THE NEW FUEL EQUATION: HOW REGULATORY FORCES RESHAPE FUEL MARKETS

The global transportation fuel industry is evolving. The industry used to be determined not only by market forces and chemistry alone. However, evolving regulatory mandates designed to reduce petroleum dependency and greenhouse gas emissions have shaped regulatory regimes and determined fuel consumption worldwide. This paper will examine three policies that are fundamental in reassessing what goes into fuel tanks, how refineries operate, and the flow of investment capital: the United States Renewable Fuel Standard (RFS), international and national Sustainable Aviation Fuel (SAF) mandates, and emission focused standards such as California's Low Carbon Fuel Standard (LCFS). The origins, mechanisms, and impacts of these policies highlight that mandates serve as not only a foundation but also a ceiling that creates pressures that misalign market signals with true environmental goals. By simultaneously examining federal rulemaking records, industry data, and regulatory analysis, this paper concludes that clear and technology neutral policy design is essential to translating legislative ambition into true measurable emission reductions.

Introduction

For more than a century, liquid fuels have been integral in driving the global economy. Yet, the environmental costs of petroleum combustion, from urban air quality to climate change, have compelled governments to re-evaluate fuel marketplace standards globally. As multiple governments collaborate to address the global fuel industry, the resulting regulatory architecture is a multi-layered response that simultaneously incentivizes fuel production, mandates blending minimums, and penalizes high-carbon fuel pathways. The emergence of these policies exerts direct and measurable influence on the chemistry of the fuel in every automobile, aircraft, and diesel truck.

This paper will focus on three central policy instruments: The Renewable Fuel Standard (RFS), Sustainable Aviation Fuel (SAF) mandates, and emission-based regulations. The RFS was established by the Energy Policy Act of 2005 and was expanded by the Energy Independence and Security Act of 2007 which required that transportation fuel sold in the United States (US) must contain minimum volumes of renewable fuel [1]. On the other hand, SAF mandates were aggressively implemented with the European Union (EU)'s ReFuelEU campaign, controlling aviation regulation by requiring the blending of low-carbon alternatives into aviation kerosene [2]. In academic reviews of the RFS, results show that the program has clearly driven biofuel market growth as "actual implementation diverged substantially from statutory targets, reaching only 20 billion gallons in 2022 versus the intended 36 billion, primarily due to failure to scale cellulosic biofuel production," [3]. Finally, emission-based regulations including California's Low Carbon Fuel Standard (LCFS) takes a different approach by setting declining carbon-intensity benchmarks rather than volumetric mandates, thus allowing fuel producers to generate tradable credits by exceeding the targets.

Together, these frameworks are the foundation to the economic and technological environment in how fuel refiners, biofuel producers, technology investors, and agricultural markets operate. The central argument of this paper is to analyze how regulatory design choices (how volumes are set, which fuel pathways qualify, and how compliance flexibility is structured, have consequences that shape supply chains, capital allocation, and the pace of decarbonization.

The Politics and Payoffs of the Renewable Fuel Standard (RFS)

1.1 Basics of the RFS Program

The RFS is the dominant policy driver of biofuel demand in the US. At its core, the program requires producers and importers of gasoline and diesel to ensure that a specified percentage of their fuel supply meets a renewable standard, expressed as a renewable Volume Obligation (RVO). Compliance is tracked through Renewable Identification Numbers (RINs), a digital certificate that is generated when a qualifying renewable fuel is produced or imported. Obligated parties can either blend biofuels and generate their own RINs, or purchase RINs from other market participants [4].

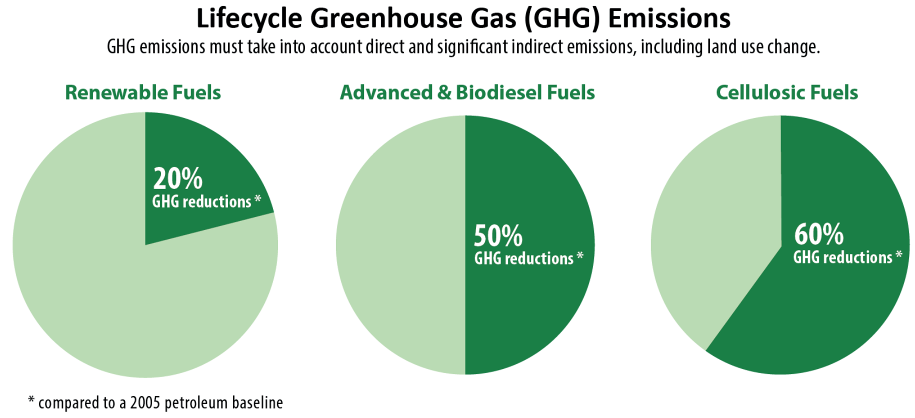

Figure 1: Lifecycle Greenhouse Gas (GHG) emissions and reductions of Renewable Fuels, Advanced & Biodiesel Fuels, and Cellulosic Fuels determined by the EPA. Reproduced from the EPA Overview of the Renewable Fuel Standard Program (2026) under the CC0 Public Domain Dedication [5].

The RFS divides qualifying fuels into four nested categories which the EPA has approved under the RFS programs: total renewable fuel, advanced biofuels, biomass-based diesel, and cellulosic biofuel shown in Figure 1. Lifecycle GHG reductions were compared with a petroleum baseline from 2005. Each category has its own volume requirement, creating a compliance framework that rewards lower-carbon fuel pathways with a premium on their RIN value. Advanced biofuels must demonstrate a lifecycle greenhouse gas reduction relative to petroleum, at least a 50% lifecycle. Cellulosic biofuel must achieve a 60% reduction. Gerveni et al. conducted a comprehensive economic review of the RFS program determining that total inflation-adjusted compliance costs for the program are estimated at $252.1 billion from 2011 to 2025, emphasizing the scale of market intervention that mandated blending volumes represent [3].

1.2 The Impact of Fuel Formulation and Characteristics

Visible effects of the RFS on fuel formation is evident with the near-universal adoption of E10, gasoline blended with 10% ethanol, as the standard automotive fuel grade in the US. This outcome predates most current volume mandates because of ethanol's octane boosting and oxygenate capacity that requires expensive additives. The current 14 billion gallon ceiling on conventional corn ethanol under the RFS how fuel suppliers already blend approximately 10% of ethanol "with or without the RFS, because doing so supplies needed levels of octane and oxygenate," [6].

Additionally, the most significant part of the RFS driven formulation regard concerns of lifecycle emissions and land use. In a landmark study by Lark et al. the production of corn-based ethanol in the US "has failed to meet the policy's own greenhouse gas emissions targets and negatively affected water quality, the area of land used for conservation and ecosystem processes." The study concluded that the RFS caused a persistent 30% increase in corn prices which drove substantial land conversion and generated lifecycle greenhouse gas emissions at least as high as those of petroleum fuels that the ethanol was intended to replace [7]. These findings have important implications for re-assessing the design of volumetric mandates by clarifying that biofuel gallons are not equivalent to tons of avoided carbon dioxide emissions.

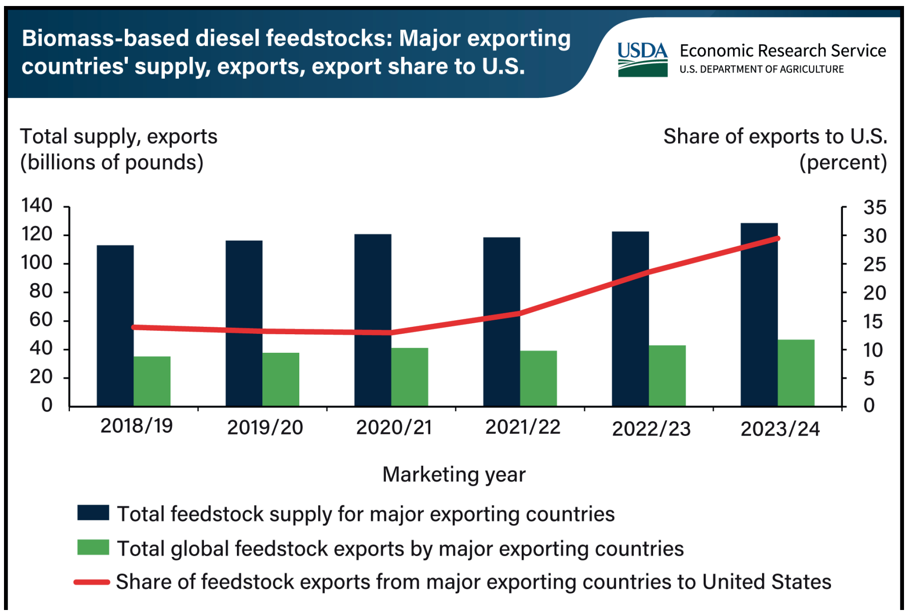

Figure 2: The supply of major exporting countries, exports, and shares to the US of biomass-based diesel feedstocks determined by the USDA Economic Research Service. Reproduced from Major exporting countries increasing exports of raw materials for U.S. production of biomass-based diesel fuels (2025) under the CC0 Public Domain Dedication [8].

Additionally, the more dynamic area of RFS-driven formulation change has been in the biomass-based diesel and renewable diesel segments. To meet growing volume obligations that cannot be entirely fulfilled by ethanol, refiners have begun analyzing hydrogenated vegetable oils and animal fats to produce renewable diesel. Gerveni et al. identifies the interconnected nature of biomass-based diesel policy as the "policy stack" [3]. Furthermore, the USDA identified that imported biodiesel feedstocks including used cooking oil, tallow, and canola oil all increased substantially in 2023 and 2024 as domestic feedstock costs remained elevated, with the US consuming nearly 30% of globally exported biofuel feedstocks in the 2023-2024 marketing year supported by Figure 2 [9]. The share of global exports that export feedstock to the US is shown by the redline to be increasing at a steady rate, especially from 2021 onwards.

The RFS has also created pressure to commercialize cellulosic biofuels, fuels derived from non-food plant matter such as agricultural residues and woody biomass. However, cellulosic production has consistently fallen short of mandated volumes, requiring the EPA to exercise statutory waiver authority. This recurring pattern illustrates a need for initiative in the RFS where mandating volumes for technologies that have not been fully integrated at a commercial scale, creating compliance stress without accelerating the underlying innovation.

2. Sustainable Aviation Fuel (SAF) Mandates and Global Decarbonization

2.1 Implementing the Framework of RefuelEU

Aviation is consistently one of the hardest sectors to decarbonize, due to the energy requirements of jet fuel and the long asset lifetimes of aircraft. Khujamberdiev et al. conducted a study and concluded that SAF technologies, including hydro processed esters and fatty acids (HEFAs), Fischer-Tropsch fuels, and alcohol-to-jet processes, have significant reductions in greenhouse gas emissions contributing to a cleaner environment. However, these SAF technologies face significant adoption challenges in the economic supply chain perspective. If SAF production has a 57% annual increase between 2022 and 2023, the study predicts that achieving net-zero emissions could be attainable [10].

The EU's ReFuelEU is part of the aviation framework and is a model as the most comprehensive SAF mandate in effect. The framework was finalized in 2023 and was placed into use in 2025. The regulation requires all aviation fuel suppliers to blend a minimum share of SAF into jet fuel at EU airports: 2% beginning in 2025 which then increases to 70% by 2050 [11]. Moreover, the mandate has a sub target that requires synthetic e-fuels to constitute at least 0.7% of aviation fuel by 2030 and 35% by 2050. According to the European Commission, this measure alone could reduce aircraft carbon dioxide emissions by two-thirds in 2050 compared to if no action is taken [12].

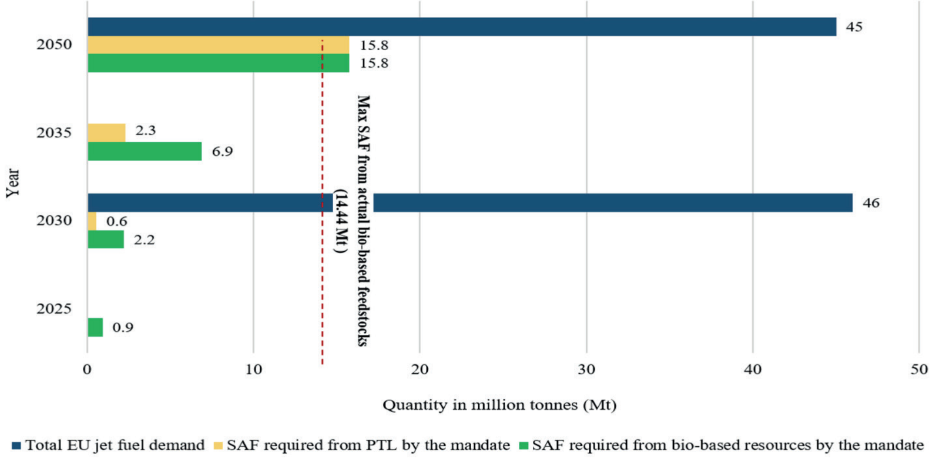

Figure 3: Potential of Biobased SAF to meet the EU targets in 2050. Reproduced from MDPI, Analysis of the Potential of Meeting the EU's Sustainable Aviation Fuel Targets in 2030 and 2050. (2023) under the CC 4.0 Creative Commons License [13].

The UK has also adopted a parallel framework through the Renewable Transport Fuel Obligations (SAF) Order 2024 which was effective at the start of 2025. The mandate requires SAF to make up 2% of the aviation fuel mix in 2025, increasing to 10% by 2030 and 22% by 2040 [11]. Specifically, this framework has a greater emphasis on reducing dependence on HEFA-based SAF, whose allowable share can decline from 100% in 2025 to 42% in 2040, with a dedicated sub-mandate for Power to Liquid SAF. Figure 3 depicts the mandates of biobased SAF and their respective EU targets for each year. As jet fuel demand is projected, the mandates show that the maximum possible SAF production from actual bio-based feedstocks is 14.44 Mt in 2050 where at least 15.8 Mt produced from bio-based feedstocks. Consequently, Figure 3 shows how the implementation of this policy needs significant deliberation to produce biomass capable of fulfilling these demands.

2.2 Gaps with Production Capacity

The central challenge for SAF policy is a stark gap between mandated demand and available production capacity. Martulli et al. cited that despite the announced production capacity of 9.1 million tons per year globally by 2024, only 24% of the announced capacity was realized on time. Over 40% of the announced capacity intended for 2030 was also reported to face risks of delays or cancellations. The study projected that global and EU SAF capacity would fall short of respective 2030 targets by 42% and 18% [14]. This evidence suggests that mandated blending requirements cannot substitute for physical infrastructure investments that only time and capital can make.

SAF mandates are fundamentally supply-chain creation tools. By writing future demand into the law, they provide the market certainty needed to justify substantial capital investments to build commercial-scale SAF production facilities. The EU reinforced this signal through financial mechanisms. Specifically in 2024, the European Commission set aside 20 million emissions allowances valued at approximately 1.5 billion Euros to support alternative fuel uptake [15].

3. Regulating Carbon Intensity: Emission Standards as Policy Levers

3.1 The California Low Carbon Fuel Standard (LCFS)

While the RFS mandates specific volumes and blending shares, California's Low Carbon Fuel Standard (LCFS) has a different approach by setting declining carbon-intensity (CI) benchmarks. Results of the CI reduction are reported annually with the targets showing promising results in CI reduction. This allows any fuel that beats the benchmark to generate tradable credits while fuel with higher CI generates deficit. The CI benchmarks are exceptionally significant to the LCFS program, identified by Table 1 from a study by Karnama et al. The table shows that the certificate receivers are reliant on definite CI reduction below annual targets, conveying the key part of the standard. Therefore, the performance based architecture is technology-neutral in principle, rewarding the cleanest fuels regardless of the source [16].

Table 1: Identification of LCFS Certificate Market. Reproduced from MDPI (2018), Impacts of Low-Carbon Fuel Standards in Transportation on the Electricity Market under the CC 4.0 Creative Commons License [17].

Market	Main Goal	Players	Certificate Receivers	Quota Obligation
LCFS	Promote low-carbon transportation fuels	Energy providers for transportation	One credit for CI reduction below decreasing annual targets	One credit for sales of fuel with higher CI than LCFS annual target

In a study by Axsen and Wolinetz on LCFS programs, they concluded that "low-carbon fuel standards have helped reduced GHG emissions, can effectively complement carbon pricing, and have received substantial public support in recent years," [18]. They further noted that California's LCFS was "developed as a reaction to the US national biofuel blending mandate, which required usage of biofuels, but initially did not differentiate biofuels based on the carbon intensity of their different feedstocks and production methods". Therefore, this makes it a precision instrument designed to correct the blunt instrument failures of the RFS.

3.2 The Consequences of Fuel Formation

The LCFS has produced measurable changes to California's fuel mix. By assigning each fuel pathway a lifecycle CI score that accounts for feedstock production, manufacturing, transportation, and combustion, the program creates granular incentives for fuel producers to reduce emissions at every stage of the supply chain. Electricity and hydrogen for vehicles, renewable diesel, biomethane, ethanol, biodiesel, and alternative jet fuel all participate in the LCFS as low-CI alternatives [16].

The 2024 LCFS amendments introduced important structural changes affecting which fuels and feedstocks can generate credits. For instance, credits for hydrogen produced by fossil natural gas will be eliminated by January 1, 2035. The amendments also limit credits for biodiesel using virgin soybean and canola oil to 20% of annual production, pushing the industry toward waste-based feedstocks. Beginning with 2024 reports, all existing fuel pathways must transition to CARB's updated GREET 4.0 lifecycle accounting model [19].

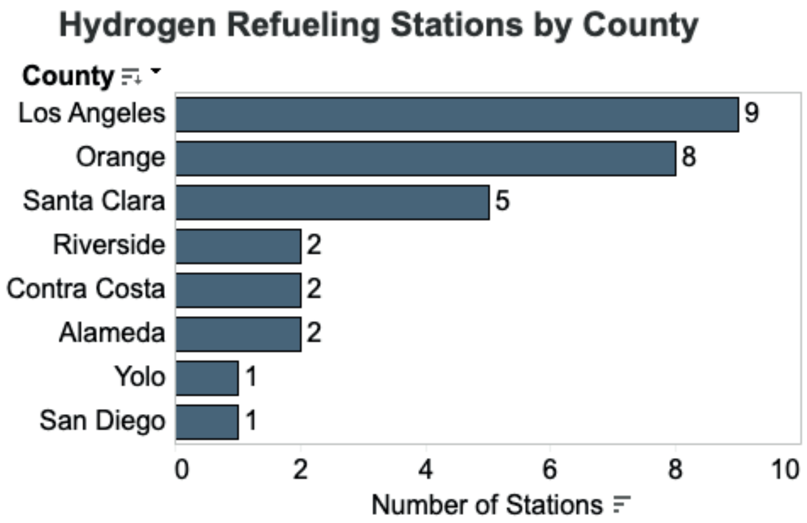

Figure 4: Light Duty Open Retail Hydrogen Refueling Stations by County in California. Reproduced from the California Energy Hydrogen Refueling Stations in California (2026) under the CC0 Public Domain Dedication [20].

Additionally, the LCFS has supported infrastructure development beyond liquid fuels. Since October 2024, 71 hydrogen refueling stations and 749 fast EV charger sites have been approved under LCFS infrastructure provisions [21]. This cycle is proven by the openings of hydrogen refueling stations in Figure 4, showing the ultimate result of the policy's improvement. CARB projected that as consumers shift to lower CI-fuels and more efficient vehicles, fuel costs per mile will decrease by 42% in 2045, translating to more than $20 billion in annual fuel expenditure savings.

4. Comparing Policies and their Cumulative Effects

4.1 Different Approaches: Volume vs Carbon Intensity

The RFS and LCFS represent distinct approaches to regulatory design. The RFS is a quantity mandate by requiring a specified number of renewable fuel gallons in the market, predictable volume demand standards. On the other hand, the LCFS is a price-on carbon mechanism which rewards marginal reduction in carbon intensity which creates continuing incentives for fuel producers to seek lower CI feedstocks, production processes, and supply chain optimizations.

One practical illustration involves corn ethanol. Under the RFS, corn ethanol is a qualifying conventional biofuel with a compliance pathway. However, under the LCFS, the CI of corn ethanol varies significantly with the production facility depending on the energy source powering the distillery, whether the plant captures biogas, and the agricultural practices used to grow corn. Therefore, the LCFS creates incentives for ethanol producers to invest in carbon reduction within the corn ethanol category, while the RFS creates no marginal incentive when volume compliance is achieved. Gerveni et al. study also shows that policy interaction confirms that both RFS and LCFS are functionally complementary where RFS drives volumes and LCFS drives quality within those volumes [3].

4.2 Interaction Effects and the Policy Stack

Although multiple overlapping policies apply to the same fuel or producer, interaction effects can produce unexpected outcomes. In Gerveni et al. study, they identified the interconnected nature of biomass-based diesel as a "policy stack" dynamic that "cannot be fully understood one policy at a time". They noted that renewable diesel boom of 2021-2024 was not only driven by RFS in isolation but also through the interaction of RFS compliance needs, LCFS carbon-intensity targets, and the economics of renewable diesel as a drop-in replacement [3]. RFS volume obligations, 45Z tax credits, LCFS credits, and state-level incentives are all ways that can make the economic case for certain fuel pathways compelling at relatively high production costs but can also distort feedstock markets in ways that undermine sustainability goals.

The global biofuel market was estimated in 2025 at $160.5 billion and is expected to grow at a CAGR of 10.3% through 2035, driven in part by "continuous and exponential mandates for decarbonization in transport," [22].While environmentally motivated, the growth requires careful monitoring to ensure that feedstock sourcing does not undermine the lifecycle emission reductions that justify the mandates in the first place. This concern is directly supported by the PNAS findings on corn ethanol land use change.

Additionally, vehicle emissions standards also interact with fuel policy in ways that can either amplify or undermine renewable fuel demand. Growth energy has argued that the EPA's proposed tailpipe emission standards risk limiting the use of liquid biofuels and undermining growth in the bioeconomy by failing to credit fuel composition improvements in emission calculations [23]. Axsen and Wolinetz's study also proves that policy mixes cautions against siloed regulatory design, taking into account that overlapping climate policies for vehicle and fuels can produce conflicting incentives and redundancies [18].

5. Critical Assessment: Achievements, Limitations, and Emerging Directions

5.1 What Policy has Achieved

The regulatory frameworks in this paper have all produced measurable results. For the RFS, a multi-billion-gallon renewable fuel market was created. In Iowa alone, the biofuels industry consumed nearly 60% of the 2024 corn crop and produced 4.61 billion gallons of fuel ethanol [9]. The SAF mandates have catalyzed investment commitments and technology development that was commercially unproven just a decade ago. The LCFS has successfully reduced the carbon intensity of California's transportation fuel pool, with the dramatic shift to net deficit territory in Q3 2025 confirming that the 2024 amendments are already reshaping the market [24].

5.2 Limitations and Unresolved Tensions

Despite these achievements, limitations remain. Lark et al. highlight that the most significant empirical challenge is the RFS' environmental rationale where lifecycle GHG emissions of corn ethanol produced to meet RFS mandates "are no less than those of gasoline, and are likely even greater when land use emissions are included" [7]. These findings suggest that profound advances in both technology and policy design that are needed to achieve the intended environmental benefits of biofuel production and use, that the volumetric mandates without robust lifecycle accounting are insufficient.

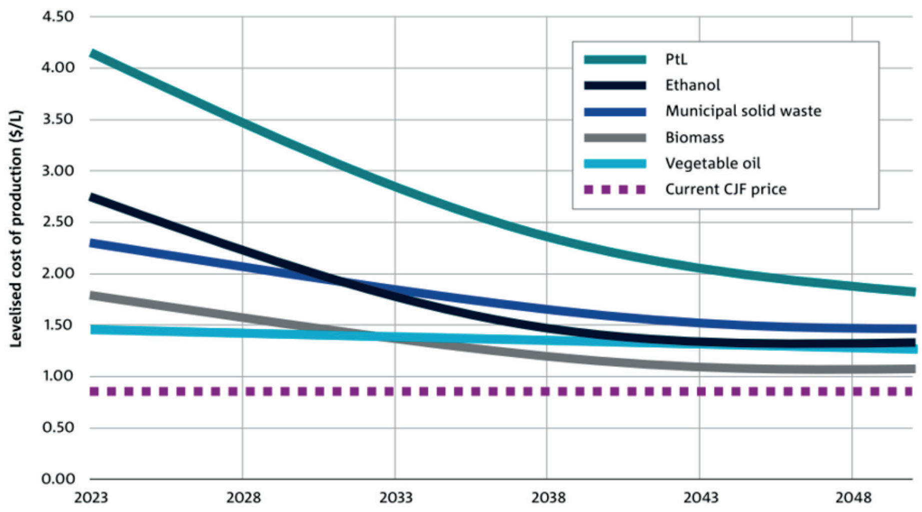

Figure 5: Projected levelized cost of production for various fuel sources from 2030 to 2050. Reproduced from MDPI (2025), Sustainable Aviation Fuels: A Review of Current Techno Economic Viability and Life Cycle Impacts under the CC 4.0 Creative Commons License [17].

Moreover, the SAF policy landscape has a stark gap between ambition and current trajectory. In Figure 5, the cost trajectory of alternative fuels overtime is compared to a baseline reference for standard conventional fuel. The graph illustrates how economic uncompetitiveness can suppress commercial adoption and can potentially keep production rates restricted and below the demand levels required by decarbonization mandates. Lark et al. quantified this gap where a scale-up scenario analysis showed that global SAF capacity would fall short of 2030 policy target by 42% [14]. This evidence underscores that the mandate can only drive production scale-up if regulatory certainty persists long enough to justify the capital investment cycles involved, and if complementary support mechanisms de-risk production facilities.

5.3 The Need for Political Continuity

Regulatory effectiveness depends critically on the continuity of the policy implementation. The RFS has been subject to significant volatility through the SRE granting process [25]. In the SAF domain, Climate Catalyst noted that while Refuel EU Aviation entered in force in 2025, the political environment has grown challenging with more right-leaning parties gaining seats in European Parliament, shifting policy priorities away from Green Deal implementation [26].

Additionally, the biofuels sectors have repeatedly demonstrated extreme sensitivity to policy decisions. In the study by Axsen and Wolinetz, they concluded that a well-designed LCFS would be an efficient complement to carbon pricing, but only if its trajectory is credible and stable enough to warrant capital investments in refuel pathway development.

Conclusion and Future Outlook

The Renewable Fuel Standard, Sustainable Aviation fuel mandates, and carbon-intensity based standards are complementary approaches using regulatory authority to reshape the fuel in vehicles, aircrafts, and ships. Each one demonstrates capacity to alter fuel formulation and redirect investment capital which changes the supply chain developments at both the small and large scale. Each also has revealed limitations of its own design logics: volumetric mandates that drive land conversion undermine their own climate rationale. Blending requirements race ahead of production capacity, and carbon-intensity benchmarks can create credit surpluses when stringency falls below market reality.

The gap between policy ambition and physical reality is an ongoing issue that remains central to fuel policy. Bridging this gap requires complementary technology investment, infrastructure development, and stable mandates that can ensure the lifecycle of emission reductions.

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