Energy Analysis of Fleet Operations using Green Liquid Hydrogen and Synthetic Sustainable Aviation Fuel

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ABSTRACT

Aircraft designs are changing more rapidly than ever, due to the disruptive technology revolution required to curb harmful emissions, and meet stringent climate targets. As a result, the role of conceptual design tools is evolving, shifting away from the tried-and-tested empirical models and theoretical design missions, to rapid, low-fidelity physics-based models that can accurately assess a range of unconventional, aircraft designs. This study presents an innovative conceptual design methodology, based on advanced conceptual design techniques observed in recent years, which enables the rapid assessment of novel technologies on a real-world airline operation schedule.

An automated simulation framework was developed to accurately model real-world flights, incorporating actual take-off weights and flight paths, followed by a validation and calibration of this simulation framework to ensure accuracy with respect to real flight data. Using the novel methodology, a comparative energy analysis was performed, measuring the 'well-to-wake' energy consumption of fleet operations, when powered using green liquid hydrogen (LH_2) and synthetic sustainable aviation fuel (e-SAF), both which are produced using 100% renewable electricity.

Despite significant in-flight performance penalties, substantial 'well-to-wake' energy savings could be achieved for hydrogen aircraft, which may be desirable to reduce operating costs, and the significant strain placed on renewable electricity resources. Furthermore, it was found that a tank gravimetric efficiency of 50% was sufficient for superior energy performance of hydrogen aircraft against all e-SAF scenarios, highlighting the potential of green hydrogen to minimise the energy demand and operating cost of short-haul operations in the context of decarbonisation.

NOMENCLATURE

LCOE	Levelised Cost Of Electricity	e-SAF	Synthetic Sustainable Aviation Fuel
LH_2	Liquid Hydrogen	SLS	Sea-Level Static
M	Million	SUAVE	Stanford Uni Aerospace Vehicle Environment
MTOW	Maximum Take-Off Weight	TOW	Take-Off-Weight
NM	Nautical Miles	TSFC	Thrust Specific Fuel Consumption
NPSS	Numerical Propulsion System Simulation	m	Mass
NS	North Sea	η_{grav}	Gravimetric Efficiency
SAF	Sustainable Aviation Fuel	η_{prod}	Production Efficiency

1. INTRODUCTION

Decarbonising aviation to achieve 'net-zero' emission flights by 2050 represents the industry's most significant challenge to date. While other sectors have taken advantage of advancements in battery technology to enable disruptive change, the solution is not so simple for aviation – unique challenges, in the limited existence of suitable replacement technologies, and the constraints of airline economics, limit the potential for sustainable air travel. In other words, aviation needs a low-cost, accessible, alternative energy source that significantly reduces harmful emissions.

Sustainable Aviation Fuel (SAF), the renewable, net-zero carbon emission alternative to jet fuel, is envisaged to be the main driver of decarbonisation towards 2050 – projected to offset 53-71% of aviation's carbon emissions [1]. SAF can be further categorised through its method of production; bio-SAF, manufactured through the synthesis of hydrogen alongside carbon sequestered through bio-derived feedstocks, or e-SAF, manufactured using carbon sequestered from the atmosphere, in a process known as direct air capture, which can be powered entirely from renewable electricity. Bio derived feedstocks are limited and compete with food and general land use, and are therefore not considered sustainable long term [2]–[4]. For this reason, synthetic SAF is the focus of this study and will be referred to interchangeably as SAF or e-SAF for the remainder of this paper.

The pathway to net-zero carbon emissions now appears straightforward – scale up the production of renewable electricity, and replace the global jet fuel supply with emission-friendly e-SAF. However, simple energy analysis calculations, accounting for the 'Well-to-Wake' (WtW) energy show the monumental scale of such a challenge, where the WtW energy comprises the energy required to produce, transport and distribute the e-SAF, in addition to the energy burned within the fuel itself. The replacement of all 2019 commercial aviation jet fuel with e-SAF could require up to 489% of the global wind and solar electricity generated throughout 2021 [5], [6], based on an e-SAF production efficiency of 25% [7]. Given that global electricity consumption is projected to grow between 62-185% by 2050 compared to 2021 figures [8], there is ever-growing competition for renewable electricity, provoking uncertainty as to whether an exclusively SAF-based solution is a truly sustainable, or feasible strategy to decarbonise the aviation industry. Therefore, efficiency improvements in aircraft and propulsion systems through introduction of novel designs and alternative fuels are of paramount importance in reducing the overall energy demand of commercial aviation, reducing the strain on renewable electricity resources required for decarbonisation.

Traditional conceptual design techniques are no longer sufficient for the disruptive change required for sustainable aviation. Typically, aircraft are characterised by incremental improvements to tried-and-tested designs [9], which is apparent when we compare current aircraft designs to that of the first jet airliner to enter service in 1952 [10]. Next-generation aircraft demand a step-change in performance, and therefore require a step-change in the conceptual design process. This means shifting the focus away from using empirical modelling techniques, to using physics-based methods to investigate new design envelopes, outside the boundaries where traditional empirical correlations are no longer valid. Furthermore, traditional conceptual design techniques place excessive focus on the 'design mission', i.e. the maximum range of the aircraft, which is rarely utilised by aircraft operators. For example, Ryanair's average mission range was 776 Nautical Miles (NM) in 2022 [11], representing almost 25% of the full design range of their aircraft. Advanced conceptual design methods aim to better characterise the performance of the aircraft through modelling various missions, better representing the actual aircraft utilisation achieved in real-world operations.

These new conceptual design methods require accurate, low-fidelity physics-based models to rapidly assess various unconventional aircraft design configurations on a range of different flight conditions. Traditional conceptual design techniques are observed in an older NASA study [12], which use several empirical models and assumptions to simulate a theoretical design mission. An example of more advanced conceptual design techniques are displayed in the design of hydrogen aircraft in the work of Karpuk and Elham [13], and Mukhopadhaya and Rutherford [14], who use physics-based models to simulate hydrogen aircraft performance for multiple payload-range combinations. This work builds upon these studies, by integrating accurate, low-fidelity aircraft modelling tools to simulate actual flight operations, enhancing the value of the results.

The aim of this study is to develop a novel conceptual design methodology, focused on the modelling of real-world flight operations. In order to enable accurate, rapid assessments of unconventional aircraft designs, techniques from advanced conceptual design will be leveraged through the use of validated and calibrated low-fidelity physics-based models. Using the novel methodology, a comparative energy analysis of real-world fleet operations was performed for hydrogen-powered aircraft against SAF-powered aircraft, where the WtW energy was quantified, equivalent to the renewable electricity required to power each set of aircraft operations. Therefore, this study aims to quantify the strain on renewable electricity resources, and determine the optimum fuel choice for decarbonisation from a WtW energy perspective, when conducting short-haul operations for aviation. Specific objectives include:

- Develop a Boeing 737-800NG airframe and propulsion system model
- Develop an automated simulation framework to model real-world Ryanair flights
- Validate and calibrate the model fuel-flow predictions against actual flight data
- Design three LH_2 Boeing 737-800NG aircraft with varying degrees of tank technology
- Simulate the performance of each aircraft on a representative Ryanair operation schedule
- Conduct a comparative energy analysis study of e-SAF vs. green LH_2 fleet operations
- Conduct a renewable electricity analysis for a projected full day of flight operations

2. MODELLING METHODS AND VALIDATION

2.1 Aircraft Model

A representative model of the Boeing 737-800NG aircraft, shown in Fig. 1 (a), was developed using the open-source Stanford University Aerospace Vehicle Environment (SUAVE) conceptual design tool, where details of the aircraft geometry were obtained from airport planning reference sheets [15]. SUAVE contains physics-based and semi-empirical methods for aerodynamics, propulsion, and mission analysis calculations [16].

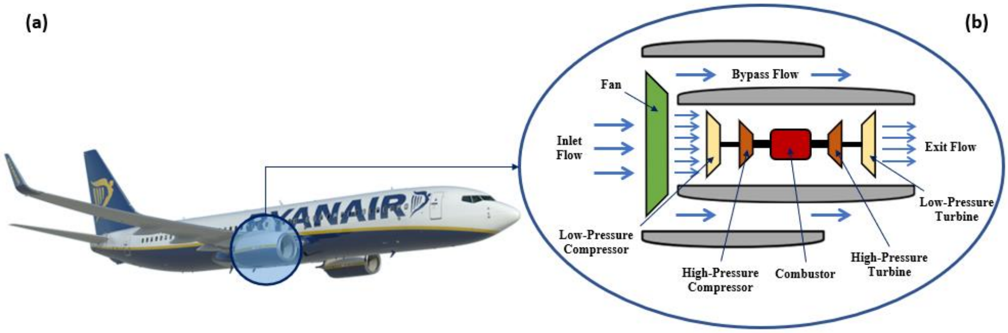

Figure 1: (a) B737-800NG modelled in SUAVE (b) CFM56-7B26 turbofan modelled in NPSS

An enhanced-fidelity propulsion system model of the CFM56-7B26 turbofan was developed using NASA's Numerical Propulsion System Simulation (NPSS) tool [17], which enabled accurate off-design analysis. The turbofan model, illustrated in Fig. 1 (b), was designed within NPSS, and incorporates component performance maps to characterise performance across the full range of engine thrust outputs. The model was calibrated by tuning the design variables of each engine component labelled in Fig. 1 (b), such as the pressure ratio, isentropic efficiency, combustor temperature, and bypass ratio. The calibration was performed in order to minimise the error between the turbofan model's performance predictions and the test data results for Sea-Level-Static (SLS) operations provided by the International Civil Aviation Organisation (ICAO) [18], and two NASA numerical predictions [19]. The propulsion model validation results are presented in Table 1.

Table 1: Validation results for CFM56-7B26 turbofan model predictions in NPSS

Op. Point	**Thrust** (lbf)	**Predicted TSFC** (lbf/hr·lbm)	**NASA/ICAO TSFC** (lbf/hr·lbm)	**Error**
Top-of-Climb	5960	0.635	0.650	-2.31%
Rolling-Take-Off	20954	0.473	0.474	-0.21%
SLS – 100% Power	26300	0.369	0.366	0.82%
SLS – 85% Power	22355	0.352	0.350	0.57%
SLS – 30% Power	7890	0.314	0.333	-5.71%
SLS – 7% Power	1841	0.464	0.466	-0.43%

The validation of the model's predicted Thrust Specific Fuel Consumption (TSFC) values in Table 1 show that the model achieved a high level of accuracy, predicting the majority of the engine operating points within 1% error with respect to the associated NASA and ICAO numerical and experimental data, respectively. The NPSS turbofan model was integrated into the overall SUAVE framework via a propulsor surrogate model, in order to facilitate the connection of the two models while increasing the computational efficiency. This surrogate model was generated using Gaussian process regression methods, formulating a continuous function for thrust and TSFC based on the nearby points of the discrete NPSS dataset, using a normal distribution [20].

2.2 Real-World Operations

A sample flight database, consisting of 29 flights and containing crucial flight data such as Take-Off Weight (TOW) and fuel burn, was provided by Ryanair to facilitate the modelling of real-world operations and validation of the model predictions. The distribution of flights in terms of TOW and flight range is seen in Fig. 2, where TOW values have been redacted due to the sensitive nature of the data. Three test cases highlighted in red, with short, medium, and long flight ranges, were selected to assess the performance of the calibrated model, discussed further in Section 2.3.

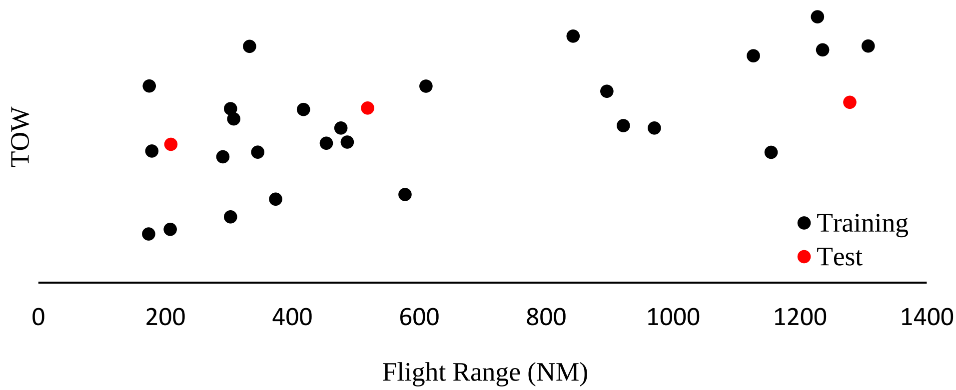

Figure 2: Distribution of B737-800NG flights in terms of TOW and flight range

To ensure the validation was representative of real-world conditions, the actual flight paths were used, rather than a theoretical ideal flight path, the latter of which is common practice when validating aircraft model predictions [21]. The flight paths were obtained from public Automatic Dependent Surveillance-Broadcast (ADS-B) data, i.e. satellite navigation data, and an automated MATLAB software routine, illustrated in Fig. 5 in Section 2.3, was developed to approximate each flight path in terms of altitude and speed using linear piece-wise segments via least squares calculations, as illustrated for the altitude in Fig. 3.

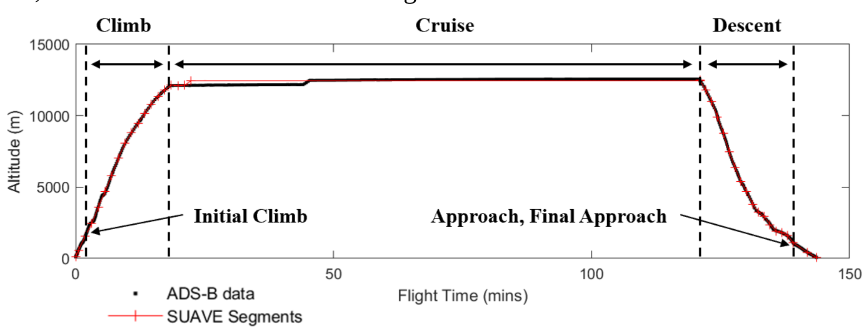

Figure 3: Linear flight path approximation of aircraft altitude for SUAVE input

2.3 Validation and Calibration

A validation of the SUAVE-NPSS model was performed for the 29 flights within the flight database. The validation was performed for each segment (e.g. cruise) within each flight, where the average fuel-flow predictions were compared to each respective average fuel-flow value provided within the flight database. Fig. 4 shows a sample flight validation of the SUAVE-NPSS predictions.

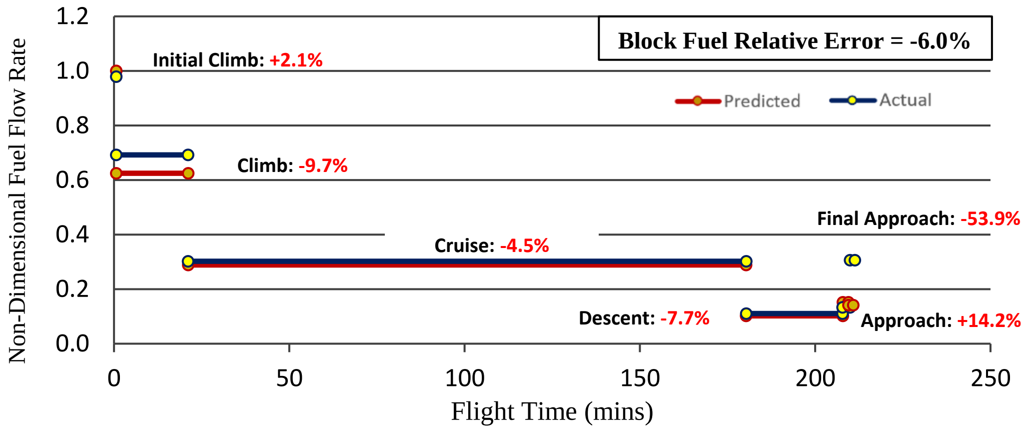

Figure 4: Validation of B737-800NG model fuel-flow predictions against actual flight data

Following the initial validation of the SUAVE-NPSS model, a calibration of the airframe aerodynamic model was performed to minimise the fuel burn errors between the model predictions and the actual flight data for each flight segment. The aerodynamic model used within SUAVE was based on the vortex-lattice method, which is a physics-based numerical model that calculates the inviscid lift produced by the wings [22]. An important feature of this aerodynamic model was that it used several correction factors to complete the lift/drag calculations.

These semi-empirical aerodynamic calculations enabled the calibration of the aerodynamic model to match the climb and cruise fuel-flow predictions to that of the actual flight data. Furthermore, a propulsion coefficient, which set the idle throttle fuel-flow of the engine, was optimised to minimise the errors of the descent fuel-flow predictions. Finally, three drag variables, which increase the drag coefficient by a prescribed amount, were used to minimise the fuel-flow errors of the initial climb, approach, and final approach segments, to account for the additional drag imposed by the deployment of flaps, slats, and landing gear. Fig. 5 illustrates the automated software routine used in the setup, validation, and calibration of the SUAVE-NPSS model.

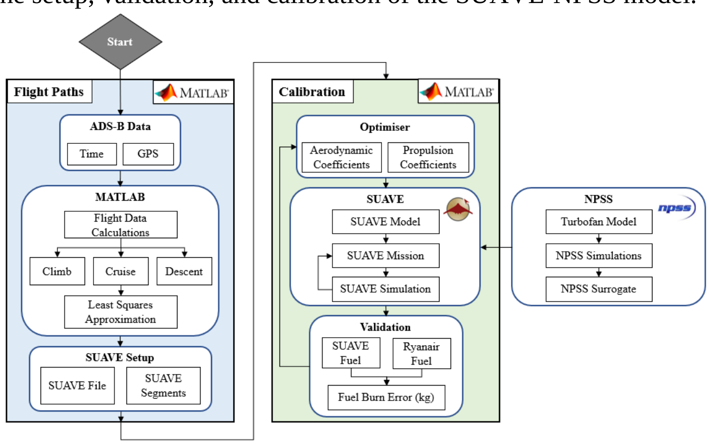

Figure 5: Structure of automated validation and calibration code for SUAVE-NPSS model

The calibration problem was set up as five consecutive single-objective optimisations, where the objective was to minimise the specified segment fuel burn error for the 26 flights within the training dataset, as outlined in the calibration block in Fig. 5. Separate optimisations were performed for each segment, as each flight segment was influenced by different aerodynamic and propulsion coefficients, as described in the previous paragraph. Setting the optimisation objective as the absolute total fuel burn error for each segment implicitly defined the weighting function for this problem, as the optimiser prioritised greater accuracy for the segments which yielded the greatest fuel burn error magnitudes. The performance of the calibration was measured through the reduction of total fuel burn errors and average fuel-flow errors for each flight for the training and test datasets, as highlighted in Fig. 6. The final optimised model yielded an average fuel-flow error of approximately 5% for each flight within the training and test datasets, representing a high-level of accuracy with respect to real-world conditions for a conceptual design tool.

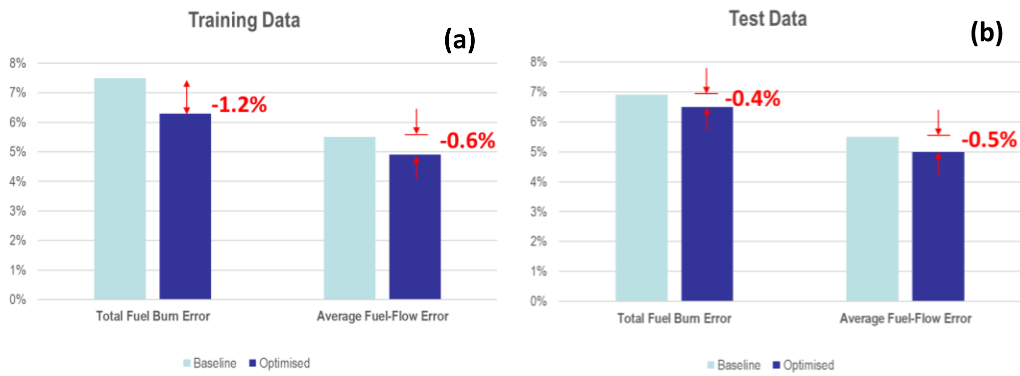

Figure 6: Total fuel burn and average fuel-flow errors for baseline/optimised SUAVE-NPSS aircraft model (a) Training data (b) Test data

2.4 Hydrogen Aircraft Design

Following the validation and calibration of the SUAVE-NPSS B737-800NG model, it was utilised for the design of three LH_2 fuelled variants of the B737-800NG aircraft. LH_2 suffers from a volumetric energy density that is almost four times lower than jet fuel, while requiring storage at an extremely low temperature of -253°C. Hence, LH_2 must be stored in cylindrical cryogenic tanks housed within the fuselage, as opposed to jet fuel which can be stored within the wings. This means that LH_2 aircraft require an extended fuselage with a heavy, cryogenic fuel tank, inducing mass and drag penalties on the aircraft. The weight of the LH_2 tank depends on the gravimetric efficiency of the tank design, which is defined as η_{grav} in Eq. (1).

$$\eta_{grav} = \frac{m_{fuel}}{m_{fuel}+m_{tank}} \cdot 100\% \tag{1}$$

The gravimetric efficiency is a figure that introduces uncertainty to the analysis, as there is no aircraft-dedicated LH_2 tank that exists today. Estimated figures for the gravimetric efficiency can be as low as 25% [7], [14], however a detailed parametric analysis from Huete et al. [23] showed that efficiencies of up to 66% are achievable for short/medium-haul aircraft, such as the B737-800. This study used the same LH_2 tank design developed by Huete et al. [23], and assumed three different gravimetric efficiencies – a pessimistic, baseline, and optimistic value, of 33%, 50%, and 66%, respectively. Given the gravimetric efficiency design values, the LH_2 aircraft were 'sized' to maintain a fixed passenger capacity, design range, thrust-to-weight ratio, and wing-loading ratio.

The characteristics of each aircraft are detailed in Table 2, where LH2-33 represents the LH_2 aircraft designed using a gravimetric efficiency of 33% etc. The significant effect of the gravimetric efficiency on the size and mass of the LH_2 aircraft is observed in the exponential increase in MTOW and fuselage length for the LH2-33 aircraft, when compared to the LH2-50 and LH2-66 designs. This is due to the compounding effect of the tank efficiency; lower gravimetric efficiency resulted in a larger tank weight, which increased the fuel required, which in turn increased the length and weight of the fuselage, and required larger wings and engines to maintain sufficient lift and thrust.

Table 2: Characteristics of the conventional SAF and the LH_2-designed B737-800NG aircraft

Aircraft Configuration	**Fuel Mass** (kg)	**Tank Mass** (kg)	**Fuselage Length** (m)	**MTOW** (kg)	**ΔMTOW**
SAF	17738.7	---	38.02	79016	---
LH2-33	11446.9	23240.8	59.95	116076	+46.9%
LH2-50	7521.7	7521.7	51.96	82935	+5.0%
LH2-66	6858.5	3533.2	50.61	76144	-3.6%

3. RESULTS AND DISCUSSION

3.1 In-Flight Energy Performance

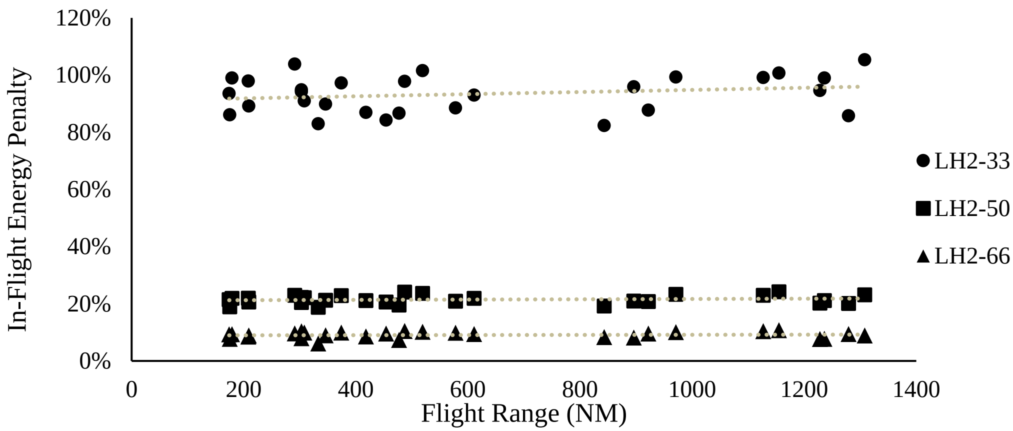

Figure 7: Fleet-wide in-flight energy performance penalties of LH_2 aircraft vs. SAF aircraft

Fig. 7 illustrates the in-flight energy performance penalties for the three hydrogen aircraft configurations when compared to the conventional SAF aircraft, for all 29 flights within the flight database outlined in Section 2.2. Given the higher rate of in-flight energy consumption for the LH_2 aircraft, greater performance penalties were anticipated with increasing flight range. For the LH2-33 configuration, there is a notable linear trend of increased performance penalties with flight range, whereas while the LH2-50 and LH2-66 data exhibits the same trend, it is of reduced significance.

3.2 Well-to-Wake Energy Performance

The previous section considered the in-flight energy performance of each aircraft, also known as the tank-to-wake energy consumption. However, as the sustainable fuels are ultimately produced using renewable electricity, this fuel production energy must be considered through the WtW energy consumption. A fixed production efficiency of 57% was utilised for the LH_2 fuel, due to the relatively stable values reported in literature [7], [14]. Reported e-SAF production efficiencies vary significantly [7], [14], hence three values were used, as outlined in Table 3.

Table 3: Production efficiency of green LH_2 and e-SAF used in well-to-wake energy analysis

Fuel Type	Pessimistic	Baseline	Optimistic
Green LH_2	57%	57%	57%
e-SAF	22%	34%	46%

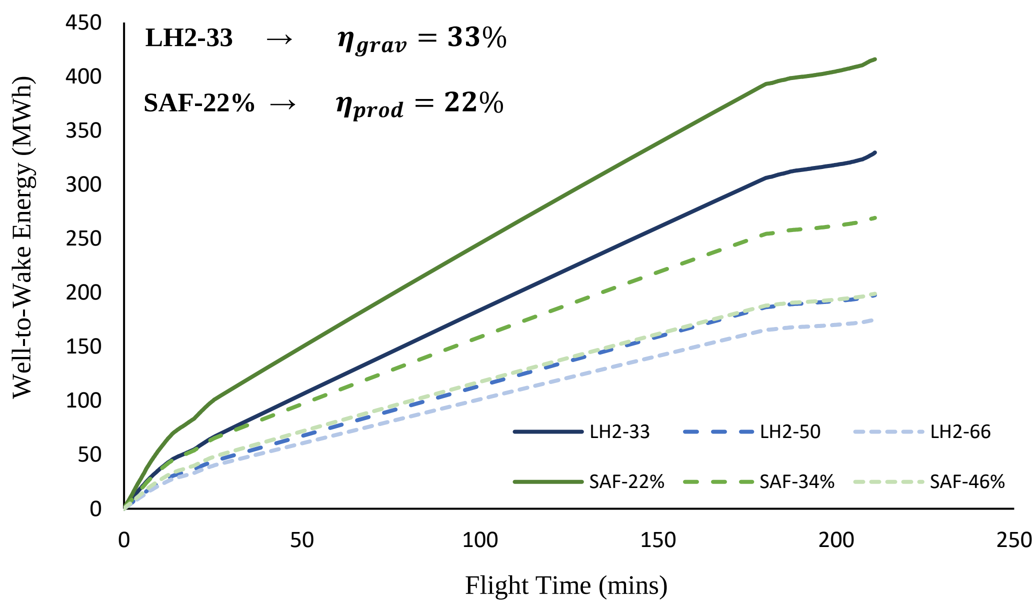

Figure 8: Well-to-Wake energy consumption for LH_2 and e-SAF aircraft (1300 NM)

Fig. 8 shows the WtW energy consumption for the longest mission within the flight database, with a flight range of approximately 1300 NM, for all six energy scenarios. Note that LH2-33 refers to a LH_2 aircraft designed with a 33% tank gravimetric efficiency, whereas SAF-22% refers to the conventional SAF aircraft, using e-SAF produced with a 22% production efficiency. It was found that the SAF-22% scenario demanded the most energy overall, requiring 26% more energy than that of the LH2-33 configuration, despite the >100% in-flight energy penalty for LH_2. Following this, it was observed that the SAF-34% scenario out-performed the LH2-33 candidate, whereas the most optimistic SAF-46% scenario performed approximately equal to the LH2-50 aircraft. Finally, the LH2-66 aircraft consumed the least energy overall.

3.3 Renewable Electricity Analysis

This section considers the fleet-wide WtW energy consumption results from the perspective of renewable electricity resources, and in particular the projected strain on renewable electricity supplies towards 2050. To enhance the relevance of this analysis, the 29 flights within the provided flight database were extrapolated to a full day of Ryanair operations, estimated at 3000 flights. Furthermore, the analysis is linked to the North Sea (NS) off-shore wind power hub, which is projected to become “Europe’s biggest green power plant” by 2050 [24], with a projected capacity of 300 GW, producing an energy output of 4.11 TWh/day based on a NS reference study [25].

Therefore, the metrics used to analyse each energy scenario are the proportion of the 4.11 TWh of daily NS wind power consumed by the daily flight operations under each scenario, along with the Levelised Cost Of Electricity (LCOE) of this off-shore wind power, projected to be €40/MWh [25]. The LCOE represents the plant-level unit costs for the production of electricity, i.e. the unit cost that electricity should be sold at in order to break-even [26], but ignores differences in plant-related CAPEX/OPEX for e-SAF and LH_2 production, figures which yield a large degree of uncertainty. Table 4 shows the total renewable electricity required to produce fuel for the 3000 flights in each scenario, the utilisation percentage of the NS wind power hub, and the LCOE for this consumption. For reference, note that the equivalent cost of Jet-A fuel, using 2050 EU projected values with a carbon tax of $400/tonne [14] was €21.46 million, and the current EU electricity demand is 7.6 TWh/day.

Table 4: LCOE and utilisation of NS daily energy production for LH_2 and e-SAF scenarios

Scenario	Renewable Electricity (TWh)	LCOE	NS Daily Production %
SAF-22%	0.5870	€23.48 M	14.3%
SAF-34%	0.3798	€15.19 M	9.2%
SAF-46%	0.2807	€11.23 M	6.8%
LH2-33	0.4396	€17.59 M	10.7%
LH2-50	0.2754	€11.01 M	6.7%
LH2-66	0.2471	€9.89 M	6.0%

The monumental scale of renewable electricity investment required is observed in the results of Table 4. This highlights the need for high e-SAF production efficiencies, or a transition to hydrogen powered aviation on the pathway to net-zero, in order to minimise the enormous strain placed on renewable electricity resources – especially given that this analysis only represents a single day of operations, for a single airline.

4. CONCLUSIONS

A novel conceptual design methodology has been developed in this study, leveraging techniques used in the advanced conceptual design of next-generation aircraft published in recent years. These techniques include the integration of accurate, physics-based, low-fidelity models, along with multi-mission simulations for next-generation aircraft. The result of which is increased fidelity models at the conceptual design stage, which are necessary in the design of unconventional aircraft. The novel aspect of this methodology was contained in the validated and calibrated operations model, which accurately represented a real-world flight schedule with an average fuel-flow error of <5%. To the author's knowledge, no pre-existing conceptual design tool fuel burn predictions have been validated or calibrated to match actual flight data, and no previous work has developed a methodology to rapidly, and accurately model real-world flights.

Using the novel modelling methodology and calibrated SUAVE-NPSS model, a comparative energy analysis study was performed, measuring the total WtW energy consumption of green LH_2 and e-SAF fleet operations given the representative flight schedule provided by Ryanair. Three LH_2 aircraft were designed using three different tank technology levels via the gravimetric efficiency. The gravimetric efficiency was found to have a significant effect on the size and weight of the LH_2 aircraft, which ultimately had a detrimental effect on the in-flight energy performance, as the LH2-33 aircraft consumed 60-78% more energy than the LH2-50 and LH2-66 aircraft, respectively, and 94% more in-flight energy than the conventional, SAF aircraft. However, when the WtW energy consumption was calculated, it was found that the e-SAF scenarios generally performed worse than the LH_2 aircraft. For the pessimistic scenarios, e-SAF consumed >33% more energy, whereas for the baseline scenarios, e-SAF consumed approximately 38% more energy, and for the optimistic scenarios, e-SAF demanded almost 14% more energy than LH_2.

Finally, a renewable electricity analysis was conducted, where the 29 flights from the flight database were extrapolated to a full day of operations, estimated at 3000 flights, and analysed in the context of the EU North Sea wind power hub, characterising the needs of each scenario by comparing the total electricity consumption and the projected cost of electricity. The results highlighted the colossal scale of renewable electricity required for decarbonisation in each scenario, but quantified the potential energy savings with hydrogen-powered operations, as the baseline e-SAF and LH_2 scenarios resulted in a daily cost saving of €4.2 M, and a reduction in the daily power utilisation from 9.2% to 6.7%.

Therefore, despite the significant in-flight performance penalties, hydrogen aircraft generally performed better than SAF aircraft in terms of the total energy consumption for short-haul operations. Although this was dependent on the liquid hydrogen tank technology level, and the e-SAF production efficiency, it was found that a tank gravimetric efficiency of 50% was sufficient for increased performance against all SAF scenarios analysed. However, this work examined fleet operations using 2005 aircraft technology levels, future work must consider how the trends develop through the transition to more fuel-efficient aircraft with advanced technologies, alongside a cost-benefit analysis accounting for the infrastructural developments required for LH_2 aircraft operations

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