Sign-Aware Mission Assessment of Thermal-Management Architectures for Hybrid-Electric Aircraft

Syed Atif Ali[1] **and Salwa Din**[2,*]

[1] Cisco CCIE, Taxes, USA.
[2] York University, ON, Toronto, Canada.
* Correspondence: salkammd@my.yorku.ca

Abstract: The hybrid-electric aircraft moves propulsion heating away from traditional locations toward electrical machines, power electronics, wiring, batteries, and controls. It changes thermal management from being aircraft architecture dependent because mass, auxiliary power, aerodynamics, mission phase, and technological maturity interrelate. The specific research question to be answered here concerns the near-term thermal management architecture that remains most tenable when pairs of aircraft data are analyzed using the correct aerodynamic sign with respect to their mission-specific thermal role. A sign-aware mission assessment approach is formulated for three aircraft design examples, namely, STARC-ABL, RVLT, and PEGASUS, with pairs of reference and advanced thermal management measures. The process computes mass, auxiliary power, and aerodynamic indices; preserves the meaning of negative drag effect; and tests sensitivity of architectural recommendation under the transport cruise, vertical lift, and distributed electric loadings. As can be seen from the case data presented, no advanced configuration scores highest for all three criteria. STARC-ABL achieves a reduction in thermal system mass from 197.97 kg to 50.77 kg and drag effect from 14.68 lbf to 4.52 lbf (by 74.35 percent and 69.21 percent, respectively) and a gain in auxiliary power by 55.00 percent. RVLT reduces thermal mass and auxiliary power by 50.15 percent and 63.85 percent, respectively, but reduces the beneficial effect of negative drag contribution by 65.21 percent. PEGASUS increases mass and drag by 28.97 percent and 28.17 percent, respectively, and auxiliary power by 36.36 percent. It can be concluded directly that the recommended near-term primary thermal management architecture is based on pumped liquid loop and ram air heat rejection at the aircraft level. Phase change material, heat pipes, passive spreading, compact sinks, and surface rejection should have a supportive rather than substitute mission-specific role.

Keywords: hybrid-electric aircraft; aircraft thermal management; sign-aware assessment; liquid cooling; ram-air heat exchanger; phase-change material; mission-segment analysis; compact heat exchanger; aerospace mechanical design

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1. Introduction

Hybrid-electric aircraft shift heat-generation location and time in that a significant fraction of propulsive power must go through electric motors, power electronics, wiring, battery packs, and control circuitry before being converted into propulsive or shaft power. While the argument for electrified propulsion in terms of its environmental benefits is well understood across aviation roadmaps and propulsion studies, the corresponding mechanical consequence has received equally well-deserved attention in terms of distributing heat through mass-constrained, volume-limited, and highly flow-condition-dependent systems [1–5]. Consequently, thermal management cannot be treated as a secondary equipment-cooling issue; it needs to be assessed side-by-side with propulsion integration, aircraft packing, mission segment, and external-flow costs.

Cooling alternatives belong to distinct design levels. A cold plate regulates equipment temperature on the surface level, a liquid loop manages heat transport through the entire aircraft, a ram-air heat exchanger dissipates heat to the outside, a phase-change material accepts a finite heat pulse, and cryogenic and hydrogen approaches alter the energy architecture itself. Confusion arises from treating these approaches as equivalent equipment choices. A near-term aircraft requires a core solution for continuously managing heat transport and dissipation, whereas local solutions make sense only in the context of reducing gradients, providing peak buffering, or improving packing at no extra mass, pressure drops, or drag cost [6–8].

There are also reasons for carrying out such a transparent analysis in the existing aircraft design literature. Multi-disciplinary design optimization, surrogate modeling, trajectory analysis, and aerodynamic shape optimization offer valuable means for future aircraft design steps, but a sign-consistent evaluation of design alternatives in terms of their quantities and trade-offs is still required at this point [9–15]. A thermal architecture that may lead to a higher component heat transfer coefficient might not make sense if it increases drag or auxiliary power consumption during the dominant mission segment of the operation. On the other hand, a certain solution with small auxiliary power penalty looks justifiable when it helps release a substantial amount of mass or alleviate external flow penalty.

The first example highlights aircraft as a single thermal entity, instead of cooling devices in isolation. The visible propulsion bay displays heat generation by electric motors, placement of inverters and batteries, coolant routing, pump integration, and ram-air heat dissipation in one airframe boundary. Phase-change material, passive spreading, enhanced heat sinks, and surface dissipation are consequently viewed as means that modify the core heat path rather than aircraft-scale solutions per se.

In particular, the aircraft design layout of Figure 1 sets up the boundaries of our analysis. Only through their effect on aircraft-level quantities (mass, auxiliary power, and external flow), do we evaluate cold plates, pumps, electrical modules, and battery modules at the component level. As a result, the fundamental question to address is: *which thermal management approach would still look most justified once all relevant aspects of mass, auxiliary power, aerodynamic effect, mission segment, and technical maturity are considered?*

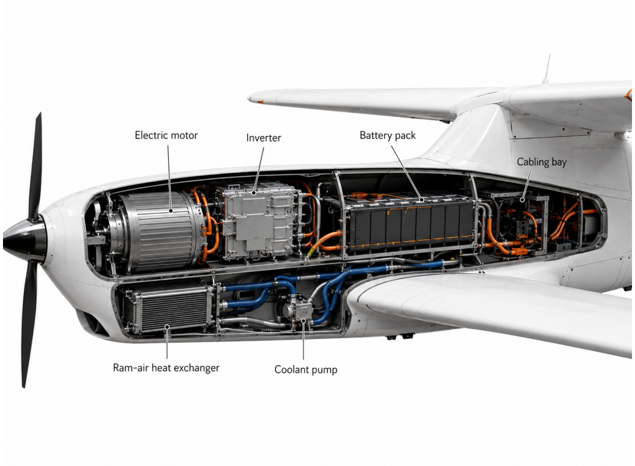

Figure 1. Aircraft thermal anatomy.

Three types of analysis allow us to solve this problem. STARC-ABL, RVLT, and PEGASUS aircraft are analyzed using the same paired advanced vs. reference calculation. The negative drag convention of RVLT is left intact in terms of positive external flow contribution rather than turning into an unsigned magnitude. These signed results are finally mapped to design functions associated with primary liquid loop, transient buffering, passive spreading, enhanced heat sink, surface dissipation, and longer-horizon hydrogen/cryogenic architectures.

1.1. Literature background and design need

There have been three partially independent streams in the development of hybrid-electric aircraft thermal management: cooling studies of more-electric aircraft systems, studies of electrified-propulsion architecture, and studies of battery and power-electronics thermal management. Cooling studies of more-electric aircraft are important because they demonstrate how the switch from hydraulic and pneumatic function toward electrical actuation had already increased thermal loads in converters, actuators, and avionics [16–19]. The architecture studies further extend this idea by adding electric machines, inverters, buses, and batteries into the propulsion chain where thermal penalties become relevant alongside energy and mission feasibility concerns.

Commercial and regional aircraft thermal management studies reveal that the architecture cannot be designed solely based on heat transfer intensity. Commercial aircraft studies focus on ram air cooling, ducting, pumping power, and exchanger placement, while trade studies at the aircraft level demonstrate the effect that heat rejection might have on mission energy consumption [20–26]. These studies motivate the proposed sign-sensitive approach because the seemingly minor aerodynamic penalty may matter during cruise and the power penalty may dominate at low-speeds or in hover.

Studying batteries and modules brings a different, but equally important point of view. Maximum temperature, temperature uniformity, avoidance of thermal runaway, and peak load handling become the key issues. However, some assumptions made in automotive applications are not valid in aircraft, where mass limits, operating altitude, packing density, and certification requirements make thermal problems substantially harder [27–31]. Phase change materials and composites help to mitigate thermal peaks, but they are regenerative systems and cannot be used repeatedly before their thermal energy is dumped out via heat rejection; they serve to buffer short heat pulses, but are far from being fully functional aircraft heat rejection architectures [32–37].

Liquid cooling, cold plates, and high-density heat exchangers present a most promising option for the high-intensity cooling of inverters, electric machines, and batteries, yet their application in aircraft depends on more than thermal conductance. Coolant choice matters for its freezing margin, viscosity, compatibility, and qualification. Pressure drop becomes a limiting factor for pumping power. Exchanger dimensions matter for aerodynamic drag, ducting, and installation mass [38,39]. Heat sinks using additive manufacturing, optimized channel geometries, and advanced heat exchangers can increase local heat transfer densities. However, their aircraft value will depend on the ability to manufacture, resist fouling, join parts reliably, and minimize pressure losses [40–44].

Passive and two-phase devices deserve consideration when used properly. Heat pipes and loop heat pipes can effectively distribute heat in a system with low complexity due to low number of moving parts. In particular, this feature makes them suitable for densely packed electronics and batteries. However, their effectiveness will depend on orientation, condenser location, contact resistance, and temperature range [45–47]. Two-phase cooling with assistance of pumps increases cooling potential, but the stability of two-phase flows introduces new challenges which can be solved only with complete modeling of heat transport in the vehicle [48–50]. Thus, these devices are used locally or in segments until their heat rejection capability and integration with mission is proven at the aircraft level.

Heat rejection to surfaces, utilization of fuel-systems for thermal management, and hydrogen propulsion systems bring fresh opportunities to the future. Surface heat exchangers and heat rejection via outer mold line will reduce penalties associated with conventional ducting. Still, this approach competes for structural area, requires aerothermal considerations [44,51–55]. Hydrogen, fuel cells, cryogenic propulsion, and superconducting propulsion systems promise to redesign the entire thermal management architecture. Nevertheless, storage, insulation, safety, and propulsion modifications are beyond the scope of conservative near-term solutions [56–61]. As a result, the choice of near-term solutions becomes less broad than the landscape of available technologies suggests.

From the above discussion regarding literature, we arrive at a well-defined requirement of design. There are component technologies as well as aircraft cases available, but at an early stage of architecture selection, there is still a need for calculation in which the sign sense of the drag coefficient must be maintained, continuous heat rejection and heat storage must be different, and mass and auxiliary power must be interpreted according to the mission of flight.

Table 1. Literature roles.

Literature stream	Direct evidence for aircraft thermal management	Limitation if used alone	Role in the assessment
More-electric and electrified aircraft studies	Establish the move from accessory cooling to propulsion-coupled heat loads [3,16,17,19].	Often emphasize architecture concepts without a common sign convention for thermal drag.	Basis for the aircraft-level question.
Aircraft thermal-management trade studies	Provide ram-air, ducting, pump-power, and heat-exchanger evidence for hybrid-electric concepts [8,20,21,24,25].	Case conclusions can be hard to compare when aircraft scale and mission differ.	Supplies the need for paired within-aircraft assessment.
Battery and module cooling	Clarify temperature uniformity, peak buffering, and safety constraints [27,29–31,37].	Many studies are not written around altitude, ram-air drag, or aircraft mass accounting.	Supports local buffering and battery-sensitive mission phases.
Liquid-loop and cold-plate studies	Provide mature heat acquisition and transport for high heat flux in machines and electronics [6,38].	Pressure drop, pump work, coolant qualification, and installation mass can offset local gains.	Near-term primary transport candidate.
Passive spreading, heat pipes, and two-phase devices	Reduce local gradients and improve local heat movement [45–47,49].	Do not by themselves provide continuous aircraft-scale heat rejection.	Supplementary heat-acquisition and spreading function.
Surface, compact, and additive exchangers	Offer drag-sensitive and packaging-sensitive improvements [40,41,44,53,54].	Structural integration, pressure drop, and off-design rejection remain limiting.	Mid-term integration and intensification candidates.
Cryogenic, hydrogen, and superconducting systems	Create future coupling among fuel, propulsion, and thermal management [57–61].	Require aircraft-level redesign beyond conservative near-term assessment.	Long-horizon architecture category.

The technology-role matrix reduces the technical claim to interpretation of architecture. There is no new cooling fluid or exchanger geometry being used here. The value addition is through the consistent sign and mission qualification of aircraft-level quantities, thereby linking each technology class to its justified function.

2. Comparative evidence base and aircraft examples

The comparative evidence base includes three aircraft examples, all commonly cited in recent studies on hybrid-electric and turboelectric aircraft. These include STARC-ABL, RVLT, and PEGASUS [8,62]. These aircraft examples are not exchangeable for each other. STARC-ABL is the single-aisle turboelectric aircraft with the aft boundary-layer propulsor and no battery pack in the selected configuration. RVLT is the tilt-wing VTOL aircraft with battery support and high sensitivity to hover, climb, and hot-day low speed regimes. PEGASUS is the short-range electric propulsion aircraft where there is a need for thermal loops serving the motor, inverter, and battery.

Aircraft Envelope for the Three Cases in Figure 2 presents the three cases within their mission framework prior to comparing the thermal metrics. STARC-ABL assesses the ability of an innovative design to minimize drag and mass penalties in a turboelectric application of transport class. RVLT assesses the effectiveness of thermal management despite the predominance of slow flight and lift integration. PEGASUS tests a small aircraft where multiple distributed loads have to be cooled without rendering the auxiliary system too disproportionate. The numerical case definitions are listed in Table 2.

It is seen from the table that there are differences in terms of scale, speed of mission, propulsion configuration, and battery inclusion. This makes a simplistic assumption, like picking the architecture with the biggest percentage mass savings, invalid. An approach in a regional or single-aisle context may accommodate a different trade-off among cooling

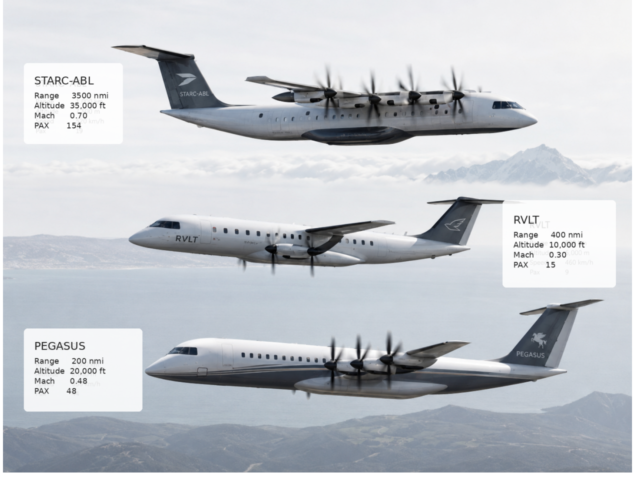

Figure 2. Aircraft case envelopes.

Table 2. Aircraft-case definitions.

Aircraft case	Type	Range	Alt.	Mach	PAX	E-motors	C-engines	Battery
STARC-ABL	CTOL	3500	35,000	0.70	154	1	2	No
RVLT	Tiltwing VTOL	400	10,000	0.30	15	4	0	Yes
PEGASUS	CTOL	200	20,000	0.48	48	5	0	Yes

drag, pump power, and installation mass than the low-speed vertical-lift approach, and a small electric aircraft is affected differently by the scaling of all other systems.

Thermal-management quantities used in the calculation are shown in Table 3. For STARC-ABL and RVLT, the reference and advanced versions refer to different thermal-management configurations within the same aircraft family. For PEGASUS, the two numbers represent a direct comparison. Pairing within an aircraft removes the mistake often made when evaluating aircraft with different propulsion scales.

Table 3. Paired thermal-management quantities.

Aircraft case	Configuration	Mass (kg)	Auxiliary power (kW)	Drag effect (lbf)
STARC-ABL	Reference	197.97	0.20	14.68
STARC-ABL	Advanced	50.77	0.31	4.52
RVLT	Reference	54.04	10.54	-39.92
RVLT	Advanced	26.94	3.81	-13.89
PEGASUS	Reference	195.55	0.22	17.64
PEGASUS	Advanced	138.89	0.30	12.67

Table 3 values also show why the aerodynamic factor should be treated cautiously. Positive drag influence of STARC-ABL and PEGASUS is a disadvantage, which implies that the smaller its value, the better. In RVLT, drag influence is negative in both systems, implying that the system's thermal management strategy contributes positively to propulsion. Making the absolute value smaller will have an opposite meaning despite it approaching zero, which makes sense from the signed calculation method shown below.

2.1. Data treatment and case normalization

The case data from Table 2 and Table 3 are analyzed using paired comparisons, not as a universal performance database. Each airplane provides a reference thermal management system and an advanced system, and what makes sense is to compare the internal movement of the airplane between the two states. This is the only logical method since a thermal-system mass for a transport STARC-ABL cannot be compared with an RVLT mass until proper scaling according to the propulsion, mission, airplane size, and thermal loads is completed. The normalization in this context preserves design meaning of the values.

The sign treatment is also critical. When a value is positive, it means that the effect of the drag is negative; hence, lowering this parameter leads to improvement. Negative values denote favorable aerodynamic effects; hence, the move towards zero is not necessarily an improvement despite the reduction in the absolute value. This case becomes the best validation for our method since we want to know whether our logic is purely mathematical or physical. In our case, the effect of the aerodynamics must retain its sign because the loss of the thrust-like effect is not favorable even with improved mass and auxiliary power.

Paired quantities can be put under three categories based on their decision significance. Quantities related to installation involve weight and packaging burdens. Quantities related to operations are associated with pump work, fan requirements, and auxiliary power. Quantities relating to flow deal with the aerodynamic effect or favorable interactions. All three groups of parameters make impact at different times. The installation burden is critical to all flight segments while auxiliary power is critical during periods of low cooling airflow recovery or high thermal loads. Aerodynamic effect will be significant during cruise phases in the total mission.

Table 4. Normalization logic.

Decision class	Quantity carried into the calculation	Why direct cross-aircraft comparison is avoided	How the quantity is interpreted
Installation burden	Reference and advanced thermal-system mass.	Aircraft size and propulsion scale differ strongly among the three cases.	A positive mass index means that the advanced state releases aircraft mass allowance.
Auxiliary demand	Pump, fan, or equivalent thermal-management power.	Mission speed, hover time, cooling-air recovery, and loop pressure loss are not identical.	A positive power index means that the advanced state reduces non-propulsive electrical demand.
External-flow effect	Drag effect, including negative values where applicable.	The sign of the effect carries physical meaning and must not be discarded.	A positive aerodynamic index means improved external-flow contribution under the adopted sign convention.
Technology maturity	Evidence from liquid loops, PCM, heat pipes, compact exchangers, and cryogenic concepts.	Component maturity does not equal aircraft-level maturity.	Near-term, mid-term, and long-term roles are separated by integration burden.

The normalization Table 4 ensures that the calculation path is clear prior to introducing any mathematical formulas. This approach also avoids using just one number aircraft example to represent the entire design process. The three examples, however, highlight a recurring pattern in architecture: liquid loop system designs consistently lighten the burden of installation; auxiliary power modifications vary according to loop and fan design; aerodynamic impacts depend on their signs within certain missions.

3. Method of mission assessment

The method is based on heat-path thinking, paired aircraft-to-aircraft normalization, signed aerodynamic interpretation, and mission role weighting. It is intended to be completely clear in all calculations: every index has its source in the reference or advanced quantities provided in Table 3, and every recommendation is evaluated on the basis of mission segment instead of inference from the single percentage result. Heat generation of an electrical or mechanical device can be formulated in general terms by

$$\dot{Q}_i = P_i(1 - \eta_i) + \dot{Q}_{\mathrm{par},i}, \tag{1}$$

where P_i is the electrical or mechanical power consumed, η_i is the corresponding efficiency of the device, and $\dot{Q}_{\mathrm{par},i}$ is extra parasitic heat associated with control circuitry, wiring, and/or control electronics. The formula is intended to be general since the evaluation compares aircraft cases and does not optimize individual components. The result shows that the thermal management effort is a direct effect of efficiency, power consumption, and component integration rather than a purely additive penalty.

Transported heat in a single-phase liquid coolant can be estimated via

$$\dot{Q}_\ell = \dot{m}_\ell c_{p,\ell}(T_{\ell,out} - T_{\ell,in}), \tag{2}$$

where $\dot{m}_\ell$ is the mass flow rate of liquid, $c_{p,\ell}$ is its specific heat, and $T_{\ell,out} - T_{\ell,in}$ is the temperature lift in the loop due to heat pickup. Higher coolant $c_{p,\ell}$ or higher permissible temperature lift will result in smaller mass flow rates, but both values have limitations in aircraft design. Choice of coolant influences parameters like viscosity, pumping work, freeze margin, compatibility with materials, and certification risks, whereas permissible temperature lift is dictated by batteries, inverters, and other equipment.

The auxiliary power of the system responsible for coolant and air flow can be approximated by

$$P_{\mathrm{aux}} = \frac{\dot{V}_\ell \Delta p_\ell}{\eta_p} + P_{\mathrm{fan}}, \tag{3}$$

where $\dot{V}_\ell$ is volume flow of liquid, Δp_ℓ is the pressure drop in the loop, η_p is pump efficiency, and P_{fan} is the fan power consumed to generate airflow in the absence of sufficient ram pressure. This equation provides a reason for the essential trade-off that exists in three aircraft cases: the lighter or smaller advanced design is still not better when it involves higher pumping or fan efforts.

Liquid flow rate can be linked to heat rejection using the heat exchanger conductance formula

$$\dot{Q}_{HX} = UA_{HX}\Delta T_{lm}, \tag{4}$$

where U is the heat exchanger's overall heat transfer coefficient, A_{HX} is the effective heat transfer surface, and ΔT_{lm} is the logarithmic mean temperature difference between the liquid and air flows. This equation reveals why heat exchanger area alone is a poor indicator of its capabilities. The heat exchanger may be sufficiently compact only when the product of UA_{HX} and allowable temperature difference will be satisfactory over the appropriate segments. For example, at altitude, during climbing, or during low speed operation, the latter can decrease substantially even if the heat exchanger looks sufficiently compact on the ground.

The aerodynamic penalty of ram air cooling and fan-powered flow can be presented via the relation

$$P_D = D_{TMS}V_\infty, \tag{5}$$

where D_{TMS} is the aerodynamic drag caused by TMS and V_∞ is the flight speed of the aircraft. This relation is helpful since it maintains original drag values while providing their physical interpretation. A small drag in cruise can be significant in comparison with low-speed operation; likewise, fan power can exceed ram effect during the latter. Consequently, the equation allows us to interpret aerodynamics and auxiliary power in terms of mission segment.

Effective thermal storage in a phase change material (PCM) can be described by the equation

$$Q_{PCM} = m_{PCM}\Big[c_s(T_m - T_0) + h_f + c_l(T_1 - T_m)\Big], \tag{6}$$

where m_{PCM} is PCM mass, c_s and c_l are the specific heats below and above the melting point, h_f is latent heat of fusion, and T_0, T_m, and T_1 are temperatures below, at, and above the melting point, respectively. The equation reveals why PCM can provide only a finite buffer: it will absorb a certain heat load, but after exhausting latent storage, the absorbed heat must be transferred further. The equation makes it clear that PCM is a local and mission-specific aid rather than a heat rejection architecture.

For the purpose of mission evaluation, a formula for weighted thermal burden can be written as

$$\bar{\dot{Q}}_{mission} = \sum_{j=1}^{N} f_j \dot{Q}_j, \tag{7}$$

where f_j is weight of segment j in time or energy terms, and $\dot{Q}_j$ is heat load of that segment. This equation is not needed to construct fictitious load history; it demonstrates why the same architecture should be assessed differently for hover, climb, cruise, descent, and ground operation. A system designed for efficient ram air cooling in cruise may still need to employ PCM or fans during take-off and low speed operation.

A weighted assessment index can be constructed to show robustness of the equal-weight result

$$S_w = w_m I_m + w_p I_p + w_d I_d, \tag{8}$$

where $w_m + w_p + w_d = 1$. Weights do not introduce any new information into analysis; they reveal how sensitive the resulting architecture recommendation is to mission mass, auxiliary power, and aerodynamic effect priorities. Thus the conclusion cannot depend exclusively on the chosen equal-weight evaluation.

As follows from Figure 3, the conversion of signed aerodynamic effect into the unsigned magnitude is impossible. STARC-ABL and PEGASUS move left in the positive effect direction, so that advanced designs eliminate external flow penalties. RVLT moves right in the negative effect direction, hence advanced design loses part of positive contribution even when drag-effect value is decreased.

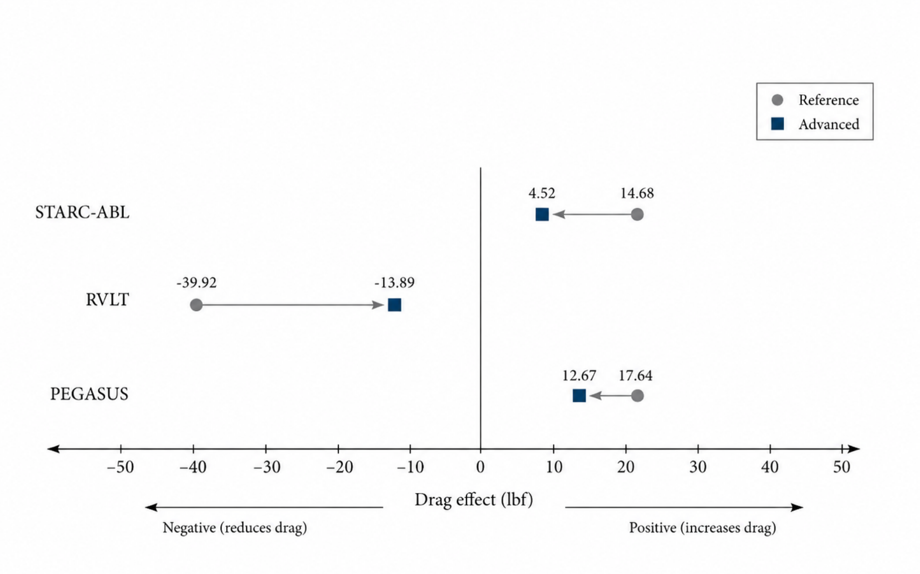

Figure 3. Signed drag-effect movement.

The mass-change index is expressed by

$$I_m = \frac{m_r - m_a}{m_r} \times 100, \tag{9}$$

in which m_r and m_a denote the reference and advanced thermal-system masses, respectively. A positive number implies a reduced mass due to the advancement of the aircraft. The mass-change index is the most obvious measure of aircraft installation benefit; however, it cannot be used alone to decide upon the architecture since changes in pump power and aerodynamic effect can be contradictory.

The auxiliary-power index is given by

$$I_p = \frac{P_r - P_a}{P_r} \times 100, \tag{10}$$

in which P_r and P_a represent the reference and advanced auxiliary power requirements, respectively. A positive number indicates a reduction in auxiliary power requirement. A negative number does not automatically rule out an architecture, although it would mean that thermal-system mass and/or drag benefits are paid for, at least partly, by extra demands for pump power and/or fan power.

The aerodynamic index is calculated from

$$I_d = \frac{D_r - D_a}{|D_r|} \times 100, \tag{11}$$

with the denominator representing the magnitude of the reference value so that the RVLT negative-drag case remains physically interpretable. A positive value represents a beneficial aerodynamic effect, whereas a negative value represents a reduction in aerodynamic advantage or an increase in drag penalty, depending on whether the original drag effect was positive or negative.

A straightforward way of combining the indices for transparent interpretation purposes is to calculate

$$S_e = \frac{I_m + I_p + I_d}{3}. \tag{12}$$

Although this score is neither designed nor intended to provide an optimization criterion, it illustrates the behavior of the three indices with no index being privileged over the others. In reality, different designers may wish to assign different weights to drag or mass depending on the mission of the aircraft.

The reason for using S_w is to avoid favoring any particular class of aircraft. In the transport-cruise mode, aerodynamic effect should have the highest priority, in the vertical lift mode auxiliary power must receive the highest attention during low-speed flight, and in the distributed electric propulsion short-range mode, mass should be most relevant.

Table 5. Weighted assessment views.

Weighting view	STARC-ABL S_w (%)	RVLT S_w (%)	PEGASUS S_w (%)	Interpretation
Transport-cruise emphasis: $w_m = 0.35$, $w_p = 0.20$, $w_d = 0.45$	46.17	0.98	15.54	Favors the case with large mass and aerodynamic improvement.
Vertical-lift emphasis: $w_m = 0.35$, $w_p = 0.45$, $w_d = 0.20$	15.11	33.24	-0.59	Rewards the RVLT auxiliary-power reduction and exposes PEGASUS sensitivity to added pump or fan work.
Short-range distributed-electric emphasis: $w_m = 0.40$, $w_p = 0.30$, $w_d = 0.30$	34.00	19.65	9.13	Keeps STARC-ABL first but narrows the difference among the cases.

The weight-score Table 5 is an exercise in sensitivity to mission roles, not the finding of an optimal new combination. In terms of transport cruise, STARC-ABL is a winner since drag and weight dominate the extended-mission case. In vertical flight mode, the RVLT score increases due to the 6.73 kW reduction in auxiliary power for the higher power required to maintain lift. From the distributed-electric perspective, STARC-ABL still comes out on top, but the relative difference has decreased, which is consistent with literature demonstrating the need to use weights sensitive to the mission role, rather than a universal ranking of the aircraft thermal system performance [21,22,26]. A liquid-loop configuration with ram air rejection is still the defendable near-future configuration choice, while its enabling technologies are mission-dependent.

Figure 4 represents the weighted scores with geometric interpretation. Weighting for more mass- and aerodynamic sensitivity results in STARC-ABL being the most favorable, weighing toward auxiliary power results in RVLT getting more attention, and distributing the load on the electrical grid reduces the distance between STARC-ABL and RVLT. This visualization makes the point of mission sensitivity to the design clearer, even though the choice of architecture does not change.

To facilitate the discussion of numerical values in the following paragraphs, the corresponding pairs of reference–advanced metrics are presented first. This figure divides the data into three groups by using three different axes of separation for mass, auxiliary power, and drag-effect. At the same time, the within-aircraft comparison framework is preserved.

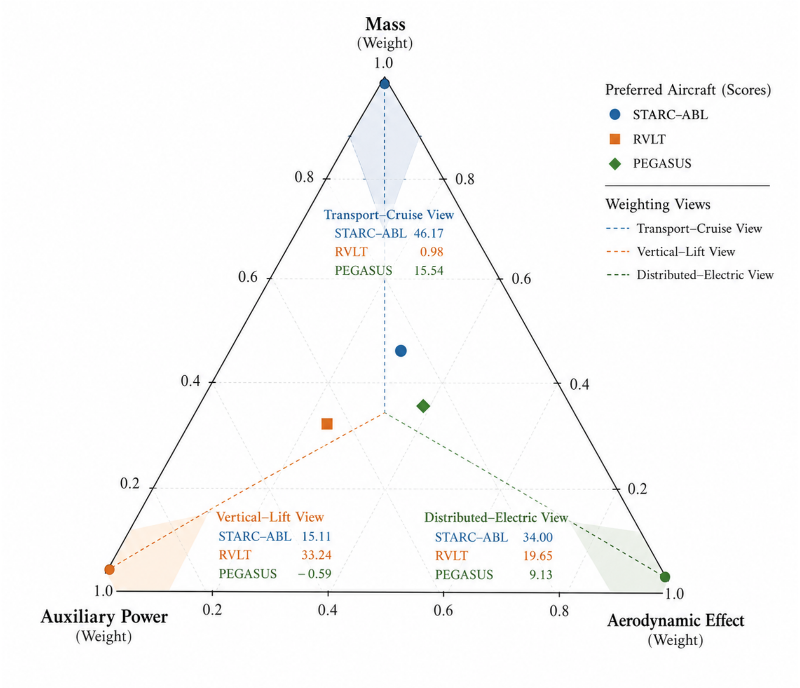

Figure 4. Mission-weighting simplex.

The paired metric plot in Figure 5 shows why different numerical changes result in different directions on the charts. It is obvious that both STARC-ABL and PEGASUS reduce mass and drag-effect, while increasing auxiliary power. RVLT shows the opposite operational emphasis: auxiliary power drops strongly, but the signed drag-effect marker moves toward zero from a favorable negative value.

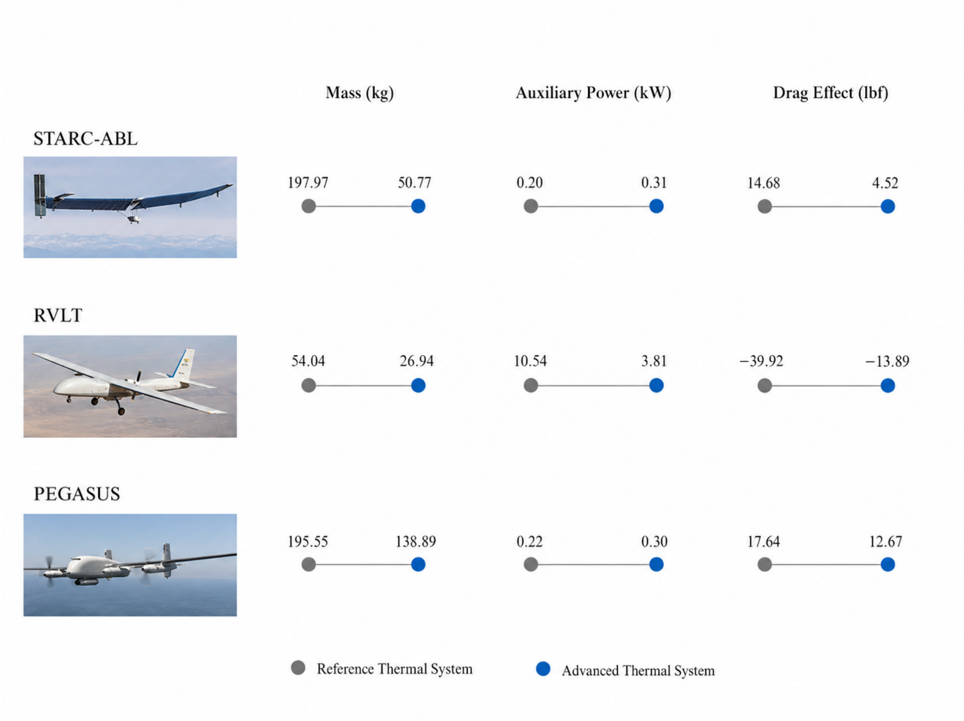

Figure 5. Paired reference–advanced quantities.

4. Results and discussion

The indices and the equal-weighted assessment value can be seen in Table 6. The sign convention will be maintained consistently throughout the Results section, in which positive entries will signify that the respective parameter improved with respect to the baseline in the advanced aircraft, while negative entries will show that there was deterioration in the respective parameter in the advanced aircraft. It is this sign convention that enables us to interpret physically the RVLT aerodynamic term.

From Table 6 we see the answer to the first question. No single advanced case exhibits superiority in all three categories of improvement. In STARC-ABL the combined indices for mass and aerodynamics are so high that even though there is an auxiliary power cost, the overall effect is positive. For RVLT the mass and auxiliary power benefits are quite large, but a significant proportion of the aerodynamic benefit has been lost due to negative drag. The PEGASUS aircraft does not make a significant improvement anywhere, and has a negative auxiliary power index.

Table 6. Signed indices and equal-weight score.

Aircraft case	Mass index I_m (%)	Power index I_p (%)	Aerodynamic index I_d (%)	Equal-weight score S_e (%)
STARC-ABL	74.35	-55.00	69.21	29.52
RVLT	50.15	63.85	-65.21	16.26
PEGASUS	28.97	-36.36	28.17	6.93

The absolute calculation trail is shown in Table 7. Values such as the percentage mass indices have a danger of obfuscating the actual amount of difference between the two cases. This can especially happen when there is an auxiliary power difference of many percent, but the power value itself is low. This would mean that the absolute difference between the two powers is small, hence insignificant, even though the percentage difference is large.

Table 7. Absolute and normalized changes.

Aircraft case	$m_r - m_a$ (kg)	I_m (%)	$P_r - P_a$ (kW)	I_p (%)	$D_r - D_a$ (lbf)	I_d (%)
STARC-ABL	147.20	74.35	-0.11	-55.00	10.16	69.21
RVLT	27.10	50.15	6.73	63.85	-26.03	-65.21
PEGASUS	56.66	28.97	-0.08	-36.36	4.97	28.17

The audit table gives a more physical interpretation of the numbers. STARC-ABL removes 147.20 kg from the thermal system and reduces drag effect by 10.16 lbf, but it requires an additional 0.11 kW of auxiliary power. RVLT removes only 27.10 kg in absolute terms, but the auxiliary-power reduction of 6.73 kW is substantial for a low-speed vertical-lift aircraft. PEGASUS removes 56.66 kg and reduces drag effect by 4.97 lbf, but its auxiliary-power increase shows that compactness alone does not guarantee better system efficiency.

The spatial representation of the index space map depicted in Figure 6 reveals the cross-case relationship between the cases more explicitly than just looking at the table. For instance, STARC-ABL lies within the quadrant that is characterized by low auxiliary-power index and high aerodynamic index. This implies that high mass effect and drag effect have been achieved at the expense of higher circulation requirement. In contrast, RVLT is located on the opposite quadrant where the beneficial auxiliary power effect becomes less significant.

In addition, the spatial distinction between the markers demonstrates why the three aircraft cases should not be treated as an average value for the universal aircraft design. STARC-ABL is dominated by mass and flow, RVLT is dominated by auxiliary power at low speed, and PEGASUS has a heat acquisition point constraint. The commonality among the three cases lies on the fact that a primary means of liquid transportation is desirable but with a distinct package of supporting mechanisms against the adverse effect.

4.1. Case-level interpretation

The result for STARC-ABL provides an interesting case for advanced liquid-loop integration because the mass savings are high from 197.97 kg to 50.77 kg. At the same time, the reduction in drag effect from 14.68 lbf to 4.52 lbf corresponds to the aircraft-level value of compact liquid-loop integration. As stated above, the negative power index is critical for interpreting the design outcome because it tells that the advanced arrangement shifts part of the penalty from installation mass and drag to internal circulation. This aspect will

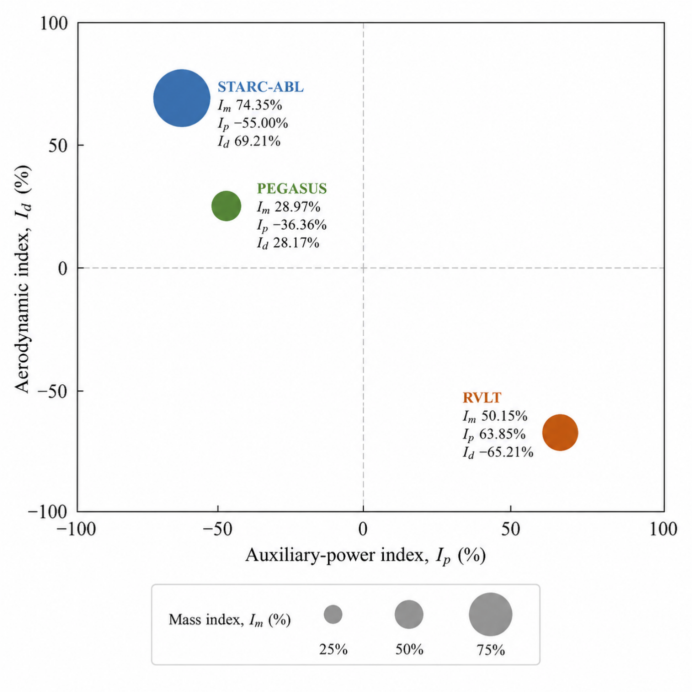

Figure 6. Signed index positions.

define the final choice of aircraft architecture in the long range mission scenario depending on the compatibility with generator loading and thermal margin.

The detailed interpretation of STARC-ABL suggests that the advanced configuration is not a miniaturized version of the reference architecture. Namely, a lower mass figure implies certain changes to the system's physical structure, such as the number of elements, the integration of exchangers, the quantity of coolant, the geometry of ducts, or the approach to packaging. The decrease in drag effect confirms the improvement in heat rejection. Therefore, the increase in auxiliary power represents the design warning regarding increased pressure loss, unfavorable flow distribution, and dependency on forced flow under off-design operating condition. Thus, the conclusion is right because the recommendation about pressure loss control is justified.

The result of RVLT requires a different mission context for an explanation. The mass reduction from 54.04 kg to 26.94 kg is useful, but the power reduction from 10.54 kW to 3.81 kW is especially significant because of a specific feature of vertical-lift craft. Namely, vertical aircraft are sensitive to auxiliary power demand for the reason that no ram recovery is available in hovering or transition. An improvement in the internal thermal system can be considered attractive if it leads to a lower power demand by 6.73 kW, despite the adverse aerodynamic index.

The result for RVLT demonstrates the necessity to account for mission conditions. Specifically, vertical aircraft cannot recover ram in hovering or transitioning mode. In addition, the load on fans or pumps can compete with the power required for the lift operation. Thus, the improvement of internal thermal system and auxiliary power reduction by 6.73 kW in the advanced design are attractive despite an adverse aerodynamic index. Hence, the present result is a confirmation rather than a contradiction to the previous conclusion about advanced liquid-loop configuration.

The result for PEGASUS provides a medium case for the liquid-loop configuration. The mass savings of 56.66 kg and drag-effect reduction of 4.97 lbf are achieved, yet the demand for auxiliary power increases from 0.22 kW to 0.30 kW. The less pronounced mass reduction in comparison with STARC-ABL means that certain factors may limit the potential mass savings in a different way. These include distributed electric loads and participation of batteries in operations. Thus, similar conclusions apply: local heat acquisition and pressure loss management are essential aspects.

In fact, the present numbers are useful because they prevent overstating the results. Specifically, 28.97 % mass savings are positive. Yet, unlike STARC-ABL, advanced PEGASUS does not change the aircraft radically. This is due to certain constraints caused by distributed loads related to motors, inverters, and batteries. Additional requirements are higher number of heat acquisition points, routing of coolant lines over extended distances, additional valves, or more restrictive temperatures. Therefore, local thermal spreading mechanisms may be equally important to the heat exchanger because of reduced temperature gradients.

Table 8 makes explicit connections between the calculations and the design recommendations. The critical point is not just the ranking of the scores; rather, the key realization is that each positive score comes along with its own integrative requirement. STARC-ABL needs to manage circulation power, RVLT needs to retain its low-speed heat rejection capability while maintaining adequate external flow interaction, and PEGASUS must alleviate routing penalty effects. Those are the real-world constraints that turn an ordered list into an airframe-capable architecture.

Table 8. Case-specific design reading.

Aircraft case	Strongest favorable evidence	Main adverse or conditional evidence	Practical design implication
STARC-ABL	Large reductions in mass and positive drag penalty.	Auxiliary power increases by 0.11 kW.	Select compact liquid-loop and ram-air rejection, but audit pressure drop and off-design circulation power.
RVLT	Auxiliary power decreases by 6.73 kW and mass decreases by 27.10 kg.	Favorable negative-drag effect weakens by 26.03 lbf.	Prioritize low-speed heat rejection, fan scheduling, and mission transients rather than cruise drag alone.
PEGASUS	Mass and drag penalty both improve, supporting the value of a refined loop.	Auxiliary power rises and improvements are moderate.	Combine the main loop with local heat spreading, compact sinks, and careful routing for distributed loads.

Duty assignments by mission phase are shown by the next duty ring (Figure 7). This ring specifies the thermal function which is most critical at each operating condition, without assigning unjustified numerical heat loadings to any phase of the mission.

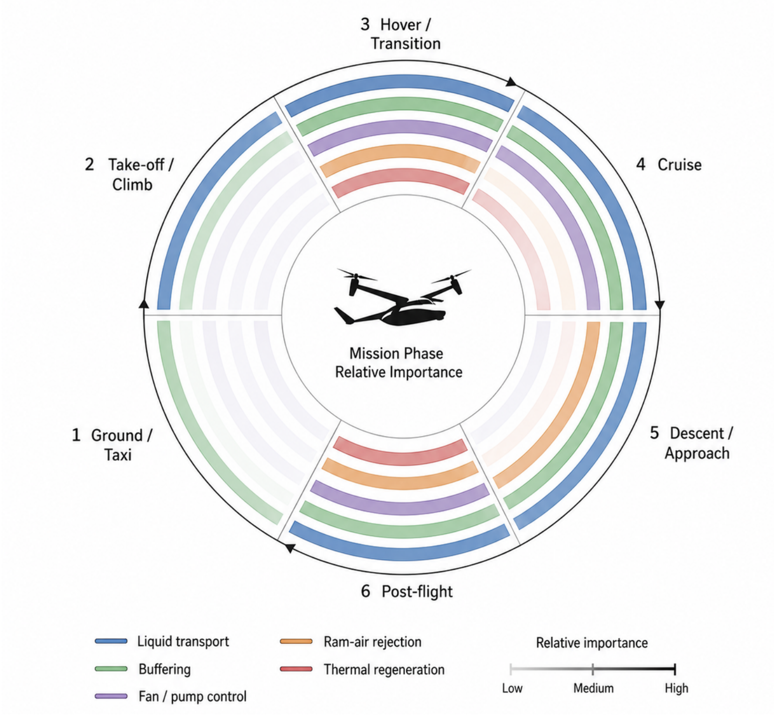

Figure 7. Thermal duties by mission phase.

That is why a mission-qualified architecture is essential. Take off, climb, and hot day low-speed flight enhance the significance of liquid loop transportation, buffering, fan requirements, and packaging. Cruise increases the attractiveness of ram air rejection due to higher velocity and better pressure recovery in the heat rejection environment. Descent and low load phases make fewer demands but may still require temperature control for batteries and electronics. An architecture which seems efficient during cruise can, in fact, be inefficient if it does not buffer transients or have fans for low-speeds.

4.2. Mission segment considerations

The mission-duty cycle is intended to be qualitative but not arbitrary. While take-off and climb feature high demands on propulsion, transients, and limited time for rejecting heat, cruise tends to favor ram air availability while making small drag changes significant due to the extended duration of the segment. Descent and approach tend to decrease the amount of heat generation, although battery thermal regulation and avionics reliability are still needed. Special conditions arise for ground operation, as the airflow may be weak while heating of cabin and avionics along with propulsion systems might require active cooling.

That is why answering the question formulated at the beginning of this section requires considering how each technology performs according to each of these segments. Thus, STARC-ABL shows great promise in all cruise-compatible indices while RVLT stands out in low-speed auxiliary heat demands, but PEGASUS is less promising in terms of distributed heat acquisition points. In consequence, the architecture chosen for a near-term aircraft needs to include an efficient main heat loop combined with additional cooling methods activated when the mission poses a particular thermal challenge.

A design development algorithm based on this consideration can look as follows. Firstly, the capacity of the main liquid loop has to be determined in order to cope with the most challenging sustained segment. Secondly, it is necessary to assess whether short transients would cause oversized loops; if true, PCM or another kind of thermal capacitance have to be applied in appropriate locations. Thirdly, one has to examine temperature gradients for various components; if such gradient dominates, heat pipes or additively manufactured sinks are recommended close to the heat generating component. Finally, ram-air rejection has to be considered in regard to drag or integration issues. However, the mission-guidance table provides further information on how to implement the optimal near-term architectures. The best short-term architecture is a controllable heat system composed of subsystems taking on different functions depending on the segment. Ground and taxi segments need heat soak, take-off and climb phases require transient margins, hover and transition phases require reduced auxiliary demand, cruise needs reduced ram air penalty, and post-flight requires heat regenerative capabilities for storing heat. It is for this reason that it can be argued that the common liquid-loop primary heat rejection system is the most justified across all three aircraft cases. However, the local heat rejection devices are case-dependent (Table 9).

It means that it is no longer correct to interpret the use of PCM as something that would replace a liquid-loop cooling system. Studies show that the real benefits of phase-change materials are derived from protecting the system against thermal peaks during take-off and hot-day operations, followed by the release of stored heat during low-load operations [24,34,35]. It is why PCM shows up as a supplemental technology, not the primary one within the near-term architecture.

Heat pipes and other spreading devices are used locally around motors, inverters, power modules, and densely-populated batteries to reduce gradient loads on the coolant loop before entering it [45,63]. Such technologies do not eliminate the necessity of rejecting heat through ram air flow, but they may help to reduce it to a minimum by improving the local cold plate design. It could be helpful in terms of the distributed loads and high density of batteries in PEGASUS case and vertical-lift application.

Table 9. Mission-segment guidance.

Mission segment	Dominant thermal concern	Most relevant architecture element	Reason for inclusion in the design logic
Ground and taxi	Low ram pressure with continued equipment heat.	Fan-assisted rejection and coolant circulation.	Prevents heat soak before take-off and avoids relying on flight-speed cooling.
Take-off and climb	High heat generation and limited transient margin.	Liquid loop with local thermal capacitance.	Maintains component limits without oversizing all steady-state hardware.
Hover or transition	High power at low airspeed for vertical-lift aircraft.	Efficient fan scheduling and low-pressure-drop loop design.	Reduces non-propulsive electrical demand when lift power is critical.
Cruise	Long-duration energy sensitivity and better air-side recovery.	Ram-air heat exchanger with low external-flow penalty.	Converts sustained heat rejection into a manageable aircraft drag problem.
Descent and approach	Lower heat generation but continued temperature-control need.	Controlled coolant bypass or reduced pump/fan operation.	Avoids unnecessary auxiliary power while maintaining electronics and battery limits.
Post-flight	Stored heat in batteries, PCM, and dense electronics.	Regeneration path and ground cooling strategy.	Ensures that transient buffers are ready for the next mission.

Nanofluids and advanced coolants are a second-layer technology in this context. Battery and compact systems show that using better coolants might reduce the temperature increase and provide higher coefficients of heat transfer [64–66]. However, the current data about aircraft thermal performance do not yet prove that nanofluid technology can become a separate architecture level. Its benefits consist in optimizing a liquid-loop heat rejection system under account of viscosity, pressure, and maintenance.

Surface and OML (outer mold line) cooling is also a promising technology. They could potentially save a conventional ram-air penalty and exploit the large surface areas of modern aircraft. However, they also involve significant challenges regarding structural integrity, weight, and cooling capacities [44,51–55]. In terms of the hierarchy of the near-term aircraft architecture, such solutions should be regarded as supplementary sinks and mid-term integration ideas only.

It is also necessary to note the hydrogen-based propulsion, fuel cell propulsion, cryogenics, and superconductors. These technologies are very promising and strategic for aviation, but they cannot become a solution for the near-term research problem. Fuel-cell systems use air and liquid cooling, and hydrogen-based systems can use fuel system for heat exchange [56,59,67]. Superconductors and cryogenics completely redefine the thermal architecture and design, so their implementation should be regarded as a long-term perspective [57,58,60,61]. These concepts therefore remain long-horizon architecture classes in the assessment logic.

4.3. Technology hierarchy and architecture choice

In other words, a hierarchy better represents the relationship between the competing technologies than a winner-take-all approach. On a first level, the aircraft requires continuous acquisition, transportation, and rejection of heat. On a second level, the aircraft requires technologies that mitigate local gradients or peak loads. On a third level, it can consider any emerging technology based on its ability to perform better if the aircraft configuration permits additional complexity.

The technology hierarchy explains an ambiguity in the results. Though the advanced configurations did not excel in all measures, the liquid-loop transport with ram-air rejection emerges as the most defensible near-term primary architecture. A primary architecture is said to be defensible if it can continuously transport and reject heat throughout the flight with an acceptable qualification risk. A technology is locally valuable if it contributes to solving a particular difficulty of the primary architecture. Consequently, PCM, heat pipes, advanced coolants, and compact sinks complement the primary architecture rather than compete with it.

It is important to stress that the analysis above does not imply that all future hybrid electric aircraft will necessarily have the same coolant, the same exchanger geometry, and the same fan control law. It neither denies the possibility that some hybrid-electric aircraft may feature advanced surface heat exchangers, hydrogen-based propulsion systems, and superconductive electric machines. Instead, a more modest claim is made here: in the context of a conservative near-term assessment of the hybrid-electric concept with STARC-ABL, RVLT, and PEGASUS missions, the most defensible primary architecture is a liquid-loop transportation system coupled with aircraft-scale heat rejection, along with corresponding locally valuable technologies.

The aircraft-specific technological package can be derived based on the results obtained from the three aircraft cases in question. STARC-ABL justifies the mass-and-drag benefit of a fine-tuned loop; RVLT justifies the priority of low-speed auxiliary power; and PEGASUS justifies the use of local heat-spreading and heat acquisition modules in addition to the main architecture. Thus, the same architecture can be justified in all three cases, while the set of complementary technologies should vary depending on aircraft case.

Finally, Table 10 shows how different the conclusions would be if the focus was not on the role of a technology in the aircraft design.

Table 10. Technology roles.

Technology group	Evidence used in the interpretation	Design role
Liquid loop with ram-air rejection	Repeated aircraft-level use in STARC-ABL, RVLT, PEGASUS, regional turbo-hybrid, partial-turboelectric, and SUSAN-related work; strongest repeated mass benefit in the three-case comparison [8,20,22,68,69].	Near-term primary architecture
PCM assistance	Useful for early-mission and short-duration peaks; reduces the need to oversize coolant inventory or exchanger capacity when used locally [24,32,34,35].	Near-term transient buffer
Heat pipes and passive spreading	Reduce local gradients and assist concentrated electronics, battery, and machine loads before heat enters the liquid loop [45–47,63].	Near-term local enhancement
Nanofluids and enhanced coolants	Improve local heat transfer but introduce pressure-drop, stability, and qualification questions at aircraft scale [64–66].	Mid-term loop enhancement
Surface or outer-mold-line rejection	Aerodynamically attractive but constrained by structural integration, rejection capacity, and aircraft-surface allocation [44,51–55].	Mid-term supplementary sink
Additively manufactured compact sinks	Offer improved heat-transfer density and integrated lightweight geometry when local heat flux is severe [40–43,70].	Mid-term component intensification
Hydrogen, cryogenic, and superconducting systems	Offer major future potential but require system-level redesign of storage, insulation, safety, and propulsion integration [57–61].	Long-term architecture class

The conclusion drawn from this table reiterates the answer to the research question. Liquid cooling using ram-air rejection is the strongest near-term primary architecture, but the term “primary architecture” is key here. A solution to the problem posed by the aircraft is not just a liquid loop, but rather a layered thermal design whereby PCM, passive spreading, compact sinks, and appropriate fan/pump control are only used when mission needs require it.

The plate showing the layered technologies in Figure 8 condenses the literature review into a choice for aircraft design. Short-term efforts should include heat collection in components, low pressure-drop liquid cooling, integration of the ram-air cooler, fan demand at low speeds, and local buffering. Medium-term efforts include denser component cooling via advanced fluids, additive manufacturing for sinks, and surface cooling where the aircraft structure can accommodate it. In addition, long-term efforts are necessary to continue exploring hydrogen-based and cryogenic cooling systems, but those solutions should not be used to distract from the immediate conclusion drawn by the three cases.

The concluding architecture plate shown in Figure 9 merges the case information into one design. The recommended short-term architecture solution is not a simple coolant mechanism, but rather a pumped liquid loop that takes heat from distributed electrical devices and rejects the heat through a ram-air cooler for the whole aircraft. STARC-ABL confirms the value of mass and drag in this solution, RVLT proves the need for auxiliary power management, and PEGASUS validates heat collection and local assistance.

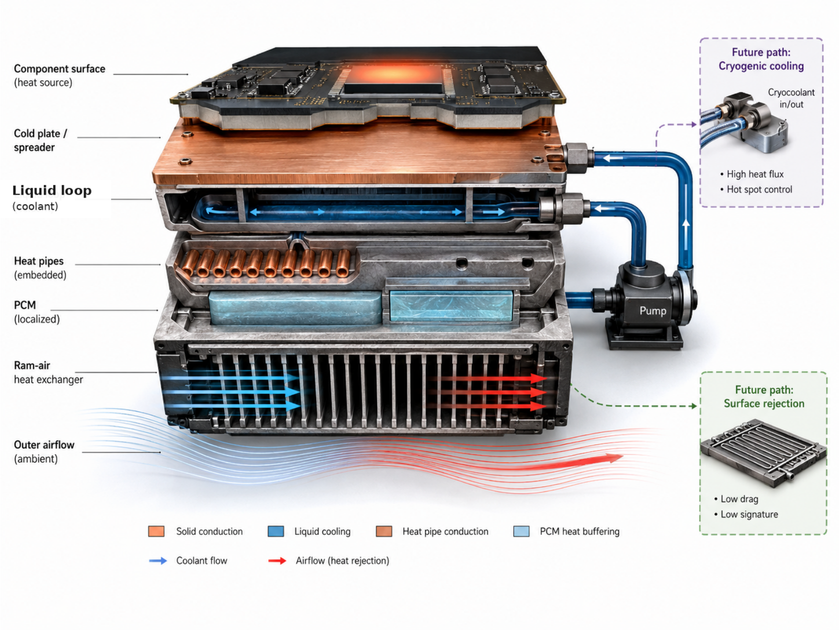

Figure 8. Layered technology roles.

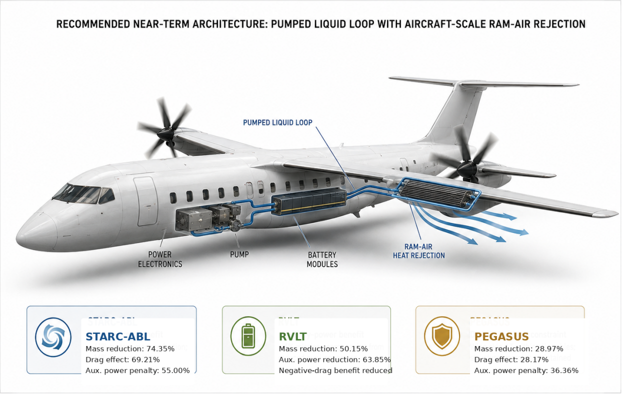

Figure 9. Recommended thermal architecture.

5. Conclusions

The assessment directly addresses the central research question. When mass, auxiliary power, aerodynamic effect, mission segment, and technology maturity are combined for analysis, the most valid architecture is a pumped liquid loop linked to aircraft-scale ram-air heat rejection. Individual air cooling, PCM cooling, heat pipe network, and speculative cryogenic cooling do not offer the near-term primary mechanism for continuous heat transport and rejection. However, these mechanisms may still play useful roles when connected to a complete aircraft heat rejection solution.

The case results set the technical bounds on the answer. Advanced configuration in STARC-ABL shows the highest improvement in mass reduction by 74.35 % and aerodynamic improvement by 69.21 % in exchange for increased auxiliary power by 55.00 %. The RVLT case has a slightly weaker improvement, with mass reduction by 50.15 % and auxiliary power reduction by 63.85 %, but much weaker negative drag improvement of 65.21 %. In the PEGASUS case, the improvement in mass by 28.97 % and aerodynamic performance by 28.17 % is accompanied by auxiliary power increase by 36.36 %. These results prove that the thermal management technology selection requires attention to multiple metrics.

Sign-aware evaluation changes the assessment conclusions. First, it ensures the RVLT case aerodynamic performance is read correctly. An approach towards zero in a negative value of the drag means worsening of external flow conditions. Second, sign-aware assessment distinguishes between primary and secondary mechanisms of thermal energy management. Aircraft-scale loops and ram-air rejection perform the continuous task; PCM absorbs short heat pulses; heat pipes and spreaders provide localized heat mitigation; compact and additive heat sinks maximize local heat absorption; surface cooling may reduce ducts penalties if feasible due to structural integration; hydrogen, cryogenic, and superconducting architectures have a longer horizon of implementation.

Therefore, the practical engineering guidelines become specific to the selected architecture but retain internal consistency. STARC-ABL should capitalize on mass and aerodynamic advantages of a liquid cooling loop and ram-air rejection while evaluating pressure drop and auxiliary power consumption. RVLT should focus on optimization of heat rejection at low speed and on fan scheduling with efficient pumps since auxiliary power saving is crucial during hover and transition. PEGASUS should implement the combination of a cooling loop with distributed heat sources collection, passive spreading and compact local heat sinks due to larger dispersity of heat-generating components and smaller room for improvement.

The key limitation of the present analysis lies in the usage of aircraft-level paired parameters as opposed to geometry-resolved models of all heat exchangers, coolant routes, fans, valves, and heat sinks. This level of detail is necessary for design optimization and thus not applicable at architecture stage when the trade-offs should be revealed first. However, future work can build upon the presented sign-aware assessment of mass, auxiliary power, and aerodynamic impact by coupling it with mission heat load profiles, pressure drop estimates, effectiveness of heat exchangers, fan behavior off-design, and uncertainty ranges. This way, the answer will become aircraft-specific design guidelines while maintaining the central point: hybrid-electric aircraft need qualified primary liquid-loop, aircraft-scale air side rejection, and properly assigned local mechanisms.

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