Technical Report – Ownership and Operating Cost Model

PROJECT NAPKIN

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1. Ownership and Operating Cost Model

Based on the technical specifications of the various aircraft concept designs, ownership and operating cost estimations are provided. The uncertainty around the future operating conditions of these concept aircraft, as well as having few (if any) existing aircraft upon which to base these assumptions, posed several challenges. Consequently, it was necessary to set and agree key assumptions amongst the consortium for parameters relevant to the model. As Raymer notes[1], "aircraft cost estimation occupies the fuzzy grey area between science, art, and politics" (p. 704).

Total cost of ownership (TCO) includes the purchase price and the costs of operating the asset. Three stages are identified within the cost estimation framework:

(1) aircraft cost estimation model
(2) maintenance cost model
(3) operating cost model.

In the first stage, the total cost to design and manufacture the aircraft is estimated. With added profit for the manufacturer or seller, this returns the total purchase price of an aircraft. In the second stage, maintenance costs are estimated. This includes two key factors: the conventional aircraft maintenance, and then based on the lifecycle analysis of fuel cells, battery and fuel tank, the engine maintenance cost for the hydrogen fuelled system. The final stage involves computing the operating cost of the aircraft based on fixed and variable direct costs. Operations costs include any expenses that are required to utilise the aircraft commercially. At this stage, a Monte Carlo simulation is developed with defined distributions to account for uncertainty. These stages are described in more detail below.

1.1 Aircraft cost estimation

To estimate the total cost required to design and manufacture an aircraft, a new design approach is undertaken. To this end, all aircraft concepts are assumed to be built from scratch, even where based on an existing aircraft/airframe while the difference was considered at the design stage of the procurement costs. The Development and Procurement Costs of Aircraft (DAPCA) model is often utilised to estimate the costs of a new design aircraft[2], including development hours, engineering hours, material cost, and quality control. These assumptions are dependent on design parameters such as the mass and speed of the proposed aircraft, based on cost estimating relationship (CER).

Eastlake and Blackwell[3] proposed a modified DAPCA-IV model with adjustments on various factors to better represent the cost of a general aviation aircraft. This approach has since been

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[1] Raymer, D. (2012). Aircraft design: a conceptual approach. *American Institute of Aeronautics and Astronautics, Inc.*.

[2] Roskam, J. (1990). Airplane design / Part VIII, Airplane cost estimation: design, development, manufacturing and operating. Ottawa, Kansas : *Roskam Aviation and Engineering Corporation*.; Raymer, D. (2012). Aircraft design: a conceptual approach. *American Institute of Aeronautics and Astronautics, Inc.*.

[3] Eastlake, C. N., & Blackwell, H. W. (2000, June). Cost Estimating Software For General Aviation Aircraft Design. *In 2000 Annual Conference* (pp. 5-173).

adopted and developed for similar studies[4]. Acknowledging the inherent uncertainty and subjectivity of some assumptions, various correction factors based on some design characteristics are proposed in the literature. For example, this approach has previously been utilised to propose cost estimation methods for a hybrid-electric general aviation aircraft[5].

A similar approach utilising a modified DAPCA model is used in this project, with cost model estimations based on a variety of sources including previous research, industry experts and researchers' opinions.

Here, there are 14 main components of the aircraft cost estimations split into three main categories: (1) airframe engineering and design cost, (2) airplane production cost, and (3) production flight test operations cost (Table 1).

Table 1: Breakdown of the main components of the aircraft cost estimations

Component		**Definition**	**Main inputs**	**Adjustments**
Engineering	C_{aed}	Manhour cost required for engineering design	Structural empty weight (SEW), maximum speed, engineering cost	Pressurised factor, Composite material factor, H_2 aircraft (new technology) factor
Tooling	C_{too}	Required preparation and design for tools	SEW, maximum speed, pressurisation, tooling cost	Pressurised factor, Composite material factor, H_2 aircraft (new technology) factor
Manufacturing	C_{man}	Manhour cost required for manufacturing	SEW, maximum speed, pressurisation, manufacturing cost	Composite material factor, H_2 aircraft (new technology) factor
Development support	C_{das}	Nonrecurring costs of manufacturing support	SEW, maximum speed, pressurisation	Pressurised factor, Composite material factor, H_2 aircraft (new technology) factor
Flight test operations	C_{fte}	Costs related to demonstrate airworthiness for certifications	SEW, maximum speed	H_2 aircraft (new technology) factor
Quality control	C_{qco}	Receiving inspections, production inspection, final inspection	Manufacturing cost	Composite material factor, H_2 aircraft (new technology) factor
Materials	C_{mat}	Cost of raw materials, hardware, and equipment	SEW, maximum speed	Pressurised factor, Composite material factor, H_2 aircraft (new technology) factor

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[4] Gudmundsson, S. (2013). *General aviation aircraft design: Applied Methods and Procedures*. Butterworth-Heinemann.

[5] Finger, D. F., Goetten, F., Braun, C., & Bil, C. (2019, December). Cost estimation methods for hybrid-electric general aviation aircraft. In 2019 *Asia-Pacific International Symposium on Aerospace Technology (APISAT 2019)* (pp. 265-277).

Component		Definition	Main inputs	Adjustments
Propulsion				
Electric motor	C_{pc1}	Cost of total propulsion system	Power (hp), number of engines (for electric motor, turboprop and RR50 mult.linkage) Thrust (lbf), number of engines (for turbofan and H2GEAR)	H_2 aircraft (new technology) factor, conversion factor
Turboprop	C_{pc2}			
Turbofan	C_{pc3}			
H2GEAR	C_{pc4}			
RR50 mult.linkage	C_{pc5}			
Hydrogen fuel cell	C_{hfc}	Cost based on power output	Power (kW), number of engines	
Power management system	C_{pms}	Cost based on propulsion	Propulsion cost	
Battery	C_{bat}	Cost based on power output	Power (kW)	
Fuel systems				
Gaseous H_2 tank	C_{tgh}	Based on mass and material of tanks	Hydrogen tank mass (kg)	Liquid H_2 storage factor
Liquid H_2 (LH_2) tank	C_{tlh}			
Propeller	C_{pro}	Cost based on design parameters	Market price based on diameter, and number of blades	
Misc.	C_{mis}	Costs related to avionics, interior design, and others	Avionics weight (lb), number of seats	

In addition to the cost elements defined, three other key assumptions are included in the model (1) the number of prototype aircraft, (2) the number of aircraft produced over a 5-year period, and (3) monthly production rate. Finally, the sales price is calculated at a defined profit margin at 10%. These figures are determined based on expert opinion and previous figures sourced from the literature.

Assumptions	
Number of prototypes	2
Number produced over 5 years	150
Monthly production rate	2.5

Engineering cost

$$C_{aed} = \beta_{aed} {W_{SE}}^{\alpha_{aed}} {V_H}^{\gamma_{aed}} {N_a}^{\delta_{aed}} f_c f_p f_h R_{eng} CPI_{year}$$

where W_{SE} is structural empty weight in kg, V_H is the maximum speed in knots, N_a is the number of aircraft to be produced over a 5-year period, f is modification factor, R_{eng} is the engineering rate ($£/h$), and β, α, γ, and δ are coefficients. Consumer price index (CPI) is determined and applied based on the year of data used.

Tooling cost

$$C_{too} = \beta_{too} {W_{SE}}^{\alpha_{too}} {V_H}^{\gamma_{too}} {N_a}^{\delta_{too}} Q^{\varepsilon_{too}} f_c f_p f_h R_{too} CPI_{year}$$

where Q is the monthly production rate over a 5-year period, and ε is a coefficient.

Manufacturing cost

$$C_{man} = \beta_{man} {W_{SE}}^{\alpha_{man}} {V_H}^{\gamma_{man}} {N_a}^{\delta_{man}} f_c f_h R_{man} CPI_{year}$$

Development support cost

$$C_{das} = \beta_{das} {W_{SE}}^{\alpha_{das}} {V_H}^{\gamma_{das}} {N_p}^{\delta_{das}} f_c f_p f_h CPI_{year}$$

where N_p is the number of prototypes.

Flight test operations cost

$$C_{fte} = \beta_{fte} {W_{SE}}^{\alpha_{fte}} {V_H}^{\gamma_{fte}} {N_p}^{\delta_{fte}} CPI_{year}$$

Quality control cost

$$C_{qco} = r_{qco} C_{man} f_c f_h$$

where r_{qco} is the coefficient defining the ratio of quality control cost to manufacturing cost.

Materials cost

$$C_{mat} = \beta_{mat} {W_{SE}}^{\alpha_{mat}} {V_H}^{\gamma_{mat}} {N_a}^{\delta_{mat}} f_c f_p f_h R_{man} CPI_{year}$$

Propulsion cost

$$C_{pc_1(electric)} = \beta_{pc_1} N_e P f_h CPI_{year}$$

$$C_{pc_2(turboprop)} = \beta_{pc_2} N_e P f_h CPI_{year}$$

$$C_{pc_3(turbofan)} = \beta_{pc_3} N_e T^{\zeta_{pc_3}} f_h CPI_{year}$$

$$C_{pc_4(H2GEAR)} = \beta_{pc_4} N_e T^{\zeta_{pc_4}} f_h$$

$$C_{pc_5(RR50\ mult.linkage)} = \beta_{pc_5} N_e P f_h$$

where N_e is the number of engines, P is the power in kW, T is the thrust in lbf, and ζ is the coefficient.

Hydrogen fuel cell cost

$$C_{hfc} = \beta_{hfc} N_e P f_h$$

Power management system cost

$$C_{pms_i} = r_{pms} C_{pc_i}$$

where $i = 1, 2, 3, 4, 5$, and r_{pms} is the coefficient defining the ratio of power management system cost to propulsion system.

Battery cost

$$C_{bat} = \beta_{bat} B f_h CPI_{year}$$

where B is the power output from battery in kWh.

Fuel systems cost

$$C_{tgh(gaseous\ H_2)} = \beta_{tgh} M_h k_{tgh}$$

where M_h is the mass of hydrogen on the aircraft, and k_{tgh} is the constant taking the density of H_2 kept in tanks in gaseous form.

$$C_{tlh(liquid\ H_2)} = \beta_{lgh} M_h k_{lgh} f_{lh}$$

where k_{lgh} is the constant taking the density of H_2 kept in tanks in liquid form, and f_{lh} is the liquid H_2 factor.

Miscellaneous costs

$$C_{mis} = (\beta_{avi} W_{avi} CPI_{year}) + (\beta_{sea} N_{sea} CPI_{year})$$

where W_{avi} is the estimated weight of avionics, N_{sea} is the number of passenger seats, β_{avi} is the coefficient for avionics, β_{sea} is the coefficient for seating.

Adjustments are included as modifications to the cost estimation model. Based on the available data, three modifications are also included in the model. These modifications were found necessary to reflect the production differences, unique materials, and/or new technologies to be used. The factors are embedded as a baseline in the model considering different cost elements and characteristics as a composite factor (f_c), pressurised factor (f_p), and hydrogen aircraft (new technology) factor (f_h), and were adjusted based on expert opinion and adapted to reflect different aircraft sizes.

Table 2: Adjustment factors

	Composite factor (f_c)	**Pressurised factor (f_p)**	**Hydrogen a/c factor (f_h)**
Engineering	1.30-1.50	0.01-0.03	1.30-1.50
Tooling	1.30-1.50	0.00-0.01	1.30-1.50
Manufacturing	1.00-1.05		1.00-1.05
Development support	1.00-1.05	0.01-0.03	1.05-1.10
Flight test operations			1.30-1.50
Quality control	1.05-1.10		1.30-1.50
Propulsion			1.05-1.50
Materials	1.00-1.05	0.00-0.01	1.05-1.10

1.2 Maintenance cost estimation

Maintenance cost estimations are developed in two stages. The first stage includes assessing maintenance costs excluding fuel cell maintenance and replacement costs. In this stage, assumptions were made based on the design parameters from the various concept aircraft as well as expert opinions. This approach follows a similar model which was developed to determine maintenance costs for larger passenger aircraft[6]. Here, the model is modified to include different propulsion systems of the concept aircraft (see Table 3).

Table 3: Components included in the maintenance cost estimation

Component		**Definition**	**Main inputs**
Line maintenance	C_{ltm}	Any maintenance carried out on apron during turnarounds, layovers, or pre-flight.	Fleet size, utilisation (h/day), flight cycle (h), aircraft cost, age of type of aircraft (months), average age (years)
Base maintenance	C_{btm}	For longer maintenance operations carried out in a hangar	Fleet size, utilisation (h/day), flight cycle (h), aircraft cost, age of type of aircraft (months), average age (years)
Propulsion		Propulsion maintenance	Utilisation (h/day), age of type of aircraft (months), number of engines, thrust (lbf)
Electric motor	C_{pm1}		
Turboprop	C_{pm2}		
Turbofan	C_{pm3}		
H2GEAR	C_{pm4}		
Piston	C_{pm5}		
RR50 mult.linkage	C_{pm6}		
Autopilot	C_{aum}	As part of avionics maintenance	Utilisation (h/day), aircraft cost, age of aircraft (months), average age (years)
Communications	C_{cmm}	As part of avionics maintenance	Fleet size, utilisation (h/day), flight cycle (h), age of type of aircraft (months), number of seats
Electrical	C_{emm}	Power and electrical components of aircraft	Utilisation (h/day), aircraft cost, number of seats
Equipment/furnishing	C_{efm}	As part of avionics and interior maintenance	Utilisation (h/day), flight cycle (h), fuselage length (ft), number of seats
Flight controls	C_{fcm}	As part of avionics maintenance	Utilisation (h/day), flight cycle (h), aircraft cost, age of type of aircraft (months), number of seats
Fuel system	C_{fsm}	Maintenance of fuel system excluding H_2 fuel cells	Utilisation (h/day), age of type of aircraft (months), average age (years), number of seats

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[6] Fioriti, M., Vercella, V., & Viola, N. (2018). Cost-estimating model for aircraft maintenance. *Journal of Aircraft*, 55(4), 1564-1575.

Component		**Definition**	**Main inputs**
Hydraulic power	C_{hpm}	As part of avionics maintenance	Flight cycle (h), age of type of aircraft (months), number of seats
Instruments	C_{imm}	As part of avionics maintenance	Fleet size, utilisation (h/day), flight cycle (h), aircraft cost, age of type of aircraft (months), number of seats
Wheels and brakes	C_{wbm}	As part of landing system maintenance	Utilisation (h/day), flight cycle (h), aircraft cost, age of type of aircraft (months), number of tires
Landing gear	C_{lnm}	As part of landing system maintenance	Utilisation (h/day), flight cycle (h), aircraft cost, age of type of aircraft (months), number of tires
Navigation	C_{nam}	As part of avionics maintenance	Fleet size, flight cycle (h), aircraft cost, age of type of aircraft (months), average age (years), number of seats
APU	C_{apm}	For aircraft with APU	Utilisation (h/day), flight cycle (h)
Thrust reversers	C_{trm}	For aircraft with thrust reversers	Utilisation (h/day), age of type of aircraft (months), number of engines, thrust (lbf)

In the second stage, fuel cell degradation estimation and relevant cost implications are investigated. The model was converted to a sequential Monte Carlo framework to allow the sensitivity of each of the individual parameters within the model to be examined. This was done using the PyMC library in python[7].

Once this was done a model for proton-exchange membrane (PEM) fuel cell degradation was created based on long term running tests which examined the effect of low levels of H_2 fuel contamination on the power output of fuel cells. The baseline degradation rate found in that study when using pure H_2 gas was approximately 8% power loss after a thousand hours running. When even small amounts of contamination are introduced this rate triples. The "contaminated" gas mix used in the study was 99.9% pure H_2 with 10ppb Sulphur (as H_2S) 0.1ppm CO, 5ppm CO_2, & 1ppm NH3[8].

This was modelled as a single number using the following formulae to approximate the power loss ($\mathrm{P_{loss}}$) due to fuel impurity (FI). It uses the rated fuel cell power output ($\mathrm{FC_{Power}}$) and the

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[7] Thomas Wiecki, John Salvatier, Ricardo Vieira, Anand Patil, Maxim Kochurov, Bill Engels, Junpeng Lao, Colin Carroll, Michael Osthege, Osvaldo A Martin, Brandon T. Willard, Adrian Seyboldt, Austin Rochford, rpgoldman, Luciano Paz, Kyle Meyer, Peadar Coyle, Marco Edward Gorelli, Ravin Kumar, … Luis Mario Domenzain. (2022). pymc-devs/pymc: v4.1.2 (v4.1.2). Zenodo. https://doi.org/10.5281/zenodo.6810847

[8] Fernando Garzon1, Francisco A. Uribe1, Tommy Rockward1, Idoia G. Urdampilleta1 and Eric L. Brosha1 , The Impact of Hydrogen Fuel Contaminates on Long-Term PMFC Performance, 2006, Electrochemical Society Transactions, Volume 3, Number 1, https://iopscience.iop.org/article/10.1149/1.2356190

fraction of starting power lost per flying hour $(\mathrm{LF}_{\mathrm{per\ fh}})$ with the total number of flying hours each year to give the total power lost in Watts. The power loss fraction is derived from the baseline degradation rate but converted from per 1,000fh to per 1fh. The term penalty factor (PF) is a calibration term which, in combination with the squaring of the impurity variable, ensures when the fuel impurity is 0.001. The decision to square the impurity and include the penalty factor was to bias the model to make the $(\mathrm{FI} * 1000)^2$ term equal to 1 when impurity is 0.001 while giving a quadratic relationship to the impact of impurity. At levels below this inflection point the impact of impurity drops off and above it, the impact rapidly climbs.

$$\mathrm{P}_{\mathrm{loss}} = \mathrm{FC}_{\mathrm{Power}} * \mathrm{LF}_{\mathrm{per\ fh}} * \mathrm{FH}_{\mathrm{annual}} * \mathrm{PF} * (\mathrm{FI} * 1000)^2$$

This was then added to the baseline degradation to find the total fuel cell degradation per year. The combination gives triple degradation at fuel impurity factor of 0.001 and the impact of impurity drops off quickly below that.

To consider what the costs of addressing this degradation in power output will be our assumption is that once 10% of capacity has been lost, the fuel cell will need replacement and that this can be done with a reconditioned fuel cell at a discount of 50% over the original costed price. This led to frequent fuel cell replacements and consequent significant costs. We anticipate the degradation rate will be improved during the operationalisation of fuel cells in aircraft and so, agreed the following baseline degradation rates to obtain mean time between replacement of three thousand (2% loss per 1k fh), five thousand (1.6% loss per 1k fh), and ten thousand hours (0.8% loss per 1k fh) respectively, based on when the different concepts will enter service. These represent improvements of 4x, 5x, and 10x over the fuel cell degradation rate using pure H_2 that was found in the literature.

Figure 1: Annual fuel cell degradation cost distribution for one of the late phase concepts with mean time between replacement of approx. 10k fh

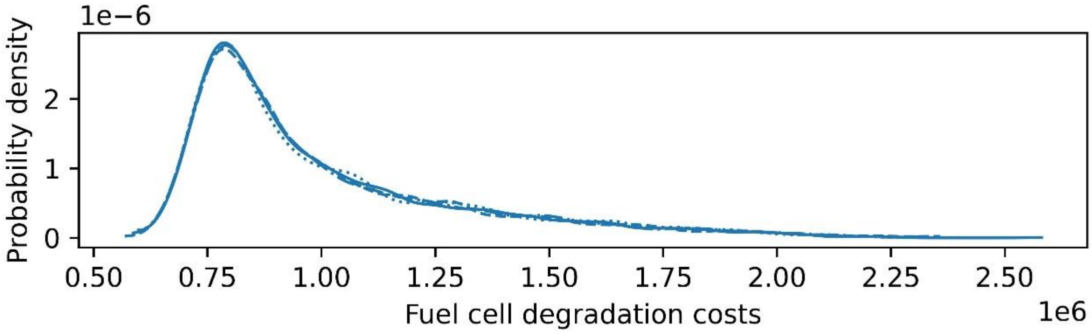
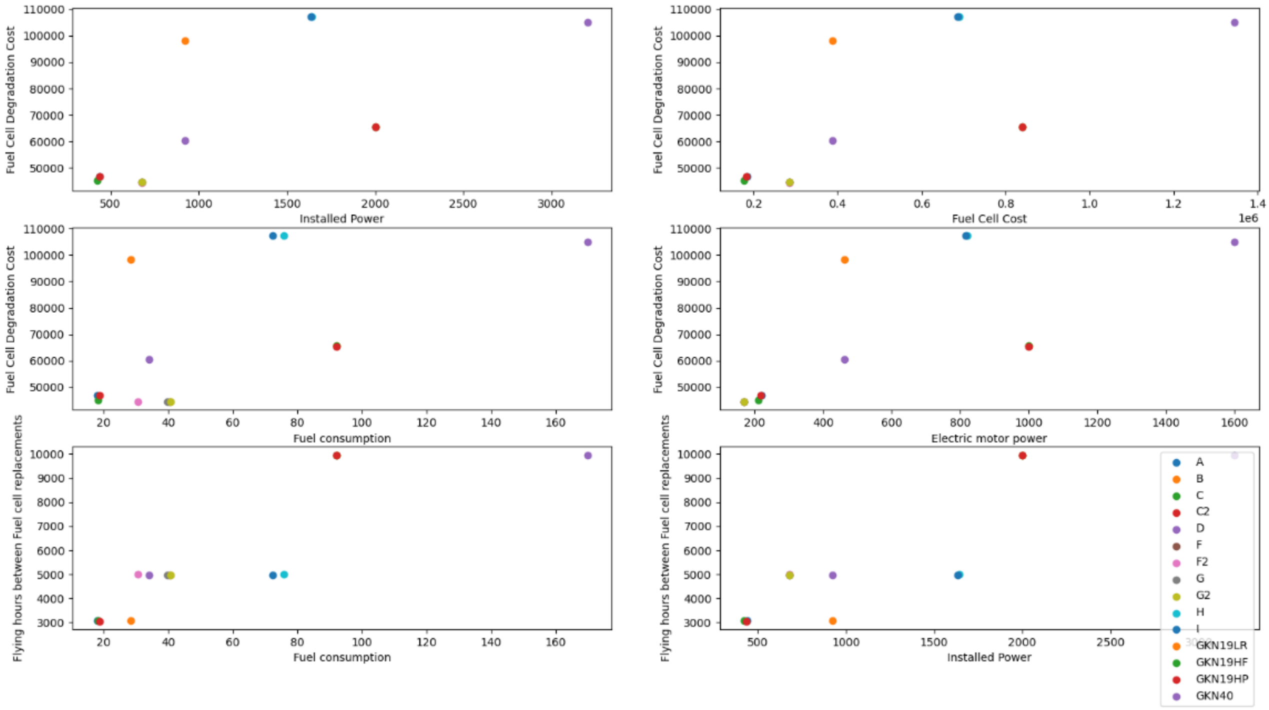


Figure 2: Mean fuel cell annual degradation costs plotted with other variables



Concepts A, B, C, & C2: Concepts assigned a 2.6 % degradation rate to give a 3,000fh mean time between fuel cell replacement.

Concepts D, E, F, F2, G, G2, H, I, & J: Concepts assigned a 1.6 % degradation rate to give a 5,000fh mean time between fuel cell replacement.

GKN19LR, GKN19HF, GKN19HP, GKN40: Concepts assigned a 0.8 % degradation rate to give a 10,000fh mean time between fuel cell replacement.

1.3 Operating cost estimations

Taking into consideration outputs from aircraft cost estimation and maintenance cost estimation, annual operating costs are estimated based on various assumptions. This is used to calculate total ownership of cost (TCO), which is then presented as TCO per flight hour

(TCO£/FH). The aircraft are assumed to be purchased directly without any financing. Table 4 presents the cost breakdown for ownership and operating figures, split between fixed and variable costs.

Table 4: Cost breakdown for ownership and operating figures

	Component		**Definition**	**Main inputs**
Fixed	Aircraft depreciation	C_{dep}	As aircraft is assumed to be purchased directly, a depreciation cost is incurred per annum.	Aircraft cost (on a linear scale assuming retaining 15% of original value after 25 years)
	Aircraft insurance cost	C_{ins}	Cost of insuring aircraft for commercial operations per annum	Aircraft cost (assuming 1.5% of original value)
Variable	Fuel cost	C_{fue}	Cost of fuel for operating aircraft per annum	Fuel consumption (kg/h), annual flight hours, fuel price (£/kg)
	Crew cost	C_{cre}	Including flight and cabin crew per annum	Annual crew hour, hourly rate of flight and cabin crew (£/h)
	Airport related cost	C_{air}	Including landing and passenger charges	Number of landings per year, landing charge per MTOW (£/ton), passenger charge (£/pax)
	Total maintenance cost	C_{tma}	Including conventional maintenance and fuel cell degradation cost	Annual flight hours, maintenance cost (£/FH), fuel cell degradation cost (£/year)

Two fixed costs included in the model are depreciation and aircraft insurance costs, which were estimated based on expert opinion and the existing literature. Four types of fuel were considered in the project including for the reference aircraft: (1) aviation gasoline (avgas), (2) jet fuel (kerosene), (3) gaseous H_2, and (4) liquid H_2. The fuel price for avgas is based on current (2022) market price across several airports in the UK. Jet fuel price is determined based on the output from the Airline Behaviour Model as well as the range and distribution for gaseous and liquid H_2 costs (see technical report UK domestic market modelling – methodology and additional outcomes). Based on the available data, fuel prices used in the operational cost calculations are presented below.

Table 5: Fuel prices used in TCO estimations.

Fuel type	**Cost (£/kg)**
Avgas	2.08
Jet A1	1.28
Gaseous H2	2.89
Liquid H2	3.45

As for the comparison to aircraft currently operating in similar markets, four reference aircraft are included. Based on publicly available data and industry experts, the operating cost for reference aircraft is computed for comparison with concept aircraft. For parameters and reference aircraft details, see Table 6 and Table 7.

Table 6: Parameters included in the comparison

	unit	
Number of pilots (min)[1]		2
Number of cabin crew (min)[2]		0
Pilot cost	$/h	180
Cabin crew cost	$/h	90
Annual crew hours	h	1,950
Annual flight hours	h	1,456

[1] Except for concepts with 9 seats and less which can have a minimum of *1* pilot

[2] Except for concepts with 40 or more seats which must have at least *1* cabin crew

Table 7: Reference aircraft details

	unit	**BN2B-26**	**DHC-6-400**	**ATR72-600**	**A220-100**
MTOW	lb	6,600	12,500	50,265	13,9112
Cruise speed	kt	120	130	271	447
Number of seats		10	19	78	135
Fuel consumption	kg/h	84.4	233.6	762.0	1,587.0
Fuel type		Avgas	Jet A	Jet A	Jet A
Number of pilots (min)		1	2	2	2
Number of cabin crew (min)		0	0	1	1