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Optimization of Air-Breathing Electric Hybrid Engines for Atmospheric-to-Orbit Vehicles

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Abstract: Air-breathing electric hybrid engines have emerged as a promising concept for future atmospheric-to-orbit (ATO) vehicles and very low Earth orbit (VLEO) missions. The primary advantage of this technology lies in its ability to reduce dependence on carried propellant by utilizing ambient atmospheric particles as the working fluid, thereby improving mission efficiency and extending operational lifespan. This review synthesizes the core principles of air-breathing propulsion, electric propulsion, hybrid engine architecture, and mission-level performance analysis, with emphasis on how these systems may enable next-generation space access. The review also examines the principal engineering challenges involved in realizing this concept. These include intake capture efficiency, aerothermal loading, onboard power availability, multi-mode transition stability, and system resilience across varying flight conditions. Performance enhancement strategies such as plasma-assisted combustion, magnetohydrodynamic (MHD) flow control, intake compression and shock optimization, and precooler thermal management are discussed as enabling technologies. In addition, thermodynamic analysis, multi-objective optimization frameworks, and mission-level design methodologies are addressed. The review concludes that air-breathing electric hybrid propulsion remains in an early but promising phase of development, offering a compelling research direction for efficient and reusable ATO systems.

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1. Introduction

A. Background and Motivation

Air-breathing electric hybrid engines have attracted substantial research interest due to their potential for sustained operation in very low Earth orbit (VLEO) and as a propulsion architecture for atmospheric-to-orbit vehicles [1]. The central concept is operationally straightforward yet consequential: rather than carrying all propellant from launch, the vehicle draws upon the surrounding atmosphere as a working fluid during the lower-altitude phase of flight. This approach reduces initial propellant mass and improves efficiency, particularly for long-duration missions in the upper atmosphere [2]. Several challenges inhibit immediate implementation, including intake collection efficiency, ionization power requirements, electrode erosion, aerodynamic drag, and strong altitude-dependent performance variability. Nonetheless, flight experiments by the Indian Space Research Organisation (ISRO) [9] demonstrate that air-breathing propulsion has transitioned from theoretical study to experimental validation, considerably strengthening the relevance of this research field**.**

B. Limitations of Rocket-Only Systems

Rocket-based systems have enabled spaceflight but impose a fundamental constraint: all propellant and oxidizer must be carried from the beginning of the mission, substantially increasing initial vehicle mass and reducing payload fraction [3]. In low Earth orbit, continuous atmospheric drag necessitates repeated propellant expenditure solely for altitude maintenance, progressively shortening mission life. Because conventional rocket systems operate

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as fully closed propulsive cycles, performance is entirely dependent on onboard mass, even when residual atmospheric particles remain available at VLEO altitudes.

C. Emergence of Air-Breathing Electric Hybrid Engines

Air-breathing electric hybrid engines developed directly in response to the propellant-mass limitation of conventional systems. By collecting and ionizing ambient atmospheric molecules as propellants in lower-altitude regions, the vehicle avoids complete dependence on stored propellant [1, 2]. This is especially applicable in VLEO, where sufficient atmospheric density remains to support propulsive intake. The integration of electric propulsion amplifies the concept's utility: while electric thrusters already achieve high specific impulse with stored xenon or argon propellant, coupling them with atmospheric intake allows further extension of mission life and reduction of the mass penalty intrinsic to conventional rockets [4]. ISRO's experimental demonstrations [9] confirm that this approach is progressing beyond conceptual analysis into active testing.

D. Objectives and Scope of This Review

The principal objective of this review is to assess how air-breathing electric hybrid engines can support atmospheric-to-orbit vehicles, under which operating conditions are most effective, and which challenges remain unresolved. A secondary objective is to establish coherent connections across the literature, spanning ABEP system reviews [1, 2], intake design studies [7], mission analysis [4], and experimental programs [9]. The scope encompasses air-breathing electric propulsion, hybrid architectures, thermodynamic analysis, intake optimization, and relevant near-atmospheric flight demonstrations. The paper proceeds from background and technical fundamentals, through key limitations and mission constraints, to optimization frameworks and future research directions.

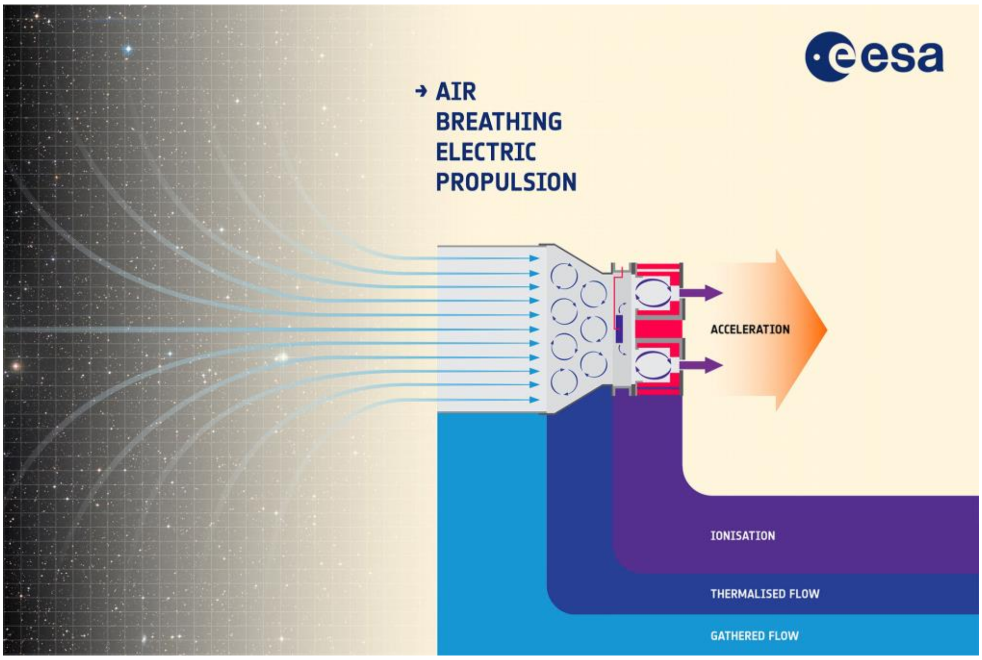

Figure-1. Air-breathing electric propulsion [Source: ESA]

2. Air-Breathing and Electric Propulsion for ATO Systems

A. Air-Breathing Propulsion in Hypersonic Regimes

Air-breathing propulsion becomes especially significant at hypersonic speeds because the vehicle can exploit atmospheric oxygen in lieu of carried oxidizer. ISRO's Scramjet Engine Technology Demonstrator confirmed this principle in flight in August 2016, operating at Mach 6 using hydrogen fuel and atmospheric oxygen as the oxidizer, while successfully demonstrating air intake function, flame holding, and supersonic ignition [9]. This test made India the fourth nation to demonstrate in-flight scramjet combustion, following the United States (NASA X-43A at Mach 9.7 in 2004), Russia, and China. The hypersonic regime thus represents a validated proof-of-concept for atmospheric oxidizer utilization in propulsion.

Nevertheless, hypersonic air-breathing operation represents only one segment of the broader atmospheric-to-orbit problem. The principal challenge is not merely initiating and sustaining combustion at high speed, but ensuring continued propulsion effectiveness as conditions evolve with altitude, air density, and mission phase. Hypersonic demonstrations are necessary but insufficient in isolation for a complete ATO solution.

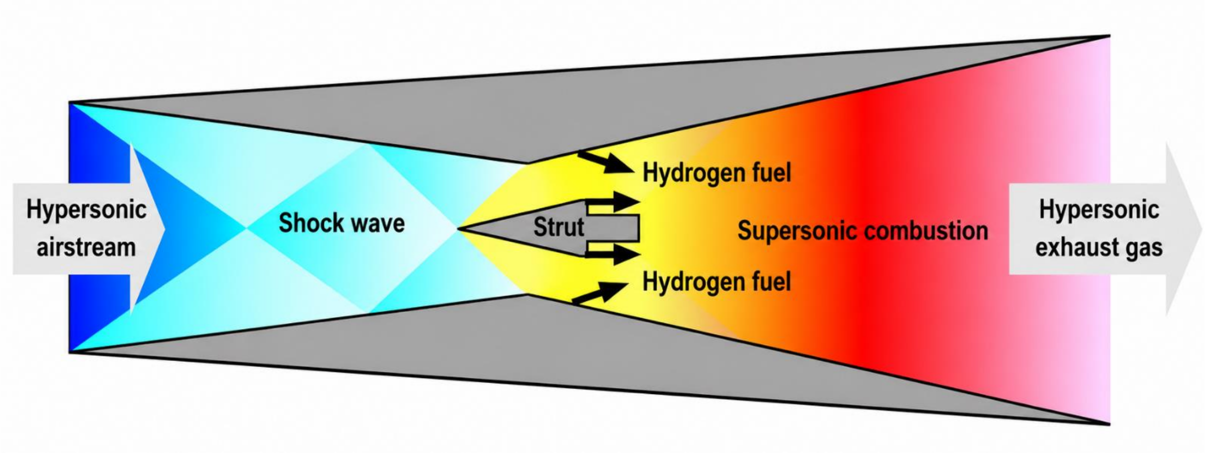

Figure-2. Scramjet Engine Technology [Source: ISRO]

B. Combined-Cycle Engines (TBCC/RBCC)

Combined-cycle propulsion concepts, including Turbine-Based Combined Cycle (TBCC) and Rocket-Based Combined Cycle (RBCC) engines, are relevant to ATO systems because they address the need for efficient operation across a wide flight envelope [10]. RBCC engines integrate rocket, ramjet, and scramjet modes within a single shared flowpath, while TBCC systems combine turbojet and ramjet/scramjet modes for ground-to-hypersonic operation [11]. Neither single air-breathing mode performs efficiently across the full ascent profile; combined-cycle architectures are therefore a natural transition strategy, linking the high-speed capability shown by scramjet demonstrations with the VLEO applicability of ABEP systems.

C. Scramjet Limitations in ATO Missions

While ISRO's demonstrator confirms that scramjet technology is operationally feasible [9], it also defines the technology's inherent constraints. The 2016 test was conducted over a brief hypersonic flight phase centered at Mach 6, not across a continuous ascent to orbit. Scramjets are therefore useful for high-speed air-breathing propulsion within a narrow operating band but are not a standalone solution for atmospheric-to-orbit transportation. This limitation motivates the integration of complementary propulsion modes, including electric and ABEP systems, which can operate effectively in the thin-atmosphere conditions where scramjets cease to function.

D. Role of Electric and ABEP Systems

In VLEO and similar near-atmospheric environments, electric propulsion systems using atmospheric intake can generate thrust from the ambient gas to compensate for orbital drag and extend spacecraft lifetime [2, 4]. ABEP technology directly addresses the propellant-carrying limitation of conventional spacecraft by exploiting in-situ atmospheric gas as a renewable propellant resource. Below approximately 220 km altitude, ABEP has been shown to be the only viable propulsion option for achieving desirable mission lifetimes using small spacecraft architectures [4]. This makes ABEP not a supplementary concept but a potentially essential enabling technology for long-duration low-altitude missions.

3. Air-Breathing Electric Hybrid Engine Architecture

A. Integrated Engine Configuration

The architecture of an air-breathing electric hybrid engine is organized around the integration of atmospheric intake, electric propulsion, and a rocket-based backup mode into a unified propulsion system [1, 2]. The engine cannot be treated as a collection of independent subsystems; the intake, compression stage, ionization or acceleration unit, power supply, and exhaust assembly must function as a coherent thermodynamic chain. This is what distinguishes the concept from simply combining existing propulsion technologies: every stage interacts with the others, and the architecture must remain stable and efficient across varying flight conditions, from dense lower-atmosphere flight to near-vacuum environments.

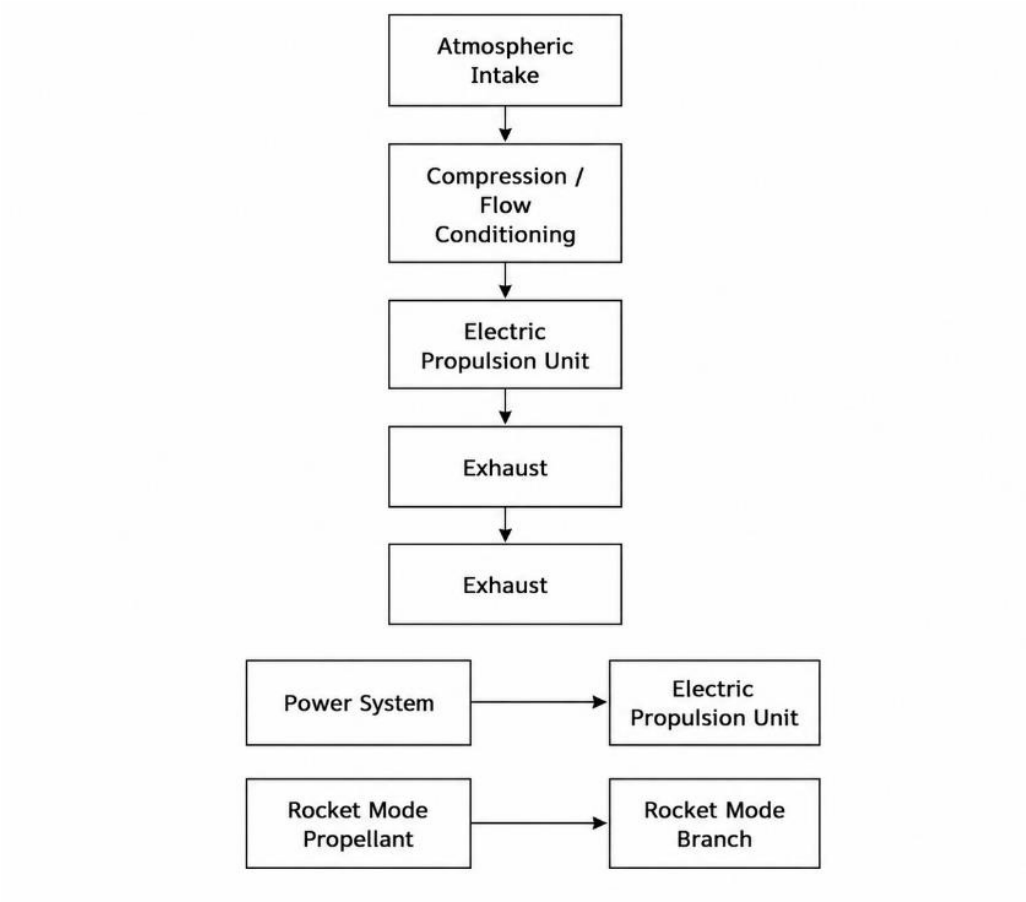

Figure-3. Air-breathing propulsion concept or architecture

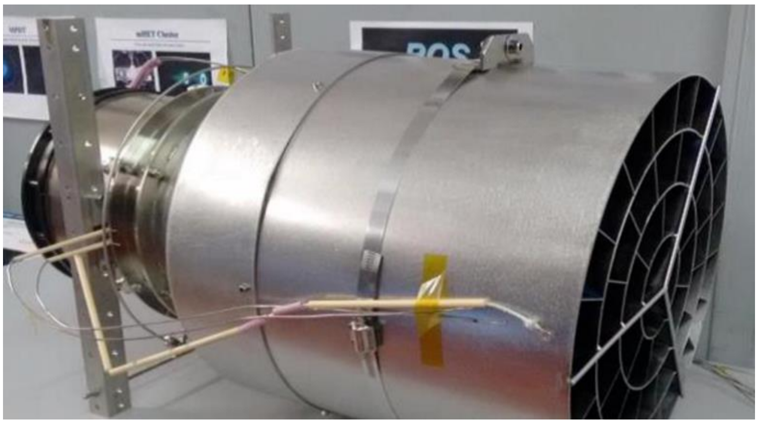

Figure-4. Air-breathing engine test setup [Source: ESA]

B. Multi-Mode Operation

A defining feature of the concept is the ability to transition between distinct propulsion modes depending on altitude, velocity, and mission phase. Three principal modes are identified in the literature:

i. Air-Breathing Mode

In the air-breathing mode, atmospheric gas is captured directly and used as the working fluid, substantially reducing carried-propellant requirements at lower altitudes [1, 3]. This mode is most relevant in VLEO, where the atmosphere remains thin but non-negligible.

ii. Hybrid Electric-Assisted Mode

In the hybrid electric-assisted mode, atmospheric intake is combined with electric propulsion to augment thrust or compensate for reduced atmospheric density [2, 4]. This mode is the most demanding from an energy management perspective, requiring simultaneous management of airflow and electrical power. It typically serves as a transition between pure air-breathing and conventional propulsion.

iii. Rocket Mode

Rocket mode is engaged when atmospheric density falls below a threshold sufficient for effective intake operation, or when the final orbital insertion burn is required [3]. This mode decouples the system from atmospheric conditions entirely and relies on stored propellant. Its reliable integration with air-breathing and electric modes is identified in the literature as one of the central design challenges of the hybrid architecture [1].

C. Flow Coupling and Energy Exchange

Effective flow coupling is the mechanism through which the integrated architecture delivers its performance advantage. Incoming atmospheric air must be captured, conditioned, and transferred to the propulsion system with minimal loss at each stage [7]. Simultaneously, electrical energy from the vehicle's power system must be delivered efficiently to the working fluid, particularly during electric-assisted operation. The coupled thermo-fluid-electrical nature of the problem means that power availability, thrust requirements, inlet losses, and temperature limits are simultaneously active constraints, each affecting the others. The more tightly the flow and energy systems are integrated, the higher the achievable performance across different flight phases. However, tighter integration also increases sensitivity to off-design conditions and makes fault management more complex [2, 4].

D. Key Design Trade-Offs

The primary design trade-off is between mission flexibility and system performance. A more integrated architecture offers greater adaptability across the mission profile, but also increases control complexity, structural mass, and sensitivity to changing operating conditions [3, 4]. Intake capture area and drag, available electrical power, and mode-transition smoothness consistently emerge as the key trade-off variables in the literature. A system optimized for peak performance in a single flight regime is likely to underperform outside it, while a fully multi-mode system may not achieve peak efficiency in any single phase. The ATO mission therefore demands a balanced architecture rather than a single-point-optimized design.

4. Performance Enhancement Technologies

A. Plasma-Assisted Combustion

Plasma-assisted combustion is studied as a means of improving ignition reliability and flame stabilization in high-speed air-breathing flows [5]. At hypersonic speeds, the extremely short flow residence time within the combustor makes sustained combustion inherently difficult. Plasma discharges can overcome this by producing reactive species and thermal excitation that lower the ignition threshold and extend the flame-holding operating range beyond what conventional methods can achieve. In the context of hybrid air-breathing electric engines, plasma assistance serves a supportive rather than primary propulsive role, extending the usable operating envelope of the air-breathing cycle without replacing it.

B. MHD / Electric Flow Control

Magnetohydrodynamic (MHD) and electric flow control techniques allow direct manipulation of the flow field without dependence on moving mechanical components [6]. Applied to the intake of an air-breathing electric hybrid engine, MHD control can regulate compression flow, mitigate shock-boundary layer interactions, and improve the quality of flow entering the propulsion stage, particularly under off-design conditions. Computational studies have demonstrated that MHD systems with feasible parameters can restore shock-on-lip conditions when operating at Mach numbers above the inlet design point, with the possibility of net power extraction from the flow field. However, this approach requires additional onboard power, adds system complexity, and must justify its performance benefit relative to the additional mass and energy cost [6].

C. Intake Compression and Shock Optimization

Intake performance is among the most critical determinants of overall system efficiency. Capture efficiency, compression ratio, and inlet geometry all directly influence the quality and mass flow of atmospheric gas delivered to the propulsion system [7]. In ABEP-relevant conditions at VLEO altitudes, intake design must contend with the highly rarefied nature of the flow, where continuum assumptions break down and particle-based simulation methods such as Direct Simulation Monte Carlo (DSMC) are required for accurate prediction. Shock optimization is equally essential because unmanaged shock structures increase total pressure losses and degrade flow quality at the combustor entrance. Inlet geometry and flow-conditioning are therefore central design elements rather than secondary components.

D. Precooler and Thermal Management Systems

Thermal management becomes a dominant engineering constraint as flight speed increases. In high-Mach operation, the temperature of incoming air can reach values exceeding 1,000°C, threatening downstream components and reducing thermodynamic cycle efficiency [8]. A precooler heat exchanger, such as that developed by Reaction Engines Limited for the SABRE engine, addresses this by rapidly reducing incoming air temperature before it enters the compressor and combustion stages. Reaction Engines' precooler demonstrated successful cooling of airflow at conditions corresponding to Mach 5 operation, validating the feasibility of precooled hypersonic propulsion [8]. Beyond thermal protection, precooling improves the effective compression ratio achievable by the cycle. The trade-off is the additional mass, pressure loss, and complexity associated with the cooling system.

Figure-5. SABRE rocket engine design includes a precooler able to chill superheated air in a fraction of a second, allowing the engine to make use of oxygen from the atmosphere as it flies [Source: ESA]

5. Thermodynamic Analysis and Optimization Frameworks

A. Multi-Mode Cycle Analysis

Thermodynamic cycle analysis for air-breathing electric hybrid engines must be treated as a mission-integrated rather than single-point problem **[2, 4]**. Atmospheric density, achievable compression ratio, and available electrical power all vary with altitude, requiring the engine cycle to be evaluated across the full flight envelope. Multi-mode cycle analysis links the atmosphere, the intake, the thruster, and the power system into a unified thermodynamic model, allowing engine architecture to be assessed at the mission level rather than only at the component level. This approach is indispensable for identifying the altitude band over which each mode is viable and for defining smooth transition conditions between modes.

B. Performance Metrics: Isp, Efficiency, and Thrust

The primary performance metrics in the literature are specific impulse (Isp), thrust, and overall propulsive efficiency **[2, 4]**. Thrust must at minimum balance aerodynamic drag for the vehicle to maintain altitude, particularly in low-altitude atmospheric operation. Specific impulse characterizes how effectively atmospheric working fluid or stored propellant is consumed. Propulsive efficiency reflects the fraction of electrical and fluid energy converted into useful thrust. These quantities are interdependent: increasing mass flow rate may raise thrust while reducing Isp if ionization or acceleration efficiency is not maintained. The design objective is to identify the balanced operating point that satisfies thrust, efficiency, and power budget constraints simultaneously.

C. Multi-Objective Optimization Problem

The design of an air-breathing electric hybrid engine is inherently a multi-objective problem. The system must simultaneously produce adequate thrust, use power efficiently, maintain viability across a usable altitude range, avoid excessive drag, and remain within realistic power budgets **[3, 4]**. Improving one parameter frequently degrades another: a larger intake improves propellant capture but increases drag; higher compression may improve low-altitude performance but degrade efficiency at higher altitudes. The optimal solution is therefore not the one that maximizes any single metric, but the one that best balances competing requirements across the full mission profile.

D. Optimization Techniques

Computational Fluid Dynamics (CFD)

CFD provides high-fidelity resolution of the flow field through intake and propulsion components, enabling accurate prediction of compression loss, shock structure, and rarefied-flow effects relevant to VLEO intake design **[7]**. Because VLEO flows deviate significantly from continuum conditions, DSMC-based particle methods are often required alongside or in place of Navier-Stokes solvers.

Genetic Algorithms

Evolutionary optimization methods, including genetic algorithms, are well-suited to this problem due to the large, nonlinear design space and the presence of multiple competing objectives **[12]**. They can search inlet geometry, thruster parameters, and mission trajectory parameters simultaneously, identifying Pareto-optimal configurations that no gradient-based method could reliably find.

Machine Learning

Data-driven approaches, including deep neural networks and surrogate modeling, are increasingly applied in the optimization workflow to reduce the computational cost of repeated high-fidelity evaluations **[13]**. Machine learning does not replace physics-based simulation; rather, it supports the design process by enabling rapid exploration of the design space once sufficient simulation data has been generated, enabling near-real-time trajectory and system optimization that would be prohibitive using CFD alone.

6. System Integration and Mission-Level Performance

A. Propulsion System Integration

For the hybrid concept to deliver its expected performance advantage, the intake, electric propulsion unit, flow-conditioning section, and power supply must function as a unified system [1, 2]. Any weakness in one subsystem propagates through the propulsion chain and erodes the overall performance benefit. This requirement is compounded by the need to sustain performance across a continuously changing atmospheric environment. The real challenge is therefore not merely starting the engine but maintaining consistent and efficient operation throughout the entire ascent trajectory.

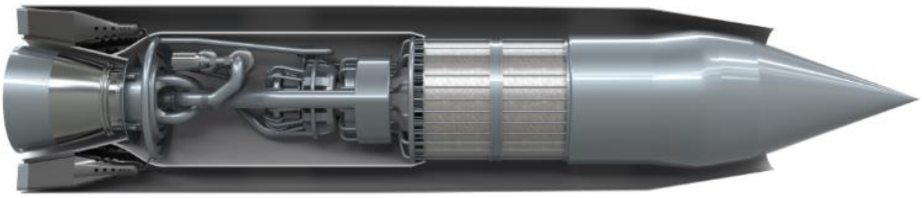

Figure-6. Air-breathing engine [Source: ESA]

B. Thermal and Power System Coupling

Thermal and power management are coupled concerns in this propulsion architecture. Electric propulsion requires continuous electrical power, and all electrical systems generate heat. If thermal loads are not managed adequately, both the efficiency and structural integrity of the vehicle degrade [8]. Equally, if the power budget is too high relative to available generation capacity, the concept loses its feasibility advantage. The relevant question is therefore not only how much thrust can be produced, but whether that thrust can be sustained within a credible thermal and power budget at vehicle scale [3, 4].

C. Atmospheric-to-Orbit Flight Profile

The ATO flight profile is inherently challenging because the vehicle must transit through radically different atmospheric environments. At lower altitudes, sufficient atmospheric density supports air-breathing operation. As altitude increases, density falls below the threshold for effective intake, requiring a transition to another propulsion mode [4]. The hybrid architecture is motivated precisely by this profile: it allows the vehicle to exploit atmospheric intake during the segment where it is most beneficial, then transition to electric-assisted or rocket operation when atmospheric resources are no longer available. The flight profile therefore does not merely constrain the engine design; it fundamentally defines it.

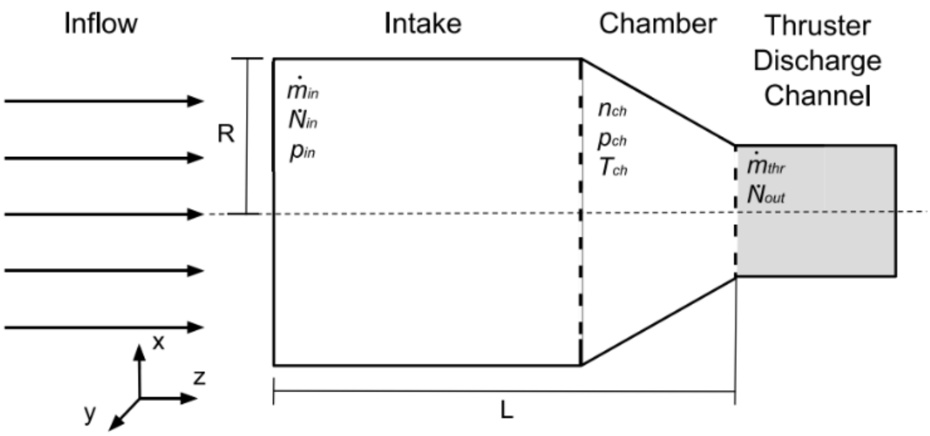

Figure-7. Intake General Design including the Thruster's Discharge Channel [Credit: F. Romano.et.al.2021]

D. Trajectory Optimization and Performance Gains

Trajectory selection has a direct bearing on how much benefit can be extracted from air-breathing operation. An optimized flight path reduces drag losses, maintains favorable intake conditions for a longer duration, and improves overall mission performance [12, 13]. The primary performance gain from hybrid air-breathing electric propulsion is not a higher thrust ceiling, but a reduction in required carried propellant and an improvement in mission flexibility. These gains are only fully realized when trajectory and propulsion system are co-designed. Treating the engine and the flight path as independent design problems causes the concept to forfeit much of its advantage.

7. Thermal and Energy Constraints

A. Aerothermal Heating Challenges

Aerothermal heating is one of the fundamental limiting factors in high-speed atmospheric flight. As vehicle speed increases, stagnation temperatures at the intake leading edges and internal flow surfaces increase rapidly, threatening structural integrity and reducing thermodynamic efficiency [8]. For air-breathing electric hybrid engines, this problem is amplified because multiple thermally sensitive systems are co-located within a single compact architecture. Thermal protection is accordingly not a secondary concern but one of the primary reasons the concept remains technically demanding.

B. Energy Storage and Power Requirements

The fundamental energy constraint of electric propulsion is that all required power must be generated or stored onboard, and both options add mass [3, 4]. For atmospheric-to-orbit missions, where every kilogram of system mass reduces payload capacity, the power system mass is a critical design driver. The question is not only how much power is needed at peak demand, but whether the system can supply sufficient power continuously over the mission duration. If energy consumption exceeds the useful thrust produced, the architecture fails to deliver its stated advantage.

C. Power-to-Weight Limitations

Power-to-weight ratio is the point at which the concept faces its most severe practical constraint. Once the mass of power electronics, energy storage, and thermal protection systems is accounted for at vehicle level, a large portion of the expected performance advantage can be negated [3]. For this reason, hybrid air-breathing electric engines are evaluated not solely on maximum thrust capability, but on the achievable thrust-to-total-system-mass ratio. If the support systems become too heavy, the architecture loses its competitive advantage over conventional rocket propulsion.

D. Impact on Engine Feasibility

Taken together, thermal loading and energy constraints determine whether the concept can be realized as a working vehicle. Feasibility is therefore not purely a matter of propulsion physics, but a systems-level question that encompasses vehicle survivability, power generation capacity, and sustained efficiency throughout the mission [1, 3, 4]. This is where most of the unresolved engineering difficulty in the concept resides, and why the field remains an active area of research rather than an established technology.

8. Challenges and Research Gaps

A. Power Availability Bottleneck

Power availability remains the most critical unresolved constraint. Air-breathing electric systems require substantial continuous electrical energy to sustain effective operation, while both power generation and energy storage are limited by mass and thermal constraints [3, 4]. Without adequate power, the electric component of the hybrid system cannot deliver the thrust levels that make the concept attractive. The power bottleneck therefore places an effective ceiling on performance that cannot be overcome through propulsion optimization alone.

B. Multi-Mode Transition Complexity

Transition between operating modes presents significant control and engineering challenges. Each mode has distinct flow, thermal, and power requirements, and the handover between modes must be accomplished without significant thrust loss, thermal excursion, or system instability [1, 2]. Individual modes can be studied in relative isolation, but the complete mode-transition sequence involves simultaneous management of intake flow, electric power delivery, and combustion stability, a combination that has not yet been demonstrated in an integrated platform. This represents one of the areas of greatest immaturity in the concept.

C. Lack of Integrated Hybrid Demonstrations

While analysis and concept development have advanced considerably [1, 2, 4], fully integrated experimental demonstrations remain rare. Experiments where the intake, electric thruster, power system, and thermal management subsystems all operate together in a representative configuration are still absent from the literature. Until such integrated demonstrations are conducted, many of the interactions and failure modes that only emerge under combined operation will remain theoretical. This gap represents the most significant obstacle between current understanding and technology readiness.

D. Limitations in Current Optimization Models

Existing optimization models provide useful guidance but remain incomplete representations of the real vehicle. The actual system involves coupled aerodynamics, heat transfer, power flow, and mode transitions acting simultaneously, a combination that current models typically address only partially [12, 13]. Models that can accurately capture multi-physics interactions across the full mission profile, and that remain computationally tractable for design iteration, are still needed. Until such tools are available, design conclusions drawn from simplified models carry significant uncertainty.

9. Future Research Directions

A. Integrated Hybrid Engine Demonstrators

The most consequential near-term step is the development and testing of a fully integrated demonstrator platform that combines intake, electric propulsion, thermal management, and mode-transition capability in a single assembly [1, 2]. Current work addresses individual subsystems with considerable rigor, but the system-level interactions that determine real feasibility only become apparent when all components operate together. An integrated demonstrator would provide the empirical evidence needed to validate models and identify unforeseen failure modes, significantly advancing technology readiness.

B. AI-Driven Optimization

As simulation and experimental datasets grow, AI-based optimization tools, including deep reinforcement learning, surrogate-assisted evolutionary algorithms, and physics-informed neural networks, offer a practical path to managing the design complexity of air-breathing electric hybrid engines [13]. For a system with a large number of interacting design variables, data-driven approaches can substantially reduce evaluation time and identify non-intuitive design configurations. The role of AI in this context is not to replace physics-based analysis but to enable more thorough and efficient exploration of the design space.

C. Advanced Thermal and Intake Technologies

Continued progress in precooler design [8] and rarefied-flow intake optimization [7] are identified as priority areas. Improvements in thermal management extend the operable speed range of the air-breathing cycle, while more efficient intake designs directly increase the mass flow available to the electric thruster. Both capabilities are critical for expanding the altitude and Mach number envelope over which the hybrid concept delivers useful performance, which is a necessary condition for ATO mission viability.

D. Sustainable Propulsion Systems

In a longer-term perspective, the research direction pursued here is consistent with the goal of more sustainable space access. A vehicle that reduces dependence on carried propellant, makes productive use of residual atmosphere, and is designed for reuse [1, 2] represents a substantially different paradigm from expendable rocket systems. This long-term value continues to attract research investment, even though engineering maturity remains limited.

10. Conclusion

This review establishes that air-breathing electric hybrid engines are a technically promising concept for atmospheric-to-orbit missions, but one currently constrained by power availability, aerothermal loading, and the absence of fully integrated experimental demonstrations [1, 2, 3, 4]. Component-level progress has been substantial, particularly in scramjet technology [9], intake design [7], and precooling systems [8], but system-level integration remains unproven. The primary benefit for ATO vehicles is the potential to substantially reduce carried propellant mass and improve mission flexibility [2, 4]. If the identified engineering challenges are resolved, particularly in power systems, thermal management, and mode-transition control, air-breathing electric hybrid propulsion could enable a new generation of reusable, atmospheric-breathing launch systems that operate with significantly lower mass budgets than conventional rocket vehicles. The concept warrants continued and intensified research investment, with emphasis on integrated demonstrators, multi-physics modeling [12, 13], advanced thermal management [8], and AI-assisted design optimization [13]. Moving the technology from component-level study to validated integrated demonstration represents the critical next step before mission-level feasibility can be assessed with confidence.

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12. Conflict of Interest

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