ENERGY MANAGEMENT STRATEGIES FOR HYBRID ELECTRIC AIRCRAFT POWERTRAINS: A CROSS-DOMAIN REVIEW, GAP ANALYSIS, AND ADAPTATION ROADMAP

Zalakben Barot*, Rudy Cepeda-Gomez*

* German Aerospace Center (DLR), Institute of Electrified Aero-Engines, Dept. of Aeronautical Requirements and Control of Propulsion Systems, Lieberoserstr. 13A, 03044 Cottbus, Germany

Abstract

Hybrid-electric and fuel cell-based aircraft propulsion requires energy management strategies (EMS) to distribute power among heterogeneous sources while satisfying state, thermal, operational, and safety constraints. Although EMS methods are well established for ground vehicles and increasingly studied for uncrewed aerial vehicles (UAVs), urban air mobility (UAM), maritime, and aircraft applications; their transferability to certifiable aircraft propulsion has not been systematically assessed. This paper presents a structured cross-domain review of 35 studies spanning ground vehicles, rail, maritime, UAVs, UAM, electric vertical take-off and landing platforms, and aircraft. Ten EMS method families are classified and compared using five dimensions. A total of 20 research gaps are identified and mapped to an adaptation roadmap towards deterministic, redundant, and certification-oriented aircraft EMS.

Keywords

hybrid-electric aircraft; energy management strategy; fuel cell; convex optimisation; model predictive control; cross-domain review; certification

1. INTRODUCTION

Aircraft propulsion is undergoing the most significant architectural change since the introduction of the jet engine. Hybrid-electric and fully electric power trains combine fuel cells (FC), lithium-ion batteries, and, in many concepts, a conventional internal combustion engine, to feed one or more electric motors. Unlike conventional propulsion, where power management is largely governed by engine operating-point control, hybrid-electric and full-electric aircraft must continuously determine how to distribute power among heterogeneous sources with different efficiencies, dynamics, degradation behaviour, and safety characteristics. This coordination problem is the energy management strategy (EMS): an EMS must simultaneously respect power balance, state-of-charge (SOC) and state-of-health (SOH) constraints, thermal limits, and an explicit reserve of stored energy for emergency operation, while remaining computationally tractable on embedded avionics hardware.

The EMS problem has been studied extensively across domains: in automotive hybrid-electric vehicles (HEVs) since the early 2000s, and more recently in rail, maritime, urban air mobility (UAM), and uncrewed aerial vehicle (UAV) applications. Aircraft propulsion introduces requirements that distinguish it from these source domains. Several narrower reviews exist. For example, Xie et al. [1] survey hybrid-aircraft conceptual design and EMS methodologies and explicitly state that current methodologies favoured in hybrid ground vehicles do not consider the aircraft safety. They, however, do not undertake a systematic, dimension-by-dimension comparison against the source domains to understand this gap. No existing review, to the authors' knowledge, systematically maps which EMS method families are transferable to certified aircraft propulsion, under which conditions, and with what evidentiary gaps. This paper addresses that gap, using six questions as guide:

- Which EMS approaches have been developed across hybrid-propulsion domains, and how mature are they?
- How do these approaches compare under a common set of evaluation criteria?
- Which characteristics make the aircraft EMS problem fundamentally different?
- Which methods are transferable to aircraft, and what adaptations are required?
- Where does the literature fall short of aircraft certification requirements?
- What research pathway could lead from the current evidence base to a certifiable aircraft EMS?

The main contribution of this review is a structured cross-domain mapping of EMS approaches and their transferability to aircraft propulsion. Rather than treating EMS methods as isolated algorithms, the review identifies the assumptions underlying each method

TAB 1. Literature search term categories

Category	Example terms
EMS	energy management, energy management strategy, power management, supervisory control, power split
Propulsion	hybrid electric, full electric
Storage	battery, fuel cell mainly PEMFC, supercapacitor
Platforms	vehicle, train, ship, UAV, UAM, eVTOL, aircraft

family, evaluates how these assumptions are affected by aircraft-specific requirements, and uses the resulting analysis to derive a research roadmap towards aircraft-ready and, ultimately, certifiable EMS architectures. Section 2 describes the review methodology and scope. Section 3 introduces hybrid-electric propulsion architectures and the generic EMS problem formulation. Section 4 develops a taxonomy of EMS method families. Section 5 presents the cross-domain evidence base, organised by application domain. Section 6 synthesises cross-domain transferability. Section 7 presents the four aircraft-specific EMS challenges. Section 8 consolidates the literature gaps identified throughout and the corresponding adaptation roadmap, and Section 9 concludes.

2. REVIEW METHODOLOGY AND SCOPE

Following Pautasso's guidance for integrative literature reviews [2], the review defines its search strategy, inclusion criteria, exclusion criteria, and comparison framework explicitly. Candidate studies were identified using Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. Searches combined terms from the EMS, propulsion, storage, and platform categories listed in Table 1. Search terms were adapted where necessary to account for domain-specific terminology.

Studies were included when they addressed hybrid or fuel cell/battery propulsion, reported an evaluable system level EMS or power split method, and provided at least one quantitative result against a stated baseline. Studies addressing only single-component control, such as isolated battery management or cell balancing functions without a system level power split decision, were excluded. The reviewed studies are organised into three application tiers according to their proximity to aircraft propulsion.

Each reviewed study is assessed, when the available evidence permits, on a four-level scale (Strong / Moderate / Weak / Untested) against five evaluation dimensions used consistently throughout Sections 5–8:

- **Fuel/H_2 economy** – quantified fuel, hydrogen, or equivalent energy saving relative to a stated baseline.
- **Charge sustaining behaviour** – SOC regulation, terminal-SOC error, or explicit reserve management.
- **Component lifetime** – whether battery or fuel cell degradation, stress, or lifetime is represented and how rigorously it is quantified.
- **Real-time implementability** – online computational cost, mission foreknowledge requirement, and level of hardware validation.
- **Aeronautical certification readiness** – evidence relevant to deterministic execution, verifiability, redundancy, fault handling, and engagement with certification-oriented development processes.

3. GENERIC EMS PROBLEM FORMULATION

The reviewed studies span four recurring propulsion architectures: (i) *series* hybrid, in which an internal combustion engine drives a generator that, together with a battery, supplies an electric motor with no direct mechanical path to the propulsor; (ii) *parallel* hybrid, in which a combustion engine and an electric motor both contribute mechanically to the propulsor shaft; (iii) *series-parallel* or power-split hybrid; (iv) *fuel cell/battery* hybrid, with no combustion engine.

Despite differences in propulsion architecture and application, the EMS problem can be represented by a common supervisory optimisation structure. The instantaneous propulsive power request must be supplied by the available sources,

$$P_{\text{req}}(t) = P_{\text{FC}}(t) + P_{\text{bat}}(t) + P_{\text{aux}}(t), \tag{1}$$

where the source terms are interpreted according to the architecture under consideration. The EMS selects the control input $u(t)$, representing the power split, to minimise a mission-level cost,

$$\min_{u(t)} J = \int_0^T \left[w_f J_f + w_d J_d + w_{\text{bat}} J_{\text{bat}}\right] \mathrm{d}t, \tag{2}$$

where J_f represents fuel or hydrogen consumption, J_d represents component-degradation cost, and J_{bat} represents an additional battery-related term when one is modelled. The optimisation is subject to state and actuator constraints, including

$$\text{SOC}_{\min} \leq \text{SOC}(t) \leq \text{SOC}_{\max}, \tag{3}$$

together with component power, current, thermal, and operating-envelope limits.

The method families in Section 4 differ in optimisation horizon, available mission information, model fidelity, and treatment of the constraints. These differences determine both achievable performance and implementation requirements.

4. TAXONOMY OF ENERGY MANAGEMENT STRATEGIES

Ten families are organised into three conventional groups, namely rule-based control, instantaneous optimisation, and global/predictive optimisation; plus two additional identified in the reviewed evidence: signal decomposition and classical feedback control.

Table 2 compares the ten families across six characteristics used consistently throughout the remainder of the paper.

4.1. Rule-based, fuzzy-logic, and hybrid-AI control

Rule-based control determines the power split from instantaneous measurements through fixed decision logic, requiring no mission foreknowledge and negligible computation [3]. Fuzzy logic replaces sharp thresholds with membership functions and is often combined with Equivalent Consumption Minimization Strategy (ECMS) or adaptive mechanisms to correct SOC drift or account for degradation [4, 5]. Hybrid-AI approaches add an offline-trained inference layer, such as Adaptive Neuro-Fuzzy Inference Method (ANFIS), to modify an underlying control law [6]. These variants retain low online computational cost but differ in optimality guarantees and, for learned methods, behavioural traceability.

4.2. Equivalent consumption minimization strategy and pontryagin's minimum/maximum principle

The ECMS converts battery use into an equivalent fuel or hydrogen cost through an equivalence factor and solves the resulting instantaneous optimisation, subject to the system constraints [7]. PMP provides the corresponding optimal control formulation through a Hamiltonian and costate , which has the interpretation of the marginal value of stored electrical energy. Under appropriate normalisation, the ECMS equivalence factor and PMP costate produce the same instantaneous power split [7]. Adaptive variants update this quantity online, while degradation costs can be incorporated into both formulations [8].

4.3. Dynamic programming

Dynamic programming (DP) computes the globally optimal trajectory over a discretised state-action space using full mission knowledge, making it primarily an offline benchmark because of its non-causal formulation [9–13]. Vehicles-tier studies mitigate this through state space reduction, representative-cycle reuse, or offline DP followed by an online tracking law [9–11].

4.4. Convex optimisation and model predictive control

Convex optimisation and Model Predictive Control (MPC) are complementary rather than mutually exclusive: convex optimisation reformulates the non-convex EMS problem which typically arises from SOC/energy-state dynamics or component efficiency maps. MPC adds a receding-horizon structure on top of this, repeatedly re-solving a finite-horizon problem as the measured state and forecast update, so that future demand and input constraints are considered explicitly rather than only instantaneously. Across the reviewed evidence, convex formulations achieve substantial computational savings relative to DP while retaining near-optimal cost. The principal limitation is that these advantages depend on model validity and, for relaxed formulations, on the tightness of the convexification. For MPC, the optimisation must additionally be solved within the control loop interval. Mixed-integer variants extend the same framework to discrete decisions, such as engine or component on/off states [14, 15], thus reproducing operating decisions which a purely continuous formulation cannot represent. However, a mixed-integer solve does not generally offer the same deterministic polynomial-time guarantee, leaving worst-case execution time as an open issue.

4.5. Signal-decomposition and classical feedback control

Signal-decomposition methods allocate power by separating the demand signal into frequency components. Empirical Mode Decomposition (EMD) and Variational Mode Decomposition (VMD), for example, assign different frequency bands to sources according to their dynamic characteristics [16]. Because the allocation follows filtering rather than an iterative optimisation, online computation can be predictable.
Classical feedback control provides an even simpler alternative. Karvekar and Karvekar [17] regulate battery SOC using PI control. Such approaches offer simple implementation and verification paths, but do not optimise competing fuel economy, degradation, and reserve objectives.

5. CROSS-DOMAIN EVIDENCE BASE

This section presents the evidence base organised by application domain, moving from the most mature (ground vehicles) to the most aerospace-specific (aircraft).

5.1. Tier I: Vehicles (ground and off-road platforms)

Automotive and off-road ground vehicles constitute the most mature EMS evidence base reviewed in this paper.
Gökçe and Özdemir [3] establish the practical floor of real-time implementability with an instantaneous rule-based controller requiring no drive-cycle foreknowledge. Mounica and Obulesu [6] raise the sophistication with an ANFIS-augmented ECMS whose Haar-wavelet stress metric recurs as a lifetime proxy elsewhere in this tier, though training-set representativeness and generalisation to unseen missions are left unexamined. Zhang et al. [16] applied a frequency-domain signal decomposition method (EMD/VMD). Although this was the lightest-weight allocation method reviewed, it was only validated in a single, non-aerospace application. Inuzuka et al. [9], Wu et al. [10], and Fares et al. [11] address DP's computational burden through three

TAB 2. EMS method-family taxonomy: horizon, model requirement, optimality, real-time suitability, and characteristic advantage/limitation, synthesised across the reviewed evidence base.

EMS family	Horizon	Model req.	Optimality	RT suitability	Main advantage	Main limitation
Rule-based / state machine	Instant.	Low	Low	Excellent	Negligible computation; simple to verify	No optimality guarantee; calibration effort
Fuzzy logic	Instant.	Low–Med.	Low	Excellent	Handles uncertainty; can adapt online (MFLC)	Rule/membership design; limited formal analysis
Hybrid AI (ANFIS)	Instant.	Med.	Low–Med.	Good (post-train.)	Fast inference; strong empirical fuel economy	Training-set traceability; generalisation unproven
Signal decomp. (EMD/VMD)	Instant.	Low	Low–Med.	Excellent	Very low, predictable cost; no tuned cost function	Validated in only one non-aerospace domain
ECMS	Instant.	Medium	Local	Very good	Efficient; intuitive equivalence-factor tuning	Equivalence factor must track true co-state
PMP	Costate	Medium	High	Good	Optimal-control basis; degradation folds into $\mathcal{H}$	Costate tuning/convergence
Dynamic programming	Full mission	High	Global	Poor (offline)	Benchmark optimum	Curse of dimensionality; non-causal
Convex optimisation	Variable	Medium	High (if tight)	Excellent–good	Polynomial-time complexity in the idealised problem formulation	Requires a valid (lossless) convex relaxation
MPC (incl. mixed-integer)	Receding	High	Near-optimal	Med.–excellent	Exploits mission preview; handles constraints	Solve-time cost; MIP worst-case time unbounded
Classical feedback (PI/PID)	Instant.	Low	N/A	Excellent	Simplest possible law; highly certification-tractable	No explicit fuel-economy/degradation trade-off

distinct mechanisms: state-space reduction, reuse of a single representative-cycle solution, and an offline-DP/online-PID split. The latter architecture is the closest analogue to a certifiable offline optimise/online execute aircraft EMS, though real-time the performance of none of the three has been benchmarked.

Instead of mitigating the tractability problem, several studies resolve it. Specifically, Fu et al. [18] use a closed-form PMP costate, Tao et al. [19] introduce a convex ADMM reformulation, Guanetti et al. [14] apply mixed-integer convex programming, and Hou et al. [15] utilize a hardware-validated mixed-integer nonlinear MPC. The hardware-in-the-loop demonstration by [15] is the strongest existing precedent in this review for a jointly optimized, real-time-capable aircraft EMS architecture. However, the worst-case solve time for the mixed-integer programming remains an open certification concern.

The remaining six studies target component lifetime through largely disjoint strategies. Song et al. [8] and Luca et al. [5] price degradation directly inside the dispatch objective, with Luca et al.'s mutative fuzzy controller being the only mechanism in this tier that adapts its durability trade-off online. Instead of pricing degradation into the objective, Molavi et al. [20] bound fuel cell power based on measured conditions. Meanwhile, Salem et al. [21] derive stress terms analytically without experimental data, Mukhopadhyay et al. [22] tune bounds on the operating envelope offline, and Hu and Zhang [23] target power-variation frequency directly. None of these six philosophies have been cross-validated against one another on a common platform.

5.2. Tier I: Rail Platforms

Jibrin et al. [24] extend convex EMS optimisation to a rail powertrain by jointly considering train speed, Proton-Exchange Membrane Fuel Cell (PEMFC)/battery power split, and battery temperature. The space-domain formulation represents the non-convex terms through convex relaxations that are shown to be tight at the optimum. For a 63 km, 87-minute journey, the formulation reduces hydrogen consumption by approximately 10% relative to a conventional four-phase driving strategy and reduces battery cooling requirements by 12%.

5.3. Tier I: Maritime Platforms

Chen et al. [25] develop a semi-empirical two-resistor-capacitor $LiFePO_4$ battery model fitted to more than 2,000 cycling tests and report approximately 13% mean absolute error. The model is embedded in lifecycle-cost optimisation for ferry battery sizing and hybrid propulsion architecture selection, reducing lifecycle cost by 26% relative to a mechanical-propulsion baseline. Fan et al. [26] develop a three-layer EMS for a 7500-tonne parallel-hybrid bulk carrier. The upper layer combines MPC and ECMS and is benchmarked against fixed-factor ECMS and offline DP-ECMS in simulation and on a hardware-in-the-loop rig. On the physical rig, MPC-ECMS reduces fuel cost by 5.01% and CO_2 emissions by 7.34% relative to ECMS. DP-ECMS shows the weakest hardware adaptability and the highest mode-switching frequency among the tested approaches.

5.4. Tier II: Uncrewed Aerial Vehicles and Helicopter/UAM rotorcraft

Tian et al. [27] propose a two-layer adaptive hierarchical energy management strategy for a PEMFC/battery fixed wing UAV. An offline sequential-convex layer generates a global SOC reference, while an online convex-MPC layer tracks it with an adaptive prediction horizon. Hydrogen savings of 19.2% and 29.7% are reported relative to nonlinear MPC and a fuzzy state-machine strategy in simulation, with 17.9–43.3% savings on a hardware-in-the-loop bench. Xie et al. [28] directly convexify a UAV hybrid powertrain and report lower energy consumption than DP at approximately 8.5% of DP's solve time. Bai et al. [4] combine fuzzy logic with ECMS to reduce front-to-back SOC deviation from 0.28 to 0.04.

Donateo et al. [29] develop a parallel hybrid UAM powertrain in which offline DP establishes reference trajectories and an ECMS controller is deployed online. Across four representative missions, the online controller achieves 10–22% fuel savings while maintaining an SOH-dependent minimum SOC reserve for electric-only operation following turboshaft failure. Taghbalout et al. [30] applies ECMS to a PEMFC/battery eVTOL for accident-rescue operations and independently cross-validates the implementation in MATLAB and OpenModelica. The reported full-flight hydrogen consumption is 6.92 kg. The study uses offline batch simulation and does not report a per-step computational-time benchmark or closed-loop hardware validation.

5.5. Tier III: Airplanes

Doff-Sotta et al. [31] formulate a convex MPC EMS for a 100-seat, 42-tonne parallel-hybrid aircraft. The method reduces fuel consumption by 11.6% relative to an gas turbine configuration and by 3.2% relative to a heuristic charge-depleting/charge-sustaining strategy. Hoenicke et al. [32] develop a redundant power management control and delivery module with threshold-based control, fault detection, and precharging. The system exceeds 98% efficiency and was demonstrated in flight on the HY4 aircraft, with a maximum reported relay turn-on delay of 130 ms. Xie et al. [1] review hybrid aircraft configurations and EMS methodologies and identify aircraft safety and emergency operation requirements that are not addressed by conventional automotive EMS approaches. Their retrofit study combines convex optimisation with fuzzy-augmented ECMS and reports 18.7% fuel savings and 12.5% improved energy economy. Pinto Leite and Voskuijl [12] apply DP to a serial hybrid lightaviation aircraft while accounting for fuel-burn mass reduction and regenerative propeller windmilling. Fuel consumption improvement relative to the baseline generator schedule is only 0.06–0.4%. Chai et al. [33] develop a degradation-conscious ECMS for a redundant multi-stack fuel cell aircraft of a size equivalent to an ATR 72-600. Fuel cell and battery degradation costs are included directly in the online objective, producing efficiency improvements of 6.09% and 4.18% relative to the two reported baselines. Penta et al. [34] compare ECMS with rule-based control for a four-seat fuel cell aircraft and impose a minimum SOC of 70% to retain battery-only capability following fuel cell failure. Ma et al. [35] develop a state-machine EMS for a distributed electric propulsion aircraft and validate fault detection and reconfiguration on an RT-LAB hardware-in-the-loop platform. Ferrulli et al. [13] apply offline DP to a parallel hybrid aircraft combining an internal combustion engine, electric motor, and fuel cell system. Cuomo et al. [36] synthesise several aircraft electrical power management projects into a hierarchical architecture combining droop control, state-machine bus-voltage management, MILP/Knapsack-based fault-tolerant reconfiguration, and MPC-based generator-efficiency tracking.

TAB 3. Count of *(S)trong* vs. *(U)ntested* evidence per evaluation dimension and domain.

	Vehicles		UAV		Helic./eVTOL		Aircraft	
Dimension	S	U	S	U	S	U	S	U
Fuel/H_2 economy	11	1	4	0	2	0	7	0
Charge-sustaining	10	1	4	0	2	0	5	1
Component lifetime	8	2	0	1	1	0	1	4
Real-time impl.	11	0	3	0	1	0	4	1
Cert. readiness	0	11	0	3	0	1	1	4

6. CROSS-DOMAIN COMPARISON AND TRANSFERABILITY

The results from Sections 4 and 5 are now compared across domains to identify which capabilities are already demonstrated beyond a single application and which characteristics determine their transferability to aircraft. The comparison focuses on four dimensions, as listed in Table 3. The table also compares the number of reviewed studies providing *Strong* quantitative evidence with those for which a dimension remains *Untested*. The counts indicate that fuel/H_2 economy and real-time implementability are comparatively mature evaluation dimensions and Charge-sustaining behaviour is also widely reported. In contrast, component lifetime evidence becomes substantially weaker outside the most mature studies, while certification readiness remains largely untested across all tiers.

Aircraft specific consequences of these findings are developed separately in Section 7.

6.1. Real-time implementability

The evidence shows a progression from low-complexity instantaneous control laws to increasingly sophisticated EMSs based on optimisation. Rule-based, fuzzy, and signal decomposition methods offer predictable computation time but no optimality, whereas PMP, convex optimisation, and MPC provide greater optimisation and constraint-handling capability. Mixed-integer formulations additionally represent discrete operating decisions but introduce less predictable computational effort. Hardware-in-the-loop demonstrations confirm practical online execution [14, 15, 18, 19, 27].

6.2. Component lifetime and stress modelling

Degradation modelling is present across several domains, but the formulations and validation procedures are heterogeneous, preventing direct quantitative comparison. The limitation is consistency rather than the absence of degradation modelling. In particular, real-time degradation proxies have rarely been cross-validated against common experimental reference data, while the reviewed UAV studies do not incorporate quantitative degradation models.

6.3. Thermal states within EMS optimisation

Thermal management provides a second example of a capability that can be transferred structurally, but whose aircraft-specific implementation remains underdeveloped. Jibrin et al. [24] incorporate battery temperature as an optimisation state alongside SOC and vehicle speed within a convex EMS formulation, demonstrating that adding a thermal state does not fundamentally require a different optimisation architecture.

This result is significant because several aircraft powertrain characteristics depend intrinsically on the temperature. Fuel cell performance, battery power capability, and cooling system demand can all vary with operating conditions. Nevertheless, the reviewed studies do not optimise power split jointly with both electrical and thermal constraints at comparable fidelity. Thus, the cross-domain evidence establishes the feasibility of thermal-aware optimisation, while its formulation in an aeronautical domain remains an open research problem.

6.4. Redundancy in the architecture

The strongest contrast between the mature EMS literature and aircraft applications appears when optimisation is considered together with fault tolerance. Hoenicke et al. [32] provide the clearest evidence of redundant power management hardware with explicit failure handling, also tested in flight. In contrast, the optimisation-based aircraft EMS studies reviewed are demonstrated primarily through simulation, hardware-in-the-loop testing, or system-level architecture studies [27, 29, 31, 35, 36]. These two evidence streams demonstrate complementary capabilities: one establishes redundancy and failure handling tested in flight, while the other establishes optimised energy dispatch.

Cuomo et al. [36] provide the closest architectural bridge by combining optimisation, supervisory control, and fault-tolerant reconfiguration within a broader aircraft power-management framework. However, the constituent techniques are not yet demonstrated as an integrated optimisation-based control loop. The cross-domain evidence therefore supports the feasibility of combining the two concepts, but does not yet demonstrate their simultaneous operation under representative aircraft failure conditions.

7. AIRCRAFT-SPECIFIC EMS CHALLENGES

The cross-domain evidence shows that the core EMS optimisation methods are transferable, but their direct application to aircraft is constrained by a set of requirements that are either absent or less critical in other domains. Four characteristics are particularly consequential are addressed in this section.

7.1. Time-varying aircraft mass

Ground-vehicle EMS formulations generally treat vehicle mass as constant or slowly varying. In aircraft, fuel represents a substantial fraction of takeoff mass, and the resulting continuous reduction in aircraft mass changes the required thrust and power throughout the mission and couples current EMS decisions to future power demand through mass in the flight-dynamics model. Pinto Leite and Voskuijl [12] show that the optimal power split changes during cruise as aircraft weight decreases, although its effect on fuel economy is small for their specific configuration. Neglecting mass variation can therefore introduce systematic sub-optimality when transferring EMS formulations to aircraft.

7.2. Predictable mission profile

Aircraft operations generally provide substantially more structured information about future operating conditions than road vehicles, including planned altitude, waypoints, and available weather or wind forecasts. This enables an improvement of energy allocation by predicting future power demand rather than relying solely on instantaneous needs, potentially optimising before departure. For example, Doff-Sotta et al. [31] exploit this information by initialising shrinking-horizon MPC from a full-flight optimum, while Tian et al. [27] show for UAVs that full-mission preview can provide near-DP performance with online optimisation.

7.3. Deterministic computation

Aviation guidelines provide a framework for software assurance, within which timing behaviour and execution performance must be appropriately verified according to the applicable certification objectives. Algorithms with uncertain iterative convergence or adaptive learned components require additional evidence to establish deterministic behaviour and timing. Convex optimisation, using deterministic solver configurations with bounded computational complexity, is particularly attractive for the development of EMS under these considerations. Rule-based state machines offer an even simpler structure.

7.4. Asymmetric emergency state-of-charge floor

The asymmetric emergency SOC requirement is the most significant constraint specific to aircraft identified. EMS formulations for ground vehicles typically target a nominal SOC or a symmetric charge-sustaining band. Aircraft must additionally retain sufficient energy for emergency operation, imposing a minimum reserve threshold. Donateo et al. [29] enforce this reserve as a function of battery SOH, while Penta et al. [34] impose a fixed 70% minimum SOC for post-failure operation. However, even these formulations use a conventional symmetric SOC-penalty structure, rather than reformulating the objective around the asymmetric emergency floor. Battery degradation further couples this reserve constraint to the available usable energy. As SOH decreases, a higher SOC may be required to guarantee the same usable reserve capacity, reducing the SOC range available for energy optimisation. This directly limits the fuel-economy benefit that an EMS can obtain from an aged battery and is consistent with the aged-battery results reported by Donateo et al. [29].

8. GAPS AND ADAPTATION ROADMAP

Twenty gaps are identified from the cross-domain synthesis in Sections 5–7. Table 4 groups them by principal barrier and maps each to an adaptation activity allocated to a certain band of Technology Readiness Levels (TRL).

Certification, redundancy, and deterministic implementation: The principal gap is the lack of an integrated EMS architecture that combines optimisation with aircraft fault tolerance and execution constraints. Flight-demonstrated work establishes redundant power-management and failure handling, whereas optimisation-based aircraft EMS remain primarily simulation- or hardware-in-the-loop-validated. G-AC1, G-AC6, and G-AC7 therefore target fault-tolerant EMS integration, while G-AC2 addresses deterministic execution-time evidence.

Mission preview and computational implementation: The second gap concerns the transfer of offline optimality into predictable online control. Existing approaches include representative-cycle rules, lookup tables, costate interpolation, and hierarchical optimisation, but their relative performance under mission deviations and certification-oriented timing constraints remains insufficiently established. G-V3, G-AC2, G-AC3, and G-SH2 target benchmarking and offline-to-online architectures.

Component lifetime and reserve-aware optimisation: The third major gap is the lack of a unified treatment of degradation, SOC management, and emergency energy reserve. Existing aircraft formulations preserve emergency SOC but largely retain conventional charge-sustaining structures, while degradation models remain insufficiently cross-validated across domains. G-AC5 targets direct integration of the asymmetric reserve requirement into SOC optimisation, while G-SH1 and G-UA1 address validation of the degradation models. The remaining gaps in Table 4 address secondary transfer questions, including signal-decomposition methods, thermal-aware optimisation, robust optimisation.

9. CONCLUSIONS

This paper presented a systematic cross-domain review of energy management strategies (EMS) for hybrid-electric aircraft powertrains, synthesising 35 studies across seven domains domains and three application tiers. The principal conclusions, corresponding to the research questions, are:

- The EMS methods developed across the reviewed non-aircraft domains provide a broad and technically transferable toolkit for hybrid-electric aircraft, but their assumptions cannot be transferred unchanged.
- The reviewed literature identifies four aircraft-specific characteristics that materially alter EMS design: time-varying mass, predictable missions, the need of a deterministic implementation, and an asymmetric emergency SOC reserve.
- Convex optimisation and MPC offer the most promising optimisation-based route to aircraft deployment because they combine explicit constraint handling with comparatively structured computation. However, the literature does not yet provide the timing, degradation validation, redundancy, and fault-tolerance evidence required to support certification.
- The 20 identified gaps point to a progression from cross-domain methods through a specific reformulation for aeronautics and hardware validation to deterministic and redundant EMS architectures. The proposed roadmap provides a structured path for this transition.

Overall, the existing EMS toolkit is technically transferable to aerospace powertrains, but certification requires targeted reformulation, deterministic implementation, and verification of the underlying methods rather than direct adoption of controllers developed for automotive, maritime, rail, or UAV applications.

Contact address:

zalakben.barot@dlr.de

References

[1] Y. Xie, A. Savvaris, A. Tsourdos, D. Zhang, and J. Gu. Review of hybrid electric powered aircraft, its conceptual design and energy management methodologies. *Chinese Journal of Aeronautics*, 34(4):432–450, 2021. DOI: 10.1016/j.cja.2020.07.017.

[2] M. Pautasso. Ten simple rules for writing a literature review. *PLOS Compu-*

TAB 4. Consolidated gap and adaptation-roadmap register: gaps identified each matched to a proposed adaptation activity. Priority: H = High, MH = Medium-High, M = Medium, L = Low.

ID (Prio.)	Gap	TRL band	Adaptation activity
G-V1 (H)	Hybrid-AI EMS validated for economy/stress, but training-set traceability and generalisation to unseen missions remain unexamined.	TRL 4→5	R-V1: transfer the offline-IDP/online-PID architecture to certification-representative HIL hardware and quantify behaviour outside the training envelope.
G-V2 (MH)	Signal-decomposition (EMD/VMD) allocation untested outside one agricultural application despite very low computational cost.	TRL 2→3	Validate EMD/VMD power allocation on an aerospace-representative duty cycle before considering it for aircraft deployment.
G-V3 (H)	No ground-vehicle DP study demonstrates compliance with a certification-relevant hard real-time deadline; “real-time” is generally defined relative to DP computation.	TRL 2→6+	R-V1: transfer the offline-IDP/online-PID architecture to an aircraft mission, validate it on certification-representative hardware, and document execution-time and software-verification evidence appropriate to the applicable certification basis.
G-V4 (H)	Mixed-integer EMS can substantially reduce online computation relative to DP, but aerospace studies do not address emergency-reserve activation as a discrete decision or establish predictable worst-case optimisation time.	TRL 2→5	R-V2: introduce an emergency-reserve activation variable into the discrete/continuous formulation and evaluate an offline-generated implementation with bounded execution time.
G-V5 (M)	Only one controller (MFLC) adapts its fuel-economy/durability trade-off online; every other weighting/bound is fixed at design time.	TRL 3→4	Extend [5]’s online membership-function mutation concept to PMP/MPC controllers ([19], [15], [8]) as an online-adapting weight; assess worst-case timing determinism.
G-V6 (M)	Degradation-cost-optimising dispatch objectives and real-time physical safe-power envelopes have never been combined in one controller.	TRL 3→4	Combine [20]’s real-time physical safe-power envelope with a degradation-cost-optimising dispatch objective ([8], [33]).
G-V7 (MH)	Power-variation-frequency control ([23]) validated only on a bench with hand-tuned thresholds, untested under an aerospace duty cycle.	TRL 2→3	Port V16’s delayed-power-reduction and minimum-power rules to an aerospace-representative duty cycle; re-derive its settling thresholds from an aerospace stack’s thermal time constant.
G-TR1 (MH)	Battery thermal state convexifies losslessly alongside SOC/speed for a train, but no Tier II/III study co-optimises PEMFC/battery thermal limits with power split.	TRL 3→4	Extend TR1’s convex thermal-EMS formulation to a PEMFC/battery aerial powertrain ([27]/ [30]), coupling altitude-dependent PEMFC polarisation losses with the same convex thermal-constraint pattern.
G-UA1 (MH)	All four UAV studies show strong economy/charge control, but none embeds a quantitative degradation model – not even an uncalibrated proxy.	TRL 2→3	Calibrate UAV battery-health checks ([27]– [4]) against a validated degradation model ([25]) or the Haar-wavelet metric ([6]/ [11]).
G-HC1 (H)	[29]’s SOH-dependent reserve constraint is the closest aerospace analogue to a discrete OEI decision, but none treats reserve activation as mixed-integer.	TRL 2→5	Reformulate [29]’s SOC_{th}(SOH) constraint as a discrete OEI-activation variable within a MINMPC/MI-CP architecture (TRL2→3); bench-test against a physical turboshaft/Li-ion rig using [29]’s validated aging model (TRL4→5).
G-AC1 (H)	[32]’s flight-validated redundant hardware uses fixed threshold logic, not an optimised policy; no paper couples optimisation with failure-aware redundancy.	TRL 3→4	R-AC1: integrate an optimisation-based EMS ([29]’s ECMS or [27]’s AHEMS) as the dispatch policy commanding [32]’s PMCD hardware, retaining its redundancy and failure-handling architecture.
G-AC2 (MH)	[31] provides the clearest certification-oriented motivation for convex MPC at transport scale, but reports neither a worst-case execution-time benchmark nor certification-oriented verification evidence.	TRL 4→5	R-AC2: benchmark convex-MPC execution on avionics-representative hardware and define the timing, numerical-robustness, and verification evidence required for a certification-oriented implementation.
G-AC3 (MH)	Two independent aircraft DP studies ([12], [13]) use DP purely offline, confirming the ground-vehicle “faster-than-DP” pattern; neither pairs with an online tracker.	TRL 2→3	R-AC3: pair [12]’s/ [13]’s DP-derived trajectories with an online tracking controller validated elsewhere ([29]’s ECMS, [11]’s PID).
G-AC4 (M)	AC5’s DECMS is the only online-solved objective to embed multi-source degradation cost, but tested only over a $\sim$25–30 s segment.	TRL 3→4	R-AC4: re-run [33]’s degradation-aware SQP objective over a full-duration flight profile with per-step solve-time logging.
G-AC5 (MH)	[34] and [29] impose emergency SOC floors, but the associated optimisation penalties retain conventional charge-sustaining structure rather than explicitly valuing energy above an asymmetric reserve floor.	TRL 2→3	R-AC5: reformulate the ECMS/PMP SOC penalty or equivalence-factor structure around the emergency reserve requirement and evaluate its interaction with SOH.
G-AC6 (MH)	[35] pairs real-time HIL validation with fault reconfiguration, but its policy is a fixed state machine, not optimisation-based; G-AC1 remains open.	TRL 3→4	R-AC6: replace [35]’s fixed state machine with an optimisation-based EMS ([31]’s convex MPC or [29]’s ECMS) inside its validated RT-LAB fault-injection harness.
G-AC7 (H)	[36]’s Global Supervisory Unit combines optimisation with fault-tolerance motivation, closest to closing G-AC1, but sub-techniques remain testbed-separate.	TRL 4→5	R-AC8: integrate ASPIRE’s fault-tolerant reconfiguration and PROSIB’s MPC efficiency controller ([36]) into one validated control loop.
G-SH1 (MH)	Real-time degradation terms remain heterogeneous and are not cross-validated against a common experimentally validated reference model.	TRL 2→5	Recalibrate candidate degradation models against representative experimental data, embed the resulting life term in a real-time PMP/MPC formulation, and assess transfer across duty cycles.
G-SH2 (H)	[26] uniquely benchmarks DP against real-time MPC-ECMS/ECMS on physical hardware, finding DP-ECMS weakest in adaptability; untested for aircraft.	TRL 4→5	R-SH2: replicate [26]’s three-way DP-ECMS/ECMS/MPC-ECMS hardware benchmark for an aircraft-tier DP study ([12] or [13]).
G-ST1 (MH)	[37] is the first study to embed robust optimisation for demand/generation uncertainty; no Tier II/III aerospace paper applies this to flight/FC uncertainty.	TRL 2→3	R-ST1: reformulate an aerospace convex/MPC EMS ([31], [24]) with an explicit robust (worst-case) counterpart following [37]’s pattern.

tational Biology, 9(7):e1003149, 2013. DOI: 10.1371/journal.pcbi.1003149.

[3] K. Gökçe and A. Özdemir. A rule based power split strategy for battery/ultracapacitor energy storage systems in hybrid electric vehicles. *International Journal of Electrochemical Science*, 11:1228–1246, 2016.

[4] M. Bai, W. Yang, D. Song, M. Kosuda, and M. Kelemen. Equivalent consumption minimization strategy based on fuzzy logic control for the energy management of hybrid unmanned aerial vehicle. *Energy Proceedings*, 20, 2021. 13th International Conference on Applied Energy, ICAE2021, paper no. 309.

[5] R. Luca, M. Whiteley, T. Neville, P. R. Shearing, and D. J. L. Brett. Comparative study of energy management systems for a hybrid fuel cell electric vehicle – a novel mutative fuzzy logic controller to prolong fuel cell lifetime. *International Journal of Hydrogen Energy*, 47(56):24042–24058, 2022. DOI: 10.1016/j.ijhydene.2022.05.192.

[6] V. Mounica and Y. P. Obulesu. Hybrid power management strategy with fuel cell, battery, and supercapacitor for fuel economy in hybrid electric vehicle application. *Energies*, 15(12):4185, 2022. DOI: 10.3390/en15124185.

[7] S. Onori, L. Serrao, and G. Rizzoni. Hybrid electric vehicles: Energy management strategies. *SpringerBriefs in Control, Automation and Robotics*, 2016. DOI: 10.1007/978-1-4471-6781-5.

[8] K. Song, X. Wang, F. Li, M. Sorrentino, and B. Zheng. Pontryagin's minimum principle-based real-time energy management strategy for fuel cell hybrid electric vehicle considering both fuel economy and power source durability. *Energy*, 205:118064, 2020. DOI: 10.1016/j.energy.2020.118064.

[9] S. Inuzuka, T. Shen, and T. Kojima. Dynamic programming based energy management of HEV with three driving modes. In *IOP Conference Series: Materials Science and Engineering*, volume 715, page 012063, 2020.

[10] X. Wu, J. Chen, and C. Hu. Dynamic programming-based energy management system for range-extended electric bus. *Mathematical Problems in Engineering*, 2015:624649, 2015. DOI: 10.1155/2015/624649.

[11] D. Fares, R. Chedid, F. Panik, S. Karaki, and R. Jabr. Dynamic programming technique for optimizing fuel cell hybrid vehicles. *International Journal of Hydrogen Energy*, 40:7777–7790, 2015. DOI: 10.1016/j.ijhydene.2014.12.120.

[12] J. P. S. Pinto Leite and M. Voskuijl. Optimal energy management for hybrid-electric aircraft. *Aircraft Engineering and Aerospace Technology*, 92(6):851–861, 2020. DOI: 10.1108/AEAT-03-2019-0046.

[13] U. M. Ferrulli, M. Tipaldi, P. R. Massenio, and D. Naso. Energy management system of a fuel-cell hybrid-electric aircraft based on dynamic programming. In *2024 16th International Conference on Information Technology and Electrical Engineering (ICITEE)*, 2024. DOI: 10.1109/ICITEE62483.2024.10808922.

[14] J. Guanetti, S. Formentin, and S. M. Savaresi. Energy management system for an electric vehicle with a rental range extender: A least costly approach. *IEEE Transactions on Intelligent Transportation Systems*, 17(11):3022–3034, 2016. DOI: 10.1109/TITS.2016.2529962.

[15] S. Hou, H. Chen, H. Yin, J. Zhao, F. Xu, and J. Gao. Energy management based on mixed-integer nonlinear model predictive control for hybrid electric vehicles. *IEEE Transactions on Intelligent Transportation Systems*, 25(11):17432–17451, 2024. DOI: 10.1109/TITS.2024.3432775.

[16] M. Zhang, X. Li, D. Han, L. Shang, and L. Xu. Energy management strategy for fuel cell hybrid tractor considering demand power frequency characteristic compensation. *Scientific Reports*, 14:27844, 2024. DOI: 10.1038/s41598-024-78832-2.

[17] A. Karvekar and S. Karvekar. Energy management system for a multi-source electric power system architecture in more electric aircraft. *Fuel Cells*, 25(5):e70019, 2025. DOI: 10.1002/fuce.70019.

[18] J. Fu, Z. Fu, and S. Song. Energy management strategy integrating self-adaptive adjustment and pontryagin's minimum principle-based optimization for fuel-cell hybrid electric vehicle. *Optimal Control Applications and Methods*, 43(4):1059–1075, 2022. DOI: 10.1002/oca.2876.

[19] F. Tao, B. Chen, Z. Fu, J. Liu, M. Li, and H. Sun. Optimization of energy management strategy for fuel cell/battery/ultracapacitor hybrid electric vehicle using distributed interior point. *Electric Power Systems Research*, 230:110287, 2024. DOI: 10.1016/j.epsr.2024.110287.

[20] A. Molavi, A. Husar, H. Hjortberg, N. Nilsson, M. Kogler, J. Sanchez Monreal, Y. Eldigair, and M. Serra Prat. State machine-based architecture to control system processes in a hybrid fuel cell electric vehicle. *International Journal of Hydrogen Energy*, 2023. DOI: 10.1016/j.ijhydene.2023.07.039.

[21] M. Salem, M. Elnaggar, M. S. Saad, and H. A. Abdel Fattah. Energy management system for fuel cell-battery vehicles using multi objective online optimization. *IEEE Access*, 10:40629–40641, 2022. DOI: 10.1109/ACCESS.2022.3167054.

[22] A. Mukhopadhyay, B. Bose, A. Garg, H. Ahuja, B. Moulik, and L. Gao. Energy management of hybrid electric vehicle considering battery and fuel cell parameters using multi-objective optimization for dynamic driving cycles. *Journal of Electrochemical Energy Conversion and Storage*, 22(4):041010, 2025. DOI: 10.1115/1.4068284.

[23] X. Hu and T. Zhang. Energy management rules for a fuel-cell-battery power system contributing to durability. *Journal of Power Sources*, 679:240236, 2026. DOI: 10.1016/j.jpowsour.2026.240236.

[24] R. Jibrin, S. Hillmansen, and C. Roberts. Convex optimization for fuel cell hybrid trains: Speed, energy management system, and battery thermals. In *2022 European Control Conference (ECC)*, pages 2130–2136, 2022. DOI: 10.23919/ECC55457.2022.9838400.

[25] L. Chen, Y. Tong, and Z. Dong. Li-ion battery performance degradation modeling for the optimal design and energy management of electrified propulsion systems. *Energies*, 13(7):1629, 2020. DOI: 10.3390/en13071629.

[26] A. Fan, H. Qiu, L. Yang, C. Guan, H. Liu, and X. Fan. Hierarchical energy management system for ships based on MPC-ECMS with multi-dimensional testing and validation. *Ocean Engineering*, 346:123875, 2026. DOI: 10.1016/j.oceaneng.2025.123875.

[27] W. Tian, L. Liu, X. Zhang, J. Shao, and J. Ge. Adaptive hierarchical energy management strategy for fuel cell/battery hybrid electric UAVs. *Aerospace Science and Technology*, 146:108938, 2024. DOI: 10.1016/j.ast.2024.108938.

[28] Y. Xie, A. Savvaris, and A. Tsourdos. Convexification in energy optimization of a hybrid electric propulsion system for unmanned aerial vehicles. In *6th CEAS Conference – Aerospace Europe, CEAS 2017*, 2017. paper no. 235.

[29] T. Donateo, C. L. De Pascalis, L. Strafella, and A. Ficarella. Off-line and on-line optimization of the energy management strategy in a hybrid electric helicopter for urban air-mobility. *Aerospace Science and Technology*, 113:106677, 2021. DOI: 10.1016/j.ast.2021.106677.

[30] M. Taghbalout. Energy management of an evtol aircraft with optimization based on the equivalent consumption minimization strategy (ECMS). *Journal of Physics: Conference Series*, 2716:012013, 2024. DOI: 10.1088/1742-6596/2716/1/012013.

[31] M. Doff-Sotta, M. Cannon, and M. Bacic. Optimal energy management for hybrid electric aircraft. *IFAC-PapersOnLine*, 53(2):6043–6049, 2020. DOI: 10.1016/j.ifacol.2020.12.1672.

[32] P. Hoenicke, D. Ghosh, A. Muhandes, S. Bhattacharya, C. Bauer, J. Kallo, and C. Willich. Power management control and delivery module for a hybrid electric aircraft using fuel cell and battery. *Energy Conversion and Management*, 244:114445, 2021. DOI: 10.1016/j.enconman.2021.114445.

[33] X. Chai, H. Sun, R. Ma, C. Wang, J. Song, and Z. Feng. An energy management strategy for all electric aircraft based on multi-stack fuel cells. In *2023 IEEE Transportation Electrification Conference & Expo (ITEC)*, 2023. DOI: 10.1109/ITEC55900.2023.10186915.

[34] M. Penta, E. Fedele, C. Manrique, D. Iannuzzi, and G. Accardo. Analysis of an equivalent consumption minimization strategy for a fuel cell electric aircraft. In *2024 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, 2024. DOI: 10.1109/ESARS-ITEC60450.2024.10819853.

[35] R. Ma, M. Yuan, Y. Zhou, Y. Zhang, and F. Yang. Energy management strategy of distributed electric propulsion aircraft hybrid power system based on state machine. In *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, 2021. DOI: 10.1109/IECON48115.2021.9589206.

[36] F. Cuomo, C. Musto, S. Bozhko, and B. Guida. Smart electric power management onboard future aircraft. In *Proceedings of the 34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024)*, 2024. paper ICAS2024_0085.

[37] M. Useche-Arteaga, W. Gil-González, O. Gomis-Bellmunt, M. Cheah-Mane, and V. Lacerda. Robust energy management in active distribution networks using mixed-integer convex optimization. *Electric Power Systems Research*, 241:111367, 2025. DOI: 10.1016/j.epsr.2024.111367.