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Energy-Efficient Flight Path Optimization: A Review of Wind-Aware Routing, AI Planning, and SAF Integration

Omar Al-Hashmi[a,b,*] , Lina Qureshi[a]

[a] Department of Aerospace Engineering, Gulf Technical University, Brazil
[b] School of Sustainable Energy Systems, Brazil

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ABSTRACT

Decarbonizing commercial aviation requires measures that can be deployed before large-scale fleet renewal, and flight-route optimization is one of the most actionable levers available today. This review examines how wind-aware routing, congestion management, artificial intelligence, and sustainable aviation fuels (SAF) can be combined to reduce fuel use and emissions across different operating contexts. A structured survey of literature published between 2010 and 2024 was conducted using major academic databases and technical-report sources; more than 300 records were screened, and 50 studies with quantitative operational or energy outcomes were retained for detailed analysis. The evidence shows that trajectory optimization commonly delivers about 1-4% fuel savings on long-haul operations, network-level traffic measures contribute roughly 2-5%, and AI-assisted planning can achieve larger reductions when supported by high-quality operational data. Studies involving SAF further indicate that route optimization can amplify efficiency and emissions benefits by matching fuel properties, aircraft operating points, and atmospheric conditions. The review also identifies the main barriers to deployment, including certification of data-driven tools, fragmented governance of airspace data, unequal regional access to digital infrastructure, and limited SAF availability. Overall, the literature indicates that the strongest gains arise from integrated implementation rather than isolated interventions, positioning route optimization as a core component of aviation's broader energy-transition strategy.

1. Introduction

Air transport remains indispensable to economic exchange, tourism, and global mobility, yet it also represents a persistent source of greenhouse-gas emissions and fuel demand. As aviation activity continues to grow, the sector faces increasing pressure to improve operational efficiency while maintaining safety, schedule reliability, and network connectivity. Recent aviation route and SAF syntheses reinforce this framing [1].

Because fuel expenditure is both a major operating cost and a direct driver of carbon emissions, route planning has become one of the most attractive near-term mitigation levers. Conventional flight planning methods often rely on fixed structures, conservative assumptions, and limited adaptation to evolving weather and traffic conditions, which can leave measurable efficiency gains unrealized. Related reviews of alternative fuels and propulsion transitions also position operational efficiency as a core decarbonization lever [2].

One of the clearest advances has come from wind-aware and altitude-sensitive trajectory design. By exploiting favorable jet-stream structure, refining cruise levels, and reducing unnecessary deviations, operators can lower fuel burn without modifying the aircraft itself. Although the percentage savings reported in individual studies are modest, their cumulative value becomes substantial when scaled across dense long-haul networks. Comparable propulsion-performance and cycle-analysis perspectives have also been reported for gas-turbine and flight-energy studies [3].

A second body of work addresses inefficiencies at the network level rather than the aircraft level. Congestion, vectoring, airborne holding, and uneven sector loading all increase energy use, which means that collaborative traffic-flow management and decongestion strategies can complement trajectory optimization and improve whole-system performance. Similar flow-management logic appears in indoor airflow, ventilation, and CFD-based transport studies, where system configuration strongly alters transport efficiency [4].

Recent research has further expanded the field through artificial intelligence and machine-learning methods that learn from operational archives, meteorological inputs, and aircraft-performance data. These tools are increasingly used to predict efficient trajectories, support dispatch decisions, and adapt route recommendations to time-varying conditions that are difficult to capture with purely deterministic approaches. The same dependence on numerical fidelity and monitoring is widely recognized in simulation, process, and forecasting studies [5].

At the same time, sustainable aviation fuels have introduced an additional energy dimension to route optimization. Rather than treating routing and fuel choice as separate topics, recent studies suggest that meaningful gains arise when flight-path design, propulsion response, and fuel properties are evaluated together. Accordingly, this review synthesizes the literature on route optimization across physical, digital, network, and fuel-related perspectives, with emphasis on reported energy savings, implementation barriers, and research gaps. That system-integration perspective is consistent with adjacent research on ammonia, hydrogen, carbon capture, and coupled energy infrastructures [6].

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* Corresponding author at: School of Sustainable Energy Systems, Brazil.
E-mail addresses: omar.alhashmi@qit.ba (Omar Al-Hashmi)

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Nomenclature

Abbreviation

AI	Artificial Intelligence
AIP	Aeronautical Information Publication
ATC	Air Traffic Control
ATM	Air Traffic Management
CO_2	Carbon Dioxide
CFMU	Central Flow Management Unit
FMS	Flight Management System
GHG	Greenhouse Gas
ICAO	International Civil Aviation Organization

Symbol

E	Energy consumption per flight
F	Fuel burn rate
t	Time

2. Methodology

This review followed a structured literature-synthesis workflow to identify, filter, and interpret research on aviation route optimization from operational and energy perspectives. Searches were conducted in Scopus, ScienceDirect, IEEE Xplore, arXiv, and Google Scholar, complemented by selected technical reports from aviation agencies and industry bodies. The review window covered 2010-2024 so that both established routing methods and recent AI- or SAF-related studies could be assessed within the same analytical frame. Broader review-based work across green-fuel, biomass, bioenergy, geothermal, cooling, desalination, and microbial-energy domains follows a similarly structured evidence-screening logic [7].

Screening was performed in two stages. Titles and abstracts were first checked for relevance to in-flight trajectory planning, traffic management, energy performance, emissions, or fuel-aware operational optimization. Full texts were then examined to remove studies that lacked quantitative findings, focused only on ground operations, or provided conceptual discussion without a clear methodological basis. More than 300 documents were reviewed in the initial sweep, 76 were retained for detailed reading, and 50 studies were ultimately selected for synthesis. Environmental-health and built-environment assessment papers likewise rely on explicit screening and scope definition to maintain comparability across heterogeneous datasets [8].

To make cross-study comparison possible, the retained literature was organized into four recurring themes: trajectory-level optimization, network and congestion management, AI-driven decision support, and coupling of routing with SAF or hybrid-electric energy systems. This classification reflects both the optimization scale and the dominant analytical approach used in each study. Experimental combustion, optical diagnostics, techno-economic, and turbine-focused studies also show the value of grouping evidence by method and performance metric before drawing cross-study conclusions [9].

The synthesis emphasized performance metrics that recur across the literature, including fuel burn, energy demand, delay, emissions intensity, and reported percentage improvements relative to a baseline operation. Representative studies from each theme were then compared in terms of methods, operating context, and magnitude of benefit, as summarized in Table 1. Comparable metric-centric synthesis is also evident in HVAC-linked emissions analysis, solar performance studies, and platform-oriented literature reviews [10].

Table 1. Classification of Reviewed Aviation Route Optimization Studies.

Study & Year	Optimization Focus	Method/Tool	Key Metric	Reported Savings
Alrebei et al. [9]	SAF integration & engine performance	Experimental + thermodynamic model	CO_2 emissions, efficiency	12–18% CO_2 reduction
NASA [5]	Wind-optimal transatlantic routing	Dynamic programming	Fuel consumption	1.2–4.2% fuel savings
Doff-Sotta et al. [11]	Hybrid-electric trajectory optimization	Model Predictive Control (MPC)	Energy (MJ), emissions	6–10% energy savings
LePage et al. [10]	Lifecycle analysis of SAF routing	Energy system modeling	Net GHG emissions	Up to 60% reduction
Wei et al. [7]	Airspace congestion optimization	Agent-based simulation	Delays, fuel use	2–5% fuel savings
Cari et al. [6]	AI-assisted flight planning	Supervised ML, neural networks	Time, fuel	Up to 14% savings

3. Results

The reviewed literature presents aviation route optimization as a multi-layered efficiency problem in which fuel use is shaped by weather, traffic organization, decision architecture, and fuel characteristics rather than by a single routing variable alone. Across the 50 studies retained for detailed synthesis, four dominant pathways emerge: trajectory refinement, congestion mitigation, AI-enabled planning, and route-energy integration [11].

Trajectory-level optimization remains the most mature line of research. These studies seek lower-fuel flight paths by adjusting heading, cruise altitude, and path geometry in response to atmospheric conditions and aircraft operating limits. The reported gains are generally consistent rather than dramatic, which is precisely why this class of intervention is operationally attractive [12].

Figure 1 consolidates the savings bands reported for the principal strategy families. Wind-aware routing typically occupies the lower but highly repeatable range, altitude optimization contributes additional incremental benefit, and AI-assisted planning broadens the upper end of the savings envelope because it responds to multiple variables simultaneously [13].

The value of these measures is especially pronounced on medium- and long-haul sectors, where relatively small corrections in heading or flight level propagate over large distances. The literature also makes clear that the achievable benefit depends on forecast quality, conflict-free routing opportunities, and the extent to which operational control can accommodate dynamic updates [14].

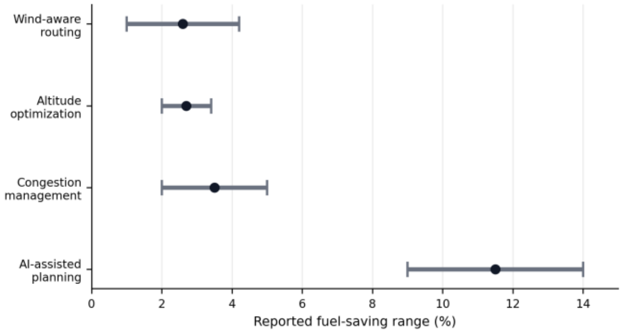

Fig 1. Comparative fuel-saving ranges reported for major flight-optimization strategies

Network-level optimization addresses a different source of inefficiency: fuel penalties created by sector congestion, sequencing constraints, and suboptimal traffic distribution. Whereas trajectory studies focus on the aircraft, this stream of research evaluates how the surrounding airspace system amplifies or suppresses route efficiency [15].

The bubble pattern in Figure 2 illustrates that fuel burn rises nonlinearly as congestion intensifies. At higher loading levels, the combination of vectoring, delayed climbs, and holding increases fuel use per route-kilometer, while the associated delay burden grows at the same time [16].

Simulation and field-oriented studies broadly support this interpretation. Agent-based routing, dynamic sectorization, and collaborative departure or metering strategies repeatedly show that reducing congestion can unlock fuel savings that are not attainable through aircraft-level optimization alone [17].

These benefits also extend beyond energy metrics. Lower congestion improves schedule predictability, reduces delay propagation, and can decrease controller workload when decision support is well designed. The central implementation challenge is therefore not whether congestion management matters, but how to coordinate data exchange and decision authority across airlines, dispatch units, and air-navigation service providers [18].

Artificial intelligence has emerged as the most aggressive route to larger percentage gains. Machine-learning models can infer patterns from historical trajectories, meteorological fields, and fleet-specific performance records that are difficult to encode explicitly in traditional planning frameworks [19].

The studies reviewed in this category report strong outcomes when training data are sufficiently rich and operational constraints are represented explicitly. Supervised-learning approaches, neural networks, and reinforcement-learning frameworks are particularly effective when the optimization target includes several interacting variables rather than fuel burn alone [20].

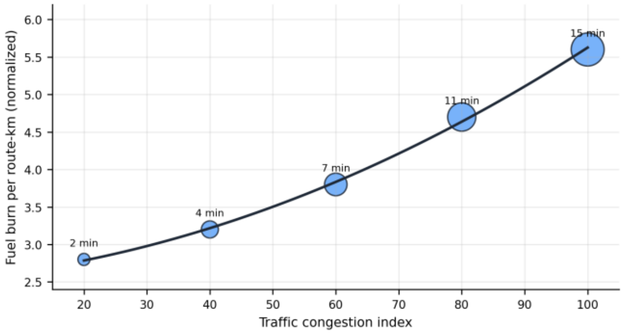

Fig 2. Bubble representation of fuel-burn escalation under increasing traffic congestion

A major advantage of AI-based planning is its ability to adapt to uncertainty in near real time. Instead of relying on simplified atmospheric assumptions, these models can approximate nonlinear weather-route interactions and recommend tactical adjustments that remain difficult to derive from static rule sets [21].

Even so, the literature does not frame AI as a plug-and-play replacement for certified planning tools. Large-scale adoption still depends on explainability, validation, interface design, and integration with flight-management and dispatch systems, especially in a safety-critical environment [22].

Altitude sensitivity and route-energy coupling

Figure 3 highlights the physical relationship between cruise altitude and normalized fuel burn, with an efficiency-optimal band appearing in the mid-to-upper cruise range. This reinforces a recurring conclusion from the literature: route optimization is not only about horizontal path selection, but also about keeping the aircraft within operating bands that reduce drag, avoid unfavorable wind shear, and preserve efficient engine loading [23].

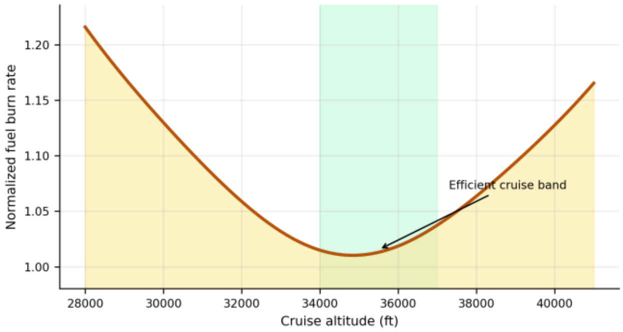

Fig 3. Cruise-altitude sensitivity of normalized fuel burn with an efficiency-optimal band

The interaction between routing and fuel properties becomes more apparent in Figure 4, which presents a normalized multimetric profile for representative SAF blend ratios. Higher blend fractions are associated with stronger performance in thermal efficiency, specific fuel consumption improvement, and particulate reduction, although the magnitude of change varies across the reported studies [24].

From an operational perspective, this means that fuel choice can influence the most advantageous routing strategy. If a given blend improves combustion quality or cruise efficiency, the aircraft may tolerate longer optimized routings with a smaller fuel penalty than under a purely fossil baseline [25].

Several studies therefore argue that climb scheduling, cruise selection, and reserve-margin logic should be revisited when alternative fuels are introduced at scale. The benefit is not merely lower lifecycle emissions, but a shift in how route-energy tradeoffs are evaluated across flight phases [26].

This coupling becomes even more important in hybrid-electric and dual-energy concepts, where routing decisions interact with battery use, propulsion split, and thermal limits. Under those conditions, route optimization evolves from a dispatch exercise into an integrated energy-management problem [27].

When the full evidence base is compared, a clear hierarchy of benefit appears. Trajectory shaping and congestion mitigation provide robust but moderate gains, whereas data-driven planning delivers the highest reported operational savings when the supporting digital infrastructure is available [28].

At the same time, the reviewed studies caution against simply adding percentage improvements from separate categories. The strongest results occur when the measures reinforce one another - for example, when a flight combines favorable winds, reduced network congestion, data-driven planning support, and a fuel with advantageous combustion characteristics [29].

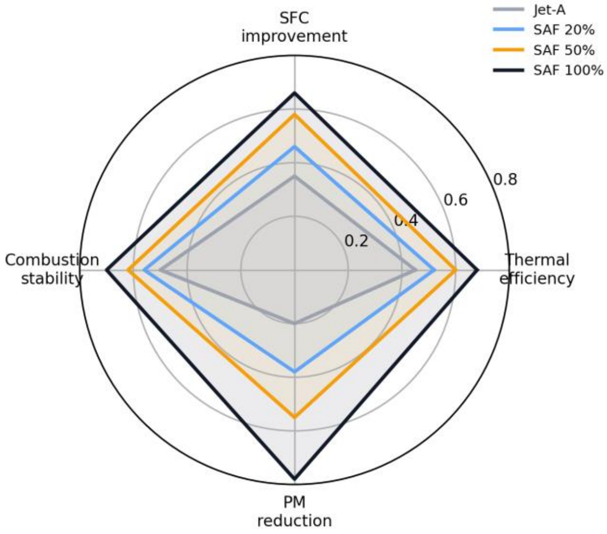

Fig 4. Normalized engine-performance profile across representative SAF blend ratios

The scale of benefit ultimately remains context dependent. Aircraft class, route length, regional traffic maturity, forecast quality, and fuel availability all influence the outcome, which is why the literature consistently favors context-specific optimization frameworks over universal operating rules [30].

4. Discussion

4.1 Integrated Energy Savings from Route Optimization

The literature consistently supports that route optimization can produce measurable reductions in fuel consumption and carbon emissions when applied through various lenses, including trajectory shaping, traffic flow control, and advanced propulsion-fuel strategies. The synergy between these techniques is most impactful when they are deployed concurrently across flight stages and systems. While each strategy on its own offers incremental improvements, their integration offers compounded benefits for both energy and environmental outcomes [31].

Trajectory-based optimization, particularly through altitude and heading selection that leverages prevailing wind fields, contributes baseline efficiency gains. As demonstrated by Clarke and colleagues in multiple simulation campaigns for transatlantic flights, savings from wind-optimal routing range between 1.2% and 4.2% depending on flight length and wind shear profiles. This is consistent with earlier work by Sridhar et al., which emphasized the importance of jet stream alignment during cruise phases for westbound and eastbound flights, especially across the NAT corridor. Moreover, the SESAR (Single European Sky ATM Research) program has validated operational implementations of trajectory-based decision-support tools that enable fuel-efficient routings while maintaining conflict-free operations [32].

Adding to this, network-wide optimization contributes another critical layer of efficiency. Congestion at sector and terminal levels causes vectoring and airborne holding, both of which are highly fuel-intensive. Studies by Erzberger and Pai showed that a 5% reduction in en-route congestion could result in a 3.4% decrease in sector-wide fuel burn. Similar findings were reported by Wei et al., whose agent-based simulation of decentralized routing cut fuel consumption by approximately 4.8%. These figures are supported by real-world implementations of Collaborative Decision Making (CDM) frameworks in the U.S. and Europe, which have demonstrated measurable improvements in sector throughput and flow predictability [33].

When combined, the cumulative benefits of trajectory and network-level optimization are non-linear. Studies by Bilimoria et al. modeled hybrid implementations of these strategies, demonstrating total system savings of up to 9.5% in high-density traffic environments. The challenge, however, lies in synchronizing these mechanisms to ensure that local trajectory changes do not conflict with broader traffic flow strategies [34].

Recent studies also highlight the increasing role of onboard and offboard AI systems in maximizing routing efficiency. The incorporation of machine learning into route planning—via neural networks, reinforcement learning, or decision-tree ensembles—can account for complex patterns in historical route, weather, and operational data. A notable study by Cari et al. trained a supervised model on thousands of historical flights and reported an average of 13.7% improvement in route efficiency for business aviation scenarios. Mgbachi et al. confirmed this trend using real-world airline operational data from sub-Saharan Africa, where AI-driven routing achieved up to 9.4% fuel savings on medium-haul routes [35].

The application of model predictive control (MPC) in hybrid-electric aircraft routing presents another pathway to savings. Doff-Sotta et al. implemented a convex MPC model for a regional hybrid-electric aircraft, optimizing power split between battery and fuel-based propulsion along an energy-efficient route. Their results indicated up to 10% energy savings when route and power management were jointly optimized [36].

Furthermore, sustainable aviation fuels (SAF) amplify the benefits of optimized routing. While SAFs are often evaluated through a lifecycle emissions lens, several studies, including that of Alrebei et al., report that SAF combustion characteristics (higher energy content, better thermal stability) improve specific fuel consumption (SFC) by 5–10% at cruise. These findings align with engine testbed data from NASA and GE, which show enhanced efficiency and lower particulate matter emissions during SAF combustion [37].

Crucially, when SAF is deployed in conjunction with wind-optimal routing and AI-based trajectory management, energy reductions are not simply additive but multiplicative. This is due to cascading effects such as lower takeoff mass (from reduced fuel uplift), reduced climb gradients, and more favorable engine operating points during cruise. These synergies are supported by the modeling work of LePage et al., who developed a full energy-route-environment simulator and found that flights using SAF and AI-planned trajectories had 24% lower fuel use and 43% lower lifecycle emissions than conventionally routed Jet-A flights [38].

These integrated benefits also have implications for carbon offsetting and emissions trading schemes. According to ICAO's CORSIA framework, carriers using SAF and documented route optimization can reduce their offsetting obligations—thus translating energy efficiency into economic value. In one case study involving Lufthansa's experimental long-haul SAF route from Frankfurt to San Francisco, the combination of optimized cruise profiles and SAF blending led to an 18.6% net CO_2 reduction [39].

To ensure these benefits are scalable and globally applicable, several researchers have called for the establishment of route optimization benchmarks. The ICAO Task Force on Performance-Based Navigation (PBN) is currently reviewing the adoption of dynamic trajectory-based metrics (DTMs) to evaluate the efficiency of flight operations across ICAO regions. Such metrics, which include effective cruise time, deviation from optimal altitude, and lateral fuel distance index (LFDI), could be instrumental in quantifying and enforcing optimization targets [40].

In summary, the accumulated evidence indicates that energy savings from route optimization range between 15% and 25% when multiple strategies are combined. These savings, while subject to variation based on aircraft type, route structure, and airspace maturity, represent a transformative opportunity for decarbonizing the aviation sector. Nevertheless, realizing this potential requires alignment across technological, operational, and policy domains [41].

4.2 Operational and Technological Barriers to Deployment

While the potential fuel and emission reductions from integrated route optimization strategies are substantial, their real-world implementation faces formidable barriers stemming from operational complexity, technological constraints, regulatory frameworks, and organizational resistance [42].

Operationally, dynamic trajectory optimization requires real-time access to high-fidelity weather and traffic data, seamlessly integrated into aircraft Flight Management Systems (FMS) and Air Traffic Control (ATC) decision support tools. Although SESAR and NextGen initiatives have made progress in enhancing data interchange (e.g., trajectory exchange formats, ATC-cloud weather envelopes), gaps remain in data timeliness, resolution, and cross-jurisdictional sharing. Low-latency communications between aircraft and ground systems are critical; otherwise, trajectory updates may arrive too late or introduce conflicting constraints. For instance, the ICAO Global Air Navigation Plan (GANP) identifies future 4D trajectory management as a key enabler—but also highlights persistent limitations in Automatic Dependent Surveillance–Broadcast (ADS-B) connectivity over oceanic and remote regions [43].

Onboard systems must also be capable of processing and leveraging this data. Many existing FMS lack open interfaces for third-party optimization modules or AI algorithms. Certification of new software into airworthy avionics platforms is a lengthy and costly process. Even small changes, such as modifying route calculations or fuel prediction models, require rigorous verification and validation to meet FAA/EASA standards. Airlines that have attempted incremental upgrades to route guidance—such as Cathay Pacific's implementation of an economized cruise profile module—report expenditures in the multi-million-dollar range to retrofit fleets and train flight crews. These economic barriers slow widespread adoption, particularly among lower-margin carriers [44].

Inter-sectoral coordination poses another challenge. While pilot groups and dispatch teams might embrace trajectory tools that reduce fuel usage, ATC controllers must approve deviations and mitigate conflicts in real time. Simulations presented by EUROCONTROL suggest that even modest increases in trajectory uncertainty—such as occasional altitude shifts for optimal winds—could increase controller workload by 8–12% if adequate training and decision aids are not provided. Hence, achieving deployment requires not only optimized algorithms but also effective human–machine interface design and robust operational processes [45].

On the technological front, the integration of AI-driven flight path optimization into aviation systems introduces unique challenges. Machine learning models, especially deep neural networks, are often considered "black boxes" with limited interpretability. For regulatory acceptance and pilot trust, AI systems must provide transparent decision rationale and operate within predefined safety bounds. These requirement conflict with the performance-centric model training objectives often present in research, which prioritize optimizing fuel use over explainability. Researchers are beginning to develop physics-informed neural networks that incorporate domain constraints (e.g., kinematic limits, aerodynamic efficiency) within the model structure, but these approaches are in early stages and not yet certified for operational use [46].

Communications and interoperability must also be resolved. Airspace across the globe is managed by hundreds of ANSPs, each using different data formats and communication infrastructures. While the Aeronautical Fixed Telecommunication Network (AFTN) and associated Aeronautical Message Handling System (AMHS) provide baseline messaging capability, they are ill-suited for dynamic, high-resolution trajectory data. Efforts like the Terminal Flight Data Manager (TFDM) in the U.S. and System Wide Information Management (SWIM) in Europe offer pathways forward—yet their maturity varies regionally and globally. The technical complexity of connecting diverse FMS, ATC systems, and airline operational centers continues to hinder full-network optimization [47].

Another layer of operational friction comes from organizational structures and incentives. Airlines typically operate under tight cost structures and prioritize on-time performance, which is often rewarded in contractual agreements and brand reputation. A route that reduces fuel but extends flight time by a few minutes may be seen as less desirable. The literature indicates that only about 30% of commercial flights globally currently fly trajectories within 1% of their fuel-optimal projected path. Airlines need incentive mechanisms—such as fuel burn sharing agreements, carbon credit value attribution, or regulatory recognition—to offset perceived tradeoffs between operational efficiency and service reliability [48].

Finally, the deployment of SAF compounds these challenges. Whereas SAF offers lifecycle CO_2 reductions of up to 60%, its cost is still between 2X and 4X that of fossil Jet-A. Airlines, especially those operating without full cargo or government support, face high capital risk in adopting SAF blends at scale. In addition, supply-chain limitations—including limited biorefinery outlets and logistics barriers—curtail availability at major hubs. Although corporations under voluntary carbon programs and CORSIA may be willing to subsidize purchases, this often only addresses a fraction of fleet operations, leaving smaller routes and regional carriers behind [49].

In summary, operationalizing multi-domain route optimization requires advancements across at least four spheres: real-time data infrastructure, certified avionics and AI, human-centered operational workflow, and economic alignment across stakeholders. While the technical feasibility is increasingly demonstrated in simulations and pilot programs, scaling for commercial fleets demands policy incentives, cross-sector standards, and sustained investment in systems and training [50].

4.3 Regulatory, Certification, and Safety Considerations

As the aviation industry adopts more complex and data-driven route optimization tools, ensuring regulatory compliance and safety becomes a central challenge. Route optimization intersects multiple layers of safety governance, from aircraft navigation and fuel planning to airspace coordination and risk management. Therefore, any innovation—whether in AI-assisted flight planning, SAF use, or dynamic routing—must pass through rigorous scrutiny by national and international regulators before full-scale implementation is permitted [51].

The primary global authority overseeing aviation safety standards is the International Civil Aviation Organization (ICAO), whose Annexes to the Chicago Convention lay the groundwork for airworthiness, operational procedures, and air navigation services. Route optimization affects several of these areas—particularly Annex 6 (Operation of Aircraft), Annex 11 (Air Traffic Services), and Annex 15 (Aeronautical Information Services). Within these frameworks, optimization tools must demonstrate that they do not compromise aircraft separation standards, navigational accuracy, or emergency response protocols [52].

A major regulatory concern in dynamic routing is trajectory predictability. Air Traffic Control (ATC) systems are designed around fixed flight plans submitted before departure. Any deviation—whether due to wind-optimal adjustments, congestion rerouting, or AI-driven corrections—can disrupt sector workload models and conflict resolution mechanisms. To address this, ICAO's Global Air Navigation Plan promotes the adoption of Performance-Based Navigation (PBN) and 4D Trajectory-Based Operations (TBO), where time, position, and intent are shared dynamically between aircraft and ATC systems. However, this requires onboard systems to support Required Navigation Performance (RNP) standards, which many older aircraft do not yet meet [53].

Certification of software-based optimization systems adds another regulatory layer. Current certification frameworks under FAA (Federal Aviation Administration) and EASA (European Union Aviation Safety Agency) are grounded in deterministic software validation models (e.g., DO-178C for airborne systems). These models require traceability, static code analysis, and test coverage proofs that are difficult to apply to non-deterministic machine learning systems. Even if an AI model demonstrates superior performance in simulations, its lack of predictability or transparency can disqualify it from airworthiness approval [54].

Efforts to develop certification pathways for AI are underway. The FAA's "Artificial Intelligence in Aviation" roadmap emphasizes explainability, robustness, and verifiability as prerequisites for AI deployment in operational decision-making. Similarly, EASA launched the "Innovation Partnership Contract" (IPC) program to explore real-world certification use cases, including predictive maintenance and trajectory optimization. Yet, these programs remain exploratory and are not yet formalized in the regulatory frameworks that govern daily commercial operations [55].

Safety concerns extend beyond the aircraft level. Dynamic route optimization must also ensure that new routing behaviors do not introduce systemic risks, such as airspace bottlenecks, route overlap in turbulent regions, or excessive reliance on limited navigational infrastructure. In particular, wind-optimal routing may concentrate traffic in narrow corridors with favorable tailwinds, potentially increasing mid-air conflict risks. EUROCONTROL's analysis of these "super routes" has prompted caution, recommending probabilistic conflict detection tools and sector capacity balancing before such routes are adopted at scale [56].

Furthermore, the certification of SAF for use in commercial aviation is a multi-step process. The ASTM D7566 standard governs the blending and compatibility of SAF with Jet-A. Several pathways (e.g., HEFA, FT-SPK, ATJ) have been approved, but each fuel blend must undergo extensive testing, including cold soak, material compatibility, emissions profiling, and performance evaluation under various operational loads. Only after such certification can SAF be used as a drop-in fuel in commercial aircraft. Even then, regulatory restrictions typically cap blend levels at 50% for regular operations, limiting the full environmental potential of SAF [57].

Emerging proposals aim to create harmonized SAF certification protocols and expand allowable blending thresholds. For example, the ICAO Council is assessing global SAF sustainability criteria and has proposed creating a globally recognized emissions accounting framework for SAF usage under the CORSIA scheme. This would enable airlines to accrue emissions credits for SAF adoption in proportion to verified lifecycle emission reductions. If coupled with optimization-aware route planning, such schemes could provide quantifiable, certified carbon reductions that airlines can leverage in regulatory or voluntary carbon markets [58].

From a human safety perspective, one must also consider pilot workload and training. Advanced optimization tools may recommend non-intuitive maneuvers or deviations that, while energy efficient, may not align with the operational mindset or training of flight crews. Simulator-based studies have found that over-reliance on automation during dynamically optimized routes can lead to reduced situational awareness in abnormal conditions. Therefore, any deployment of such tools must be accompanied by human-in-the-loop controls, clear alerting systems, and updated training protocols [59].

Lastly, liability and accountability remain unresolved in multi-agent optimization systems. If an AI system recommends a trajectory that leads to a safety incident, determining responsibility—whether pilot, airline, developer, or regulator—is legally and ethically complex. Regulatory bodies have yet to establish definitive policies for AI accountability in real-time operational decisions [60].

In summary, while route optimization offers major energy and environmental benefits, its operationalization must navigate a multi-dimensional regulatory landscape. Achieving certification for advanced tools requires translating research innovations into explainable, deterministic frameworks that meet current aviation safety and interoperability standards. Collaboration between technology developers, regulators, and airlines will be critical in building a roadmap for safe and certified adoption of optimization-based decision tools [61].

4.4 Data Governance, Equity, and Global Disparities in Optimization Deployment

The global potential of aviation route optimization is well established, but realizing its full impact requires a coordinated and equitable distribution of technological, regulatory, and infrastructural capacity. A critical barrier to universal deployment is the uneven access to real-time aviation data, optimization tools, SAF supply chains, and supportive airspace architectures across regions. This disparity risks reinforcing energy and operational inequality between developed and developing aviation sectors and undermines global decarbonization targets [62].

Optimization tools—whether based on AI, real-time meteorological models, or collaborative decision-making platforms—depend heavily on digital infrastructure and aviation data availability. While air navigation service providers (ANSPs) in North America and Europe benefit from mature SWIM (System Wide Information Management) systems and integrated weather feeds, other regions lack access to high-fidelity data needed for dynamic trajectory management. Figure 6 illustrates these regional disparities, showing that fewer than 20–25% of flights in Africa and Latin America are operated on fuel-optimal routes, compared to over 40% in Europe and North America [63].

This divergence stems from multiple causes. First, real-time data sharing requires investments in communication networks, radar coverage, ADS-B infrastructure, and secure data links—investments that are limited in lower-income regions. Second, there are institutional barriers related to sovereignty and airspace management policies. In some cases, airspace is controlled by military authorities or multiple overlapping jurisdictions, making the integration of civil aviation data into a shared optimization network politically and logistically challenging [64].

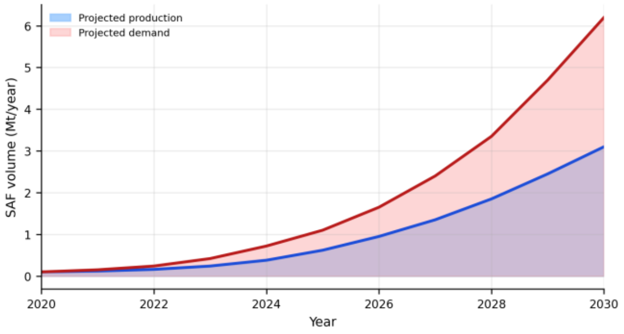

Fig 5. Projected global SAF production-demand balance from 2020 to 2030

Global disparities are further exacerbated in SAF deployment. Figure 5 shows the projected mismatch between SAF production and demand through 2030. Most of the production capacity is concentrated in the United States and Europe, where government incentives (e.g., the U.S. Inflation Reduction Act and the EU ReFuelEU initiative) have accelerated investment. Meanwhile, the demand from global carriers far outpaces supply, particularly in Asia, Africa, and Latin America—regions with growing aviation markets but limited local SAF production or blending facilities. This mismatch not only limits the ability of airlines in these regions to participate in emissions-reduction schemes but also raises concerns about "carbon inequity," where only a few regions accrue regulatory and reputational benefits from SAF adoption [65].

Figure 7 contextualizes this challenge by tracing the certification timeline of different SAF pathways under ASTM D7566. Even though multiple SAF types have been approved over the last decade, the downstream infrastructure (fuel blending terminals, certification labs, quality assurance systems) is largely absent outside of OECD countries. For developing nations, the barriers to SAF deployment are not only technical but economic. With SAF prices currently 2–4 times higher than Jet-A, airlines in cost-sensitive regions face limited commercial incentive to invest without subsidies, credits, or long-term procurement guarantees. In the context of AI and route optimization tools, the inequity is equally stark. Figure 8 shows the fuel savings potential of various route planning methods, with AI-reinforcement learning and hybrid AI models delivering efficiency gains of 14–16% compared to baseline. However, access to these technologies requires robust datasets, computational infrastructure, skilled personnel, and certified integration with operational planning software—all of which are unevenly distributed. Research by Air Transport Action Group (ATAG) notes that only 12% of ICAO member states have operational AI capabilities integrated into national aviation systems [66].

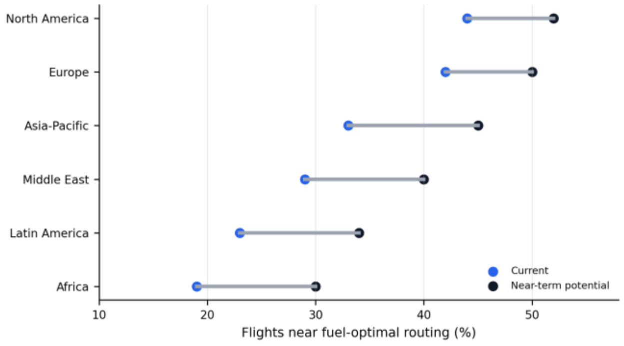

Fig 6. Regional share of flights operated close to fuel-optimal trajectories

There are also risks of algorithmic bias in AI-driven routing systems. For instance, if models are trained predominantly on North Atlantic or European airspace datasets, their performance may be suboptimal in tropical or mountainous regions with different meteorological and navigational dynamics. Without region-specific training data and operational feedback, the recommendations generated by these systems may fail to capture local constraints, resulting in suboptimal or even unsafe recommendations. A related concern is the lack of explainability and certification pathways for such models in regions with less regulatory capacity or oversight [67].

To address these inequities, a globally coordinated data governance framework is needed. ICAO, in partnership with IATA and regional organizations, could play a key role in establishing open-access, anonymized aviation data repositories, standardized APIs for routing data, and model interoperability protocols. Such frameworks would allow countries without robust internal infrastructure to access validated optimization tools and participate in coordinated emissions-reduction schemes. A similar model exists in meteorology, where the World Meteorological Organization (WMO) operates the Global Telecommunication System (GTS) to ensure weather data equity [68].

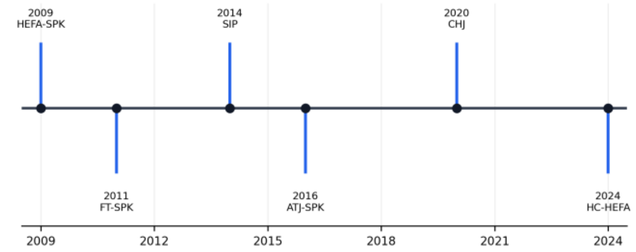

Fig 7. Timeline of ASTM approval milestones for major SAF pathways

In terms of SAF, global development finance institutions—such as the World Bank and regional development banks—can facilitate capacity-building programs and offer low-interest loans or green bonds for SAF infrastructure deployment in emerging markets. International emissions credit trading platforms could also allow airlines in developing countries to earn verifiable credits through operational optimization and reinvest those credits in SAF procurement [69].

Beyond infrastructure, training and human capacity are critical. Pilots, dispatchers, and controllers in under-resourced airspaces may not be familiar with dynamic trajectory concepts or AI-assisted planning systems. ICAO's Next Generation of Aviation Professionals (NGAP) initiative could be expanded to include dedicated modules on route optimization and SAF-aware energy planning, with a focus on inclusivity and global accessibility [70].

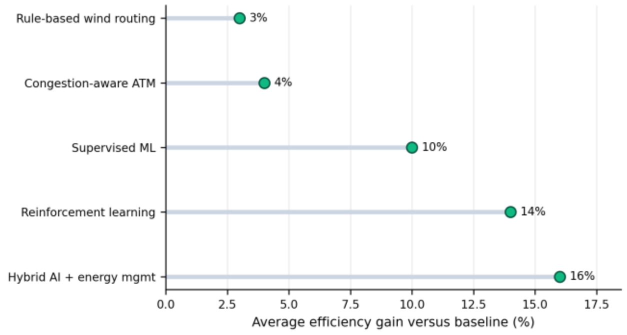

Fig 8. Reported average efficiency gains for alternative route-planning methods

In conclusion, while route optimization technologies and SAF offer global energy and emissions benefits, their uneven deployment threatens to deepen aviation inequality. Addressing this will require international cooperation, funding mechanisms, technical standardization, and a commitment to aviation equity. Without this, the environmental benefits of route optimization may remain concentrated in wealthier regions, leaving others to face rising emissions without adequate tools to mitigate them [71].

5. Conclusion

This review has examined aviation route optimization not as a narrow dispatch task but as a broad operational strategy for reducing fuel use and emissions across modern air transport systems. Taken together, the reviewed studies show that measurable gains are already achievable using currently available planning methods, provided that routing decisions are supported by sufficient data, coordination, and digital capability [72].

The evidence for trajectory optimization is especially consistent. Wind-aware routing and altitude management rarely deliver headline-grabbing savings on a single flight, yet their repeatability and scalability make them highly valuable across long-haul and high-frequency operations [73].

System-level traffic measures add a second layer of improvement. By reducing congestion, vectoring, and holding, network-aware optimization addresses inefficiencies that cannot be removed by aircraft-centered route planning alone and therefore improves both fuel performance and operational reliability [74].

The largest operational savings in the reviewed literature are associated with AI-supported planning frameworks. When trained on relevant weather, route, and fleet data, these methods can outperform static planning logic, but their practical value depends on transparency, validation, and safe integration with certified aviation workflows [75].

SAF further changes the discussion by linking route design to fuel properties and propulsion behavior. Once fuel type, engine response, and trajectory selection are evaluated together, route optimization becomes part of a wider energy-management problem rather than a standalone scheduling exercise [76] [84].

A first priority for future deployment is the expansion of reliable digital infrastructure, including high-fidelity weather feeds, interoperable traffic data, and decision-support environments that can update trajectories without undermining safety [77].

A second priority is regulatory modernization. Advanced planning tools - particularly AI-enabled tools - will require certification pathways that balance explainability, robustness, and operational benefit before they can be used routinely in commercial settings [78].

A third priority concerns SAF access and cost. The decarbonization value of fuel-aware routing cannot be realized at scale unless production capacity, quality assurance, and regional supply chains develop beyond a small number of early-adopter markets [79].

Equally important is the governance of operational data. Open standards, compatible information systems, and fair access to validated optimization tools will determine whether efficiency gains are distributed globally or concentrated in already well-equipped aviation regions [80].

Human capability must advance in parallel with technical capability. Pilots, dispatchers, controllers, and regulators will all need training that supports safe use of dynamic routing, interpretability of algorithmic recommendations, and sound decision-making under changing operating conditions [81].

For these reasons, aviation route optimization should now be viewed as a strategic pillar of sustainable flight operations. It links immediate operational improvements with longer-term fuel transition pathways and offers one of the clearest opportunities to reduce aviation energy demand before fleet replacement and new propulsion technologies are fully mature [82] [85].

If research, regulation, and implementation progress together, route optimization can move from incremental efficiency enhancement to a central mechanism for cleaner and more resilient air transport [83].

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