

Current and Alternative Propulsion Systems in Europe; Technologies and Their Integration

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Abstract

Europe's transition to climate-neutral aviation, guided by the Clean Aviation Joint Undertaking, is accelerating research into alternative propulsion. This review examines hybrid-electric architectures, hydrogen combustion and fuel-cell systems, battery-electric propulsion, radical propulsion concepts, and related energy conversion and storage principles for future European aircraft. It compares efficiency, power and energy capacity, maturity, and technology readiness, showing how these factors shape aircraft performance and operational feasibility. The paper also reflects Clean Aviation research and industry collaboration, including Swedish activities between Chalmers and GKN Aerospace on integrated architectures, turbomachinery, thermal management, electrification, and hydrogen technologies. Beyond component advances, it addresses challenges in system integration, certification, qualification, and distributed propulsion using new energy carriers. Sustained academia-industry collaboration is emphasized as essential for risk reduction, technology maturation, and robust system design, within a broader sustainability and design-space perspective balancing environmental, technical, and operational requirements for future deployment.

Keywords: Propulsion Systems, Europe, Integration, Sustainability, Hybrid, Hydrogen

1 Introduction

European aviation is moving from a phase dominated by incremental gas-turbine improvement toward a broader portfolio of propulsion and energy-carrier solutions for climate-neutral flight. Commercial aviation is expected to continue to expand, which will result in increased carbon emissions, which are estimated to double by 2050 in business-as-usual scenarios for the aviation sector alone [1]. ACARE has released Strategic Research Agendas since 2001 [2] where European aeronautics research has increasingly linked competitiveness, safety, environmental performance and societal value. More generally, the European Union strategy emphasise sustainable transformation within the European Green Deal [3] and the EU Circular Economy Action Plan [4]. More recently, the economic dimension on strategic development is influenced by the Draghi Report [5], emphasising sovereignty and scalability for industrial competitiveness. The Aerospace Research and Innovation Strategy, ARIS [6], which frames aviation decarbonisation as a continued key challenge of technology maturation, industrial capability and system deployment. ACARE recently published a position paper [7] suggesting a vision and roadmap for 2028-2034.

Propulsion systems remain central to aerospace sustainable and industrial transition. Major reductions in fuel burn and CO_2 emissions have been achieved through improved thermodynamic efficiency, higher component efficiencies, increased pressure ratios, advanced combustors and high by-pass ratio turbofan architectures. These developments have also pushed engine and aircraft design toward higher levels of optimisation, where performance depends on the combined effect of aerodynamics, structures, materials, thermal behaviour, manufacturing, controls, noise, reliability and maintainability.

The next step is substantially more complex. Hybrid-electric propulsion, hydrogen combustion, fuel cells, battery-electric systems, sustainable aviation fuels, distributed propulsion and advanced thermal

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management cannot be evaluated as isolated solutions and technologies. Their feasibility depends on how they are integrated into evolving powerplant and aircraft architectures. Energy storage, conversion, distribution, heat rejection, controls, safety systems, installation effects, certification requirements and operational constraints interact strongly. As a result, the same technology may lead to very different aircraft-level outcomes depending on the architecture into which it is embedded. This has been studied and reported in the European SIENA project in more detail [8]. Integration of technologies into engines, aircraft and the air transport system more widely is therefore critical for realisation and scale up. Novel technologies may constrain-, or be constrained by, other system conditions.

Advancing aerospace technology depends not only on maturing individual technologies, but also on developing the knowledge required to integrate and realise them within a wider systems context. This knowledge must be created, transferred and validated across system levels and life-cycle phases, from fundamental research and component development to integration, demonstration, qualification, certification and deployment. Early phases require scientific understanding, modelling and architectural reasoning; intermediate phases demand multidisciplinary integration; and later phases require manufacturing capability, operational evidence, life-cycle assessment and regulatory confidence. Because architectural decisions are often made while technologies and interactions remain immature, uncertainty and integration risk must be explicitly managed. Knowledge maturation is therefore a systematic process of reducing uncertainty and risk until technologies can be integrated and committed to with sufficient system-level confidence

Universities, research organisations, industry, authorities and suppliers all play essential roles in this process. Academia contributes upstream knowledge, education, modelling, independent validation and test infrastructure, while industry transforms technologies into reliable and manufacturable systems. The European Aerospace Science Network (EASN) provide a forum to discuss and promote European research and the role of academia [9]. The ambition of the present paper is to review the propulsion technology landscape based on recent and ongoing research in Europe. Given the breadth of the scope, authors do not claim to provide an exhaustive review, rather address some examples of the effects that have been reported and discuss selected topics that likely require attention. Opinions and interpretations of other works are made by the authors and not official positions of their organisations.

2 Critical technologies for propulsion

Future aerospace propulsion will not converge on one dominant “green” architecture. It will split by aircraft segment because each energy carrier imposes different mass, volume, thermal, certification, and infrastructure constraints. SAF-compatible gas turbines dominate near-term and larger-aircraft pathways; batteries are credible mainly for small aircraft; hydrogen fuel cells fit shorter-range regional aircraft if cryogenic storage and MW fuel-cell systems mature; hydrogen combustion may scale better than fuel cells but requires new airframes, tanks, combustors, and airport infrastructure. Gas turbine technology is a reliable propulsion system solution, that will continue to be a fundament for propulsion and subject to further development and renewal.

We first review critical technologies thereafter the propulsion systems looking into the evolutionary trajectory and discussion of some of their limitations.

2.1 Gas-turbine core and propulsive-efficiency technologies

Gas-turbines remain central even in a decarbonisation roadmap for several reasons. Its technology and the ubiquitous turbofan engine remains the most viable option for medium and long-range applications, providing a robust, silent and safe platform with low to moderate level of systems and regulatory impact of new technologies and with the focus on increase efficiency and use of alternative fuels.

The turbofan cycle has matured since the mid-70s, continuously improving its efficiency annually by 1.3% [10]. Historically, new aircraft introductions have required double-digit reductions in fuel burn to provide high enough impetus for the airlines to start replacing older aircraft. Achieving such improvements by employing the turbofan propelled tube-and-wing aircraft becomes increasingly costly and will at some point become impossible. Taking a look at the fundamental losses of a typical turbofan, see Figure 1 [11], we see that there are three main areas that can be improved; 1) Reduction

of combustor irreversibility, 2) recovery of exhaust heat and 3) through improvement of the propulsive efficiency. In addition, continued progress on turbomachinery aerodynamics may give considerable benefits. Ambitious projects on reducing the bypass flow losses, through increase in propulsive efficiency, are ongoing. Progress is expected both from advancing the geared engine architecture through a series of generations of propulsion systems and more radically through exploring open rotor architectures ([12] – OFELIA project 2026). This path latter is likely the lowest risk next step for drastically reducing energy need of future aircraft. More radical routes are provided through the reduction of combustor irreversibility and recovery of exhaust heat.

To achieve substantial advances on the core heat recovery, low-pressure loss ultra-efficient heat exchangers need to be designed. Without reaching new levels of performance, heat exchangers tend to become either too heavy or induce excessive pressure losses, thereby not providing sufficient benefits to motivate development risk. Key European efforts on exploring and developing new engine architectures that rely heavily on heat management are the IRA engine [13] and more recently the WET cycle ([14] – SWITCH project 2026).

Reduction of combustor irreversibility may be achieved through pressure rise combustion. For pressure rise combustion, the technical challenges may be even higher than for the heat recovery concepts. However, it could be argued that such an engine was developed already in the 1950ies, represented by the Napier Nomad engine [15]. Plagued by poor reliability it was superseded by turbojet and later turbofan engine concepts despite their substantially lower efficiency. Recent efforts to realise the massive efficiency potential that such a cycle would have, is pursued in the on-going MINIMAL project [16] and recent updates on the concept can be found in [17].

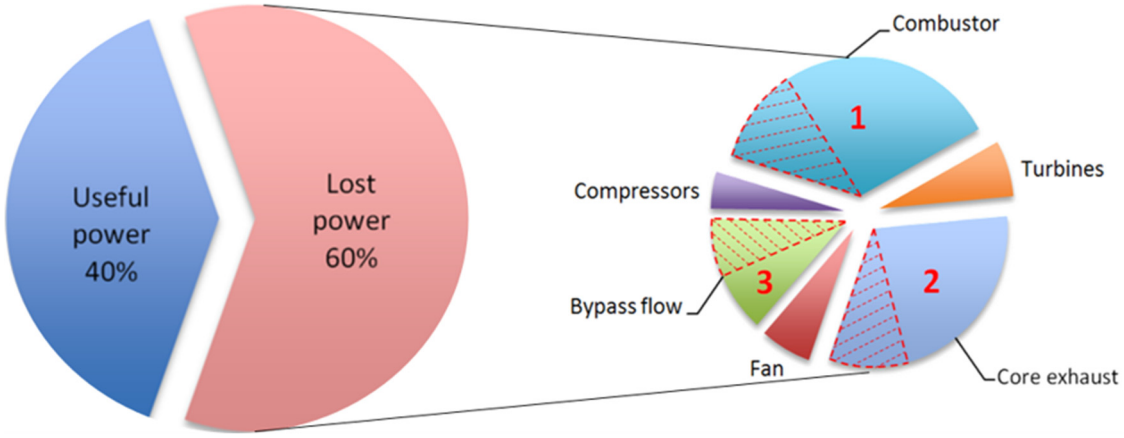


Figure 1: Losses in typical turbofans grouped into Combustor (1), Core exhaust (2), Bypass flow (3) and turbomachinery losses [11].

Notice that the three major loss sources illustrated in Figure 1 above can also be reduced indirectly. An example would be if small-size turbomachinery delivering very high efficiency could be built then this could enable increasing overall pressure ratio of the engine. Then, the combustor losses shown in Figure 1 would be reduced and at the same time the core exhaust heat losses may drop due to that the temperature drop over the turbines increase as the overall pressure ratio go up.

Irrespective of whether a radical new engine architecture is selected or if an update of the turbofan engine is pursued, key technologies need to advance. Key technologies that receive substantial research funding are:

Compact high-pressure cores, turbine cooling technologies, advanced thermal barrier coatings and advances in turbine materials, ceramic matrix composites and environmental barrier coatings, additive manufacturing, small-size turbomachinery aerodynamics advancement, closer engine airframe

integration including boundary layer ingestion, improved seals and lightweight structures. These improve thermal efficiency but increase materials, cooling and durability demands. Noteworthy past European technology projects are LEMCOTEC [18] and NEWAC [19].

Geared fans, ultra-high bypass ratio fans and open fans improve propulsive efficiency by accelerating a larger air mass to a lower jet velocity. This is why open fan and geared fan architectures are tightly linked to future single-aisle aircraft design rather than being just engine upgrades.

Low-emissions combustors and SAF/hydrogen-compatible combustion connect engine research to fuel transition. SAF compatibility is near-term; hydrogen combustion requires new injector, flame-stability, NOx-control and safety approaches.

European research positions the gas turbine not as a legacy technology to be replaced immediately, but as a progressively transformed propulsion platform: higher-efficiency cores, UHBR/geared/open-fan propulsors, advanced materials and manufacturing, and combustion systems adapted to SAF and eventually hydrogen.

2.2 SAF technologies

Sustainable Aviation Fuel (SAF) is best treated as a fuel-system and lifecycle-compliance technology rather than a new propulsion architecture: its near-term value lies in drop-in compatibility with existing aircraft, engines and airport fuel infrastructure, while its main constraints concern certified blending, fuel quality, feedstock sustainability, lifecycle accounting, traceability, cost and supply scale [20, 21]. IATA estimates that 2026 SAF production will cover only about 0.8% of aviation fuel use, making SAF essential but strongly supply-constrained [21]. It is expected that SAF will supply 70% of aviation fuel by 205o and is a major component to reaching net zero CO2 targets. SAF is largely compliant with Gas Turbine Technologies, yet a major issue for operating at scale on 100% SAF is that many synthetic paraffinic fuels contain almost no aromatics. Aromatics help certain legacy fuel-system seals swell and function correctly, although they also contribute to particulate emissions. Density and material compatibility can therefore prevent some neat synthetic paraffinic fuels from being used directly as 100% replacements. Technologies for SAF rely predominately on the production technologies, and will not be further examined here.

2.3 Electrification and Hybrid Electric technologies

Electrification should be split into three categories, based on to what degree they contribute to propulsion of the aircraft.

First, what is referred to as more-electric aircraft systems replace hydraulic or pneumatic functions and improve aircraft energy management, making de-icing more efficient etc. This trend supports all architectures and has been going on for decades, where air-bleed system solutions have been replaced by bleedless designs and increased the power outtake to the aircraft other than propulsion. These solutions have been introduced into recent architectures, such as Rolls Royce Trent 1000 engines and the redistributed power outtake impact the design of the reminder of the engine, as surge margins and compressor maps are adjusted.

Second, Hybrid-electric propulsion uses electric machines to assist a gas turbine also for its propulsive function, redistribute power, enable distributed propulsion, or optimize engine operating conditions. This is most promising where aircraft-level benefits can offset added mass, high-voltage complexity, and cooling requirements. These aspects have brought up atypical trade-off studies between different technologies and some examples can be found in the technology roadmap for regional aircraft electrification [22, 23]. These included the trade-off study between the RPM of the motor of the wing-tip electric propulsor and the overall wing size and shape, due to the dependency between the motor and the propeller and subsequently the wing-tip aerodynamic effects influencing the overall stability and performance of the aircraft.

Third, battery-electric propulsion is attractive for very short missions because electric motors are efficient, quiet, and mechanically simple [24]. The barrier is energy storage: batteries add mass that does not reduce during flight, limiting range and payload. In addition, reliability connect to endurance and availability, where degradation of the battery capacity is an issue. Safety is another matter; capacity fades over the battery's life and reserves must always be retained, the design point is set by end-of-life rather than beginning-of-life energy. The margin needed to guarantee range and reserves

throughout service compounds the mass penalty already inherent to battery storage. All these characteristics should be scalable and compatible with industrial practice (industrialization). Battery-electric aircraft are therefore most credible for training, commuter, and specialized short-range missions, not mainstream medium- or long-range transport.

The relation to electric and hybrid technologies and architectures is fundamental. Advancements on technology level, such as battery technologies, will have an impact onto the conditions on how to integrate. At present, architectural development, infrastructure for energy provision, including grid infrastructure as well as certification and regulatory development are likely to be a critical factor for time to implementation in practice.

2.4 Hydrogen technologies

Hydrogen should be viewed as an aircraft- and propulsion-architecture transition rather than simply a substitute fuel. Its specific energy is high—about 120 MJ/kg compared with approximately 43 MJ/kg for jet fuel—but liquid hydrogen contains only about 8.4 MJ/L, versus 32–34 MJ/L for Jet A. Aircraft therefore require roughly four times the fuel volume, excluding insulation and system equipment. Conventional wing tanks are generally unsuitable, requiring insulated tanks in the fuselage, wing roots or purpose-designed airframe volumes. This affects aircraft geometry, centre of gravity, payload–range performance and ground operations. Critical technologies include lightweight cryogenic tanks, insulation, boil-off control, pumps, valves, leak detection, ventilation, crashworthiness and airport storage and refuelling systems.

The European ENABLEH2 project [25] demonstrated that hydrogen must be assessed through integrated aircraft, propulsion, fuel-system and safety design. It evaluated 31 airframe architectures and 21 propulsion arrangements. A tube-and-wing configuration with enlarged wing-root tanks was selected for a 200-passenger, 3,000-nautical-mile mission, while a blended-wing-body concept was favoured for a 414-passenger, 7,500-nautical-mile mission. ENABLEH2 [25] also advanced micromix hydrogen combustion towards Technology Readiness Level 3, using many small diffusion flames to reduce flame temperature, flashback risk and nitrogen oxide formation [26-30].

Liquid hydrogen can also serve as a cryogenic heat sink for fuel preheating, compressor precooling and intercooling. Depending on the temperature by which the hydrogen may be pre-heated, up to 10% SFC reduction may theoretically be attained [31], but including component losses and material limitations about half of that number may be achieved in real engines [31].

Two main propulsion routes are being pursued. *Direct hydrogen combustion* retains gas-turbine power density and much of Europe's existing competence in turbomachinery and combustion. It may therefore scale more readily to larger regional and short-to-medium-range aircraft. Although it eliminates fuel-related carbon dioxide emissions, nitrogen oxides, water vapour and contrail effects remain. Hydrogen's high reactivity also creates challenges involving flashback, auto-ignition, combustion instability and injector durability.

Fuel-cell-electric propulsion converts hydrogen electrochemically to power electric motors. Proton-exchange-membrane fuel cells avoid combustion-related nitrogen oxide emissions and are attractive for commuter and regional aircraft. Their feasibility depends on megawatt-class stack power density, compressors, water management, high-voltage distribution, redundant motors, cryogenic storage and effective thermal rejection. Cooling is particularly demanding because waste heat must be removed at relatively low temperatures, increasing radiator mass and drag. Efforts on maturing MW size driveline technology is on-going in the HEROPS project *aiming* to develop PEM fuel cell propulsion system for regional aircraft. This is achieved through maturing MTU's Flying Fuel Cell concept, with liquid hydrogen as the sole energy source and a scalable 600 kW system designed yt%uwtizhj%63=R \ 3%

The project cleared its preliminary design phase and is now progressing towards a ground demonstrator of the 1.2 MW drive aiming to validate the system to TRL5/6. MTU and Airbus have signed an MOU targeting a joint venture [32] The EU project NEWBORN, which is a Honeywell-led Clean Aviation project aiming to develop a scalable megawatt-class hydrogen fuel-cell propulsion system for regional aircraft building on PowerCell Group technology [33].

Solid oxide fuel cells operate at higher temperatures and may offer greater efficiency and integration

with gas turbines. However, slow start-up, limited transient response, thermal cycling and low specific power currently make them more suitable for longer-term hybrid systems or auxiliary power than for near-term primary propulsion.

Rolls-Royce has, as part of their collaboration with EasyJet, now demonstrated a full-cycle 100% hydrogen jet engine test. A modified Peal 15 engine reached full take-off power running on 100% gaseous hydrogen closing out a four year Rolls-Royce/easyJet testing programme [34].

Hydrogen offers Europe opportunities for deep lifecycle-emission reductions and leadership in cryogenic systems, fuel cells, combustion, electric propulsion and airport infrastructure. Scaling it to commercial aviation is nevertheless a system-of-systems challenge requiring simultaneous development of aircraft, propulsion, certification, hydrogen supply and airport operations. Initial deployment is most credible in selected commuter and regional markets. Broader use will depend on improved tank efficiency, fuel-cell specific power, low-nitrogen-oxide combustion, thermal management, infrastructure availability and affordable low-carbon hydrogen. Fuel cells are likely to suit shorter-range aircraft, while hydrogen combustion may better preserve the power density needed for larger commercial aircraft.

2.5 Certification, industrialisation and compliance of novel propulsion technologies

Certification should be treated as an enabling technology and integrated into propulsion research from its early stages since radical technologies introduce operating conditions, failure modes and system interactions not adequately covered by existing specifications. Technical performance must therefore be advanced together with evidence of safety, environmental compliance, manufacturability, maintainability and continued airworthiness.

Electric and hybrid-electric propulsion introduce batteries, high-voltage distribution, power electronics, electric machines and tightly coupled thermal-management systems. Certification must address thermal runaway, fire containment, electromagnetic compatibility, insulation failure, software-intensive control and common-cause failures. Hybrid systems are especially challenging because electrical, mechanical and thermal subsystems interact in ways not present in conventional propulsion. EASA has responded through Special Condition SC E-19 for electric and hybrid propulsion systems.

The European FUTPRINT50 project [22] demonstrates the value of regulatory involvement during technology development. The project developed a roadmap towards a 50-seat hybrid-electric regional aircraft for entry into service around 2035–2040. EASA participated through the advisory board and a dedicated research contract, assessing gaps in CS-25 requirements for electrical systems, propulsion batteries, powerplants and fuel systems. Certification constraints could therefore influence the aircraft architecture and research roadmap before formal certification began.

Hydrogen aircraft similarly require new means of compliance for cryogenic storage, leakage, fire and explosion hazards, pressure management, venting, crashworthiness and refuelling. Hydrogen combustion adds flashback, combustion instability and nitrogen-oxide concerns, while fuel-cell propulsion introduces high-voltage, cooling and degraded-operation challenges. EASA's hydrogen-certification roadmap identifies gaps in existing specifications, standards and technology-maturation timelines.

Certification challenges also apply to radical gas-turbine and aircraft architectures. Open fans, ultra-high-bypass engines, distributed propulsion and boundary-layer ingestion create stronger coupling between propulsion and airframe. Compliance evidence must address blade release, debris, noise, vibration, installation loads, aerodynamic interaction and aircraft controllability at the integrated aircraft–propulsion level. The Clean Aviation CONCERTO project [35] reflects this approach by developing certification methods and safety evidence alongside disruptive aircraft and propulsion concepts rather than after technology demonstration.

Both industrial competitiveness and novel functionality drive the need to use advanced materials and manufacturing technologies which introduce further challenges. Metal additive manufacturing enables integrated cooling channels, lightweight structures and complex heat exchangers, while nano-engineered materials and coatings may provide thermal, electrical, sensing or wear-resistant functionality. Qualification must nevertheless address material variability, defects, anisotropy, residual stresses, inspection, repair and production repeatability. Certification may therefore extend beyond

the component to include the manufacturing process, equipment, digital build definition and quality-control chain through product life.

Disruptive technologies may also require new production, maintenance, training and airport strategies. Europe's involvement of EASA through projects such as FUTPRINT50 [22] and CONCERTO [35], together with advisory boards, research contracts and Innovation Services, helps identify regulatory gaps while technologies are still being shaped. This reduces the risk that technically successful demonstrators later encounter prohibitive certification or industrialisation barriers.

Environmental compliance is also expanding beyond carbon dioxide. Since 1 January 2025, European aircraft operators have been required to monitor aviation's non-CO_2 effects, strengthening the need to assess nitrogen oxides, soot, water vapour, contrails, lifecycle emissions and material impacts. Certification and sustainability evidence should therefore mature alongside technical performance, making regulatory agencies active research partners rather than final-stage approval bodies.

2.6 Consolidated overview: propulsion architectures and critical technologies in aerospace

Future aerospace propulsion is best understood as a segmented architecture problem, not as a single transition from kerosene to one "green" technology. Each propulsion option combines an energy carrier, an energy-conversion system, and an aircraft integration concept. The decisive question is whether the aircraft can absorb the mass, volume, cooling, safety, certification, and infrastructure penalties while still delivering useful payload, range, dispatch reliability, and lifecycle sustainability evidence.

The overall trend is therefore not replacement of the gas turbine in the short term, but diversification by aircraft segment. SAF-compatible gas turbines are the dominant near-term pathway for existing and larger aircraft. Battery-electric propulsion is credible mainly for small aircraft and short missions. Hydrogen fuel cells are most plausible for commuter and regional aircraft if MW-class systems, cooling, and storage mature. Hydrogen combustion may scale better than fuel cells for larger aircraft, but it requires major changes in airframe layout, cryogenic fuel systems, airport infrastructure, and certification. Aslo, the increased use of AI impact certification procedures, which is underway through EASA [36] who participate and collaborate to develop and understand certifiability of novel technologies.

3 Current propulsion systems and evolutionary pathways

3.1 Baseline: current turbofan and turboprop propulsion

Current commercial aviation is built around gas-turbine propulsion for any medium- and large-aircraft system. Turbofans dominate short-, medium-, and long-range aircraft because they provide high power density, reliability, maintainability, and compatibility with global infrastructure. Turboprops remain attractive for commuter and regional aircraft because propellers are highly efficient at lower cruise speeds and shorter ranges and subject to development of hybrid propulsive solutions.

This baseline is important: alternative propulsion must compete against an architecture that is already highly optimized. The relevant comparison is not only emissions, but also payload-range capability, safety, certification maturity, operating cost, operational flexibility, airport compatibility, and fleet scalability.

Near-term propulsion research continues to target both thermal efficiency and propulsive efficiency.

Thermal-efficiency levers include higher pressure ratio, higher turbine temperature, improved compressor and turbine aerodynamics, advanced materials, ceramic matrix composites, improved cooling and compact cores.

Propulsive-efficiency levers within the continuing evolution of conventional aircraft propulsion include higher bypass ratios, geared fans, larger fan diameters, improved nacelle integration, lightweight fan structures and, at the more radical end, open-fan architectures. Rolls-Royce states that its UltraFan demonstrator targets a 25% fuel-efficiency improvement over first-generation Trent engines and a 10% gain over the Trent XWB, while CFM's RISE programme targets more than 20% improvement relative to current engines for potential application in the second half of the 2030s. For regional aircraft, established turboprop technology provides an important near-term reference pathway, offering high propulsive efficiency at moderate speeds and short-to-medium ranges. Continued

improvements in propeller aerodynamics, engine efficiency, lightweight integration and compatibility with SAF or partial hybridisation can further reduce emissions without requiring a fundamentally new aircraft or propulsion architecture.

3.2 SAF as the transition pathway

Sustainable aviation fuel should be treated as a near-term transition pathway for gas-turbine architectures, not as a fundamentally new propulsion system. Its advantage is compatibility with existing aircraft and infrastructure. The propulsion architecture remains essentially the same, while the lifecycle carbon intensity of the fuel is reduced.

However, SAF does not remove tailpipe CO_2, and its climate benefit depends on production pathway, feedstock, hydrogen/electricity inputs, land-use effects, certification, and traceability. In Europe, the ReFuelEU Aviation mandate starts at 2% SAF in 2025 and increases to 70% by 2050, with a specific sub-mandate for synthetic aviation fuels beginning in 2030.

3.3 Expanding the view of sustainability compliance and circular economy

It has become increasingly evident that the sustainability challenges facing aviation extend far beyond climate change alone. Achieving the Flightpath 2050 vision of net-zero emissions, while also reducing NO_x emissions and noise, will require transformative efforts throughout the entire aerospace value chain. Society, policymakers, and customers increasingly expect the aviation industry to address a broader range of sustainability challenges, prompting the introduction of new regulations and policy frameworks. Examples include the European Green Deal and the Critical Raw Materials Act, which will significantly influence the future development of the European aerospace sector [37].

Consequently, sustainability assessment is moving beyond a narrow focus on tailpipe CO_2 emissions towards a more comprehensive life cycle and systems perspective. Future propulsion concepts must therefore demonstrate their sustainability performance across multiple dimensions, including lifecycle greenhouse gas emissions, non-CO_2 climate effects, material and resource use, airport energy infrastructure, and operational feasibility. This is particularly important for hydrogen- and electric-powered aircraft. While these technologies have the potential to significantly reduce or eliminate in-flight CO_2 emissions, their overall environmental benefits depend on factors such as hydrogen production pathways, electricity generation, battery materials, system-level efficiency, and non-CO_2 effects including NO_x emissions and contrail formation.

Reflecting this broader perspective, non-CO_2 effects are increasingly being incorporated into regulatory frameworks. The European Union introduced its Monitoring, Reporting and Verification (MRV) requirements for non-CO_2 aviation effects on 1 January 2025, supported by the Non-CO_2 Aviation Effects Tracking System (NEATS) [38], which enables airlines to calculate and report the climate impacts of non-CO_2 emissions. Together, these developments illustrate the growing need for holistic sustainability assessment methods capable of supporting technology development and decision-making across the aerospace sector.

While the dominant effort in aerospace target direct emissions of green house emissions and noise with an increased interest also in non-CO2 emissions, the trajectory to sustainable propulsion and aviation bring additional challenges and opportunities for manufactures. Aero-engine innovation must be assessed through lifecycle value, not only propulsion efficiency or emissions, something which is driven partially by legislation in Europe but also from cost and resource efficiency including accounting for material criticality [39]. Bringing sustainable and circular solutions to market is also considered a competitive advantage for manufactures. Aviation business is built around through-life availability, safety, performance retention, reliability, and cost, which means new propulsion architectures must be credible in technology readiness, certification, manufacturing, MRO, and business viability. Maintainability, repair, remanufacture, modular replacement, and upgradeability should therefore be considered already in early architecture design [40]. The Circular Economy business logic offer both opportunities and challenges for the aviation sector [41] and is expected to increase in importance. Additive manufacturing can support this by enabling lightweight parts, complex cooling, part consolidation, local repair, and reduced material waste. Condition and health monitoring are equally central, especially as batteries, fuel cells, hydrogen systems, and hybrid-electric architectures introduce new degradation, safety, and maintenance challenges.

3.4 Pathways to implementation

Reaching the ambitious net zero targets by 2040 or 2050 will require the introduction of high potential and often disruptive technologies. A near term pathway rely on scaleable and relatively mature technologies and likely to be the credible pathway for initial commercial introduction during the next aircraft generation—approximately 2030–2040—whereas possible disruptive pathways require more fundamental advances in aircraft architecture, energy storage, infrastructure or certification to be solved. The table below is assembled for the purpose of this paper discussion on scenarios based on how mature and integrable technologies are. Higher degree of uncertainty and less self containted technologies result in more integration and research efforts before implementation, and is classified as disruptive. These pathways are illustrated in Table 1

Table 1 Plausible pathways to implementation

Segment	Near-term probable pathway	Possible disruptive pathway	Main reason
Commuter/Training Aircraft Typically up to 9–19 passengers and short missions	Battery-electric propulsion for trainers and very short missions; hybrid-electric propulsion or SAF-compatible thermal engines/turbogenerators for longer commuter missions; progressive improvements in batteries, electric machines, and energy management.	Fully electric commuter aircraft with commercially useful range; liquid-hydrogen fuel-cell-electric propulsion; distributed electric propulsion combined with STOL or other novel configurations.	Short missions and low power requirements favour electrification; payload–range, battery mass, hydrogen storage, and local infrastructure constrain scaling.
Regional Approximately 20–100 passengers; mainly turboprop missions	Next-generation turboprops combining advanced propellers, ultra-efficient SAF-compatible thermal cores, more-electric systems, and partial hybridisation. Integrated hybrid-electric regional aircraft are plausible for entry into service from around 2035.	High levels of hybridisation; distributed electric propulsion; hydrogen fuel-cell-electric propulsion; hydrogen combustion; and, for the shortest missions, fully battery-electric propulsion.	Efficient propellers and shorter sectors make regional aircraft the first commercially relevant multi-megawatt hybrid application; battery mass, thermal management, high-voltage systems, and liquid-hydrogen integration remain major barriers.
Short / medium range (SMR) Single-aisle aircraft, broadly 100–250 passengers	SAF-compatible ultra-efficient gas turbines, advanced high-pressure-ratio cores, geared ultra-high-bypass ducted fans, lightweight nacelles, more-electric systems, and limited hybridisation within a largely conventional tube-and-wing architecture.	Open-fan or unducted propulsion; deeper propulsion–airframe integration; liquid-hydrogen combustion; fuel-cell-electric propulsion at the shorter-range end; distributed propulsion and novel wing or energy-storage architectures.	Required thrust and mission energy still favour thermal propulsion and energy-dense liquid fuels; open fans and hydrogen require major changes to noise control, aircraft integration, storage, certification, and airport infrastructure.
Large aircraft Long-range and widebody aircraft	Advanced geared ultra-high-bypass turbofans, very-high-pressure-ratio cores, high-temperature materials, more-electric auxiliaries, and increasing SAF use, combined with aerodynamic and structural improvements.	Post-2040 ultra-efficient engine cores deeply integrated with blended-wing-body or other novel airframes; boundary-layer-ingesting or distributed propulsion; hydrogen or other cryogenic fuels, most plausibly on a post-2050 horizon.	Long-range energy demand and global operational compatibility strongly favour gas turbines and liquid fuels; alternative carriers require major aircraft-volume, storage, infrastructure, and certification changes.

The central message is that technology choice and propulsion architecture cannot be separated. SAF preserves today's architecture, yet have significant production capacity challenges. Batteries simplify the drivetrain but constrain aircraft range for the foreseeable future. Fuel cells require hydrogen storage and major cooling integration. Hydrogen combustion preserves turbine power density but disrupts the aircraft fuel system and airport infrastructure. Advanced gas turbines remain essential because every credible pathway benefits from lower required energy, whether that energy comes from Jet-A, SAF, hydrogen, or electricity. An important factor differentiating near term and disruptive pathways are the system-, and infrastructure- integration and regulatory aspects, which need to be co-designed and adapted to new technologies of more disruptive nature. This is less of a problem for the near term pathways, as existing platforms and regulatory conditions are likely to be deployable.

One way to classify technology development projects are into **product technologies** and **enabling technologies.** Product technologies focus on technologies- that when integrated into products and

systems- provide novel or improved performance and functions to the market. Enabling technologies are the technologies necessary to ensure that the product technologies can be realized. These include design, evaluation and testing technologies during product development, the manufacturing and production technologies and the technologies to sustain and circular use of products and systems, such as for MRO and resource utilisation.

3.5 Limits of evolutionary improvement

Incremental gas-turbine improvement is ongoing, but it faces diminishing returns. Higher pressure ratio increases compressor and turbine difficulty. Higher turbine temperature increases cooling and material demands. Larger fans improve propulsive efficiency but increase nacelle drag, fan weight, ground-clearance constraints and installation complexity. Open fans offer larger gains but raise integration, noise, safety and certification questions. Manufacturing and repair technologies become increasingly critical, and often more costly.

This is the reason alternative and more disruptive propulsion is being explored: not because gas turbines have stopped improving, but because fuel-burn reduction alone is unlikely to offset traffic growth and meet deep decarbonisation goals. ICAO has adopted a long-term global aspirational goal of net-zero carbon emissions from international aviation by 2050, but the pathways require a combination of aircraft efficiency, SAF, operational improvements, market measures and possibly hydrogen/electric aircraft in suitable segments.

4 Examples from European projects

European research in aviation has been dominated by the Clean Sky and Clean Aviation programmes. The effect of the research investments have been evaluated on program level for Clean Sky 1(2008-2016) [42] and Clean Sky 2 (2014-2024) [43]. Clean Aviation programme is still active (2021-2031). European projects are typically set up with multiple industrial and research partners as participants across Europe.
Clean Aviation lays out in their Strategic Research and Innovation Agenda [44] bold plans to reshape aircraft technology by 2035. The goal is to significantly reduce greenhouse gas emissions by at least 30% compared to 2020 tech, aiming for climate neutrality by 2050. They want disruptive new aircraft that can cut CO2 by up to 90% with less fossil-based fuel or even zero emissions using hydrogen. The vision also includes making Europe a leader in sustainable aviation innovation while keeping air travel safe, reliable, and cost-effective worldwide.
Position the Clean Aviation portfolio around three research thrusts: ultra-efficient regional aircraft, ultra-efficient short/medium-range aircraft, and hydrogen-powered aircraft. Then map engine-related activities to three propulsion families: ultra-efficient gas turbines/open fan, hybrid-electric turbomachinery, and hydrogen/fuel-cell propulsion.

Below a couple of European projects are revisited and commented as how these relate to what has been discussed above.

4.1 OFELIA—Open Fan for Environmental Low Impact of Aviation

OFELIA is a €139 million Clean Aviation project coordinated by Safran Aircraft Engines, with €100 million of EU funding and 26 European partners [45]. Running from November 2022 to June 2027, the project is intended to mature the CFM RISE Open Fan architecture for future short- and medium-range aircraft. Its objectives include a full-scale engine ground-test campaign, definition of a flightworthy propulsion system and preparation for an open-fan flight demonstration. The project targets approximately 20% lower fuel consumption and CO_2 emissions than 2020-generation narrow-body propulsion systems, with a potential entry into service around 2035.



Figure 1 Projects illustration (made by Safran) of the Open Fan concept studied [46]

OFELIA provides an example of the possible disruptive pathway for the short- and medium-range segment identified in the preceding table. Although the technology retains a gas-turbine core and can use conventional jet fuel or SAF, removing the fan duct permits a much larger effective bypass ratio and lower specific thrust, thereby increasing propulsive efficiency. Earlier European research has demonstrated that open-rotor designs can be aerodynamically optimised for high propeller efficiency, but also that efficiency and acoustic performance must be treated as coupled design objectives rather than independently optimised characteristics.

The open fan is therefore disruptive primarily because of its system-integration implications, rather than because it introduces a completely new energy carrier. Fan diameter, engine location, pylon and wing interaction, rotor loading and aircraft attitude affect both performance and external noise. The exposed rotating blades also introduce demanding requirements concerning blade release, bird impact, lightning, ground safety and aircraft-level certification. Structural flexibility and the gyroscopic and aerodynamic forces generated by the rotating system can produce whirl-flutter instabilities, linking propulsor aerodynamics directly to nacelle, mounting and wing stiffness. Early results reported investigated design parameters influencing whirl flutter that will be used to design the physical experimentation in OFELIA [47]. These studies emphasise the need for experimental determination of propeller forces and validation of analytical aeroelastic models, providing evidence for treating structural dynamics and certification as core parts of open-fan development.

GKN Aerospace contributes to OFELIA through the design and manufacture of advanced load-carrying and multifunctional engine structures. Its work includes demonstrating one of the largest titanium engine cases produced using wire-fed laser directed-energy deposition. This manufacturing route supports large, lightweight, near-net-shape structures with lower material waste, but it also requires the manufacturing process, material properties, inspection methods and structural substantiation to be qualified together.

4.2 Hybrid-electric turbofan integration: SWITCH

The Clean Aviation project SWITCH—Sustainable Water-Injecting Turbofan Comprising Hybrid-Electrics—provides a European example of hybridising a recognisable turbofan architecture rather than replacing the gas turbine with an entirely new propulsion concept [48]. Coordinated by MTU Aero Engines, the €67.6 million project runs from January 2023 to December 2026 and receives €48.5 million in EU funding. SWITCH combines a second-generation Pratt & Whitney geared turbofan with two Collins Aerospace megawatt-class motor-generators, dual-spool hybridisation, waste-heat recovery and low-emissions combustion. The project targets approximately 20% lower fuel burn and energy consumption and a 50% reduction in the climate impact associated with NOx and contrails compared with a state-of-the-art engine. Ground demonstration at TRL 5 is planned within the project,

followed by flight demonstration at TRL 6 by 2030 and a potential entry into service around 2035.

The efficiency opportunity arises from coordinating the thermal and electrical parts of the propulsion system. Motor-generators connected to both engine spools can transfer, extract or supply power according to the flight condition, helping the turbomachinery operate closer to favourable operating points while supporting functions such as electric taxiing. Waste-heat recovery seeks to convert part of the exhaust-energy loss into useful cycle energy, while steam or water integration can support lower-emissions combustion and water recovery. However, these benefits introduce substantial mass, volume and control interactions involving electric machines, power electronics, heat exchangers, condensers, pumps, high-voltage distribution and cooling. SWITCH is therefore evolutionary in its basic turbofan architecture but potentially disruptive in the degree of propulsion-system integration required.

The first results from SWITCH are being published, such as the aerothermal performance of heat recovery heat exchanger (HEX) [49]. Their Aero–Thermo Analysis of a Waste Heat Recovery Heat Exchanger combines experiments and numerical simulation of a non-standard engine heat-exchanger configuration. Although the overall results agreed well, local discrepancies and sensitivity to baffle spacing, flow stability and pressure-loss distribution remained important, illustrating why heat recovery cannot be assessed independently of turbine-rear-structure aerodynamics and engine performance. A central result is how a relatively simple experimental set up at Chalmers University together with numerical simulations can reveal non-trivial insights for design of HEX configurations.

GKN Aerospace provides a concrete bridge between the propulsion architecture and qualification of its electrical integration. Within SWITCH, GKN contributes multifunctional engine structures capable of integrating electric machines and heat exchangers, supported by test capabilities in Trollhättan. It has also designed, assembled and tested high-voltage AC electrical wiring interconnection system—EWIS—harnesses for megawatt-class propulsion. The first harnesses were delivered in 2025 for powertrain-system testing at Collins Aerospace's Grid laboratory and are intended subsequently to support full-scale geared-turbofan demonstrator testing.

This progression is important because megawatt-class hybridisation requires the wiring, connectors, insulation, cooling, electromagnetic compatibility, fault protection and propulsion controls to be demonstrated as an integrated safety-critical system. EASA similarly identifies electrical generation, distribution, wiring, cooling and power management as parts of an electric or hybrid propulsion system whose certification boundaries may extend across the conventional aircraft–engine interface. SWITCH consequently supports the pathway table's distinction: hybridisation can extend a near-term SAF-compatible turbofan pathway, but deep dual-spool electrification and heat recovery remain disruptive integration technologies until their weight, reliability, thermal behaviour and means of compliance have been demonstrated at engine and aircraft level

4.3 DIAS—Development of Interdisciplinary Assessment for Manufacturing and Design

The DIAS project [50-53] was initiated by GKN as a Clean Aviation support project to develop enabling technologies. DIAS demonstrates that manufacturability must be addressed during propulsion-system conceptualisation rather than after the aerodynamic and structural configuration has been selected. Coordinated by Chalmers University of Technology and implemented from June 2020 to February 2023, DIAS developed multidisciplinary design tools for structural components associated with future open-rotor propulsion systems. GKN Aerospace acted as the industrial topic leader, ensuring that the methods were evaluated against realistic aero-engine manufacturing requirements.

DIAS is therefore best understood as an enabling technology for the propulsion pathways discussed above. Advanced concepts such as open fans, hybrid-electric engines and highly integrated turbine structures may offer substantial improvements in propulsion efficiency, but they also introduce unfamiliar geometries, loads, interfaces, materials and production requirements. A concept that appears attractive from an aerodynamic or weight perspective may be difficult to weld, assemble, inspect or industrialise. If these limitations are discovered only during detailed design, the result may be costly redesign, reduced performance, delayed qualification or abandonment of the technology.

To address this problem, DIAS connected function- and architecture-level models with generative CAD, automated simulation and interactive decision support . Alternative structural configurations and manufacturing concepts were generated systematically, after which robot access and weld-path feasibility could be evaluated for each candidate geometry. Mechanical performance, mass,

manufacturing lead time, cost and risk could consequently be compared within the same digital design experiment. The project reported that as many as 1,000 geometrical alternatives could be assessed concurrently, allowing feasible regions of the design space to be identified before major architectural commitments were made.

The project's scientific publications provide evidence for this approach. Isaksson et al. proposed and demonstrated a multi-domain conceptual-design framework in which functionally defined aerospace structures were converted into parametric geometries and assessed through welding-process simulation. The resulting measures of weld feasibility and production lead time were integrated with structural, cost and resilience information to support interactive trade-off decisions. The study explicitly argues that critical manufacturing processes must be assessed during conceptual design when radical aerospace technologies are being evaluated.

A second publication by Panarotto et al. [52] demonstrated how function–means models and Design Structure Matrices could be automated to generate multiple system architectures and transfer them to simulation tools. This enables designers to vary functions, physical solutions and their interconnections simultaneously, rather than evaluating only incremental modifications of a fixed product architecture. The approach is particularly relevant when new propulsion technologies create dependencies across component design, manufacturing processes, supply chains and system performance.

From GKN Aerospace's perspective as an aero-engine component manufacturer, DIAS illustrates why generative design, manufacturing-process simulation and automated trade-space exploration are critical technologies. Early quantitative understanding of weldability and production feasibility allows manufacturing constraints to be treated as design variables rather than late restrictions. This supports better-informed compromises between aerodynamic performance, structural mass, cost, producibility and risk. DIAS therefore strengthens the central argument of the preceding sections: disruptive propulsion solutions depend not only on proving their physical performance, but also on demonstrating that their critical structures can be manufactured, qualified and industrialised with acceptable risk.

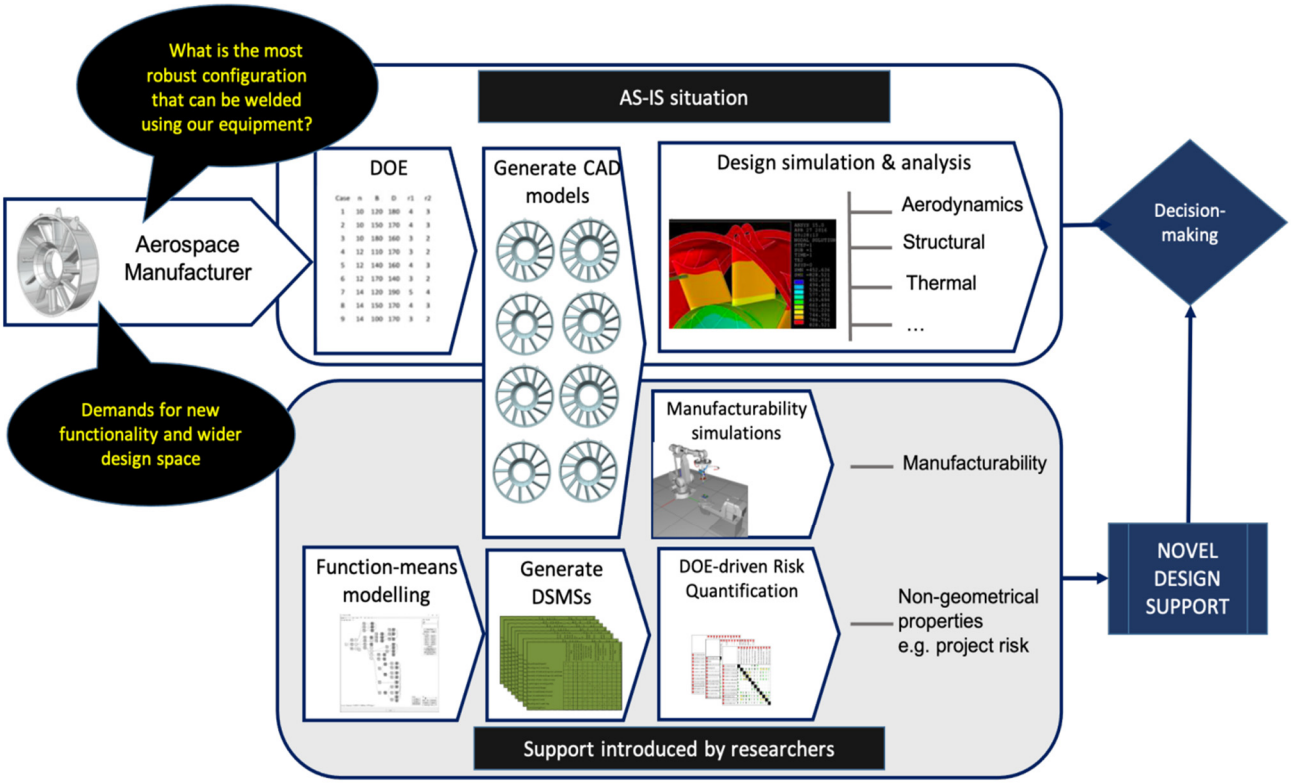


Figure 2 Including weldability of structural engine components as a part of conceptual studies, in DIAS

4.4 Forward looking

A recent prestudy on enabling technologies was EXPEED (Explorative the Potential Benefit of Systems Modelling State-of-the-art Design Tools) [54], funded through Swedish VINNOVA's national aeronautics programme NFFP, cross-fertilised systems-modelling and design tools from leading

aeronautics research actors in Europe and the USA, and fed into the European Aviation Research and Innovation Strategy (ARIS). Such capabilities matter because the decisive commitments in alternative propulsion are architectural and taken early, when maturity is low. The ability to model system-level impact and compare architectures under uncertainty is therefore an important enabling technology, complementing the physical hardware evaluation and demonstration activities.

The EXPEED study clarifies the potential of muti-domain technological approaches also to enabling technologies, such as design and evaluation methods and tools. Such enabling technologies are introduced in advanced propulsion technology demonstration projects in Sweden, such as SIJET - Swedish industrial capability for jet engines [55].

5 Concluding Discussion

Future aviation propulsion should not be understood as a sequence of isolated technology substitutions, but as a system transformation in which propulsion, energy carriers (i.e. what medium used to store and transform energy on the aircraft), aircraft architecture, manufacturing capability, operational use, maintenance, certification, and sustainability co-evolve. The review has shown that gas turbines, SAF, hybrid-electric systems, batteries, hydrogen combustion and fuel-cell propulsion each offer important opportunities, but that their value depends strongly on the aircraft segment, mission profile, energy infrastructure, certification pathway and industrial readiness into which they are introduced. In this sense, the decisive challenge is not only to mature individual technologies, but to mature the systems in which they can be useful, certifiable, manufacturable, maintainable, and advance sustainable development. This means that the potential of a novel technology must include its implications on the targeted system, or even systems of systems.

A central implication is that technology research must be more closely integrated with systems innovation. Component-level advances in turbomachinery, electric machines, fuel cells, cryogenic tanks, combustion, thermal management, structures and materials remain essential. However, their ultimate contribution to climate-neutral aviation can only be assessed when they are embedded in realistic propulsion and aircraft architectures. A high-efficiency electric motor, a lightweight hydrogen tank, an advanced combustor or an additively manufactured structure has potential, but that potential is realised only when the technology can be integrated into a system that delivers payload, range, safety, availability, cost, regulatory compliance and environmental benefit in actual operation. Hence, the scalability aspect of the technology must be included already on low TRL research.

This places new demands on aviation research and innovation programmes. Manufacturability, circularity, sustainability and MRO considerations should not be treated as downstream consequences after the main technology choices have been made. They need to be included much earlier as design drivers. Future propulsion systems will introduce new materials, new degradation mechanisms, new repair needs, new safety cases, and new end-of-life challenges. Batteries, fuel cells, high-voltage electrical systems, hydrogen storage, cryogenic distribution and advanced thermal-management systems will all require new approaches to inspection, health monitoring, modular replacement, repair, remanufacturing and lifecycle assessment. Similarly, additive manufacturing and advanced materials should be evaluated not only for weight and performance, but also for production scalability, quality assurance, repairability, resource use and circular value creation. What is sometimes referred to as enabling technologies need to be co-developed to ensure desired impact to the right time and cost.

Knowledge development must therefore become more integrated across the full innovation chain. Research is needed to identify which technologies should be put forward, how they should be designed, how they should be combined into propulsion and aircraft architectures, how they can be manufactured at industrial scale, and how they can be sustained through long operational lives. This calls for closer coupling between fundamental research, modelling, component development, system integration, demonstrator testing, certification evidence, production engineering and MRO knowledge. In practice, technology maturation and knowledge maturation are the same process: a technology becomes credible only when the surrounding knowledge base is strong enough to support design decisions, qualification, certification, industrialisation and through-life operation. The operative demands, driven by both technological and societal development, further impact the conditions, under which technologies are developed. A good example is the servitisation, where e.g. Rolls Royce power-by-the-hour concept changed incentives and conditions for the manufacturer. The digitalisation in society, including AI, affect most aspects of society – including transport behaviour and solutions.

The aviation transition is therefore system-transformative rather than merely technology-driven. No

single pathway will solve the challenge. SAF and advanced gas turbines will remain central for existing fleets and larger aircraft. Hybrid-electric architectures may provide benefits where power redistribution, operating-point optimisation or distributed propulsion offset their added complexity. Battery-electric propulsion will be relevant mainly for short-range and low-energy missions. Hydrogen fuel cells may become attractive for commuter and regional aircraft if storage, if cooling and power-density challenges are solved. Hydrogen combustion may scale further, but only with major changes in airframe layout, fuel systems, infrastructure, safety assurance and certification. These pathways are not mutually exclusive; they form a heterogeneous technology and systems landscape.

For the business and research ecosystem, the strategic task is therefore to master this heterogeneity. Future competitiveness will depend on the ability to combine propulsion technologies, aircraft architectures, manufacturing systems, maintenance models, infrastructure assumptions and sustainability evidence into robust solutions for different market segments. This requires research programmes that deliberately connect technology development with system integration and industrial deployment. It also requires collaboration across universities, research institutes, OEMs, suppliers, operators, airports, regulators and MRO organisations. Only through such integrated efforts can promising technologies move from laboratory potential to operational climate benefit.

The concluding message is that future propulsion research should be framed less as a search for “the” winning technology and more as the development of the capability to design, integrate, manufacture, certify, operate and sustain multiple propulsion solutions. The technologies themselves are necessary, but not sufficient. Their real value emerges when they are embedded in viable aviation systems and used at scale. Engaging certification authorities already in research, such as EASA in European Research projects directly is a good example of such action. It can be argued that other enabling technologies, such as for manufacturing and overhaul, will be more tightly integrated in propulsive programs and projects.

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