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# Hybrid-Electric Seaplanes: Route-Level Economics and Break-Even Conditions

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**Abstract**

Decarbonising regional air mobility is a priority for the European aviation sector, and short coastal and island routes are a natural early market for battery-assisted propulsion. Whereas the operating economics of land-based hybrid-electric commuters have been studied repeatedly, the economic and operational implications of applying hybrid-electric propulsion to a *seaplane* remain largely unexplored. This paper addresses that gap by extending validated Direct Operating Cost (DOC) and project-finance models to a clean-sheet, 18-seat hybrid-electric flying boat sized through a surrogate-based multi-objective optimisation. The optimised configuration is benchmarked against a DHC-6 Twin Otter on a representative Mediterranean route, Valencia–Palma de Mallorca, and compared on three levels: a per-block-hour DOC breakdown, route-level productivity indicators, and a 15-year discounted assessment of Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period. The hybrid-electric seaplane reaches DOC parity with the turboprop (difference below 1 %): large energy- and $CO_2$-cost savings are almost exactly offset by higher capital charges, new electric-powertrain maintenance and mass-driven airport and navigation fees. At project level the outcome is decided by ticket yield: at a yield of 1.50 €/pax-nm the hybrid-electric seaplane is *not* viable (negative NPV, IRR below the discount rate), whereas at 1.75 €/pax-nm it becomes viable (positive NPV, IRR

above 3 %). The break-even yield is about 1.55 €/pax-nm, a ticket of roughly 295 €. The decisive result is therefore not a fixed ranking but a threshold: the business case is shallow and yield-elastic, and modest movements in fare, battery cost, carbon price and low-emission fee schemes are sufficient to cross it. The hybrid-electric flying boat is best read as a forward-looking investment whose competitiveness is governed by policy and cost-learning levers rather than by aircraft technology alone.

**Keywords:** Hybrid-electric seaplane, Regional aviation, Direct operating cost, Project finance, Break-even analysis, Sustainable air transport

# Abbreviations

| | |
|---|---|
| ADP | Aircraft Delivery Price |
| ASM | Available Seat Miles |
| BSFC | Brake Specific Fuel Consumption |
| CASM | Cost per Available Seat Mile |
| DOC | Direct Operating Cost |
| DoE | Design of Experiments |
| EM | Electric Machine |
| HE | Hybrid-Electric |
| IRR | Internal Rate of Return |
| MDAO | Multidisciplinary Design Analysis and Optimization |
| MTOM | Maximum Take-Off Mass |
| NPV | Net Present Value |
| OEM | Operating Empty Mass |
| PP | Payback Period |
| RASM | Revenue per Available Seat Mile |
| RPM | Revenue Passenger Miles |
| SAF | Sustainable Aviation Fuel |
| SBO | Surrogate-Based Optimization |
| TLAR | Top-Level Aircraft Requirements |

# 1 Introduction

In 2023, instrument-flight-rule (IFR) movements in Europe totalled 10.1 million flights, and EUROCONTROL projects demand reaching 12.2 million flights per year by 2050 even in a low-impact scenario, an average annual growth of +0.7 % [1]. Rising traffic translates into rising $CO_2$ emissions, and the pressure to decarbonise has driven intense research into propulsion alternatives. Sustainable Aviation Fuels (SAF) are the primary near-term lever for long-haul flights [2], whereas battery-based and hydrogen-based architectures are the most promising routes to decarbonise short-haul and regional operations [3, 4]. Hydrogen offers long-term environmental benefits, while battery-electric and hybrid-electric powertrains are credible transitional solutions in the short-to-medium term [5]. Retrofit studies show that hybrid-electric powertrains

can cut $CO_2$ emissions by about 30 % on missions below 600 NM [6], with projections up to 90 % for all-electric platforms using batteries above 800 Wh/kg [7].

These environmental gains, however, come at an economic price. Hybrid-electric and full-electric variants of general-aviation and regional aircraft typically show higher operating costs [3, 8], driven by elevated delivery prices, airframe modifications and higher capital intensity [9, 10]. The penalty is compounded by fee policy: airport and ground-handling charges scale with maximum take-off mass (MTOM), and current schedules rarely grant the discounts to hybrid-electric concepts that they sometimes grant to full-electric ones, so a heavier hybrid aircraft can pay *more* than the conventional baseline [9]. Designing a competitive hybrid-electric aircraft is therefore as much an economic problem as a technical one, and economic constraints must enter the design loop from the conceptual phase.

Small commuter aircraft (fewer than 30 seats) are widely regarded as the ideal entry platform for electrified propulsion: they fly short point-to-point routes with minimal infrastructure and low fleet-management overheads [11–13], yet they emit comparatively high $CO_2$ per revenue-passenger-kilometre because of high cycle frequency and lighter regulation [14]. They thus combine a real decarbonisation opportunity with a tractable economic model in which the aircraft delivery price (ADP) and DOC dominate.

Within this category, a hybrid-electric *flying boat* is a deliberately specific choice. Seaplanes operate from water-based infrastructure—harbours and coastal inlets—and avoid the cost of building land runways, an advantage in archipelago regions such as the Balearic Islands, the Greek islands or the Scandinavian coast where new airports are prohibitively expensive [15]. Among water-based configurations, flying boats were favoured over floatplanes and amphibians for hydrodynamic robustness, lower drag penalty and wave resilience [16]. A COLOSSUS-project case study on the Aegean reported up to 90 % lower fuel per passenger than ferries and up to 30 % faster travel times, with 15-minute turnarounds and minimal waterport facilities (a single runway, one 450 kW fast charger and a fuel pump), and load factors 10–14× higher than maritime alternatives during peak season [15]. Those analyses shaped a top-level envelope of 12–19 seats, 250–400 km/h cruise and up to 600 km range [16].

The operating economics of land-based hybrid-electric commuters and retrofits have been quantified by the authors and others [8, 10, 17], but the economic and operational consequences of putting a hybrid-electric powertrain on a seaplane—with its higher structural mass and water-base operations—have not been assessed at project level on a real route. This study addresses one question:

> *Under what economic and policy conditions does a clean-sheet hybrid-electric seaplane become a financially competitive alternative to a conventional turboprop on short European regional routes?*

To answer it, the paper (i) sizes an 18-seat hybrid-electric flying boat with a surrogate-based multi-objective optimisation that trades mission fuel against ADP under commuter-class top-level aircraft requirements (TLARs); (ii) benchmarks the optimum against a DHC-6 Twin Otter and reports a complete per-block-hour DOC breakdown on the LEVC–LEPA route; and (iii) elevates the analysis to a 15-year

discounted assessment (NPV, IRR, Payback) and, crucially, a break-even and sensitivity analysis that quantifies how far ticket yield, battery cost, carbon price and low-emission fee schemes must move for the hybrid-electric seaplane to match or beat the baseline. The design and DOC layers establish credibility; the financial layer is the novel contribution and the spine of the discussion.

# 2 Methodology

The assessment is built from three coupled models: a multidisciplinary aircraft-design and surrogate-optimisation framework that produces the sized configuration and its performance (Sect. 3); a DOC model, together with the productivity indicators that link it to the financial layer, that converts the configuration into a per-block-hour cost structure (Sect. 2.2); and a project-finance model that converts annual cash flows into discounted indicators (Sect. 2.3).

## 2.1 Surrogate-based design and optimisation framework

Conceptual aircraft design is multidisciplinary and iterative, and the tight coupling between aerodynamics, structures, thermal and electric propulsion, power management and mission analysis makes a full multidisciplinary design analysis and optimisation (MDAO) computationally expensive [18, 19]. To keep a large design space tractable while retaining acceptable fidelity, this study replaces the direct MDAO by a surrogate-based optimisation (SBO): metamodels approximate the disciplinary chain, are cheap to query, smooth noisy high-fidelity data and admit gradient-based search [20–22]. A generic multi-objective problem is written

$$\min_{\mathbf{x}} \ \mathbf{f}(\mathbf{x}) = \big[f_1(\mathbf{x}), \ldots, f_n(\mathbf{x})\big] \quad \text{s.t.} \quad g_m(\mathbf{x}) \leq 0, \tag{1}$$

where $\mathbf{x}$ is the design vector and $g_m$ are linear or non-linear constraints. The workflow comprises four steps—design of experiments (DoE), surrogate training, infilling and optimisation [23–25]—and is iterated until the prediction error stabilises. Surrogates are Kriging (KRG) models built with the SMT toolbox [26] on a design space of continuous variables, trained on a 300-sample dataset (80 % for training, 20 % held out for validation); the multi-objective search over the trained surrogates is run with `pymoo` [27] using the NSGA-II algorithm [28]. The population size was set to 150 individuals, corresponding to approximately ten times the number of design variables. Additionally, an offspring injection rate of 25% the size of the initial population was employed at each generation. The full application of this framework to the hybrid-electric seaplane—validation, requirements, design space, problem statement and resulting optimum—is developed in Sect. 3.

## 2.2 Cost structure and productivity metrics

The DOC model follows established aircraft-economics practice [8] extended for hybrid-electric aircraft as in Ref. [10], and groups all operationally dependent expenses

into financial, energy, crew, maintenance and charge items computed per block hour (€/BH), consistent with ATA Spec 105.

Capital charges split total investment into depreciation, interest and insurance,

$$DOC_{\text{dep}} = \frac{TI}{DP}\,(1 - RV), \qquad DOC_{\text{int}} = ADP \cdot r_i, \qquad DOC_{\text{ins}} = TI \cdot r_a, \tag{2}$$

with $TI$ total investment, $DP$ depreciation period, $RV$ residual value, $r_i$ interest and $r_a$ insurance rate; depreciation accounts for battery replacement and recyclability-driven residual value. Energy combines fuel and electricity,

$$DOC_{\text{fuel}} = P_{\text{fuel}}\, m_{\text{fuel}}, \qquad DOC_{\text{EE}} = P_{\text{EE}}\, E_{\text{trip}}, \tag{3}$$

at market unit prices $P_{\text{fuel}}$ and $P_{\text{EE}}$. Maintenance is decomposed into airframe, thermal-engine (ATA method) and electric-machine line/base terms,

$$DOC_{\text{m}} = DOC_{\text{m,AF}} + DOC_{\text{m,ICE}} + DOC_{\text{m,EM}_{\text{line}}} + DOC_{\text{m,EM}_{\text{base}}}, \tag{4}$$

and charges cover terminal/approach navigation service (TANS), en-route navigation (mass- and distance-based, per EUROCONTROL) and ground handling,

$$DOC_{\text{charges}} = DOC_{\text{TANS}} + DOC_{\text{en-route}} + DOC_{\text{GHC}}. \tag{5}$$

For the seaplane, conventional landing/parking charges are complemented by water-base usage fees, generally lower than at large international airports.

These per-block-hour cost items are, in turn, linked to the financial layer through the standard set of unit metrics used in airline economics [29, 30], summarised in Table 1. Two metrics describe capacity and demand: Available Seat Miles, ASM = Departures × Stage length × Seats, the supply offered to the market; and Revenue Passenger Miles, RPM = $\text{Pax}_{\text{paid}}$ × Stage length, the traffic actually carried. Their ratio RPM/ASM is the load factor, which for the present route is fixed at 72.2 % for both architectures so that the comparison is mission-consistent (Sect. 4). Three further metrics describe economics: the average fare Yield = Pax revenue/RPM; the unit cost CASM = Total operating cost/ASM; and the unit revenue RASM = Operating revenue/ASM.

CASM and RASM are the pivot of the whole assessment: CASM aggregates the per-block-hour DOC above into a single seat-mile cost and is therefore the quantity on which the powertrain choice acts most directly, while RASM is set by the commercial environment (yield) and is identical for the two architectures at a given fare. The gap RASM − CASM is unit profitability and is the seed of the cash flow in Eq. (7). For a fixed network, productivity (ASM) can in principle be raised by shortening turnaround to add departures, by extending stage length within the mission envelope, or by denser cabin layouts [30]; in this study ASM is held constant across architectures so that all differences in profitability are attributable to cost structure and yield rather than to capacity. This is what makes yield the single most transparent lever in the financial results of Sect. 6.

**Table 1** Productivity and unit-economic indicators used in the assessment.

| Indicator | Description | Definition |
|---|---|---|
| ASM | Supply-side capacity: total seat capacity offered | Departures × Stage length × Seats |
| RPM | Demand-side traffic actually carried; RPM/ASM is the load factor | $\text{Pax}_{\text{paid}}$ × Stage length |
| Yield | Average fare per passenger nautical mile | Pax revenue/RPM |
| CASM | Average cost of flying one seat one mile | Total operating cost/ASM |
| RASM | Unit revenue per seat mile offered | Operating revenue/ASM |

## 2.3 Project-finance model

The financial layer adopts a Total Cost of Ownership (TCO) view, integrating capital and operating expenditures into a single project model and then discounting the resulting cash flows (Fig. 1). Capital and operating items first aggregate into the per-block-hour DOC of Sect. 2.2; DOC and revenue then form an annual cash flow; and the cash flow is finally condensed into the three capital-budgeting metrics that drive the investment decision.

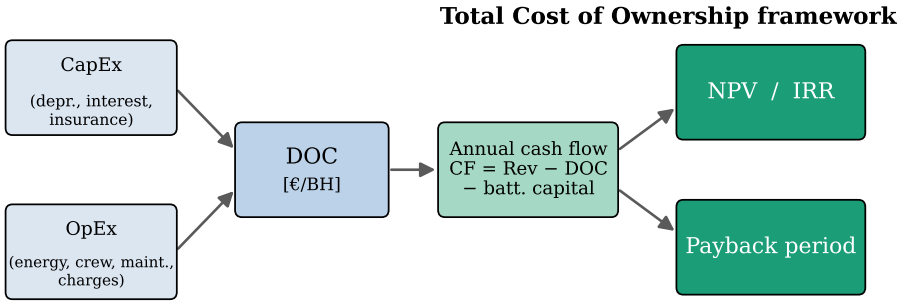



**Fig. 1** Total Cost of Ownership framework linking the DOC structure to the discounted financial indicators.

Viability is assessed with three metrics [31]. The Net Present Value (NPV) is

$$\text{NPV} = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} - I_0, \tag{6}$$

with $CF_t$ the net annual cash flow, $r$ the discount rate, $T = 15$ years the horizon and $I_0$ the initial investment; the Internal Rate of Return (IRR) solves NPV $= 0$ and must exceed $r$ for acceptance; the Payback Period (PP) is the time to recover $I_0$ and measures liquidity and risk. The discount rate is $r = 3.0\,\%$ [32], consistent with European cost–benefit guidance for sustainable-transport infrastructure.

The annual net cash flow is

$$CF_t = \text{Revenue}_t - \text{DOC}_t - \text{Battery capital cost}_t. \tag{7}$$

Revenue is the product of yield, RPM and operating days; the DOC term is the annualised per-block-hour structure of Table 9 scaled by the ≈1 375 h/year utilisation; and the third term is the distinguishing feature of the hybrid-electric platform. Batteries are a consumable capital item: the model charges the initial pack inside $I_0$ and treats subsequent replacements as an annualised cost. With a 485 kWh pack rated at 800 charge/discharge cycles and priced at 250 $/kWh, and given the route's cycle count, the replacement charge is spread over the operating life and escalated for technological learning and a 2 % annual inflation [33]. Fixed annual overheads are held identical for both aircraft so that no spurious difference enters the comparison. Both architectures fly the same route at the same 72.2 % load factor and therefore generate the same RPM and the same revenue at a given fare; the entire financial difference between them is concentrated on the cost and capital side—a slightly larger $I_0$ (5.81 vs 5.12 M€) and the recurring battery charge. It is precisely this structure—per-block-hour DOC parity (Sect. 5) but a heavier annualised capital outflow—that makes the project outcome hinge on ticket yield (Sect. 6).

# 3 Hybrid-electric seaplane design and optimisation

This section applies the framework of Sect. 2.1 to size the hybrid-electric flying boat and to benchmark it against the conventional baseline. The conceptual and preliminary design of a hybrid-electric aircraft couples aerodynamics, structures, thermal and electric propulsion, power management, mission and cost analysis through a dense web of interdependencies; the resulting MDAO problem is sketched, in extended-design-structure-matrix (XDSM) form, in Fig. 2. Solving this coupling directly at every optimiser iteration would be prohibitively expensive, which motivates the surrogate-based strategy: the disciplinary chain is sampled once through a design of experiments, replaced by metamodels, and then explored by the optimiser at negligible marginal cost.

Before sizing the new concept, the framework was validated on the DHC-6 Twin Otter, a widely documented commuter aircraft representative of the conventional baseline. By reproducing its certified design weights and principal in-flight and on-ground performance, the models were verified to capture real-world behaviour: Table 2 compares public data with the framework output and reports the percentage error for each metric. Errors remain within a few percent on the design-critical quantities (MTOM, landing weight, fuel weight, take-off and landing distances). The larger equipped-empty-weight discrepancy (−7.8 %) is conservative for the present comparison, since

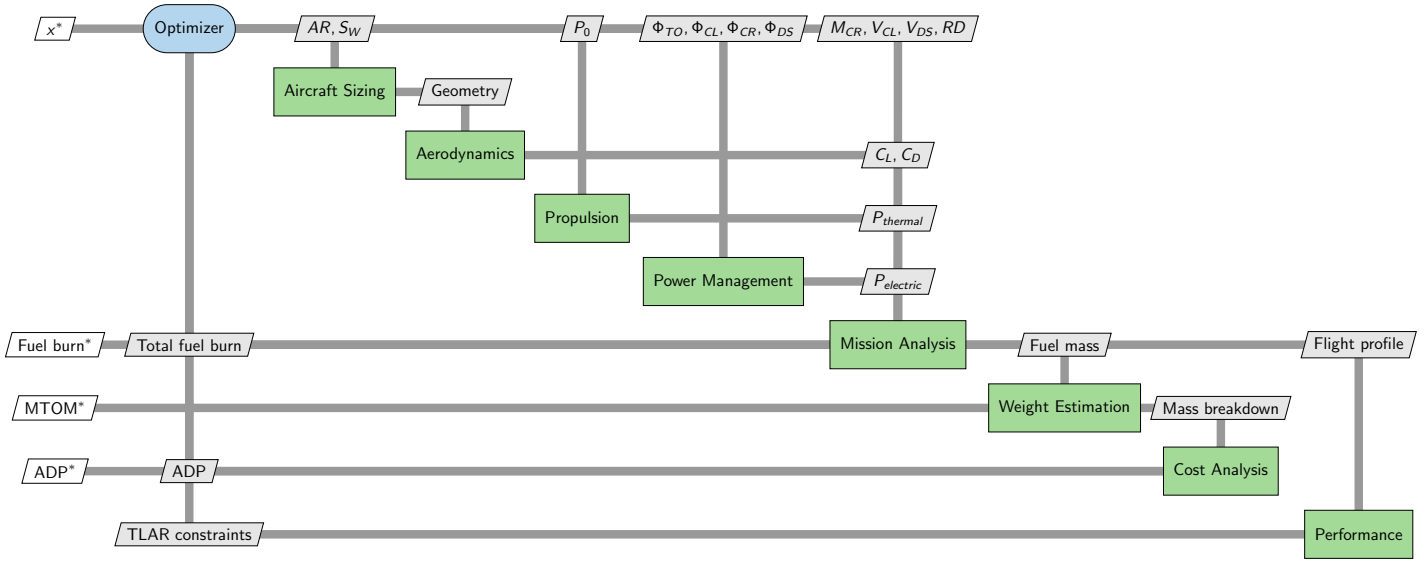



**Fig. 2** Conceptual XDSM of the multidisciplinary design problem for the hybrid-electric aircraft (illustrative), showing the coupling between sizing, aerodynamics, propulsion, power management, mission, weight and cost analysis.

it does not flatter the hybrid-electric configuration, and the cruise-speed offset reflects the use of a single representative powerplant rating.

**Table 2** DHC-6 Twin Otter: framework validation against public data [34].

| Item | Public data | MDO framework | Error (%) |
|---|---|---|---|
| Maximum take-off mass | 12 500.0 lb | 12 510.0 lb | +0.08 |
| Maximum landing weight | 12 300.0 lb | 12 295.6 lb | −0.04 |
| Equipped empty weight | 7 940.0 lb | 7 231.2 lb | −7.8 |
| Standard fuel weight | 2 576.0 lb | 2 559.0 lb | −0.7 |
| FAR 23 take-off distance[1] | 1 965.0 ft | 1 804.5 ft | −8.2 |
| FAR 23 landing distance[2] | 1 851.0 ft | 1 955.0 ft | +5.6 |
| Maximum cruise speed | 162.0 ktas | 173.0 ktas | +6.8 |

[1]At MTOW, to a 50 ft obstacle.

[2]At max landing weight, from a 50 ft obstacle.

The performance-based requirements that size the vehicle and its energy reserves are derived from the anticipated island-connectivity scenarios introduced in Sect. 1. They combine *mission* requirements (payload, range, cruise and alternate profiles, ground performance) with *aircraft* requirements that fix the powertrain architecture and guarantee economic and environmental relevance. Table 3 collects these combined TLARs: an 18-passenger payload over a 400 nmi design range at FL 100, within the EASA CS-23 MTOM limit of 19 000 lb, propelled by four turbocharged-diesel reciprocating engines assisted by four nacelle-mounted electric machines and two fuselage battery packs at a Gen-3a specific energy of 280 Wh/kg.

The DoE explores the variables with the greatest influence on mission and configuration: the rated thermal-engine power, the hybridisation ratios in each flight phase, the cruise Mach number, the climb and descent speeds and rate, and the wing geometry. Given the dimensionality, a Latin Hypercube Sampling strategy is used with at least ten samples per variable; the eleven variables and their bounds are listed in Table 4. The conceptual design is then posed as the bi-objective problem

$$\begin{aligned} &\min_{\mathbf{x}} \ \big(f_1(\mathbf{x}),\, f_2(\mathbf{x})\big), \quad f_1 = \text{mission fuel burn},\ f_2 = \text{ADP}, \\ &\text{s.t. } \text{MTOM} \le 19\,000 \text{ lb},\ \text{TO} \le 3\,280 \text{ ft},\ \text{LDG} \le 3\,280 \text{ ft}, \\ &\qquad \text{ROC} \ge 1\,250 \text{ ft/min},\ \text{Ceiling} \ge 22\,500 \text{ ft}, \end{aligned} \tag{8}$$

with design vector $\mathbf{x} = \{P_0, \Phi_{\text{TO}}, \Phi_{\text{CL}}, \Phi_{\text{CR}}, \Phi_{\text{DS}}, M_{\text{CR}}, V_{\text{CL}}, V_{\text{DS}}, RD, AR, S_W\}$. The two objectives encode the central tension of the study—an environmental objective (mission fuel and, through it, $CO_2$) against an economic one (acquisition cost). The corresponding SBO data flow, in which the optimiser exchanges $\mathbf{x}$ with the surrogate block and receives the two objectives and the TLAR constraint values, is shown in

**Table 3** Top-level aircraft requirements and powertrain assumptions for the hybrid-electric commuter.

| **Parameter** | **Value** | **Notes** |
|---|---|---|
| *Mission requirements* | | |
| Maximum take-off mass (MTOM) | $\leq$ 19 000 lb | EASA CS-23 limit |
| Design payload | 3 762 lb | 18 passengers at 209 lb/passenger |
| Design block range | 400 nmi | – |
| Cruise altitude | FL 100 | – |
| Minimum cruise Mach number | $\geq$ 0.20 | Block time $<$ 3 h |
| Maximum take-off distance | $\leq$ 3 280 ft | – |
| Maximum landing distance | $\leq$ 3 280 ft | – |
| Alternate range | 150 nmi | Similar to DHC-6 operational assumptions |
| Alternate altitude | 6 000 ft | Similar to DHC-6 operational assumptions |
| Holding time | 15 min | ICAO reserve assumption |
| Holding altitude | 1 500 ft | ICAO reserve assumption |
| *Aircraft configuration and powertrain assumptions* | | |
| Number of thermal engines | 4 | Turbocharged diesel reciprocating engines |
| Brake specific fuel consumption | 0.35 lb/(hp h) | Sea level, 75% rated power |
| Number of battery packs | 2 | Fuselage pod installation |
| Battery efficiency | 97% | Assumed constant over the mission |
| Battery specific energy | 280 Wh/kg | Gen. 3a Li-ion cells |
| Number of electric machines | 4 | Nacelle installation |
| Electric machine efficiency | 96% | Projection from Ref. [35] |
| Electric machine specific power | 6.8 kW/kg | Projection from Ref. [35] |

Fig. 3; surrogate accuracy is quantified in Appendix A, where relative RMSE is a few percent of the mean KPI value and $R^2$ exceeds 0.96 throughout.

The design loop is iterative to control approximation error. After each optimisation run the current optimum is re-evaluated with the original high-fidelity models, the new sample is added to the training set, and the surrogate is retrained; the procedure repeats until the prediction error stabilises between successive iterations. Figure 4 depicts this two-phase workflow, comprising the surrogate-generation phase (A) and the surrogate-based optimisation phase (B).

The bi-objective problem of Eq. (8) is solved over the trained Kriging surrogates with NSGA-II [28], a well-established elitist genetic algorithm for two-objective search, as implemented in `pymoo`. The population size is set to 150 individuals—approximately ten times the number of design variables—and an offspring injection rate of 25 % of the

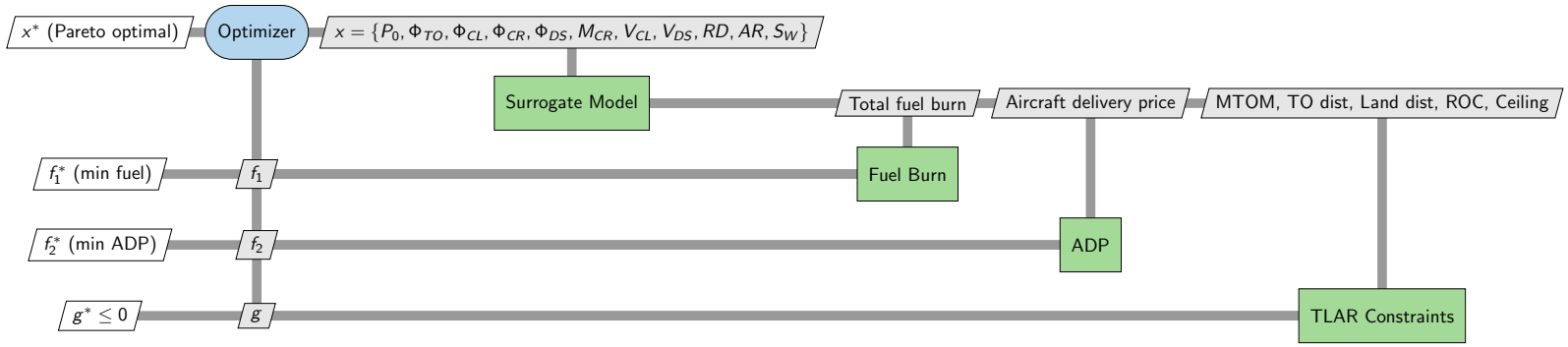



**Fig. 3** XDSM of the surrogate-based optimisation problem: the optimiser exchanges the design vector with the surrogate block, which returns fuel burn, aircraft delivery price and the TLAR constraint values.

**Table 4** Design-space variables and bounds used in the DoE.

| Variable | Unit | Bounds |
|---|---|---|
| Thermal engine power, $P_0$ | hp | 300–450 |
| Hybrid ratio (TO/CL/CR/DS), $\Phi$ | – | 0.0–0.55 |
| Cruise Mach number, $M_{\mathrm{CR}}$ | – | 0.20–0.35 |
| Climb speed, $V_{\mathrm{CL}}$ | kt | 85–140 |
| Descent speed, $V_{\mathrm{DS}}$ | kt | 140–210 |
| Rate of descent, $RD$ | ft/min | 500–850 |
| Wing aspect ratio, $AR$ | – | 7.5–10.0 |
| Wing surface area, $S_W$ | $\mathrm{m}^2$ | 37–50 |

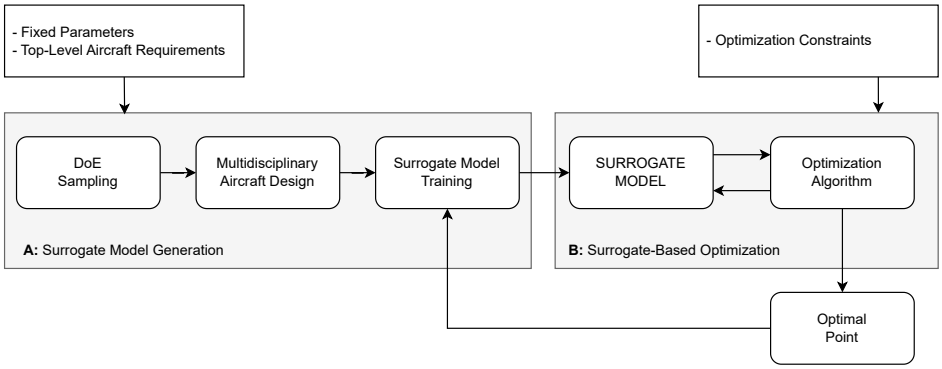



**Fig. 4** Iterative workflow: surrogate-model generation (A) feeding the surrogate-based optimisation (B).

initial population size is applied at every generation to preserve diversity and reduce the risk of premature convergence.

Optimising the surrogate yields the Pareto front of Fig. 5, which trades total fuel burn against aircraft delivery price; each circular marker is a non-dominated design, the star marks the utopia point (the unattainable simultaneous minimum of both objectives) and the diamond marks the selected optimum. The representative design carried forward is the non-dominated point that minimises the normalised Euclidean distance to the utopia point. A striking feature of the front is that the delivery price varies only weakly across it and remains close to that of the conventional baseline, despite very different certified masses. The reason is the powerplant acquisition cost: a 330 hp-class diesel piston engine costs about \$51 100 (2024 USD), whereas the Pratt & Whitney PT6A-27 turboprop of the DHC-6 reaches about \$485 000. The hybrid-electric configuration needs four piston engines, four electric motors and two battery packs for a total powertrain acquisition of roughly \$405 520—about a 58 % reduction relative to the two PT6A-27 engines of the Twin Otter. The cheaper thermal core therefore offsets most of the cost of electrification at the acquisition stage,

which is what makes the downstream financial question genuinely open rather than foreclosed by purchase price.

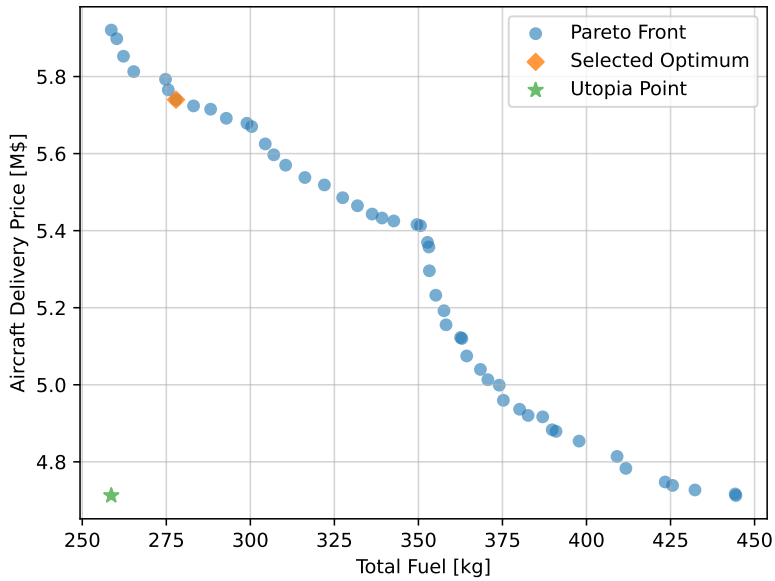



**Fig. 5** Pareto front from the surrogate-based multi-objective optimisation: total fuel burn (horizontal) versus aircraft delivery price (vertical). Circles are non-dominated candidate designs, the diamond is the selected optimum and the star is the utopia point.

Table 5 compares the mass breakdown and powerplant of the selected optimum with the DHC-6 at the 400 nmi reference stage length. The hybrid-electric seaplane almost doubles the operating empty mass (6 114 vs 3 278 kg) and raises MTOM from 5 674 to 8 227 kg, the increase being dominated by the powertrain mass (2 775 vs 418 kg) that the battery packs and electric machines introduce. Against this the trip fuel mass roughly halves (321 vs 686 kg). The design thus converts fuel mass into battery mass—the physical root of both the energy/$CO_2$ savings and the mass-driven fee penalty analysed in Sections 5 and 6.

## 3.1 Geometry of the optimised configuration

The optimised hybrid-electric seaplane was exported from the design framework to CPACS [36] format (schema version 3.2, via the in-house `openAD` exporter) for downstream aerodynamic and wind-tunnel-model work; the fuselage outer mould line was additionally exported as a STEP solid for manufacturing of a wind-tunnel test article. Figure 6 shows a schematic three-view reconstructed directly from these parametric definitions, and Table 6 collects the corresponding fuselage, wing, horizontal tailplane (HTP) and vertical tailplane (VTP) dimensions.

The fuselage is 14.53 m long, with a maximum height of 1.92 m and a maximum width of 1.92 m, sized to accommodate the 18-passenger cabin and the two

**Table 5** Mass breakdown and powerplant characteristics: DHC-6 versus optimised hybrid-electric seaplane (stage length 400 nmi).

| Item | Unit | DHC-6 | HE seaplane |
|---|---|---|---|
| Airframe mass | kg | 1 553.85 | 1 904.18 |
| Systems mass | kg | 1 031.19 | 1 324.08 |
| Powertrain mass[1] | kg | 417.92 | 2 774.72 |
| Operating empty mass | kg | 3 278.49 | 6 114.19 |
| Maximum payload | kg | 1 710.00 | 1 710.00 |
| Fuel mass (@max payload) | kg | 686.00 | 321.18 |
| Maximum take-off mass | kg | 5 674.49 | 8 226.56 |
| Thermal engine power | hp | 680.0 | 330.0 |
| Battery pack energy | kWh | – | 485.0 |
| Electric machine power | kW | – | 130.0 |

[1]Includes thermal engines, propellers, electric machines and battery packs.

fuselage-mounted battery packs. The wing, mounted high on the fuselage in a parasol arrangement typical of flying boats (to keep it clear of water spray during taxi and step-off), spans 19.30 m for a reference area of 37.54 $m^2$ and an essentially unswept planform (leading-edge sweep 0°). The empennage follows a conventional layout: an HTP of 3.80 $m^2$ with a modest 5° leading-edge sweep, and a more heavily swept VTP (40° at the leading edge) of 3.62 $m^2$, both mounted at the rear fuselage/tail-cone junction.

# 4 Reference mission and case-study definition

The reference route connects Valencia (LEVC) and Palma de Mallorca (LEPA) across the Balearic Sea—a high-frequency, strongly seasonal regional link with a short stage length, well matched to hybrid-electric operation. The flight plan was generated in SimBrief with Navigraph charts following current Spanish IFR procedures (ORVUS2H SID, airway M871, GODOX3P STAR to LEPA RWY 24L), with Barcelona (LEBL) as alternate. Cruise is at FL 100, $M_{CR} = 0.23$, over ≈190 nm, giving a mission time of about 84–86 min. The identical route is flown by both the conventional Twin Otter and the hybrid-electric seaplane to guarantee a mission-consistent comparison (Fig. 7).

Market sizing uses an annual demand of 71 855 passengers on the corridor [37]; at the modelled capacity the hybrid-electric seaplane serves an 11.9 % market share, with an annual utilisation of ≈1 375 flight hours.

The two configurations entering the comparison are defined in Table 7 (platform and economic inputs) and Table 8 (route-level operating outcome on the LEVC–LEPA mission). The conventional configuration (CC) is a Twin Otter–class turboprop; the hybrid-electric (HE) seaplane is the optimised flying boat of Sect. 3. The two share payload and capacity but differ sharply in mass and energy: on the reference mission

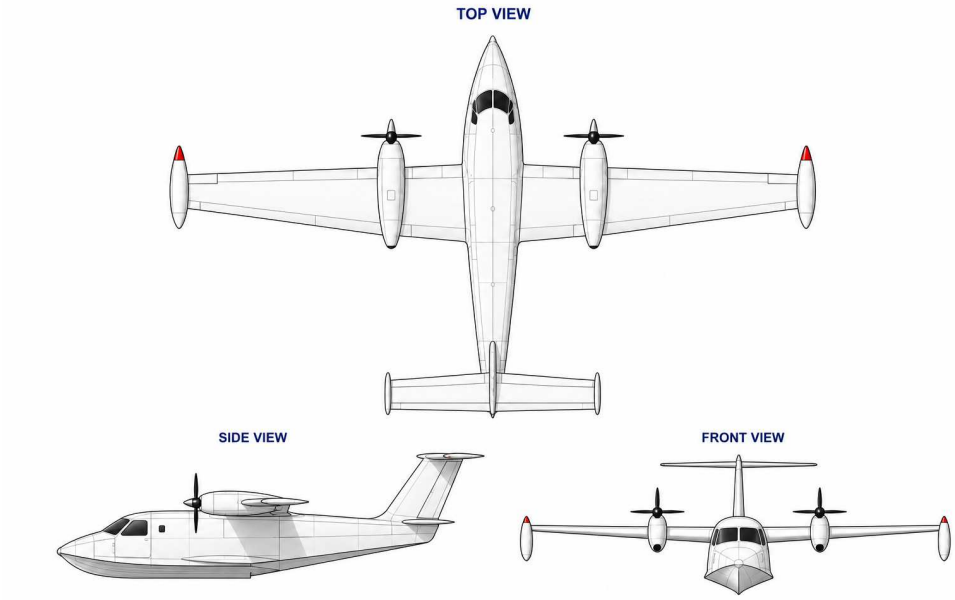



**Fig. 6** Schematic three-view of the optimised hybrid-electric seaplane, reconstructed from the CPACS geometric definition (top, side and front views; not all secondary fairings are represented).

the HE seaplane burns roughly 40 % less trip energy in fuel terms (343 vs 586 kg of fuel including reserves) while drawing 134 kWh of battery energy, and its battery pack—a consumable rated at 800 cycles and priced at 250 $/kWh—is the element that later drives the recurring capital charge of Eq. (7).

# 5 Direct operating cost assessment and comparison

A detailed assessment of the Direct Operating Cost (DOC) was carried out for the two configurations of Sect. 4: the reference Twin Otter–class turboprop (conventional configuration, CC) and the proposed hybrid-electric (HE) seaplane. The comparison isolates the cost impact of moving from a gas-turbine powertrain to a hybrid architecture combining a reciprocating engine with a battery-electric system. Costs are computed per block hour (€/BH), consistent with the ATA Spec 105 methodology, and grouped into financial costs (depreciation, interest, insurance), energy-related costs (fuel, electricity, $CO_2$ charges), crew, airport and navigation charges, and maintenance. The complete absolute data are collected in Table 9.

## 5.1 Cost structure of the conventional turboprop baseline

The DOC profile of the conventional turboprop is governed by the operational and maintenance burden of its gas-turbine engine. A Pratt & Whitney Canada PT6-class turboprop offers the high power-to-weight ratio needed for short take-off and landing performance, but at the price of mechanical and thermodynamic complexity. The

**Table 6** Geometric characteristics of the optimised configuration, extracted from the CPACS model.

| **Parameter** | **Unit** | **Fuselage** | | |
|---|---|---|---|---|
| Length | m | 14.531 | | |
| Height (max.) | m | 1.921 | | |
| Width (max.) | m | 1.920 | | |
| **Parameter** | **Unit** | **Wing** | **HTP** | **VTP** |
| Reference area | $m^2$ | 37.540 | 3.797 | 3.620 |
| Span | m | 19.298 | 4.336 | 1.983 |
| MAC | m | 1.968 | 0.891 | 1.928 |
| $x_{LE,MAC}$ | m | 5.091 | 13.182 | 11.965 |
| $z_{LE,MAC}$ | m | 0.963 | 2.700 | 1.356 |
| Sweep, LE | deg | 0.00 | 5.00 | 40.00 |
| Sweep, $c/4$ | deg | −0.92 | 2.39 | 33.07 |
| Root chord | m | 2.15 | 1.07 | 2.57 |
| Tip chord | m | 1.53 | 0.68 | 1.08 |




**Fig. 7** Planned Valencia–Palma de Mallorca route (SimBrief–Navigraph).

dominant cost drivers are fuel consumption, at 287.40 €/BH (about 18.9 % of DOC), reflecting the high specific fuel consumption of small turboprops on short sectors with a large climb/descent fraction; thermal-engine maintenance, at 178.24 €/BH (11.7 %), driven by hot-section inspections, compressor refurbishment and overhauls with strict hour and cycle limits; and financial costs, whose combined depreciation and interest (464.28 €/BH) reflect the airframe and engine capital outlay. Airport and navigation

**Table 7** Case-study platform and economic inputs for the two configurations.

| Item | Twin Otter (CC) | HE seaplane |
|---|---|---|
| Maximum take-off mass | 12 510 lb | 18 139 lb |
| Operating empty mass | 7 231 lb | 13 482 lb |
| Payload | 3 771 lb | 3 771 lb |
| Fuel mass | 1 513 lb | 708 lb |
| Thermal engine type | Turboprop | Piston (diesel) |
| Thermal engine power | 680.0 × 2 hp | 330.0 × 4 hp |
| Battery pack energy | – | 485 kWh |
| Battery life span | – | 800 cycles |
| Electric motor power | – | 130 × 4 kW |
| Aircraft price | 5.55 M$ | 5.71 M$ |
| Battery unit price | – | 250 $/kWh |

**Table 8** Route-level operating comparison on the LEVC–LEPA mission.

| Quantity | Twin Otter (CC) | HE seaplane |
|---|---|---|
| Range | 190 nm | 190 nm |
| Flight level | FL 100 | FL 100 |
| Cruise Mach | 0.23 | 0.23 |
| Payload (72 % load factor) | 13 pax | 13 pax |
| Mission time | 86 min | 84 min |
| Trip fuel + reserves[1] | 586 kg | 343 kg |
| Battery energy (mission) | – | 134 kWh |
| Utilisation | 1 375 h/yr | 1 375 h/yr |

[1]Reserves include contingency, alternate and final reserve.

charges add roughly 265 €/BH, a substantial burden that depends largely on MTOM and on the fee schedules set by European airport and air-navigation service providers. The resulting distribution is the "Twin Otter" bar of Fig. **??**.

## 5.2 Cost structure of the hybrid-electric seaplane

Electrification restructures the DOC profile, shifting cost away from energy consumption and towards capital investment and new maintenance categories.

The most immediate effect is a 29.5 % cut in fuel cost relative to the turboprop (from 287.40 to 202.72 €/BH). This follows from peak-shaving: the battery-electric system supplies auxiliary power during the high-demand take-off and climb phases, letting the primary reciprocating engine operate closer to its optimum or be downsized.

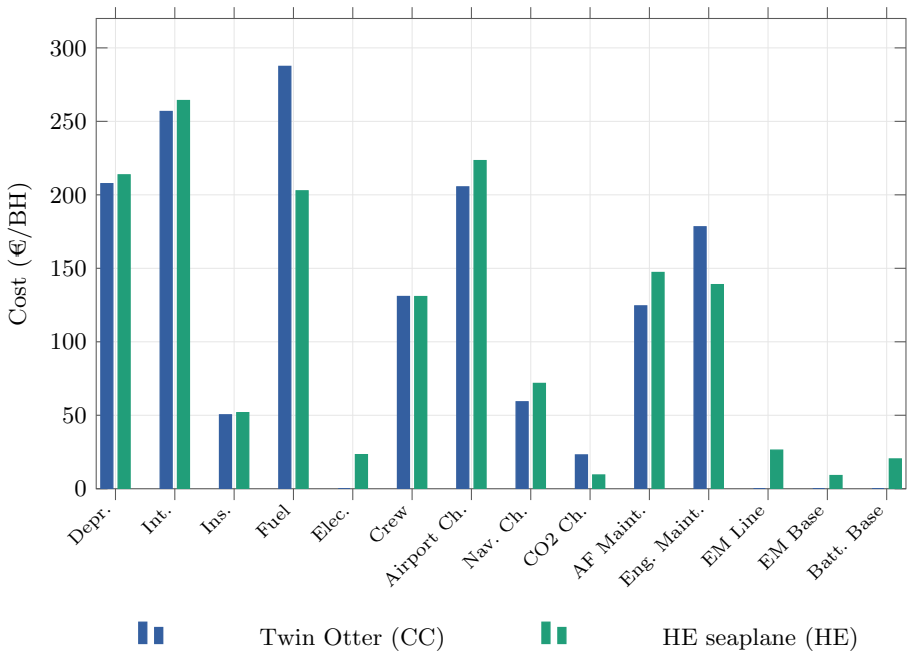



**Fig. 8** Comparative absolute DOC breakdown (€/BH) for the Twin Otter (CC) and the hybrid-electric seaplane (HE).

The electrical energy cost remains low (23.19 €/BH). Lower fossil-fuel burn in turn reduces $CO_2$ emission charges by 59.3 % (from 23.01 to 9.36 €/BH), a tangible benefit of compliance with the EU Emissions Trading System and a clear lever for future policy-driven DOC reductions on electrified platforms.

The maintenance profile is reshaped rather than simply reduced. The reciprocating piston engine, mechanically simpler and operating in milder conditions than a gas turbine, lowers thermal-engine maintenance by 22.1 % (from 178.24 to 138.88 €/BH). Electrification, however, introduces new mandatory items—inspection of electric machines, inverters, controllers and thermal-management systems, plus base maintenance for battery health and replacement. The combined cost of the new electric-machine and battery maintenance (roughly 55 €/BH) is modest against turboprop overhaul costs, but it is a fresh category with limited service history and is therefore a key area for future life-cycle-cost refinement.

Airport and navigation charges rise markedly: +8.7 % for airport charges and +21.1 % for navigation charges. This is a direct consequence of the additional structural mass needed to carry the battery packs and associated systems. Because both airport tariffs and air-navigation service fees scale with MTOM, the heavier hybrid-electric seaplane falls into a higher bracket, partially offsetting its energy savings—the single mechanism that most strongly prevents a net DOC advantage.

## 5.3 Numerical comparison and discussion

Table 9 shows that the total per-block-hour cost is essentially unchanged between the two architectures: 1 523.03 €/BH (CC) versus 1 532.00 €/BH (HE), a difference below 1 %. This parity is significant: it indicates that, on short regional sectors and under current assumptions, the hybrid-electric powertrain is already cost-competitive at the operating level.

**Table 9** DOC comparison: Twin Otter versus hybrid-electric seaplane (€/BH).

| **Cost item** | **Twin Otter** | **HE seaplane** | **Difference** |
|---|---|---|---|
| Depreciation | 207.58 | 213.60 | +2.9 % |
| Interest | 256.70 | 264.15 | +2.9 % |
| Insurance | 50.30 | 51.76 | +2.9 % |
| Fuel | 287.40 | 202.72 | −29.5 % |
| Electricity | – | 23.19 | – |
| Cockpit crew | 130.81 | 130.76 | 0.0 % |
| Airport charges | 205.41 | 223.28 | +8.7 % |
| Navigation charges | 59.16 | 71.66 | +21.1 % |
| $CO_2$ charges | 23.01 | 9.36 | −59.3 % |
| Airframe maintenance | 124.43 | 147.15 | +18.3 % |
| Thermal engine maintenance | 178.24 | 138.88 | −22.1 % |
| EM line maintenance | – | 26.27 | – |
| EM base maintenance | – | 8.96 | – |
| Battery base maintenance | – | 20.27 | – |
| **Total DOC** | **1 523.03** | **1 532.00** | **+0.6 %** |

The parity is achieved by a structural *transfer* rather than a coincidental cancellation. Combined energy-related costs (fuel + electricity + $CO_2$) fall from 310.41 to 235.27 €/BH, a 75.14 €/BH saving, which is then re-absorbed by higher financial/capital charges (+15.03 €/BH), higher maintenance (+38.86 €/BH) and higher MTOM-driven airport and navigation charges (+30.37 €/BH). The overall maintenance cost of the HE seaplane (341.53 €/BH) is comparable to the CC's (302.67 €/BH): the reduction in turboprop maintenance is largely balanced by the new battery and electric-component items, which become the critical lever for future life-cycle-cost improvement. The 2.9 % increase in depreciation, interest and insurance is consistent with the slightly higher capital outlay for electric motors, inverters and high-capacity battery packs.

Importantly, the present model does not capture future DOC reductions that evolving policy is likely to bring to the HE configuration. Differential charging mechanisms, green landing fees and stricter carbon pricing would penalise the conventional architecture more heavily, improving the relative DOC—and, as Sect. 6 shows, the relative profitability—of the hybrid-electric seaplane.

# 6 Financial performance: a yield-dependent business case

The operating-cost comparison of Sect. 5 stops at the block hour. The investment decision, however, is taken over the life of the asset, so the per-block-hour structure is now propagated through the project-finance model of Sect. 2.3: the DOC and revenue streams are turned into the annual cash flow of Eq. (7), discounted at $r = 3\,\%$ over a 15-year horizon, and condensed into NPV, IRR and Payback through the TCO chain of Fig. 1.

The per-block-hour parity of Sect. 5 does not survive this step. Once the slightly larger initial investment ($I_0 = 5.81$ vs 5.12 M€) and the recurring battery replacement are annualised through Eq. (7), the hybrid-electric seaplane carries a higher annualised cost; with both architectures flying the same route at the same 72.2 % load factor—hence the same RPM and the same revenue at a given fare—this translates directly into a higher unit cost (CASM of 0.87 vs 0.85 €/nm·seat at the baseline yield) and a lower unit profitability, despite the HE's lower specific energy use. The financial ranking is therefore not fixed: because RASM is set by yield and is identical for the two aircraft, the outcome is governed entirely by how the common fare compares with each platform's unit cost.

Table 10 reports the full comparison at two representative fares. At a yield of 1.50 €/pax-nm (a ticket of ≈285 €) the conventional turboprop is comfortably viable (NPV = 1.66 M€, IRR = 7.06 % > $r$), whereas the hybrid-electric seaplane is *not*: its NPV is negative (−0.88 M€), its IRR (0.79 %) falls below the 3 % discount rate, and the investment does not pay back within the 15-year horizon. Raising the yield to 1.75 €/pax-nm (a ticket of ≈332 €) reverses the verdict: the hybrid-electric seaplane becomes viable, with a positive NPV (3.50 M€) and an IRR (10.39 %) well above $r$, though it still trails the turboprop (NPV 6.00 M€, IRR 16.29 %) and pays back two years later (8 vs 6 years). This contrast is shown in Fig. 9.

The single number that summarises the result is the break-even yield: the fare at which the hybrid-electric NPV turns positive. Interpolating between the two scenarios (Fig. 10) places it at about 1.55 €/pax-nm, equivalent to a ticket of roughly 295 €—only a few percent above the baseline fare. Below this threshold the hybrid-electric seaplane destroys value; above it, the project is viable and the gap to the turboprop narrows steadily as yield rises. The turboprop's own break-even is lower (≈1.40 €/pax-nm), so a band of fares exists in which the conventional aircraft is profitable while the hybrid-electric one is not—precisely the regime of the 1.50 € baseline.

Yield is the most direct lever but not the only one. Because the gap is shallow and concentrated in a few DOC items (Table 9), it is equally responsive to a lower battery unit cost (which shrinks both $I_0$ and the recurring replacement charge), a stricter carbon price (which penalises the fuel-heavy turboprop far more than the hybrid-electric seaplane, whose $CO_2$ charge is already 59 % lower), and low-emission fee schemes that would remove part of the mass-driven airport and navigation penalty. Each acts on a distinct cost item, and any combination of them shifts the break-even yield downward—towards, and eventually below, the prevailing market fare.

**Table 10** Comparative operational and financial assessment at two ticket yields (15-year horizon, $r = 3\,\%$). The hybrid-electric seaplane crosses from non-viable to viable between the two fares.

| | Yield 1.50 €/pax-nm | | Yield 1.75 €/pax-nm | | |
|---|---|---|---|---|---|
| **Indicator** | **CC** | **HE** | **CC** | **HE** | **Unit** |
| ASM | 2.257 | 2.257 | 2.257 | 2.257 | M seat-miles/yr |
| RPM | 1.630 | 1.630 | 1.630 | 1.630 | M pax-miles/yr |
| Revenue | 2.45 | 2.45 | 2.85 | 2.85 | M€/yr |
| Annual profit | 0.56 | 0.48 | 0.93 | 0.85 | M€/yr |
| CASM | 0.85 | 0.87 | 0.85 | 0.89 | €/nm·seat |
| RASM | 1.08 | 1.08 | 1.26 | 1.26 | €/nm·seat |
| Profitability | 0.25 | 0.21 | 0.41 | 0.37 | €/nm·seat |
| $I_0$ | 5.12 | 5.81 | 5.12 | 5.81 | M€ |
| NPV | 1.66 | −0.88 | 6.00 | 3.50 | M€ |
| IRR | 7.06 | 0.79 | 16.29 | 10.39 | % |
| Payback period | 10 | 15 | 6 | 8 | years |

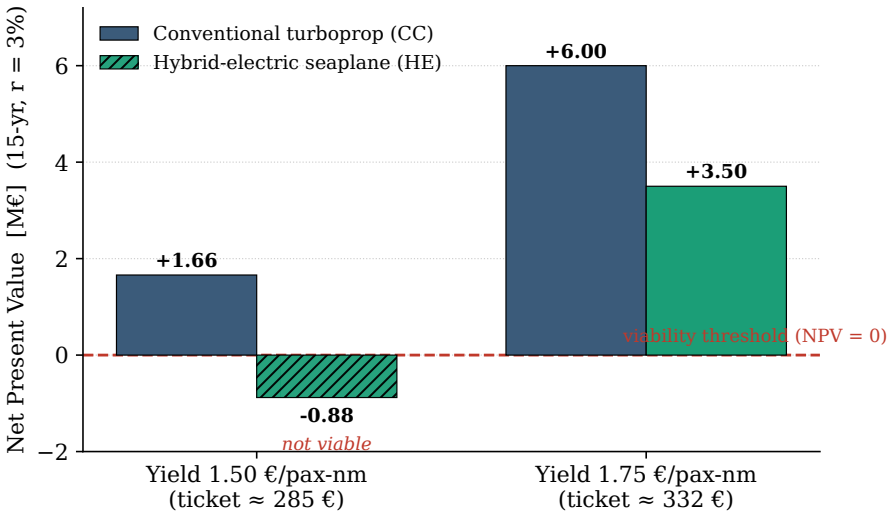



**Fig. 9** Net Present Value of the two architectures at the two ticket yields. The hybrid-electric seaplane crosses the viability threshold (NPV = 0) between 1.50 and 1.75 €/pax-nm.

Two further observations frame the risk profile. First, the payback period of the hybrid-electric seaplane is not only longer than the turboprop's at every fare (15 vs 10 years at 1.50, 8 vs 6 years at 1.75) but also more sensitive to it, because a larger share of its cash outflow is fixed capital rather than fuel; this concentrates the investor's exposure in the early years and makes the concept more dependent on stable, premium-yield routes. Second, the very feature that depresses the financial

**Fig. 10** NPV as a function of ticket yield for both architectures. The hybrid-electric seaplane is viable only above a break-even yield of ≈1.55 €/pax-nm; the shaded band marks the non-viable region.

ranking—capital intensity rather than operating inefficiency—is also what makes the case improvable without touching the aircraft: every external lever above acts on cost or revenue, not on the airframe. The answer to the research question is therefore quantitative and conditional: on this route the hybrid-electric seaplane is competitive above a break-even yield of about 1.55 €/pax-nm, and the practical question for a prospective operator or policymaker is not whether the technology works but whether the market fare, the fee regime and the battery-cost trajectory place the operating point on the favourable side of that threshold.

# 7 Conditions for competitiveness and policy implications

The results admit a compact reading: the hybrid-electric seaplane is operationally ready but financially borderline, and the margin is governed by a small set of external levers rather than by the aircraft itself. On a real short route the hybrid-electric seaplane reaches DOC parity with the conventional turboprop, with a per-block-hour difference below 1 % (Table 9). For an operator this means there is no day-to-day cost penalty to overcome: the platform can be flown at the same unit operating cost as the incumbent. Operationally, then, the technology is already at the threshold of competitiveness on this class of mission, and the obstacle to adoption lies one level up, in the project economics rather than in the cost of flying. The project-level outcome is not a fixed ranking but a narrow yield threshold. At the 1.50 €/pax-nm baseline the concept destroys value, yet a break-even fare of only ≈1.55 €/pax-nm—a few percent higher—separates it from viability, and by 1.75 €/pax-nm it earns an IRR above 10 %. Because this shortfall is driven by capital intensity rather than by operating inefficiency (specific energy use is in fact lower), it is improvable without any change to the airframe: it responds to prices, fees and financing, not to aerodynamics or propulsion. Four levers move the threshold, each acting on a cost item already isolated in the DOC analysis. (i) *Carbon pricing*: the hybrid-electric $CO_2$ charge is already 59 % lower, so a stricter EU ETS price penalises the turboprop disproportionately and narrows the gap. (ii) *Battery cost-learning*: a lower unit price reduces both the initial investment and the recurring replacement charge, the two terms that most depress the hybrid-electric cash flow. (iii) *Low-emission fee schemes*: the airport and navigation surcharges that follow from the higher MTOM are, in part, a policy artefact rather than a physical cost, and a discount for low-emission aircraft—of the kind already applied to full-electric concepts—would remove much of the mass-driven penalty. (iv) *Yield and market design*: premium island-connectivity routes, where seaplanes also save journey time over ferries, are precisely those able to sustain the fares above break-even. The competitiveness of the concept is therefore set as much by regulation and market structure as by technology, which is consistent with the wider literature reporting cost premia for first-generation electric and hybrid aircraft [3, 8, 10] and underlining the decisive role of fuel price, battery energy and policy incentives.

Read this way, the hybrid-electric flying boat is best understood as a forward-looking investment whose attractiveness improves along the very trajectories that European decarbonisation policy is designed to create: rising carbon prices, falling battery costs and differentiated, emission-aware charging. It is most compelling in island and coastal markets, where the water-based architecture additionally avoids the capital cost of building or expanding land airports—a benefit not even credited in the present route-level model and therefore a conservative omission.

The analysis is single-route and single-aircraft, uses conceptual-level mass and cost estimates, and treats indirect operating costs as fixed and identical across architectures. The break-even yield is obtained by interpolation between two fare scenarios and should be refined with a denser yield sweep. The battery-replacement schedule and residual-value assumptions are influential and uncertain, and currency and 2024-base-year price effects propagate into the absolute figures. Fleet-level effects, certification cost and waterport capital expenditure are out of scope. These considerations bound the absolute numbers but not the structural conclusion, which rests on the cost *transfer* of Table 9 and the shallow, lever-sensitive threshold of Sect. 6.

# 8 Conclusions

This paper assessed whether, and under what conditions, a clean-sheet hybrid-electric seaplane can be a financially competitive alternative to a conventional turboprop on short European regional routes. A surrogate-based multi-objective design produced an 18-seat flying boat whose delivery price is close to that of a DHC-6, thanks to inexpensive reciprocating engines; on the Valencia–Palma route it reaches DOC parity (difference $< 1\,\%$) by trading large energy and $CO_2$ savings against higher capital, new electric-powertrain maintenance and mass-driven fees. At project level the verdict is decided by ticket yield: at 1.50 €/pax-nm the hybrid-electric seaplane is not viable (negative NPV, IRR below the discount rate), whereas at 1.75 €/pax-nm it is, with the break-even fare sitting at only ≈1.55 €/pax-nm (≈295 € per ticket). The contribution of the work is to quantify this threshold and to show that it is shallow and lever-sensitive: realistic movements in fare, battery cost, carbon price and low-emission fee schemes are enough to cross it. The hybrid-electric flying boat is best interpreted as a forward-looking investment whose competitiveness is set by policy and cost-learning trajectories rather than by aircraft technology alone, and it is most attractive precisely in the island and coastal markets where seaplanes also avoid land-airport capital expenditure. Future work will extend the assessment to a fleet and network level and incorporate waterport capital and certification costs.

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# Appendix A Surrogate-model accuracy

The Kriging (KRG) surrogate models, implemented in the SMT toolbox [26] on a design space consisting exclusively of continuous variables, were trained on a dataset of 300 samples: 80 % (240 samples) for training and the remaining 20 % (60 samples) held out for validation. Surrogate accuracy is quantified by Root Mean Squared Error (RMSE) and coefficient of determination ($R^2$) on the validation split. Relative RMSE is a few percent of the mean KPI value and $R^2 > 0.96$ throughout (Table A1), supporting the reliability of the optimisation.

**Table A1** Surrogate-model accuracy per key performance indicator.

| **Performance metric** | **Unit** | **RMSE** | $\boldsymbol{R^2}$ |
|---|---|---|---|
| Take-off distance | ft | 45.0 | 0.987 |
| Landing distance | ft | 65.0 | 0.970 |
| Absolute ceiling | ft | 356.0 | 0.977 |
| Rate of climb | ft/min | 24.5 | 0.982 |
| Maximum cruise Mach number | – | 0.005 | 0.989 |
| Mission block time | min | 1.92 | 0.970 |
| Battery energy consumption | kWh | 25.83 | 0.993 |
| Fuel consumption | lb | 72.06 | 0.966 |
| Operating empty weight | lb | 506.3 | 0.969 |
| Maximum take-off weight | lb | 557.8 | 0.966 |
| Aircraft delivery price (ADP) | M USD | 0.065 | 0.991 |

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