TURNING BLUE SKIES GREEN

POLICY, TECHNOLOGY AND THE FUTURE OF AVIATION

Abstract

Aviation contributes a relatively small share of global greenhouse gas emissions, yet its environmental impact is disproportionately high due to high-altitude effects such as contrails, cirrus cloud formation and complex atmospheric interactions driven by NO_x emissions. As air traffic continues to expand, the sector faces increasing pressure to align with global climate goals included in the Paris Agreement. While much of the decarbonization focus remains on sustainable fuels and next-generation aircraft, this article highlights Maintenance, Repair and Overhaul (MRO) as a critical and often overlooked driver of emissions across the aircraft lifecycle.

The paper examines how maintenance practices directly influence fuel efficiency through engine performance restoration, aerodynamic integrity and weight management. Even marginal degradation in engine or airframe condition leads to measurable increases in fuel burn and emissions. However, timely and optimized maintenance can recover efficiency and reduce environmental impact. The study explores how digital technologies enable predictive and condition based maintenance. This approach serves as a key enabler for minimizing degraded operations, cutting unnecessary test flights and enhancing system efficiency. The study moves beyond operational performance to evaluate the lifecycle impact of aircraft replacement decisions. This analysis weighs the extension of existing aircraft life against new, efficient models by considering both operational and embedded carbon costs. It further examines sustainability within MRO operations, including green infrastructure, eco-friendly materials, additive manufacturing and circular economic practices. The role of regulatory frameworks in shaping environmentally responsible maintenance is analysed, alongside the unique challenges of implementing emissions controls in military aviation, where operational readiness takes precedence.

The article concludes that MRO is not merely a support function but a strategic lever for aviation decarbonization, influencing emissions across manufacturing, operations and end-of-life phases. A holistic, data driven and sustainability focused approach to aircraft maintenance is essential in achieving meaningful and sustained reductions in aviation’s environmental footprint.

Introduction

Aviation contributes a small share of global greenhouse gases, but its impact is disproportionately high because of emissions occurring at high altitudes. Aircraft release CO_2, NO_x and water vapour thereby forming contrails and cirrus clouds that trap more heat than they reflect. Thereby, creating a net warming effect causing positive radiative forcing i.e. the earth system is gaining more energy than it is losing. In short positive radiative forcing will cause warming and negative forcing will cool. These emissions also change atmospheric chemistry. Nitrogen Oxides, NO_x raise ozone (a strong greenhouse gas) while reducing methane, leading to complex climate effects. As air traffic grows, these aviation-specific impacts accelerate warming, ice melt and extreme weather. This puts pressure on the sector to meet goals like the Paris Agreement through solutions such as sustainable aviation fuels, better aircraft efficiency and improved maintenance practices.

Aviation's climate challenge is typically framed around new fuels, new aircraft design and new propulsion systems. Yet Maintenance, Repair & Overhaul (MRO) sits at the heart of emissions performance across an aircraft's entire lifecycle. MRO determines whether aircraft is operating at peak efficiency, how long they remain in service, how often they burn excess fuel and when they should be upgraded or retired. Therefore, poor maintenance causes instant increase in emissions, whereas smart sustainment programs reduce emissions consistently over the life cycle. Fuel-burn accounts for ~98–99% of aviation's direct CO_2 emissions and Maintenance condition strongly affects fuel efficiency.

Engine Performance Degradation

Jet engines gradually lose efficiency over time due to factors like compressor fouling, turbine erosion, seal wear and increased blade tip clearances. Among these, compressor fouling is a key driver of fuel inefficiency and higher emissions. If not corrected during scheduled overhauls, specific fuel consumption (SFC) increases, meaning the aircraft burns more fuel to produce the same thrust. Regular engine maintenance, repair and overhaul (MRO) by OEMs help restore engine performance and recover lost efficiency. Practices like on-wing washing and predictive monitoring are essential for both cost control and sustainability. Even small improvements of 1% gain in engine efficiency can cut fleet-level CO_2 emissions by millions of tons annually for large operators.

Aerodynamic Efficiency

Maintenance directly affects aerodynamic drag through factors like surface roughness, panel misalignment, damaged fairings, seal degradation and paint condition. When these are not properly maintained, parasitic drag increases, forcing engines to burn more fuel to maintain performance. Modern aircraft like the Boeing 787 Dreamliner and Airbus A350 rely on precise composite surface integrity for optimal aerodynamic performance. However, poor structural or surface maintenance can degrade this advantage. Increase in drag will reduce fuel efficiency, in turn, leading directly to higher fuel burn and increased emissions.

Weight Management

Maintenance plays a key role in aircraft weight management through decisions on replacement parts, cabin reconfigurations, structural reinforcements, and corrosion repairs. If not carefully controlled, these can gradually add unnecessary weight to the aircraft. Even small increase matter, excess weight raises fuel burn on every flight. For high-utilization fleets, an added 100 kg can translate into significant extra fuel consumption annually, increasing both operating costs and emissions.

Predictive Maintenance Reduces Emissions

Predictive maintenance enables aircraft systems to be serviced based on actual condition rather than fixed schedules, using sensor data and analytics to detect inefficiencies early. This approach improves operational efficiency by identifying performance degradation like, engine inefficiency or component wear, before it leads to excessive fuel burn. Studies show that predictive maintenance frameworks using remaining useful life (RUL) analysis and real-time monitoring can optimize maintenance timing, reduce unplanned downtime and enhance overall system efficiency. By ensuring that engines and aerodynamic surfaces operate at optimal performance, predictive maintenance directly reduces fuel consumption and thereby lowers greenhouse gas emissions, making it an important enabler of sustainable aviation.

Digital MRO Transformation as a Climate Tool

The digital transformation of Maintenance, Repair and Overhaul (MRO) through AI, data analytics and connected systems is increasingly being recognized as a climate enabler rather than just an operational upgrade. Digital MRO integrates predictive analytics, real-time health monitoring and data-driven decision-making for optimizing aircraft performance and maintenance cycles. Research highlights that AI-driven predictive analytics and intelligent transportation systems are being developed specifically to support sustainability goals, including carbon emission reduction in aviation. By reducing unnecessary maintenance, preventing performance degradation, and enabling efficient resource utilization across the fleet, digital MRO systems help minimize fuel burn and operational inefficiencies. As a result, MRO is evolving from a support function into a strategic tool for emissions management and environmental compliance.

Condition-Based Maintenance (CBM)

Modern aircraft use sensors to monitor engine vibration, temperature, fuel flow, and oil debris, enabling early detection of performance degradation before it becomes critical. This data-driven approach supports predictive maintenance, reducing downtime and improving efficiency. Advanced platforms like the F-35 Lightning II and commercial fleets using systems from Airbus increasingly rely on such smart sustainment to optimize performance and control costs.

Predictive and efficient maintenance delivers clear emission benefits by avoiding operation in degraded states, where engines burn more fuel than necessary. It also reduces the need for maintenance-related flights and minimizes unscheduled disruptions, all of which help lower overall fuel consumption and emissions while improving operational efficiency by Reduced Ground Running and Test Flights

Efficient diagnostics

Efficient diagnostics are central to green aircraft MRO, as advanced health monitoring and data-driven fault isolation reduce the need for prolonged engine ground runs and repetitive post-maintenance check flights. By accurately identifying and rectifying issues on the ground, maintenance teams can minimize trial-and-error testing and avoid unnecessary airborne validation sorties. Each avoided test flight translates directly into reduced fuel burn, lower CO_2 emissions, and decreased operational strain, making diagnostic precision not just a technical advantage but a tangible environmental benefit in modern aviation sustainment. Each avoided test flight directly prevents fuel burn and CO_2 emissions.

Lifecycle Decisions: The Sustainability Trade-Off

Lifecycle decisions in aircraft MRO sit at the heart of the sustainability trade-off, as maintainers must choose whether platforms are retained and upgraded, overhauled, converted or retired based on both operational value and environmental impact. Approaches like condition-based maintenance and predictive maintenance enable more informed decisions by revealing true asset health and remaining useful life, helping avoid premature retirement while also preventing inefficient operation of degraded systems. Retaining or upgrading aircraft can conserve the embedded energy and materials of existing platforms, while overhauls and conversions extend service life with targeted improvements. Conversely, timely retirement of inefficient or high-emission aircraft avoids disproportionate fuel burn and maintenance overheads. In this balance, data-driven MRO ensures that lifecycle choices are not just cost-effective, but aligned with emission reduction and sustainable aviation goals. Extending Aircraft Life vs Replacing with New Models

Older aircraft typically burn more fuel, operate with less efficient engines, and emit higher CO_2 per seat-kilometre, making them environmentally less sustainable in day-to-day operations. However, replacing them is not a straightforward decision, as manufacturing new aircraft carries a significant embodied carbon cost from material extraction, production, and supply chains. This creates a sustainability trade-off where lifecycle emissions must be carefully balanced. In many cases, modern replacements such as the Airbus A320neo or Boeing 737 MAX offer a compelling advantage, delivering approximately 15–20% lower fuel burn through advanced aerodynamics and more efficient engines. Consequently, the decision to replace older fleets must weigh immediate operational emission reductions against the long-term carbon cost of new production, ideally guided by data-driven MRO and lifecycle analysis.

Sustainable MRO Operations

Sustainable MRO operations are increasingly critical as maintenance facilities themselves contribute to emissions through energy-intensive hangars, chemical treatments, paint stripping and repainting, and the generation of hazardous and non-hazardous waste. Traditional processes often rely on high energy consumption and environmentally taxing materials, making MRO not just a support function but a direct part of aviation’s environmental footprint. Integrating greener practices—such as safer chemical alternatives, waste minimization, and optimized maintenance planning enabled by predictive and condition-based approaches—can significantly reduce unnecessary resource use and emissions, aligning aircraft upkeep with broader sustainability goals.

Green Hangars and Energy Efficiency

Green hangars and energy-efficient infrastructure represent a practical pathway to lowering this footprint. Modern MRO facilities are increasingly adopting solar installations to offset grid dependence, transitioning to LED lighting for substantial energy savings, and deploying electric ground support equipment to cut local emissions and noise. These measures, combined with smarter energy management systems, transform maintenance bases into more sustainable ecosystems, reducing operational costs while supporting the aviation sector's push toward lower carbon intensity.

Sustainable Materials & Processes

Sustainable materials and processes are reshaping aircraft MRO by reducing the environmental impact of routine maintenance activities. The shift toward water-based coatings and reduced volatile organic compound (VOC) chemicals minimizes harmful emissions and improves workplace safety, while advanced corrosion inhibitors extend component life and reduce the frequency of replacements. Together, these innovations lower the overall chemical footprint of maintenance operations and align MRO practices with stricter environmental standards, without compromising aircraft performance or durability.

Additive Manufacturing

Additive manufacturing, commonly known as 3D printing, further strengthens sustainability in MRO by enabling on-demand production of parts with significantly less material waste compared to traditional subtractive methods. It also reduces logistics-related emissions by minimizing the need to transport spares across long supply chains, as components can be produced closer to the point of use. Additionally, the ability to design and manufacture lighter parts contributes to improved fuel efficiency over the aircraft's lifecycle, reinforcing the role of advanced manufacturing in driving greener aviation maintenance.

Engine Overhaul Cycles and Emissions Timing

Engine overhaul cycles directly influence when and how emissions are generated across an aircraft's life. Delaying an overhaul can keep an engine operating in a degraded state, increasing fuel burn and CO_2 output, while conducting it too early drives unnecessary material use, resource consumption, and embedded carbon from parts and processes. The optimal point lies in balancing timely recovery of fuel efficiency with cost considerations and overall environmental impact. This is where digital lifecycle modeling becomes central—by combining real-time condition data with predictive analytics, it identifies the most efficient intervention window, ensuring engines are neither overused nor over-maintained, thereby minimizing total lifecycle emissions while sustaining operational effectiveness.

Role of Regulators

Regulators play a decisive role in driving green aircraft operations and maintenance by setting standards, enforcing compliance, and shaping incentives that align safety with environmental performance. Bodies such as the International Civil Aviation Organization, European Union Aviation Safety Agency, and national authorities like Directorate General of Civil Aviation establish the regulatory ecosystem within which MRO operates. Traditionally, regulations such as EASA Part-145 focus on safety, quality systems, and compliance, requiring approved procedures, traceability, and controlled maintenance environments . However, regulators are increasingly integrating environmental objectives—through emissions standards, reporting frameworks, and operational guidance—into these rules. At the global level, ICAO develops Standards and Recommended Practices (SARPs) on emissions and environmental protection, while initiatives like CORSIA mandate monitoring, reporting, and verification (MRV) of CO_2 emissions, ensuring transparency and accountability across operators . Importantly, ICAO recognizes that operational measures—including maintenance practices—directly influence fuel burn and emissions, placing MRO within the regulatory scope of environmental performance.

From a policy perspective, regulators can implement several targeted measures to ensure greener MRO. First, they can mandate emissions-linked maintenance standards, such as requiring engine performance monitoring, limits on degraded operation, and adoption of predictive maintenance to minimize fuel inefficiency. Second, regulations can enforce green certification of MRO facilities, including energy efficiency benchmarks, waste management protocols, and restrictions on high-VOC chemicals. Third, digital reporting requirements—similar to CORSIA's MRV framework—can be extended to maintenance-induced emissions, creating accountability for ground operations. Fourth, regulators can incentivize sustainable materials and processes, such as water-based coatings or additive manufacturing, through certification credits or tax benefits. Fifth, lifecycle-based policies can guide optimal overhaul and retirement decisions, ensuring aircraft are neither prematurely replaced nor inefficiently retained. Some of these elements already exist in fragmented form: ICAO's environmental standards (Annex 16), CORSIA's emissions accounting, and EASA's structured oversight of maintenance organisations provide the regulatory backbone. The next step for regulators is integration—embedding sustainability explicitly into airworthiness and MRO regulations so that environmental performance becomes as auditable and enforceable as safety itself.

Military Aviation Perspective

From a military aviation perspective, emissions management is inherently difficult to regulate because operational imperatives consistently override environmental considerations. Combat aircraft operate in highly dynamic conditions—high thrust regimes, afterburner use, low-level penetration, and rapid response sorties—all of which are fuel-intensive by design. Unlike civil aviation, where schedules and routes are predictable, military flying is irregular and threat-driven, making standardized emissions benchmarks or limits impractical. Fleet diversity further complicates matters, with legacy and modern platforms operating simultaneously, often under different maintenance philosophies. In such an environment, even maintenance decisions—like delaying or advancing overhauls—are guided more by mission readiness than by fuel efficiency or emission optimization.

This makes the formulation and enforcement of regulations particularly challenging. Civil regulatory bodies such as the International Civil Aviation Organization, European Union Aviation Safety Agency, and Directorate General of Civil Aviation primarily govern commercial aviation, while military aviation remains largely outside their direct jurisdiction. Frameworks like Annex 16 and CORSIA are not binding on armed forces, and even where adopted in spirit, verification and transparency are constrained by security and confidentiality concerns. Emissions data, sortie profiles, and engine performance parameters are often classified, limiting the feasibility of monitoring, reporting, and verification (MRV) systems that are standard in civil aviation. Additionally, imposing rigid environmental compliance risks unintended consequences—such as reduced training realism or delayed mission response—which are unacceptable in a defence context.

As a result, regulating military aviation emissions requires a fundamentally different approach—one that is flexible, internally driven, and capability-sensitive rather than externally enforced. Instead of strict regulations, defence forces tend to adopt policy guidelines and best practices, selectively drawing from civil frameworks where operationally feasible. Measures like predictive maintenance, efficient ground operations, green MRO infrastructure, and lifecycle optimization can be implemented without compromising readiness. However, the core difficulty remains: any regulatory construct must accommodate the unpredictable, high-stakes nature of military operations. Therefore, progress in this domain is likely to come not from prescriptive regulation, but from incremental integration of sustainability into doctrine, technology, and maintenance philosophy, ensuring that environmental responsibility evolves alongside, rather than in opposition to, operational effectiveness.

Conclusion

In conclusion, aircraft emissions must be viewed across the entire lifecycle rather than only during flight operations. While operational fuel burn constitutes the largest share, significant emissions are also embedded in manufacturing, generated through maintenance activities, and released during end-of-life disposal or recycling. This holistic perspective highlights that sustainability in aviation is not confined to efficient flying alone, but is equally dependent on how aircraft are built, maintained, and retired. Therefore, meaningful emission reduction requires an integrated approach—combining efficient operations, data-driven MRO practices, sustainable materials and processes, and informed lifecycle decisions to minimize the overall environmental footprint of aviation.