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Operational performance in sustainable aviation: an in-depth analysis of turnaround times of future commercial narrowbody liquid hydrogen aircraft

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Abstract

Liquid hydrogen (LH2) aircraft are expected to play a significant role in decarbonising the aviation industry. Their adoption will have multiple operational impacts, one of the most relevant for airlines being associated with the potential changes in turnaround times. This paper quantifies the expected changes in turnaround times of commercial narrowbody LH2 aircraft and assesses the impact of these new turnaround times on airline operational performance using actual empirical data. The main conclusion of this study is that the changes in turnaround times of LH2 aircraft are expected to have a rather marginal impact on airline operational performance, and therefore LH2 aircraft propulsion technology has the potential, following the implementation of the necessary adjustments and accommodations, to be compatible with existing operations. Overall, this study provides multiple new insights valuable for industrial decision-makers in making key strategic decisions regarding the adoption of LH2 aircraft technology.

Keywords: Sustainable aviation; Aviation decarbonization; Hydrogen aviation; Liquid hydrogen-fuelled aircraft; LH2 refuelling; Airline operational performance; Airline operation management

1 Introduction

Liquid hydrogen (LH2) aircraft propulsion is anticipated to play a significant part in the sustainability transition of the aviation industry (Rondinelli et al., 2017; Van der Sman et al., 2021; Hoelzen et al., 2022a; Mukhopadhaya and Rutherford, 2022; Steer, 2023). Both ICAO and IATA assign this emerging sustainable technology a role of considerable importance in their decarbonisation roadmaps, forecasting that it will account for a progressively rising percentage of emission reductions from 2035–2040 onward (IATA, 2019, 2023; ICAO, 2022a, 2022b). LH2 aircraft propulsion offers not only substantial environmental benefits—completely eliminating CO2 and most other air pollutant emissions—but also promising long-term economic advantages, as the cost of green LH2 is projected to decrease substantially in the next decades (Cole et al., 2022; Hoelzen et al., 2023a). Nonetheless, the impact that the adoption of this new propulsion technology may have on the operational performance of its end-users (i.e., airlines) remains uncertain. Existing studies (e.g., McKinsey, 2020; Postma-Kurlanc et al., 2022; Abel and Allfroggen, 2023; Babuder et al., 2024) suggest that the most significant cause of operational performance disruption for carriers is associated with the potentially longer turnaround times required by LH2 aircraft. Specifically, Postma-Kurlanc et al. (2022) highlight that the expected increase in turnaround times of LH2 aircraft could lead to an exceedance of aircraft and airport operating limits, resulting in negative operational ramifications for airlines. Similarly, both McKinsey (2020) and Steer (2023) suggest that the possibly longer ground times of LH2 aircraft could result in carriers being able to operate fewer flights per day, adversely impacting average daily aircraft utilisation. Abel and Allfroggen (2023) went a step further, calculating how the reduced aircraft utilisation induced by the longer turnaround times of LH2 aircraft may negatively affect the airline industry in terms of lost revenue. Despite offering a high-level overview of the predominant expected impacts on airline operational performance, existing studies provide only limited insights into their nature and estimated magnitude. This is problematic because, without a clear understanding of this aspect, airlines cannot make informed strategic decisions regarding the adoption of LH2 aircraft technology nor effectively navigate its deployment process. In particular, further investigation is required to:

1) quantify the expected changes in turnaround times of commercial LH2 aircraft; and

2) assess the impact of these new turnaround times on airline operational performance based on more accurate data and robust analysis. It is with the overall aim of exploring the turnaround process-induced operational disruption of LH2 aircraft that this paper puts forward the following research question:

How are the changes in turnaround times of LH2 aircraft expected to impact airline operational performance?

To address this question, a model is developed to estimate the new turnaround times required by a reference 180-seat 'turbofan' LH2 aircraft in different scenarios, taking into consideration various LH2 refuelling speeds and restrictions on parallel turnaround operations during LH2 refuelling. This analysis is based on real-world operational data provided by easyJet, the major European budget airline. The choice of the company is driven by two main factors:

(1) European short-to-medium haul operations, as multiple studies (e.g., McKinsey, 2020; ATAG, 2021; Van der Sman et al., 2021) have suggested that this is the market segment where the introduction of LH2 aircraft is most promising.

(2) low-cost operations, since, considering that low-cost carriers have the shortest turnaround times in the industry, this is the operations segment in which the impact of the changes in turnaround times of LH2 aircraft is expected to be the highest.

The rest of the paper is organized as follows: Section 2 introduces the key airline operational performance indicators and associated operational parameters considered in this study. Section 3 describes the empirical context, explaining how the case company, the reference aircraft, and the reference operation were selected. Section 4 focuses on the methodology, providing details on scenario development, data collection, and data analysis. Section 5 presents the study's results, summarised in multiple graphs. Section 6 discusses the results, while Section 7 concludes the paper.

2 Operational Performance of an Airline Company and Potential Impact of LH2 aircraft

The operational performance of an airline company represents a comprehensive measure of its operational efficiency and the resulting profit-generating potential. Among the numerous key performance indicators (KPIs) typically used to assess this multidimensional construct, the two selected as the reference ones for this study are those that, as emphasized in existing literature (e.g., Wu and Caves, 2000; More and Sharma, 2014; Camilleri, 2018; Waltenberger and Ruff-Stahl, 2018; Hutter and Pfennig, 2023), are generally recognized as being the most susceptible to changes in turnaround time:

- **Crew Factor:** The crew factor, based on the number of Full-Time Equivalent (FTE) crew members, represents the average number of full crews required to operate a single aircraft. For example, considering that a typical narrowbody short-to-medium haul aircraft crew usually consists of two pilots and four cabin crew, a crew factor of 6.0 indicates the need for six full crews, equivalent to 36 FTE crew members, per aircraft. To minimise labour costs, airlines try to keep this parameter as low as possible.
- **Aircraft Utilisation:** Aircraft utilisation, a measure of aircraft productivity, represents the average number of block hours flown by each aircraft per day (Mirza, 2009). Airlines aim to maximize returns from their assets by maintaining this parameter at the highest possible level. This is achieved through the optimisation of flight schedules and the minimisation of ground times.

Both KPIs are closely monitored by carriers due to their direct impact on costs and revenues: any increase in the crew factor leads to an increase in labour costs, while any decrease in aircraft utilisation negatively affects revenue generation. These KPIs primarily depend on two key elements:

- **Crew Pairings:** Crew pairings consist of a series of consecutive flights, originating and terminating at the home base, operated by a single crew during a specific flight duty period (Desaulniers et al., 1997; Ye, 2007). Airlines tend to optimise crew pairings by combining the longest possible flights to maximise crew members' work hours within contractual and legal flight duty limitations (Kasirzadeh et al., 2017). Alterations in existing crew pairings, which are already optimised, generally lead to an increase in the crew factor and a subsequent increase in labour costs.

- **Aircraft Routings:** Aircraft routings consist of a series of consecutive flights operated by a single aircraft during a day (Parmentier and Meunier, 2020). Similar to crew pairings, airlines tend to optimise aircraft routings by assigning as many flights as possible to each aircraft, compatibly with possible night flight airport operating restrictions. Any changes in existing aircraft routings, which are already optimised, typically result in decreased aircraft utilisation rates and, consequently, lower revenue for the airline.

Considering that LH2 aircraft could potentially require longer turnaround times (as will be discussed in more detail in the subsequent sections of this paper), existing crew pairings and aircraft routings may need to be modified. Consequently, as already partially highlighted by the relevant literature (e.g., McKinsey, 2020; Abel and Allfroggen, 2023; Steer, 2023) current crew factors and aircraft utilisation rates could be adversely affected, thereby negatively impacting airline operational performance.

3 Empirical Context

This section first discusses the motivation for choosing easyJet as the case company and then the reference aircraft and operations selected for developing the model presented in the following sections.

3.1 Case Company

Out of several possible candidate operators (e.g., Ryanair, Wizz Air, Eurowings, Vueling, Transavia, Volotea), easyJet was chosen as the case company for this study for several reasons. First, in terms of passengers carried, easyJet is one of the ten largest airlines in the world and the second biggest low-cost in Europe (OAG, 2021; Eurocontrol, 2022; European Commission, 2022). This makes a study focusing on such a company particularly relevant, especially for the European aviation industry. Second, easyJet is one of Europe's largest operators of Airbus A320 aircraft (Airbus, 2022; easyJet, 2022a). Considering that numerous studies (e.g., Debney et al., 2022; Hoelzen et al., 2022b; Postma-Kurlanc et al., 2022; Steer, 2023) suggest that commercial LH2 airliners are expected to be similar to narrowbody aircraft like the Airbus A320, easyJet's fleet is particularly suitable for a direct comparison between kerosene and hydrogen aircraft. Third, easyJet is actively supporting the development of hydrogen aircraft propulsion through several partnerships with multiple industrial actors (including Airbus, Rolls-Royce, and GKN Aerospace) and has publicly committed to being one of the early adopters of LH2 aircraft (easyJet, 2022a; easyJet, 2022b; GKN Aerospace, 2022; Rolls-Royce, 2022). Consequently, an easyJet-focused study has significant methodological and industrial relevance.

3.2 Reference Aircraft

To ensure a direct and meaningful comparison between current and future airline operations, kerosene and hydrogen aircraft that closely resemble each other are used. Specifically, the current-generation Airbus A320neo is selected as the kerosene reference. For the hydrogen reference, a single-aisle ‘turbofan’ aircraft similar to the Airbus A320neo is chosen. The specifications of this aircraft were derived from other published works (e.g., Debney et al., 2022; Hoelzen et al., 2022b, 2023b; Mukhopadhaya and Rutherford, 2022) that offer a high level of detail in modelling aircraft performance with conservative techno-economic assumptions rather than highly disruptive technology assumptions. Table 1 provides more details on the features of the chosen reference kerosene and hydrogen aircraft.

Table 1 – Specifications of the selected reference kerosene and hydrogen aircraft

	REFERENCE KEROSENE AIRCRAFT (Airbus A320neo)	**REFERENCE HYDROGEN AIRCRAFT (Single-aisle ‘turbofan’)**
Propulsion system	2X turbofan engines	2X modified gas turbine engines (direct LH2 combustion)
Design entry-into-service	currently in service	2035
Seating capacity[1]	186 (high-density, single-class layout)	180 (high-density, single-class layout)
Design range	2,520 NM	2,000 NM + final reserves
Energy requirements	same energy requirements	

Regarding onboard fuel storage, it is assumed that the reference hydrogen aircraft has two lightweight, cryogenic LH2 tanks located in the aft section of the fuselage, behind the rear bulkhead of the passenger cabin—this is in line with the assumptions of previous studies (e.g., Debney et al., 2022; Hoelzen et al., 2022b, 2023b; Mangold et al., 2022; Mukhopadhaya and Rutherford, 2022; Postma-Kurlanc et al., 2022). In order to keep the stored LH2 below its boiling point (-253°C) for as long as possible, these cryogenic tanks are expected to have a spherical/cylindrical shape (to minimize heat gains) and multilayer insulations with a vacuum in between (to reduce heat transfer by radiation)— for further details, see Verstraete et al. (2010), Gomez and Smith (2019), Airbus (2021), and Hoelzen et al. (2022b).

In terms of aircraft efficiency, it is assumed that the energy requirements of the reference hydrogen aircraft are the same as those of the reference kerosene aircraft. This assumption is grounded in two key considerations:

1. Existing studies indicate that, due to decreased aerodynamic efficiency resulting from the storage of LH2 tanks in the aft section of the fuselage, a 180-seat LH2 aircraft entering service in 2035 is anticipated to be approximately 10% less efficient than its kerosene-powered equivalent designed to enter service in the same year (Hoelzen et al., 2022b; Mukhopadhaya and Rutherford, 2022).
2. The engine efficiency of the Airbus A320neo aircraft is projected to increase by approximately 10% between the present and 2035 (Hoelzen et al., 2022b). This implies

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[1] The seating capacity depends on the passenger cabin layout chosen by the airline. The reported figures are based on the typical high-density, single-class layout used by low-cost airlines such as easyJet.

that a kerosene-powered Airbus A320neo entering service in 2035 would be 10% more efficient than the current-generation model (Hoelzen et al., 2022b).

When these two factors are considered together, it is reasonable to assume that a 180-seat single-aisle LH2 aircraft entering service in 2035 (incorporating future aircraft technology with a new propulsion system – the reference hydrogen aircraft) is expected to have efficiency levels and, consequently, energy requirements comparable to those of a state-of-the-art kerosene-powered narrowbody aircraft of the present day (such as the current-generation Airbus A320neo – the reference kerosene aircraft).

3.3 Reference Operation

Considering the importance of basing the model on a critical time period to assess the full potential impact of LH2 propulsion on airline operational performance, the summer of 2023 was selected as the reference. This period marked the busiest flying season following the COVID-19 crisis, as the intensity of operations was close to pre-pandemic levels (Eurocontrol, 2023). Within this period, the focus is set on the busiest full week for which data was available at the time of access, spanning from the 19th to the 25th of June 2023.

The selection of the airports for the reference operation was guided by specific criteria: sub-networks characterized by busy flight schedules, similar A320 fleet size[2], and opposite night curfew restrictions (since the objective was to analyse and compare the effects of cumulative LH2 aircraft delays on aircraft routings for aircraft based at airports with and without night flight restrictions).

Based on independent route network analysis and feedback from easyJet management, the flight operations conducted from the Milan Malpensa (MXP) and Berlin Brandenburg (BER) home base airports were selected as the reference ones for the study.

4 Methodology

In this section, the key factors expected to influence the turnaround time of LH2 aircraft are examined, thereby justifying the selection of the fundamental assumptions for the modelling. Subsequently, the expected turnaround processes for the reference LH2 aircraft are introduced, and the reference turnaround scenarios are presented. Finally, the data collection and analysis processes are described.

4.1 Scenario Development

4.1.1 Key Factors Affecting Turnaround Time of LH2 Aircraft

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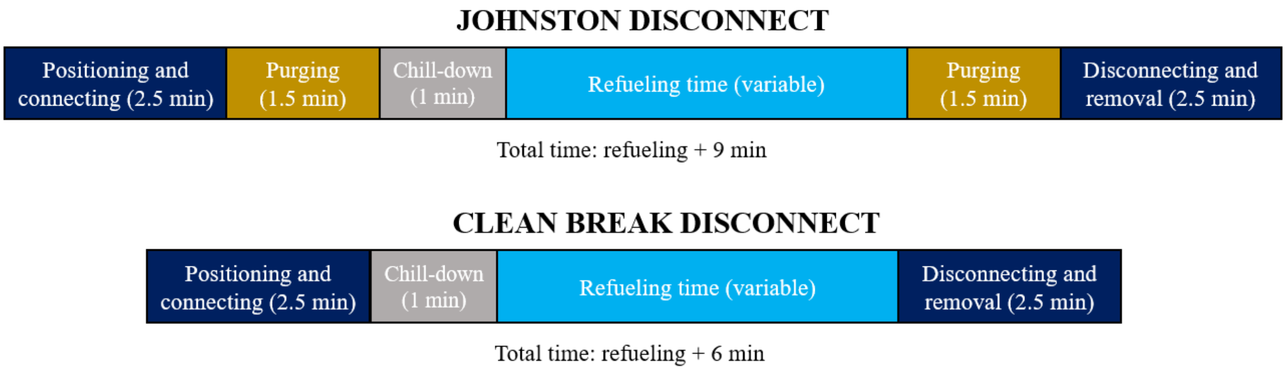
[2] It should be noted that while easyJet's fleet also includes Airbus A319 and A321 aircraft, only operations performed by Airbus A320 aircraft were considered for consistency. This is because Airbus A319 and A321 aircraft have different turnaround times due to variations in passenger cabin size, making direct comparisons with the selected reference LH2 aircraft inappropriate.

The literature highlights that there are three key factors expected to potentially affect the turnaround time of LH2 aircraft:

1. **LH2 Refuelling Method**: As described by Mangold et al. (2022), LH2 airliners are likely to be refuelled using one of the following two methods[3]: the Johnston disconnect and the clean break disconnect. While both methods involve a 1-minute chill-down phase during which the refuelling hose(s) are cooled to cryogenic temperatures before refuelling, they differ in their purging requirements. Specifically, the Johnston disconnect necessitates purging the LH2 refuelling hoses with inert gas before and after refuelling (1.5 minutes per step) to prevent contamination from foreign gases. In contrast, the clean break disconnect does not involve any purging, as it accepts that a small amount of spillage may occur during hose connection and disconnection. In both cases, the positioning and removal of the LH2 refuelling bowser (or LH2 hydrant dispenser truck) and equipment are expected to take 2.5 minutes each (Mangold et al., 2022). Figure 1 provides a detailed temporal comparison of the two methods, illustrating the estimated time needed to perform each step.

Figure 1 – Comparison of the Johnston and clean break disconnect methods
(based on Mangold et al., 2022)



As can be noted, due to the absence of purging steps, the clean break disconnect method is quicker (allowing for an estimated 3-minute saving in the overall refuelling procedure) and more cost-effective (as no inert gas is required). Because of this, such a method was chosen as the reference for the model – while it is true that this method is currently under development, it is estimated that it will be fully operational by 2035, which aligns with the expected service entry of the reference LH2 aircraft.

2. **LH2 Refuelling Speed[4]**: Currently, there is no consensus regarding the LH2 mass flow rate at which commercial hydrogen aircraft could be refuelled. Postma-Kurlanc et al. (2022) estimate

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[3] Although the 'Johnston disconnect' and 'clean break disconnect' are not standalone refuelling methods, they represent specific technical equipment and procedural choices influencing the LH2 refuelling process. The use of the term 'methods,' as adopted by Mangold et al. (2022), aims for clarity in discussing the impact of these technical and procedural choices on the overall refuelling approach. For further information, refer to Mangold et al. (2022).

[4] The terms 'LH2 refuelling speed' and 'LH2 mass flow rate' are used interchangeably.

that with a refuelling volume flow similar to the one currently used for kerosene aircraft (i.e., 900 L/min), a 6-inch inner diameter LH2 refuelling hose—previously calculated as the optimal dimension for LH2 refuelling (see Mangold et al., 2022 and Postma-Kurlanc et al., 2022)—would allow achieving an LH2 mass flow rate of approximately 5 kg/s. However, it is important to acknowledge that this speed would significantly extend refuelling times due to the much lower volumetric density of LH2 compared to Jet A-1. In response, both McKinsey (2020) and Postma-Kurlanc et al. (2022) suggest using two LH2 refuelling hoses simultaneously, effectively doubling the total mass flow rate and reaching approximately 10 kg/s. On the other hand, Mangold et al. (2022) indicate that, with proper precautions and technological advancements, a 6-inch diameter refuelling hose could theoretically deliver an LH2 mass flow rate of 20 kg/s—a substantial improvement compared to existing Jet A-1 refuelling flow rates. Given this uncertainty, the model presented in this paper is based on three LH2 refuelling speeds: 5 kg/s (conservative scenario), 10 kg/s (intermediate scenario), and 20 kg/s (optimistic scenario).

3. **Fuel Safety Zone for LH2 Refuelling and Restrictions on Parallel Turnaround Operations**: Several studies (e.g., Brewer, 1976; ACI and ATI, 2021; Postma-Kurlanc et al., 2022) highlight that the Fuel Safety Zone[5] (FSZ) required for LH2 refuelling operations is expected to be significantly wider than the current standard used for Jet A-1 (which is generally 3 meters in radius for narrowbody aircraft) (IATA, 2020). Brewer (1976) calculates that an FSZ of 27.4 meters (in radius) will be necessary to protect LH2 aircraft from potential hazards posed by spark ignition ground vehicles. On the other hand, Postma-Kurlanc et al. (2022) and Babuder et al., (2024) estimate that, pending testing and assessment, the FSZ may be designed to be around 20 meters for LH2 refuelling hose connection/disconnection (the most safety-critical phases in the refuelling process) and 8-10 meters for actual LH2 refuelling. Regardless of the exact size decided by regulatory authorities, the FSZ for LH2 refuelling operations will likely incorporate a substantial portion of the aircraft's fuselage and the surrounding stand area (see Figure 2).

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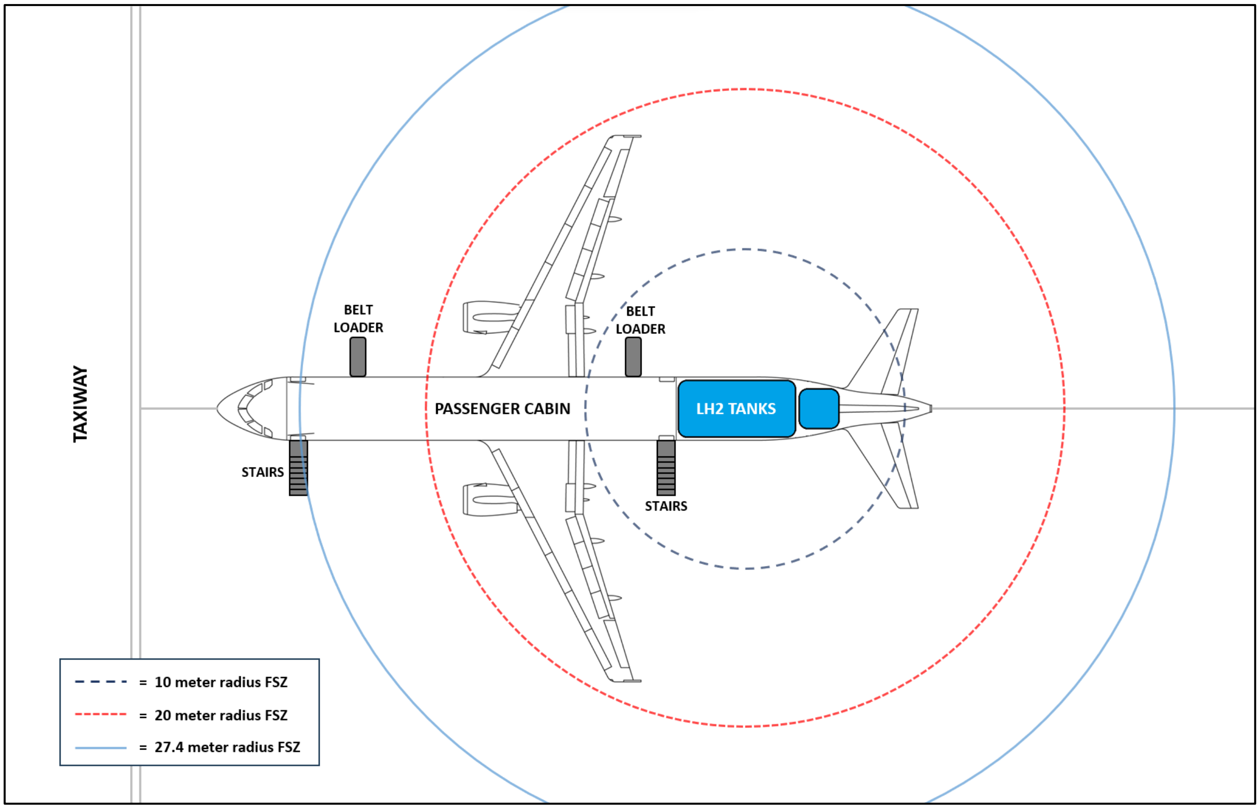
[5] The Fuel Safety Zone is the area around the refuelling equipment that, due to safety concerns, must be free of any non-refuelling related objects or personnel during refuelling operations (Airbus, 2020a).

Figure 2 – Possible dimensions of the FSZ during LH2 refuelling[6]



This wider FSZ will inevitably impact (at least some) parallel turnaround operations, most likely subjecting them to restrictions and requiring them to be conducted either before or after the LH2 refuelling process. However, none of the existing studies indicate precisely when these restrictions on simultaneous turnaround activities are expected to start and end (i.e., will they begin when the refuelling/dispenser truck is positioning and connecting, during the chill-down step, or only when LH2 is actually flowing through the refuelling hose?). The expectation is that, at least initially, regulators are likely to adopt strict safety measures and opt for the safest course of action. As a result, the model presented in this paper assumes that the restrictions on parallel turnaround operations will begin as soon as the LH2 refuelling truck approaches the aircraft and will only end when the refuelling procedure is completed (i.e., when the refuelling truck is moving away) – this aligns with the current practice for Jet A-1 refuelling with passengers on board (EASA, 2023a; EASA, 2023b). For further details, see figure 3.

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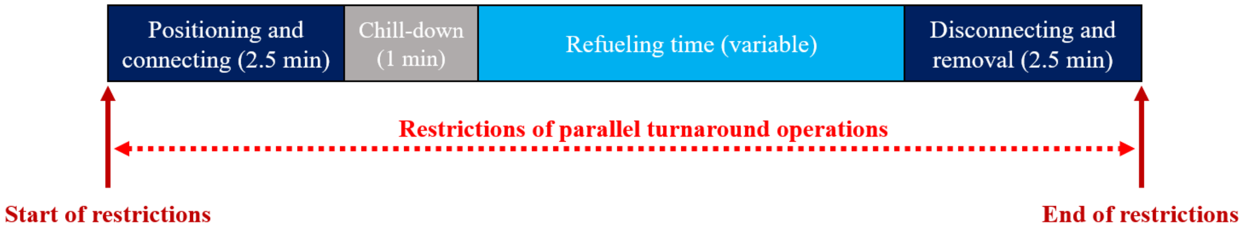
[6] The fuselage of the illustrated aircraft (which is the reference LH2 aircraft) has dimensions similar to an existing Airbus A321. This is because, due to the storage of the LH2 tanks behind the rear bulkhead of the passenger cabin, single-aisle LH2 aircraft are expected to have a longer fuselage compared to their kerosene equivalent (Mukhopadhaya and Rutherford, 2022; Debney et al., 2022). Additionally, the shown FSZs are centred at the ‘refuelling coupling point,’ which, for narrowbody LH2 aircraft, is expected to be in the aft section of the aircraft, in the proximity of the LH2 tanks (Mangold et al., 2022; Postma-Kurlanc et al., 2022).

Figure 3 – Assumed start and end of restrictions on parallel turnaround operations during LH2 refuelling



4.1.2 Reference Turnaround Scenarios

The reference turnaround scenarios are of primary importance because they serve as the foundational elements upon which the model relies to calculate the potential impact of LH2 aircraft on crew pairings and aircraft routings. When developing these scenarios, the first step was to determine what the turnaround process of the reference LH2 aircraft could look like. To ensure realism, such a process was derived by implementing necessary modifications to the current turnaround process of an easyJet A320 aircraft, whose specific details were provided by easyJet. Since the goal was to minimize total turnaround time, the new process was designed with the following considerations: (1) optimizing all turnaround activities to occur simultaneously wherever possible, as is the current practice; and (2) using both the forward and back cabin doors (i.e., doors 1L and 2L) simultaneously for passenger embarking and disembarking – this necessitates the use of either two sets of stairs, or a passenger boarding bridge (at the front) combined with a set of stairs (at the back). Considering the existing regulatory uncertainty, two different levels of restrictions were taken into account[7]:

1. **Type A restrictions** (Figure 4): No parallel turnaround operations allowed during LH2 refuelling, and even the crew must move out of the FSZ (possibly disembarking the aircraft) during this operation. These restrictions are due to the significantly larger size of the FSZ, which encompasses most of the LH2 aircraft's fuselage. In this case, the LH2 refuelling operation is the limiting factor, driving the increase in turnaround time.
2. **Type B restrictions** (Figure 5): No parallel ground turnaround operations permitted during LH2 refuelling. However, despite the fact that the passenger cabin (at least partially) falls within the FSZ, the cabin crew can remain onboard and carry out their normal turnaround duties (i.e., cabin tidying and searching). This allows for a 6.5-minute window of overlapping LH2 refuelling and cabin operations, resulting in a reduced total turnaround time compared to when type A restrictions are applied. In this case, the limiting factor is the 'extra LH2 refuelling time,' which refers to the additional time required to complete the refuelling procedure after the end of the cabin tidying and searching operation.

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[7] While this study considers only two types of restrictions on parallel turnaround operations, a more optimistic scenario could theoretically exist where, with a number of precautions, parallel turnaround operations (including passenger deboarding and boarding) are allowed during LH2 refuelling – this is currently the practice at most airports during Jet A-1 refuelling. However, this scenario is not taken into account since, in this case, there would be no impact on turnaround time, implying a null effect on airline operational performance.

The combining of these two types of LH2 refuelling restrictions with the three LH2 refuelling speeds considered by the model (i.e., 5 kg/s, 10 kg/s, and 20kg/s) resulted in the creation of a total of six distinct scenarios, which are detailed in Table 2.

Table 2 – Reference LH2 aircraft turnaround scenarios

		Restrictions on parallel turnaround operations	
		Type A	**Type B**
Refuelling speed	**5 kg/s**	Scenario A1	Scenario B1
	10 kg/s	Scenario A2	Scenario B2
	20 kg/s	Scenario A3	Scenario B3

Figure 4 – Turnaround process of the reference LH2 aircraft with type A restrictions (applicable in Scenarios A1, A2, and A3)

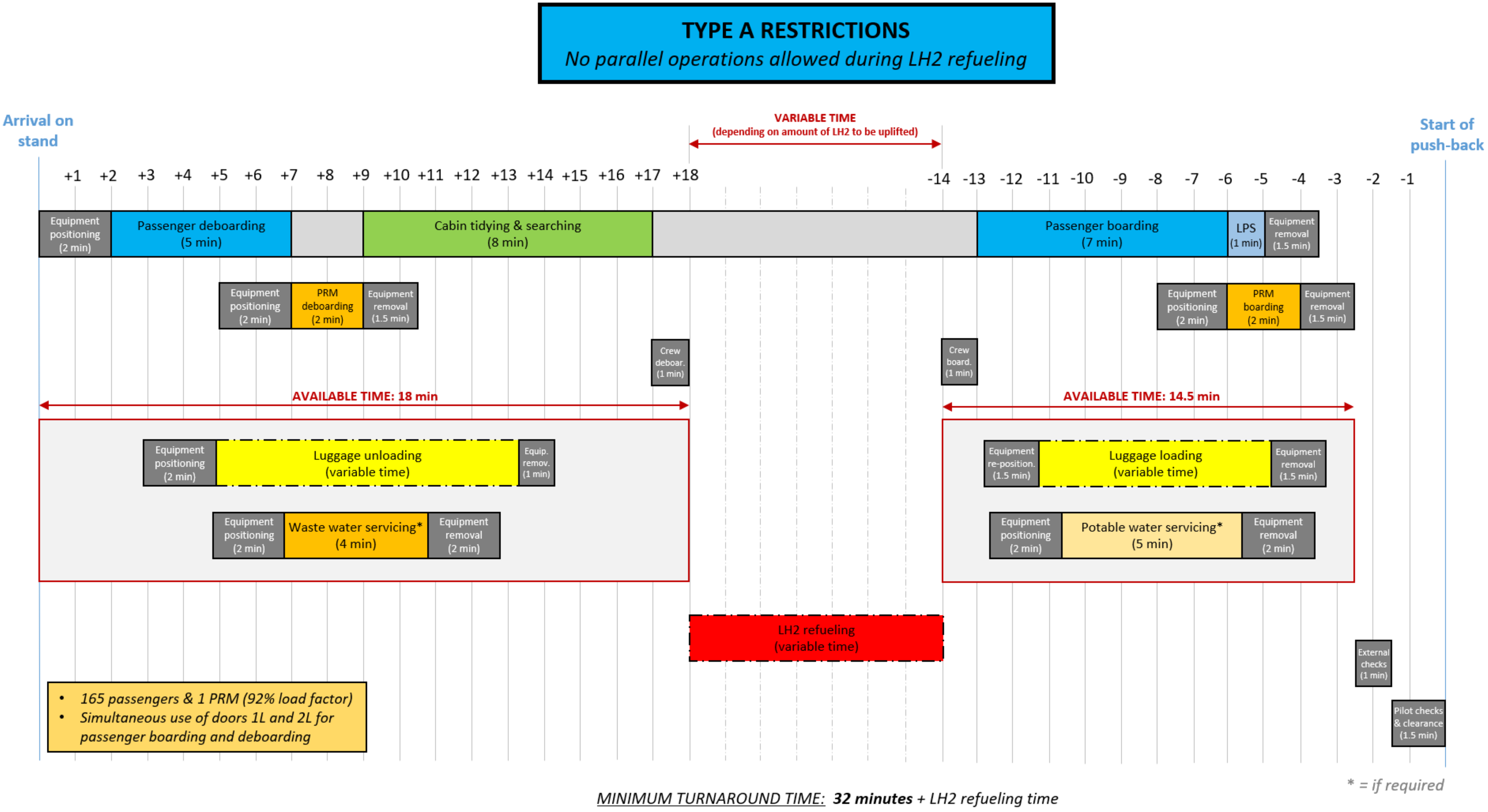
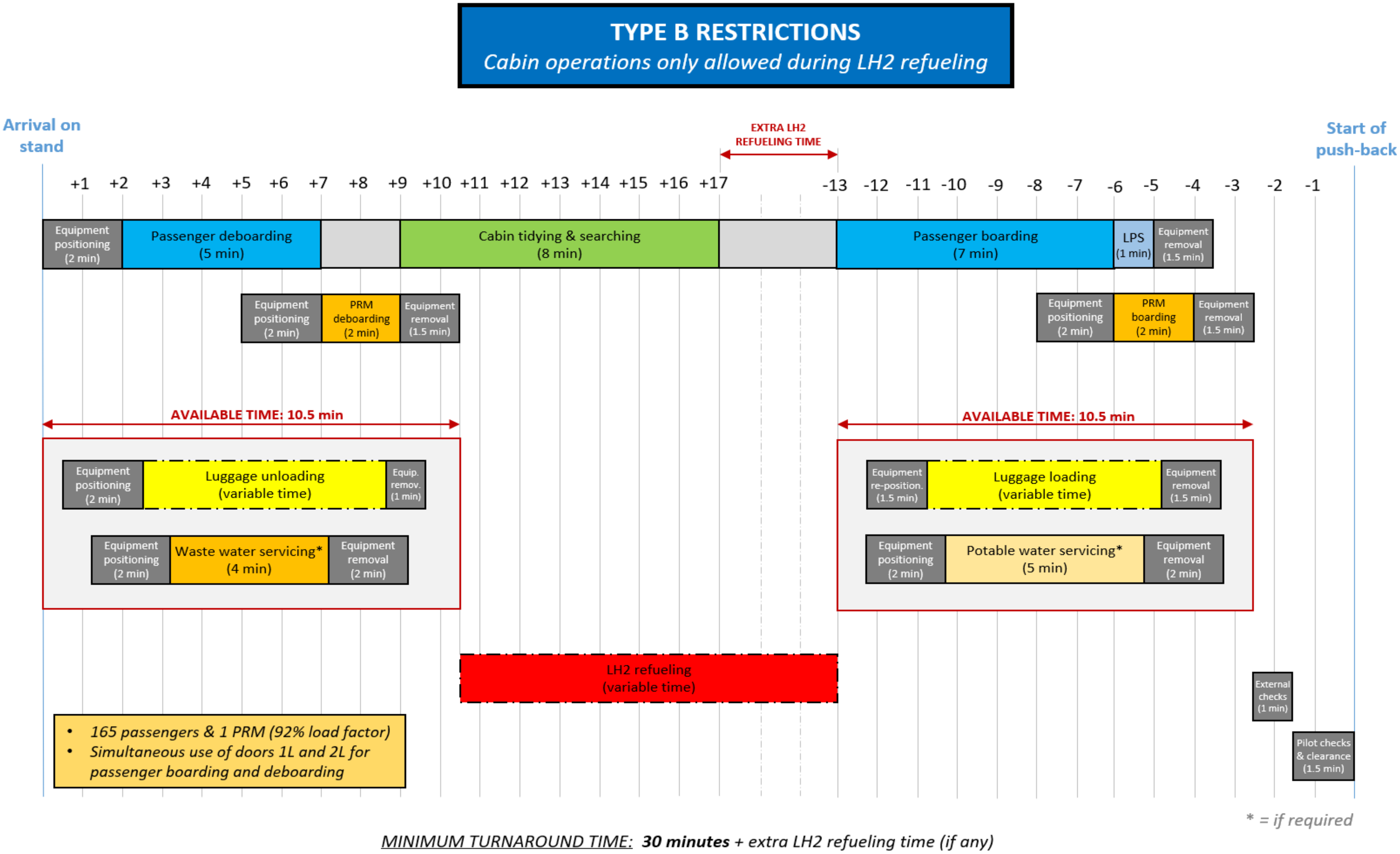


Figure 5 – Turnaround process of the reference LH2 aircraft with type B restrictions (applicable in Scenarios B1, B2, and B3)



4.2 Data Collection

To ensure high levels of data reliability, the data collection process for this study involved several steps and utilised multiple sources:

1. In January-February 2023, two easyJet operations managers were consulted via phone and asked to provide clarifications on the current easyJet Airbus A320 turnaround process.
2. Assumptions regarding the LH2 refuelling method and speeds were derived from existing industrial and academic literature, as discussed in Section 4.1.1.
3. In January 2023, a representative from a major European civil aviation authority was consulted during a Microsoft Teams call to provide feedback on the most probable restrictions on parallel turnaround operations during LH2 refuelling, including their assumed start and end times in the refuelling process.
4. Assumptions used to develop the reference LH2 aircraft turnaround processes introduced in the previous section (e.g., the number of passengers to be deboarded/boarded; the duration of each turnaround activity, including pre- and post-activity steps) were obtained from publicly available Airbus documents, public and internal easyJet documents, and the feedback provided by multiple easyJet air crew members (12 pilots and 10 cabin crew). Specific details on these assumptions and their sources are available in Table A.1 (Annex A).
5. In March 2023, an easyJet ground operations specialist was engaged via email to provide feedback on the developed LH2 aircraft turnaround processes and evaluate their potential validity.
6. All real-world operational data required to calculate the reference LH2 aircraft turnaround time, determine the cumulative aircraft delays, and evaluate the resulting impacts on the selected KPIs were provided by easyJet. More specifically, the provided data included existing crew pairings and aircraft routings, scheduled departure and arrival times, buffer windows, average kerosene block fuel figures, and average residual fuel at engine shutdown.
7. The contractual maximum flight duty limitations, which represent the company-specific contractual maximum working-hours for aircrew members, were also provided by easyJet.
8. The legal maximum flight duty limitations, which represent the absolute maximum working hours for aircrew members currently in force at a European Union level, were derived from EASA's ORO.FTL.205 'Maximum daily FDP – Acclimatised crew members' table.

4.3 Data Analysis

The data analysis involved several key steps to assess the potential impact of different LH2 aircraft turnaround times on airline operational performance:

1. **Calculation of max usable range and max tankering range**: The reference operation was analysed to identify flights and routes suitable for LH2 aircraft deployment.

Additionally, the total number of routes on which LH2 tankering[8] could be performed was determined. This enabled the definition of the segment of the selected easyJet operation where LH2 aircraft integration is potentially feasible. This segment became the new reference for all subsequent steps.

2. **Determination of LH2 aircraft turnaround time and calculation of the extra delay**: The LH2 fuel uplift requirements for the reference LH2 aircraft were derived from the average block fuel figures of the reference kerosene aircraft. Then, the LH2 refuelling times were computed and subsequently the LH2 aircraft turnaround time for each scenario was calculated. Figure 6 illustrates a graphical representation of the calculated 'minimum theoretical turnaround times'[9] for various LH2 refuelling quantities and provides a comparison with current turnaround times. To ensure realistic results, these minimum theoretical turnaround times were then adjusted by incorporating existing turnaround buffers, which represent additional time allowances allocated to account for potential inefficiencies during the turnaround process. By comparing these corrected turnaround times with the ones of the reference kerosene aircraft, the extra delay possibly induced by the use of LH2 aircraft was calculated, considering both a normal refuelling schedule and an optimised refuelling operation with tankering.
3. **Determination of the impact of extra delay on existing crew pairings and calculation of the potential increase in the crew factor for LH2 aircraft**: The impact of cumulative LH2 aircraft delays on existing crew pairings was determined by verifying whether the buffer from current contractual and legal maximum flight duty limitations would be infringed. Subsequently, the new crew factor potentially required by LH2 aircraft in each of the different scenarios was derived.
4. **Evaluation of compatibility of extra delay with existing aircraft routings and night curfew restrictions**: The cumulative LH2 aircraft delays were evaluated for compatibility with existing aircraft routings and, for the Berlin operation, with night curfew restrictions. This analysis allowed discerning the distinct operational consequences of basing LH2 aircraft at airports with and without night flight restrictions.

For a detailed breakdown of the methodological steps undertaken, refer to Appendix B. It is important to note that, to achieve high levels of data reliability and accuracy in the results, the data analysis protocol followed involved multiple levels of data verification and cross-validation to minimise potential errors.

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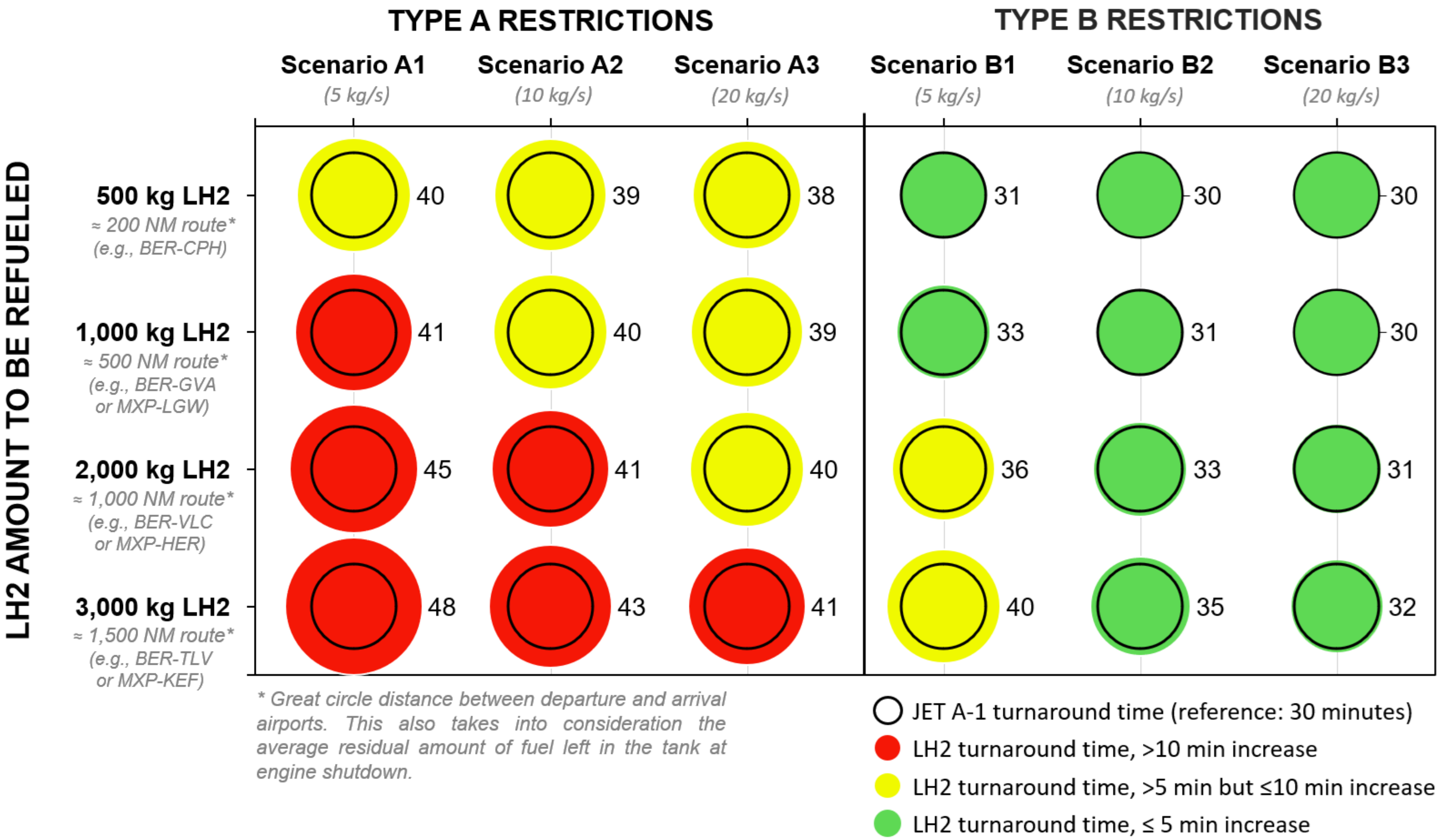
[8] In this context, LH2 tankering can be defined as the practice whereby an LH2 aircraft uplifts return fuel at its departure airport to avoid refuelling at the destination airport. While it is true that this results in additional fuel consumption on the outbound flight due to the extra weight of the carried return fuel, the penalty factor for LH2 tankering is extremely low (less than 1% increase in specific energy consumption) thanks to the lightweight nature of LH2 (Postma-Kurlanc et al., 2022; Hoelzen et al., 2023).

[9] The 'minimum theoretical turnaround time' has to be intended as the turnaround time that the reference LH2 aircraft requires under ideal conditions (i.e., all turnaround activities occurring exactly as planned, with no delays).

Figure 6 – 'Minimum theoretical turnaround times' required by the reference LH2 aircraft in the different scenarios



* Great circle distance between departure and arrival airports. This also takes into consideration the average residual amount of fuel left in the tank at engine shutdown.

5 Results

5.1 Flights and Routes Suitable for LH2 Aircraft Deployment

Figures 7 and 8 illustrate the max usable range and max tankering range lines, centred at Milan and Berlin airports, respectively. As depicted in Figure 7, the deployment of LH2 aircraft at Milan Malpensa airport would be highly effective, with the reference LH2 aircraft capable of operating 98.9% of the existing flights and 97.8% of the current routes. Furthermore, LH2 tankering would be possible on 68.8% of LH2 aircraft routes. The situation for the Berlin operation (Figure 8) is somewhat similar, albeit with slightly lower effectiveness, as LH2 aircraft could cover 93.0% of the existing flights and 86.8% of the current routes. Similarly, the percentage of LH2 aircraft routes where LH2 tankering could be performed is slightly lower, at 60.6%.

Figure 7 – Flights and routes suitable for LH2 aircraft deployment – Milan Malpensa operation

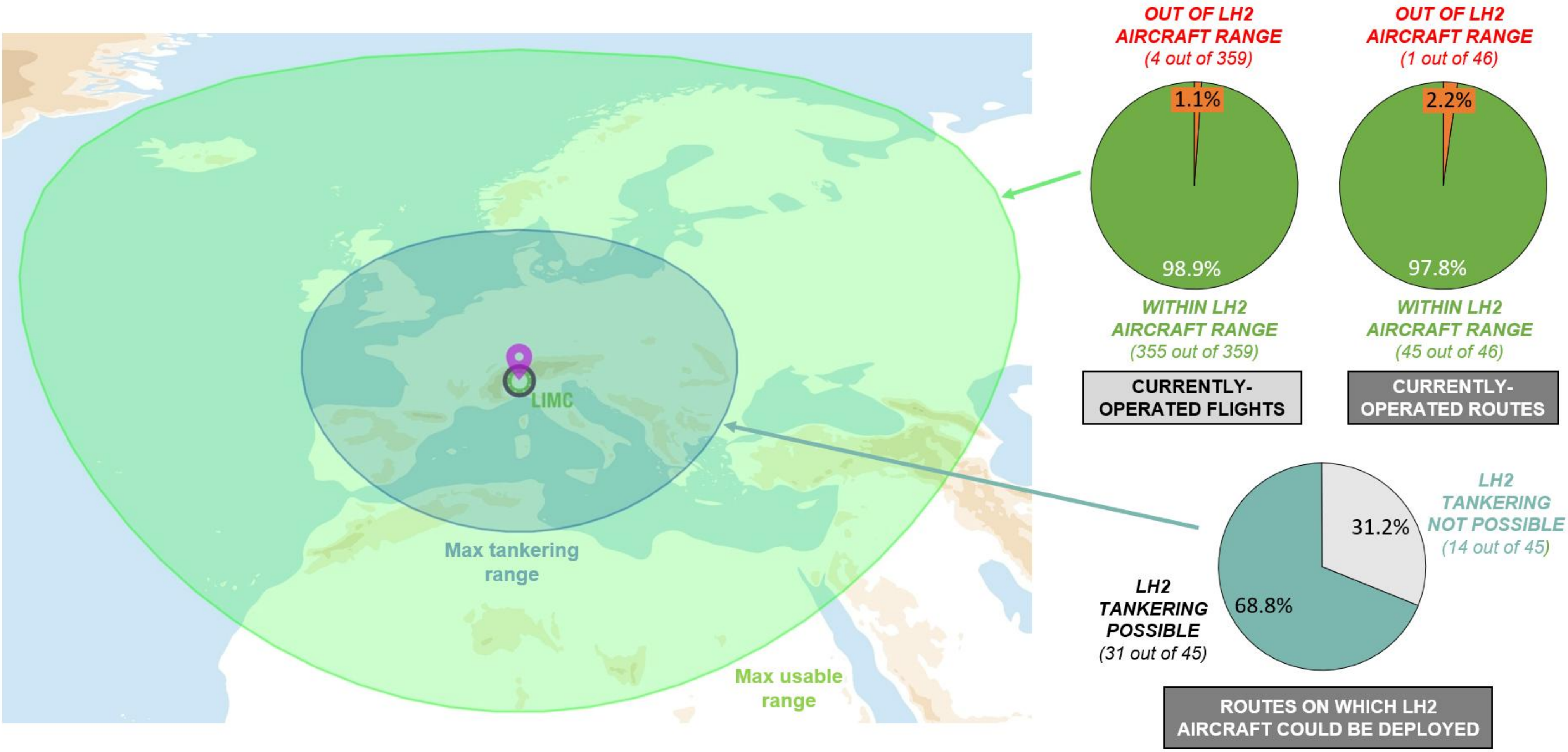
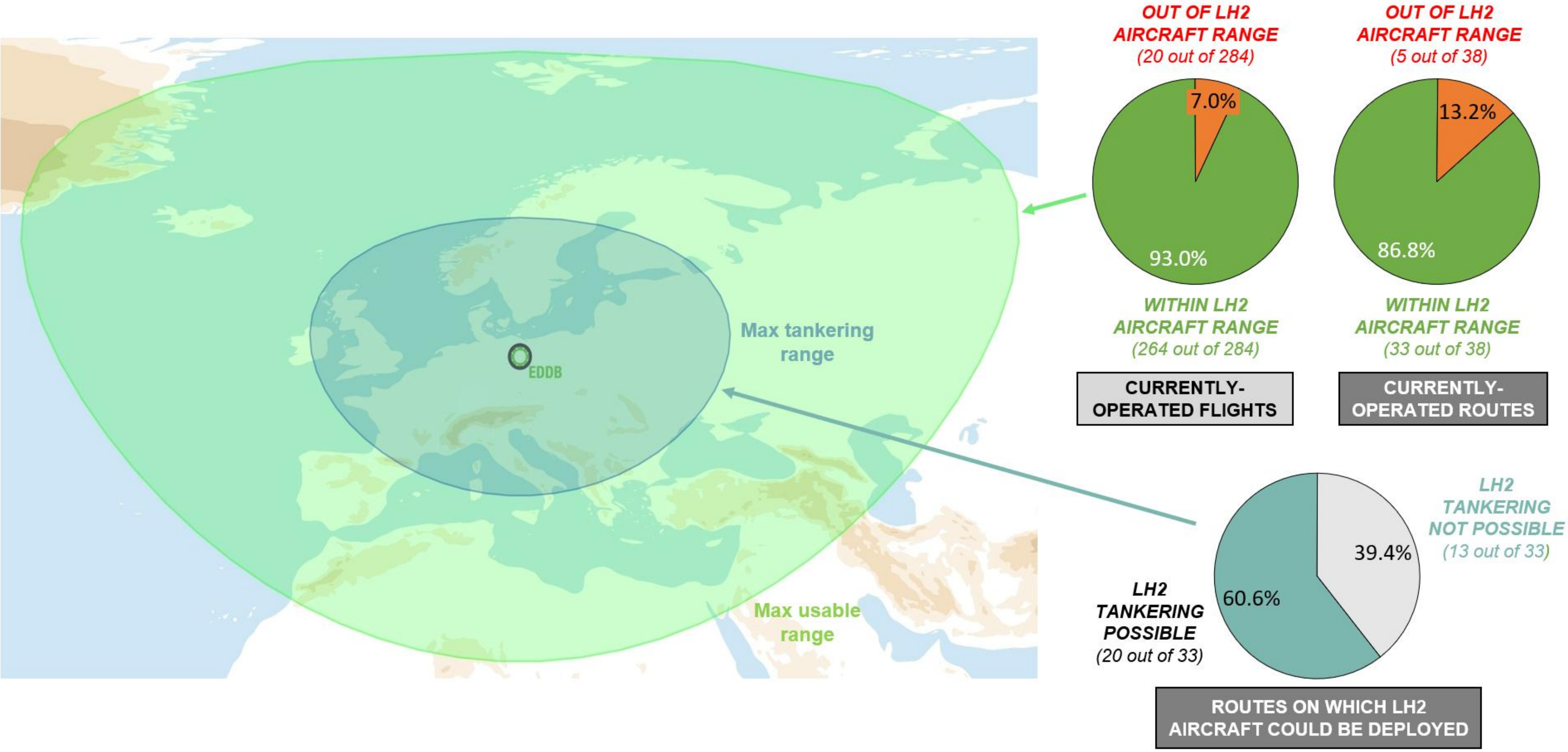


Figure 8 – Flights and routes suitable for LH2 aircraft deployment – Berlin Brandenburg operation



5.2 Impact of Extra Delay on Existing Crew Pairings and Potential Increase in Crew Factor

Figure 9 illustrates how the cumulative extra delay accumulated by LH2 aircraft would impact existing crew pairings. As can be observed, with a normal refuelling schedule, the percentage of crew pairings infringing the contractual and legal limitation buffers ranges from 4.9% (Scenario A1) to 0.8% (Scenario B3). These percentages become even lower when considering the optimised refuelling operation with tankering. Notably, this impact is primarily caused by compatibility issues (i.e., infringement of the buffer from the applicable maximum flight duty hours) with contractual limitations rather than legal ones.

Figure 10 presents the potential increase in the crew factor for LH2 aircraft caused by the need to reschedule the "problematic crew pairings" identified in Figure 9. It needs to be stressed that the presented results are based on the assumption that: (1) the current crew factor is 6.0, and (2) all crew pairings infringing the contractual and legal limitation buffers are split (i.e., each problematic four-sector crew pairing is divided so that two new, shorter two-sector crew pairings are created). This represents the worst-case scenario, as in reality, when a four-sector crew pairing becomes "problematic," airlines often opt to re-couple the assigned city pairs so as to still have a four-sector crew pairing, but with shorter flights – this approach helps maintain high crew productivity levels. Unsurprisingly, even in this case, the overall impact on the crew factor is reduced when considering the optimised refuelling operation with tankering. That said, the increase in crew factor[10] is most pronounced (+5.0% for a normal refuelling schedule and +4.5% for the optimised refuelling operation with tankering) with low LH2 refuelling speeds and strict restrictions on parallel turnaround operations (Scenario A1). Conversely, with high LH2 refuelling speeds and less severe restrictions on parallel turnaround operations (Scenario B3), the projected increase in crew factor is limited to +0.8%.

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[10] Since the average crew factor varies (slightly) from airline to airline, its projected potential increase (caused by the need to reschedule the "problematic crew pairings") is also expected to vary from one company to another. As a general rule, the lower the current crew factor, the higher the projected increase in the "extra crew factor required by LH2 aircraft."

Figure 9 – Impact of cumulative extra delays on existing crew pairings
(the Milan and Berlin operations are considered together – sample composed of 243 crew pairings)

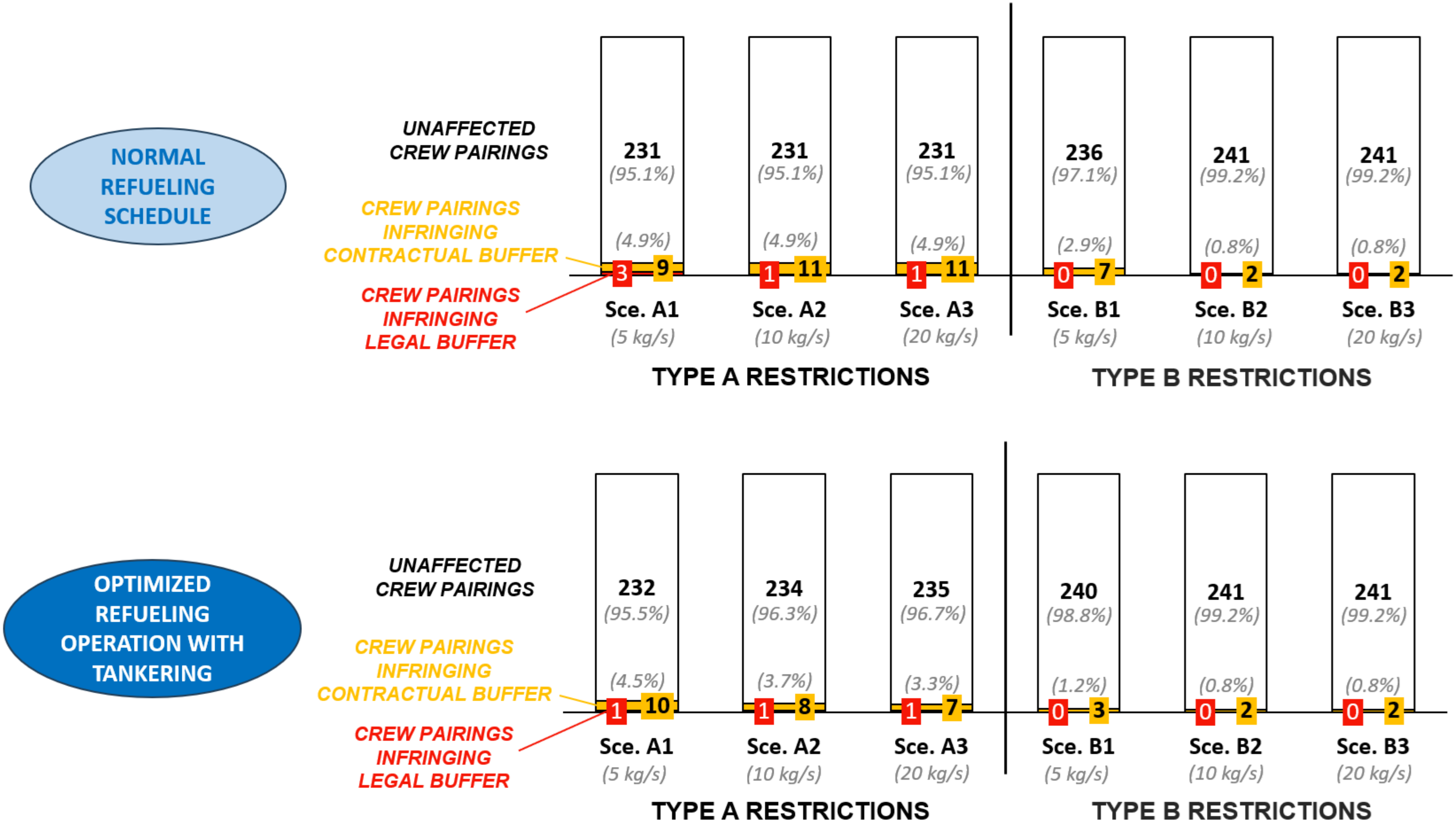


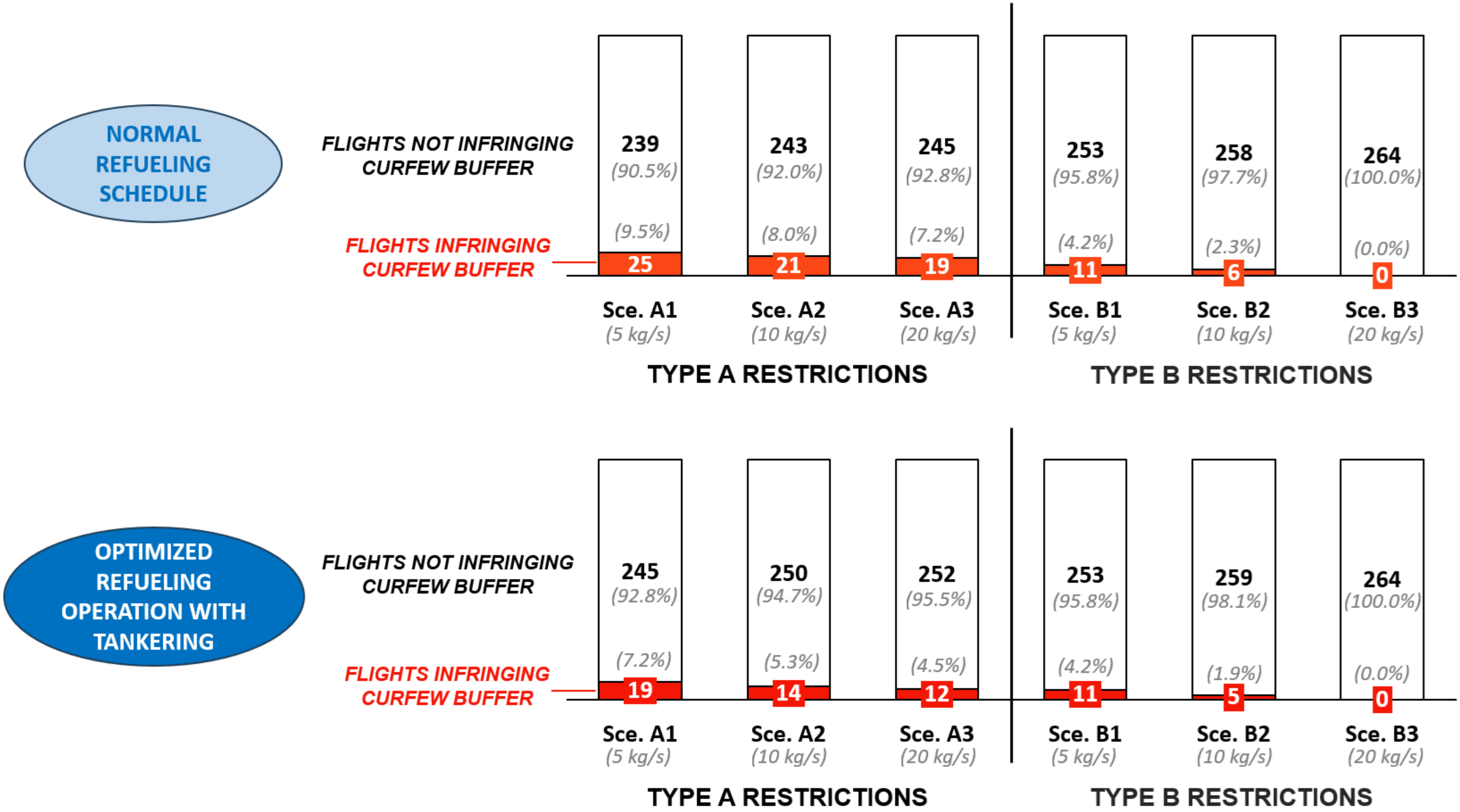
Figure 10 – Potential increase in crew factor for LH2 aircraft (as a result of splitting of the “problematic crew pairings” depicted in Figure 9)

5.3 Compatibility of Extra Delay with Existing Aircraft Routings and Night Curfew Restrictions

When considering the potential impact of cumulative extra delays on aircraft routings, significant differences emerge between the Milan and Berlin operations. Specifically, in the case of Milan, there is no impact as the airport does not have a curfew – i.e., the fact that an aircraft would land with a certain delay on its last flight is essentially inconsequential in operational terms. Conversely, in Berlin, there is a noticeable impact: as illustrated in Figure 11, there are numerous instances in which the cumulative aircraft delay would cause the last flight of the day to infringe the night curfew buffer. This is problematic because it implies that the relevant aircraft routings would have to be changed.

It is worth noting that, when compared to the crew pairings case, on average, the impact is higher, even for the optimised refuelling operation with tankering. The only exception is Scenario B3, in which, regardless of the adopted refuelling schedule, there is no impact.

Figure 11 – Flights infringing the night curfew buffer at Berlin airport due to cumulative aircraft delays
(sample composed of 264 flights)



6 Discussion

The results provide several new insights into the nature and magnitude of the impacts of changes in turnaround times of LH2 aircraft in six different scenarios.

Firstly, concerning crew pairings (Figure 9), the findings reveal that the impact predominantly stems from compatibility issues with existing contractual flight duty limitations, which are more stringent than legal regulations. As a potential mitigation strategy, airlines could attempt to renegotiate the contractual maximum flight duty periods to align them more closely with legal limits. This would allow for the complete elimination of the impact in Scenarios B1, B2, and B3 and a significant reduction in Scenarios A1, A2, and A3. However, even if contractual limitations remain unchanged, the projected increase in the crew factor (and, consequently, crew costs) does not exceed +5% even in the worst-case scenario (Scenario A1 with a normal refuelling schedule). This finding represents an expansion of the literature since, to the best of the authors' knowledge, no prior study has ever addressed this aspect.

Regarding aircraft routings, the results indicate that the impact is entirely contingent on night curfew restrictions. Specifically, at airports with no night flight limitations, such as Milan, no impact is registered. Nevertheless, the cumulative delays, which would result in LH2 aircraft landing later at night, would lead to a reduced available nighttime window for performing the required daily maintenance. This implies that night maintenance operations would necessitate more careful coordination and potentially a higher number of engineers. Conversely, a non-negligible impact is estimated at airports with night curfew restrictions, like Berlin, as the cumulative LH2 aircraft delay would lead to several home-base-night-return flights infringing the curfew buffer. To address this problem, airlines would have two main options: (1) cancel the "problematic flights" (i.e., those infringing the curfew buffer), along with their corresponding outbound legs, to prevent aircraft from being stranded away from their home base overnight. However, this would result in the number of affected flights being twice the number reported in Figure 11; or (2) revise existing aircraft routings. While the second option is clearly preferable as it mitigates adverse consequences compared to the first, it does not come without its challenges: altering already optimised aircraft rotations could potentially reduce aircraft utilisation rates and subsequently increase operating costs for airlines. To a certain extent, this finding aligns with Postma-Kurlanc et al.'s (2022) report, which, in generic terms, indicated that the extended turnaround times of LH2 aircraft could lead to an exceedance of airport operating limits. The results of this study, however, provide a higher level of detail and more insights, not only clearly revealing that the existence of a night curfew is the discriminating element for the onset of an impact on aircraft routings, but also providing a quantification of the expected impact in different operational scenarios.

Moreover, this research demonstrates that, for both crew pairings and aircraft routings, restrictions on parallel turnaround operations during LH2 refuelling have a more significant impact than LH2 refuelling speeds. In other words, the average difference in impact between Scenarios A and B is much more pronounced than that between Scenarios A1 and A3 or B1 and B3. This emphasizes the key importance of safety-driven regulatory restrictions, whose central role in defining the operational disruptiveness of LH2 aircraft was previously suggested, albeit in a more general and less detailed manner, by McKinsey (2020) and Abel and Allfroggen (2023).

It is important to note that the results presented in this paper are based on the analysis of a single high-peak summer week schedule, a critical time for airlines. In less critical periods, such as winter, the impacts may be lower because crew and aircraft are utilised to a lesser extent, which provides wider margins from the relevant operating limitations. Nevertheless, regardless of the fact that the specific magnitude of the identified impacts may vary slightly over the course of the year, the results emphasize the need for airlines, in collaboration with other key aviation industry stakeholders, to implement multiple strategies simultaneously to mitigate the potential operational impacts of LH2 aircraft. These strategies include: (1) redesigning existing refuelling schedules to maximize LH2 tankering; (2) urging civil aviation authorities to explore how less restrictive refuelling restrictions (i.e., type B restrictions) could be implemented as soon as feasible without compromising safety standards; (3) investing in technological advancements that enable the achievement of high LH2 refuelling speeds; and (4) possibly renegotiating existing contractual flight duty limitations to align them more closely with legal regulations, thereby minimizing the potential impact on crew pairings.

Finally, the network suitability analysis conducted to assess the feasibility of LH2 aircraft deployment for the easyJet Milan and Berlin operations (shown in Figures 7 and 8) reveals a remarkable collateral implication for the aviation industry, which has been (at least partially) overlooked in the literature so far: the development of LH2 supply and infrastructure is crucial at airports situated between the max tankering range and max usable range lines, since this is where LH2 aircraft will inevitably need to refuel. However, many of these airports, primarily located outside the European Union, often lack well-defined plans for introducing hydrogen into their operations. To ensure the successful deployment of LH2 aircraft, it is imperative for the aviation industry to take proactive measures to encourage and incentivise these airports to invest in the necessary LH2 supply and infrastructure development.

In summary, the results of this study offer a number of new insights into the nature and estimated magnitude of the impacts that the potential changes in turnaround times of LH2 aircraft may have on airline operational performance. The added value of this novel type of information is that it provides valuable support for airlines and aviation-industry decision-makers in the planning and future managing of the LH2-aircraft-propulsion-driven radical sustainability transition of the air transport industry.

7 Conclusions

This paper investigated the turnaround process-induced operational disruption of LH2 aircraft, exploring the potential impacts of the expected changes in turnaround times of LH2 aircraft on airline operational performance. The results, which are based on six different scenarios, reveal that the cumulative LH2 aircraft delays (caused by the longer ground times) lead to certain compatibility issues with: crew pairings (hence possibly causing an increase in the crew factor) and, when LH2 aircraft are based at airports with night curfew restrictions, with aircraft routings (hence possibly causing a reduction in aircraft utilisation rates). The magnitude of the impacts depends on three key factors: (1) restrictions on parallel turnaround operations during LH2 refuelling; (2) LH2 refuelling speed; and (3) the use of an optimised refuelling operation with LH2 tankering.

In light of the identified root causes behind the investigated impacts, this study offers a range of mitigation strategies that airlines, in collaboration with other key aviation industry stakeholders, could implement to minimise the potential operational disruptiveness of LH2 aircraft.

It is important to remark that the results of this study are derived from real-world operational data provided by a major European low-cost airline. This approach allowed to obtain results that, thanks to their high levels of accuracy, are of significant relevance for practitioners and the industry. This is an element of crucial differentiation from existing literature, which has thus far relied exclusively on generic and average industrial values.

Overall, the main conclusion of this study is that, since the changes in turnaround times of LH2 aircraft are expected to have a rather marginal impact on airline operational performance, LH2 aircraft propulsion technology has the potential, following the implementation of the necessary adjustments and accommodations, to be compatible with existing operations

While this research presents valuable insights, it has four limitations: (1) it focuses exclusively on a specific time period and a portion of an airline's operational scope; (2) it is based on a single company, whose operational dynamics may not necessarily align with those of other airlines, especially when different operating models are used; (3) it does not take into account that the increased turnaround times of LH2 aircraft and the resulting cumulative delays may lead to extra congestion at airports as well as possible compatibility issues with existing airport slots; and (4) it does not quantify the economic consequences of the identified operational impacts, as this aspect falls outside the scope of the paper. To address these limitations, future research could: (1) analyse a broader segment of the easyJet operation—i.e., a longer time window and/or operations conducted from other bases—to further refine the results presented by this study; (2) examine the operations of other airlines, especially those employing diverse operating models (e.g., legacy carriers), to capture the nuances and characteristics of the different impacts on different industry actors; (3) investigate the effects of the increased turnaround times of LH2 aircraft on airport capacity and existing airport slots; and (4) quantify the economic consequences of the identified operational impacts (e.g., calculate the potential decrease in aircraft utilisation rates and increase in crew costs) and assess their resulting impact on airline economic performance.

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References

Abel, J. and Allfroggen, F. (2023) ‘Global Costs and Infrastructure Requirements for LH2 Airport Refuelling’, *AIAA AVIATION 2023 Forum*, 12-16 June 2023, San Diego, CA, https://doi.org/10.2514/6.2023-3406

ACI and ATI (2021) ‘Integration of Hydrogen Aircraft into the Air Transport System: An Airport Operations and Infrastructure Review’, Airport Council International & Aerospace Technology Institute, Report, https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf (accessed 11 November 2023).

Airbus (2020a) ‘Safe aircraft refuelling’, https://mms-safetyfirst.s3.eu-west-3.amazonaws.com/pdf/safety+first/safe-aircraft-refuelling.pdf (accessed 1 June 2024).

Airbus (2020b) ‘A320 Aircraft Characteristics – Airport and Maintenance Planning’, pp. 194–205, https://www.airbus.com/sites/g/files/jlcbta136/files/2021-11/Airbus-Commercial-Aircraft-AC-A320.pdf (accessed 19 May 2024).

Airbus (2021) ‘How to store liquid hydrogen for zero-emission flight’, https://www.airbus.com/en/newsroom/news/2021-12-how-to-store-liquid-hydrogen-for-zero-emission-flight (accessed 5 October 2024).

Airbus (2022) ‘easyJet confirms order for a further 56 A320neo Family aircraft’, https://aircraft.airbus.com/en/newsroom/press-releases/2022-07-easyjet-confirms-order-for-a-further-56-a320neo-family-aircraft (accessed 12 March 2024).

ATAG (2021) ‘Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century’, Air Transport Action Group, https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf (accessed 16 June 2023).

Babuder, D., Lapko, Y., Trucco, P. and Taghavi, R. (2024) ‘Impact of emerging sustainable aircraft technologies on the existing operating ecosystem’, *Journal of Air Transport Management*, Vol. 115, March 2024, 102524, pp. 1–18, https://doi.org/10.1016/j.jairtraman.2023.102524

Brewer, G. D. (1976) ‘LH2 airport requirements study’, National Aeronautics and Space Administration, Technical report, https://ntrs.nasa.gov/api/citations/19770003090/downloads/19770003090.pdf (accessed 16 October 2023).

Camilleri, M. A. (2018) ‘Aircraft Operating Costs and Profitability’ in *Travel Marketing, Tourism Economics and the Airline Product*, Chapter 12, pp. 191–204, Cham, Switzerland: Springer Nature, https://doi.org/10.1007/978-3-319-49849-2_12

Choi, Y. and Lee, J. (2022) ‘Estimation of Liquid Hydrogen Fuels in Aviation’, *Aerospace 2022*, Vol. 9, No. 10, 564, https://doi.org/10.3390/aerospace9100564

Cole, J., McClintock, W. and Powis, L. (2022) ‘Market Forecasts & Strategy’, Report, https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-REP-0043-Market-Forecasts-and-Strategy.pdf (accessed 12 June 2023).

Debney, D., Beddoes, S., Foster, M., James, D., Kay, E., Kay, O., Shawki, K., Stubbs, E., Thomas, D., Weider, K. and Wilson, R. (2022) ‘Zero-Carbon Emission Aircraft Concepts’, Report, https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf (accessed 22 May 2023).

Desaulniers, G., Desrosiers, J., Dumas, Y., Marc, S., Rioux, B., Solomon, M.M. and Soumis, F. (1997) ‘Crew pairing at Air France’, *European Journal of Operational Research*, Vol. 97, No. 2, March 1997, pp. 245–259, https://doi.org/10.1016/S0377-2217(96)00195-6

EASA (2023a) ‘Easy Access Rules for Air Operations (Regulation (EU) No 965/2012)’, European Union Aviation Safety Agency, https://www.easa.europa.eu/en/document-library/easy-access-rules/easy-access-rules-air-operations-regulation-eu-no-9652012 (accessed 3 February 2024).

EASA (2023b) ‘Easy Access Rules for Aerodromes (Regulation (EU) No 139/2014)’, European Union Aviation Safety Agency, https://www.easa.europa.eu/en/document-library/easy-access-rules/easy-access-rules-aerodromes-regulation-eu-no-1392014 (accessed 3 February 2024).

easyJet (2016) ‘Annual Report 2016 – Investing in our strengths’, https://corporate.easyjet.com/~/media/Files/E/Easyjet/pdf/investors/result-center-investor/annual-report-2016.pdf (accessed 12 December 2023).

easyJet (2017) ‘Annual Report 2017 – Purposeful and disciplined growth’, https://corporate.easyjet.com/~/media/Files/E/Easyjet/pdf/investors/results-centre/2017/2017-annualreport-and-accounts-v1.pdf (accessed 12 December 2023).

easyJet (2018) ‘Annual Report 2018 – The warmest welcome in the sky’, https://corporate.easyjet.com/~/media/Files/E/Easyjet/pdf/investors/results-centre/2018/2018-annual-report-and-accounts.pdf (accessed 12 December 2023).

easyJet (2019) ‘Annual Report 2019 – Resilient focused data driven’, https://corporate.easyjet.com/~/media/Files/E/Easyjet/pdf/investors/results-centre/2019/eas040-annual-report-2019-web.pdf (accessed 12 December 2023).

easyJet (2022a) ‘Annual Report 2022 – Making low-cost travel easy’, https://corporate.easyjet.com/~/media/Files/E/Easyjet/pdf/investors/results-centre/2022/annual-report-2022.pdf (accessed 7 April 2024).

easyJet (2022b) ‘Net-Zero Pathway’, https://corporate.easyjet.com/~/media/Files/E/Easyjet/documents/easyjet-nz-roadmap.pdf (accessed 14 March 2024).

Eurocontrol (2022) ‘Performance 2022 – Outlook 2023’, Aviation Intelligence Unit, https://www.eurocontrol.int/archive_download/all/node/13931 (accessed 18 September 2023).

Eurocontrol (2023) ‘Overview of air traffic figures June – July – August 2023’, https://www.eurocontrol.int/press-release/overview-air-traffic-figures-june-july-august-2023 (accessed 15 December 2023).

European Commission (2022) ‘State aid: Commission approves award of slots at Lisbon airport to easyJet following TAP Group’s restructuring’, https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_22_3783/IP_22_3783_EN.pdf (accessed 16 October 2023).

GKN Aerospace (2022) ‘easyJet partners with GKN Aerospace to accelerate adoption of hydrogen in aviation’, https://www.gknaerospace.com/en/newsroom/news-releases/2022/easyjet-partners-with-gkn-aerospace-to-accelerate-adoption-of-hydrogen-in-aviation/ (accessed 18 July 2023).

Gomez, A., and Smith, H. (2019) ‘Liquid hydrogen fuel tanks for commercial aviation: Structural sizing and stress analysis’, *Aerospace Science and Technology*, Vol. 95, December 2019, 105438, https://doi.org/10.1016/j.ast.2019.105438

Hoelzen, J., Flohr, M., Silberhorn, D., Mangold, J., Bensmann, A. and Hanke-Rauschenbach, R. (2022a) ‘H2-powered aviation at airports – Design and economics of LH2 refuelling systems’, *Energy Conversion and Management: X*, Vol. 14, May 2022, 100206, https://doi.org/10.1016/j.ecmx.2022.100206

Hoelzen, J., Koenemann, L., Kistner, L., Schenke, F., Bensmann, A., and Hanke-Rauschenbach, R. (2023a) ‘H2-powered aviation – Design and economics of green LH2 supply for airports’, *Energy Conversion and Management: X*, Vol. 20, October 2023, 100442, https://doi.org/10.1016/j.ecmx.2023.100442

Hoelzen, J., Silberhorn, D., Schenke, F., Stabenow, E., Zill, T., Bensmann, A. and Hanke-Rauschenbach, R. (2023b) ‘H2-Powered Aviation – Optimised Aircraft and Green LH2 Supply in Air Transport Networks’, Preprint, http://dx.doi.org/10.2139/ssrn.4613255

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B. and Hanke-Rauschenbach, R. (2022b) ‘Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – review and research gaps’, *International Journal of Hydrogen Energy*, January, Vol. 47, No. 5, pp.3108–3130, https://doi.org/10.1016/j.ijhydene.2021.10.239

Hutter, F. G. and Pfennig, A. (2023) ‘Reduction in Ground Times in Passenger Air Transport: A First Approach to Evaluate Mechanisms and Challenges’, *Applied Sciences*, Vol. 13, No. 3, 1380, https://doi.org/10.3390/app13031380

IATA (2019) ‘Liquid hydrogen as a potential low-carbon fuel for aviation’, Fact sheet, https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf (accessed 3 October 2024).

IATA (2020) ‘Standard into-plane fueling service levels and safety’, International Air Transport Association, https://www.iata.org/contentassets/828efe1a6a2a487aacaa8fe7642f0c72/iftpstandard-fueling-procedures_service-levels-and-safety-v1.00.pdf (accessed 12 September 2023).

IATA (2023) 'Aircraft Technology – Net Zero Roadmap', Report, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/aircraft-technology-net-zero-roadmap.pdf (accessed 3 October 2024).

ICAO (2022a) 'Hydrogen, a key solution to decarbonize aviation', Assembly – 41st Session, Working Paper, https://www.icao.int/Meetings/a41/Documents/WP/wp_514_en.pdf (accessed 3 October 2024).

ICAO (2022b) '2022 Environmental Report – Innovation for a green transition', Report, pp. 106-112 and 126-130, https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf (accessed 3 October 2024).

Kasirzadeh, A., Saddoune, M. and Soumis, F. (2017) 'Airline crew scheduling: models, algorithms, and data sets', *EURO Journal of Transportation and Logistics*, Vol. 6, No. 2, June 2017, pp. 111–137, https://doi.org/10.1007/s13676-015-0080-x

Mangold, J., Silberhorn, D., Moebs, N., Dzikus, N., Hoelzen, J., Zill, T. and Strohmayer, A. (2022) 'Refuelling of LH2 Aircraft—Assessment of Turnaround Procedures and Aircraft Design Implications.' *Energies*, Vol. 15, No. 7, 2475, https://doi.org/10.3390/en15072475

McKinsey (2020) 'Hydrogen-powered aviation. A fact-based study of hydrogen technology, economics, and climate impact by 2050', Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU, Report, https://op.europa.eu/en/publication-detail/-/publication/55fe3eb1-cc8a-11ea-adf7-01aa75ed71a1/language-en (accessed 11 May 2023).

Mirza, M. (2009) 'Economic Impact of Airplane Turn-Times', Boeing, *Aeromagazine*, http://www.lb.boeing.com/commercial/aeromagazine/articles/qtr_4_08/pdfs/AERO_Q408_article03.pdf (accessed 25 May 2024).

More, D. and Sharma, R. (2014) 'The turnaround time of an aircraft: a competitive weapon for an airline company', *Decision*, Vol. 41, pp. 489–497, https://doi.org/10.1007/s40622-014-0062-0

Mukhopadhaya, J. and Rutherford, D. (2022) 'Performance analysis of Evolutionary Hydrogen-Powered Aircraft', International Council on Clean Transportation, White paper, https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf (accessed 17 April 2024).

OAG (2021) 'OAG Take-off 2021 – Essential metrics on the world's major airlines', https://www.oag.com/hubfs/take-off-2021.pdf?hsCtaTracking=7393cfd4-1ad4-404e-8cd0-ed64bd741ad5%7C28f834ca-ed34-4a41-8efa-dd9a20068cbe (accessed 8 February 2024).

Ozion (2021) 'PRM penetration rates – Comparative report 2021 vs 2020 vs 2019', https://www.ozion-airport.com/product/prm-penetration-report-comparative-report-2021-vs-2020-vs-2019/ (accessed 23 July 2023).

Parmentier, A. and Meunier, F. (2020) ‘Aircraft routing and crew pairing: updated algorithms at Air France’, *Omega*, Vol. 93, June 2020, 102073, https://doi.org/10.1016/j.omega.2019.05.009

Postma-Kurlanc, A., Leadbetter, H. and Pickard, C. (2022) ‘Hydrogen infrastructure and operations. Airports, Airlines and Airspace’, FlyZero, Aerospace Technology Institute, Report, https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf (accessed 22 August 2023).

Rolls-Royce (2022) ‘easyJet and Rolls-Royce partner on hydrogen technology demonstrator programme’, https://www.rolls-royce.com/media/press-releases/2022/19-07-2022-easyjet-and-rr-pioneer-hydrogen-engine-combustion-technology-in-h2zero-partnership.aspx (accessed 19 September 2023).

Rondinelli, S., Gardi, A., Kapoor, R. and Sabatini, R. (2017) ‘Benefits and challenges of liquid hydrogen fuels in commercial aviation’, *International Journal of Sustainable Aviation*, Vol. 3, No. 3, pp. 200–216, https://doi.org/10.1504/IJSA.2017.086845

Steer (2023) ‘Analysing the costs of hydrogen aircraft’, Final report, April 2023, https://www.transportenvironment.org/wp-content/uploads/2023/05/Study-Analysing-the-costs-of-hydrogen-aircraft.pdf (accessed 4 March 2024).

Van der Sman, E., Peerlings, B., Kos, J., Lieshout, R. and Boonekamp, T. (2021) ‘Destination 2050 – A route to net zero European aviation’, Netherlands Aerospace Centre and SEO Amsterdam Economics, Report, https://www.destination2050.eu/wp-content/uploads/2021/02/Destination2050_Report.pdf (accessed 22 May 2024).

Verstraete, D., Hendrick, P., Pilidis, P., and Ramsden, K. (2010) ‘Hydrogen fuel tanks for subsonic transport aircraft’, *International Journal of Hydrogen Energy*, Vol. 35, No. 20, pp. 11085–11098, https://doi.org/10.1016/j.ijhydene.2010.06.060

Waltenberger, J. and Ruff-Stahl, H. K. (2018) ‘Implications of Short Scheduled Ground Times for European Carriers’, *International Journal of Aviation, Aeronautics, and Aerospace*, Vol. 5, No. 3, pp. 1–18, https://doi.org/10.15394/ijaaa.2018.1244

Wu, C. and Caves, R. E. (2000) ‘Aircraft operational costs and turnaround efficiency at airports’, *Journal of Air Transport Management*, Vol. 6, No. 4, pp. 201–208, https://doi.org/10.1016/S0969-6997(00)00014-4

Ye, X. (2007) ‘Airlines’ Crew Pairing Optimisation: A Brief Review’, Johns Hopkins University, https://www.cis.jhu.edu/~xye/papers_and_ppts/ppts/airline_crewpairing.pdf (accessed 28 June 2023).

Yilmas, I., Ilbas, M., Tastan, M. and Tarhan, C. (2012) ‘Investigation of hydrogen usage in aviation industry’, *Energy Conversion and Management*, Vol. 63, November 2012, pp. 63–69, https://doi.org/10.1016/j.enconman.2011.12.032

Annex A

Table A1 – Assumptions used in the Gantt charts shown in Figures 4 and 5

Category	**Parameter / Operation**	**Value / Time**	**Source**		**Sources and Comments**
			Airbus	easyJet	
PASSENGER HANDLING & CABIN OPERATIONS	Number of passengers to be deboarded/boarded	165 + 1 PRM requiring an ambulift		✓	*Sources: easyJet (2016); easyJet (2017); easyJet (2018); easyJet, (2019); Ozion (2021)* - 92% load factor for a 180-seat aircraft – this is based on easyJet's historical average load factor - The number of Passenger with Reduced Mobility (PRM) is in line with the European aviation industry's average rate of approximately 1 % - One PRM requires an ambulift to deboard/board the aircraft*
	Equipment positioning (stairs) + aircraft doors opening	2 min	✓		*Source: Airbus (2020b)*
	Passenger deboarding	5 min (deboarding rate: 18 pax/min per door)	✓		*Source: Airbus (2020b)*
	Cabin tidying & searching	8 min		✓	*Source: data provided by the company ('easyJet Turn Card')*
	Passenger boarding	7 min (boarding rate: 12 pax/min per door)	✓		*Source: Airbus (2020b)*
	Ambulift positioning & connecting + aircraft door opening	2 min		✓	*Source: 12 easyJet pilots and 10 easyJet cabin crew (the reported value represents the average of the collected responses)*
	PRM deboarding/boarding via ambulift	2 min		✓	*Source: 12 easyJet pilots and 10 easyJet cabin crew (the reported value represents the average of the collected responses)*
	Ambulift removal & disconnection + aircraft door closure	1.5 min		✓	*Source: 12 easyJet pilots and 10 easyJet cabin crew (the reported value represents the average of the collected responses)*
	Last Pax Seating (LPS) allowance	1 min	✓		*Source: Airbus (2020b)*
	Aircraft doors closure + equipment removal (stairs)	1.5 min	✓		*Source: Airbus (2020b)*
CREW	Cabin crew deboarding aircraft/ moving out of the FSZ before LH2 refuelling	1 min		✓	*Source: 12 easyJet pilots and 10 easyJet cabin crew (the reported value represents the average of the collected responses)* This is only applicable in Scenarios A1, A2, and A3
	Cabin crew boarding aircraft/ returning to their workstations after LH2 refuelling	1 min		✓	*Source: 12 easyJet pilots and 10 easyJet cabin crew (the reported value represents the average of the collected responses)* This is only applicable in Scenarios A1, A2, and A3

BAGGAGE HANDLING	Initial hold door opening + equipment positioning (belt loaders)	2 min	✓		*Source: Airbus (2020b)*
	Equipment removal before LH2 refuelling (leaving hold door open)	1 min		✓	*Source: 12 easyJet pilots (the reported value represents the average of the collected responses)* It is assumed that baggage handling equipment has to be removed before the start of LH2 refuelling since it will probably fall within the FSZ; however, the aircraft hold door can be left open to save some time when re-positioning the equipment
	Equipment re-positioning after LH2 refuelling (with hold door already open)	1.5 min		✓	*Source: 12 easyJet pilots (the reported value represents the average of the collected responses*
	Baggage unloading/ loading time	Variable	N/A		Time is variable since baggage amount varies on every flight. In any case, there should be no problem in performing this operation in the 'available time windows,' which are significantly longer than the required times calculated by Airbus (2020b) for the A320
	Equipment removal + hold door closure	1.5 min	✓		*Source: Airbus (2020b)*
WASTE WATER SERVICING**	Equipment positioning	2 min	✓		*Source: Airbus (2020b)* This operation is required only for 'full servicing turnarounds'
	Waste water servicing procedure (for a full tank)	4 min	✓		
	Equipment removal	2 min	✓		
POTABLE WATER SERVICING**	Equipment positioning	2 min	✓		*Source: Airbus (2020b)* This operation is required only for 'full servicing turnarounds'
	Potable water servicing procedure (for a full tank)	5 min	✓		
	Equipment removal	2 min	✓		
FINAL CHECKS (after aircraft doors closure)	Ramp agent walkaround & external checks	1 min		✓	*Source: data provided by the company ('easyJet Turn Card')* These operations are performed after aircraft doors closure
	Pilot checks & push-back clearance	2 min		✓	

** Not all PRMs require an ambulift to board/deboard the aircraft. The so-called 'WCHR PRMs,' which are one of the three categories into which PRMs are typically divided, board and deboard using normal stairs as they only require assistance over long walking distances. As a result, it was assumed that, per flight, only one person needs to use the ambulift for boarding and deboarding. While this is obviously an approximation, it was considered acceptable for the purpose of this study.*

*** The waste water and potable water servicing procedures can be performed interchangeably (i.e., either of the two can be performed before or after the other one in the two 'available time windows')*

Annex B

B.1. Calculation of Max Usable Range and Max Tankering Range

To determine the flights and routes suitable for LH2 aircraft deployment, it was first necessary to calculate the 'max usable range' of LH2 aircraft as a great circle distance. This was achieved using the following formula:

$$\text{max usable range} = \text{design range} - \text{difference between direct and flown distance} - \text{destination/alternate distance}$$

In this formula, 'difference between direct and flown distance' refers to the average variance between the direct distance and the actual distance travelled (which is always greater), while 'destination/alternate distance' represents the average flying distance from the destination to the alternate aerodrome. Although these parameters vary from flight to flight, for these calculations both terms were assumed to be 150 NM, which is a reasonable approximation based on the analysis of easyJet historical operational data. Considering that the reference LH2 aircraft has a design range of 2,000 NM, the max usable range (as a great circle distance) was calculated to be 1,700 NM.

Similarly, to identify the LH2 aircraft routes suitable for LH2 tankering, it was necessary to calculate the 'max tankering range' of LH2 aircraft as a great circle distance. This was done using the following formula:

$$\text{max tankering range} = \frac{\text{design range} - (2 * \text{difference between direct and flown distance}) - \text{destination/alternate distance}}{2}$$

As can be observed, the 'difference between direct and flown distance' is multiplied by 2 because it applies to both outbound and return flights. On the other hand, the 'destination/alternate distance' is only considered once since it is not relevant during the tankering flight. After performing the calculations, the max tankering range of LH2 aircraft as a great circle distance was determined to be 775 NM.

Both the max usable and tankering great circle ranges were plotted on a map, with their centres co-located at the reference airports (i.e., MXP and BER). By comparing the currently-operated flights and routes with the relevant circles, the segment of the considered easyJet operation suitable for LH2 aircraft deployment and tankering was identified. The results of this analysis are shown in Figures 7 and 8.

B.2. Determination of LH2 Aircraft Turnaround Time and Calculation of Extra Delays

The determination of LH2 aircraft turnaround time and the quantification of the extra delay involved creating tables that incorporate all relevant operational parameters and formulas to generate automatic results. This section explains the logic behind these tables and discusses how the results were obtained. An example of one of such tables is reported in Table B1.

The initial step involved inserting operational data into the relevant columns (i.e., those titled: 'sector,' 'off-chocks,' 'on-chocks,' 'Jet A-1 block fuel') – the cells where operational data were inserted are coloured in light blue (see Table B1).

The 'turnaround time' was calculated as the difference between the 'on-chocks' time (of the ending sector) and the ‘off-chocks’ time (of the following sector).

The ‘turnaround buffer’ represents the extra turnaround time assigned by an airline to absorb possible inefficiencies during the turnaround process (e.g., delays in the provision of required services or turnaround activities taking longer than planned). Based on information from easyJet, this buffer, varying from airport to airport, is generally derived from historical turnaround performance. Considering easyJet’s assumption that an A320 aircraft can be turned around in 30 minutes under ideal conditions, any time exceeding this threshold was classified as ‘turnaround buffer.’ Although there are other factors, such as slot restrictions at slot-constrained airports, that play a role in determining the assigned turnaround time, this approximation was considered sufficiently reasonable for the purpose of this study.

The ‘Jet A-1 fuel to be uplifted’ was determined by subtracting the average residual JET A-1 fuel left in the tanks at engine shut-down—which examination of easyJet historical flight plans revealed to be around 2,500 kg on average—from the ‘Jet A-1 block fuel.’

As reported by Yilmas et al. (2012) and Choi and Lee (2022), 1 kg of Jet A-1 contains the same energy as 0.36 kg of LH2. Thus, the ‘equivalent LH2 quantity’ was derived by multiplying the ‘JET A-1 fuel to be uplifted’ by 0.36.

When tankering, the ‘equivalent LH2 quantity’ was corrected for the LH2 tankering penalty factors reported by Hoelzen et al. (2023b).

The ‘LH2 refuelling time’ was obtained by dividing the ‘required LH2 quantity’ by the ‘LH2 refuelling speed.’ As the model considers three different LH2 refuelling speeds, this and all subsequent calculations were performed three times.

The ‘total length of the LH2 refuelling procedure’ was determined by adding the extra 6 minutes required by the clean break disconnect method for pre- and post-LH2 refuelling steps (i.e., LH2 truck positioning and connecting, chill-down, LH2 truck disconnecting and removal) to the ‘LH2 refuelling time.’

For A Scenarios, the ‘total length of the LH2 refuelling procedure’ had to be considered in its entirety (since, as discussed in Section 4.1.2, the refuelling operation is the factor driving the increase in turnaround time). However, for B Scenarios, the situation is different. This is because, for 6.5 minutes, the LH2 refuelling procedure takes place in parallel with the cabin crew tidying and searching operation (as shown in Figure 5). Consequently, the ‘extra LH2 refuelling time’ (applicable only for B Scenarios) was calculated by subtracting 6.5 minutes from the ‘total length of the LH2 refuelling procedure’ – for graphical reasons, this is not reported in Table B1.

As illustrated in Figures 4 and 5, for the given conditions, the minimum time required to perform all turnaround activities that are non-LH2-refuelling-related is 32 minutes for A Scenarios and 30 minutes for B Scenarios. Consequently, the ‘turnaround time of LH2 aircraft’ was calculated as follows:

turnaround time of LH2 aircraft (A Scenarios) = total length of the LH2 refuelling procedure + 32 min + turnaround buffer

turnaround time of LH2 aircraft (B Scenarios) = extra LH2 refuelling time + 30 min + turnaround buffer

Existing turnaround buffers were included in the calculations to generate results that are as realistic as possible.

The ‘extra delay’ accumulated during each turnaround was calculated by comparing the new turnaround time required by LH2 aircraft with the one currently assigned to the reference kerosene aircraft. It must be emphasized that extra delays are assumed to be accrued only during actual turnarounds since these are the critical periods on which the LH2 refuelling operation can have an impact (i.e., during initial aircraft preparation and firebreaks no delays are accumulated as the time windows are long enough to absorb the extra time required by the LH2 refuelling procedure).

The ‘cumulative delay’ (for the crew or the aircraft) was calculated by summing all relevant ‘extra delays’ (i.e., those accumulated during a certain flight duty period or throughout the day).

Table B1 – Example of one of the tables used to determine the turnaround time of LH2 aircraft and the extra delay (normal refuelling schedule)

								LH2 REFUELLING TIME (min)		
								LH2 refuelling speed		
SECTOR (in IATA 3-letter codes)	**OFF-CHOCKS** (UTC time)	**ON-CHOCKS** (UTC time)	**TURNAROUND TIME** (min)	**TURNAROUND BUFFER** (min)	**JET A-1 BLOCK FUEL** (kg)	**JET A-1 FUEL TO BE UPLIFTED** (kg)	**EQUIVALENT LH2 QUANTITY** (kg)	5 kg/sec (300 kg/min)	10 kg/sec (600 kg/min)	20 kg/sec (1,200 kg/min)
BER-OLB	10:45	13:05								
Turnaround			35	5	6694	4194	1510	5	2.5	1.5
OLB-BER	13:40	16:00								
Turnaround			40	10	5378	2878	1036	3.5	1.5	1
BER-ARN	16:40	18:30								
Turnaround			30	0	5378	2878	1036	3.5	1.5	1
ARN-BER	19:00	20:45								

TOTAL LENGTH OF THE LH2 REFUELLING PROCEDURE (min)			**TURNAROUND TIME OF LH2 AIRCRAFT and EXTRA DELAY** (min)											
LH2 refuelling speed			**SCENARIO A**						**SCENARIO B**					
5 kg/sec	10 kg/sec	20 kg/sec	A1 (5 kg/sec)	EXTRA DELAY	A2 (10 kg/sec)	EXTRA DELAY	A3 (20 kg/sec)	EXTRA DELAY	B1 (5 kg/sec)	EXTRA DELAY	B2 (10 kg/sec)	EXTRA DELAY	B3 (20 kg/sec)	EXTRA DELAY
11	8.5	7.5	48	13	45.5	10.5	44.5	9.5	39.5	4.5	37	2	36	1
9.5	7.5	7	51.5	11.5	49.5	9.5	49	9	43	3	41	1	40.5	0.5
9.5	7.5	7	41.5	11.5	39.5	9.5	39	9	33	3	31	1	30.5	0.5
			CUMULATIVE DELAY	36		29.5		27.5		10.5		4		2

B.3. Determination of Compatibility of Extra Delays with Existing Crew Pairings and Calculation of New Crew Factor for LH2 Aircraft

To assess the impact of cumulative extra delays on existing crew pairings, a second set of tables was developed (see Table B2 for an example). The purpose of these tables was to verify whether the additional delays caused by the use of LH2 aircraft are compatible with existing crew pairings or if they result in a violation of the buffer from the contractual and legal maximum flight duty time limitations.

The ‘original FDP’ (short for maximum Flight Duty Period) was determined by subtracting the ‘crew report time’ from the ‘final sector’s on-chocks time’ – the ‘crew report time’ was provided by easyJet.

The applicable ‘max contractual FDP’ was derived from easyJet’s contractual max FDP tables. The ‘existing buffer from contractual limit’ was determined by subtracting the ‘original FDP’ from the ‘max contractual FDP.’

The applicable ‘max legal FDP’ was derived from EASA’s ORO.FTL.205 ‘Maximum daily FDP – Acclimatised crew members’ table, which represents the current FDP limit at a European level. The ‘existing buffer from legal limit’ was determined by subtracting the ‘original FDP’ from the ‘max legal FDP.’

The ‘cumulative delay (induced by the use of LH2 aircraft)’ was determined by adding all the previously calculated ‘extra delays’ encountered by the crew throughout the flight duty period. The ‘new FDP’ was calculated by adding the ‘cumulative delay (induced by the use of LH2 aircraft)’ to the ‘original FDP.’ The new buffers (from contractual and legal limits) were computed by simply subtracting the ‘new FDP’ from the relevant max FDP (contractual/legal). To align with the currently used planning guidelines, the results were colour-coded, with green indicating that the new buffer is equal to or higher than 30 minutes (i.e., sufficient margin from the relevant max FDP), and red indicating that this buffer is below 30 minutes (i.e., insufficient margin from the relevant max FDP, making the crew pairing “problematic”).

To calculate the ‘new crew factor’ for LH2 aircraft, two formulas were used:

$$\textit{new number of crew pairings to be operated} = \textit{current number of crew pairings operated} + (\textit{number of duties affected by contractual/legal buffer infringement} * 2)$$

$$\textit{new crew factor} = \frac{\textit{current crew factor} * \textit{new number of crew pairings to be operated}}{\textit{current number of crew pairings operated}}$$

As can be noted, the ‘number of duties affected by contractual/legal buffer infringement’ is multiplied by 2. This is because, as discussed in Section 5.2, it is assumed that all “problematic crew pairings” are split, which results in a doubling of the number of crew pairings that need to be operated.

Table B2 – Example of one of the tables used to determine the impact of the extra delays on crew pairings (the table uses the same crew pairing as Table B1)

ORIGINAL FDP	11:00						
MAX CONTRACTUAL FDP	11:45						
EXISTING BUFFER FROM CONTRACT. LIMIT	00:45						
MAX LEGAL FDP	12:00	**SCENARIO A**			**SCENARIO B**		
EXISTING BUFFER FROM LEGAL LIMIT	1:00	A1 (5 kg/sec)	A2 (10 kg/sec)	A3 (20 kg/sec)	B1 (5 kg/sec)	B2 (10 kg/sec)	B3 (20 kg/sec)
CUMULATIVE DELAY (induced by the use of LH2 aircraft)		00:36	00:30	00:28	00:11	00:04	00:02
NEW FDP		11:36	11:30	11:28	11:11	11:04	11:02
NEW BUFFER FROM CONTRACTUAL LIMIT		00:09	00:15	00:17	00:34	00:41	00:43
NEW BUFFER FROM LEGAL LIMIT		00:24	00:30	00:32	00:49	00:56	00:58

B.4 Determination of Compatibility of Extra Delays with Existing Aircraft Routings and Night Curfew Restrictions

To determine the impact of cumulative extra delays on existing aircraft routings and assess potential compatibility issues with night curfew restrictions at BER airport, a third set of tables was developed (see Table B3 for an example).

The 'cumulative delay (at the end of the day)' represents the delay experienced by LH2 aircraft at the end of the assigned routing.

The 'original on-chocks time (local time)' was derived from easyJet operational data.

The 'new on-chocks time (local time)' was calculated by adding the 'cumulative delay' to the 'original on-chocks time.'

Considering that the planning night curfew at Berlin airport is 23:30 and that, according to the currently used scheduling guidelines, a 30-minute buffer must exist, the 'new on-chocks time' of Berlin-based aircraft was colour-coded. Specifically, green was used to indicate new on-chocks times before or equal to 23:00 (i.e., a sufficient margin from the curfew), and red was used for new on-chocks times after 23:00 (i.e., an insufficient margin from the curfew, making the aircraft rotation "problematic").

Table B3 – Example of one the tables used to determine the new on-chocks time of LH2 aircraft at the end of the day (the table refers to a Berlin-based aircraft)

	SCENARIO A			**SCENARIO B**		
	A1 (5 kg/sec)	A2 (10 kg/sec)	A1 (5 kg/sec)	B1 (5 kg/sec)	B2 (10 kg/sec)	B3 (20 kg/sec)
CUMULATIVE DELAY (at the end of the day)	00:55	00:48	00:44	00:13	00:05	00:02
ORIGINAL ON-CHOCKS TIME (local time)	22:25					
NEW ON-CHOCKS TIME (local time)	23:20	23:13	23:09	22:38	22:30	22:27