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NLR-TP-2026-217 | October 2026

Promising First Deployments of Hydrogen-powered Aircraft Operations in the European Commercial Flight Network

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Royal NLR - Netherlands Aerospace Centre

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Problem area

The aviation sector contributes to approximately 2.5% of global CO₂ emissions and is considered a 'hard-to-abate' sector, one where emissions are particularly difficult to reduce. Hydrogen-powered aircraft are seen as a promising path towards climate neutrality. However, a 'chicken-or-egg problem' persists: airlines are hesitant to invest in hydrogen aircraft without guaranteed refuelling infrastructure, while airports are reluctant to invest in that infrastructure without confirmed demand. A gap in existing literature is the absence of a systematic methodology to identify which origin-destination (OD) airport pairs in Europe are best suited for early adoption of hydrogen aircraft.

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Description of work

A multi-criteria scoring methodology was developed to evaluate and rank European origin-destination airport pairs for hydrogen aircraft operations, focusing on the 2035 and 2040 deployment timeframe scenarios. Using publicly available data all European airport pairs were first filtered using exclusion criteria based on aircraft range, runway requirements and minimum flight frequency. The remaining pairs were scored across ten criteria related to the compatibility with the hydrogen TRANSCEND aircraft range and seat capacities, proximity to hydrogen infrastructure, potential number of hydrogen flights, effect on passenger volume, available airport area, production costs of hydrogen, availability of renewable electricity, and commitment of airlines and airports to hydrogen operations. Last, the criteria were weighted through a hybrid weighting approach combining CRITIC and Rank Sum weighting methods.

Results and conclusions

For the 2035 scenario, Stockholm Arlanda – Charles de Gaulle were identified as top-ranked airport pair. In the 2040 scenario, Tallinn Airport – Riga International Airport emerged as best-suited pair. Furthermore, routes involving Amsterdam Schiphol Airport were prominently featuring in the top 10 of both timeframes. The study concludes that no single factor determines suitability, rather it is a complex interaction of factors. The methodology is sensitive to assumptions and weights, as final scores among top-ranked pairs are closely spaced.

Recommendations

Future research should extend the methodology by incorporating network effects, including adjustments to flight routes and passenger demand in response to hydrogen aircraft introduction. Additionally, the inclusion of a wider range of hydrogen aircraft types, including announced OEM designs, as well as a detailed matching of airport-level hydrogen demand with available hydrogen supply are recommended.

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Summary

Airlines require assurance of adequate infrastructure at airports before investing in hydrogen aircraft, while airports require confirmation of long-term airline commitments before investing in hydrogen infrastructure as both airlines and airports operate with small profit margins, creating a "chicken-or-egg problem". This challenge extends beyond airlines and airports alone, encompassing, amongst others, OEMs, hydrogen fuel suppliers, land-side supply chains, land-use planners and regulatory bodies. To address part of this stalemate, this study presents a methodology to identify promising origin-destination airport pairs for early deployment of hydrogen-powered aircraft operations in the European commercial flight network. The airport pair suitability is quantified using compatibility with the hydrogen TRANSCEND aircraft range and seat capacities, proximity to hydrogen infrastructure, potential number of hydrogen flights, effect on passenger volume, available airport area, production costs of hydrogen, availability of renewable electricity, and commitment of airlines and airports to hydrogen operations. The outcome of this study is a concise ranking of European origin-destination pairs, with comprehensive scorecards detailing their suitability for hydrogen operations across various criteria. The study identified ESSA-LFPG (Stockholm Arlanda Airport – Charles de Gaulle Airport) as the top-ranked origin-destination pair for hydrogen aircraft operations in the 2035 scenario using the TRANSCEND aircraft, while EETN-EVRA (Tallinn Airport – Riga International Airport) emerged as the best pair in the 2040 scenario, with routes from and to EHAM (Amsterdam Schiphol Airport) also featuring prominently in the top 10. The analysis is based on the 2023 flight network without adapting routes or demand to reflect the introduction of hydrogen aircraft. The methodology prioritises compatibility between airport pair flights and TRANSCEND aircraft characteristics and impacts on airline passenger-revenue-kilometre values when transitioning to hydrogen flights. The study demonstrated that the suitability of airport pairs depends on complex interaction of the identified factors, highlighting that there is no one-size-fits-all solution. This research is intended as a foundation for future evaluation that can inform relevant potential investments, ultimately contributing to addressing the chicken-or-egg problem in hydrogen aircraft adoption.

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1 Introduction

The aviation sector is a substantial contributor to global greenhouse gas emissions, accounting for 2.5% of global CO₂ emissions in 2023 [1]. The sector is considered hard-to-abate in Europe's path to climate neutrality, requiring technological innovations, infrastructure investments, changes in consumer behaviour and operational practices. The European Union has set ambitious targets to achieve climate neutrality by 2050 outlined in the European Green Deal [2] and Destination 2050 roadmap [3] with hydrogen propulsion seen as a promising solution. Hydrogen-powered aircraft offer the possibility of zero in-flight CO₂ emissions and possible reductions in non-CO₂ effects.

Significant traction is gained through investments by major players such as Airbus and large European projects like TRANSCEND [4]. However, the operational deployment of hydrogen aircraft remains efforts have been made by for example the European Hydrogen Backbone [5], an industry-led initiative to map a hydrogen transport network, and research projects such as GOLIAT [6], TULIPS [7], STARGATE [8] and OLGA [9], helping to pave the way for future implementation of hydrogen infrastructure at airports. While these efforts have helped to advance the development of hydrogen aircraft and infrastructure, a chicken-and-egg problem still persists, where OEMs and airlines are hesitant to invest in hydrogen-powered aircraft without access to refuelling limited by key constraints, including the need for supportive infrastructure such as refuelling facilities at airports. Several infrastructure, and airports are reluctant to invest in infrastructure without guaranteed demand from airlines.

To address this challenge, it is crucial to consider both aircraft and airline operations as well as infrastructure developments together. Previous studies have examined hydrogen aircraft operations and airport considerations, but gaps remain in identifying promising origin-destination (OD) airport pairs for initial deployment. The study of Rau et al. [10] incorporate future H₂ aircraft by examining changes in the flight network. The study however relies on pre-defined hydrogen hubs as outlined by the researchers from DLR in the European Commission report [11]. This study provided rollout scenarios for hydrogen aircraft from an airport perspective by identifying top airports for hydrogen aircraft operations. While several relevant criteria were identified, the method identifies promising airports rather than airport pairs based on the assumption of hydrogen tankering, where an aircraft carries extra hydrogen fuel to cover return due to potential lack of refuelling infrastructure at airports. The current researchers do not consider hydrogen tankering viable for longer-term strategies. Tankering would limit the range of flights that can be operated due to the volumetric inefficiency of hydrogen fuel. Additionally, tankering poses additional safety concerns related to cryogenic boil-off. While the document provides a useful framework for evaluating airport suitability for hydrogen operations, its scoring method is considered somewhat ambiguous due to unclear definitions of some key scoring criteria. The study by Lawrence-Griffiths et al. [12] identified airports in the US using a mathematical k-means clustering scoring approach. Although this method indirectly considers airport pairs by examining connectivity to other suitable airports, it has limitations due to its narrow focus on only two scoring criteria: proximity to green hydrogen hubs and connectivity to other airports within those hubs.

The current work aims to determine key drivers and barriers towards deployment of hydrogen aircraft in transport networks by addressing the following research question:

'Which origin-destination (OD) airport pairs have the highest potential to become early adopters of hydrogen aircraft operations in the timeframe of 2035?'

Additionally, this study will explore two sub-questions: What criteria are essential for evaluating and comparing the suitability of OD airport pairs for hydrogen operations, and, how does the potential of these OD airport pairs evolve in 2040?

Geographically, the project is focussed on airports in the EU+ countries, with the focus on the initial deployment period between 2035 and 2040. The study aims to inform potential early investment decisions by identifying suitable OD airport pairs within the existing flight network, and does not extend to modelling broader network effects, airline competition, or detailed hydrogen demand and supply balances, which are left for further research.

2 Methodology

A systematic approach was employed to evaluate the suitability of OD airport pairs for hydrogen operations. The process involves gathering publicly available and licensed data on flights, airports, aircraft and future hydrogen infrastructure projects. This enables the evaluation of all airports within the scope, without relying on airport specific data that would require individual collaboration with each airport. The OD airport pairs are then filtered by applying exclusion criteria to remove those that do not meet initial requirements. After this, scoring criteria are defined and applied to evaluate the suitability of each remaining OD airport pair for hydrogen aircraft operations. Eventually, a final score for each OD airport pair is calculated by weighting the individual scoring criteria.

2.1 Data gathering

To identify promising OD airport pairs for hydrogen operations, a comprehensive dataset is compiled from various sources. The foundation of the dataset is the scheduled flight data from the year 2023 obtained from OAG [13] which provides information on currently flown routes in the worldwide flight network. The data is supplemented with current aircraft information from CIRIUM aviation analytics [14] and airport characteristics from OurAirports [15]. This provides detailed insights into the type of aircraft operating between an origin and destination, their frequency of operation, the distance between the airports and general information about the airports themselves, such as runway lengths. The analysis uses an existing flight network, and therefore assesses how hydrogen aircraft would fit within current operations. Potential effects of hydrogen aircraft introduction on flight demand, route restructuring and airline competition are not considered in this study.

In addition to flight and airport data, information on hydrogen aircraft concepts is obtained from the Clean Sky 2 JU TRANSCEND project [4], where NLR conducted conceptual sizing studies. The TRANSCEND project identified three aircraft types with varying entry-in-service (EIS) dates as seen Table 1.

Table 1. TRANSCEND aircraft types [4]

Aircraft type	Reference aircraft	Propulsion type	EIS	Design Range	Pax	Runway ¹
Regional turboprop	ATR 42-600	Hydrogen fuel cell	2035	~869 nm (1000km)	50	1107 m
Short medium range (SMR) single aisle (SA) turbofan	A321-Neo	Parallel hybrid: hydrogen fuel cell and hydrogen combustion	2035	2000 nm	176	2000 m
Short medium range (SMR) twin-aisle (TA) turbofan	B787-8	Hydrogen combustion	2040	2000 nm	300	2820 m

The TRANSCEND concept aircraft are used to represent expected future hydrogen aircraft characteristics. Although announced aircraft by original equipment manufacturers (OEM) could also be considered, the necessary performance information on payload-range and payload-runway trade-offs is often not (yet) publicly available. Furthermore, these aircraft are expected to have similar performance characteristics of the same order of magnitude.

¹ Runway performance assumed to be similar to reference aircraft

The hydrogen infrastructure map [16] is used to assess available hydrogen infrastructure in Europe, providing an overview of projects, transport routes, and corridors. This map is the result of a collaborative effort between ENTSG, GIE, EUROGAS, CEDEC, GD4S, GOEDE, and the European Hydrogen Backbone initiative and offers detailed information on pipelines, distribution, production and storage sites.

Together, these data sources are used to provide an indication of aircraft capabilities and hydrogen infrastructure availability near airports, however, no matching between airport-level hydrogen demand and available hydrogen supply is performed, as both detailed aircraft performance modelling and hydrogen allocation between aviation and competing industries falls outside the scope of this study.

2.2 Exclusion

The identification of promising OD airport pairs begins with applying exclusion criteria to remove unsuitable pairs that do not meet the minimum performance requirements. The exclusion criteria are based on performance specifications, as shown in Table 1, that affect the viability of hydrogen aircraft operations and ensure that only viable OD airport pairs are considered for further evaluation. The criteria are:

Hydrogen aircraft range: OD airport pairs are excluded if the distance between the airports exceeds the range of all considered hydrogen aircraft types. Aircraft range is determined for the required payload, or for maximum payload if the required payload exceeds the aircraft's capacity.

Hydrogen aircraft runway distance: OD airport pairs are excluded if the required runway length of the hydrogen aircraft exceeds the available runway lengths at either airport, evaluated using the same payload logic as for aircraft range.

Number of absolute hydrogen flights: OD airport pairs are excluded if the number of hydrogen flights that can be replaced by hydrogen aircraft falls below a minimum threshold. This indicates that the potential for H2 infrastructure at the airport is deemed too low, rendering it infeasible. The threshold is set at a minimum of 1 flight per week.

2.3 Scoring

After applying the exclusion criteria, the remaining OD airport pairs are evaluated using scoring criteria to assess their suitability for hydrogen aircraft operations, considering various factors that impact their feasibility and deployment potential.

The scoring criteria can be categorized into different levels:

- **Flight-level:** directly score the OD airport pair based on the flights between the pair.
- **Airport-level:** the origin and destination airports are scored separately and afterwards combined into one OD airport pair score.
- **Country-level:** the countries in which the origin and destination airports are located are scored separately and combined into one OD airport pair score.

The different levels for scoring are presented in Figure 1.

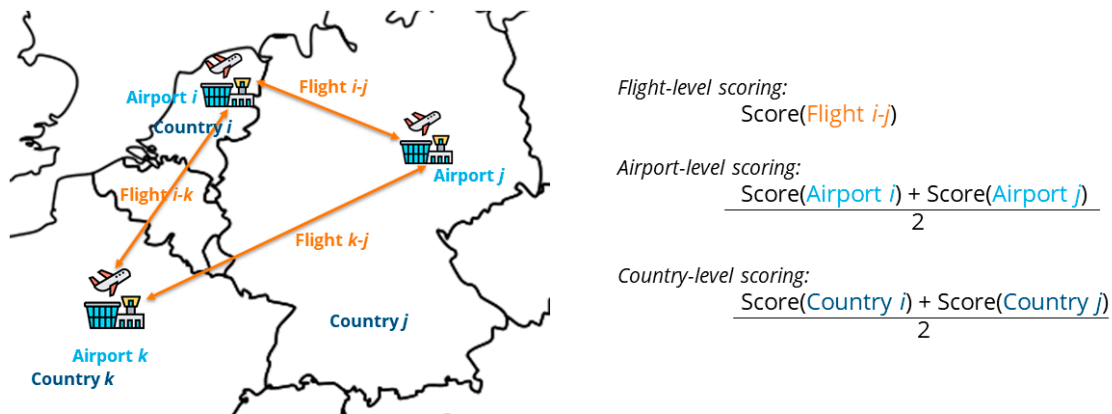


Figure 1. Scoring criteria levels

2.3.1 Flight-level criteria

Absolute number of hydrogen flights (*H2 Flights*): This criterion investigates the absolute number of flights between the OD airport pair that can be replaced by hydrogen-powered aircraft, based on distance and runway requirements. The criterion is an indicator of the potential scale of implementing hydrogen flights between the OD airport pair.

Compatibility between flight and hydrogen aircraft (*Flight Compatibility*): This criterion investigates the compatibility between the operational requirements of flights between the OD airport pair and the capabilities of the hydrogen aircraft, based on the ratio of flight distance to aircraft range at given payload and the ratio of the expected amount of flown passengers to the hydrogen aircraft's maximum seat capacity. The two factors are combined into a single metric using a weighted average (10:1 seats vs range), as airlines tend to be more reluctant to use an aircraft with excess capacity than one with excess range. This criterion identifies OD airport pairs for which a relatively straightforward transition to hydrogen flights is possible.

Airline commitment to hydrogen operations (*Airline Commitment*): This criterion investigates an airline's commitment to hydrogen aircraft operations. A list of committed airlines was compiled from [17]. The extent of these commitments vary, ranging from signing memorandums of understanding with OEMs for specific projects, to making direct investments in these companies or even placing pre-purchase orders of hydrogen (or battery-powered) aircraft. For each airline group or parent company listed, it is assumed that the underlying airlines with their own IATA/ICAO code are committed to hydrogen operations, without further subdivision into small subsidiary airlines. The percentage of flights operated by committed airlines with respect to the total amount of flights between the OD airport pair is used to score the OD airport pair. This percentage provides an indication of the likelihood that the flight will be operated by hydrogen as the airline itself publicly expressed interest in hydrogen operations.

Missing revenue-passenger-kilometres and slot-constrained airports (*Missed RPK and slots*): This criterion investigates the impact of replacing a kerosene flight with a hydrogen flight on the revenue-passenger-kilometre (RPK) value. For the replacement of a flight with a hydrogen aircraft, only range and runway requirements were limiting, while the seat capacity was not, as it is possible to replace a single kerosene flight by multiple hydrogen flights to meet the same passenger capacity. This criterion assesses the missed RPK value due to potential seat capacity limitations of hydrogen aircraft. Additionally, this criterion considers the effect of slot-constrained airports, where adding additional flights is not possible, resulting in lower scores for affected OD airport pairs. The score is based on the total missed RPK value,

with lower values indicating better suitability for hydrogen operations as this indicates limited potential revenue implications of transitioning to hydrogen operations.

2.3.2 Airport-level criteria

Percentage of hydrogen flights departing from the airport (% H2 Departures): This criterion investigates the proportion of flights departing from an airport that can be replaced by hydrogen-powered aircraft, based on distance and runway requirements. The criterion reflects the potential scale of hydrogen powered flights as a proportion of the total airport departing flights, indicating the relevance of hydrogen operations for the airport.

Distance from airport to hydrogen infrastructure (H2 Infra Distance): This criterion investigates the proximity of airports to existing or planned hydrogen infrastructure facilities, including production, storage, distribution and transmission sites, as identified in the hydrogen infrastructure map [16]. The distance to the nearest facility is considered, taking into account the projected use of pipelines for medium and large airports from 2040 onwards, while trucks will be used for smaller airports or prior to 2040. In this study, no distinction has been made between liquid and gaseous hydrogen, both are seen as available hydrogen. This distance serves as an indicator of the ease, cost, and safety of transporting hydrogen to the airport, as longer distances can increase logistical complexity, expenses, and risks associated with hydrogen transportation.

Available surface area for hydrogen operations at the airport (H2 Infra Area): This criterion investigates the availability of space for hydrogen infrastructure at airports by calculating the area footprint of each airport using OpenStreetMap (OSM) data, and then evaluating the ratio of total yearly departing passengers with respect to this airport area. The ratio reflects the density of passenger traffic per unit area, with lower values suggesting that there may be more space available at the airport for accommodating hydrogen infrastructure, while higher values indicate that a larger proportion of the airport's current area is already utilized to handle existing passenger traffic. The assessment only considers existing areas and does not account for potential expansion.

Airport commitment to hydrogen operations (Airport Commitment): This criterion investigates an airport's commitment to hydrogen operations by compiling a list of airports through a multi-step process. Initially, a list of airports was gathered from Accredited Airports [18], which identifies airport striving to reduce their carbon emissions. However, the list does not specifically focus on hydrogen operations and was therefore supplemented with information from [17] which gives a list of airports or airport groups that have publicly announced their commitment to deploying hydrogen infrastructure. Additional desk research was then conducted to expand the list, adding airports such as Budapest Airport (part of the GOLIAT project), Stuttgart Airport (involved in GOLIAT and H2FLY research [19]), Eindhoven Airport (through Royal Schiphol Airport's participation in GOLIAT), and Riga International Airport (part of the Baltic Sea Region hydrogen BSR HyAirport program [20]). The resulting list was further verified against Airbus's Hydrogen Hubs program. A binary scoring is applied, where each airport receives a score based on its inclusion in the list. The criterion provides an indication of an airport's willingness to invest in and support hydrogen operations.

2.3.3 Country-level criteria

H2 production cost in airport country (*Production Cost*): This criterion investigates the hydrogen production cost in the country where the airport is located, using data from Agora Industry [21]. This digital tool provides a high-resolution overview of the levelized cost of renewable hydrogen in Europe, considering optimal shares of wind onshore and photovoltaic energy. Minimum and maximum cost data is available per country for the years 2023 and 2030, for low-cost and high-cost storage scenarios. For this criterion, the average hydrogen production cost in low-cost scenario in year 2030 is used to score the airport. It is assumed that this value of 2030 is representative for scoring the airports in 2035 and 2040 timeframes as well, due to lack of historical data on cost trends. The criterion aims to identify OD airport pairs that are likely to benefit from more competitive hydrogen production costs, making them more attractive for hydrogen powered flights.

Available renewable electricity per country departing passengers (*Renewable Electricity*): This criterion investigates the availability of renewable electricity per departing passenger for each country, using data from EMBRER [22] which provides renewable electricity generation trends between 1990 and 2024. The renewable electricity generation per country is extrapolated to the 2035 and 2040 timeframes using the mean percentage change between 2020 and 2024. This value is divided by the total amount of yearly departing passengers in order to identify OD airport pairs that are likely to benefit from an abundance of renewable electricity, making them more attractive for green hydrogen production and subsequent hydrogen-powered flights.

2.3.4 Scoring method

For the flight-level criteria, each flight between an OD airport pair, performed with a certain aircraft type and by a certain airline, is evaluated per scoring criterion and is then combined into a single value scaled by yearly flight frequencies. For the airport-level and country-level criteria, the value per origin and destination airports/countries are combined into a single OD airport pair value using the average. Table 2 gives example data of multiple flights within a single OD airport pair, with the combined value per scoring criterion being calculated in Table 3.

Table 2: Example criteria values of one OD airport pair containing multiple flights

OD airport pair	Aircraft	# Flights	Country Origin	Country Destination	H2 Cost Origin	H2 Cost Destination	Infra Distance Origin	Infra distance Destination	Hydrogen capable?
A-B	B787	10000	DE	GB	6.0 €/kgH ₂	5.0 €/kgH ₂	30 km	50 km	Yes (1)
A-B	B777	2000	DE	GB	6.0 €/kgH ₂	5.0 €/kgH ₂	30 km	50 km	Yes (1)
A-B	A320	5000	DE	GB	6.0 €/kgH ₂	5.0 €/kgH ₂	30 km	50 km	No (0)

Table 3: Example combination of multiple flights, airports and countries into single values per OD airport pair

OD airport pair	H2 Flights	Production Cost	H2 Infra Distance
A-B	$(10000 \times 1 + 2000 \times 1 + 5000 \times 0) = 12000 \text{ Flights}$	$(6.0 + 5.0)/2 = 5.5 \text{ €/kgH}_2$	$(30+50)/2 = 40 \text{ km}$

To enable a comprehensive evaluation of the OD airport pairs, a uniform scoring method is necessary to consolidate the individual criteria values. Each criterion is transformed into a score between 0 and 1, where 1 represents the most favourable outcome and 0 the least. Additionally, the method needs to account for differences in scale and spread between the criteria, allowing for relative comparison across options. To achieve this, a variant of a robust z-score transformation is applied to each criterion to normalise the data relative to the median and interquartile range (IQR) [23]. The normal robust z-scoring method makes use of the Median Absolute Deviation (MAD), however this assumes more normally distributed than the distributions used in this research. For this reason, the IQR is used. This approach reduces the influence of extreme outliers, which would otherwise skew the scaling. Because the robust z-score can still range from negative to positive infinity and the values are not bounded, a sigmoid function was applied to map the values into standardised [0,1] range. This transformation compresses extreme values, and emphasizes differences near the median. After applying the sigmoid, the values were scaled so that the best-performing OD airport pair for each criterion received a score of 1, and the worst a score of 0.

2.4 Weighting

To determine a final score for each OD airport pair, weighting of the scoring criteria was required to reflect their relative importance. Weighting methods can generally be categorised as either objective, based on statistical properties of the data, or subjective, relying on expert judgement. For this research, a hybrid weighting approach was adopted, combining both perspectives.

The objective weighting was calculated using the Criteria Importance Through Intercriteria Correlation (CRITIC) method [24], which weighs the criteria based on spread (standard deviation) and correlation. Criteria with high variability and low correlation with others are considered more informative and therefore receive higher weights. A criteria correlation matrix is made to visualize Pearson-correlation coefficients between two criteria in Figure 7 of Appendix A.1, showing that none of the criteria exhibit excessively high correlations.

The subjective weighting was derived using the Rank Sum (RS) method [25]. In this approach, expert judgement is used to rank the criteria based on their perceived importance, after which the RS method converts these rankings into quantitative weights.

Finally, the RS and CRITIC weights are combined through averaging. An overview of the criteria ranks for the RS method, the RS weights, CRITIC weights and final averaged weights is given in Table 4.

Table 4. Overview of criteria ranks and weights

Criteria	RS Rank	RS Rank Rationale	RS Weight	CRITIC Weight	Average Weight
<i>H2 Flights</i>	3	Highly ranked, indicates potential return on investment, an important aspect for considering hydrogen operations between the OD airport pair, however is influenced by airport traffic volume	0.145	0.109	0.127
<i>Flight Compatibility</i>	1	Ranked highest, provides a direct measure of whether a hydrogen aircraft can be operated between the OD airport pair.	0.182	0.097	0.140
<i>Airline Commitment</i>	9	Lower ranked, due to data limitations and airline list subject to change.	0.036	0.147	0.092

Criteria	RS Rank	RS Rank Rationale	RS Weight	CRITIC Weight	Average Weight
<i>Missed RPK and slots</i>	6	Medium ranked, indicates level of needed flight adaptations for the airport to include H2 flights, but quite binary.	0.091	0.177	0.134
<i>% H2 Departures</i>	4	Highly ranked, similar to criteria of absolute hydrogen flights, but counters the dependency on airport traffic volume by looking at relative values.	0.127	0.068	0.098
<i>H2 Infra Distance</i>	2	Highly ranked, crucial for determining the feasibility and ease of performing hydrogen operations at the airports.	0.164	0.084	0.124
<i>H2 Infra Area</i>	5	Medium ranked, indicates ease of performing operations due to space constraints, but not invincible.	0.109	0.073	0.091
<i>Airport Commitment</i>	10	Lowest ranked, due to data limitations, airport list subject to change and solely binary evaluation.	0.018	0.095	0.057
<i>Production Cost</i>	7	Lower ranked, country-level consideration therefore less specific for route feasibility .	0.073	0.071	0.072
<i>Renewable Electricity</i>	8	Lower ranked, country-level consideration, impact on feasibility of hydrogen flights may be more nuanced.	0.055	0.080	0.067

The final averaged weights are applied to the criteria and result in a ranked list of identified OD airport pairs suitable for hydrogen aircraft operations.

3 Results and Discussion

In order to have the resulting list of most promising OD airport pairs for first deployment of hydrogen aircraft operations, the described method is followed. First the OD airport pairs were scored for each of the defined criteria, after which the weights were applied. Figure 2 shows some information on the criteria scores by plotting the score distributions per criterion in a histogram, with on the x-axis the score between 0 and 1 and on the y-axis the count of OD airport pairs. Underneath the distributions, the criteria weights are depicted which are used to come up with the final weighted score.

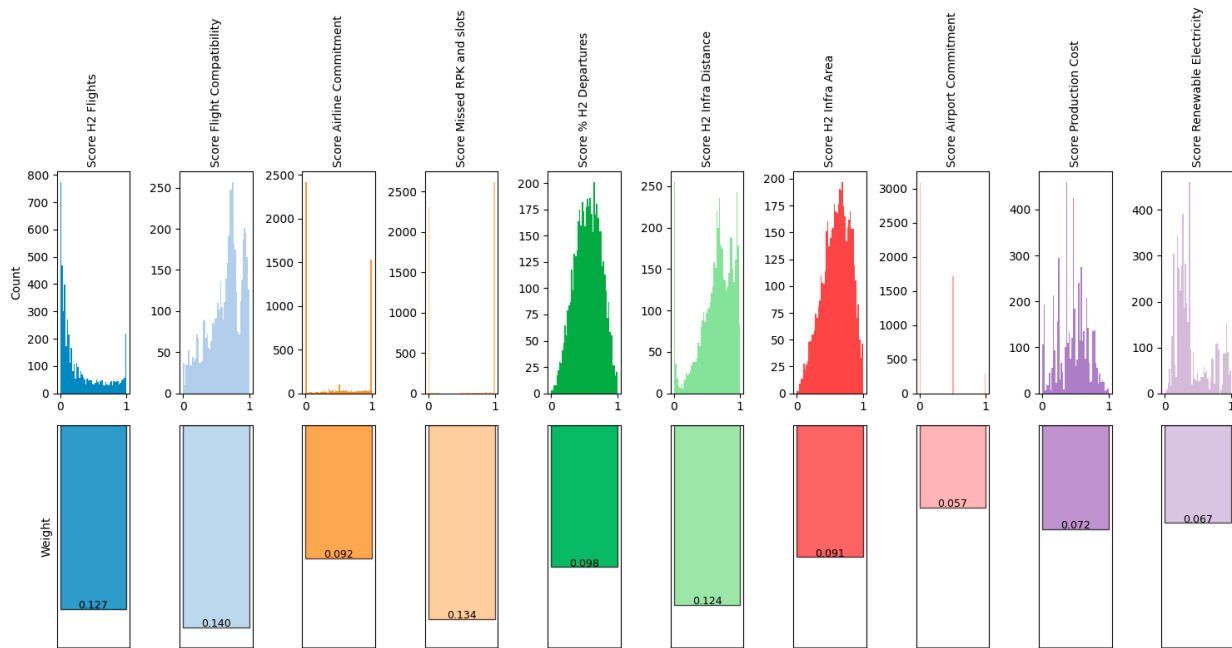


Figure 2. Scoring criteria scoring distributions and weights

The figure illustrates the binary nature of the *Airport Commitment* scores. A similar pattern appears for the criterion *Missed RPK and slots*: airports with no missed RPK score 1, while airports with missed RPK and slot constraints score 0. Only a small number of OD airport pairs have missed RPK but are not slot-constrained. A comparable score distribution is observed for the *Airline Commitment* criterion. Most OD airport pairs have either 0% or 100% of flights operated by committed airlines, with only a few pairs falling in between.

The weighting results indicate that the *Flight Compatibility* criterion receives the highest weight, consistent with the RS ranking. However, the *Missed RPK and slots* criterion also receives a relatively high weight, despite being ranked only sixth in importance (out of 10 criteria) in the RS evaluation. This higher weight arises from the CRITIC method, which assigns more importance to criteria with high data spread and low correlation to other criteria, which is in this case driven by the large standard deviation produced by the binary spread. The CRITIC method's reliance on standard deviation therefore may be a limitation when applied to binary scores, as the high standard deviation may not accurately reflect the underlying variability of the criterion.

Table 5 lists the resulting top 10 OD airport pairs which show the highest potential to become early adopters of hydrogen aircraft operations in the timeframe of 2035. The table presents the scores of each individual OD airport pair with respect to the scoring criteria, as well as the weights of the criteria and the total weighted score. The top 10 airport pairs are visualized on a map in Figure 3.

Table 5. Top 10 OD airport pairs for 2035, with scoring criteria, weights and total weighted score

Rank	OD airport pair	H2 Flights	Flight Compatibility	Airline Commitment	Missed RPK and slots	% H2 Departures	H2 Infra Distance	H2 Infra Area	Airport Commitment	Production cost	Renewable electricity	Weighted score
	Weight	0.127	0.140	0.092	0.134	0.098	0.124	0.091	0.057	0.072	0.067	
1	ESSA-LFPG	0.927	0.573	1.000	1.000	0.490	0.765	0.666	1.0	0.683	0.739	0.782
2	EHAM-EKYT	0.853	0.141	1.000	1.000	0.683	0.918	0.763	0.5	0.966	0.930	0.764
3	EETN-EVRA	0.925	0.342	1.000	0.725	0.720	0.987	0.595	1.0	0.888	0.630	0.763
4	EHAM-LFSB	0.968	0.231	1.000	1.000	0.488	0.966	0.662	0.5	0.764	0.920	0.753
5	EDDF-EETN	0.547	0.697	1.000	1.000	0.542	0.968	0.654	0.5	0.783	0.617	0.750
6	EDDM-LFBO	0.820	0.518	1.000	1.000	0.747	0.931	0.765	0.5	0.555	0.332	0.750
7	EETN-EHAM	0.329	0.368	1.000	1.000	0.593	0.987	0.681	1.0	0.930	0.966	0.749
8	EEKE-EETN	0.867	0.566	0.000	1.000	0.896	0.854	0.930	0.5	0.936	0.784	0.749
9	EHAM-EICK	0.803	0.270	1.000	1.000	0.517	0.986	0.650	0.5	0.849	0.888	0.746
10	ESSA-LSZH	0.909	0.558	1.000	1.000	0.609	0.764	0.507	0.5	0.519	0.773	0.736

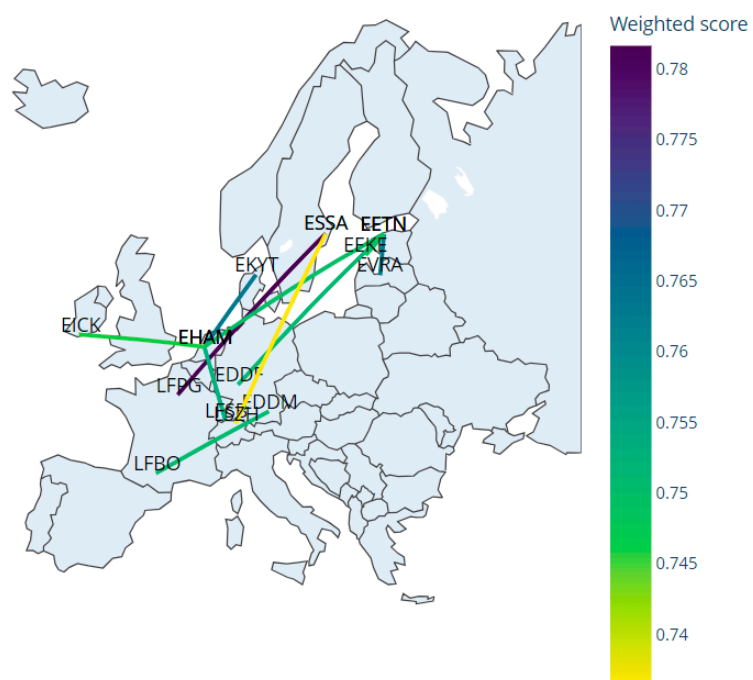


Figure 3. Top 10 OD airport pairs for H2 aircraft operations in 2035 on a map

For the top 5 OD airport pairs, score cards are created, providing more information on the scored metrics. Figure 4 provides the score card for the highest-ranked airport pair ESSA-LFPG (Stockholm Arlanda Airport – Charles de Gaulle Airport), the other score cards can be found in Figure 8 to Figure 11 of Appendix A.2.

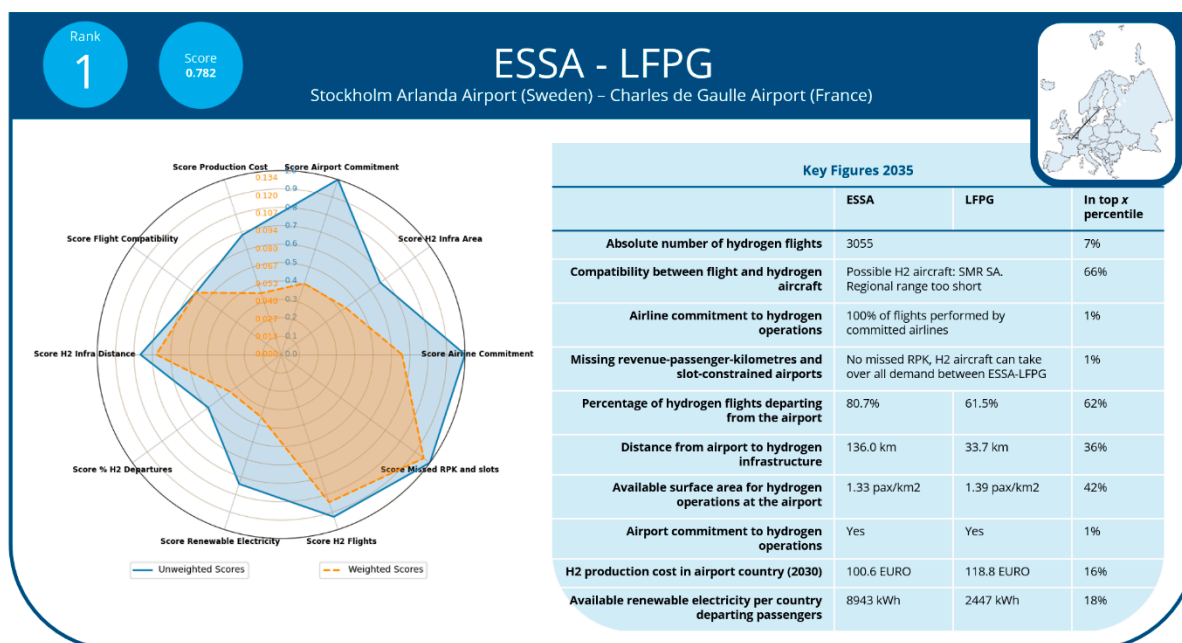


Figure 4. Score card for highest-ranked OD airport pair in 2035 hydrogen aircraft deployment scenario

The same method is applied to identify the top 10 OD airport pairs for hydrogen aircraft operations in 2040. With respect to 2035, an extra hydrogen aircraft is in service with a higher seat class: the SMR TA aircraft. Furthermore, hydrogen distribution to the airport is now also feasible by pipelines for larger airports, and additional hydrogen infrastructure (production, storage, distribution and transmission sites) is available. Additionally, the amount of renewable electricity is scaled for the new timeframe. For the 2040 scenario, the best identified OD airport pair is EETN-EVRA (Tallinn Airport – Riga International Airport), which appeared in third place in the 2035 timeframe. Furthermore, there are some similarities and changes in the top 10 OD airport pairs for the two timeframes, with some pairs remaining, others disappearing and new ones emerging. This is visualised in the Venn diagram in Figure 5. The top 10 OD airport pairs are again visualised on a map in Figure 6. Results of the scores and the weighted total score in the 2040 scenario can be found in Table 6 of Appendix A.3.

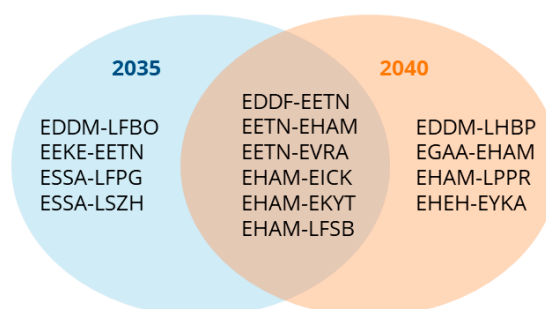


Figure 5. Venn diagram of top ranked OD airport pairs for 2035 and 2040 timeframes

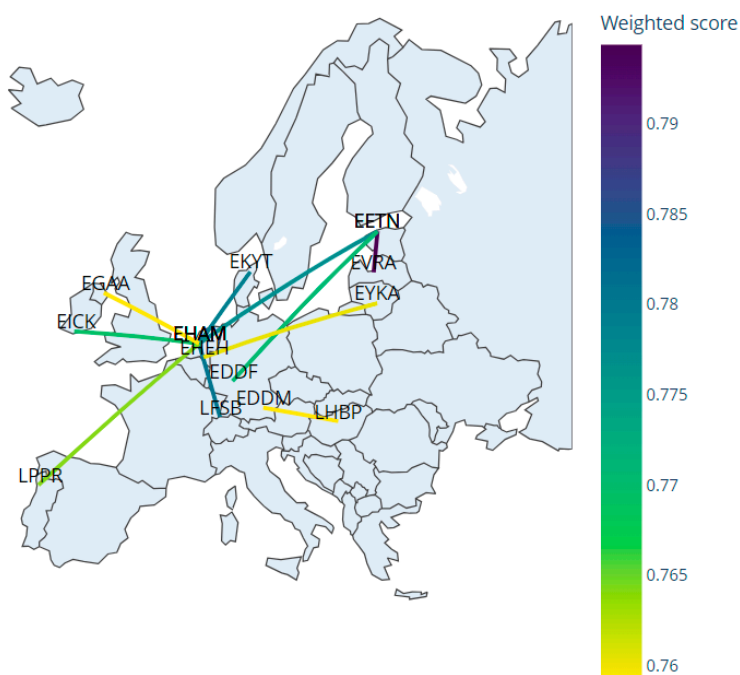


Figure 6. Top 10 OD airport pairs for H2 aircraft operations in 2040 on a map

A notable observation is that many OD airport pairs appear in both scenarios, but some, such as the top-ranked pair in the 2035 reference scenario (ESSA-LFPG), do not maintain their position in the 2040 scenario, instead ranking 14th. One reason for this shift is the adjustment of weights in the CRITIC method, due to a new distribution of data. A slight adjustment in weights can significantly alter the overall ranking. The most substantial changes in criteria weights include an increased weight for the criteria of *H2 Infra Distance* (+4.8%) and *Renewable Electricity* (+7.5%), as well as a decrease in weight in the *Flight Compatibility* criterion (-6.4%).

Furthermore, the addition of an extra hydrogen aircraft type allows for more routes to be flown by this aircraft and additionally possibly improving the scores for the *Flight Compatibility* criterion by providing better matches with aircraft range and seat capacity. The inclusion of pipelines and additional H2 infrastructure also reduces the distance to H2 infrastructure for more airports. In summary, the total score of ESSA-LFPG decreases by a few hundredths, while the scores of other pairs increase, resulting in a relative drop to 14th place. Moreover, it is notable that connections to and from EHAM experience increased prominence in the 2040 scenario.

As there are many variables and assumptions at play in this model, a sensitivity analysis was also performed. This can be found in Appendix A.4. This analysis shows the model outputs are dependent on the chosen methods and assumptions. The main takeaway from this analysis is that scoring criteria with higher weights, combined with clustered scoring distributions, have a relatively high effect on the final outcome. While this is logical, it is still important to take into account in future implementations and variations of this model.

4 Conclusions and Recommendations

This study identified ESSA-LFPG (Stockholm Arlanda Airport – Charles de Gaulle Airport) as the top-ranked origin-destination pair for hydrogen aircraft operations in the 2035 scenario. However, when considering a different timeframe, changes in the top-ranked origin-destination (OD) airport pairs occur due to the introduction of new hydrogen aircraft types, which enables more routes and potential better compatibility with existing routes, as well as expanded infrastructure such as new production sites and pipelines to the airports. In 2040, EETN-EVRA (Tallinn Airport – Riga International Airport) is identified as the best OD airport pair, furthermore routes from and to EHAM (Amsterdam Schiphol Airport) are frequently present in the top 10 OD airport pair list. These differences highlight the importance of considering timeframe-specific technological developments and their effects on hydrogen operations and deployments. The suitability of an OD airport pair for hydrogen operations is influenced by a complex interaction of factors, including aircraft range and seat capacity, proximity to hydrogen infrastructure, potential number of hydrogen flights, effect on revenue-passenger-kilometre (RPK), available airport area, production costs of hydrogen, availability of renewable electricity, and commitment from airlines and airports to hydrogen operations. As a result, no specific airport characteristics consistently outperforms others. Instead, a combination of factors contributes to the OD airport pair suitability for hydrogen operations.

The current methodology prioritises the compatibility between the flight and the hydrogen aircraft's characteristics in terms of flight range and seats performance, as a key criterion for feasibility of hydrogen aircraft operations. As a result, airport pairs whose existing routes align well with the performance of the TRANSCEND aircraft are inherently favoured in the ranking. This should be taken into account when interpreting the result. Additionally, it considers the impact on passenger volumes, measured by revenue-passenger-kilometre (RPK) values and its relation to slot-constrained airports, as an important factor. Lastly, the methodology incorporates the absolute number of hydrogen flights at the airport as a scoring criterion. Notably, when this criterion is omitted, several other OD airport pairs gain prominence in the top 10 ranking, suggesting that this factor can have a constraining effect on the identification of suitable OD airport pairs for hydrogen deployment. It is essential to note that the ranking of OD airport pairs is highly sensitive to the assumptions and weights used in the analysis, as the final scores of the top-ranked pairs are close together.

Ultimately, this study sheds light on key criteria that influence the suitability of OD airport pairs for hydrogen operations and provides a high-level methodology to identify airports and airport pairs with high potential for initial hydrogen deployment. The study provides a valuable starting point for additional investigation of airport- and route-specific studies that can further determine the opportunities and challenges associated with hydrogen adoption at specific airports.

As a recommendation for future work, the study could be extended with adjustments in the flight network. The current work is based on the scheduled flights network of 2023 and evaluates how hydrogen-powered aviation could be introduced in the existing network. In practice, the introduction of new aircraft technologies may lead to adjustments in the flight network. Future research could explicitly consider modelling true origin-destination demand, passenger travel preferences and potential changes in routing, such as the role of stop-over connections. Additionally, further research could incorporate a broader range of hydrogen aircraft types, including announced OEM designs (when performance specifications become available) and include the matching of airport-level hydrogen demand with available hydrogen supply.

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Appendix A

Appendix A.1 Criteria scoring and weighting

Figure 7 presents the correlation heat map of the considered scoring criteria, calculated using Pearson-correlation coefficients. The matrix shows weak (<0.3) to moderate correlation values (< 0.5), with a maximum absolute correlation value of 0.34 (-0.34), indicating that the criteria are sufficiently uncorrelated to be considered for scoring.

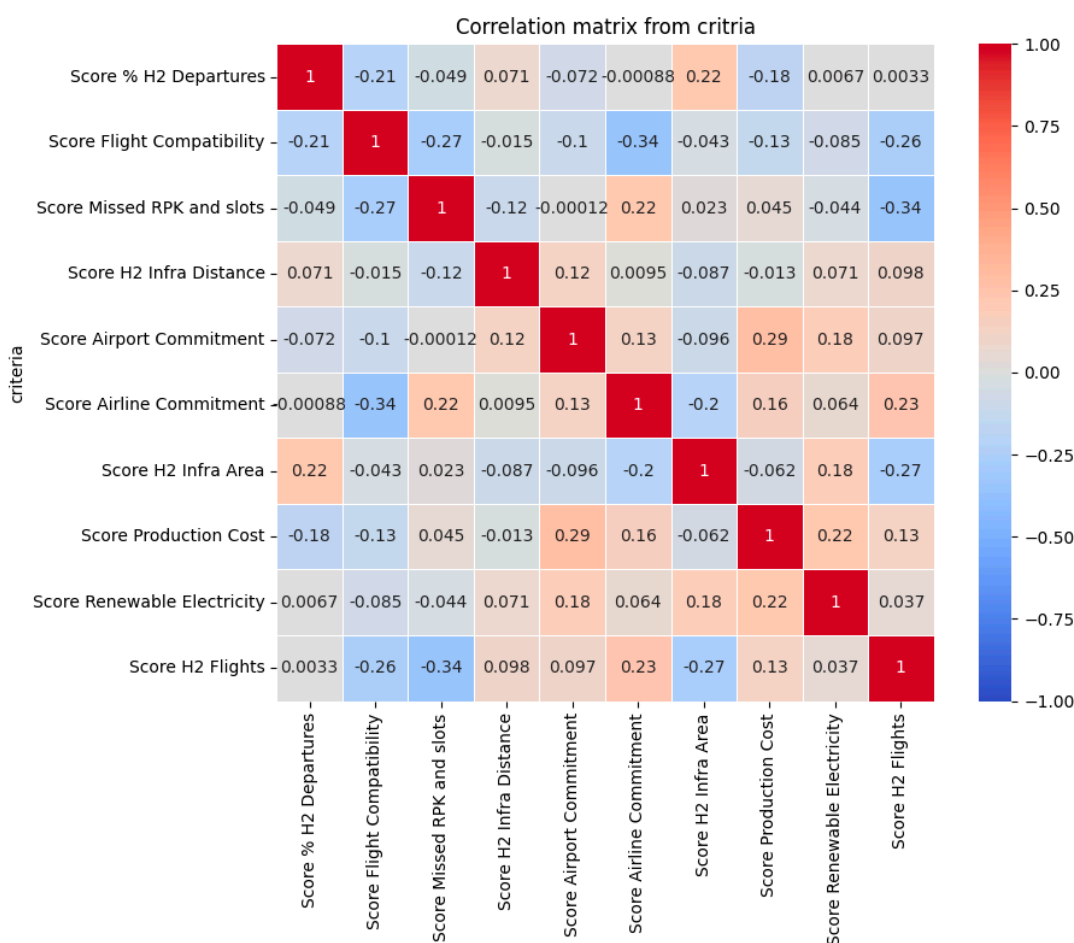


Figure 7. Criteria correlation matrix

Appendix A.2 Results for 2035 timeframe

For the 2035 timeframe scenario, the top 10 ranked OD airport pairs were provided in Table 5. For the 5 highest ranked OD airport pairs, score cards were created to give more insights on the scored metrics. The score card for the highest-ranked airport pair ESSA-LFPG (Stockholm Arlanda Airport – Charles de Gaulle Airport) was shown in Figure 4, the four other score cards can be seen in Figure 8 to Figure 11.

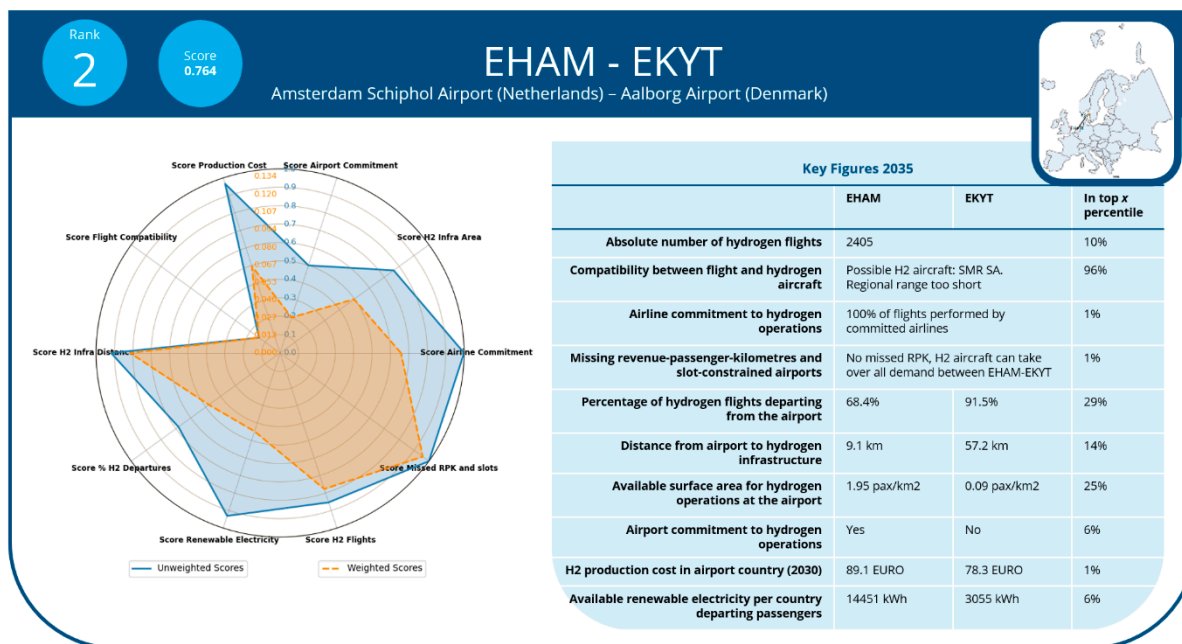


Figure 8. Score card for second highest-ranked OD airport pair in 2035 hydrogen aircraft deployment scenario

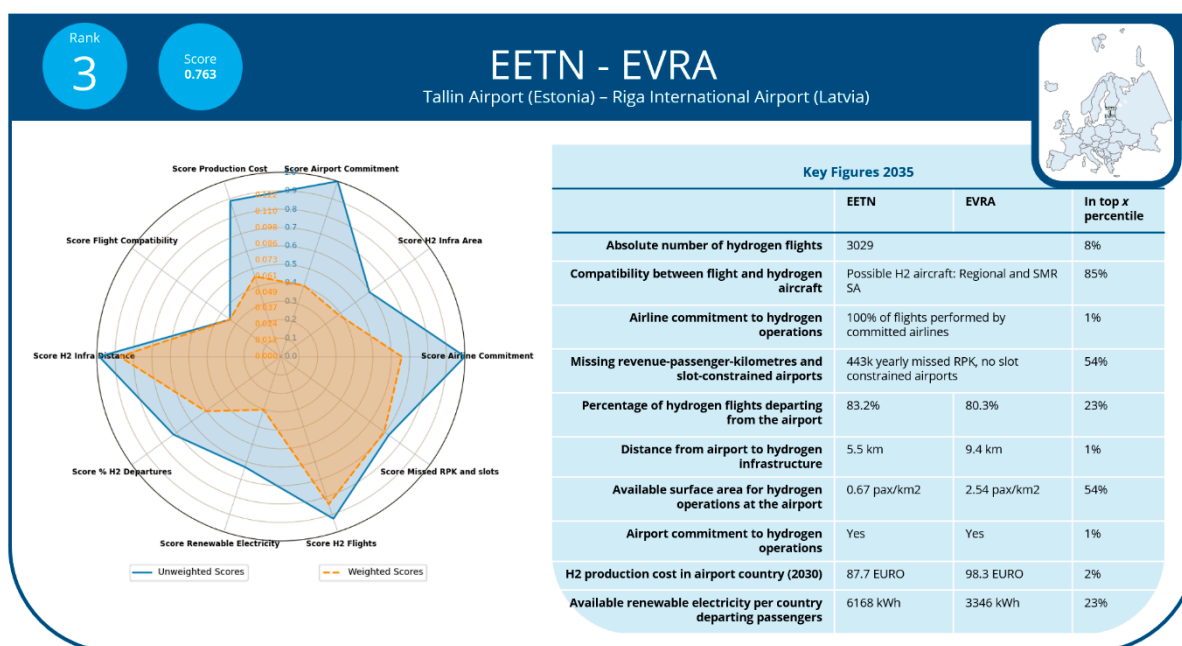


Figure 9. Score card for third highest-ranked OD airport pair in 2035 hydrogen aircraft deployment scenario

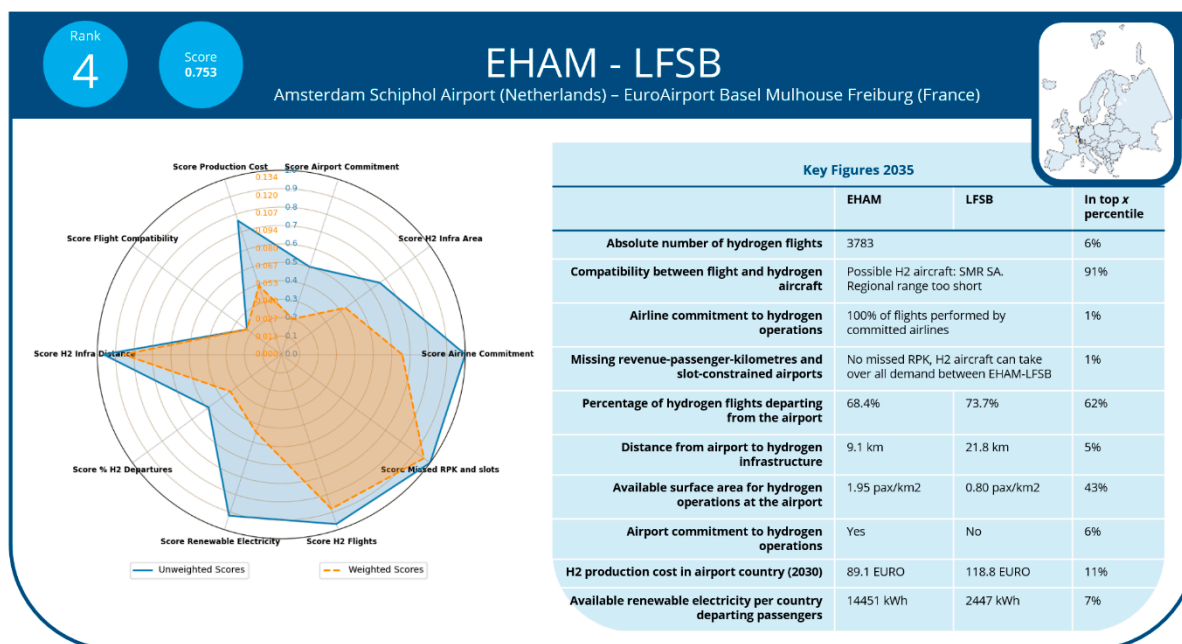


Figure 10. Score card for fourth highest-ranked OD airport pair in 2035 hydrogen aircraft deployment scenario

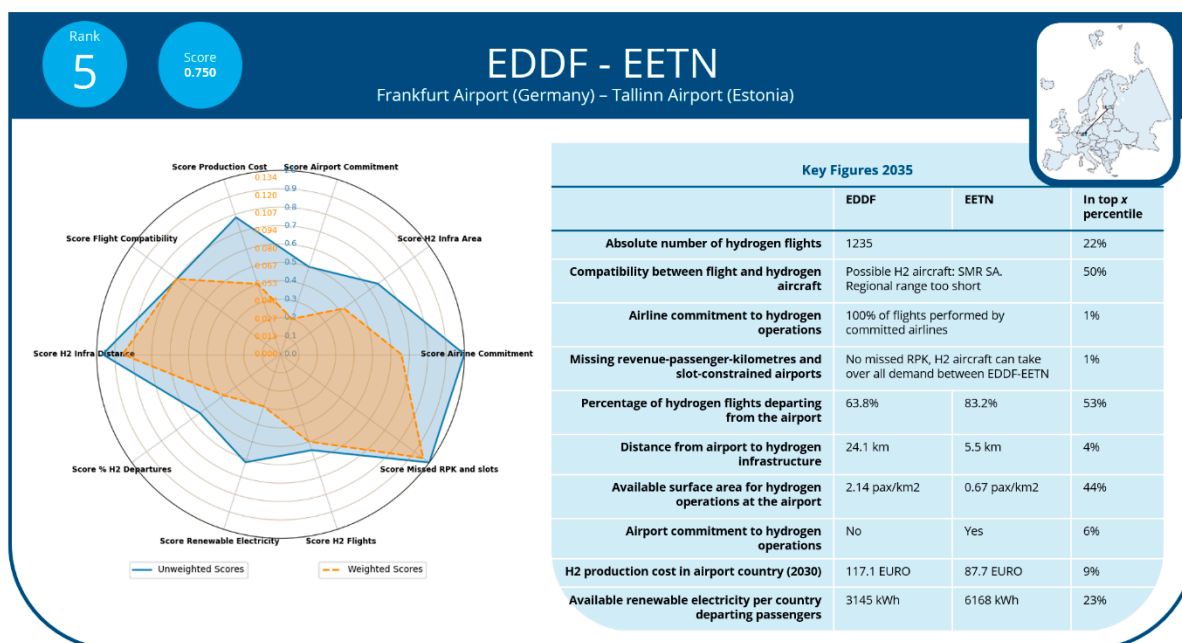


Figure 11. Score card for fifth highest-ranked OD airport pair in 2035 hydrogen aircraft deployment scenario

Appendix A.3 Results for 2040 timeframe

The top 10 highest potential OD airport pairs for hydrogen aircraft operations were also investigated in the 2040 timeframe. Table 6 shows the results for each OD airport pair for the different criteria, as well as the weights and the total weighted scores.

Table 6. Top 10 OD airport pairs for 2040, with scoring criteria, weights and total weighted score

Rank	OD airport pair	H2 Flights	Flight Compatibility	Airline Commitment	Missed RPK and slots	% H2 Departures	H2 Infra Distance	H2 Infra Area	Airport Commitment	Production cost	Renewable electricity	Weighted score
	Weight	0.126	0.131	0.090	0.133	0.0996	0.130	0.090	0.056	0.071	0.072	
1	EETN-EVRA	0.920	0.496	1.000	0.725	0.764	0.964	0.593	1.0	0.890	0.722	0.794
2	EHAM-LFSB	0.965	0.389	1.000	1.000	0.415	0.992	0.660	0.5	0.765	0.997	0.780
3	EHAM-EKYT	0.846	0.285	1.000	1.000	0.644	0.846	0.762	0.5	0.966	0.998	0.779
4	EETN-EHAM	0.322	0.520	1.000	1.000	0.619	0.980	0.680	1.0	0.931	0.999	0.777
5	EDDF-EETN	0.763	0.626	1.000	1.000	0.522	0.972	0.652	0.5	0.785	0.658	0.770
6	EHAM-EICK	0.794	0.429	1.000	1.000	0.438	0.978	0.648	0.5	0.850	0.996	0.769
7	EHAM-LPPR	0.864	0.376	0.716	1.000	0.638	0.987	0.409	1.0	0.721	0.998	0.764
8	EHEH-EYKA	0.000	0.777	1.000	1.000	0.430	0.934	0.893	1.0	0.873	1.000	0.760
9	EDDM-LHBP	0.900	0.545	1.000	1.000	0.512	0.988	0.548	0.5	0.316	0.991	0.759
10	EGAA-EHAM	0.224	0.663	1.000	1.000	0.664	0.813	0.658	1.0	0.864	0.997	0.759

Appendix A.4 Sensitivity Analysis

In order to test the robustness of the proposed model, the choices and assumptions made were evaluated in a sensitivity analysis. The exclusion, scoring and weighting aspects of the model were evaluated as explained below. The reference year for this analysis is 2035.

Appendix A.4.1 Exclusion

This model uses exclusion criteria to remove OD airport pairs that are deemed infeasible. It removes OD airport pairs which have a too large distance, where the runways cannot facilitate the hydrogen aircraft, and where there are too few flights that can be performed with hydrogen aircraft. This exclusion removes 1919 OD airport pairs from being

scored, resulting in a total of 5104 OD airport pairs. As the exact performance of the hydrogen aircraft and the scheduling of these aircraft is not yet set, this analysis shows the effect of relaxing these constraints. The distance and runway exclusions are relaxed by 20% and the absolute hydrogen flights exclusion is relaxed from a 52 flight minimum to a 1 flight minimum. In total, this results in 1102 extra OD airport pairs added to the overall ranking (with 817 OD airport pairs still being excluded), giving a total of 6206 OD airport pairs to be ranked. Table 7 shows the effect of relaxing the exclusion criteria, explained in section 2.2, on the ranking.

The effect of relaxing the distance and runway exclusion criteria are minimal. For distance, while it does add 343 OD airport pairs to be scored, only 3 of these were in the top 200 routes. This minimal effect can be explained by the fact that a relaxed exclusion criterion does not mean that the aircraft has increased performance. As such, the *Flight Compatibility* score will perform significantly worse, the same being true for other factors such as *Missed RPK and slots*. Relaxing the runway exclusion criterion leads to 190 OD airport pairs from not being excluded, with only 1 of them being in the top 50. However, as these airports already could not accommodate the regional and single aisle hydrogen aircraft, which requires a relatively short runway distance, it can be surmised that these airports are not suited for larger scale commercial flights. As some scoring criteria also link to the amount of flights and the overall scale of an airports operations, it is expected that these airports will not score high.

For the *H2 Flights* criterion, the effect is more notable. This can be explained due to the fact that some OD airport pairs fall just short of the cut-off point of 1 hydrogen capable flight per week or 52 flights per year. For instance, the initially excluded OD airport pair EHAM-LGKF (Amsterdam Schiphol Airport – Kefalonia International Airport) has 39 hydrogen flights per year and is now ranked 4th.

Overall, this analysis shows that relaxing the exclusion criteria, specifically for the distance and runway criteria, has little effect on the outcome. The absolute amount of hydrogen flights does change and this is mostly due routes falling just short of the cutoff point.

Table 7: Exclusion relaxation sensitivity analysis results. Amount of previously excluded OD airport pairs in the top x

Scenario	OD airport pairs added	In top 10	In top 20	In top 50	In top 100	In top 200
Distance	343	0	0	0	0	3
Runway	190	0	0	1	1	4
Abs. Hydrogen	596	1	2	4	7	14
Combined	1102	1	2	5	8	21

Appendix A.4.2 Scoring

The model developed in this research uses a multi-criteria scoring approach, where the combined scores yield a final ranking. This analysis investigates the impact of each scoring criterion on the final ranking by creating scenarios in which each criterion is removed individually, adjusting the weights accordingly, and recalculating the final weighted score and rank. Table 8 shows how the ranking of the top 10 OD airport pairs shifts for each of these scenarios. It can be seen that some factors, such as *Missed RPK and slots* and *H2 flights*, have a large effect on the overall ranking. This can mainly be attributed to their relatively high weight in the final scoring.

Table 8: Top 10 ranking comparison for scenarios where each scoring factor is excluded individually. Total # of OD airport pairs: 5104

Base rank	OD airport pair	H2 Flights	Flight Compatibility	Airline Commitment	Missed RPK and slots	% H2 Departures	H2 Infra Distance	H2 Infra Area	Airport Commitment	Production cost	Renewable electricity	Weighted score
	Weight	0.127	0.140	0.092	0.134	0.098	0.124	0.091	0.057	0.072	0.067	
1	EETN-EVRA	34	6	2	18	1	1	1	2	1	1	6.18
2	EHAM-LFSB	43	1	7	39	4	4	4	1	9	9	11.18
3	EHAM-EKYT	58	3	5	7	9	7	2	11	4	3	10.18
4	EETN-EHAM	110	2	12	61	2	12	5	5	6	14	21.18
5	EDDF-EETN	16	39	15	66	5	16	6	6	8	6	17.09
6	EHAM-EICK	62	15	10	73	12	11	15	3	3	2	19.27
7	EHAM-LPPR	2	7	17	60	8	20	7	20	14	20	16.55
8	EHEH-EYKA	82	17	1	85	21	6	28	4	18	12	25.64
9	EDDM-LHBP	63	4	19	72	7	21	9	8	12	19	22.09
10	EGAA-EHAM	146	34	25	94	14	8	8	10	5	17	33.73

Some scoring factors, specifically *Airport Commitment* and *Missed RPK and slots*, have heavily clustered scores around 0,1 and 0.5. This is due to the fact that for *Airport Commitment*, either an airport is (giving a 1) or is not (giving a 0) committed to adopt hydrogen infrastructure (0.5 if one airport in OD airport pair is committed while the other is not). For *Missed RPK and slots* this “binary” effect comes from the combination of looking at slot constraints and potential RPK missed by employing hydrogen aircraft. The combination of which leads to either very high, or very low scores with a small selection of OD airport pairs in-between. In this analysis, these “binary” scoring factors are removed both individually and simultaneously. As seen in Table 9, the effect of removing the *airport commitment* factor does lead to some shifting, but overall nothing too significant. The *Missed RPK and slots* on the other hand results in significant shifting while removing both has an even larger effect. This can be attributed to the combination of the relatively high weight of the *Missed RPK and slots* factor, and the binary distribution of both scoring factors.

Table 9: Top 10 results over excluded scoring scenarios (*airport commitment* and *missed RPK and slots*)

OD airport pair	Baseline Rank	<i>Airport Commitment</i> Excl.	<i>Missed RPK and slots</i> Excl.	Both criteria Excl.
ESSA-LFPG	1	2	18	42
EHAM-EKYT	2	1	39	26
EETN-EVRA	3	11	7	16
EHAM-LFSB	4	15	61	47
EDDF-EETN	5	6	66	50

OD airport pair	Baseline Rank	Airport Commitment Excl.	Missed RPK and slots Excl.	Both criteria Excl.
EDDM-LFBO	6	3	73	57
EETN-EHAM	7	20	60	156
EEKE-EETN	8	4	85	79
EHAM-EICK	9	18	72	72
ESSA-LSZH	10	10	94	100

Overall, while varying per criterion, the effect of each scoring criterion has a significant effect on the ranking. This effect is amplified by criteria with higher weights and clustered score distributions. That being said, the effects shown in Table 8 and Table 9 are relative to 5104 OD airport pairs, meaning that the largest shift of rank 10 → rank 146 is only a ~2.6% shift overall.

Appendix A.4.3 Weighting

The weighting method employed in this study combines the CRITIC and RS (as explained in section 2.4) methods. To evaluate the impact of each weighting method, this analysis examined each method in isolation, as well as an equal weighting approach (i.e., averaging the scores of all criteria) for comparative purposes. Table 10 gives an overview of the analysis performed around the weighting factors. As shown in the table, looking at the Top 100 OD airport pairs, while a large portion of OD airport pairs remains consistent compared to the baseline scenario, there are also some significant shifts.

Table 10. Weighting sensitivity analysis for Top 100 OD airport pairs

Scenario	Stability %	Common Routes	Unique Routes
No Weighting (Simple Average)	62%	62	38
CRITIC Only	72%	72	28
RS Only	54%	54	46

These shifts can be seen in more detail in Table 11, which looks at the top 10 OD airport pairs. It is clear that for some OD airport pairs, the effect of altering the weighting method has a significant effect on the rank. However, overall, the average rank remains quite consistent with the method employed. These findings suggest that while the weighting method has a significant influence on the model's outcomes, the overall highest-scoring routes consistently rank highly, regardless of the weighting method used.

Table 11. Top 10 results over weighting scenarios

OD airport pair	Baseline Rank	RS Only Rank	CRITIC Only Rank	No Weighting (Simple Average) Rank	Average Rank
ESSA-LFPG	1	4	1	2	2
EHAM-EKYT	2	7	3	4	4
EETN-EVRA	3	5	5	3	4
EHAM-LFSB	4	10	6	8	7
EDDF-EETN	5	6	14	18	10.75
EDDM-LFBO	6	3	19	32	15
EETN-EHAM	7	41	2	1	12.75
EEKE-EETN	8	1	130	16	38.75
EHAM-EICK	9	16	9	9	10.75
ESSA-LSZH	10	17	15	37	19.75



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