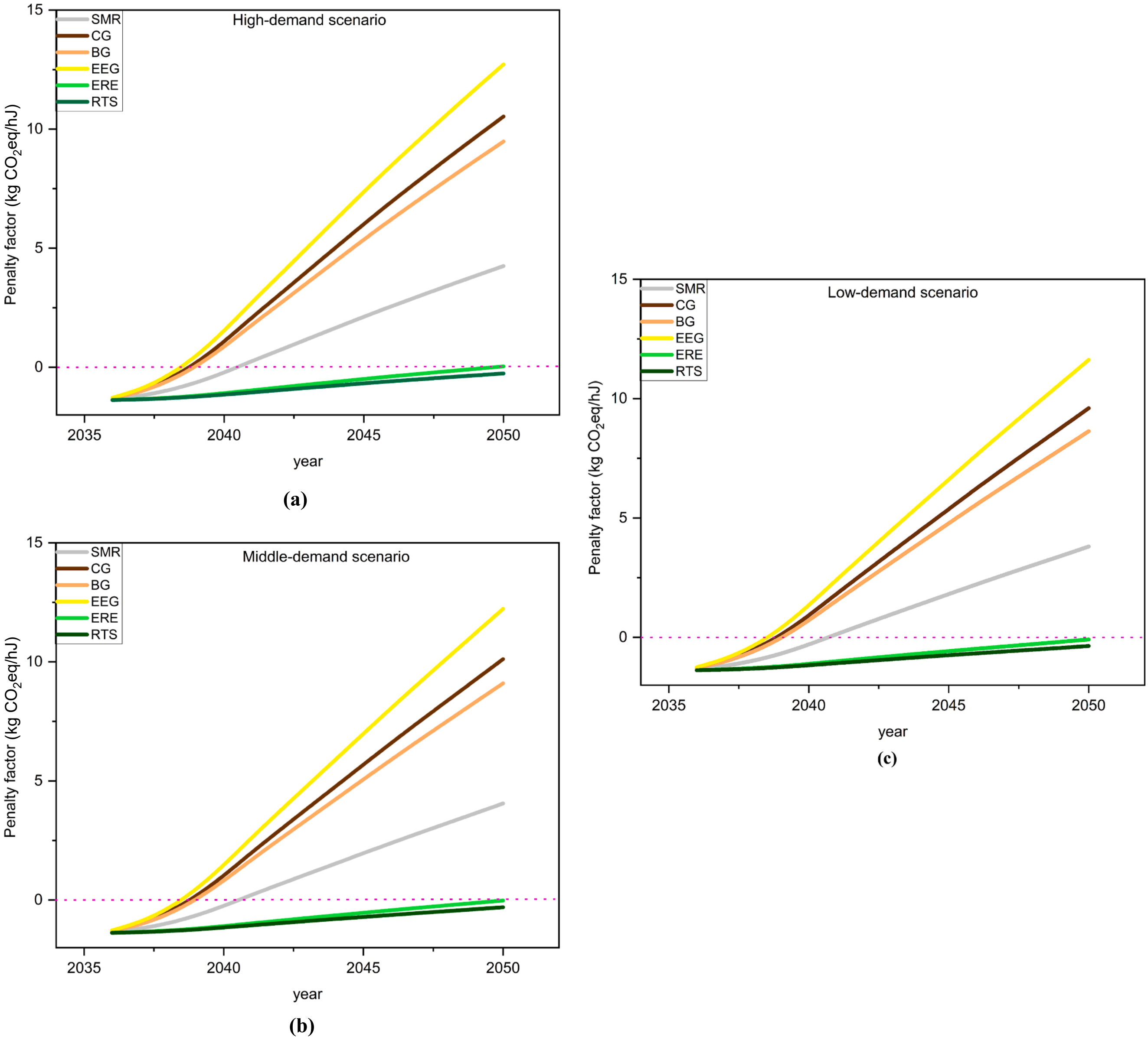


Fig. 9. Comparison of CO_2eq (Mt) emissions across different hydrogen production pathways for high, medium, and low-demand scenarios in the years 2040, 2045, and 2050.



(a)

(b)

(c)

Fig. 10. Penalty factor for different hydrogen production pathways **(a):** High-demand, **(b):** Middle-demand **(c):** Low-demand scenarios.

penalty factors. It starts negative in 2036 but rises sharply, surpassing all other methods by a significant margin in 2050. Electrolysis using renewable electricity (ERE) and renewable thermochemical splitting (RTS) are two pathways that stand out as the most environmentally friendly options. They maintain negative penalty factors throughout the period, indicating that they consistently perform better than kerosene in emissions. ERE gradually improves (becoming less damaging) over time, while RTS maintains a more stable negative value. The precise data regarding the penalty factor is provided in the supplementary file.

5. Discussion

This section consists of three subsections: “cost-environmental trade-offs,” “impact of policy shifts on penalty factor,” and “recommendations for policymakers and researchers,” each comprehensively explained herein.

5.1. Cost-environmental trade-offs

The comparison of hydrogen production pathways for aviation highlights important trade-offs between environmental impact and economic feasibility. SMR and BG offer relatively low costs but produce higher emissions. While these pathways may provide practical short-term solutions due to their affordability, their carbon footprint makes them less appealing for airlines aiming to meet strict emissions targets. CG also illustrates this trade-off, as it has moderate costs but generates considerable carbon emissions, reducing its viability in a sustainable aviation strategy. Conversely, pathways like ERE and RTS produce minimal emissions; however, these benefits come with significant costs, posing economic challenges for large-scale adoption. Although RTS is more affordable than ERE, it still requires substantial investment, though its low-emission profile makes it an attractive option for long-term sustainability. EEG, which has the highest emissions profile and is the most expensive option, remains the least viable choice until energy grids transition more fully to renewable sources. In summary, the trade-off between cost and emissions indicates that while lower-cost pathways may alleviate financial constraints, they lack the environmental benefits essential for achieving net-zero goals in aviation. In contrast, renewable-based pathways offer a sustainable, low-emission future but need cost reductions to become widely feasible.

5.2. Impact of policy shifts on penalty factor

The pronounced increase in penalty factors for pathways like EEG primarily results from the high CO_2 emissions associated with grid electricity, which often relies heavily on fossil fuels. As hydrogen demand scales up to meet aviation needs, EEG's reliance on carbon-intensive electricity sources amplifies its overall emissions impact. This factor causes EEG's penalty to escalate dramatically over time, especially if grid decarbonization lags behind hydrogen adoption. In contrast, pathways such as ERE and RTS maintain stable, negative penalty factors because they rely on renewable energy sources, which inherently produce minimal CO_2 emissions during hydrogen production. Since these renewable-based pathways are insulated from the carbon emissions tied to fossil fuels, they consistently outperform kerosene in terms of emissions, resulting in more stable, environmentally friendly profiles over time.

Considering potential policy shifts, the dynamics of penalty factors could change significantly. For example, carbon taxes on fossil fuel-based energy could make high-emission pathways like EEG, CG, and BG less economically viable by raising the cost of their emissions-intensive energy inputs. This shift would likely accelerate the transition toward cleaner pathways, reducing the environmental impact by making options like ERE and RTS comparatively more cost-effective. Similarly, renewable energy mandates could reduce EEG's penalty factor by encouraging a cleaner energy mix in the grid, thus lowering the CO_2 emissions associated with hydrogen production. As grids become less carbon-intensive, EEG would gradually align closer to ERE in terms of emissions, stabilizing its penalty factor over time. Direct subsidies and financial incentives for clean hydrogen production like RTS and ERE can lower their operational costs, making them more competitive with higher-emission pathways. This can lead to a reduction in their penalty factors by enhancing their economic viability. Enforcing stringent regulations on hydrogen leakage and associated emissions can compel producers to adopt technologies that minimize leaks, thereby reducing the overall CO_2eq emissions from pathways like EEG. This would mitigate the increase in penalty factors over time.

5.3. Recommendations for policymakers and researchers

The findings of this study highlight significant environmental effects across hydrogen production pathways for aviation, underscoring the need for strategic policy and research interventions to achieve sustainable outcomes. The following recommendations aim to guide the development of a viable hydrogen-based aviation sector that aligns with long-term climate goals.

- Enact carbon pricing for high-emission pathways (EEG, CG, BG): The study shows that EEG exhibits the steepest increase in penalty factors. Similarly, CG and BG demonstrate high penalty factors due to substantial emissions. Carbon pricing mechanisms such as carbon taxes or cap-and-trade systems could be implemented to deter reliance on these high-emission pathways.
- Promote renewable energy infrastructure: Investing in renewable energy infrastructure will support pathways with lower emissions, such as ERE and RTS. Policies that encourage grid decarbonization can significantly reduce the environmental impact of EEG, making it a more sustainable option as grid reliance shifts toward renewables.
- Incentivize hydrogen-specific research and development: Funding R&D for hydrogen production and storage technologies could lead to efficiency gains and cost reductions in clean hydrogen pathways.
- Establish emission and leakage regulations: Given the potential atmospheric impacts of hydrogen leakage, policymakers should implement strict standards for hydrogen emissions across production, storage, and transportation stages.
- Advance studies on hydrogen emissions impact: Further research is needed to understand the indirect effects of hydrogen emissions on atmospheric composition, particularly the implications of hydrogen oxidation on greenhouse gases like methane and ozone. Improved modeling can refine penalty factor calculations and support informed policymaking.
- Conduct sensitivity analyses on demand scenarios: Considering the study's projected hydrogen demand scenarios (high, medium, low), further analysis of how policy shifts and technology adoption rates influence demand can provide more adaptive pathways to meet climate goals. Sensitivity studies would clarify which scenarios are most feasible for achieving net-zero targets by 2050.

6. Concluding remarks

The aviation industry is responsible for emission more than 1500 Mt of CO_2eq; however, relying solely on kerosene combustion to satisfy the industry's escalating energy demands (anticipated to surpass 30 EJ by 2050) unquestionably falls short of meeting the objectives set forth by the IPCC. Consequently, hydrogen has emerged as a promising alternative among potential energy transition opportunities within the aviation sector. When solely considering emissions from fuel combustion, hydrogen presents itself as an appealing option for emission reduction. Nonetheless, it is crucial to acknowledge that the various pathways involved in hydrogen production emit diverse forms of GHGs. Therefore, undertaking a comprehensive comparison of emissions throughout the life cycle of hydrogen and kerosene provides valuable insights into hydrogen's pivotal role in facilitating the aviation industry's energy transition. Conversely, it is essential to recognize that a substantial quantity of pure hydrogen is released into the atmosphere, both during transmission and storage, as well as in its unburned state. This emission of pure hydrogen carries significant consequences for the troposphere and stratosphere, signifying that choosing the hydrogen pathway in the aviation sector incurs penalties in the form of these emissions. The present study critically examines the emissions associated with six distinct hydrogen production pathways, diligently appraising the contribution of GHG emissions based on an amalgamation of diverse studies. In conclusion, based on the investigation conducted, several vital facts can be inferred:

- On average, the TTW CO_2eq emissions within the hydrogen pathway exhibit a notable reduction of 28 % compared to the kerosene-only pathway, while kerosene usage experiences an average decrease of 53 %.
- Based on the assumption of this study, the SMR pathway fails to provide a significant advantage over traditional kerosene fuel usage. The CG, BG, and EEG pathways emit more WTW CO_2eq than the kerosene-only pathway. Among these, if EEG relies heavily on fossil fuels, it results in the highest emissions.
- The ERE and RTS pathways demonstrate lower emissions than the kerosene-only pathway. In both the RTS and ERE pathways, CO_2eq emissions experience a reduction ranging from 28 % to 32 % across high, medium, and low demand scenarios.
- Based on the underlying assumptions, it is predicted that 12.2 Mt, 10.6 Mt, and 7.3 Mt of unburned hydrogen will permeate the atmosphere in 2050 across the high, medium, and low demand scenarios, respectively.
- ERE shows a penalty factor improving from −1.37 to −0.02 kg CO2eq/hJ (mid-demand scenario). RTS maintains a stable negative penalty, ending at −0.30 kg CO2eq/hJ in 2050. EEG's penalty factor will increase dramatically from −1.27 to 12.23 kg CO2eq/hJ by 2050 (mid-demand scenario).

CRediT authorship contribution statement

Saeed Rostami: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Khodayar Javadi:** Supervision, Project administration, Investigation, Conceptualization. **Abbas Maleki:** Supervision, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2024.119369.

Data availability

Data will be made available on request.

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