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Evaluating the Potential of Sustainable Aviation Fuel for Decarbonization of the Aviation Sector: An Agent-based Model

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ABSTRACT

The aviation sector represents one of the most pressing challenges in the energy transition due to its strong reliance on energy-dense liquid fuels and established fuel infrastructure. Sustainable Aviation Fuel (SAF), particularly from agricultural residues, offers a near-term mitigation pathway; however, large-scale adoption is shaped by policy mandates, infrastructure expansion, market price formation, and passenger demand responses. These coupled dynamics are difficult to capture using aggregate or equilibrium-based models. This study develops an agent-based model to analyze SAF transition pathways and applies it to India's civil aviation system. Results show that SAF adoption emerges from the coordination between infrastructure entry, cost learning, and market responses rather than mandate ambition alone. Even moderate mandates fall short of intended adoption levels without timely infrastructure expansion, while aggressive mandates become infeasible under binding supply and price constraints. Passenger demand feedbacks further influence outcomes by linking fuel cost increases to airline operations and route-level allocation decisions. The findings highlight infrastructure coordination and price formation as critical leverage points for aviation decarbonization and demonstrate the value of agent-based models for evaluating realistic SAF transition strategies under policy and market uncertainty.

Keywords: Energy Systems, Agent-Based Modeling, Energy Transition, Sustainable Aviation Fuel, Aviation Decarbonization

INTRODUCTION

Decarbonization of the global energy system has become a central objective of climate mitigation efforts, with particular attention directed toward hard-to-abate sectors. The transport sector contributes nearly 28% of global CO_2 emissions, of which aviation accounts for approximately 2–3%, a share that is expected to increase due to sustained growth in air travel demand. Global aviation demand is projected to double relative to 2024 levels by the early 2040s, with annual growth rates in the range of 3.6–4.2% [1]. Unlike road transport, where electrification and efficiency improvements have already delivered substantial emissions reductions, aviation faces fundamental constraints related to energy density requirements, safety certification, long asset lifetimes, and fleet turnover [2, 3]. These constraints severely limit the near- to medium-term feasibility of alternative propulsion systems, positioning aviation as one of the most challenging sectors to decarbonize. A range of mitigation options is being pursued within aviation, including operational efficiency improvements, demand management, carbon offsetting mechanisms, and the development of hydrogen- and electric-powered aircraft. However, these pathways remain either incremental in their emissions impact or constrained by low technology readiness and infrastructure limitations at scale. Within this landscape, Sustainable Aviation Fuel (SAF) has emerged as the most viable near-term pathway for reducing aviation emissions while maintaining compatibility with existing aircraft fleets and fuel infrastructure. As a drop-in fuel, SAF can be blended with conventional aviation turbine fuel at levels of up to 50% and used in current aircraft without modifications, enabling near-term emissions reductions without disruptive changes to aircraft or airport infrastructure. When produced from renewable and waste-based feedstocks, SAF can reduce life-cycle greenhouse gas emissions by up to 60–80% relative to fossil jet fuel [4].

LITERATURE REVIEW

SAF can be produced through multiple technological pathways, including Hydroprocessed Esters and Fatty Acids (HEFA) from waste oils and fats, Fischer–Tropsch synthesis via biomass or waste gasification, Alcohol-to-Jet (ATJ) conversion of bio- or waste-derived alcohols, and power-to-liquid routes based on renewable electricity and captured carbon. These pathways differ substantially in technology maturity, capital intensity, and cost trajectories, indicating that large-scale SAF deployment extends beyond a purely technological challenge. Techno-economic analyses consistently identify a substantial cost gap between SAF and conventional aviation turbine fuel. Across production pathways and regional contexts, SAF minimum selling prices are typically estimated to be 3 to 5 times higher than fossil jet fuel, with reported values in the range of USD 1.8–3.5 per kg at industrial scales of 400–600 million liters per year, compared to jet fuel prices of approximately USD 0.4–0.7 per kg [5, 6]. Capital investment dominates costs in gasification-based pathways, while feedstock costs account for more than 50% of operating expenditures in HEFA and ATJ routes. Although learning-by-doing, economies of scale, by-product valorization, and targeted policy support can reduce production costs over time, the magnitude and timing of such reductions remain uncertain. As a result, SAF deployment has been closely tied to policy intervention through blending mandates, tax credits, carbon pricing, and penalties for non-compliance.

Existing studies analyze the impacts of SAF mandates on airline behavior, airline adoption decisions shaped by interactions with airports and fuel suppliers, certification and chain-of-custody requirements for SAF producers, and the role of feed-in tariffs and capital subsidies in enabling biojet fuel supply chains [7, 8, 10]. Scenario-based modeling studies indicate that global SAF deployment faces persistent challenges related to high production costs, feedstock availability, and spatial concentration of supply. Co-benefit analyses further suggest that airlines adopt SAF primarily when SAF price premiums are comparable to carbon prices, while benefit–cost ratios decline when SAF availability is limited to a small number of airports, highlighting the importance of spatial scale and infrastructure coverage [9-11].

Despite these insights, much of the existing literature examines SAF adoption by focusing on individual actors or isolated system components, limiting its ability to capture emergent system behavior. Critical dynamics remain insufficiently explored, including passenger responses to SAF-induced ticket price changes, SAF market behavior under supply–demand imbalances, airline strategies for allocating SAF across airport networks, and the effectiveness of penalties under constrained supply conditions. Moreover, the interaction between short-term operational decisions and long-term strategic investments, which is central to understanding infrastructure lock-in and transition pathways, remains underdeveloped. These limitations point to the need to conceptualize SAF deployment as a socio-technical system in which outcomes emerge from interactions among heterogeneous actors operating under distinct objectives and constraints. The aviation fuel value chain comprises airlines, fuel producers, feedstock suppliers, airports, passengers, markets, and regulators whose decisions interact through non-linear economic, spatial, and temporal feedbacks. Fuel procurement choices influence market prices and investment incentives, infrastructure availability constrains feasible adoption pathways, and early policy signals shape long-term transition trajectories. Such adaptive and path-dependent dynamics are difficult to capture using aggregate, equilibrium-based, or centrally optimized modeling approaches. Agent-based modeling offers a suitable alternative by explicitly representing decentralized decision-making, heterogeneous behavior, and emergent system outcomes [13]. ABMs have been successfully applied in energy and transport systems to study technology diffusion, infrastructure evolution, and policy experimentation under uncertainty [14, 15].

Motivated by these gaps, this study develops Greening Aviation's Energy Requirements through Optimal SAF Supply (Green-AEROS), an agent-based model designed to analyze SAF adoption in aviation as an integrated, multi-actor transition process. Green-AEROS explicitly represents interacting agents across the aviation fuel value chain and links short-term operational behavior, such as route-level fuel blending and passenger demand responses, with long-term strategic decisions, including capacity expansion and infrastructure emergence. The model is applied to India's civil aviation sector, a rapidly growing aviation market with increasing policy interest in SAF deployment, to examine how regulatory ambition, market dynamics, and infrastructure evolution jointly shape SAF adoption pathways and long-term aviation decarbonization outcomes.

AGENT-BASED IMPLEMENTATION OF GREEN-AEROS

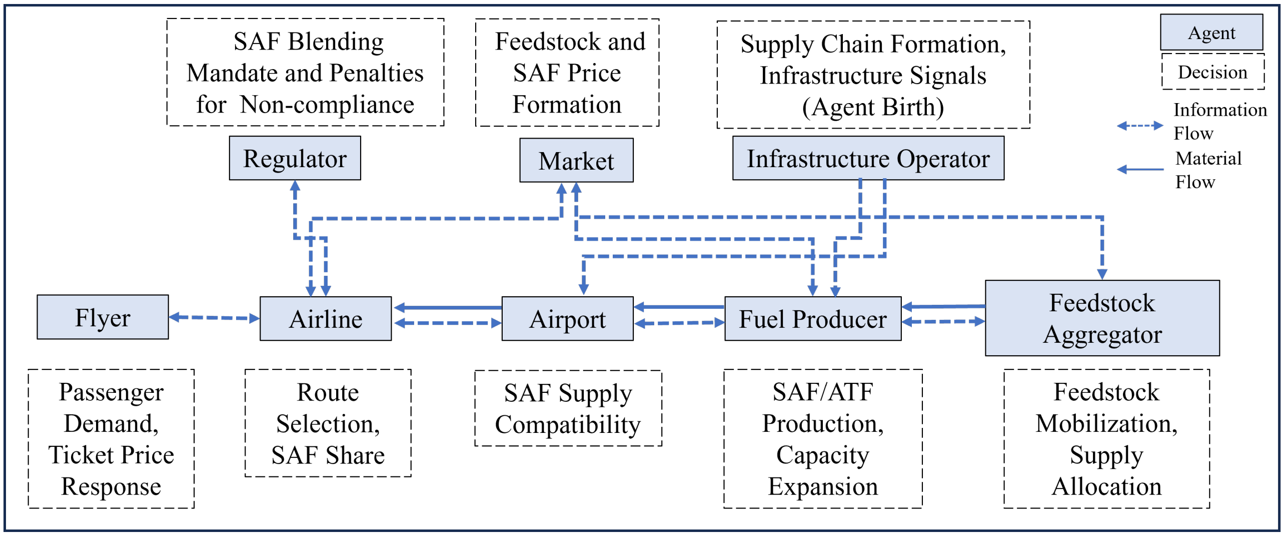

Figure 1. Conceptual architecture of Green-AEROS highlighting major agent decision interactions. Solid arrows denote physical flows such as, fuel use, and SAF supply across routes and airports. Dashed arrows indicate information, policy, price, and coordination signals governing market responses, regulatory enforcement, and infrastructure emergence.

Green-AEROS is an agent-based model developed to explore transition pathways for the aviation sector toward SAF. The model represents decentralized decision-making across the aviation fuel value chain by explicitly modeling 8 interacting agent types: flyers, airlines, airports, fuel producers, feedstock aggregators, infrastructure operator, market, and regulator **Figure 1**. Airline agents represent commercial carriers operating across multiple airports. To capture spatially localized behavior, each airline agent comprises airport-specific subagents that make route-level decisions, including passenger demand forecasting and ticket price formation. The allocation of SAF and ATF shares on routes originating from each airport is determined through a linear programming formulation that minimizes penalties, subject to a maximum SAF blending limit of 50% and airport-level SAF availability constraints. Baseline passenger demand is driven by exogenous socio-economic factors such as population growth and GDP per capita, which evolve over time. Flyer agents respond endogenously to ticket price changes, with price sensitivity expressed through the effective fuel cost resulting from SAF–ATF blending. Airport agents decide on SAF infrastructure activation based on airline demand for SAF and local availability from fuel producers. Fuel producer agent consists of two sub-agents: conventional refinery agents supplying ATF and SAF producer agents supplying SAF. SAF producer agents make decisions regarding production volumes, capacity expansion, technology deployment, and feedstock procurement. Production decisions are primarily driven by feedstock availability and learning effects associated with cumulative production. SAF is assumed to be transferred to existing refinery infrastructure for blending with ATF and subsequently transported to connected airports. This assumption reflects the utilization of existing fuel infrastructure and supports early-stage SAF deployment without requiring immediate system-wide retrofitting. Feedstock aggregator agents are spatially distributed according to regional agricultural residue availability and make decisions related to feedstock mobilization and supply network formation with SAF producers. The infrastructure operator agent governs the endogenous emergence of SAF supply chains by signaling the entry of new SAF production facilities and airport-level SAF infrastructure. This agent coordinates linkages between feedstock aggregators, SAF producers, and airports by optimizing the use of existing fuel infrastructure and minimizing system-level bottlenecks. The infrastructure operator signals the need for new SAF production capacity based on airline demand and the capacity expansion decisions of existing SAF producers. Regulator and market agents provide the policy and price-formation environment. The regulator sets national SAF blending mandates for airlines and enforces penalties for non-compliance, with penalties anchored to SAF prices discovered by the market agent. The market agent receives SAF demand from airlines and supply from SAF producers, as well as feedstock supply from feedstock aggregators and feedstock demand from SAF producers, and discovers SAF and feedstock prices in response to supply–demand imbalances. The resulting SAF prices evolve over time with changes in production scale, feedstock availability, and learning effects. To ensure numerical stability and avoid unrealistic price volatility, a min–max capping mechanism is applied to bound SAF price variations. Given the early stage of SAF deployment, the model assumes a uniform

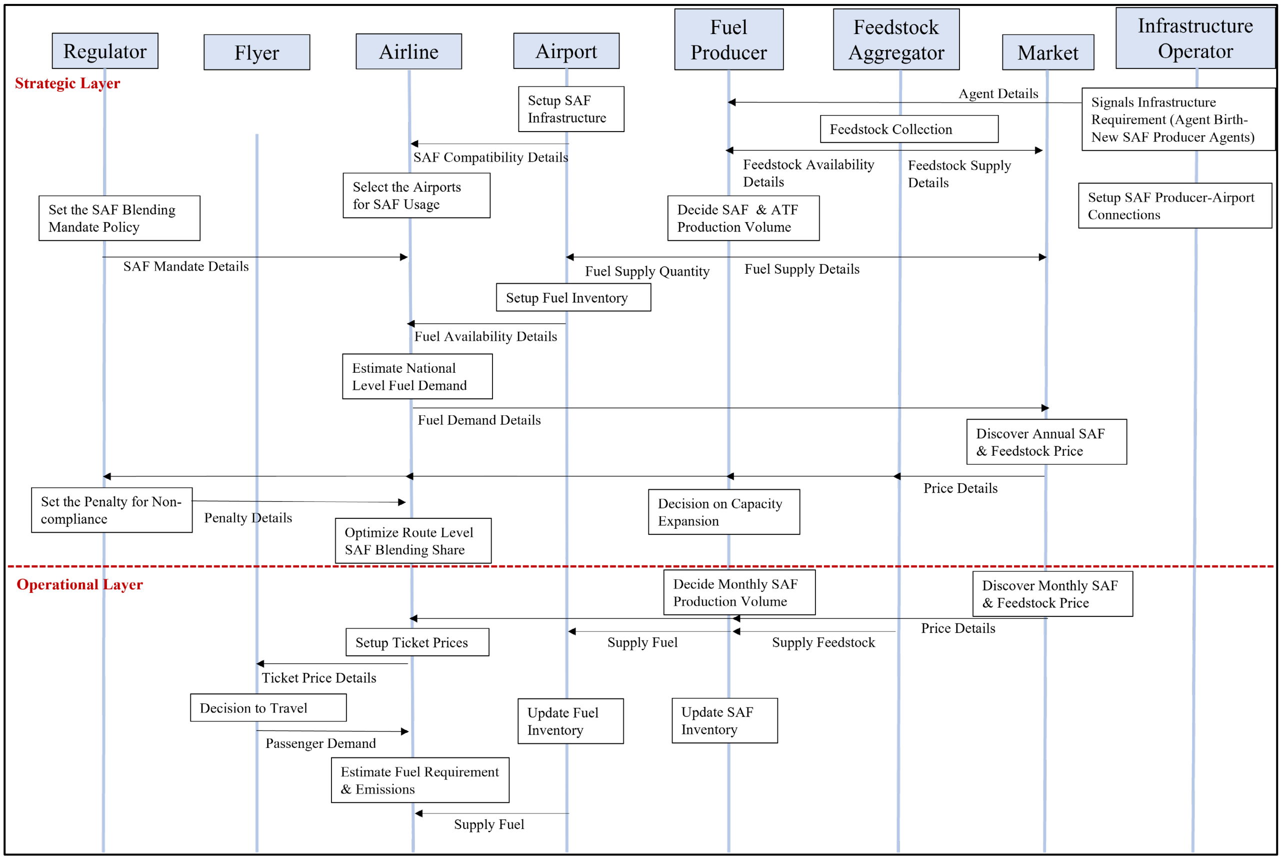

Figure 2. Agent-interaction and decision sequence in the Green-AEROS model.

national SAF price, while feedstock prices vary spatially to reflect regional availability. All agents are equipped with forecasting and optimization modules that enable forward-looking decision-making under uncertainty, incorporating costs, risks, incentives, and learning over time. Agent decisions in Green-AEROS occur at two levels, operational and strategic, and evolve over different time scales that jointly shape the transition dynamics. **Figure 2** presents the sequence of agent-level decisions and their interactions within each time step. It highlights the predefined order of decision updates and the exchange of information through shared system variables such as prices, demand, and capacity, thereby representing coordination across agents within a decentralized framework. For instance, at the strategic level, the infrastructure operator signals the birth of new SAF producer agents and determines SAF compatibility at connected airports, which is used by airline agents to optimize SAF blending shares at the route level. These decisions propagate to the operational level, where airlines set ticket prices that are communicated to flyer agents, whose responses capture passenger demand sensitivity to SAF adoption.

CASE STUDY: INDIA'S CIVIL AVIATION SECTOR

The performance of Green-AEROS is evaluated using a case study of India's Civil Aviation Sector (ICAS), the third-largest domestic aviation market globally, with more than 7, 100 daily aircraft movements and annual carbon dioxide emissions of approximately 30–35 million tonnes [16, 17]. Green-AEROS is implemented in Repast4Py and instantiated to represent 11 major airports (DEL, BOM, BLR, CCU, MAA, HYD, GOI, COK, LKO, AMD, and IDR) and 110 domestic routes, together capturing approximately 69% of domestic air traffic. A single representative airline agent is modeled to capture aggregate airline behavior, incorporating system-level risk preferences and strategic decision-making. Route-level passenger demand is forecast by the airline agent using exogenous socio-economic drivers, including gross domestic product, fuel prices, population, and per capita income. Conventional refineries are assumed to supply the required quantities of ATF, while SAF is produced from agricultural residues through the Alcohol-to-Jet pathway. Blending of SAF and ATF is assumed to occur at refineries located nearest to airports. Feedstock aggregator agents are distributed across 14 states and 374 districts and supply agricultural residues derived from rice, maize, and sugarcane.

The number and capacity of SAF production sites evolve endogenously over time, driven by airlines' willingness to adopt SAF in order to reduce penalties for non-compliance and by feedstock availability within a procurement distance (P_d) from production sites which. Strategic decisions are modeled at an annual resolution, while operational decisions occur monthly over a 20-year simulation horizon spanning 2024–2044. In line with current policy timelines in India, SAF blending mandates are applied from 2027 onward, starting at 1% in 2027, increasing to 2% in 2028, and reaching 5% by 2030. The model is initialized with a single SAF production site with a capacity of 43.75 million liters, supplying SAF to one airport (DEL) at an initial SAF price ($Price_{SAF}$) of 275.23 INR per liter, with a lead time of two years before the facility becomes operational. SAF blending mandates are imposed exogenously as policy requirements; however, realized SAF adoption emerges endogenously from agent interactions and may fall short of mandated levels when supply-side, infrastructure, feedstock availability, or cost constraints become binding.

To examine the implications of increasing policy ambition, three policy configurations are evaluated. All policies follow an identical SAF blending trajectory until 2030, reflecting the current national mandate pathway. **Policy 1** represents a low-ambition pathway, in which the SAF blending requirement increases to a maximum of 5% by 2030 and remains constant thereafter. **Policy 2** reflects a moderate ambition pathway, in which the blending requirement continues to increase beyond 2030, reaching a maximum of 15% over the 20-year horizon. **Policy 3** represents a high-ambition pathway, in which the blending requirement rises further to a maximum of 30% over the same period. These policy configurations are used to assess how infrastructure emergence, market dynamics, and airline decision-making jointly shape feasible SAF adoption trajectories under progressively stronger regulatory targets.

RESULTS AND DISCUSSION

The evolution of SAF adoption under Policies 1, 2, and 3 by comparing imposed blending requirements with realized SAF shares emerging from agent interactions is illustrated in **Figure 3(a)**. For ICAS, passenger demand across 110 domestic routes increases from 100.4 million passengers in 2024 to 182 million by 2044, with total aviation fuel demand rising from 2.6 billion liters to 4.8 billion liters. Over the same period, ATF prices increase by 8.1%. Against this growth trajectory, early SAF uptake across all policies remains highly localized. In 2027, a national SAF blending level of 1% is achieved with a total SAF requirement of approximately 30 million liters, accomplished by deploying SAF on a single high-volume route (DEL–BLR), where SAF accounts for 24% of the fuel used on that route.

By 2030, the mandated blending level increases to 5%, yet realized SAF adoption remains limited to approximately 1.4% across all three policies. This divergence indicates that mandate escalation alone is insufficient in the absence of supporting infrastructure. From 2031 onward, realized adoption trajectories begin to diverge as infrastructure expansion is triggered endogenously by airlines' incentives to reduce penalties for non-compliance. Policies 2 and 3 achieve the 5% blending target by 2032, requiring approximately 206 million liters of SAF, while Policy 1 reaches the same level by 2033. This earlier achievement under Policies 2 and 3 reflects accelerated entry of SAF production sites and expansion of airport-level SAF compatibility driven by higher post-2030 policy ambition.

Table 1: Number of airports supplying SAF and SAF producers operating by 2044.

	Airports	SAF Producers
Policy 1	3	3
Policy 2	7	5
Policy 3	10	8

Under Policy 2, SAF adoption continues to increase steadily, reaching 15% blending by 2040 with a corresponding SAF requirement of 682 million liters. In contrast, under Policy 3, realized SAF adoption plateaus at a maximum of 25.15% by 2044 despite stronger policy signals. This saturation occurs even though additional SAF production capacity is available, indicating that airport-level blending constraints and limited route coverage restrict further demand growth. **Table 1** shows that achieving a 5% blending level by 2044 requires 3 SAF production sites supplying DEL, BLR, and BOM, whereas higher blending levels depend more strongly on expanding SAF compatibility across additional airports rather than increasing the number of producers alone. Under Policy 2, the addition of 2 SAF producers supplying HYD and MAA, along with SAF availability at LKO and GOI from existing SAF producers, enables higher system-wide adoption. Under Policy 3, even with 8 SAF production sites supplying 10 airports, a 16% SAF shortfall is observed by 2044.

These first-order insights indicate that mandate ambition alone does not determine realized SAF adoption. Instead, adoption is constrained by the timing and spatial alignment of SAF production sites, airport-level blending compatibility, and airline route-level allocation decisions. **Figure 3(b)** shows the regional distribution of India's SAF

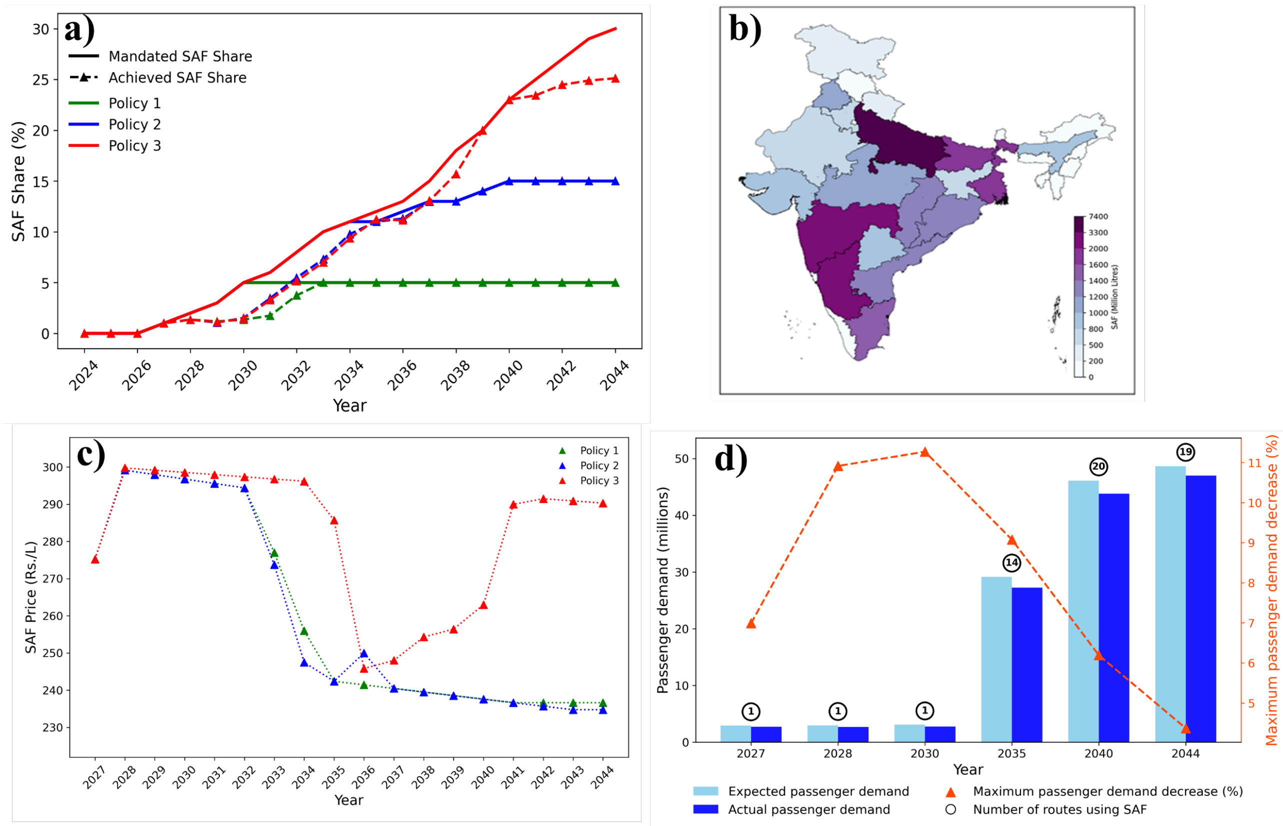

Figure 3. (a) SAF uptake under different policies. (b) Spatial distribution of potential SAF production from agricultural residues across India. (c) SAF market price evolution across policy pathways. (d) Passenger response to SAF adoption under Policy 2(only for routes using SAF).

production potential derived from agricultural residues of rice, maize, and sugarcane, which together amount to an estimated 7, 600 million liters annually. While this potential substantially exceeds the SAF requirement even under higher blending policies, it is unevenly distributed across regions and does not automatically translate into effective supply at demand centers. As a result, SAF adoption concentrates at airports with high route volumes and favorable blending conditions, even under a nationally uniform SAF price. This spatial mismatch between feedstock availability, production capacity, and airport demand explains why higher blending levels remain unattainable despite sufficient aggregate resource potential, highlighting the need for coordinated infrastructure expansion alongside policy mandates.

Figures 3(c) and 3(d) together reveal how SAF price dynamics translate into uneven passenger demand responses across spatial and temporal scales. In the early phase of Policy 2, limited SAF availability results in high blended fuel costs. In 2027, with a SAF price of 275.23 INR/L, airlines achieve the mandated 1% blending by concentrating SAF usage on a single high-volume route (DEL–BLR), where a 24% SAF share leads to a route-level passenger demand reduction of 6.8%. As SAF prices increase further by 8.2% in 2028 due to continued supply constraints, the maximum route-level demand reduction deepens to nearly 10%, despite SAF still being used on only one route. This illustrates how early SAF adoption manifests as localized demand shocks driven by price pressure rather than system-wide contraction.

As SAF supply expands and prices moderate, these dynamics evolve. By 2035, increased SAF availability lowers prices sufficiently to enable airlines to distribute SAF usage across 14 routes. While the maximum route-level demand reduction remains noticeable at 8.9%, the aggregate passenger demand reduction across all SAF-using routes is limited to 6.6%, indicating a diffusion of impacts rather than intensification. By 2042, SAF prices stabilize under Policy 2 as supply better aligns with demand, allowing SAF usage to expand to 19 routes. At this stage, both maximum and aggregate demand impacts decline further, with a maximum route-level reduction of 4.2% and an overall reduction of 3.4%. These results highlight a key emergent insight: passenger responses to SAF adoption are highly non-linear and scale-dependent. Localized impacts at the route level do not translate proportionally to system-wide outcomes, underscoring the importance of bottom-up modeling approaches in capturing how micro-level airline allocation strategies shape macro-level demand trajectories during the SAF transition.

CONCLUSION

In the present study, Green-AEROS is developed as an agent-based model to examine Sustainable Aviation Fuel transition dynamics as an emergent outcome of decentralized decision-making across the aviation fuel value chain. Applied to India's civil aviation sector, this work constitutes one of the first agent-based, system-level representations of the SAF socio-technical system, explicitly integrating airlines, passengers, fuel producers, infrastructure evolution, markets, and regulation within a unified framework. The results show that realized SAF adoption is governed less by mandate ambition in isolation and more by the alignment of infrastructure emergence, supply-side learning, and market-mediated price signals. Moderate mandates fall short of intended adoption levels when SAF infrastructure does not emerge in a timely manner, while highly ambitious mandates become infeasible under binding supply, blending, and price constraints. By jointly representing passenger demand responses, airline operational choices, SAF production expansion, infrastructure birth, and endogenous price discovery, the study reveals tightly coupled policy–infrastructure–market feedbacks that shape realistic SAF transition pathways.

Future work will extend Green-AEROS along several dimensions to strengthen its applicability and policy relevance. Planned developments include representing multiple airline agents with heterogeneous route-selection strategies and incorporating evolving technology maturity to capture strategic diversity in SAF deployment decisions. The model will also be expanded to account for regional feedstock constraints arising from competing uses, which may significantly influence the spatial feasibility of SAF production. In addition, integrating detailed techno-economic assessments at the SAF production site level will enable explicit evaluation of long-term economic viability under alternative policy and market conditions. Given its modular structure, Green-AEROS is readily extendable to other national and regional aviation systems, providing a transferable modeling framework for analyzing SAF transitions across diverse geographies and policy contexts.

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