

## RECENT ADVANCES IN AEROSPACE PROPULSION SYSTEMS: A REVIEW OF EFFICIENCY, SUSTAINABILITY, AND EMERGING TECHNOLOGIES

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### ABSTRACT

This review examines recent advances in aerospace propulsion systems with a focus on three interrelated dimensions: efficiency improvement, sustainability, and emerging technologies. The article aims to synthesise current developments in conventional and advanced propulsion concepts across both aviation and space applications. The review adopts a thematic and analytical approach. It surveys major propulsion categories, including air-breathing, rocket, electric, hybrid-electric, hydrogen-based, and advanced space propulsion systems. The discussion is organised around propulsion fundamentals, efficiency-oriented innovations, sustainable propulsion pathways, emerging technologies, key technical and regulatory challenges, and future research directions. The review shows that aerospace propulsion is evolving from a performance-centred discipline toward a more integrated framework that combines thermodynamic efficiency, environmental responsibility, and digital intelligence. Conventional systems continue to improve through advances in engine design, lightweight materials, thermal management, and predictive maintenance. At the same time, sustainable aviation fuels, hydrogen, electric, and hybrid-electric propulsion are gaining strategic importance for low-emission aviation. Emerging technologies such as hypersonic propulsion, detonation-based engines, ion and plasma propulsion, and nuclear-based space propulsion are expanding the future scope of aerospace missions. However, major barriers remain in energy storage, thermal control, infrastructure readiness, safety, and certification. The article offers an integrated review of propulsion developments across aviation and space, highlighting how efficiency, sustainability, and technological innovation are converging to shape the next generation of aerospace propulsion systems.

**Keyword:** Aerospace Propulsion; Sustainable Aviation; Hydrogen Propulsion; Electric Propulsion

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## **1. Introduction**

Modern aviation and space transport are based on the technological basis of aerospace propulsion systems. They facilitate the flight of aircraft and spacecraft to convert stored chemical or electrical energy to thrust, which makes it possible to accomplish a variety of civilian, military, and scientific missions. Since commercial airliners and cargo aircraft, as well as launch vehicles and deep-space probes, all rely on propulsion systems, what enables a vehicle to fly, how well it can fly, and how safely and sustainably it can do so are also governed by propulsion systems. This is why propulsion has traditionally been one of the most important aspects of aerospace engineering, which impacted the design of aircraft, their mission potential, cost effectiveness, and environmental footprint (Farokhi, 2014; Mattingly, 2006; Sutton & Biblarz, 2017).

Aerospace propulsion has a long history of technological advancement. Initial aviation propulsion used piston engines and propellers, which were later overtaken by gas turbine engines when it came to high-speed flight. The advent of turbojet propulsion brought a significant change to aircraft performance, and turbofan, turboprop, and turboshaft engine designs provided increased effectiveness in various flight regimes. Simultaneously, rocket propulsion developed as the leading method of high-speed ascent into the atmosphere, orbital insertion and interplanetary travel due to its capability to function even in the absence of atmospheric oxygen. These types of propulsion evolved over the years to become more specialised, with various architectures tailored to particular operating conditions and performance goals (Cumpsty & Heyes, 2015; El-Sayed & El-Sayed, 2017; Rolls-Royce, 2015; Sutton & Biblarz, 2017).

This technological maturity notwithstanding, aerospace propulsion is now going through a phase of significant change. Traditionally, innovation in propulsion was more about adding thrust, reliability and speed, and less about fuel economy, given the limitations of the traditional hydrocarbon fuels and established engine structures. These classic goals continue to be important today but are being redefined as more environmental, economic and regulatory pressures are exerted. The aerospace industry is currently anticipated to offer not just high performance but also reduced emissions, enhanced energy consumption, decreased noise and lifecycle sustainability. This transformation has made propulsion an activity that can be studied in a multidimensional way, and engineers and researchers should concentrate on environmental compliance and classical performance parameters such as specific fuel consumption, thrust-to-weight ratio, and thermal efficiency (Farokhi, 2014; International Civil Aviation Organization, 2025; Mattingly, 2006).

Of special interest in recent years is the environmental aspect of propulsion. Conventional approaches to aeroplane propulsion are quite dependent on fossil fuels, which have been reported to lead to carbon dioxide, nitrogen oxides, and particulate matter, among other atmospheric effects associated with climate change and a decrease in air quality. Although the world economy and global interconnectivity are inseparable due to the aviation industry, the environmental influence of the sector is under increased questioning as governments, international organisations, and industry stakeholders intensify the decarbonization efforts. The presence of the overall impact of aviation on the atmosphere is not a recent issue, and the ongoing climate commitments have enhanced the necessity to develop propulsion systems that are not only cleaner but also more efficient (International Civil Aviation Organization, 2025; Penner et al., 1999). This has made sustainability a non-peripheral issue in propulsion research. It now occupies a central position in the conceptualisation, evaluation and prioritisation of future aerospace systems.

In the meantime, the aspects of operations and economy are also tightly connected with the pressure of the need to have more efficient propulsion. The cost of fuel is still a major factor in the operation of the aircraft, and the propulsion efficiency has a powerful impact on the economics of the airlines, the endurance of their missions, cargo capacity, and competitiveness of their systems. Even now, development of engine cycle, aerothermal performance, new materials, lightweight structures and computerised control has made tremendous changes in the efficiency of conventional propulsion systems. Nevertheless, additional enhancements are being actively sought, as well as other energy directions, such as sustainable aviation fuels, hydrogen, electrification, and hybrid-electric propulsion. These patterns indicate that it is likely that the future of aerospace propulsion will not only be the evolution of the currently existing technologies but also the evolution of new disruptive concepts and ideas that can radically transform the aviation and space systems (Farokhi, 2014; International Air Transport Association, 2023; International Energy Agency, 2025).

Besides the advances in the aviation industry, propulsion innovation is also crucial in the space industry. The space missions require propulsion systems, which can guarantee launch, orbital manoeuvring, station-keeping, planetary transfer, as well as deep-space exploration, and the conditions are quite different from the conditions that can be experienced in atmospheric flight. Chemical rocket engines continue to play a key role in the launch, but electric propulsion, concepts of advanced in-space propulsion and mission-specific architecture are becoming more relevant to enhance spacecraft capability and to enhance the economy of propellant. This helps to substantiate the bigger thesis that aerospace propulsion ceased to be a narrow field of engineering that deals with the engines of aircraft exclusively. It is a multidimensional and dynamic discipline that is used both in the atmosphere, exo-atmosphere, and in interplanetary space (Mattingly, 2006; Sutton & Biblarz, 2017).

Against this backdrop, the recent developments in aerospace propulsion need to be looked into in some greater detail. Developments of both efficiency and the discovery of sustainable energy carriers and the discovery of new propulsion technologies that could be applicable in space and aviation are all influencing the field. However, these developments are equally associated with technical, economic, infrastructural and regulatory challenges which complicate them to adopt and implementation in the long run. This review thus looks into recent developments in aerospace propulsion systems with specific reference to three interconnected themes, namely, efficiency, sustainability, and emerging technologies. Through the synthesis of the progress in traditional propulsion advancement, alternative fuel directions, electrification, and advanced propulsion directions, the article intends to present a systematic comprehension of the propulsion advancements in the aerospace domain and how such advancements will impact the future of flight and space transportation. Figure 1 shows the wide technological development of propulsion systems in aerospace.

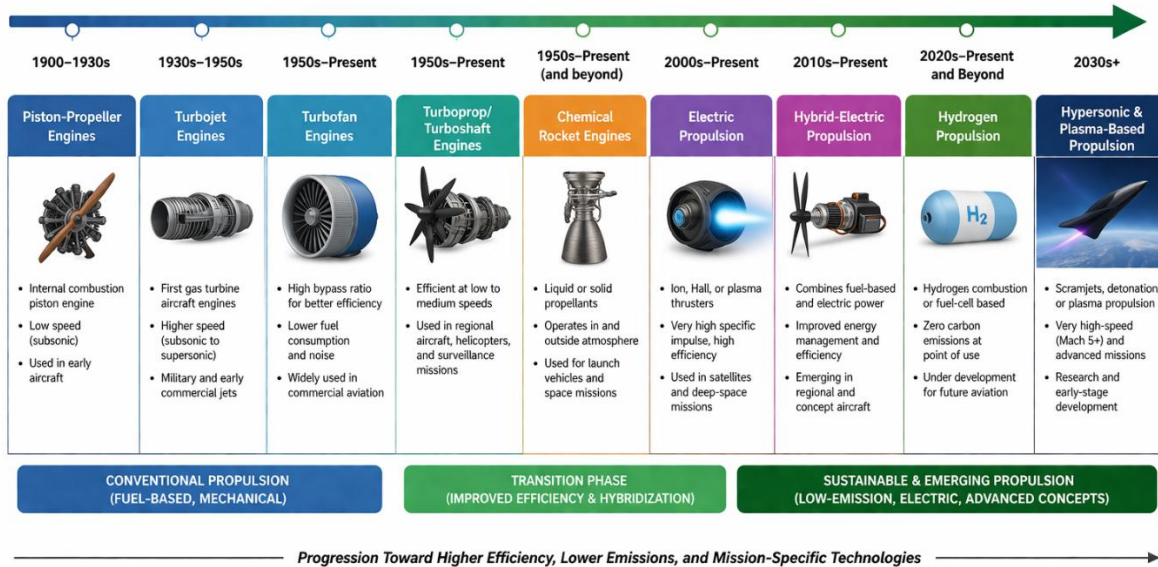


Figure 1. Evolution of Aerospace Propulsion Systems

## 2. Overview of Aerospace Propulsion Systems

Aerospace propulsion systems give the necessary force to propel aircraft and spacecraft by creating thrust through the controlled acceleration of mass. On the simplest level, propulsion is controlled by the third law of Newton: when a system expels a working fluid in one direction, the reaction acts in the opposite direction to cause forward motion. Various propulsion architectures, which vary in terms of their energy source, operating environment and thrust production methodology, are used to apply this basic principle in aerospace applications. The choice of a propulsion system is directly dependent on mission requirements, such as speed, altitude, endurance, payload, and operating medium, so propulsion is one of the most important factors that determine the design and performance of a vehicle (Hill & Peterson, 1992; Sforza, 2016).

A general categorisation of aerospace propulsion systems is between air-breathing engines and non-air-breathing systems. Air-breathing propulsion systems are applied in atmospheric flight and depend on atmospheric oxygen to be burned, and so do not require an onboard oxidiser. Other types in this category are turbojets, turbofans, turboprops, ramjets, and scramjets, each with unique goals of specific flight regimes and performance targets. The gas turbine-powered systems are still prevalent in the aviation sector due to the good balance that it offers in terms of thrust power, reliability, and operational flexibility. Their work relies on compressing incoming air, fuel-air combustion, and the expansion of high-energy gases using turbines and nozzles to produce a helpful propulsive force (Saravanamuttoo et al., 2017; Walsh & Fletcher, 2004).

Contrastingly, the rocket propulsion systems do not depend on the intake of the atmosphere since the fuel and oxidiser are carried onboard. This renders them essential to exo-atmospheric flight, launch vehicles, orbital manoeuvring, as well as deep-space missions. There are three types of rocket engines: liquid-propellant, solid-propellant, and hybrid engines, with liquid-propellant engines typically having higher controllability and flexibility of performance. Their design comprises complicated trade-offs between

combustion stability, chamber pressure, cooling needs, propellant properties and structural limits. Since rockets can be used in the atmosphere as well as in a vacuum, they are specially adapted to tasks where air-breathing engines cannot be used or are ineffective (Huzel, 1992; Larson et al., 1995).

Along with the traditional air-breathing and rocket propulsion, electric propulsion has gained significance in space usage. Electric propulsion systems accelerate ions or plasma with electromagnetic fields instead of generating thrust by releasing chemical energy at a high rate. They have relatively low thrust, but provide very high propellant efficiency and are very desirable in long-duration missions where fuel economy is more significant than acceleration. This has seen electric propulsion specifically useful in satellite station-keeping, orbit transfer and deep-space exploration (Choueiri, 2009; Jahn, 2006; Martinez-Sanchez & Pollard, 1998).

Aerospace propulsion systems are generally measured by using a combination of key indicators, such as thrust, specific impulse, and efficiency. Thrust is the net propulsive force produced by the engine, and it has a direct influence on the acceleration and payload capacity. Specific impulse is an important parameter of propellant efficiency, especially in rocket and electric propulsion, as it is a measure of how efficient a system is in converting propellant mass into useful momentum. Efficiency is commonly measured in thermal and propulsive terms, or how efficiently a propulsion system transforms stored energy into kinetic output and useful vehicle motion. These parameters give us a comparison of propulsion technologies in both aviation and space use, and the compromises in engineering that develop them (Hill & Peterson, 1992; Sforza, 2016; Turns, 1996). Table 1 summarises the major propulsion systems, operating principles, and areas of use.

Table 1. Classification and key characteristics of major aerospace propulsion systems

<b>Propulsion system type</b>	<b>Energy source</b>	<b>Oxidizer source</b>	<b>Typical application</b>	<b>Main advantages</b>	<b>Main limitations</b>
Turbojet	Aviation fuel (chemical energy)	Atmospheric air	Military aircraft, high-speed aircraft	High specific thrust, suitable for high-speed flight, relatively simple configuration	High fuel consumption at subsonic speeds, high noise, and lower propulsive efficiency than turbofans
Turbofan	Aviation fuel (chemical energy)	Atmospheric air	Commercial airliners, transport aircraft, military aviation	High propulsive efficiency, lower fuel consumption, lower noise than turbojets, suitable for subsonic and transonic flight	Larger engine diameter, performance penalties at very high supersonic speeds
Turboprop	Aviation fuel (chemical energy)	Atmospheric air	Regional aircraft, short-haul transport, surveillance	Very efficient at low to medium speeds, good short-runway	Limited cruise speed, reduced efficiency at high altitude and high

			aircraft	performance, and lower fuel burn for regional missions	speed
Ramjet / Scramjet	Aviation fuel or specialised high-energy fuel	Atmospheric air	Hypersonic vehicles, missiles, and experimental high-speed aircraft	Capable of very high-speed operation, no major rotating compressor components, efficient in hypersonic regimes	Requires high initial speed for operation, severe thermal loads, combustion stability challenges, and limited operational maturity
Liquid rocket	Liquid propellants (fuel and oxidiser)	Onboard oxidizer	Launch vehicles, spacecraft, orbital manoeuvring	Operates inside and outside the atmosphere, with high thrust, controllable thrust and restart capability	Complex feed systems, storage challenges, high cost, demanding thermal and structural requirements
Solid rocket	Solid propellant (fuel and oxidiser combined)	Onboard oxidizer	Missiles, launch boosters, tactical propulsion	Simple design, high reliability, long storage life, high thrust-to-weight ratio	Limited controllability, no easy restart capability, and lower operational flexibility
Electric propulsion	Electrical energy	Not based on combustion; propellant accelerated electromagnetically	Satellites, deep-space probes, station-keeping, orbit transfer	Very high specific impulse, excellent propellant efficiency, suitable for long-duration space missions	Low thrust, requires substantial electrical power, unsuitable for launch from Earth's surface
Hybrid-electric propulsion	A combination of fuel-based and electrical energy	Atmospheric air for combustion-based component	Regional aircraft, distributed propulsion concepts, next-generation low-emission aviation	Improved energy management, reduced fuel burn, supports distributed propulsion, and lower emissions potential	Battery mass, thermal management complexity, integration challenges, and limited current scalability

### 3. Advances in Propulsion Efficiency

The recent developments in the efficiency of aerospace propulsion have been necessitated by the necessity to cut down fuel consumption, decrease emissions, and enhance the overall performance of the engines without affecting the reliability of the functioning. Both in aviation and in new electrified propulsion designs, efficiency gains are now actively sought through combined efforts in engine architecture, thermodynamic optimisation, materials development, thermal control and numerical control. These are also indicative of a larger shift away from incremental component-level optimisation to system-level optimisation of propulsion performance on a wide variety of mission profiles (Barbosa, 2020; Ranasinghe et al., 2019).

A significant advancement is in the sphere of engine design and thermodynamic performance. Current studies in propulsion have aimed at enhancing propulsive efficiency by increasing bypass ratios, pressure ratios, improving combustion properties and decreasing specific fuel consumption. The purpose of these strategies is to obtain more efficient work out of the fuel and reduce the aerodynamic and thermal losses. Here, improved engine designs like open rotor engines have received a lot of interest due to the fact that they have the potential to combine the speed capability of turbofan engine-based aircraft with the fuel-saving benefits of turboprops. It has been found that open rotor propulsion could result in major fuel burn and environmental effects reduction, especially when combined with an advanced airframe design and aerodynamically and noise-optimised blade designs (Guynn et al., 2012; Hendricks et al., 2013; Hughes et al., 2011; Zante & E, 2015). On a bigger scale, the research on low-emission propulsion has focused on the idea that the improvement in efficiency cannot be disentangled from the environmental goals, as the thermodynamic advantage directly affects the fuel economy and the intensity of emissions (Barbosa, 2020; Ranasinghe et al., 2019).

Improvements in materials, cooling processes and lightweight structural design have all been very strong in promoting the gains in efficiency. The thermal resistance of engine materials, their durability, and mass are critical determinants of the ability of propulsion systems to work under high temperatures and pressures. Lightweight structures decrease the total weight of the propulsion system and increase aircraft-level efficiency, and more efficient cooling strategies enable the aircraft to perform in increasingly challenging thermal environments. These concerns are particularly significant in electrified and hybrid-electric propulsion designs, whereby thermal loads of power electronics, electric machines, and distributed propulsion devices introduce new engineering factors. Proper thermal control, then, is not only crucial to component protection but also to long-term propulsion efficiency, since too much heat may decrease the performance of the systems, increase losses, and decrease operational flexibility (Brelje & Martins, 2019; Chapman et al., 2020). With increasingly integrated propulsion systems coupled with aircraft energy architectures, structural weight, cooling demand and energy efficiency are increasingly interacting.

Another propulsion efficiency change has been brought forth by digital optimisation, control systems, and predictive maintenance. The high-tech monitoring and control systems enable the propulsion systems to achieve a nearer optimal design performance in varying flight regimes. On the operational level, condition-based maintenance is aided by data-based diagnostics and prognostics to determine the degradation patterns of equipment even before they lead to significant efficiency losses or failure. This enhances reliability and minimises unwarranted maintenance operations and unforeseen downtime. Rotating machinery is especially suitable as prognostics and health management systems can help ensure

that wear, vibration and thermal stress slowly reduce the efficiency of the equipment over time. These systems help to better utilise assets and provide more consistent propulsion performance over the service life of the engine by providing earlier fault detection and more accurate predictions of life (Jardine et al., 2006; Lee et al., 2014). The major efficiency-oriented propulsion advances discussed in this review are synthesised in Table 2.

Table 2. Major advances in propulsion efficiency and their implications for aerospace performance

<b>Technological advance</b>	<b>Area of application</b>	<b>Efficiency contribution</b>	<b>Additional benefits</b>	<b>Key limitations or challenges</b>
Higher bypass ratio engine architectures	Commercial and transport aviation	Improves propulsive efficiency by accelerating a larger mass of air at a lower velocity, thereby reducing specific fuel consumption	Lower noise levels, improved fuel economy, better suitability for subsonic transport missions	Larger nacelle size, drag and weight penalties, integration constraints with airframe design
Open rotor propulsion	Advanced subsonic aircraft concepts	Offers substantial fuel-burn reduction through very high propulsive efficiency compared with conventional turbofan configurations	Lower emissions potential, improved mission fuel economy, renewed interest in future green aviation platforms	Noise concerns, aerodynamic integration complexity, certification and public acceptance challenges
Advanced blade and propulsor design	Open rotor and turbomachinery systems	Enhances aerodynamic loading distribution and reduces flow losses, improving overall engine performance	Better noise-performance trade-off, improved stability and operational refinement	Complex design optimisation, manufacturing precision requirements, and structural durability concerns
Improved thermodynamic cycle performance	Gas turbine propulsion systems	Raises thermal efficiency through better pressure ratios, combustion performance, and optimised energy extraction	Lower fuel consumption and reduced emissions intensity	Higher operating temperatures, material stress, cooling demands, and increased system complexity
Lightweight materials and structural optimisation	Aircraft engines and electrified propulsion systems	Reduces propulsion system mass, indirectly improving aircraft-level fuel efficiency and payload capability	Improved structural performance, better range and mission flexibility	Material cost, manufacturability, durability, and maintenance requirements
Advanced thermal management	Electrified, hybrid-electric,	Maintains efficient operation of motors,	Greater component reliability, improved	Added system complexity, weight

systems	and turboelectric aircraft	batteries, and power electronics by controlling heat generation and dissipation	safety, and better sustained performance	penalties, integration difficulty, and cooling power demand
Digital engine optimisation and smart control systems	Conventional and next-generation propulsion systems	Enables operation closer to optimal efficiency conditions across changing flight regimes	Better control precision, adaptive performance, and improved mission-level energy management	Dependence on advanced software, data quality, cyber-physical integration, and validation requirements
Predictive maintenance and prognostics	Rotating machinery and fleet-level engine management	Reduces efficiency losses caused by undetected degradation and supports condition-based maintenance	Lower downtime, improved reliability, extended component life, and reduced operating cost	Requires robust sensing, high-quality diagnostic models, and reliable failure prediction methods
Hybrid-electric and turboelectric integration	Next-generation regional and concept aircraft	Improves energy utilisation by combining fuel-based and electric power pathways according to mission needs	Supports distributed propulsion, lowers fuel burn, and enables new aircraft design possibilities	Battery limitations, thermal loading, integration complexity, and infrastructure dependence

Taken together, these developments show that advances in propulsion efficiency are no longer limited to improvements in isolated engine parameters. Instead, they increasingly arise from the coordinated enhancement of aerodynamic design, thermodynamic effectiveness, thermal control, structural integration, and digital intelligence. This integrated approach is shaping the next generation of efficient propulsion systems for both conventional and electrified aerospace applications (Brelje & Martins, 2019; Ranasinghe et al., 2019).

#### 4. Sustainable Propulsion Pathways

The shift to sustainable aerospace propulsion has taken centre stage, with the traditional propulsion systems being subjected to mounting environmental questions. The current conventional aircraft propulsion is largely dependent on fuels derived mostly through hydrocarbons, which are linked to high levels of carbon dioxide emissions, nitrogen oxides, and particulate matter, among other effects that are climate-related. What is especially important about these environmental burdens is that aviation is a hard-to-abate industry where high energy density, long range, and high safety standards limit the decarbonization speed. Consequently, sustainable propulsion pathways are not intended to be developed as a single technological option, but as a set of complementary technologies to minimise the emissions of the lifecycle and remain operationally viable (International Air Transport Association, 2025b).

Sustainable aviation fuel is one of the most direct avenues due to its potential to be implemented with relatively few modifications to the current aircraft and fuel system. SAF provides a transitional solution, which aims at reducing the carbon intensity of aviation through the use of feedstocks and production

processes with better lifecycle performance compared to standard jet fuel. Its practical value is that it can be used to reduce emissions without requiring a radical redesign of propulsion architectures since it can be integrated with existing turbine-based propulsion systems. Even though SAF does not remove all the environmental effects, it is commonly accepted as one of the most viable near- to medium-term solutions to decrease the carbon footprint of aviation as the wider propulsion changes are still being developed (International Air Transport Association, 2025b).

One of the most high-profile long-term proposals in sustainable aviation has been hydrogen propulsion due to the promise of these emissions being close to zero at the point of use. Hydrogen can be utilised via direct combustion in modified gas turbines or via electrochemical conversion in fuel-cell-based technologies. Liquid hydrogen is of particular interest to aviation due to its high gravimetric energy density, although it presents significant challenges to cryogenic storage, fuel tank integration, insulation, safety, and aircraft design. These problems not only impact the design of the propulsion systems but also the overall airframe and airport support ecosystem. Hydrogen is still a highly promising possibility of future low-emission aircraft, though in the cases where its environmental benefits can outweigh the complexity of infrastructure and vehicle redesign (Adler & Martins, 2023; International Air Transport Association, 2025a; Soleymani et al., 2024; Tiwari et al., 2024; Yusaf et al., 2024).

Another significant direction in sustainable propulsion is electrification, which is particularly required in short-range and regional operations. Battery-electric propulsion produces no direct in-flight emissions and has the potential to be quieter in operation and with simpler mechanical systems. Its broader use is, however, limited by the low specific energy of existing battery technologies compared to liquid fuels, which restricts range, payload, and scalability of larger aircraft. These constraints have rendered fully electric propulsion to smaller aircraft and niche missions instead of mainstream commercial aviation, which is currently the case (Viswanathan et al., 2022).

To address these limitations, concepts of hybrid-electric and hybrid-gas-electric propulsion have become the focus of attention as a more viable intermediary solution. These systems are equipped with traditional engines and electric machines to enhance the overall energy use, decreasing fuel consumption, and offering more flexibility in aircraft power control. Hybrid architectures have the potential to facilitate distributed propulsion, load balancing and more effective mission-dependent operation and are of special interest to support the sustainable development of near-term aviation. Meanwhile, electrification also needs parallel improvements in power electronics, thermal control, energy storage, and integrated propulsion control, which underscores that the sustainability in propulsion is as much about the integration of the system as it is about the source of energy (Cardone et al., 2024; Kuśmierek et al., 2023; Lisovin et al., 2023). Table 3 indicates that every sustainable propulsion path has a unique balance of potential to reduce emissions, technological maturity, and infrastructure preparedness.

Table 3. Comparative assessment of sustainable propulsion pathways in aerospace

<b>Propulsion pathway</b>	<b>Emissions reduction potential</b>	<b>Technology maturity</b>	<b>Infrastructure requirement</b>	<b>Key advantages</b>	<b>Key constraints</b>
Sustainable aviation fuel (SAF)	Moderate to high lifecycle emissions	Relatively high compared with other alternative	Moderate, because existing aircraft and	Compatible with current gas turbine fleets, supports near-	Limited feedstock availability, high

	reduction depending on feedstock, production route, and blending level	propulsion pathways	fueling systems can be used with varying degrees of adaptation	term decarbonization, lower transition barrier, suitable for large-scale commercial aviation	production cost, uncertain large-scale supply, and lifecycle benefits vary by source
Hydrogen combustion propulsion	High potential for reducing carbon emissions at the point of use	Low to moderate, still in developmental and demonstration stages for aviation	Very high, requiring cryogenic storage, airport fueling systems, transport infrastructure, and aircraft redesign	High gravimetric energy density, potential for low-carbon aviation, applicable to modified turbine systems	Volumetric storage challenges, cryogenic handling complexity, aircraft integration difficulty, infrastructure cost, and safety concerns
Hydrogen fuel-cell propulsion	Very high potential for zero carbon emissions at the point of use	Low to moderate, more promising for short-range and regional applications	Very high, including hydrogen production, storage, distribution, and onboard fuel-cell system integration	High efficiency, low direct emissions, quieter operation, promising for small and regional aircraft	Limited power density, storage complexity, thermal management issues, constrained scalability for large aircraft
Battery-electric propulsion	Very high potential for zero in-flight emissions	Low to moderate, mainly suitable for small aircraft and short-range missions at present	High, requiring charging infrastructure, grid capacity, energy storage support, and new maintenance systems	No direct operational emissions, low noise, simpler mechanical architecture, attractive for urban and regional aviation	Low specific energy of batteries, range and payload limitations, charging time, thermal safety risks
Hybrid-electric propulsion	Moderate emissions reduction depending on configuration and mission profile	Moderate, with strong research and prototype activity	High, but generally less disruptive than fully electric or hydrogen systems	Better energy management, lower fuel burn, supports distributed propulsion, useful as a transition technology	System complexity, battery mass, thermal management challenges, certification and integration difficulties

Taken together, sustainable propulsion pathways indicate that the future of aerospace propulsion will likely be pluralistic rather than singular. SAF provides a near-term decarbonization route, hydrogen offers transformative long-term potential, and electric and hybrid-electric systems create promising options for selected operational segments. The challenge lies in aligning these pathways with technical feasibility, infrastructure readiness, and lifecycle environmental performance.

## **5. Emerging Aerospace Propulsion Technologies**

The advent of new aerospace propulsion technologies is widening the scope of speed, efficiency, mission flexibility, and operational environment to new levels that conventional propulsion systems cannot achieve. The technologies are being designed to meet not only the needs of hypersonic flight in the atmosphere, but also long-duration deep space missions, and the needs of the more general aspects: fuel economy, mission durability, and minimised environmental impact. In contrast to conventional propulsion philosophies, many new systems are specifically designed to meet highly specialised applications and, in many cases, represent a major integration challenge at the vehicle level. Not only can they be crucial to their performance potential, but also in their ability to redefine how propulsion is scaled to future aerospace missions.

One of the most prominent areas of development is hypersonic and detonation-based propulsion. Hypersonic air-breathing systems are designed to fly at very high Mach numbers continuously, and when turbojet and turbofan engines fail to work. Scramjet propulsion has become of special interest in this regime due to the fact that the burning takes place within the supersonic airflow that allows propulsion to be achieved at velocities that are beyond the viable range of ramjets. These systems provide the promise of a high-speed atmospheric transit, high-speed access to space, and sophisticated defence uses, yet they encounter extreme technical obstacles of combustion stability, inlet design, thermal loads and aerodynamic integration (Curran & Murthy, 2000; Heiser & Pratt, 1994). Together with scramjets, detonation-based propulsion systems have gained more and more interest due to their ability to utilise pressure gain combustion, potentially providing thermodynamic benefits over traditional deflagration-based cycles. The potential of more efficient and thrust-generating engines like pulsed detonation engines and rotating detonation engines is under investigation in the context of selected applications (Nävligu et al., 2026).

The other important direction is distributed and electrically enabled propulsion architectures. These systems are not confined to the old architecture of a few centralised propulsion units by decentralising the generation of thrust to a series of propulsors, which are mounted on the airframe. Such plans can result in aerodynamic effectiveness, greater control power, and the development of new possibilities in future planes. Although the idea of distributed propulsion is commonly mentioned in the hybrid-electric and electric aircraft, it is significant as well since it reinvents the propulsion airframe integration. Architectures based on electricity provide additional support for modularity, flexible power distribution, and the potential to bring renewable energy sources into niche applications like solar-assisted flight. Although solar-electric propulsion is still constrained by the low-power density and reliance on environmental conditions, it still shows potential in high-endurance, low-power flight systems and specialised unmanned systems. Beyond it, the analysis of electric propulsion is becoming more assessed with the consideration of not just the thrust generation, but also propellant selection, system cost, and optimisation to specific missions (Teffah et al., 2026).

One of the most transformative fields of the new propulsion technologies is advanced space propulsion systems. Electric propulsion, such as ion propulsion and plasma-based propulsion, has gained particular significance in spacecraft with high propellant efficiency needs across long mission periods. They are highly effective in accelerating charged particles to very high exhaust velocities, and are thus highly adapted to orbital manoeuvring and station-keeping, as well as deep-space exploration, although their thrust is relatively low. Ongoing space electric propulsion development has been directed at higher efficiency of the thrusters, power processing, alternative propellants and increased mission flexibility, especially in Hall and other plasma-based systems (Levchenko et al., 2025; Tirila et al., 2023). In addition to electric propulsion, nuclear propulsion is also receiving a new revival as a concept in future deep-space missions due to its ability to offer high energy density and shorter transit periods. Nuclear thermal and other in-space propulsion solutions are beginning to be considered as strategic solutions to ambitious scientific and exploration missions beyond Earth orbit (Polzin & Houts, 2023; The Aerospace Corporation, 2023; Thomas, 2024).

Combined with the new propulsion technology, the future of aerospace systems will be based on a more comprehensive and mission-specific propulsion portfolio. Hypersonic, detonation-based, distributed, electric, plasma, and nuclear systems all serve different operational needs, and are all indicative of the broader change to high-performance propulsion concepts to serve those areas and mission profiles that the conventional systems are incapable of efficiently serving. Figure 2 summarises the association between the emerging propulsion technologies and their probable mission applications.

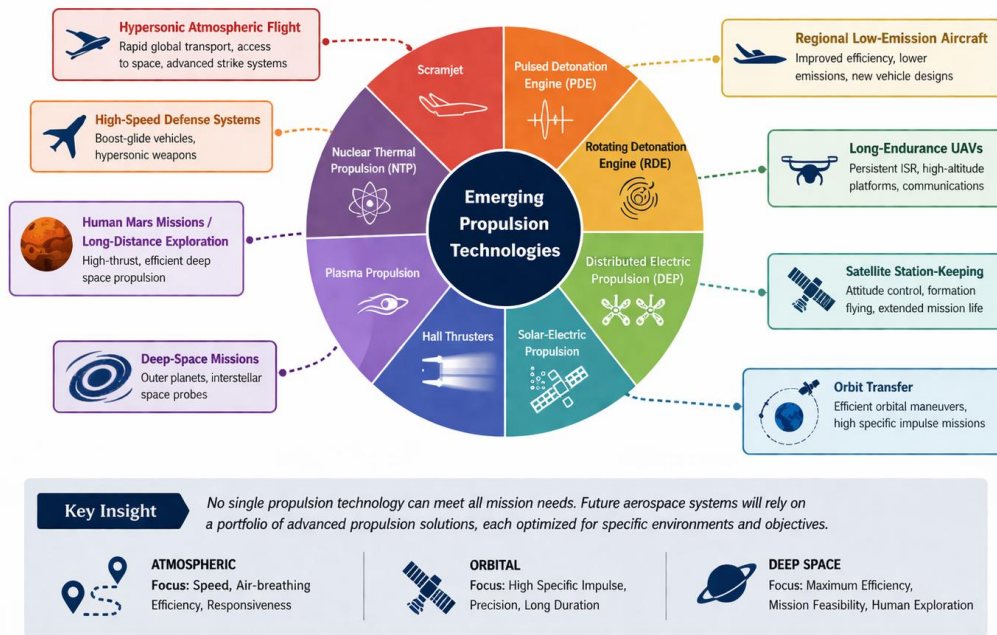


Figure 2. Emerging aerospace propulsion technologies and their principal application domains across atmospheric, orbital, and deep-space missions.

## 6. Challenges and Limitations

Although there has been a strong push towards next-generation aerospace propulsion systems, their penetration has been limited by a number of technical, economic, infrastructural, and regulatory barriers.

Most of the propulsion routes suggested as ways of enhancing efficiency and sustainability have shown potential in their theoretical or experimental applications, but the practical application of these concepts to large-scale operational applications is not easily achieved. The key constraints do not necessarily limit themselves to propulsion hardware but also to energy storage, thermal regulation, infrastructure, safety, and certification.

The difficulty of attaining decent performance in managing the energy storage and thermal loads is one of the most enduring technical obstacles. Battery, power electronics, motor, and related control system integration in hybrid-electric and electric propulsion systems poses significant thermal management challenges. Heat emission influences performance, stability and the lifetime of the components, and it is particularly troublesome when power densities are required to be high, and the weight limitations are severe. With the increased electrification of propulsion architectures, thermal management is no longer a secondary design effort, but rather a primary consideration that affects feasibility and system-level performance (Asli et al., 2024). One of the key limiting factors is also battery technology. Despite advances in battery chemistry and energy storage capabilities, the present-day technologies exhibit substantial limitations in terms of specific energy, charging properties, safety factors, and the lifecycle of the systems compared to the needs of commercial aviation. Such constraints limit the range of operation and payload of aircraft that rely on batteries and delay the feasibility of full-scale electric propulsion application (Pattanayak & Mavris, 2025; Tiede et al., 2022).

The use of hydrogen-based propulsion presents a new but equally important group of technical challenges. Although hydrogen has promising environmental characteristics, its storage and handling needs are much more challenging than those of traditional aviation fuels. Its use in the aviation industry is complicated by the presence of cryogenic storage, insulation of tanks, boil-off control, volumetric inefficiency and aircraft integration. The problems not only impact the design of propulsion, but also vehicle design, airport, fueling logistics and maintenance. Consequently, the technical feasibility should be considered on the basis of the entire aviation ecosystem instead of just the engine level (European Commission, 2023; Federal Aviation Administration, 2024).

Other significant barriers to implementation are economic and infrastructure constraints, on top of technical constraints. The advent of hydrogen and new high-technology electric propulsion systems will entail large-scale investment in new supply chains, energy distribution networks, ground servicing systems, and maintenance facilities. Such investments cannot be easily justified when there are no clear ways of market maturity and regulatory acceptance. Similarly, battery-powered aviation relies on charging infrastructure, grid capacity and operation models that are quite different to those of traditional aircraft. As a result, despite technical feasibility, a concept of propulsion might not be commercially adopted due to its cost, infrastructure availability, and unpredictability of future payback (European Commission, 2023; Pattanayak & Mavris, 2025).

The deployment of emerging propulsion systems is further complicated by safety, certification and regulatory issues. The current certification schemes have been mostly created based on the traditional propulsion based on hydrocarbon and thus fail to entirely represent the risks of hydrogen storage, battery thermal runaway, or electric powertrain integration or new aircraft energy architectures. Hydrogen-powered aircraft certification is particularly complicated due to the necessity to assess new risks associated with fuel containment, leakage, and ignition, as well as crashworthiness and the redundancy of systems. Recent reports have shown that there are still critical certification gaps for both normal-category

and large hydrogen-powered aircraft, and that it is likely that regulatory adaptation will be required before such airplanes can be supplied into service in large numbers (Federal Aviation Administration, 2024; Jézégou et al., 2025). In a broader context, laws and regulations surrounding zero-emission propulsion are still in their infancy and are inconsistent and disjointed, throwing into a state of uncertainty manufacturers, operators, and investors (European Commission, 2023).

Overall, the problems of advanced propulsion systems are interrelated and complicated. The technical performance, thermal control, storage constraints, infrastructure preparedness, economic feasibility, and certification needs have to be tackled simultaneously. This implies that the sustainability of the sustainable and emerging propulsion systems in the future will not be pegged on the technological advances, but also on the policy, industry and regulatory convergence of efforts.

## **7. Future Trends and Research Directions**

The convergence of digital intelligence, the low-emission energy pathways and the more mission-specific system architectures are likely to dominate the future of aerospace propulsion. Since the technologies of propulsion have surpassed the traditional gas turbine and chemical rocket models, the research is now becoming integrated solutions, which are grounded on optimising performance, environmental accountability, and flexibility in operation. In this case, the additional evolution will not be based solely on the progress in propulsion devices, but also on the solutions of the system-level design, control strategies and cross-functional engineering.

The incorporation of artificial intelligence, smart systems, and multidisciplinary optimisation into the development of propulsion is one of the key trends. The aerospace propulsion systems are getting more sophisticated due to the introduction of electrification, hybrid systems, distributed propulsion, and sophisticated thermal management needs. This complexity renders conventional design approaches as being less adequate in themselves. AI-assisted design, digital twins, predictive control, and intelligent health monitoring systems are thus likely to be used more in future research to enhance efficiency, reliability, and lifecycle performance. Intelligent propulsion can facilitate real-time response to fluctuating flight parameters, proactive fault identification and finer control of energy usage among engines, batteries, power electronics and airframe subsystems. Multidisciplinary optimisation will be needed at the research level since the propulsion performance cannot be considered independently of aerodynamics, structures, thermal systems, environmental impact, and operating economic factors.

A second urgent course is the routes to low-emission and net-zero propulsion. It is not a one-size-fits-all solution that is likely to be applied to the decarbonization of aerospace. Sustainable aviation fuels can still be significant in the near future due to the ability to minimise the lifecycle emissions whilst not requiring significant changes to current aircraft and infrastructure. In the medium and long term, hydrogen propulsion, hybrid-electric systems, and some battery-electric applications will grow, especially in regional aviation and specialised aircraft and new concept airframe designs. Meanwhile, future propulsion studies will require placing more emphasis on lifecycle assessment, supply chain sustainability, and energy infrastructure, as well as the overall environmental implications of propulsion decisions. Net-zero propulsion, thus, is not just an engine problem, but a systems change of fuel production, storage, operations, certification, and industrial scalability.

The future of the new generation of aviation and space missions is also promising. In aviation, the technology of future propulsion can underpin more efficient, cleaner and quieter aircraft tailored to short-haul, regional, and potentially long-range flights along various technological lines. High-speed electric, plasma and nuclear-based propulsion technologies are projected to increase the capability of deep-space exploration, long-duration missions, and the capability to perform more versatile orbital missions in space applications. With increasing diversity in the range of aerospace missions, it is likely that the propulsion systems will become more specialised, with various technologies being used in the different niches of operation. The future of propulsion, thus, is in integrated, adaptive, and sustainable systems that can support the dynamic requirements of both atmospheric and space transportation.

## 8. Conclusion

Aerospace propulsion is experiencing a major change wave with the twin demands of increased performance and increased environmental sustainability. It has been demonstrated in this review that recent developments in propulsion systems go far beyond the simple development of traditional engines. Advances in thermodynamic design, open rotor development, lightweight materials, thermal control, and digital control have enhanced the efficiency of propulsion, and new directions are under development, such as sustainable aviation fuels, hydrogen, electric, and hybrid-electric propulsion. Concurrently, hypersonic, detonation-based, plasma and nuclear propulsion technologies are pushing the limits of what is potentially achievable in future aviation and space missions. Another point that the review makes is that there is no one propulsion technology that will probably take over all aerospace applications. Rather, the future of propulsion will be defined by a diversified technological environment where various systems will be associated with a particular mission's needs, scale of operation, and operational goals. Traditional gas turbine-based systems will probably have a role to play in the coming years, especially with SAF and efficiency-focused modifications, and hydrogen and electrified propulsion concepts are likely to gain a more significant role in decarbonization plans over the long term. In space, sophisticated electric and nuclear propulsion systems will be at the core of facilitating ambitious exploration goals. But the move to next-generation propulsion is limited by unresolved issues in the energy storage, thermal management, infrastructure preparedness, economic viability and certification. The next step will thus require integrated developments in engineering, regulation and integration of the systems. Comprehensively, the development of aerospace propulsion is moving towards a more efficient, more specialised, and more consistent with the global sustainability objectives in the future.

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