REPORT

INDIA'S AVIATION OPPORTUNITY: TURNING AGRICULTURAL RESIDUE AND LOW-COST SOLAR INTO COMPETITIVE SUSTAINABLE AVIATION FUEL WITH POWER-AND-BIOMASS-TO-LIQUIDS

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ABSTRACT

India faces several threats from its rapid development, including increasing reliance on imported crude oil, worsening air pollution from agricultural residue fires, and rising greenhouse gas emissions from its aviation sector. However, India also has emerging advantages in its world-leading low-cost green hydrogen and development of large-scale agricultural residue supply chains. This paper provides a vision for how India can leverage these advantages to develop a power-and-biomass-to-liquids (PBtL) sustainable aviation fuel (SAF) industry that can deliver a domestic cost-competitive drop-in alternative to imported crude oil-dependent fossil jet fuel, create value from agricultural residue that is currently burned, and decarbonize India's aviation sector. We show that PBtL is ready for commercial demonstration and growth, outcompetes other SAF technologies on cost, carbon intensity, and resource efficiency, and delivers a range of co-benefits such as avoiding premature deaths from local air pollution. Specifically, India's PBtL route can produce SAF at costs up to roughly 40% below global SAF benchmarks, driven by record-low green hydrogen prices and low agricultural residue costs. These results suggest that, until Indian PBtL SAF can compete directly with fossil jet fuel, it can economically serve rising international SAF demand while hedging against crude oil price spikes. We also show that PBtL SAF has an enormous market size and could feasibly satisfy all of India's 2050 aviation demand; that PBtL SAF production costs can fall below fossil jet fuel prices in the 2030s or earlier depending on market conditions and policy developments; and that domestic PBtL SAF has less monetary risk exposure than fossil jet fuel. We provide a spatially detailed, district-level assessment showing that surplus agricultural residue availability and low green hydrogen costs align in the areas surrounding the Delhi, Pune, and Mumbai airports, suggesting they may be best suited for supporting the PBtL industry's near-term growth. We conclude that if India can drive early investment and use smart policy to overcome first-of-a-kind deployment barriers and protect against unintended consequences, it can unlock a virtuous cycle of scale and cost reduction that boosts India's self-reliance, public health, and global climate leadership.

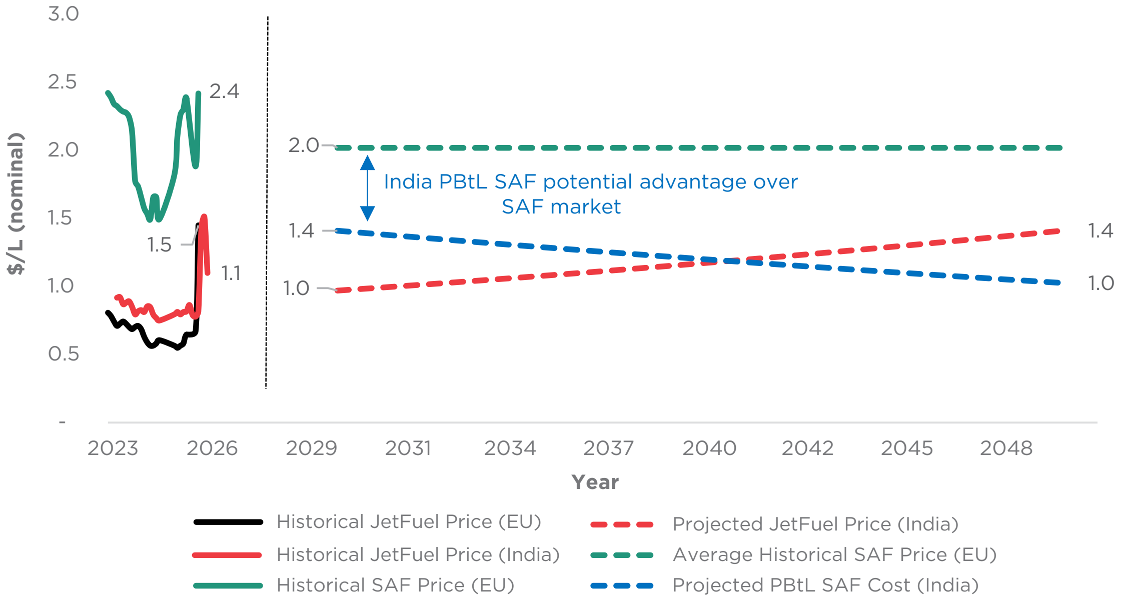

FIGURE A-1: Comparison of projected Indian power-and-biomass-to-liquids (PBtL) sustainable aviation fuel (SAF) production costs for a project commissioned in 2030 vs. historical Indian and European Union (EU) jet fuel market prices, historical and average EU SAF market prices, and projected imported Indian fossil jet fuel prices. Sources: World Economic Forum, Argus, and IndianOil.[1–3]

Notes: See Appendix A for Indian fossil aviation turbine fuel (ATF) and PBtL SAF levelized cost projection methodology. Prices are converted to United States dollars per liter using a jet fuel density of 0.808 kilograms per liter. The PBtL SAF cost declines as Indian Rupee-denominated green hydrogen and renewable electricity costs fall, with renewable power locked in via long-term Indian Rupee-denominated power purchase agreements; the imported ATF (business-as-usual) price rises over the projection period due to inflation.

DATA AVAILABILITY

Data used to estimate district-level production quantities and costs of SAF are available on our open-source dashboard.

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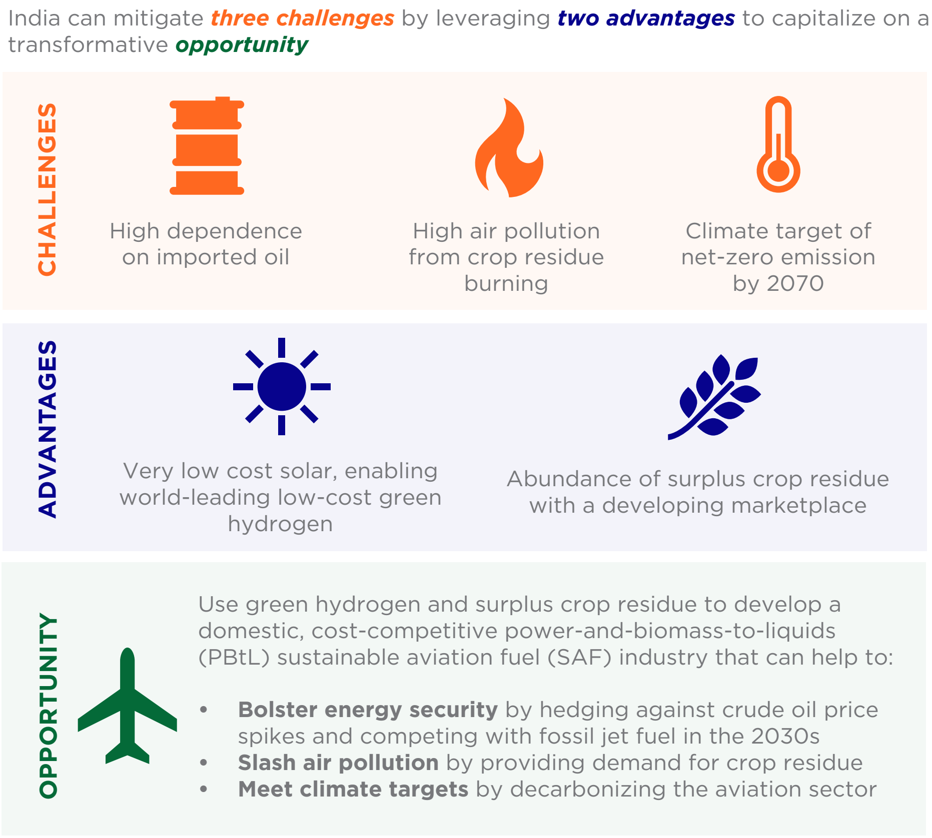
1. INTRODUCTION

1.1. INDIA'S SUSTAINABLE AVIATION FUEL OPPORTUNITY

India stands at a pivotal moment to mitigate three national challenges by leveraging two emerging advantages to capitalize on a transformative sustainable aviation fuel opportunity. How India responds to this moment could have long-lasting implications for its energy security, economic development, public health, and ability to meet its climate targets.



India can mitigate ***three challenges*** by leveraging ***two advantages*** to capitalize on a transformative ***opportunity***

CHALLENGES

High dependence on imported oil

High air pollution from crop residue burning

Climate target of net-zero emission by 2070

ADVANTAGES

Very low cost solar, enabling world-leading low-cost green hydrogen

Abundance of surplus crop residue with a developing marketplace

OPPORTUNITY

Use green hydrogen and surplus crop residue to develop a domestic, cost-competitive power-and-biomass-to-liquids (PBtL) sustainable aviation fuel (SAF) industry that can help to:

- **Bolster energy security** by hedging against crude oil price spikes and competing with fossil jet fuel in the 2030s
- **Slash air pollution** by providing demand for crop residue
- **Meet climate targets** by decarbonizing the aviation sector

FIGURE 1.1.1: India's sustainable aviation fuel opportunity.

THREE NATIONAL CHALLENGES

The first challenge is India’s high dependence on imported crude oil. India has a mission of achieving self-reliance—defined by goals like reducing import dependence and strengthening domestic supply chains—which in turn is closely linked to its goal of becoming a developed nation by 2047.[4] Unfortunately, India imports nearly 90% of its crude oil, which has exposed it to economic turmoil from geopolitical events outside of its control—most recently from Iran closing the Strait of Hormuz in response to strikes by the United States (U.S.) and Israel, causing fuel price spikes, unsustainable government spending, rationing, and flight cancellations, among other crises.[i ,5–8] Among India’s many uses of oil, the aviation sector looms large: while aviation turbine fuel (ATF) made up less than 4% of India’s oil products consumption in 2024, ATF demand is on a trajectory to rise approximately six-fold by 2050.[ii ,9] This suggests the aviation sector risks making India even more vulnerable to crude oil price shocks and supply shortages.

The second challenge is India’s severe air pollution. For example, New Delhi has the worst air quality of any global capital city, and India includes 17 of the 30 cities with the world’s worst air pollution.[10] A major contributor to this dilemma is seasonal crop residue combustion. India’s farmers burn an estimated 130 million metric tons (Mt) of agricultural residue annually as a fast and cheap method of clearing fields ahead of the next crop cycle.[iii] The particulate matter pollution from these fires is estimated to have caused between 44,000 and 98,000 premature deaths annually in India from 2003 to 2019, and it is responsible for more than 40% of this pollution in Delhi’s peak season.[11,12] It also contributes to lower work attendance and performance, reduced economic activity, higher healthcare expenditures, worsened soil quality, and lower tourism.[10,12]

The third challenge is India’s shared imperative to decarbonize its economy. India’s carbon dioxide (CO2) emissions have been skyrocketing this century, tripling since 2000.13 While India is on track to meet its 2030 and 2035 climate goals, analysts stress that much more ambitious actions will be needed across all sectors to achieve its target of net-zero greenhouse gas (GHG) emissions economy-wide by 2070. [iv,14–16] As part of such planning, India must anticipate its rapidly rising demand for aviation and adjust accordingly to taper the sector’s GHG emissions over the coming decades.

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[i] Approximately 20% of the world’s crude oil flows through the Strait of Hormuz, and 84% of this oil is delivered to Asian markets. India had been relying on the strait for 40-50% of its crude oil and has had to rapidly diversify to other suppliers to close some of its supply gap.

[ii] See Section 3.1.

[iii] See Section 4.

[iv] India’s 2030 and 2035 climate goals include reducing the emissions intensity of gross domestic product by 45% and 47% (respectively) below 2005 levels, among other objectives.

TWO EMERGING ADVANTAGES

India's first advantage is its world-leading green hydrogen (H_2) prices, in turn owing to its very low solar electricity prices. India's high solar resource quality, low cost of labor, favorable supply chain access, and competitive bidding processes—paired with global trends of plummeting photovoltaic module costs—have brought its solar prices down to $0.025–0.030 per kilowatt-hour (kWh), which are among the lowest in the world.[v,17–19] India has also made the development of a domestic green hydrogen industry a national priority, supported by its $2.4 billion National Green Hydrogen Mission launched in 2023. Together, these developments have led to recent auctions revealing hydrogen prices in the range of $3.1–4.5 per kilogram (kg).[19–22]

India's second advantage is a vast agricultural residue supply, along with developing marketplaces for collecting, transporting, processing, storing, and transacting on biomass products. Recent estimates suggest India has approximately 685–700 Mt of agricultural residue, with most of it finding productive use as cattle feed, animal bedding, and a natural soil nutrient source.[23,24] The remaining estimated 210–235 Mt of "surplus" agricultural residue—of which approximately 130 Mt is currently burned in open fields and the remainder left to decompose or used informally—has mostly been a nuisance that farmers burn to dispose of, contributing to seasonal spikes in air pollution.[23,24] This surplus is a valuable product, however, having been broadly recognized as a sustainable biomass source that has far less risk of negative land use change impacts that complicate food-, feed-, and energy-crop biofuels' viability as a climate solution.[vi,25] In recent years, marketplaces have launched to help collect, aggregate, and valorize this resource. For example, BiofuelCircle's platform had roughly 0.5 Mt of biomass briquettes offered on its platform in 2025.[26] Should robust demand arise for this resource, these marketplaces would be poised to scale and supply it. See Appendix C for more detail on India's agricultural residue supply chain and marketplaces.

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[v] All monetary values in this report are in terms of United States Dollars (USD) unless otherwise stated. This is because USD is the standard unit for aviation fuel pricing, and the Indian Rupee (INR) to USD exchange rate fluctuates meaningfully year-to-year, so the choice of a single, arbitrary conversion rate would introduce false precision across the paper, particularly when comparing to other sources' aviation fuel price benchmarks.

[vi] This is only true as long as the residue is truly "surplus," i.e., such that its collection and use does not diminish soil quality (which would require extra fertilizer to mitigate) or displace other beneficial uses of this residue (if these uses then risk turning to fossil fuels or food crops as replacements for previously-used residue). For this reason, we consider 130 Mt (the amount burned in India) to be a floor for residue that can be diverted to serve a useful purpose and 210-235 Mt to be a ceiling.

ONE TRANSFORMATIONAL OPPORTUNITY

Together, India's low-cost green hydrogen and surplus agricultural residue advantages enable the cost-competitive production of "power-and-biomass-to-liquids" (PBtL) sustainable aviation fuel (SAF)—a drop-in alternative to fossil ATF with near-zero GHG emissions. By developing a domestic power-and-biomass-to-liquids sustainable aviation fuel (PBtL SAF) industry, India can mitigate its energy security, air pollution, and climate challenges, with the added benefits of boosting its economic competitiveness and providing a new revenue stream for farmers.

First, PBtL SAF can bolster India's energy security by providing a domestically-produced alternative to fossil ATF that can act as a hedge against crude oil price spikes—and crucially, that can eventually reach price parity with fossil ATF. In order to achieve this cost-competitiveness, PBtL SAF will need to scale and fall in price, and it will be able to do so by undercutting other SAF production pathways to help satisfy other countries' rising SAF blending mandates and corporations' SAF procurement goals.

Second, PBtL SAF can reduce air pollution by providing an enormous demand pull for agricultural residue, helping India's nascent biomass marketplaces and supply chains to scale. This can change the paradigm from farmers burning residue as a quick and inexpensive way to clear fields between crop cycles to farmers being paid for the collection of a now-valuable feedstock.

Third, PBtL SAF can help meet India's climate goals by providing a runway to decarbonize its aviation sector. SAF is expected to play a major role in any aviation decarbonization plan, yet other prominent SAF production pathways have run into cost, climate integrity, and resource use barriers that have capped or stunted their growth. PBtL provides a genuinely low-carbon SAF option that can achieve low costs and a balanced use of resources, enabling growth at scale.

Specifically, we find that PBtL could produce SAF at a cost that is competitive with fossil ATF prices in the 2030s, with the timing dependent on factors like crude oil prices, policies that value PBtL SAF's emissions reduction benefits, and the U.S. Dollar (USD) to Indian Rupee (INR) exchange rate. We also find that PBtL SAF production costs can undercut those of other SAF pathways in India at green hydrogen prices of $3.4/kg—a price some producers have already beat in India's recent auctions—suggesting it should be able to immediately find willing buyers in markets covered by SAF blending mandates, even at these higher initial costs.

This opportunity is enormous: surplus agricultural residue supplies are large enough for PBtL SAF to feasibly satisfy India's 2050 aviation demand. This means that if India can demonstrate and scale a PBtL SAF industry, it could provide a path to full domestic supply of stable and low-cost aviation fuel, the elimination of crop residue fires that have plagued its air quality, and the complete decarbonization of its aviation sector.

1.2. PURPOSE OF THIS STUDY

This paper presents a vision of India's PBtL SAF opportunity by demonstrating its potential and proposing initial steps for kickstarting the industry. We do not intend to predict the price trajectories of SAF pathways or fossil ATF. Instead, we choose defensible assumptions to show how PBtL SAF could be transformative if these conditions were to come to fruition, and we discuss how Indian policymakers can improve the chances of this vision becoming reality.

In Section 2, we summarize the global push for SAF and demonstrate why PBtL is the best option for India. Rising regulatory and corporate demand for SAF means Indian SAF producers will have access to buyers who are willing to pay a premium over fossil ATF, reducing the financial burden India must overcome to commercialize, scale, and lower the cost of SAF. Our analysis shows why PBtL is preferable to the many other prominent SAF production pathways that India may be considering, emphasizing the importance of prioritizing it over alternatives. Specifically, this section provides an overview of the global SAF context, descriptions of the main SAF production pathways, comparisons of technology readiness levels, techno-economic analyses, lifecycle analyses, and co-benefits under India-specific conditions, and a summary of the pathways' economic and environmental considerations.

In Section 3, we move to compare Indian PBtL SAF with fossil ATF, showing how the former can hedge against the price volatility of the latter and eventually achieve price parity. Under this trajectory, Indian PBtL SAF becomes valuable not merely by boosting economic prowess through exports to SAF buyers abroad, but by bolstering energy security as a domestically produced aviation fuel. Specifically, we estimate the total market size for PBtL SAF relative to India's aviation market in 2050, then compare PBtL SAF and fossil ATF economics—including on market dynamics, monetary risk exposure, and combined effects.

In Section 4, we discuss how India can choose sites to give the nascent PBtL SAF industry the best chance of success and shed light on how it might scale up from there. We do this by providing a spatial analysis of solar resource quality, agricultural residue availability, and major airport locations, examining where the three overlap to identify targets for first-of-a-kind projects and midstream infrastructure investments alike.

In Section 5, we summarize our key results, provide a brief discussion of unintended consequences and how to avoid them, and offer an initial list of policy recommendations to help Indian policymakers and developers seize this opportunity. We also provide appendices describing our methods in more detail (Appendix A), offering extra detail on certain technical points and assumption choices (Appendix B), and characterizing India's agricultural residue supply chain.

2. POWER-AND-BIOMASS-TO-LIQUIDS VS. OTHER SUSTAINABLE AVIATION FUEL PATHWAYS

In this section, we summarize the global SAF context, introduce the most prominent SAF pathways, evaluate their technological maturity, production costs, scalability, and co-benefits under India-specific conditions, and conclude that India stands to gain the most from prioritizing PBtL over other SAF pathways.[vii]

2.1. GLOBAL SAF CONTEXT

Aviation is one of the most challenging sectors to decarbonize, largely due to its need for highly energy-dense, lightweight fuels for passenger- and cargo-carrying aircraft to achieve liftoff, maintain high speeds, and travel across continents. Global air travel has also continued to rise and is projected to nearly triple by 2050, driven in part by rising income in much of the world.[27] This has created a dilemma of how to accommodate soaring demand while still meeting climate commitments.

Battery-electric aircraft and hydrogen propulsion remain technically and economically unviable for most commercial aviation for the foreseeable future. Both technologies benefit from not having to secure a source of sustainable carbon, and electric aircraft benefit further from a substantial energy efficiency advantage (at least for shorter-distance flights).[28] However, both are limited in the near term by a need for new aircraft and airport infrastructure, and in the longer term by their lower energy densities relative to ATF.[29,30] These realities mean SAF is the only realistic option for decarbonizing commercial aviation in the near-to-medium term—given that it can replace fossil ATF in today's aircraft—and will likely remain important in the long term for at least long distance routes due to its high energy density.

This understanding has translated into government blending mandates for and voluntary corporate procurement of SAF. Notwithstanding recent backtracking in the U.S., many countries are signaling predictable, long-term demand for SAF. This is most prominent in the European Union (EU) via its RefuelEU Aviation regulation, which requires a 2% SAF blend in 2025 that rises to 70% by 2050, as well as the United Kingdom's (UK) SAF mandate

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[vii] India-specific conditions reflect localized capital expenditure adjustments, domestic labor and operating cost assumptions, current Indian-market feedstock prices, and other factors deriving from Indian sources.

that rises from 2% in 2025 to 22% by 2040.[31,32] However, blending targets are already established from Brazil to Thailand to the Republic of Korea, and India hosts its own SAF blending goal of 5% by 2030 (initially only for international flights).[33,34] Additionally, major airlines such as United, Delta, Lufthansa, and British Airways have signed multi-year SAF offtake agreements with many extending into the 2030s, while others including Emirates, Air France–KLM, and Qantas have committed to long-term procurement strategies aligned with national mandates and corporate net-zero pledges.[35]

There are many different methods of producing SAF, but they all require a sustainable carbon feedstock and a clean energy source. These methods differ in technological maturity, cost, lifecycle carbon intensity, resource intensity (in using feedstocks, electricity, land, and water), and co-benefit profiles. SAF production technologies must receive technical certification to be approved for safe use in aircraft, and they must also receive carbon intensity certification to comply with regulatory mandates and emissions accounting frameworks or qualify for incentive programs—see Appendix B.2 for more detail.

The primary barrier to scaling up SAF production is cost, particularly in the highly competitive environment of the airline industry where fuel makes up 20–30% of operating costs globally and is even higher in India at approximately 30-40% due to elevated ATF taxes.[viii,36,37] SAF is currently much more expensive than fossil ATF, owing to a combination of: low availability of and high competition for today's main feedstocks (primarily waste oils and fats); the relatively early-stage maturity of several advanced SAF pathways that can use other feedstocks; the higher cost of renewable energy and lower availability of sustainable carbon feedstocks in jurisdictions with high SAF mandates; and insufficient financial support mechanisms to bridge the price differential between SAF and conventional jet fuel.

For example, SAF prices in Northwest Europe and Asian markets were 2.5–4 and 3.5–4.5 times more expensive than fossil ATF in 2025, respectively.[38,39] SAF prices were also several times more volatile than fossil ATF in recent years (prior to the Strait of Hormuz closure), reflecting both limited SAF supply and the price sensitivity of today's dominant feedstocks.[38] Yet emerging synthetic SAF production pathways (i.e., those that synthesize SAF from hydrogen and carbon-containing feedstocks rather than refine it from oils and fats) can reportedly come in at prices several times more expensive than today's conventional SAF.[38]

As a result, both current global SAF supply and investments for future production remain a fraction of what is required to meet policy goals and private pledges. The International Air Transport Association (IATA) forecasts that SAF will have to contribute 65% of total aviation emissions reductions, which would require upwards of 360 Mt (446 million kL) of SAF annually by 2050.[40] However, the current trajectory falls dramatically short of achieving this goal—the IATA projects around 2.4 Mt (3.0 million kL) of SAF in 2026, which is only 0.8% of global jet fuel demand.[41] This would represent a mere 26% increase from

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[viii] In the months following the closure of the Strait of Hormuz, Indian ATF expenses reportedly reached 55-60% of airline operating costs.

2025, slowing from a doubling of SAF production from 2024 to 2025.[41] This deceleration of production, paired with the very high costs of SAF in Europe, led the IATA to warn of a risk of airlines downgrading their commitments—with this already materializing through companies softening language around SAF targets.[41,42]

Mandated SAF demand is far outpacing production. Buyers may not have the appetite to pay exorbitant prices, but based on today's SAF selling at prices several times higher than fossil ATF, there is clear evidence of a green premium. These dynamics provide the conditions for India to scale cost-competitive SAF production, as Indian developers can sell into premium regulatory markets abroad to drive costs down and toward domestic fossil ATF parity. Capitalizing on this opportunity will require pursuing the most advantageous SAF production pathway.

2.2. OVERVIEW OF SAF PRODUCTION PATHWAYS

The most prominent SAF production pathways are hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (ATJ), and Fischer-Tropsch (FT), with FT including biomass-to-liquids (BtL), power-to-liquids (PtL), and power-and-biomass-to-liquids (PBtL). "Liquids" refers to hydrocarbon liquid fuels produced by these processes, which can be refined or fractionated into jet-grade kerosene (e.g., SAF), diesel, and naphtha. Below, we introduce each pathway, accompanied by process-flow diagrams (Figures 2.2.1–2.2.5) that outline the conversion steps from feedstock collection through to final SAF output.

Hydroprocessed esters and fatty acids (HEFA) converts fats, oils, and greases (FOG) into jet fuel, with hydrogen used to treat and upgrade these feedstocks (without being an energetic component of the final SAF product).[ix] HEFA is today's most commercially mature and market-dominant SAF pathway, benefiting from well-established process reliability and relatively low capital and operating costs. This is reflected in its strong current and expected near-term market share: HEFA makes up about 80% of today's SAF production, and it is expected to remain the most prominent source of SAF globally through at least 2030.[43–45]

HEFA has traditionally relied on waste FOGs like used cooking oil (UCO) and tallow, as SAF mandates—such as those in the EU and UK—often restrict the use of virgin vegetable oils due to land use change concerns (e.g., expansion of palm oil cultivation into rainforests). However, these feedstocks are severely constrained, both in absolute availability and by competition from other uses like renewable diesel production.[1,46] There are already documented concerns of fraud such as virgin oil being falsely marked as UCO, which in turn has led to regulatory caps on waste FOGs for SAF production.[47–49] These considerations greatly limit HEFA's long-term contribution to the SAF market to perhaps only a few

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[ix] While HEFA has historically relied on "gray" hydrogen derived from natural gas, this analysis assumes the use of green hydrogen from water electrolysis and solar electricity.

percent of global aviation fuel demand. This has driven policymaker and developer interest in advanced pathways that can make use of other feedstocks and enable scale (i.e., ATJ and FT).

India's circumstances reflect the global situation, and even optimistic improvements in UCO or tallow collection efficiency or partial imports would be insufficient for HEFA to meet post-2030 SAF demand.[24] HEFA's potential is further constrained by developers primarily using it for renewable diesel production, with SAF being a co-product that requires additional infrastructure investment and supportive policies.[50]

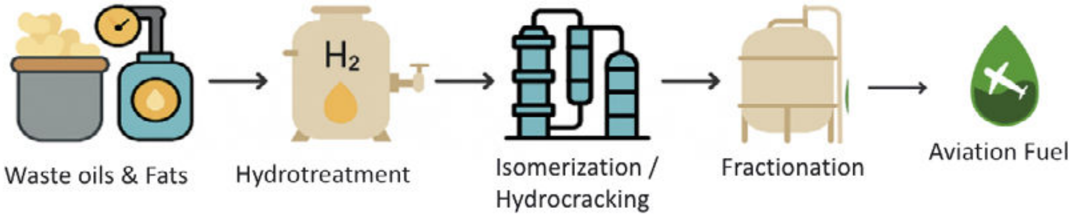

FIGURE 2.2.1: Process flow and system boundary for HEFA.

Alcohol-to-jet (ATJ) converts alcohols like ethanol into jet fuel through dehydration, oligomerization, and hydrogenation. This pathway is technologically proven and is considered attractive as a way to grow, diversify, or redirect large existing ethanol industries (predominantly used today as a fuel blend with gasoline). While ATJ SAF can benefit from this existing ethanol infrastructure, the current competition for ethanol from gasoline blending can constrain its growth and limit its cost-competitiveness. Ethanol also faces similar—if comparably less severe—land use change concerns as virgin vegetable oils when derived from food and feed crops like corn and sugarcane (deemed "first generation" or 1G), while ethanol derived from lignocellulosic residues and wastes (deemed "second generation" or 2G) is relatively inefficient (see Section 2.4.2). As a result, ATJ SAF from 1G ethanol often faces regulatory restrictions, while ATJ SAF from 2G ethanol has struggled to commercialize.[51]

India has a large and expanding ethanol ecosystem (overwhelmingly 1G ethanol), with most committed to its national petrol-blending mandate that targets a 30% blend by 2030.[52] This leaves only a small surplus available for SAF production without additional incentives or structural changes, as India controls crop usage to protect food security—and even this SAF will struggle to qualify in certain regulatory markets.[24]

Over the longer term, the increasing electrification of India's road transport sector is expected to reduce gasoline demand and, by extension, the ethanol volumes required to maintain the 30% petrol-blending target. While gasoline demand is likely to continue rising through at least the mid-2030s given India's still-growing internal combustion engine vehicle fleet, the eventual decline in favor of electric vehicles could lead to a redirection of ethanol volumes away from gasoline blending and toward SAF production.[53] This dynamic suggests ATJ may eventually have increasing access to ethanol, with its success in the SAF market depending on its competitiveness relative to other technologies (see Section 2.4), the carbon intensity score it receives or its ability to pivot to 2G ethanol (see Section 2.5), and policymakers' broader interest in supporting farmers through its ethanol industry.

FIGURE 2.2.2: Process flow and system boundary for ATJ.

Biomass-to-liquids (BtL) converts agricultural residues and forestry waste into jet fuel through thermochemical gasification, syngas conditioning, and FT upgrading.[x] Its value proposition stems from being able to convert lignocellulosic residues more efficiently than fermentation-based routes like ATJ for 2G ethanol (see Section 2.5), with this efficiency advantage contesting ATJ's advantage of having an existing infrastructure network for ethanol.

BtL's growth has been stunted globally by residue aggregation, feedstock heterogeneity, and seasonal logistics challenges. Additionally, because BtL relies solely on the syngas from biomass, the FT process is highly suboptimal: it lacks enough hydrogen to react with the carbon in producing liquids, causing a substantial fraction of this carbon to be lost as CO_2 and lowering the overall efficiency of converting biomass into liquids.

In general, BtL is attractive in India given India's large surplus agricultural residue base and the recent progress it has made in developing a residue supply chain and marketplace (see Appendix C).[23,24] However, costs and inefficiencies from BtL's hydrogen deficiency present barriers to commercialization and scale.

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[x] Syngas is a mixture primarily made up of hydrogen and carbon monoxide (CO).

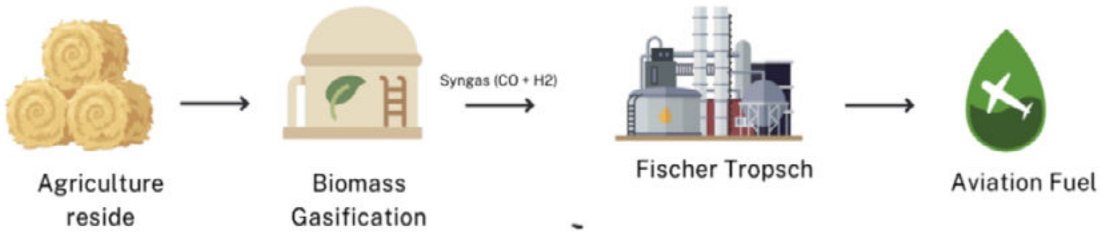


FIGURE 2.2.3: Process flow and system boundary for BtL.

Power-to-liquids (PtL), often referred to as e-kerosene or e-SAF, produces jet fuel from green hydrogen and captured CO_2, representing a high-potential but early-stage SAF pathway that can avoid reliance on biofeedstocks entirely. The "power" in PtL refers to using electricity as the primary feedstock for both hydrogen production (i.e., splitting water into hydrogen and oxygen through electrolysis) and CO_2 capture—such as from industrial point sources or via direct air capture. If using clean electricity and a net-zero source of carbon (e.g., from sustainable biofeedstocks or the air), PtL can achieve near-zero lifecycle emissions. In the nearer term, regulatory frameworks for SAF often allow the use of fossil fuel- or process-based CO_2 as a means to scale both PtL and carbon capture technology, so long as the emissions savings are not double-counted for SAF and the originating industrial process.

PtL's growth has been constrained worldwide and in India by high electricity requirements (particularly for hydrogen electrolysis and direct air capture) and the scarcity of CO_2 capture and transport infrastructure (particularly for industrial point sources).[xi,54] We focus our analysis on CO_2 captured from industrial facilities due to point-source carbon capture equipment's higher technological maturity, lower cost, and greater role in Indian planning relative to direct air capture.[xii,55–57] However, PtL will need to eventually transition to non-fossil CO_2 sources to remain relevant for SAF production long term.

[xi] India currently has no commercial-scale carbon capture projects, and planned projects are largely confined to industrial point sources such as refineries and cement plants.

[xii] Direct air capture can be on the order of 20 times more expensive as a CO_2 source relative to point-source capture, so we did not consider it in our analysis.

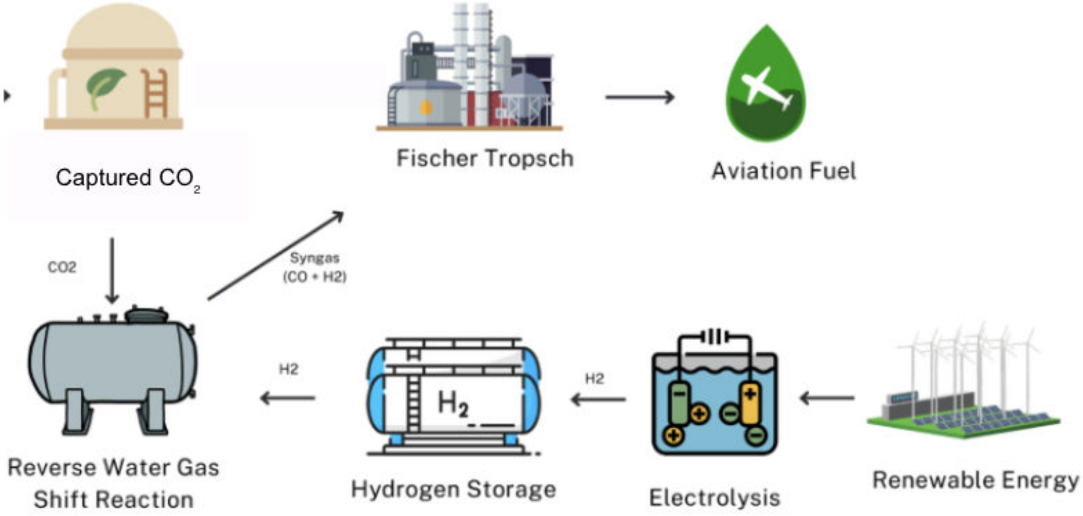


FIGURE 2.2.4: Process flow and system boundary for PtL.

Power-and-biomass-to-liquids (PBtL) is an emerging SAF pathway that combines the strengths of BtL and PtL in a single integrated process: it uses agricultural residue as a sustainable, lower-cost carbon source (the BtL strength) and electrolytic hydrogen to overcome BtL's hydrogen deficit (the PtL strength), avoiding both BtL's carbon inefficiency and PtL's higher dependence on electricity and carbon capture infrastructure. PBtL is functionally the BtL process paired with electrolytic hydrogen to improve the stoichiometric ratio of hydrogen and carbon monoxide (CO), boosting liquids output. A reverse water-gas shift (rWGS) step can further improve liquids yields by recycling remaining CO_2 from the FT process back into the reactor as CO, paired with additional green hydrogen.

PBtL is often ignored in SAF literature and feasibility studies as it can seem to instead combine BtL and PtL's perceived downsides—namely reliance on agricultural residue (which has faced challenging collection, separation, processing, and storage logistics) and green hydrogen (which remains very expensive in many parts of the world). However, PBtL is ripe for success in India, as India has seen tremendous progress in building a supply chain and marketplace for its vast surplus agricultural residue supply as well as in developing a low-cost green hydrogen industry grounded in its high-quality solar resource. As these conditions continue to improve, PBtL's advantage over other SAF pathways will only grow, at least until surplus residues remain available.

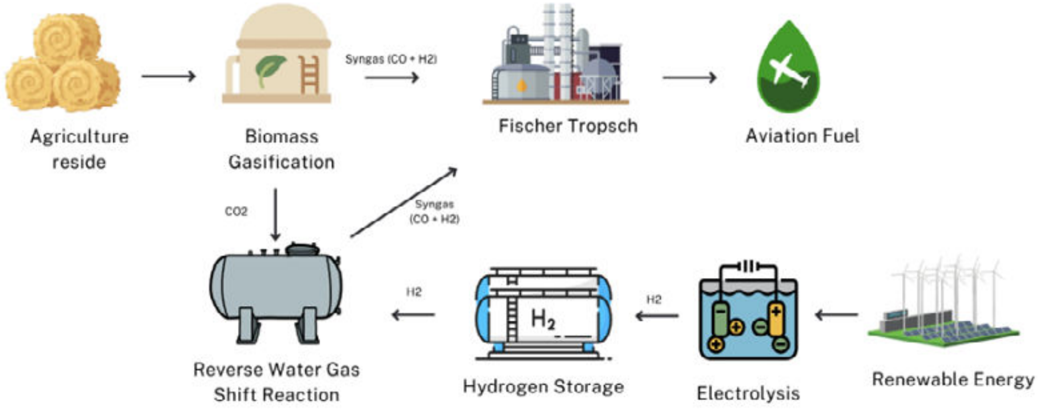
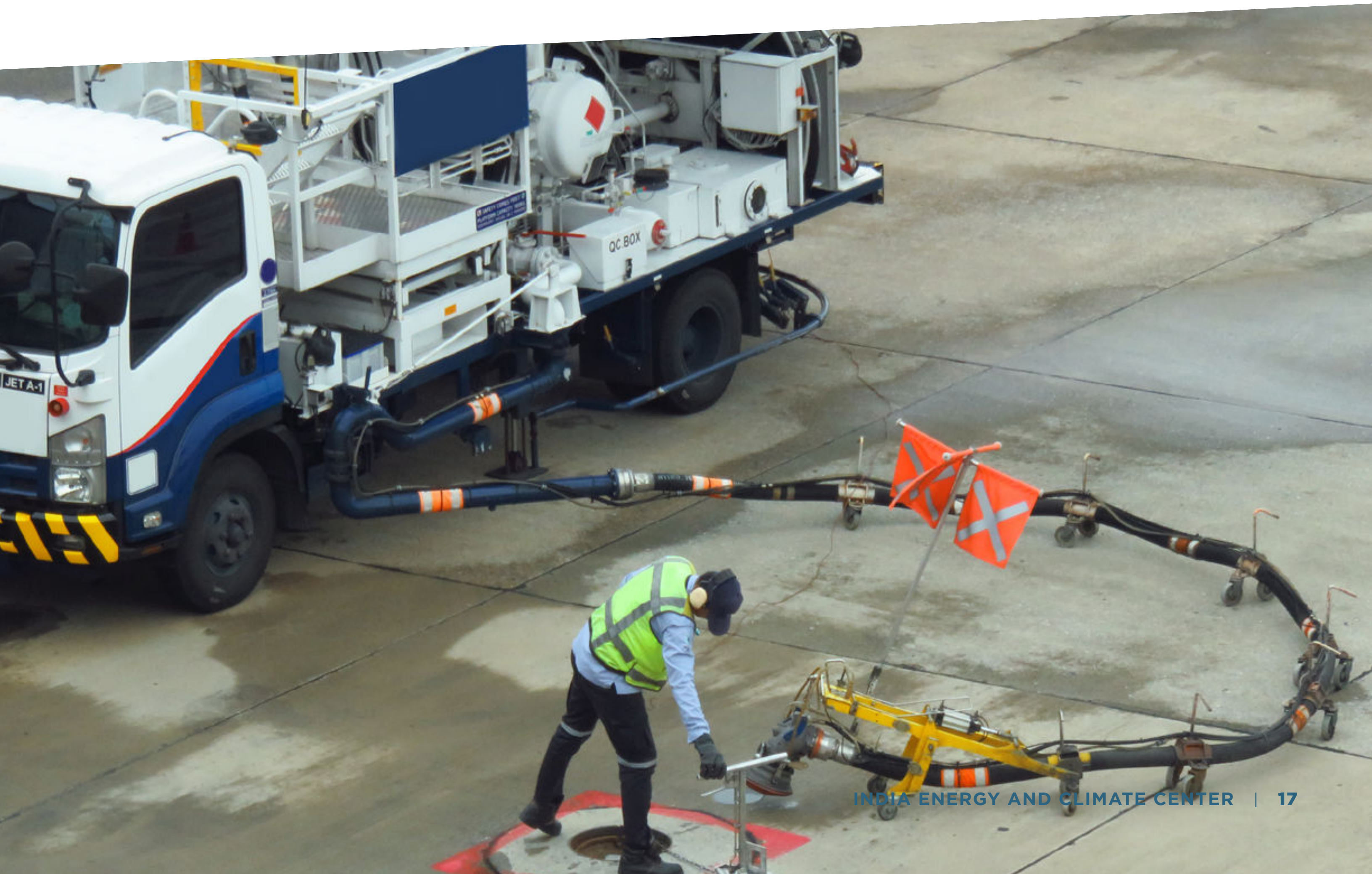


FIGURE 2.2.5: Process flow and system boundary for PBtL.



2.3. PBTL'S READINESS FOR DEMONSTRATION AND GROWTH

Technology readiness levels (TRL) convey a technology's progress toward proven readiness for full commercial deployment (denoted TRL 9). TRL levels 1–5 range from basic research to laboratory testing of integrated systems, while TRL levels 6–8 involve various stages of testing prototypes, pilots, and demonstration projects.[58] Figure 2.3.1 illustrates the relative TRL ranges for the five SAF production pathways, based on current global and Indian conditions.[59]

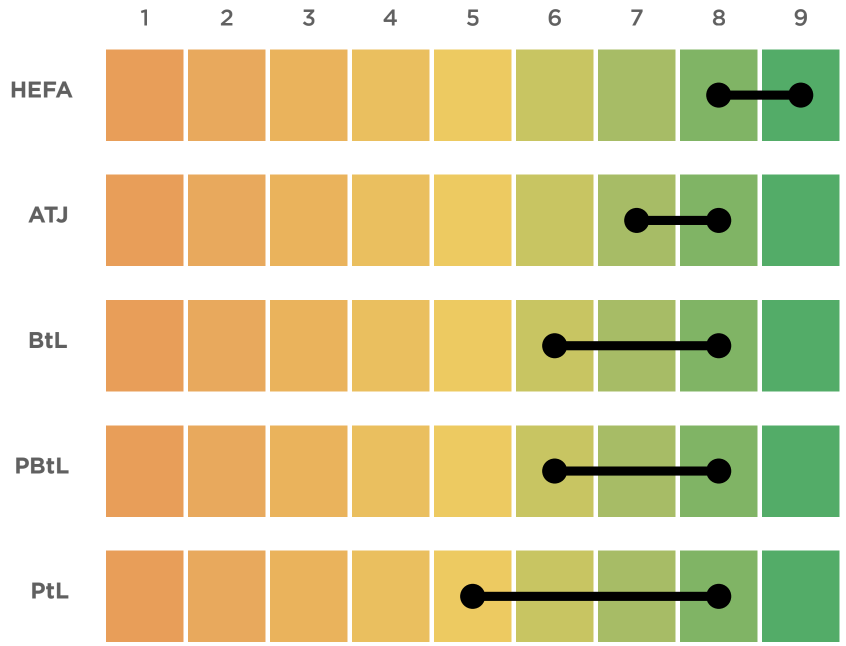


FIGURE 2.3.1: TRL ranges for five SAF production pathways in India.

- **HEFA (TRL 8–9)** is the world's only fully commercial SAF pathway, currently supplying around 80% of global SAF.[43] Large facilities—such as Neste's in Finland and Singapore, with a combined SAF production capacity of 1 Mt/yr (~3,400 kL/day)—demonstrate mature production and global supply chains.[60] In India, HEFA capacity is emerging through Indian Oil Corporation Limited's (IOCL) 35,000 t/yr (~120 kL/day) Panipat refinery and IIP's 20 kL/day pilot project.[61,62]

- **ATJ (TRL 7–8)** is transitioning from demonstration to early commercial scale, led by LanzaJet's 10 million gallons per year (~100 kL/day) Freedom Pines facility in the U.S.[63] India's first large-scale ATJ plant of 86,800 t/yr (~300 kL/day)—also via IOCL's Panipat refinery—is under development with a planned start-up in 2028.[61]

- **BtL and PBtL (TRL 6–8)** are technically proven internationally but pre-commercial in India. BtL and PBtL are grouped together because PBtL merely builds on the BtL process (of gasifying biomass and using the FT process to produce SAF) by supplementing the FT stage with green hydrogen. As green hydrogen (water electrolysis) is commercially proven, this extra step does not diminish PBtL's TRL relative to BtL, particularly given the real-world demonstrated project pipeline. DG Fuels' Louisiana PBtL project in the U.S. will be the world's largest FT SAF facility at 13,000 barrels/day (~2,100 kL/day), targeting ~97% carbon conversion efficiency and with airline offtakes secured.[64,65] Another example is Energy China's 100,000 tons/year (~342 kL/day) PBtL project, aiming to begin operations in 2027.[xiii,66]

- **PtL (TRL 5–8)** is the least mature. While more than 60–85 PtL projects have been announced globally, most remain in early development stages.[67] More than half are only at announcement or initial engineering phases, accounting for nearly 77% of planned global PtL capacity. Only 8 pilot- or demonstration-scale facilities were operational by year-end 2024, collectively producing limited volumes (approximately 4,000 tons in 2024, or 14 kL/day).[68] Limited availability of low-cost green hydrogen and captured CO_2 continue to be the primary barriers to commercial deployment.

India's domestic technological maturity largely mirrors global patterns: HEFA is most advanced, ATJ is commercializing, BtL and PBtL require demonstration, and PtL is still at an early stage due to CO_2 constraints and higher costs. Despite PBtL being relatively new or underdiscussed, it sits well within the broader SAF technology set in terms of commercial readiness, and success in the demonstration phase would position it for rapid growth under the right conditions.

2.4. PBTL'S PRODUCTION COST ADVANTAGE OVER OTHER SAF PATHWAYS

This techno-economic analysis compares PBtL SAF production costs with those of the other leading SAF pathways.[xiv] The analysis reflects India-specific cost assumptions, uses 2030 as a base year, and expresses all costs in 2025 USD (unless otherwise stated).

The most important assumption for this comparison is the green hydrogen price, as it is a major cost driver for PBtL and PtL. We use a baseline price of $3/kg, grounded in recent real-world project price discoveries, independent forecasts of green hydrogen cost trajectories, and our own modeling of an off-grid electrolysis project powered by solar

[xiii] All references to tons are metric tons—denoted "t"—unless otherwise stated.

[xiv] This analysis technically estimates the production cost of hydrocarbon liquids, but we estimate that these costs are approximately the same as SAF production costs. See Appendix B.1.

and battery storage (see Appendix A.1). Other assumptions shared across SAF pathways include the $90/t delivered cost of agricultural residue which are used in the BtL and PBtL pathways, the 25-year facility lifetime, the operational expenses (OPEX) of 5%, and the 10% real discount rate.[xv] Our estimates of the levelized costs of SAF production are shown in Figure 2.4.1 for each SAF pathway, with descriptions of our methodology and sensitivity analyses provided in Appendix A.2.

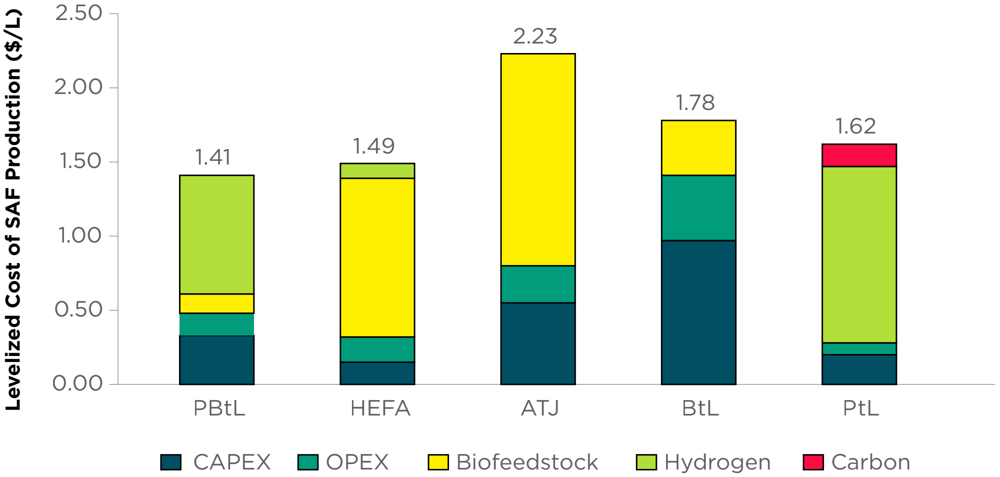


FIGURE 2.4.1: Levelized cost of SAF production in 2030 for five SAF production pathways under Indian cost conditions. Biofeedstock is agricultural residue for PBtL and BtL, UCO for HEFA, and 1G ethanol for ATJ. PtL uses carbon from point-source capture at an industrial facility.

HEFA achieves a levelized cost of SAF production of **$1.49/L** ($1,844/t). The UCO feedstock dominates the cost structure ($1.07/L), followed by OPEX ($0.17/L), CAPEX ($0.15/L), and hydrogen ($0.11/L). The SAF production cost is higher than earlier estimates in the literature (e.g., $1.32/L) due to the recent rise in global UCO prices ($1,100/t), even though India benefits from below-average capital and operating expenses.[69,70]

ATJ achieves a levelized cost of SAF production of **$2.23/L** ($2,759/t) using regulated 1G ethanol ($0.86/L).[71] Ethanol is the dominant cost driver for ATJ SAF ($1.43/L), followed by CAPEX ($0.55/L) and OPEX ($0.25/L). This estimate is higher than literature values for sugarcane (e.g., $1.86/L) because it assumes a standalone ATJ facility purchasing ethanol at the regulated price, rather than vertically integrating with a sugar mill.[69] Such integration depends on site-specific co-location opportunities and may not be scalable nationwide.

[xv] The delivered cost of agricultural residue was provided by BiofuelCircle via email, referencing the platform's real-world transactions. Specifically, BiofuelCircle quoted the current price range for agricultural residue biomass pellets at $80–90/t as of March 2026, with baled agricultural residue at $35–40/t and biomass briquettes at $60–70/t. We chose $90/t as a conservative assumption. See Appendix C.

The standalone assumption therefore reflects a conservative and modular deployment framework consistent with broader SAF commercialization. When using 2G ethanol from crop residues (costing upwards of $1.0–1.1/L), the ATJ SAF production cost rises to roughly $2.7/L.[69] This underscores ATJ's main challenge: it is strongly dependent on low-cost ethanol, yet 1G ethanol is prioritized for gasoline blending in India, SAF regulations often exclude 1G feedstocks from food and feed crops due to land use change concerns, and 2G ethanol is expensive.

BtL achieves a levelized cost of SAF production of **$1.78/L** ($2,200/t), dominated by high CAPEX ($0.97/L) and OPEX ($0.44/L), with the biomass feedstock having a smaller impact ($0.37/L). The SAF production cost estimate is lower than literature values for FT-based SAF using agricultural residue (e.g., $1.98/L), in part owing to India's lower-cost residue supply.[69]

PtL achieves a levelized cost of SAF production of **$1.62/L** ($2,000/t). Hydrogen is the dominant cost component ($1.19/L), followed by CAPEX ($0.19/L), CO_2 capture from industrial point sources ($0.15/L), and OPEX ($0.09/L). These findings align with estimates from the literature for 2030, which typically reports PtL costs substantially higher than conventional SAF pathways, such as in the range of $1.8–2.6/L under U.S. (on the lower end) and European (on the higher end) electricity and hydrogen price assumptions.[57] The comparatively lower SAF production cost estimated here reflects India's projected low-cost solar electricity and hydrogen prices under 2030 deployment scenarios.

PBtL achieves a levelized cost of SAF production of **$1.41/L** ($1,746/t). This is materially below common global SAF cost benchmarks of $1.6-2.4 /L, and roughly 30-40% lower than upper-end global benchmark estimates, reflecting India's record-low green hydrogen prices and low agricultural residue costs.[1,2] Moreover, this production cost is 5 times lower than e-SAF reference prices in the EU of $7.2/L, with e-SAF being a relevant market for a fraction of the PBtL production.[65,72] Hydrogen is the dominant cost component ($0.79/L), followed by CAPEX ($0.33/L), OPEX ($0.15/L), and biomass ($0.14/L). Under these baseline conditions, PBtL has the lowest SAF production cost among these five prominent SAF pathways.

Figure 2.4.2 illustrates pathways' SAF production costs as a function of the green hydrogen price. PBtL becomes the least-cost option once green hydrogen prices fall below approximately $3.4/kg—levels already approached or surpassed by India's recent auctions (even after taxes) and that seem consistently achievable in the near future (see Appendix A.1). PtL does not eclipse PBtL in price until green hydrogen prices reach $1.5/kg, which is not anticipated even by 2050 (see Appendix A.3); PtL will also eventually have to procure CO_2 from non-fossil sources (e.g., direct air capture instead of point-source industrial facilities), which will put upward pressure on prices. HEFA is largely insensitive to the price of hydrogen, and ATJ and BtL are not affected at all. Thus, their costs will not meaningfully decline as India's renewable power costs fall further.

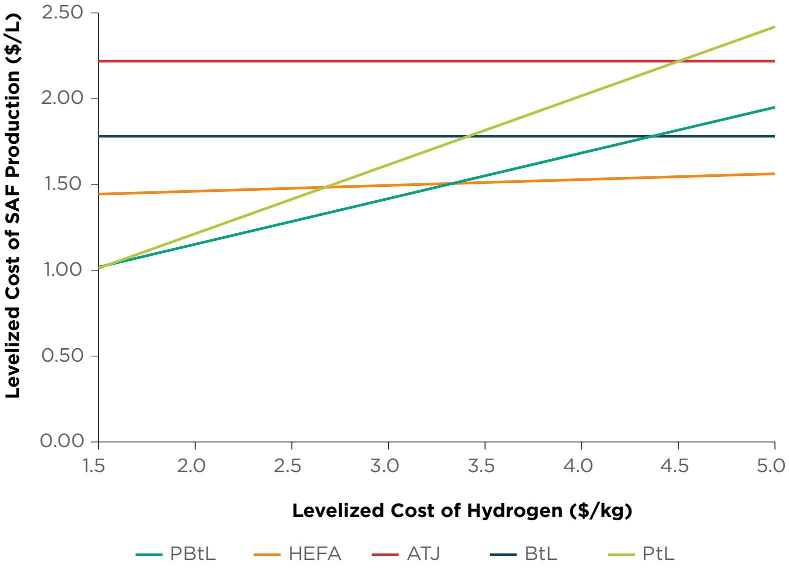


FIGURE 2.4.2: Sensitivity of SAF costs to the green hydrogen price across the main SAF production pathways in India. PtL uses CO_2 captured from point-source industrial facilities, not the more electricity-intensive direct air capture.

Overall, the techno-economic analysis results suggest that PBtL can produce SAF at least cost, assuming it can procure green hydrogen at prices below approximately $3.4/kg and has ready access to agricultural residue. HEFA may continue to be competitive in the near term given its current strong market position and the nascency of the green hydrogen industry, but it remains limited by feedstock availability and sustainability concerns (e.g., fraud, land use change). PtL may find a niche in locations with inadequate agricultural residue supplies, industrial facilities with point-source CO_2 capture and delivery infrastructure, and low renewable electricity prices. It may also be an important long-term backstop should SAF demand outpace what biogenic pathways can sustainably supply, particularly if direct air capture costs fall sufficiently over that period. BtL is scalable but faces higher costs than PBtL due to its lower carbon efficiency (though has an edge if green hydrogen prices are only available above approximately $4.4/kg). ATJ faces regulatory barriers to cost-competitiveness, with domestic petrol-blending mandates and other jurisdictions' limits on 1G feedstocks (thereby implying the need for 2G ethanol) both driving high ethanol prices.

2.5. PBTL'S RESOURCE USE ADVANTAGE OVER OTHER SAF PATHWAYS

The five SAF pathways under consideration differ greatly in the intensities of their carbon emissions as well as the biomass, electricity, land, and water resources they require. In this section, we highlight the differences between PBtL and other SAF pathways across these five environmental metrics. We rely on data from the literature as well as our own high-level estimates rather than conducting a comprehensive lifecycle analysis.[xvi] We find that PBtL SAF achieves the deepest GHG emissions reduction while striking the best balance among its use of various inputs, thereby giving it the clearest path to scale.

Carbon intensity (CI) measures the GHG emission reductions each SAF pathway can achieve relative to fossil ATF. PBtL SAF achieves the deepest GHG emissions cuts across all biogenic SAF pathways at upwards of a 95% reduction relative to fossil ATF. We refer to the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) lifecycle emissions values for SAF technology-feedstock combinations of interest in India, which are available for HEFA, ATJ, and BtL pathways.[73] We use other estimates from the literature and our own analysis to provide carbon intensities for PtL and PBtL. We compare these SAF pathways against a fossil ATF carbon intensity benchmark of 88.7 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ), which represents a weighted global average value.[74] We also note that CORSIA estimates include relatively low indirect land use change (ILUC) emissions estimates compared to NGO and academic literature, and therefore we are likely understating PBtL's CI advantage relative to pathways dependent on food or energy crops.[xvii,75–77]

- HEFA SAF from used cooking oil has among the lowest carbon intensities per CORSIA, at 13.9 gCO_2e/MJ (84% reduction from fossil ATF). In theory, there are no land use change impacts from the cultivation of waste oil feedstocks, and any emissions come from collection, transportation, and pretreatment. However, in practice, HEFA can have large hidden or unaccounted-for ILUC impacts to the degree it ends up driving more virgin oil production, whether directly through fraud (i.e., selling virgin oil as UCO) or indirectly through the displacement of waste oils from other buyers.[xviii] In fact, known supplies of UCO and animal fats may be nearly fully consumed by rising renewable diesel and SAF demand before the end of the 2020s.[80] Per CORSIA, HEFA reliant on oil crops like palm oil, soybeans, and rapeseed would only reduce emissions by approximately 10–26% relative to fossil ATF due to energy-intensive cultivation and ILUC impacts. Recognition of the risks brought by this limited sustainable feedstock availability has led the UK and EU to effectively cap HEFA's contributions to SAF mandates and set stronger guardrails on UCO imports.[32,81,82] Despite these concerns, we use the 13.9 gCO_2e/MJ value in our analysis to compare the best-case scenario with PBtL SAF.

[xvi] We use single-point estimates with clearly stated assumptions throughout this section for simplicity, but we recognize that each SAF technology-feedstock combination has a range of plausible values across each metric. We also note that, since we are relying on multiple sources and methodologies, the boundaries of these lifecycle analysis estimates are not necessarily equivalent across SAF categories or metrics. However, the estimates used throughout this section were chosen or designed to be robust- and consistent-enough to convey relative magnitudes across SAF pathways.

[xvii] Land use change impacts occur from either converting natural environments to crop cultivation directly for use in SAF production (direct) or by diverting existing crops to SAF production, thereby causing similar land use change elsewhere to serve the food or feed demand these crops were previously serving (indirect).

[xviii] Fraud is a major concern because the incentives for fraud are enormous (i.e., sellers can earn much more from waste oils than virgin oils), it is very difficult to verify if oil is waste or virgin, trade volumes and flows are suspicious, auditing is weak, etc.[47,78] Waste oils and fats were also already being used by other industries like oleochemicals, soaps, and animal feeds—as these industries are generally not subject to decarbonization requirements, they can turn to palm and other virgin oils if waste oils are diverted to HEFA, with highly detrimental impacts to climate (e.g., rainforest clearing).[79]

- ATJ SAF from sugarcane-derived ethanol has a carbon intensity of 32.6 gCO_2e/MJ (63% reduction) per CORSIA, with emissions coming from crop cultivation and ILUC. These emissions decline slightly when using agricultural residue (24.6 gCO_2e/MJ, or 72% reduction), with higher processing emissions but no ILUC impacts.[xix] ATJ emissions can also worsen substantially if using other crops like corn (80.3 gCO_2e/MJ, or 9% reduction).

- BtL SAF from agricultural residue has a very low carbon intensity of 7.7 gCO_2e/MJ (91% reduction)—well below when this same feedstock is used in the ATJ process, owing in part to the efficiency advantage of not having to first make ethanol.

- PtL SAF has a wide range of carbon intensity estimates in the literature, depending on the sources of CO_2, hydrogen, and electricity. For example, one literature review finds estimates ranging from -8.3 gCO_2e/MJ (109% reduction) to 441.14 gCO_2e/MJ (397% increase—well beyond the range of qualifying as "SAF").[83] Here, we use an estimate of 5 gCO_2e/MJ (94% reduction) from using green hydrogen and CO_2 captured from a cement production facility (with electrolyzer, carbon capture, and FT equipment powered by clean electricity), with the credit for the captured CO_2 being owned exclusively by the FT facilities.[84] Such a framework is allowable under current EU rules through 2040, after which PtL SAF may need to use CO_2 from biogenic sources or direct air capture to retain eligibility.[85] Direct air capture projects are highly energy intensive—with higher costs and competing demand for renewable power in other applications making viability unlikely in the near-to-medium term—but if powered by clean electricity, they can achieve PtL SAF production at similarly low carbon intensities.[83,84]

- PBtL SAF from agricultural residue can achieve a carbon intensity below 4.5 gCO_2e/MJ (>95% reduction). This value falls below BtL SAF due to using much less agricultural residue per unit SAF produced, owing to the efficiencies provided by green hydrogen upgrading. This estimate assumes the use of 5% grid power in hydrogen production, but 100% clean electricity could make this a near-zero emissions product.

[xix] Agricultural residue—and other wastes and residues—are not immune to the fraud or ILUC concerns that we identified for waste oils and fats in the HEFA pathway. See Section 5 for a brief discussion on how policy should think about protecting against these risks for agricultural residue.

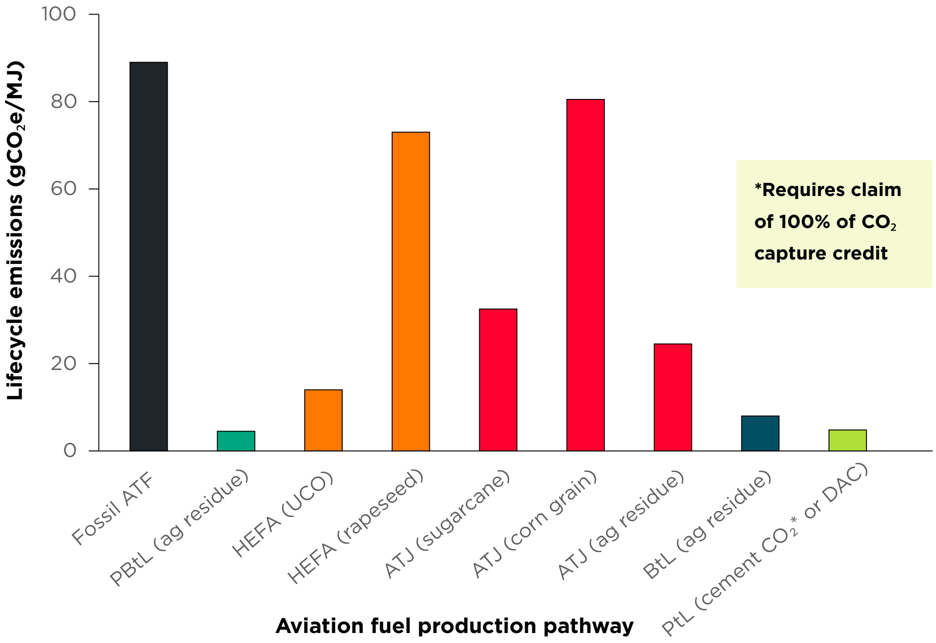


FIGURE 2.5.1: Carbon intensity comparison across key SAF pathways.

Biomass use intensity measures the amount of biofeedstock needed to produce a ton of hydrocarbon liquids.[xx] A lower intensity allows for lower costs and higher yields given a limited biofeedstock resource. PBtL can produce far more liquids for a given amount of biofeedstock (agricultural residue) than competing pathways.

We compare PBtL with ATJ and BtL, as these pathways can utilize India's abundant (but not limitless) agricultural residue resource as a feedstock.[xxi] ATJ most commonly uses sugar-derived ethanol from the sugarcane crop (1G ethanol), but it can also use agricultural residue (e.g., sugarcane bagasse for 2G ethanol)—we include both feedstock types in this comparison. We do not discuss HEFA (due to its feedstock limits) or PtL (as it does not depend on biomass).[xxii]

The ATJ pathway converts sugarcane juice or bagasse to ethanol, then ethanol to hydrocarbon liquids. The conversion of ethanol to liquids has an efficiency on par with the best PBtL pathway; both produce approximately 0.56–0.57 t liquids per t feedstock.[69,86] However, ethanol production has its own losses, particularly when using agricultural residue as a feedstock; for example, sugarcane juice and bagasse yield 0.22 and 0.14 t ethanol per

[xx] See Appendix B.1 for a discussion of how liquids production translates to SAF production.

[xxi] That is, India has a very large supply of surplus agricultural residue, but it remains bounded by the size of the overall agricultural sector. This residue is highly valuable as an essentially zero-carbon feedstock (on a lifecycle basis), and its efficient use should be prioritized.

[xxii] PtL can source its CO_2 from biomass, but this would either happen through gasification (in which case it is equivalent to PBtL) or from capturing CO_2 from its combustion in a power plant or industrial facility (in which case the efficiency with which carbon from the biomass feedstock makes it into SAF relative to PBtL is downgraded by losses from the carbon capture process).

t feedstock, respectively.[87] This makes the ATJ pathway far less efficient on net relative to PBtL, with this gap widening when using more climate-friendly 2G ethanol over the more controversial 1G ethanol.

The BtL pathway gasifies biomass and uses the FT process to convert hydrogen and carbon into hydrocarbon liquids. However, it lacks sufficient hydrogen to react with the available carbon. This, paired with other losses, means BtL only converts approximately 37–40% of the carbon to liquids, while most is lost to the atmosphere as CO_2.[86,88–90]

PBtL solves BtL's inefficient carbon utilization by supplementing the process with additional hydrogen (i.e., beyond that produced from gasifying biomass) from electrolysis. The literature reports a wide range of carbon efficiencies that PBtL can achieve, from approximately 60–70% at the lower end to 91–98% under more optimized conditions (e.g., lower electricity prices for higher green hydrogen use, higher rates of recycling CO_2 off-gases back into the reaction).[86,88–90] In the rest of this section, we refer to low carbon utilization (LCU) and high carbon utilization (HCU) PBtL cases corresponding to carbon efficiencies of 67% (without rWGS) and 97% (with rWGS), respectively.[86] In the rest of the paper, we use the HCU case, assuming this higher biomass efficiency is achievable in India given its world-leading low green hydrogen prices and suggesting PBtL can get approximately 2.6 times more SAF from the same agricultural residue input as BtL.

In sum, PBtL requires 4.5-6.5 times less agricultural residue as ATJ and 1.8-2.6 times less residue as BtL.[xxiii] Of the produced liquids, ATJ has a standard SAF yield of 70–90% (with the remainder being light ends and renewable diesel), while FT pathways (PBtL and BtL) have a standard SAF yield of 25–40%.[91] While this improves ATJ's favorability for SAF production, it does not close the gap, even under the most favorable condition for ATJ (90% SAF selectivity) and least favorable conditions for PBtL (25% SAF selectivity, LCU case). As discussed in Appendix B.1, it is possible to increase SAF selectivity for the FT process (including by reprocessing byproducts); this would add costs and reduce the sale of byproducts (such as renewable diesel), but it could make sense if SAF were sufficiently prioritized by policy or favored by the market.

[xxiii] We apply an arbitrary 90% multiplier to PBtL and BtL biomass efficiencies from the literature for use in our analysis to make our estimates more conservative. This is meant to account for the fact that these literature estimates are often using optimized conditions that are difficult to achieve in practice.

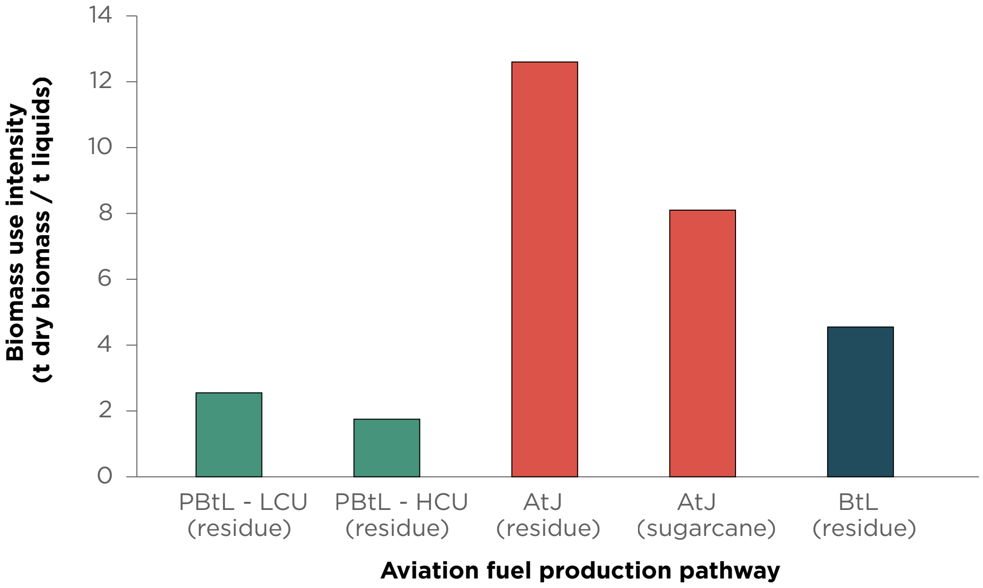


FIGURE 2.5.2: Biomass use intensity comparison across key SAF pathways.

Electricity use intensity measures the electricity required to produce a ton of hydrocarbon liquids. While all five SAF pathways use electricity, all such uses are overwhelmed by that of hydrogen electrolysis. As such, HEFA, ATJ, and BtL have very low electricity use intensities.[xxiv] PBtL's electricity use intensity is about 1.6–2.1 times lower than that of PtL—approximately 10–14 megawatt-hours (MWh) per ton of hydrocarbon liquids for PBtL's LCU and HCU cases, respectively, vs. 21–23 MWh/t for PtL depending on whether heat integration is utilized.[86,93] This gap is primarily explained by PBtL's lower hydrogen requirement, which in turn owes to being able to utilize the hydrogen produced from gasifying biomass. This advantage is also conservative, as it does not consider electricity use required to capture CO_2 for PtL, which would be relatively marginal for point-source capture but substantial for direct air capture.

[xxiv] HEFA does require hydrogen but uses approximately 4–6x less hydrogen than PBtL to produce the same quantity of hydrocarbon liquids, with similar implications for its electricity, land, and water use (assuming the use of waste oils and fats with no fraud or ILUC impacts).[69,92]

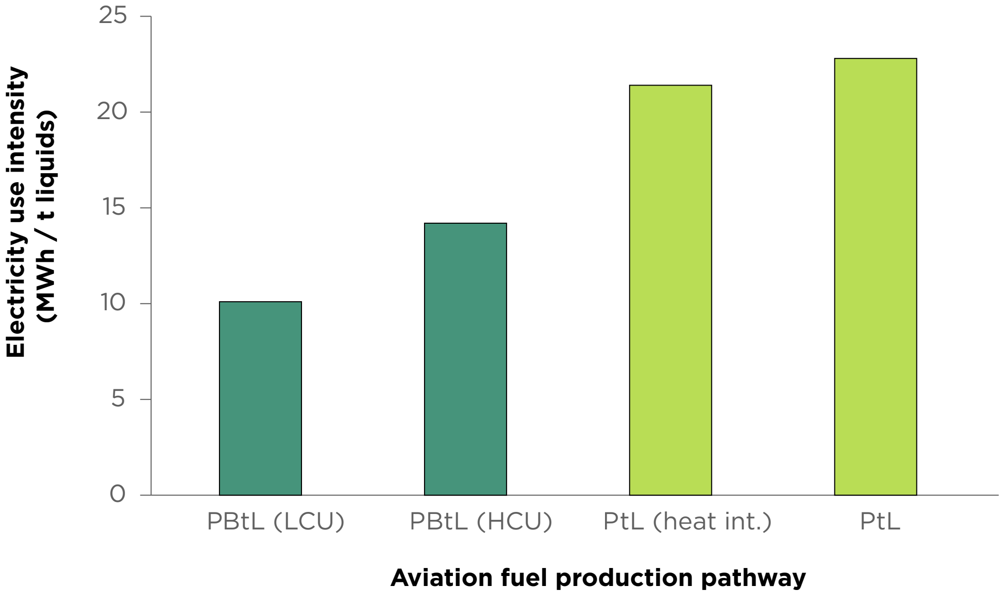


FIGURE 2.5.3: Electricity use intensity comparison across key SAF pathways (excluding electricity needed for CO_2 capture for PtL).

Land use intensity measures the dedicated land required to produce a ton of hydrocarbon liquids. The two components responsible for nearly all land use across these SAF production pathways are crops for biomass cultivation and solar panels for electrolytic hydrogen production. We do not attempt to estimate other land use impacts (e.g., SAF production facility site footprint), as they are negligible in comparison. We also do not differentiate between the use of fertile and marginal land, though crops require the former (to the detriment of ATJ) while solar can be sited on the latter (to the benefit of PBtL and PtL). PBtL has a slightly higher land use footprint than BtL or HEFA, a considerably lower footprint than PtL, and a dramatically lower footprint than ATJ (when using 1G ethanol).[xxv]

HEFA and BtL have negligible land use impacts, as they are assumed to rely on wastes and residues with very little need for electricity; that is, while some electricity is used as part of these fuel production processes, this amount is washed out relative to electrolytic hydrogen production used in PBtL and PtL.

PBtL has the next-lowest land use intensity, at approximately 0.01–0.02 hectares (ha) per ton of hydrocarbon liquids, followed by PtL at 0.01–0.03 ha/t. These estimates are derived from multiplying these SAF pathways' electricity use requirements by a high (22.5%) or low

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[xxv] Again, this assumes HEFA uses waste oils and fats with no fraud or ILUC impacts. If HEFA caused an expansion of virgin oil crops (directly or indirectly), its land use intensity would be of a similar magnitude as ATJ with 1G ethanol.

(16.0%) solar capacity factor, as well as a high-efficiency (3 acres per megawatt) or low-efficiency (5 acres/MW) solar land use requirement.[94–97]

ATJ has by far the highest land use impact when relying on 1G ethanol, at approximately 0.34 ha/t—nearly 17 times higher than PBtL's upper bound. This estimate assumes India-specific yields of 79 t/ha sugarcane, 84 L/t of ethanol from sugarcane, and 0.56 t/t of hydrocarbon liquids from ethanol.[69,98,99] However, ATJ using agricultural residue would have a land use intensity on par with HEFA and BtL.

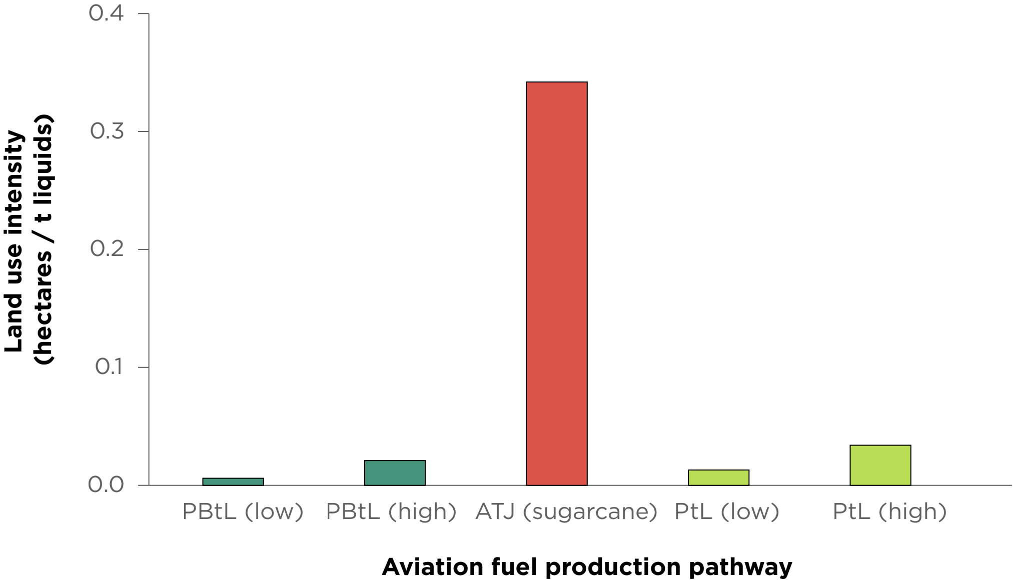

FIGURE 2.5.4: Land use intensity comparison across key SAF pathways. "Low" represents the LCU case for PBtL and heat integration case for PtL, with high solar capacity factor and high-efficiency solar land use efficiency assumptions. "High" represents the HCU case for PBtL and no heat integration case for PtL, with low solar capacity factor and low-efficiency solar land use efficiency assumptions.

Water use intensity measures the water required to produce a ton of hydrocarbon liquids. The two components that require the vast majority of water across these SAF pathways are crop cultivation and hydrogen electrolysis, with the former being several orders of magnitude more water-intensive than the latter. PBtL therefore uses dramatically less water than sugarcane-based ATJ and notably less water than PtL; while it uses more water than HEFA and BtL, the quantities are relatively marginal.[xxvi]

[xxvi] Again, this assumes HEFA uses waste oils and fats with no fraud or ILUC impacts. If HEFA caused an expansion of virgin oil crops (directly or indirectly), its water use intensity would be of a similar magnitude as ATJ with 1G ethanol (though there is a lot of variability in water requirements by crop and water availability by region).

We estimate the water use intensity of ATJ using 1G ethanol from sugarcane at approximately 4,800 to 9,300 kiloliters per ton of hydrocarbon liquids.[xxvii] Our analysis uses total water requirements from a case study of sugarcane cultivation in Maharashtra (in units of cubic meters of water per ton of sugarcane); we then apply our earlier assumptions of ethanol and ATJ liquids yields to arrive at our estimate.[100] This total water requirement includes both "blue water," which estimates surface water or groundwater reservoirs withdrawn for irrigation, and "green water," which estimates rainwater utilized by crops.

The case study finds that Indian sugarcane relies somewhat more on blue than green water, though the exact share can vary greatly by location (e.g., soil quality) and weather (e.g., rain available from monsoons). We refer to the total water requirement, but if the analysis were limited to blue water, ATJ's water intensity would remain very high relative to other pathways. We also cross-checked our findings with the literature on water intensity of sugarcane-derived ethanol production for India and a global average, and other studies' findings aligned with the lower end of our water requirement range.[101–103]

For pathways using hydrogen electrolysis, we use a base assumption of 20–30 L/kg of water for hydrogen production, then apply this to pathways' hydrogen requirements for hydrocarbon liquids production.[104] We find electrolysis water requirements of 4–8 kL/t of water for liquids production for PBtL and 10–15 kL/t for PtL.[86,93] In sum, PBtL uses 1.8–2.7 times less water than PtL and hundreds-to-thousands of times less water than ATJ with 1G ethanol. Notably, the water requirements for electrolysis and FT may be zero or even negative on a net basis for the PBtL pathway, as water consumed by electrolysis is returned in FT synthesis and condensation.[86]

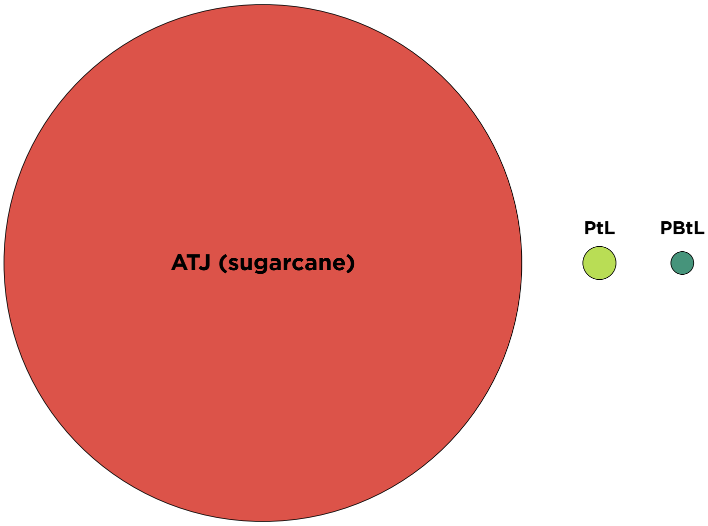

FIGURE 2.5.5: Water use intensity comparison across key SAF pathways (kL water per t hydrocarbon liquids), using the lower estimate of total water consumption for ATJ (4,800 kL/t) and averaged estimates of total water consumption for PtL (13 kL/t) and PBtL (6 kL/t).

[xxvii] Water use is fully attributed to crops' primary use (e.g., food production) rather than to agricultural residue. Residue should only have water use attributed to it if the use of residue became a determining factor in whether or not the crops would have been cultivated.

In summary, PBtL achieves the deepest GHG emissions reduction among all SAF pathways while using resources most efficiently on balance. HEFA is extremely feedstock-constrained, and expanding beyond waste oils would eliminate its GHG benefits. ATJ with 1G ethanol uses an enormous amount of water and land and contributes to land use change to the detriment of its carbon intensity. BtL requires much more agricultural residue than PBtL, and ATJ with 2G ethanol uses far more than both BtL and PBtL. PtL requires considerably more electricity—and by extension, land and water—than PBtL, and it will eventually need to source CO_2 from sustainable bioresources or ambient air (each with their own resource use implications) to continue to serve SAF mandates. These factors position PBtL to be the most scalable SAF pathway, as it does not rely on dedicated crop production, gets much more fuel out of India's limited (if large) surplus agricultural residue supply, and leverages this residue to reduce its electricity demand to much more reasonable levels. In other words, PBtL presents the most balanced resource use profile.

2.6. PBTL'S CO-BENEFIT ADVANTAGE OVER OTHER SAF PATHWAYS

SAF production can deliver a range of co-benefits relative to fossil ATF, including strengthening domestic energy security, supporting domestic jobs, and monetizing waste products like agricultural residue.[xxviii] In this section, we describe and quantify two particularly important co-benefits—reducing GHG emissions and reducing premature mortality from local air pollution—and explain why PBtL can maximize these co-benefits relative to other SAF production pathways.

SAF's primary co-benefit lies in reducing GHG emissions and their associated negative impacts, which are often expressed in terms of the social cost of carbon—an estimate of the monetary damage caused by emitting one ton of CO_2. India has one of the highest estimated social costs of carbon globally at \$86/tCO_2, reflecting its high vulnerability to extreme heat, floods, and crop loss.[xxix,106]

Regulatory markets can give some insight into how low carbon intensity scores can translate into financial benefit. India's Carbon Credit Trading Scheme (CCTS) is its first market to explicitly price CO_2 emissions, though its coverage is limited to certain industrial sectors (i.e., it does not cover aviation).[107] While CCTS trading has not yet started, analysts expect near-term prices to trade around \$2-16/tCO_2.[108] As another point of reference, the EU's Emissions Trading System Carbon Permits have frequently traded above \$86/tCO_2 over the last four years, at times surpassing \$100/tCO_2, and are forecast to approach \$150/tCO_2 by 2030—showing that low-CI products are already demonstrating market value for SAF at

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[xxviii] The term "co-benefit" assumes SAF's core benefit is providing aviation fuel.

[xxix] There are a wide range of estimates of the social cost of carbon in the literature. For example, another study finds that the social cost of carbon in India ranges from \$80-130/tCO_2, and global estimates have reached upwards of \$1,000/tCO_2.[105] We use \$86/tCO_2 in our analysis as an India-specific estimate that falls within the band of carbon pricing schemes implemented elsewhere.

levels comparable to India's estimated social cost of carbon.[109,110] SAF pathways with low CI scores, especially PBtL (with green hydrogen and agricultural residue) and PtL (with clean power), therefore bring deeper market value through their climate benefits, especially in jurisdictions with higher carbon prices like the EU.

Another potential major co-benefit of SAF is reducing local air pollution by redirecting agricultural residue away from being burned and toward a productive use. This benefit is only realized by pathways that utilize this residue, namely PBtL and BtL. Recent epidemiological studies estimate that crop residue burning has contributed 44,000–98,000 premature deaths annually in India from 2003–2019, imposing a $23 billion premature mortality cost each year, equivalent to roughly $230 per ton of rice straw burned.[xxx,11] Redirecting even a fraction of India's estimated 130 Mt/yr of burned crop residue into SAF production would avoid this premature mortality and deliver a series of co-benefits that are not captured in this $230/t valuation estimate, such as avoided health expenditures (e.g., hospitalizations, chronic morbidity treatment), avoided productivity losses from illness, new job creation in residue collection and densification, and reliable income for farmers.[xxxi,11,111] Thus, the true value of avoided local air pollution is likely much higher than quantified as part of this analysis.

In Figure 2.6.1, we compare each SAF pathway's 2030 levelized cost of SAF production when accounting for financial estimates of the social cost of carbon and avoided premature mortality from local air pollution (which does not include other co-benefits of reducing crop residue combustion). All SAF pathways have lower CO_2 costs relative to fossil ATF, and SAF pathways that utilize surplus agricultural residue (namely PBtL and BtL) have large additional benefits relative to the other SAF pathways as well as fossil ATF. We assume a social cost of carbon of $86/t$CO_2$ (which adds $0.22/L to the fossil ATF price) and a benefit of avoiding premature deaths from local air pollution of $230/t (which subtracts $0.36/L from the PBtL SAF cost).

[xxx] The $230/t estimate comes from dividing the $23 billion annual average premature mortality cost from 2003–2019 by the 100 Mt annual average crop residue burned from 2003–2016.

[xxxi] See Section 4 for the basis for our estimate of 130 Mt/yr of agricultural residue being burned in India.

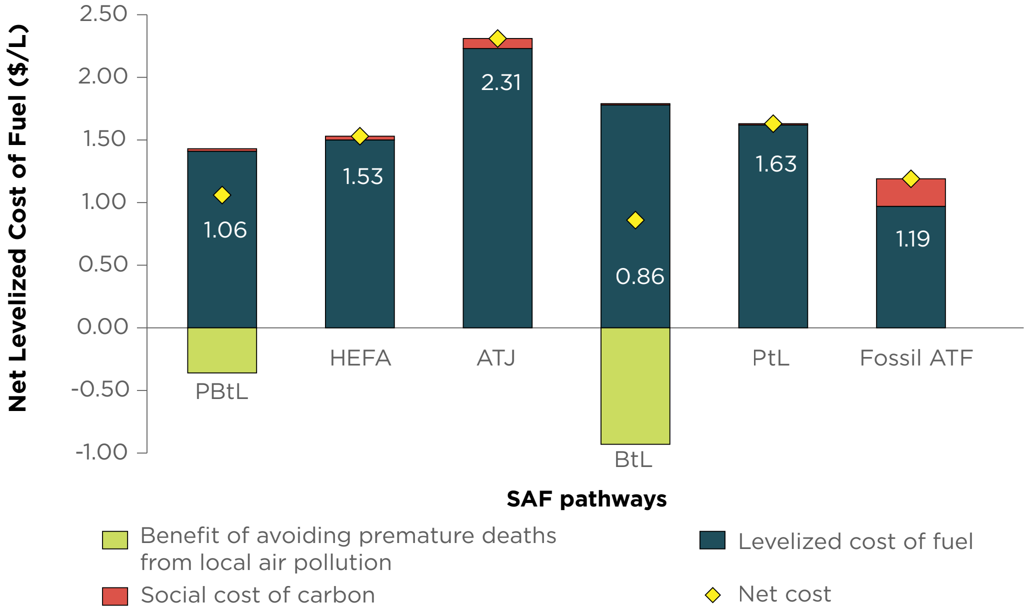


FIGURE 2.6.1: Estimates of the net levelized cost of SAF production and fossil ATF prices in 2030 when valuing the social cost of carbon (using $86/tCO$_2$) and the benefit of avoiding premature deaths from local air pollution (using $230/t residue).

Monetizing the avoided premature deaths benefit makes BtL the most cost-effective option among SAF pathways on a per-liter basis. But the cumulative avoided premature deaths benefit between BtL and PBtL would be identical if all surplus agricultural residue were put to use, and PBtL would produce several times more SAF. Additionally, unless policy provides a financial reward for this pollution-reduction benefit, PBtL SAF will be less expensive than BtL in the market.

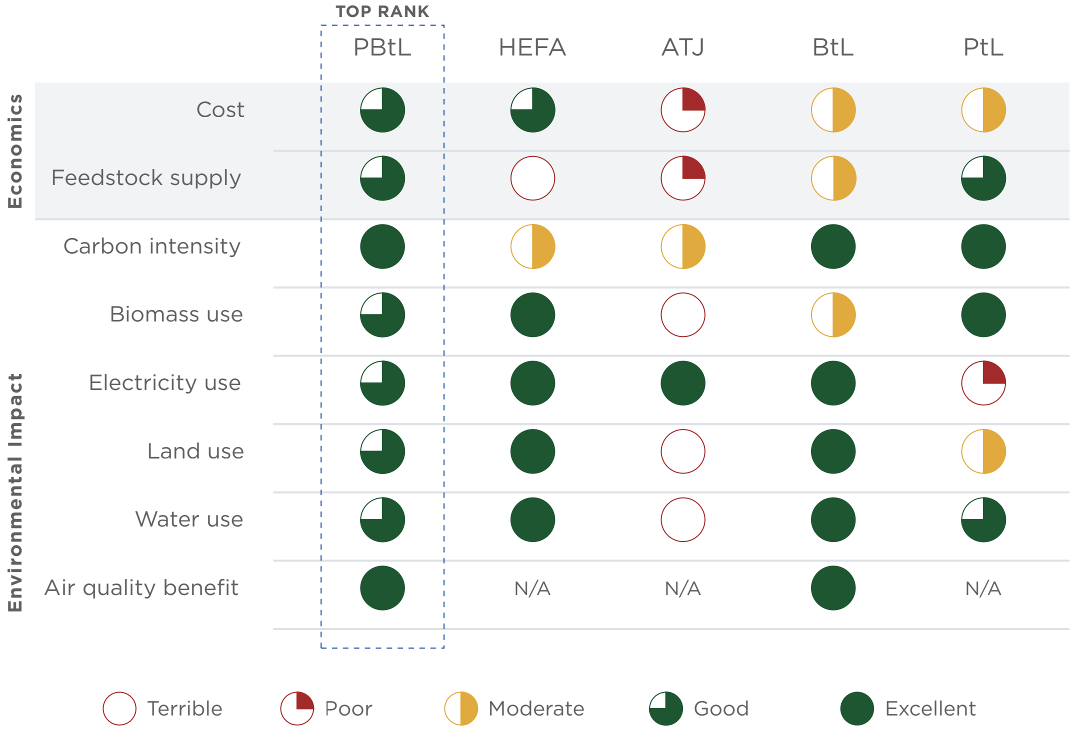
Incorporating the social cost of carbon and the benefit of avoiding premature deaths from local air pollution makes the 2030 production cost of PBtL SAF lower than India's fossil ATF price for international runs (the less-expensive ATF price indicator). These price dynamics are explained further in Section 3.2.

Overall, this analysis demonstrates how Indian policy supporting residue-based SAF could make immediate financial sense, even when limiting monetization of externalities to just the social cost of carbon and avoided premature deaths from local air pollution. Supporting residue-based SAF would provide a range of additional benefits to those quantified here, possibly including increased tourism in New Delhi (currently heavily affected by local air pollution from burning crop residues), reduced national health burdens, stronger rural supply chains, more financially secure farmers, and a more stable and affordable aviation sector.

2.7. SUMMARY

Across the five SAF production pathways, HEFA dominates current SAF production and is currently cost-competitive, but its growth is severely constrained by limited domestic waste oil supply in India and globally, with the market already plagued by concerns over fraud and indirect land use change. ATJ has challenging fundamentals—our analysis suggests ATJ with 1G ethanol has the highest costs among SAF pathways, questionable climate benefits (which could preclude its use in markets that cap or ban the use of food and feed crops), and substantial water and land use requirements. Using 2G ethanol would reduce ATJ's carbon and resource use intensities but further raise its costs. However, ATJ could play a complementary role to the degree it supports energy security by facilitating a quicker transition away from fossil ATF or if vehicle electrification frees up ethanol that is today blended with gasoline. BtL struggles with low carbon efficiency, and PtL faces high electricity demands and a lack of CO_2 capture infrastructure.

PBtL emerges as the most cost-competitive and scalable pathway for SAF production in India. While this route is highly sensitive to hydrogen prices, PBtL is already on the precipice of being the least-cost SAF option given India's rapidly declining green hydrogen costs, as evidenced in recent tenders (see Appendix A.1). Moreover, PBtL is uniquely positioned to maximize value from India's abundant surplus agricultural residues, which do not contribute to food security conflicts or violate jurisdictional SAF regulations. It also makes efficient use of India's electricity, land, and water resources. Lastly, PBtL achieves the largest lifecycle GHG reductions among all SAF pathways while simultaneously reducing local air pollution. Figure 2.7 provides a qualitative summary of our analysis throughout Section 2, illustrating at a glance why India should prioritize PBtL among SAF production pathways.



		TOP RANK PBtL	HEFA	ATJ	BtL	PtL
Economics	Cost	◕	◕	◔	◑	◑
	Feedstock supply	◕	○	◔	◑	◕
Environmental Impact	Carbon intensity	●	◑	◑	●	●
	Biomass use	◕	●	○	◑	●
	Electricity use	◕	●	●	●	◔
	Land use	◕	●	○	●	◑
	Water use	◕	●	○	●	◕
	Air quality benefit	●	N/A	N/A	●	N/A

○ Terrible ◔ Poor ◑ Moderate ◕ Good ● Excellent

FIGURE 2.7.1: Summary of power-and-biomass-to-liquids' (PBtL) advantage over competing sustainable aviation fuel production pathways, assuming the use of agricultural residue for PBtL and biomass-to-liquids (BtL), waste oils for hydroprocessed esters and fatty acids (HEFA), first-generation ethanol for alcohol-to-jet (ATJ), and industrial point-source carbon dioxide with an eventual transition to direct air capture for power-to-liquids (PtL).

3. POWER-AND-BIOMASS-TO-LIQUIDS VS. FOSSIL AVIATION TURBINE FUEL

In this section, we offer a perspective on the market size of ATF in India and SAF globally, then provide forecasts of PBtL SAF production costs and fossil ATF prices based on market dynamics, monetary risk exposure, and their combined effects.[xxxii] We find PBtL can satisfy regulated SAF demand (and much of the broader Indian ATF market), insulate Indian aviation markets against fossil ATF price spikes, and achieve SAF production costs that could fall below fossil ATF prices in the 2030s.

3.1. PBTL'S ENORMOUS MARKET OPPORTUNITIES

India's aviation sector is widely expected to experience rapid growth, due in part to new airport infrastructure investments, increased aircraft capacity and regional interconnectivity, and rising incomes.[111] A broad range of industry stakeholders—including airlines, manufacturers, trade associations, and consulting groups—forecast passenger traffic and ATF growth rates of 11–15% in the near term and 6–9% over the longer term.[111–115] This analysis uses a growth rate of 7.7%, putting India on the same development trajectory as China and on track to reach China's current ATF consumption in 20 years.[xxxiii]

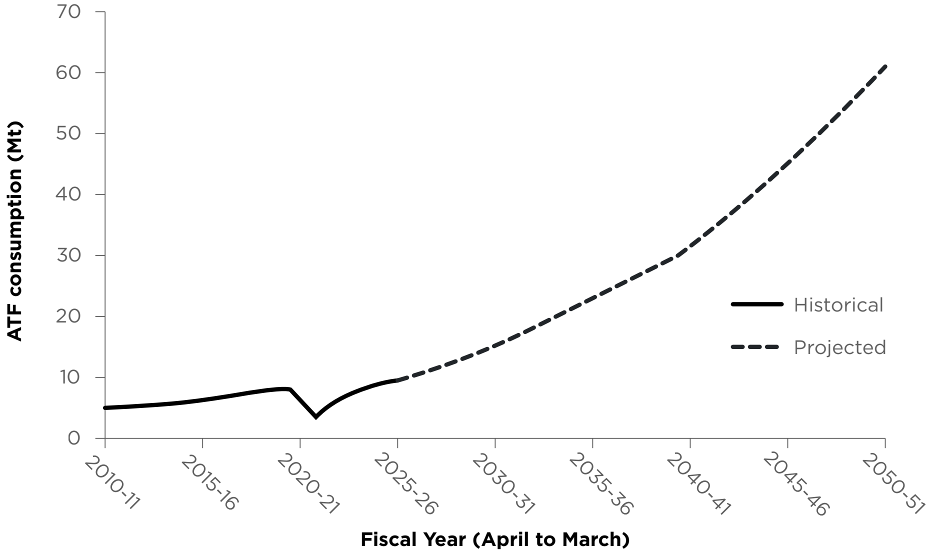


FIGURE 3.1.1: India ATF demand.

[xxxii] This analysis technically estimates the production cost of hydrocarbon liquids, but we estimate that these costs are approximately the same as SAF production costs. See Appendix B.1.

[xxxiii] This high-level forecast does not account for efficiency gains, which could lower demand by 10–20%.

This development trajectory implies India's ATF consumption will grow by approximately five times by 2047. Without timely drastic changes, India—which currently imports nearly 90% of its crude oil—risks becoming even more vulnerable to crude oil price shocks and supply shortages, undermining its goal of self-reliance.[5]

Section 2 finds that PBtL SAF is a scalable, cost-effective option for supplying much of this new ATF demand with domestically produced fuel that uses local agricultural residue and India's high-quality solar resource. PBtL's limiting factor is the supply of residue available to SAF production. We assume the absolute ceiling is the upper estimate of India's surplus agricultural residue of 235 Mt—if exclusively used in the PBtL process, this could produce as much as 67 Mt (83 million kL) of SAF (assuming 0.574 tons of FT liquids per ton of dry biomass and 50% SAF selection from FT).[24, 86,91] A more conservative estimate is the amount of agricultural residue burned in fields of 130 Mt, which could produce 37 Mt (46 million kL) of PBtL SAF.[xxxiv] Burned residue is clearly problematic and well-suited for diversion to PBtL, while some of the unburned surplus residue may be providing a service that is not clearly documented. If PBtL's use of this residue were to cause previous users to find replacements (e.g., more chemical fertilizer or animal bedding), it could undermine the SAF's climate benefit. Lastly, other applications may also seek to compete for this same limited pool of residue (e.g., brick kilns, chemicals production facilities), further depressing PBtL SAF supply.

While it is difficult to know how much PBtL SAF can be sustainably produced, these estimates help bound its potential. The high-end estimate of 67 Mt exceeds our estimated ATF demand for India in 2050 of 62 Mt, implying PBtL SAF has the technical potential to fully replace India's fossil fuel jet consumption.[xxxv,xxxvi] At more likely lower levels, it could still play the dominant role in reducing India's dependence on imported fossil ATF, supported by improvements in aircraft efficiency, small amounts of HEFA and ATJ SAF, and the longer-term development of PtL SAF (presumably relying on direct air capture CO_2).

Before PBtL SAF is competitive with fossil ATF, it will likely depend on regulatory demand for SAF domestically and abroad. India has a SAF blending goal of 5% by 2030, which initially only applies to international flights.[34] This implies a quantity of approximately 0.18 Mt (0.22 million kL), or 0.70 Mt (0.87 million kL) if expanded to include domestic flights. The EU represents a much larger market with a mandate for fuel suppliers to blend 2% SAF in 2025, rising to 70% by 2050—suggesting a SAF demand of 2.8 Mt (3.5 million kL) by 2030 and growing continuously thereafter.[31,116] Notably, the EU's mandate excludes the use of SAF derived from food and feed crops, which would rule out ATJ SAF from sugarcane

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[xxxiv] See Section 4 for the basis for our estimate of 130 Mt/yr of agricultural residue being burned in India.

[xxxv] Current ASTM standards limit FT-based SAF to a 50% blend with fossil ATF, but this limit may be increased or eliminated by 2050.

[xxxvi] PBtL's market opportunity in the aviation and power sectors is enormous for the relatively small amount of land it would require. Supplying all 62 Mt of India's forecast 2050 ATF demand with ATJ SAF from 1G sugarcane ethanol would require on the order of 6–7% of India's land, all of which must be fertile. By contrast, supplying this SAF exclusively with PBtL would require on the order of 1,000 gigawatts of solar, requiring approximately 0.4% of India's land (none of which must be fertile). This would also greatly boost India's clean energy industry while supporting farmers by paying them for the surplus residue that they previously had to burn or otherwise remove.

crops, for example.[51] The UK also has a mandate for a 2% SAF blend in 2025, 10% blend by 2030, and 22% blend by 2040, while excluding SAF derived from food, feed, or energy crops—providing another estimated 2.9 Mt (3.6 million kL) of SAF demand by 2040.[32,117,xxxvii] Collectively, these regulatory demands can support the commercialization, scaling, and downward cost trajectory of India's PBtL SAF industry.

3.2. PBTL'S FAVORABLE LONG-TERM MARKET DYNAMICS OVER FOSSIL ATF

This analysis models PBtL SAF production costs and fossil ATF prices through 2050, focusing on the impact of market drivers like crude oil, green hydrogen, and agricultural residue prices as well as financial policy drivers like taxes and subsidies.[xxxviii] The most influential factor affecting PBtL SAF costs is the price of green hydrogen, whereas fossil ATF prices are most impacted by crude oil prices, the jet crack spread (i.e., the difference between the price of jet fuel and the price of the crude oil used to produce it), and local and national taxes (which may not be applied identically to SAF). See Appendix A.3 for methodological details and sensitivities.

Under our base case assumptions, PBtL SAF production costs would fall below baseline fossil ATF prices (for domestic airlines on international runs) in 2041 at approximately $1.01/L ($1,253/t) in real 2024 dollars. However, PBtL SAF costs could fall below fossil ATF prices as early as 2033 if global oil prices follow the EIA High Case trajectory or jet crack spreads reach their 2016-2025 high of $70/bbl.

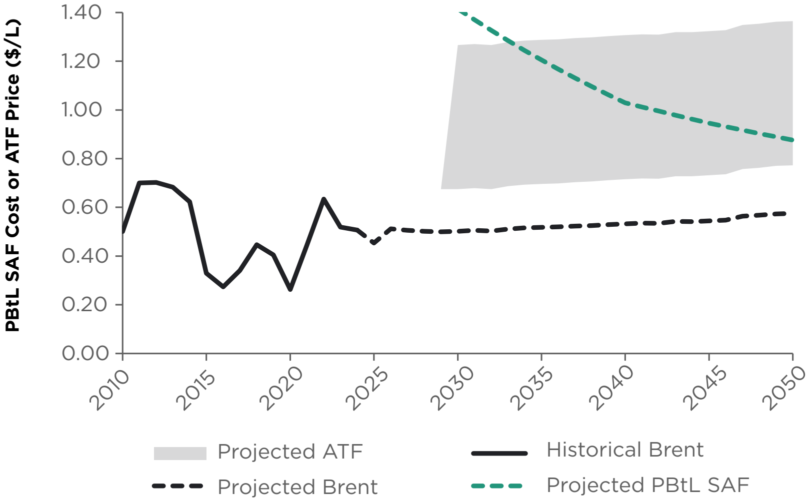

FIGURE 3.2.1: India PBtL SAF production cost vs. fossil ATF price forecast (international runs), in real (2024) dollars.

[xxxvii] Both the EU and UK SAF regulations have carve-outs for synthetic aviation fuels (effectively PtL), equal to 35% by 2050 and 3.5% by 2040 of total jet fuel demand, respectively. A small share of PBtL fuel may be able to qualify (e.g., to the degree it uses waste CO_2 from the process rather than syngas), but further regulatory clarification is needed on this distinction.

[xxxviii] The differential between the production cost and market price of PBtL SAF depends on go-to-market components embedded in any market price such as certification, logistics, and seller margin, so this analysis is not a like-for-like comparison of SAF vs. fossil ATF. Instead, this analysis is meant to show broader cost trajectory trends, demonstrating how PBtL SAF could become competitive with fossil ATF under the right conditions or policy support.

PBtL SAF costs could fall below fossil ATF prices for domestic airlines on domestic runs (which industry reporting shows is more expensive than international runs) by 2034 under baseline crude oil and jet crack spread price trajectories, assuming the factors responsible for this difference in ATF prices do not affect SAF.[xxxix,118]

PBtL SAF costs could also fall below fossil ATF prices much earlier if India provides policy support for domestic PBtL SAF production. Our base case finds a gap between PBtL SAF production costs and fossil ATF prices for international runs of \$0.45/L (\$554/t) in 2030 and declining thereafter, but there is strong evidence in favor of using policy to close this gap sooner. For example, as discussed in Section 2.6, PBtL SAF provides an avoided premature death benefit of \$230 per ton of avoided crop residue burning, equivalent to \$0.38/L (\$469/t) if offered as a subsidy. Additionally, pricing in the carbon cost of fossil jet fuel would add \$0.22/L (\$277/t) if using the estimated social cost of carbon for India (\$86/tCO_2), and it would add a near-term approximation of \$0.03/L (\$32/t) if instead expanding India's CCTS scheme (expected at prices of approximately \$10/tCO_2) to include aviation. Whether by creating systems to value these co-benefits or offering a direct financial incentive to PBtL SAF production, there is justification for policy to make PBtL SAF production lower-cost than fossil ATF prices as early as 2030—even for the cheaper international runs.

Our base case reflects conditions before the U.S.–Israel strikes on Iran and the resultant closure of the Strait of Hormuz. This recent crisis has led to a historic increase in both crude oil prices (averaging \$197/bbl or \$1.24/L for week ending March 20, 2026) and jet crack spreads (averaging \$86.22/bbl or \$0.54/L).[119] It remains to be seen how much further prices could rise, how long they will remain elevated, and what impact this conflict will have on the broader industry.[xl] The event demonstrates that even our wide band of forecasted fossil ATF prices does not capture the real volatility of the oil market, and price parity with PBtL SAF costs could be closer than described in the remainder of this section. In fact, holding the rest of our assumptions constant, recent crude oil prices and jet crack spreads would put Indian fossil ATF prices (for domestic airlines on international runs) at \$2.39/L, or 70% higher than estimated 2030 PBtL SAF costs.

[xxxix] For example, this fossil ATF price difference for international vs. domestic runs could be due to tax structures that could also affect PBtL SAF to an equal or greater degree. However, we would not expect PBtL SAF to be subject to the same taxes as fossil ATF, as the vast majority of fossil ATF in India depends on imported crude oil, whereas PBtL SAF would be produced domestically (with any taxes on solar, electrolyzers, and agricultural residue already priced into our analysis).

[xl] IndianOil has not been publishing current-day Indian jet fuel prices since the closure of the Strait of Hormuz (as of May 22, 2026), so we cannot validate this conflict's impact on the domestic market using the same source that we relied on for our core analysis. Independent outlets reported that IndianOil doubled its jet fuel price to 207,341 rupees per kiloliter (\$2.19/L) before quickly revising them back down to 104,927 rupees per kiloliter (\$1.12/L), with the government stepping in to moderate the price increase for domestic flights.[120,121]

3.3. PBTL'S LOWER MONETARY RISK EXPOSURE RELATIVE TO FOSSIL ATF

This analysis models the levelized SAF production cost of a PBtL facility commissioned in 2030 versus the levelized cost of purchasing fossil ATF over this facility's lifetime, focusing on the estimated impacts of monetary risks like commodity price inflation and rupee depreciation against the U.S. dollar. It builds from the analysis in Section 3.2 to offer insight on how PBtL projects' contract structures could help close the cost gap with fossil ATF by offering resilience to these monetary effects. We find that Indian PBtL projects built in 2030 may produce SAF at costs that are only 18% more expensive than fossil ATF purchases over these projects' lifetime (rather than 46% as estimated by a single-year comparison in Section 3.2).

India imports the vast majority of its ATF feedstock as crude oil, which is purchased in U.S. dollars. ATF wholesale prices in India have inflated at an average of 5.0% per year in nominal rupee terms over the period 2005–2025.[122] When converted to U.S. dollar terms using annual average INR/USD exchange rates, ATF prices have inflated at approximately 1.9% per year. The remaining 3.1% is attributable to rupee depreciation against the dollar over the same 20-year period.

By contrast, domestic PBtL SAF projects represent a one-time capital expenditure that can deliver long-term, rupee-denominated jet fuel contracts that provide price stability over the life of the project. The dominant input costs (renewable electricity and green hydrogen) are either integrated on the project structure or contracted through long-term, rupee-denominated power purchase agreements at fixed nominal tariffs, consistent with the structure of recent Solar Energy Corporation of India (SECI) auctions.[123,124] Electrolyzer stack replacements and other operating expenditures are incorporated in OPEX and do not carry USD-denominated import exposure. As a result, the levelized cost of PBtL SAF is largely insulated from both international commodity price inflation and the historical trend of rupee devaluation against the dollar.

Figure 3.3.1 decomposes the levelized cost of fossil ATF purchased over the same 25-year life of the PBtL facility to illustrate the impacts of inflation and rupee devaluation.[xli] At the 2030 base price of 87 INR/L ($0.97/L, assuming a 90 INR/USD exchange rate in 2030), the 25-year levelized cost increases by 11 INR/L due to ATF inflation in USD terms (1.9%/yr) and by 9 INR/L due to an assumed half of historical rupee depreciation (1.6%/yr), yielding a combined levelized cost of 108 INR/L. Considering our estimated levelized cost of PBtL SAF at 127 INR/L, this is only 18% over the fossil ATF price. Error bars reflect ranges based on historical inflation and rupee depreciation rates, with lower bounds of 1% and upper bounds of 4% for each parameter. The higher ranges of both parameters could immediately close the gap between the levelized costs of PBtL SAF production and fossil ATF purchases. See Appendix A.4 for more detail.

[xli] All costs are levelized at a nominal discount rate of 10%.

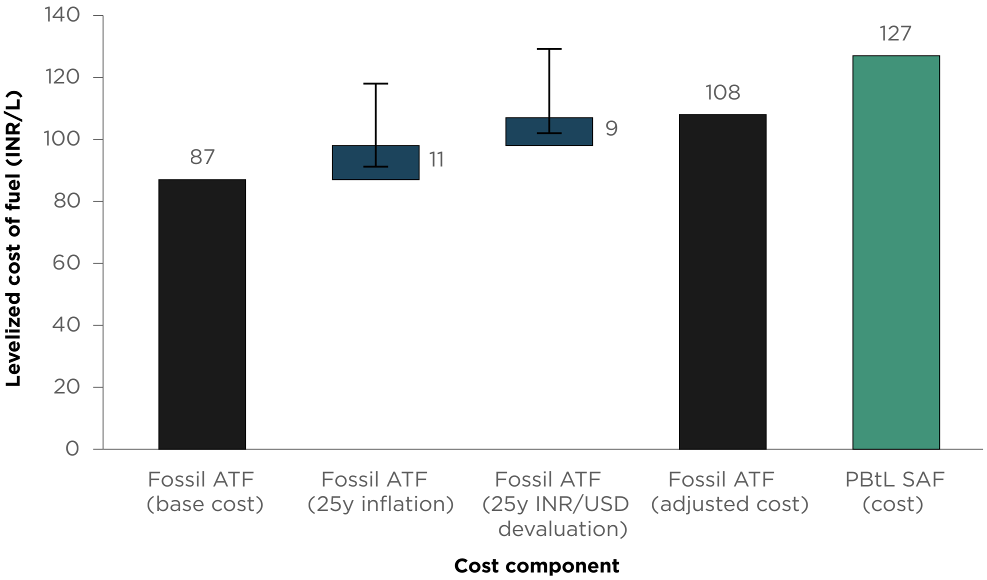

FIGURE 3.3.1: Levelized cost comparison of fossil ATF (based on imported crude oil) and domestic PBtL SAF production for plants commissioned in 2030.

3.4. SUMMARY

The previous two sections examine PBtL economics from two complementary angles. Section 3.2 compares PBtL SAF production costs against fossil ATF market prices in real dollar terms, finding crossover under base case assumptions in 2041. Section 3.3 shows how domestic PBtL SAF projects are structurally insulated from two monetary forces that drive up nominal fossil ATF costs year after year: USD-denominated commodity price inflation and rupee depreciation against the dollar. This section combines these two analyses to estimate the year in which a commissioned PBtL project will achieve lower levelized SAF production costs over 25 years than fossil ATF purchases over this same time span. We find that PBtL SAF production reaches levelized cost parity with fossil ATF purchases for projects commissioned in 2036 under base case conditions.

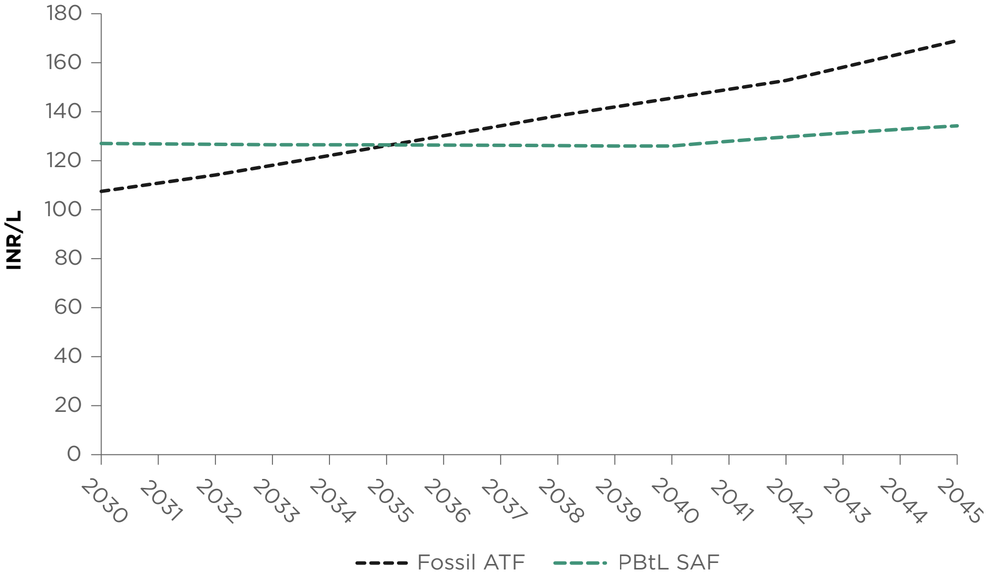

FIGURE 3.4.1: Nominal 25-year levelized production costs for PBtL SAF projects commissioned in the reference year (or fossil ATF purchases beginning in the reference year).

In sum, Indian PBtL SAF has access to a large regulated market (especially in Europe) that it is price-advantaged to sell into and which can help to spur the industry's development and downward cost trajectory. Depending on the share of sustainable agricultural residue it has access to, PBtL SAF can supply a large proportion of India's rapidly growing ATF demand. At first, this SAF can hedge against unpredictable, uncontrollable price spikes in fossil ATF while bringing a suite of other benefits—such as bolstered energy self-sufficiency, increased export opportunities, progress toward Indian SAF blending goals, and reduced local and global air pollution. Over a longer time span, our analysis suggests it can compete directly with fossil ATF.

While we estimate that levelized cost parity will arrive for PBtL projects commissioned in 2036, we do not want to give a sense of false precision—many variables will determine whether this year of cost-competitiveness arrives earlier or later. Oil price spikes, policy incentives, tax rate adjustments, and monetary trends (e.g., higher rates of commodity price inflation or rupee devaluation) would all improve domestic PBtL SAF projects' economics relative to fossil ATF reliant on imported crude oil. On the other hand, costs to bring PBtL SAF to market (e.g., fuel transport costs, producer's markup) will favor fossil ATF's relative economics. A broader conclusion is that cost parity is possible in the 2030s under base case conditions. Beginning to develop a domestic PBtL SAF industry can ensure India is positioned to capitalize on this opportunity, and from there, policymakers will be able to tune its growth based on market and monetary conditions as well as government self-sufficiency goals.

4. POWER-AND-BIOMASS-TO-LIQUIDS' NEAR-TERM GROWTH OPPORTUNITY

As laid out in Sections 2 and 3, analysis suggests PBtL is the most cost-competitive and scalable pathway for SAF production in India and that it will eventually undercut fossil ATF. In this section, we provide a spatial analysis of surplus agricultural residue availability and green hydrogen economics on a district-level basis to estimate local PBtL SAF production costs and supply potentials, with our methodologies described in Appendix A.5. This can help identify where demonstration projects and early commercial investments may find the most success en route to a much larger and broader PBtL SAF industry.

Figure 4.1 shows the estimated magnitude of surplus agricultural residue burned annually by state and union territory. Uttar Pradesh leads with 22.8 Mt of surplus agricultural residue burned each year, followed by West Bengal (11.9 Mt/y) and Madhya Pradesh (10.5 Mt/y). This suggests that northern and eastern India have the most readily available surpluses of agricultural residue. The feasibility of aggregating this agricultural residue at industrial scale is demonstrated by India's emerging biomass supply chain, which includes aggregators operating networks of rural storage depots with managed seasonal collection and year-round delivery (see Appendix C).

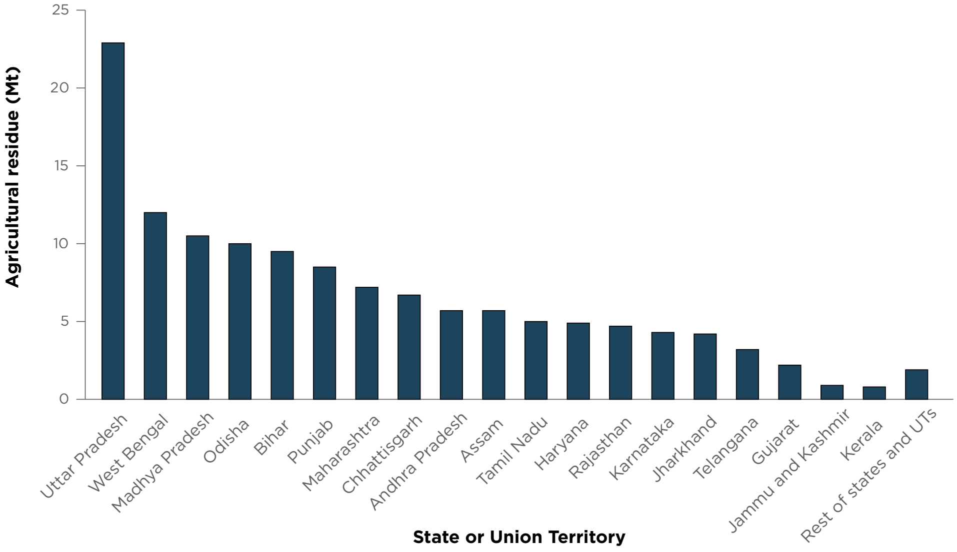

FIGURE 4.1: Aggregate tons of agricultural residue burned annually by Indian state and union territory (total of 130 Mt).

Next, we estimated the levelized costs of solar electricity and green hydrogen in India at the same spatial resolution. The levelized cost of green hydrogen was estimated using a flat-block solar configuration, which complements solar electricity with 15 hours of co-located battery storage to enable electrolyzers to operate above a 95% load factor.[17]

Figure 4.2 combines these analyses to present quantities of agricultural residue that are currently burned and PBtL SAF production costs along the same spatial dimensions. It also overlays India's ten busiest airports, which represent 71% of cumulative air traffic and 73% of cumulative ATF consumption.[125]

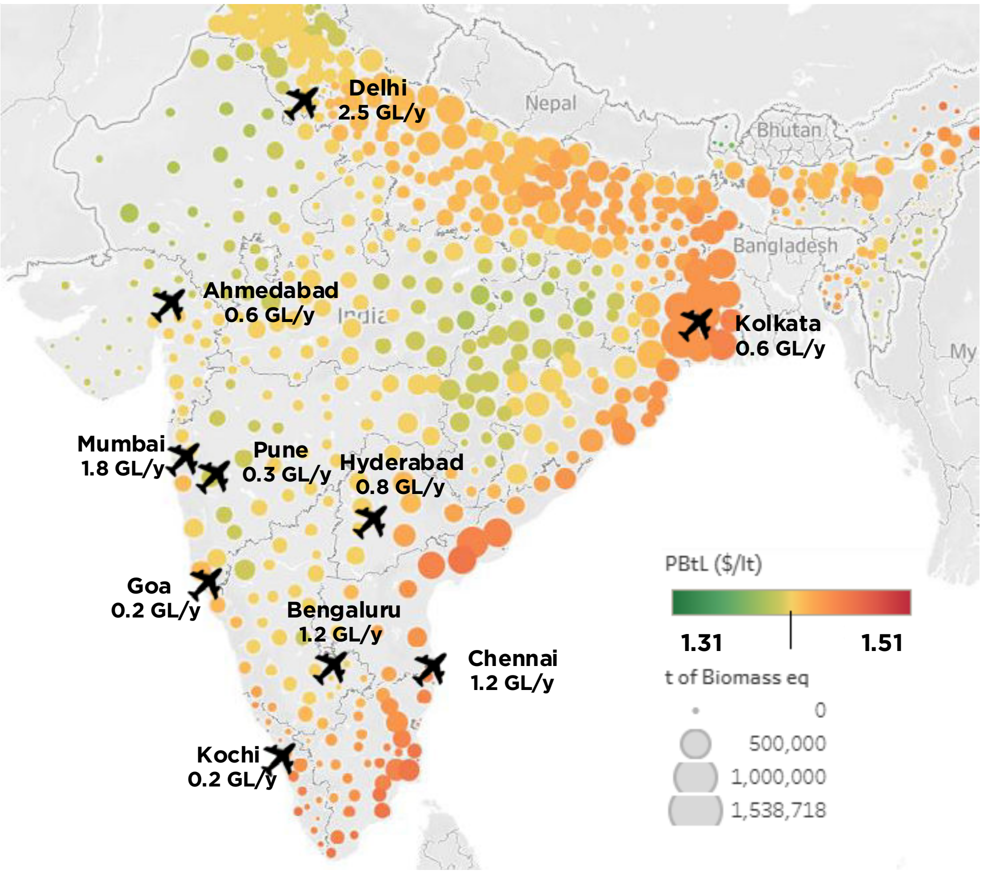

FIGURE 4.2: Levelized cost of PBtL-derived SAF mapped against India's busiest airports (2030).

In general, a spatial mismatch is evident: the districts with the largest supplies of surplus agricultural residue generally do not coincide with the districts with the highest solar resource quality—and the region where they do (central-eastern corridor) has no top-10 airports in close proximity. This underscores the importance of strategically choosing where to site and support early-stage PBtL SAF projects to set them up for the highest chance of success.

Based on this assessment, the areas surrounding the Delhi, Pune, and Mumbai airports appear most favorable to support first-of-a-kind, fully integrated PBtL SAF production projects (i.e., where agricultural residue collection, green hydrogen production, and PBtL SAF production all happen in the same locale). Specifically, Maharashtra, Haryana, Rajasthan, and Uttar Pradesh may be best suited for demonstration projects and early PBtL SAF industry development.

In further growing the industry, developers and policymakers will want to weigh several factors to better gauge how to achieve lowest delivered SAF prices, including:

- The amount of surplus agricultural residue in the region (or the cost of transporting it from an area of high supply);
- The cost of PBtL SAF production, including whether lower costs are achievable if a developer is able to build or access a hydrogen pipeline from a region with lower green hydrogen prices; and
- The logistics and cost of transporting SAF to airports, noting it is generally easier and cheaper to transport liquid aviation fuel than it is to transport solid biomass (often heavy and bulky) or gaseous hydrogen (which requires pipelines designed specifically to carry hydrogen).

In the industry's earlier stages, it may be best to prioritize low-cost PBtL SAF production, then screen these sites for residue sufficiency (i.e., to ensure there is enough to support a large-scale facility) and the logistics of transporting fuel to airports. As costs fall and demand rises, the priority may shift to areas of high residue supply despite relatively higher PBtL production costs, such as West Bengal (home of Kolkata airport).

5. DISCUSSION AND RECOMMENDATIONS

5.1. RECAP

India has an opportunity to use its low-cost green hydrogen and large surplus agricultural residue resources to develop a domestic power-and-biomass-to-liquids sustainable aviation fuel industry, which can help address its high dependence on imported oil, high air pollution from crop residue fires, and aviation sector's rising greenhouse gas emissions.

These advantages translate to PBtL being the least-cost SAF pathway for India—at least when green hydrogen prices fall below $3.4/kg, which may have already been achieved in recent auctions. PBtL SAF can also deliver the deepest GHG emission reductions while offering the most balanced resource use profile, meaning it should not face the same structural barriers that limit HEFA, ATJ, and BtL's scalability and PtL's nearer-term growth. PBtL SAF production delivers a range of co-benefits that justify policy support, including reducing local air pollution (which in turn avoids premature deaths, increases productivity, boosts tourism, etc.) and strengthening India's rural economy (e.g., by valorizing farmers' surplus agricultural residue and boosting jobs for collection and densification).

Indian PBtL developers will be able to sell into regulatory markets for SAF—thanks in part to not relying on food, feed, or energy crops—where they can attract higher prices and support the industry's initial demonstration and deployment. Because this estimated production cost is already below global SAF benchmarks while international mandate-driven demand is growing, India has a significant export opportunity that can finance early scale-up before PBtL SAF reaches stable parity with domestic fossil ATF. As PBtL prices fall, its SAF can act as a hedge against volatile fossil ATF, then compete directly on price. We estimate that price parity is achievable in the 2030s, with oil price spikes, public policy that values health and climate externalities, and fossil ATF's exposure to monetary risk (e.g., commodity price inflation, rupee devaluation) all able to push this date sooner, while costs to bring SAF to market could situationally push this date later. There is too much price volatility to expect a clean, single year of price parity—for example, we estimate PBtL SAF production costs are already 40% cheaper than recent fossil ATF prices due to the Strait of Hormuz closure—but efforts to develop a PBtL industry can improve India's fuel security in such crises and ensure it is ready to quickly scale when PBtL achieves a more stable price advantage.

Policymakers and developers will want to site initial projects where PBtL costs are low, agricultural residue is abundant, and large airports are nearby. We identify the regions around the Delhi, Pune, and Mumbai airports to be advantageous for first-of-a-kind projects and the industry's early growth. Expansion thereafter will depend on more complex assessments that balance green hydrogen prices (produced on site or delivered via pipeline), residue availability (aggregated in the region or delivered via truck or ship), and SAF transport and delivery to airports.

5.2. POLICYMAKER CONSIDERATIONS

The case for PBtL SAF is strong in theory, and critical pieces are falling into place, including successful green hydrogen auctions at low prices (see Appendix A.1), an emerging agricultural residue supply chain and marketplace with long-term storage (see Appendix C), and a global need to expand SAF beyond HEFA due to feedstock constraints. However, the PBtL SAF industry likely will not develop on its own—it needs government support to help bring all the pieces together, de-risk first-of-a-kind demonstration projects, and connect it to regulatory markets at home and abroad.

One example of such support would be working with India's integrated public sector undertakings (PSUs)—Indian Oil Corporation, Bharat Petroleum, and Hindustan Petroleum—alongside upstream majors like ONGC, as these companies dominate India's aviation fuel supply chain.[126] These entities are well-positioned to anchor early PBtL deployment for several reasons: they control refining, fuel distribution, and ATF supply infrastructure that PBtL SAF must integrate into; their balance sheets and access to government-backed financing can absorb the high capital costs and first-of-a-kind risks associated with novel SAF facilities; and they are the primary participants in government-led tenders for green hydrogen, biofuels, and SAF initiatives. At the same time, private developers and green hydrogen specialists (e.g., Ocior, ACME, ReNew, L&T) are likely to play complementary roles, particularly in the upstream green hydrogen supply that PBtL requires. Policy support for PBtL demonstration will be most effective when designed to leverage both PSU integration capabilities and private-sector specialization.

However, policymakers must also take care with how they support PBtL in order to protect against unintended consequences. For example:

- Policymakers should exclusively support green hydrogen, with electrolyzers powered by new, deliverable, hourly-matched clean power (which our flat-block solar modeling as laid out in Appendix A.1 would achieve).[127] PBtL's use of hydrogen derived from a methane feedstock (e.g., steam methane reformation, autothermal reforming) or from water electrolysis using dirty electricity would end up increasing India's exposure to fossil fuels and their price volatility, eroding PBtL's value proposition.

- Policymakers should implement guardrails to maximize the redirection of agricultural residue that is currently burned to PBtL SAF production and minimize instances in which farmers sell residue that they then need to replace with other purchases like chemical fertilizer (as this would indicate the residue is not surplus, with its use causing downstream impacts). Policymakers should also be careful not to set incentives so high as to encourage farmers to grow crops that they would not have grown if not for the value that these crops' residue provides, as this would cause land use change that puts the SAF's emissions reduction integrity in doubt.

- Policymakers should not categorically support SAF without tuning it for PBtL. Doing so could lead to expansions of HEFA with virgin oil feedstocks, ATJ with 1G ethanol, and BtL, all of which are simpler than PBtL (i.e., don't have the same early industry barriers to overcome) and could crowd the market with more expensive, lower-value fuel. For example, the use of food crops (e.g., sugarcane for ethanol) will require more fertilizer, most of which relies on imported fossil fuels, again worsening rather than improving self-sufficiency.

- Policymakers should think strategically about how to continue the development of its large but limited agricultural residue supply chain. For example, as the biomass marketplace becomes more robust, there will be more interested buyers for this valuable resource—however, aviation and chemicals are the highest-priority users from a climate standpoint, as they have no realistic alternate to sustainable biofeedstocks to displace imported oil and gas or decarbonize.[128] Policymakers should therefore consider prioritizing surplus residue resources for PBtL SAF production.

PBtL need not be the sole focus of India's SAF strategy. HEFA can provide limited volumes (ideally with explicit feedstock caps and chain-of-custody requirements), ATJ can opportunistically use excess ethanol to stabilize that market (but ideally wouldn't expand ethanol production due to land use change impacts), and PtL will have to scale over the long term to complement PBtL in fully displacing fossil ATF. But the best value on cost, emissions reductions, export opportunities, scale, and co-benefits comes from PBtL, and policymakers can help make it the centerpiece of achieving energy security in and decarbonization of India's aviation sector.

5.3. POLICY RECOMMENDATIONS

Indian policymakers can support PBtL's demonstration and growth to realize this vision in myriad ways. A sample of policy suggestions include:

1. Launch several first-of-a-kind PBtL demonstration projects in the regions surrounding the Delhi, Pune, and Mumbai airports with concessional finance, viability-gap support on hydrogen, streamlined siting and environmental approval, and airport pipeline integration. Support the coordination of developers given the various components that must come together (e.g., solar, batteries, electrolyzers, biomass suppliers, gasifiers, Fischer-Tropsch providers). Mobilize PSU oil companies (e.g., IOCL, BPCL, HPCL, ONGC) as anchor developers for early PBtL projects by including PBtL in their medium-term capital expenditure plans through ministerial direction, similar to how PSUs have been directed to lead recent green hydrogen auctions. Provide technical and regulatory support to potential developers or suppliers who may have little or no experience working in India.

2. Use trade policy to monetize early volumes: align sustainability criteria with EU ReFuelEU and UK mandates that exclude SAF derived from food and feed crops, consider negotiating recognition of India's residue-based PBtL under synthetic aviation fuel carve-outs given its extensive reliance on green hydrogen, and enable bonded logistics for export via key hubs.

3. Establish an incentive program targeted at scaling PBtL deployment beyond the first-mover demonstration projects, such as taxing or penalizing fossil ATF for its GHG emissions (e.g., at India's estimated social cost of carbon of \$86/tCO_2) and providing incentives tied to the use of crop residue that would otherwise be burned (e.g., at the estimated \$230/t biomass benefit of avoiding premature deaths from air pollution). This may more realistically take the form of expanding India's CCTS to include aviation and providing more direct subsidies for PBtL projects that meet certain thresholds (e.g., verifiable use of green hydrogen and surplus agricultural residue). Any incentive program should be reviewed periodically against key indicators, such as whether crop fires are declining relative to a baseline trajectory or whether there are signs that farmers are expanding crop cultivation due to the value that agricultural residue now provides. As a failsafe, provide a cap on agricultural residue use economy-wide that is based on current uses (i.e., that which provides the current definition of "surplus" residue) and does not exceed current or forecast levels of surplus residue.

4. Expand India's SAF blending targets to include domestic runs. Increase the blending target beyond 5% in 2030 to provide longer-term business certainty. Provide a floor or carve-out in the blending mandate for PBtL SAF using green hydrogen and agricultural residue. Complement this support with airport-level tenders.

5.4. CONCLUSION

India's rapid development is amplifying domestic strains—its growing reliance on imported crude oil, worsening air pollution from crop residue fires, and rising greenhouse gas emissions from air travel all contribute to increased economic vulnerabilities and public health risks. Sustainable aviation fuel may not be the answer categorically, as many production pathways face high costs, rely on unsustainable feedstocks, or overleverage biomass, electricity, land, and water resources. However, India's plummeting green hydrogen costs and emerging agricultural residue supply chains have created a unique, transformational opportunity for power-and-biomass-to-liquids to deliver domestically-produced jet fuel that is low-cost, low-emissions, and resource-efficient. If Indian policymakers can work with technology suppliers, project developers, and the broader network of agriculture and aviation industry stakeholders to demonstrate and scale this concept, they can advance national self-reliance and climate goals, improve air quality and rural economies, and position India as a global leader on the aviation decarbonization challenge.

APPENDICES

A. ASSUMPTIONS AND METHODOLOGIES

A.1 GREEN HYDROGEN PRICE

We assume a green hydrogen price of $3/kg for India in 2030, based on recent real-world project price discoveries, independent forecasts of green hydrogen cost trajectories, and our own modeling of an off-grid electrolysis project powered by solar and battery storage.

Real-world project price discoveries

A series of recent green hydrogen tenders have demonstrated an empirical trend of rapidly falling prices. IOCL's June 2025 reverse auction revealed an after-tax green hydrogen price of ₹397.33/kg ($4.67/kg at time of auction) from L&T Energy Green Tech.[19,129] Hindustan Petroleum's July 2025 reverse auction selected Ocior Energy for green hydrogen priced at $3.82/kg before taxes, which implies an after-tax price of $4.51/kg under the old 18% goods and services tax (GST) rate, or $4.01/kg under the updated 5% GST rate for green hydrogen.[130,131] Most recently, NeuEN won a tender from Numaligarh Refinery for green hydrogen priced at ₹279/kg ($3.08/kg) before taxes—already nearing our 2030 assumption of $3/kg—implying an after-tax price of $3.63/kg (old rate) or $3.23/kg (new rate).[132] This near-$3/kg value is consistent with discovered hydrogen costs from green ammonia SECI auctions in August 2025, ranging from $2.8–3.8/kg. Table A.1.1 and Figure A.1.1 provide detail on recent green hydrogen or green ammonia tenders (as hydrogen prices can be estimated from ammonia prices).

Announced Project	COD	Hydrogen Eq Price ($/kg)	Ammonia Price (Rs)	Hydrogen Price (Rs)	Source
TNO (Netherlands)	2024	15.5			A
BCG (EU)	2023	7.4			A
UK Auction (UK)	2027	11.9			A
TotalEnergies (EU)	2026	9			A
ArcelorMittal (EU)	2024	7.3			A
HyDeal (EU)	2024	4.7			A
L&T Hydrogen	2027	4.5		397	B
Ocior Energy (excl GST)	2028	3.8		328	C
Numaligarh Refinery	2029	3.2		279	D
ACME Cleantech	2029	3	51.9		E
ACME Cleantech	2029	3.1	54.7		E
ACME Cleantech	2029	3.2	55.8		E
ACME Cleantech	2029	3.7	64.7		E
ACME Cleantech	2029	2.8	49.8		E
ACME Cleantech	2029	3.6	62.8		E
Jakson Green	2029	2.9	50.8		E
SCC Infrastructure	2029	3	53.1		E
SCC Infrastructure	2029	3.3	57.7		E
NTPC RE	2029	3	51.8		E
Oriana Power	2029	3	52.3		E
Onix Renewable	2029	3	52.5		E
Suryam International	2029	2.8	50		E

TABLE A.1.1 Green hydrogen (equivalent) prices revealed by green hydrogen (and green ammonia) tenders. Sources: A[133], B[134], C[130], D[135], E[123].

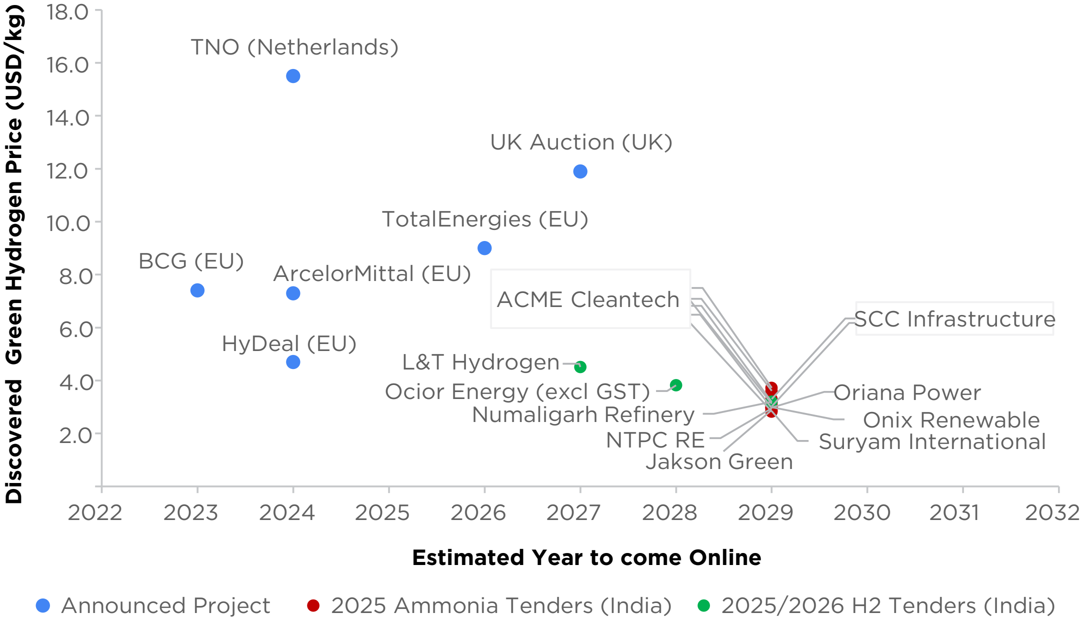

FIGURE A.1.1 Figure A.1.1. Green hydrogen (equivalent) prices revealed by green hydrogen (and green ammonia) tenders.

This progress is supported by India's National Green Hydrogen Mission—an initiative launched in January 2023 that aims to build a domestic green hydrogen industry. Its budget of $2.5 billion is further supported by a combined estimated $61 billion in potential financial support from state-level green hydrogen policies across 12 states, which includes power tariff waivers and transmission and wheeling charge exemptions (62% of support) as well as capital subsidies, interest subvention, and state GST reimbursements (38% of support).[136]

INDEPENDENT FORECASTS

Several forecasters see pathways to Indian green hydrogen developers reaching prices of $3/kg or lower by 2030. The Indian government estimates the levelized cost of green hydrogen will fall to $3 to $3.75/kg by 2030.[137] The Council on Energy, Environment, and Water (CEEW) reports "current industry estimates" of the levelized cost of green hydrogen in the range of $3.5 to $5/kg, with room to fall to $1.63 to $3.13/kg with policy support and technology cost declines.[138] RMI finds the cost of producing green hydrogen is approximately $4.4/kg today but could drop to $2.4/kg by 2030.[139]

MODELING OF SOLAR- AND STORAGE-POWERED ELECTROLYZERS

Our green hydrogen price model is based on an off-grid arrangement of electrolyzers, solar power, and battery storage, allowing for "flat-block" operations (i.e., solar available around-the-clock via its pairing with sufficient battery storage). This configuration leverages India's exceptionally low photovoltaic tariffs of less than $0.03/kWh.[16] Reliance on combined solar and battery storage raises the electrolyzer capacity factor by smoothing the solar profile and therefore amortizes the electrolyzer capital costs over more operating hours. This reduces the levelized costs of hydrogen while guaranteeing the resultant hydrogen is clean (in accordance with various jurisdictions' definitions of "clean hydrogen").[19,140]

We use hourly resolution solar energy resource data from the Global Solar Atlas to estimate the amount of solar energy that is available at a representative 20% capacity factor DC-solar site in India over one year.[17,141] This data was used to calculate the amount of hydrogen that could be produced through electrolysis at each site, as well as the corresponding hydrogen storage requirement, potential curtailment, and cost of hydrogen. For the electrolyzer, we assume alkaline technology as it is the lowest-cost today, with costs and technical parameters based on BloombergNEF.[142] We then size the hydrogen production (solar, electrolyzer, and storage) by minimizing the levelized cost of hydrogen, targeting a desired output capacity factor defined as the quantity of hydrogen input to the hydrocarbon liquid fuel production facility per hour divided by the total hours in a year. This methodology is based on NRL Capital Recovery Factor, using a plant life of 25 years and a Weighted Average Cost of Capital (WACC) of 10%.[17,143,144]A full list of cost assumptions for energy costs and electrolyzers is provided in Table A.1.2.

The levelized cost of solar electricity (LCOE, in $/MWh) is calculated as:

$$\mathrm{LCOE_{solar}} = (\mathrm{CRF} + \mathrm{f_{OPEX}}) \times \mathrm{CAPEX_{solar}} \times \frac{10^6}{(8{,}760 \times \mathrm{CF_{AC}})}$$

where CRF is the capital recovery factor, f_{OPEX} is the annual O&M cost as a fraction of CAPEX (1.5%), $CAPEX_{\mathrm{solar}}$ is the solar PV capital cost (M$/MW$_{\mathrm{AC}}$), and CF_{AC} is the AC capacity factor. The AC capacity factor is derived from DC capacity factors sourced from the Renewables.ninja database by applying a DC-to-AC inverter loading ratio (ILR) of 1.3:

$$\mathrm{CF_{AC}} = \mathrm{CF_{DC}} \times \mathrm{ILR}$$

The storage cost adder for the battery energy storage system (BESS), which enables flat-block delivery at 95% capacity factor, is:

$$C_{\mathrm{storage}} = \mathrm{CAPEX}_{\mathrm{BESS}} \times D_{\mathrm{BESS}} \times (\mathrm{CRF} + f_{\mathrm{OPEX}}) \times \frac{1{,}000}{8{,}760 \times \mathrm{CF}_{\mathrm{elec}}}$$

where $CAPEX_{BESS}$ is the battery storage capital cost ($/kWh), D_{BESS} = 15 hours is the storage duration, and CF_{elec} = 95% is the target electrolyzer capacity factor. Grid backup is priced at 5% of annual hours at $90/MWh. The total flat-block electricity cost is:

$$\mathrm{LCOE}_{\mathrm{RTC}} = \mathrm{LCOE}_{\mathrm{solar}} + C_{\mathrm{storage}} + C_{\mathrm{grid}}$$

The levelized cost of hydrogen (LCOH, in $/kg$H_2$) is the sum of electrolyzer capital recovery, electrolyzer O&M, and electricity costs from solar, storage, and grid:

$$\mathrm{LCOH} = \left[\left(\mathrm{CRF} + f_{\mathrm{OPEX,elec}}\right) \times \mathrm{CAPEX}_{\mathrm{elec}} \times 10^{6} / \left(8{,}760 \times \mathrm{CF}_{\mathrm{elec}}\right) + \mathrm{LCOE}_{\mathrm{RTC}}\right] \times \left(\eta_{e} / 1{,}000\right)$$

where $CAPEX_{elec}$ is the electrolyzer capital cost (M$/MW), $f_{OPEX,elec}$ is the electrolyzer O&M rate (3.5% of CAPEX, inclusive of stack replacement), η_e is the electrolyzer specific energy consumption (kWh/kg H_2), and CF_{elec} = 95% is the electrolyzer capacity factor. The $\times 10^6$ and ÷1,000 terms convert M$ to $ and kWh to MWh, respectively.

The capital recovery factor is:

$$\mathrm{CRF} = r(1 + r)^{n} / \left[(1 + r)^{n} - 1\right]$$

where r is the real WACC and n is the project lifetime in years.

Parameter	Units	2030 term
Solar PV CAPEX	M$/MW_AC	0.43
BESS CAPEX	$/kWh	86
Electrolyzer CAPEX	M$/MW	0.45
Electrolyzer efficiency	kWh/kg H_2	52
Electrolyzer OPEX (incl. stack)	% CAPEX	3.5%
Solar PV OPEX	% CAPEX	1.5%
DC/AC inverter loading ratio	—	1.3
Electrolyzer capacity factor	—	95%
BESS duration	hours	15
Grid backup share	% hours	5%
Grid electricity cost	$/MWh	90
WACC (real)	—	10%
Plant lifetime	years	25

TABLE A.1.2 Key input assumptions for hydrogen production cost estimation.

At a representative 25% AC capacity factor site with 2030 assumptions, this model yields a levelized cost of hydrogen of approximately $2.9/kg. We round up to $3/kg, which we think is reasonable to achieve in 2030, as it requires only modest price declines from 2025's auctions (which, given Numaligarh Refinery's auction results, may have already been achieved on a pre-tax basis) and falls within other groups' forecast ranges.

A.2 TECHNO-ECONOMIC ANALYSIS OF SAF PATHWAYS

GENERAL FRAMEWORK

The levelized cost of liquids production (LCOF, in $/L) for each SAF pathway is estimated as:[xlii]

$$\mathrm{LCOF} = \mathrm{CRF} \times \frac{\mathrm{CAPEX_u}}{\mathrm{CF}} + \mathrm{f_{OPEX}} \times \frac{\mathrm{CAPEX_u}}{\mathrm{CF}} + \mathrm{C_{H2}} \times \eta_{\mathrm{H2}} + \frac{\mathrm{C_{biomass}}}{\eta_{\mathrm{biomass}}} + \mathrm{C_{CO2}} \times \frac{\eta_{\mathrm{CO2}}}{1{,}000}$$

where:

$CAPEX_u$ is the unitary capital cost ($/L per year of installed capacity)

CF is the plant capacity factor (90%)

f_{OPEX} is the annual O&M cost as a fraction of CAPEX (5% for most pathways)

C_{H2} is the hydrogen price ($/kg) and η_{H2} is hydrogen consumption (kg H_2/L liquids)

$C_{biomass}$ is the delivered biomass cost ($/t) and $\eta_{biomass}$ is the biomass-to-liquids yield (L liquids/t dry biomass)

C_{CO2} is the CO_2 capture cost ($/t CO_2) and η_{CO2} is CO_2 consumption (kg CO_2/L); the ÷1,000 converts kg to tons

Not all terms apply to every pathway: BtL has no hydrogen input; HEFA and ATJ use pathway-specific feedstock costs in place of the biomass term; and only PtL requires captured CO_2.

[xlii] Here, we discuss the levelized cost of producing hydrocarbon liquid fuels. See Appendix B.1 for an explanation of why we assume these are equal to the levelized cost of producing SAF.

PATHWAY-SPECIFIC ASSUMPTIONS

Parameter	Units	PBtL	BtL	PtL	HEFA	ATJ
Unitary CAPEX	$/L/yr	2.68	7.93	1.59	1.22	4.47
f_{OPEX}	% CAPEX	5%	5%	5%	(a)	5%
H_2 consumption	kg/L	0.264	—	0.396	0.035	—
Biomass yield	L/t feed	639	245	—	—	—
CO_2 consumption	kg CO_2/L	—	—	2.91	—	—
CO_2 capture cost	$/t CO_2	—	—	50	—	—
Capacity factor	—	90%	90%	90%	90%	90%
H_2 price (base)	$/kg	3.00	—	3.00	3.00	—
Biomass cost	$/t	90	90	—	—	—
UCO cost	$/kg	—	—	—	1.10	—
Ethanol cost (1G)	$/L	—	—	—	—	0.81
GHG reduction	vs ATF	95%	91%	54%	84%	63%
Plant lifetime	years	25	25	25	25	25
WACC (real)	—	10%	10%	10%	10%	10%

TABLE A.2.1 Key techno-economic assumptions for each SAF pathway (2030, India conditions). (a) HEFA OPEX estimated at $0.17/L based on technology data rather than as a percentage of CAPEX.[145] Notes and sources: PBtL and BtL biomass yield assumptions based on literature.[86] PtL CO_2 consumption assumes point-source industrial capture, with CO_2 cost from government reporting and literature.[57,146] HEFA CAPEX based on assumption from literature adjusted by 1.1x for EUR/USD and 1.3x per inflation.[145] UCO price of $1,100/t and 0.97 kg feed per liter based on literature.[70] ATJ CAPEX based on literature.[1] GHG reductions are lifecycle values relative to fossil ATF at 2.6 $kgCO_2e$/L. PtL GHG reduction of 54% reflects fossil point-source CO_2; biogenic or direct air capture CO_2 would yield higher reductions.

EXTERNALITY VALUATION

When valuing externalities (Section 2.6) with the social cost of carbon set at \$86/tCO_2 and the benefit of avoiding premature deaths from local air pollution set at \$230/t of agricultural residue diverted from open-field burning, PBtL SAF production costs fall, and PBtL's advantage over most SAF pathways widens. BtL SAF production costs would be lower until green hydrogen prices fall to approximately \$2-2.5/kg, but PBtL would allow for much more SAF production from the same amount of residue resource.

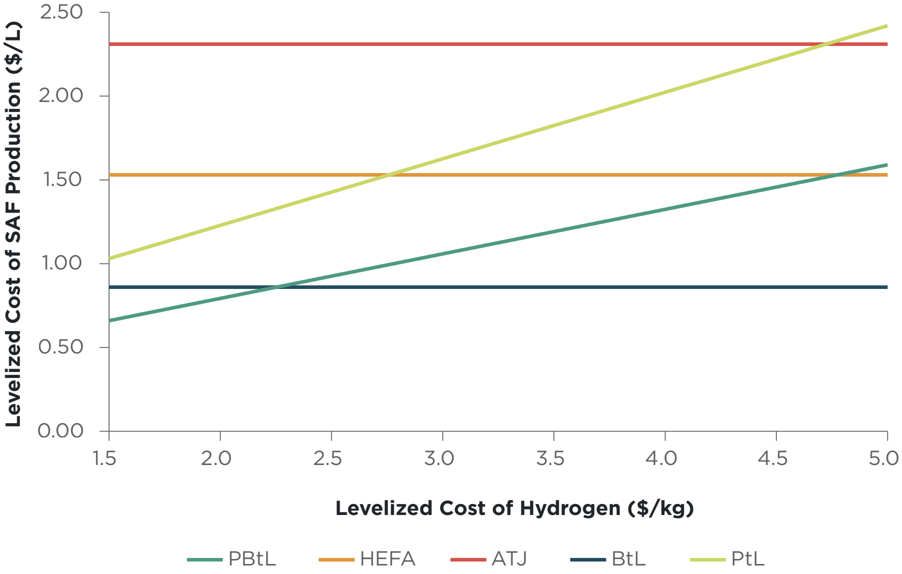

FIGURE A.2.1 Net levelized cost of SAF production for SAF pathways when including the social cost of carbon and the benefit of avoiding premature deaths from local air pollution.

SENSITIVITY ANALYSIS

The sensitivity analysis varies one parameter at a time while holding all other techno-economic inputs constant at their baseline values. For each pathway, we recompute the levelized cost of SAF under a "low" and "high" value for the selected lever, then report the resulting deviation from the baseline. CAPEX and OPEX are adjusted symmetrically by ±20%. Feedstock and hydrogen sensitivities use the empirical ranges described below; because these ranges are not always symmetric around the baseline (e.g., varying biomass costs by −33% to +67%), the resulting cost deviations are correspondingly asymmetric. Figures A.2.2–A.2.6 visualize these one-at-a-time deviations, allowing direct comparison of the relative influence of biofeedstock, hydrogen, CAPEX, and OPEX on each pathway's production cost.

For HEFA, varying the UCO price across the observed range from $0.85/kg to $1.20/kg (a change of −23% to +9%) results in a SAF production cost shift of approximately −$0.24/L (−16%) to +$0.10/L (+6%). In contrast, ±20% changes in CAPEX and OPEX alter the SAF production cost by only ±$0.03 (±2%), and varying hydrogen from $2.5–4.5/kg shifts the cost by −$0.03/L (−2%) to +$0.05/L (+4%).

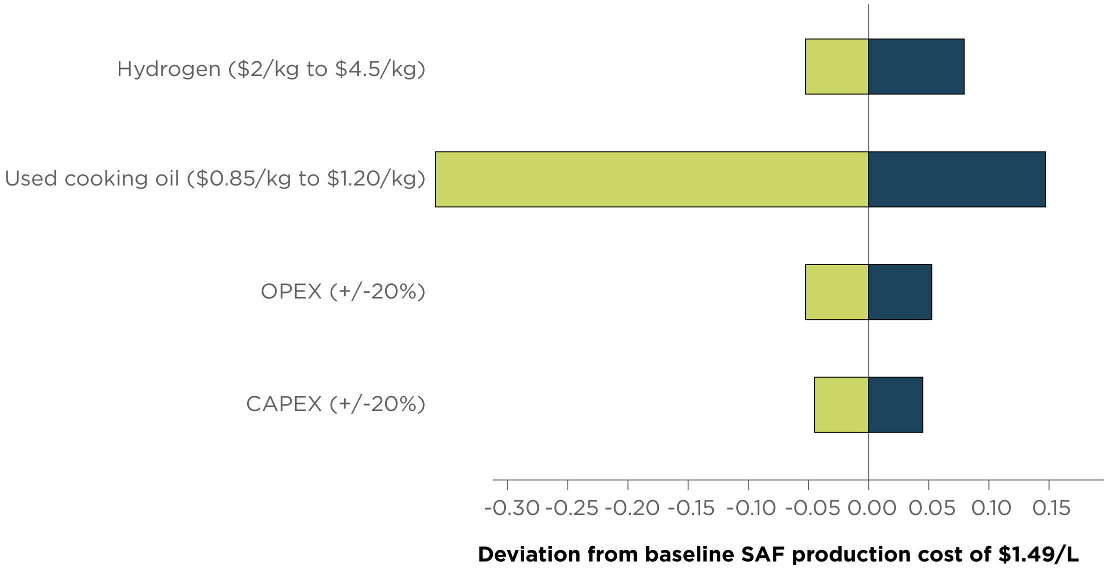

FIGURE A.2.2 Impact of varying key assumptions on the levelized cost of HEFA SAF production.

For ATJ, varying the ethanol price across the observed range of $0.64/L to $1.14/L (a change of −21% to +41%) results in a SAF production cost shift of approximately −$0.30/L (−13%) to +$0.58/L (+26%). In contrast, ±20% changes in CAPEX and OPEX shift the SAF production cost by only ±$0.11/L (±5%) and ±$0.05/L (±2%), respectively.

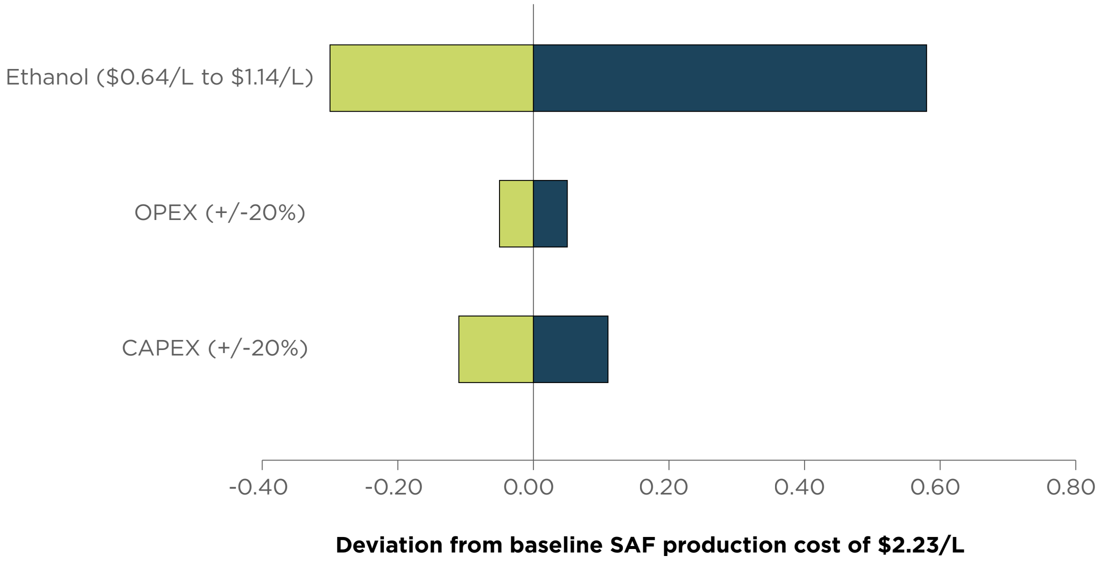

FIGURE A.2.3 Impact of varying key assumptions on the levelized cost of ATJ SAF production.

For BtL, a ±20% change in CAPEX shifts the SAF production cost by approximately ±$0.19/L (±11%), while a ±20% change in OPEX shifts the cost by approximately ±$0.09/L (±5%). Varying the biomass price from $90/t to $60–150/t (a change of −33% to +67%) results in a SAF production cost shift of approximately −$0.12/L (−7%) to +$0.24/L (+14%). The biomass price sensitivity's downshift represents a reasonably achievable lower price point as the agricultural residue market scales, and the sensitivity's upshift is consistent with high-end third-party reporting of recent agricultural residue biomass pellet prices in India.[147]

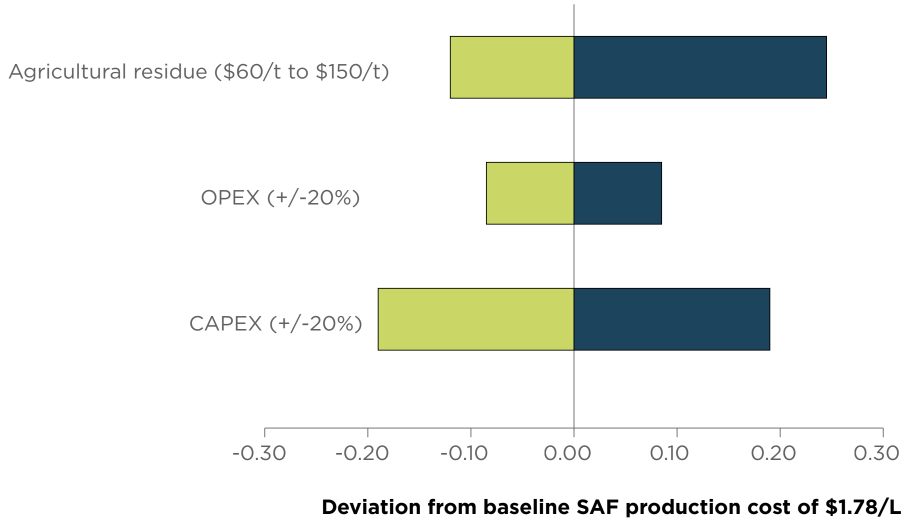

FIGURE A.2.4 Impact of varying key assumptions on the levelized cost of BtL SAF production.

For PtL, varying hydrogen from $3/kg to $2–4.5/kg (a change of –33% to +50%) shifts the SAF production cost by approximately –$0.40/L (–25%) to +$0.59/L (+37%). Varying the CO_2 capture cost from $50/t to $40–150/t (a change of –20% to +200%) results in a SAF production cost shift of approximately −$0.03/L (–2%) to +$0.29/L (+18%), with this CO_2 cost range reflecting estimates across a variety of point-source industrial processes.[57,146] In contrast, ±20% changes in CAPEX and OPEX shift the SAF production cost by only ±$0.04/L (±2%) and ±$0.02/L (±1%), respectively.

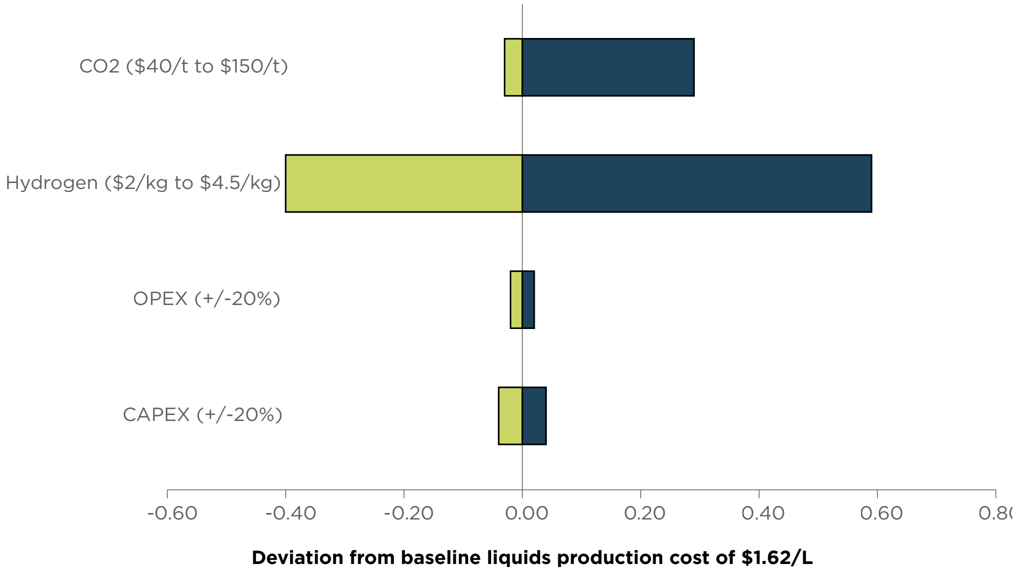

FIGURE A.2.5 Impact of varying key assumptions on the levelized cost of PtL SAF production.

For PBtL, varying hydrogen from \$3/kg to \$2–4.5/kg (a change of –33% to +50%) shifts the PBtL SAF production cost by approximately –\$0.26/L (–19%) to +\$0.40/L (+28%). Biomass cost variation from \$90/t to \$60–150/t (following the range used for BtL) changes the SAF production cost by roughly –\$0.05/L (–3%) to +\$0.09/L (+7%), and ±20% changes in CAPEX and OPEX alter the cost by ±\$0.07/L (±5%) and ±\$0.03/L (±2%), respectively.

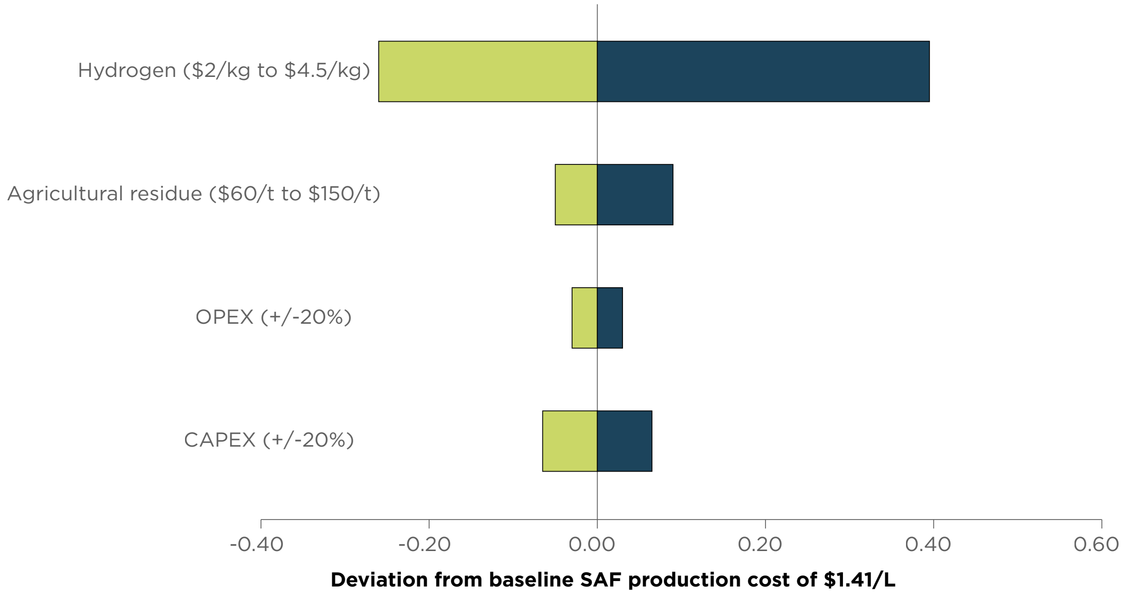

FIGURE A.2.6 Impact of varying key assumptions on the levelized cost of PBtL SAF production.

A.3 PBTL SAF COST VS. FOSSIL ATF PRICE FORECAST METHODOLOGY AND SENSITIVITIES

Our PBtL SAF production cost forecast follows the techno-economic analysis methodology used in Appendix A.2 to arrive at a 2030 cost. We trend green hydrogen prices linearly from \$3/kg in 2030 to \$1.97/kg in 2040 and \$1.64/kg in 2050 following BNEF's green hydrogen price forecast for India, which includes corporate taxes.[148] We decrease CAPEX and OPEX at an assumed 2% per year learning rate. We assume a U-shape for the biomass cost, falling by 2% per year from 2030-2040 as logistics improve, stabilizing from 2040-2045, and rising by 1% per year from 2045-2050 as the lowest-cost supplies are exhausted (i.e., residue procurement cost increases outpace cost declines from logistics improvements).

Our baseline fossil ATF price forecast seeks to estimate prices for fossil ATF used by domestic airlines on international runs, as these are cheaper than fossil ATF used in domestic runs and therefore represent a more conservative scenario. The forecast takes the global average jet fuel price in November 2025 as reported by the IATA (\$0.61/L or \$760/t) and compares it to the respective Indian ATF price for domestic airlines on international runs as reported by IndianOil for select high-traffic Indian airports (averaging $0.83/L or $1,022/t).[118,119] It uses these empirical prices to estimate a multiplier that is used to convert from global average ATF prices to India-specific delivered ATF prices (e.g., accounting for the 11% central excise duty at ATF production, state VATs, and other country or local dynamics that are difficult to isolate for a bottom-up analysis).[149,150] As crude oil and jet fuel prices can fluctuate dramatically, the forecast is then tied to the U.S. Energy Information Administration's Brent crude oil price Reference Case forecast, applying a jet crack spread adder of $35/bbl—which roughly tracks recent history (i.e., after the volatility of 2022 and early 2023 from Russia's invasion of Ukraine but before the U.S.-Israel strikes on Iran in early 2026)—to estimate global average jet fuel prices.[119] From there, it applies the previously estimated multiplier to arrive at India-specific fossil ATF prices.

In general, this forecast holds the jet crack spread adder and India-specific multiplier constant while following the trajectory of the Brent crude oil forecast. However, it uses a price band that can be interpreted as either flexing the jet crack spread to $0/bbl or $70/bbl (reflecting its observed range from 2016–2025) or switching to the EIA's Low or High Case for its Brent crude oil forecast (which has a similar impact on ATF prices). This band accounts for the fact that fossil ATF prices can swing wildly from year to year due primarily to global oil market volatility, with these geopolitical dynamics largely outside of India's control.

For example, from 2016–2025, Brent crude oil prices have been as low as $20/bbl (at the start of the COVID-19 pandemic with its sudden drop in oil demand) and as high as $130/bbl (in the early days of Russia's invasion of Ukraine, reflecting substantial supply risk), though prices have more commonly floated between $50-80/bbl.[151] By contrast, PBtL costs are expected to fall over time, with the pace dependent on the speed of green hydrogen's cost decline. With green hydrogen, however, there should not be much year-to-year price variability, as solar electricity costs are stable once projects are built, and water and agricultural residue prices (the other key inputs) are also relatively stable.

The following figures compare PBtL SAF production costs with fossil ATF prices along two dimensions: international vs. domestic runs (affecting the price of fossil ATF) and excluding vs. including two externalities (the social cost of carbon and the benefit of avoiding premature deaths from local air pollution). See Section 3.2 for additional commentary.

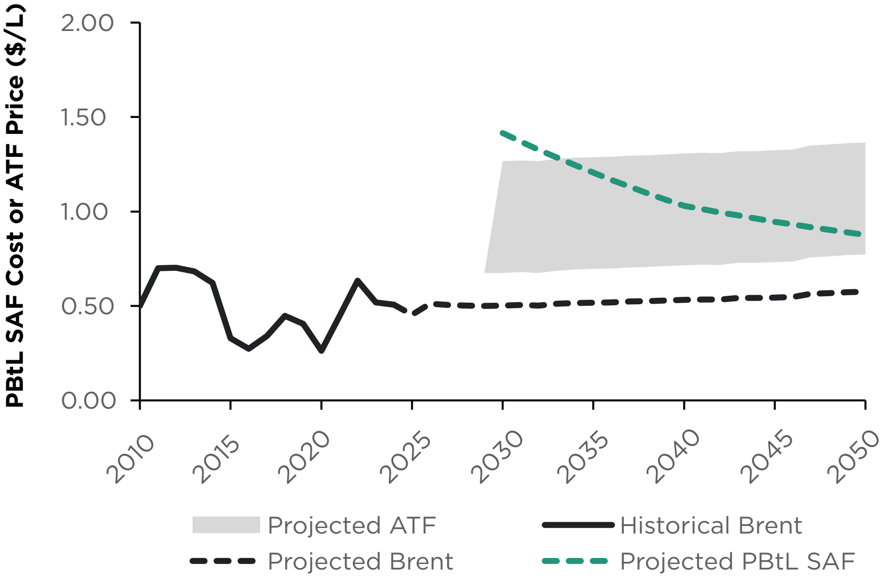

FIGURE A.3.1 India PBtL SAF production costs vs. fossil ATF price forecast (international runs, excluding externalities), in real (2024) dollars.

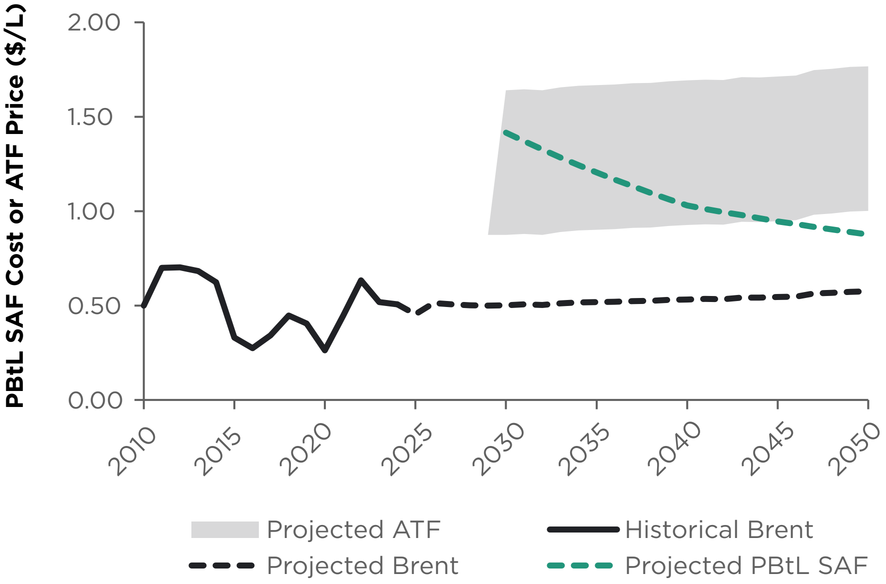

FIGURE A.3.2 India PBtL SAF production costs vs. fossil ATF price forecast (domestic runs, excluding externalities), in real (2024) dollars.

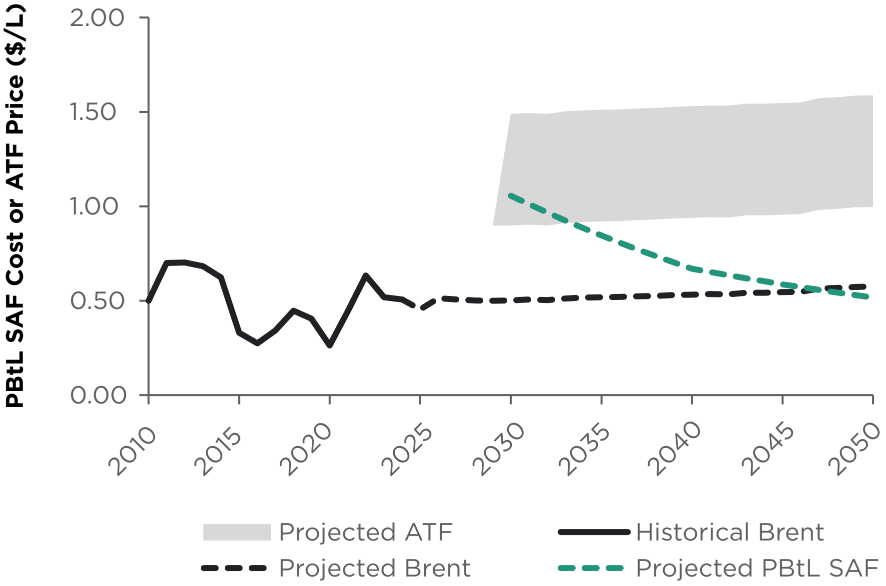

FIGURE A.3.3 India PBtL SAF production costs vs. fossil ATF price forecast (international runs, including externalities), in real (2024) dollars.

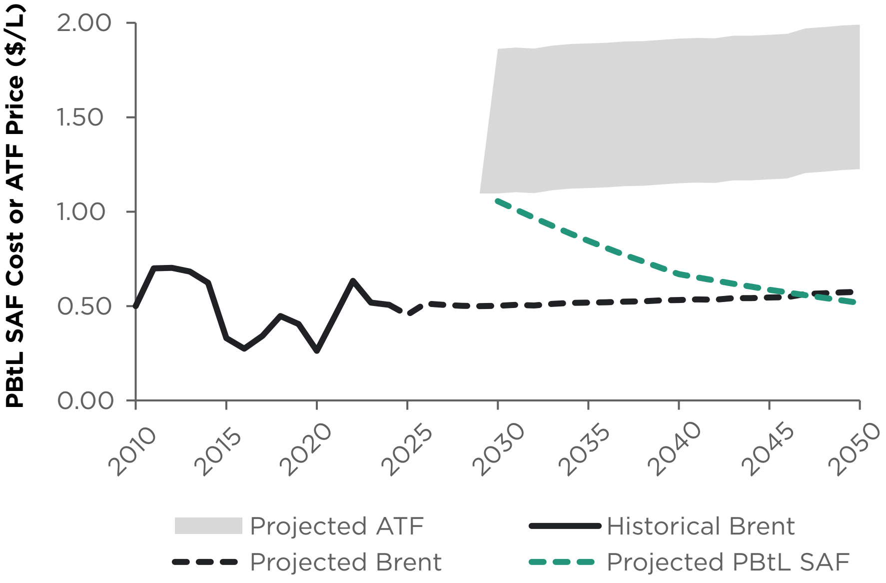

FIGURE A.3.4 India PBtL SAF production costs vs. fossil ATF price forecast (domestic runs, including externalities), in real (2024) dollars.

A.4 PBTL SAF COST VS. FOSSIL ATF PRICE MONETARY RISK EXPOSURE DETAIL

We provide two additional perspectives for illustrating the impacts of crude oil inflation and rupee devaluation against the dollar. Figure A.4.1 shows the trajectory of nominal rupee-denominated costs over the 2030–2050 period. Fossil ATF costs escalate from approximately 87 INR/L to over 200 INR/L, while PBtL SAF costs remain flat at 127 INR/L, reflecting the latter's domestic fixed cost structure. Figure A.4.2 presents the same comparison in nominal U.S. dollars. Fossil ATF rises from 1.0 to 1.4 USD/L with global commodity price inflation, while PBtL SAF declines from 1.4 to 1.0 USD/L—a consequence of rupee depreciation reducing the dollar-equivalent cost of rupee-denominated production.

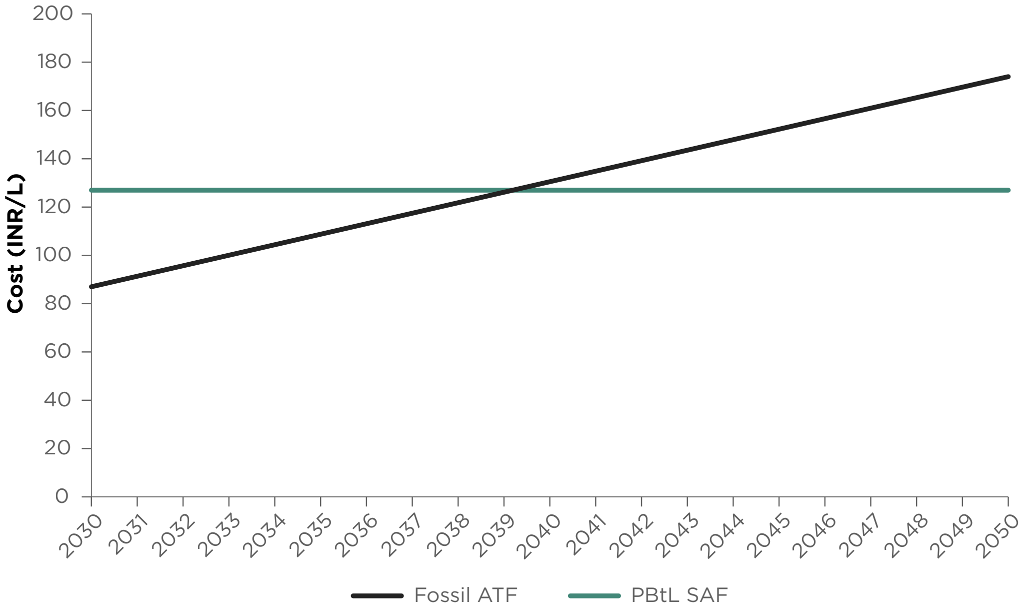

FIGURE A.4.1 Levelized cost of fuel (fossil ATF) and SAF production (PBtL) in nominal Indian rupees.

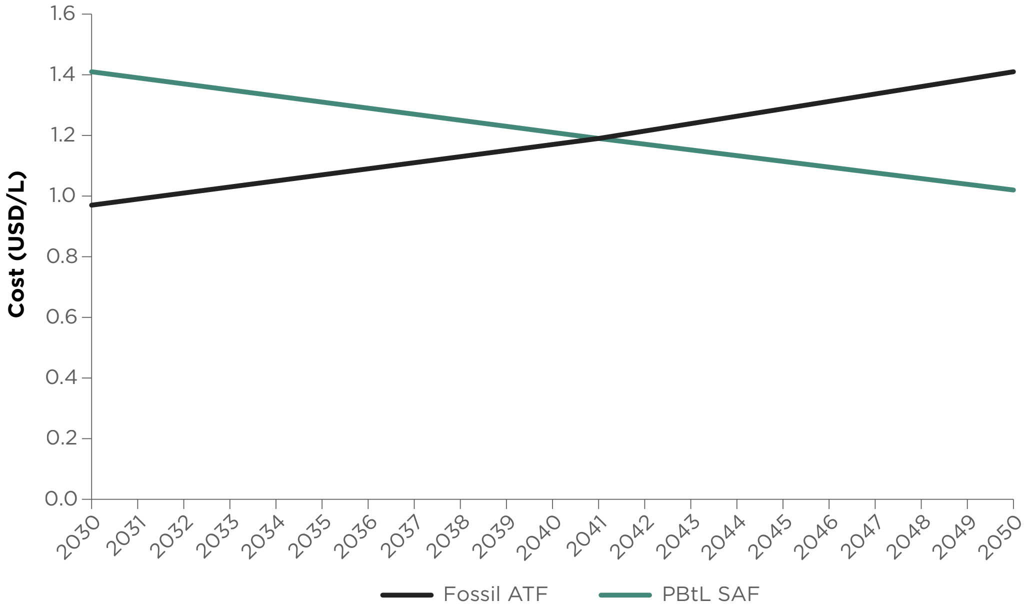

FIGURE A.4.2 Levelized cost of fuel (fossil ATF) and SAF production (PBtL) in nominal U.S. dollars.

A.5 DISTRICT LEVEL SPATIAL ANALYSIS METHODOLOGY

District-level surplus agricultural residue quantities are estimated from Climate TRACE's emissions database, which is obtained primarily through satellite remote sensing and active fire detection and reports annual CO_2 emissions from cropland fires for 635 Indian districts.[152,153] We convert reported CO_2 emissions to equivalent dry biomass using a stoichiometric factor derived from the average carbon content of agricultural residue:

$$\mathrm{m_{biomass}} = \mathrm{m_{CO2}} \times \left(\frac{\mathrm{C}}{\mathrm{f_C}}\right)/\mathrm{M_{CO2}} = \mathrm{m_{CO2}} \times \left(\frac{12}{0.48}\right)/44 \approx \mathrm{m_{CO2}} \times 0.57$$

where f_C = 0.48 is the mass fraction of carbon in dry biomass, C = 12 g/mol is the atomic mass of carbon, and M_{CO2} = 44 g/mol is the molar mass of CO_2. This yields a conversion factor of approximately 0.57 t dry biomass per t CO_2 emitted. Using this method, the cumulative emissions from 635 districts resulted in 129.6 tons per year of burned biomass, which is consistent with public estimates.[11]

The district-level LCOE is computed using the same flat-block model described in Appendix A.1, substituting the district-specific AC capacity factor (CF_{DC} × 1.3). The district-level LCOH follows the equation in Appendix A.1, with electrolyzer parameters held constant at 2030 baseline values (Table A.1.2).

The district-level levelized cost of SAF for PBtL is:

$$\mathrm{LCOF_d} = \left(\mathrm{CRF} + \mathrm{f_{OPEX}}\right) \times \frac{\mathrm{CAPEX_u}}{\mathrm{CF}} + \eta_{\mathrm{H2}} \times \mathrm{LCOH_d} + \frac{\mathrm{C_{biomass}}}{\eta_{\mathrm{biomass}}}$$

where $\mathrm{LCOH_d}$ is the district-specific LCOH and all other parameters are held at the 2030 baseline values in Table A.2.1. This approach isolates spatial variation in PBtL competitiveness driven by the solar resource, while holding technology and feedstock cost assumptions constant. The resulting map (Figure 4.2) overlays SAF production costs to identify districts where both resource availability and economic conditions favor early PBtL deployment.

B. TECHNICAL EXPLANATIONS

B.1 SUSTAINABLE AVIATION FUEL VS. HYDROCARBON LIQUID FUELS

Hydrocarbon liquid fuels (deemed "hydrocarbon liquids" or just "liquids" throughout this paper) are those products resulting from SAF production processes that are liquid at standard conditions (i.e., 25 degrees Celsius and 1 atmosphere of pressure). The jet fuel share of these liquids (i.e., SAF) can differ depending on the technology as well as how the process is tuned (i.e., to favor one liquid over the rest), and other products like renewable diesel have their own market value and policy support. Our analysis in Section 2.4 estimates the cost of producing hydrocarbon liquids from different SAF production pathways. We argue that these liquids production costs are effectively equivalent to SAF production costs, and when discussing production costs throughout this paper, we use SAF and liquids interchangeably.

SAF selectivity—the kerosene fraction of total hydrocarbon liquids produced by HEFA, ATJ, and FT technologies—varies across and within production pathways. Conventional FT synthesis yields a maximum straight-run kerosene fraction of approximately 40%, but advanced FT reactor designs with wax hydrocracking and tail-gas recirculation achieve kerosene selectivity in the range of 61–77%, with commercial configurations such as Johnson Matthey and bp's FT CANS™ technology targeting even higher selectivity through single-stage recycle loops with carbon monoxide conversion above 90%.[91,154–156]

Regardless of the exact kerosene fraction, the remaining FT coproducts—primarily renewable diesel and naphtha—are fungible drop-in energy products with comparable or higher market value per liter. In addition, the refining and upgrading step is relatively low in capital intensity. For example, the capital cost of refining and upgrading FT hydrocarbon liquids to finished fuels is estimated at approximately 10% of total FT facility capex (excluding gasification).[157]such as coal, natural gas, biomass and waste, can be converted into transportation fuels by combining appropriate gasification, Fischer–Tropsch and refining technologies. Efficient refining of the Fischer–Tropsch synthesis derived syncrude requires a different approach to refinery design than commonly applied to crude oil refinery design. The design of refineries to optimise the production of on-specification motor-gasoline, jet fuel and diesel fuel respectively from both high temperature Fischer–Tropsch (HTFT Because our estimated FT-plus-gasification capex is only approximately 20–25% of the levelized cost of PBtL liquids, the upgrading step accounts for less than 2% of that levelized cost—and our cost figures already include this step, as it is embedded in the source data we rely on. For this reason, and consistent with other PBtL techno-economic studies that treat the liquid hydrocarbon fraction as the final product, the cost of liquids production closely approximates the effective production cost of SAF, and the relative cost ranking of pathways presented in Section 2 is preserved across the range of plausible selectivity assumptions.[156]

While the cost of liquids production closely approximates the effective unit cost of SAF, estimating SAF market prices requires a series of complex assumptions around market supply and demand. In this paper, we focus on production costs to more clearly compare financial viability across SAF pathways. While we acknowledge that production costs are qualitatively different from fossil ATF and SAF market prices and thus cannot be directly compared (e.g., throughout Section 3), our analysis does illuminate how themes such as India's declining solar electricity prices and global crude oil price volatility affect the relative competitiveness of PBtL SAF with fossil jet fuel.

B.2 SAF CERTIFICATION

ASTM International has certified 11 SAF production pathways for use in aircraft, with additional routes under evaluation.[158] Technical certification requires meeting the same stringent performance and safety specifications as conventional ATF. Separately, the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) determines whether airlines can claim emissions reductions from using SAF. Fuel eligibility requires meeting CORSIA's lifecycle GHG emissions reduction threshold (currently 10% below a fossil jet fuel baseline) and adhering to sustainability frameworks such as the International Sustainability and Carbon Certification (ISCC) or Roundtable on Sustainable Biomaterials (RSB).[159]

Each of the ASTM-certified SAF pathways also has a maximum blend ratio with fossil ATF, which currently range from 5–50%.[91] Most SAF today is synthetic paraffinic kerosene (SPK), which lacks aromatics—a small but important component of conventional ATF that prevents fuel leakage and fire risks. Blending conventional ATF with SPK allows for enough aromatics for the fuel mix to work with existing aircraft. However, many organizations and companies are working to allow for the use of 100% SAF, and the EU's blending mandate calls for 70% by 2050, so today's 50% blend rate is not a fixed ceiling. Achieving this goal could entail improvements and testing of synthetic kerosene with aromatics (SKA or SPK/A) products, developing synthetic aromatic kerosene (SAK) to blend with SPK, or designing and deploying aircraft that do not need aromatics to safely work with SPK.[160,161] In practice, today's 50% blend limit is not a meaningful barrier to the SAF industry, as SAF supply and blending goals are far below this constraint.

C. INDIA’S AGRICULTURAL RESIDUE SUPPLY CHAIN

The biomass delivered cost used in our analysis ($90/t) is grounded in transactions on India’s emerging agricultural residue marketplace, where multiple companies now operate active aggregation, storage, and densification services. This appendix summarizes discussions with BiofuelCircle and Biome Industria that give visibility into how the supply chain functions in practice. These examples are not exhaustive but are representative of the broader ecosystem maturing in India.

C.1 BIOFUELCIRCLE: AGGREGATION AND STORAGE AT SCALE VIA THE BIOMASS BANK

BiofuelCircle is a digital marketplace for agricultural residue that operates a network of physical rural storage depots called Biomass Banks. Each Biomass Bank is a managed warehouse facility—roughly 10 acres in footprint with 8,000–10,000 tons of indoor biomass storage capacity—that serves as the aggregation and storage hub for a cluster of approximately 10 surrounding villages within a 10–15 km radius. The depot is the physical core of the model: it solves the mismatch between agriculture’s seasonal collection opportunities and industry’s year-round feedstock requirements that has historically made residue utilization uneconomic.

Around each storage depot, the Biomass Bank coordinates roughly 2,000 farmers, 40 rural partners (small tractor drivers and fleet owners), and 10 aggregation fleets equipped with balers, rakers, shredders, and trolleys. During and immediately after harvest, rural partners collect baled residue from farms—by either scheduled pickup or farmer walk-in delivery—and transport it to the depot for storage. Network partners then provide transportation from depot storage to end customers (e.g., compressed biogas plants, briquette and pellet manufacturers) throughout the year. Storage facilities include integrated weighbridges and temperature and humidity tracking to maintain quality, and depots themselves are solar-powered with digitally enabled operations. A typical Biomass Bank generates around $400,000 in annual business at approximately 10,000 tons of throughput and requires an investment of $300,000 to $350,000 to establish.

Operations are coordinated through BiofuelCircle’s digital platform, which combines proprietary rural data (e.g., land records, farm polygons, historic yields), AI-based supply forecasting, satellite imagery for yield and harvest date prediction, and GIS-based aggregation planning. Tractor drivers receive task allocations via WhatsApp chatbots and a mobile app, log loading data in real time via GPS trackers, and are managed via digital fuel dispensing at the depot.

The Biomass Bank model inverts farmers' cost structure for managing agricultural residue. Farmers have traditionally borne the time and cost of field clearing themselves, with burning being the cheapest and fastest option. Under the Biomass Bank model, the aggregator and its rural partners bear the collection cost—scheduling pickup or accepting walk-in delivery immediately after harvest—and farmers receive payment via direct bank transfer for the residue they would otherwise burn. This shifts the farmer's choice from "burn vs. bear collection cost" to "burn vs. receive payment," which makes residue diversion economically viable at scale.

As of March 2025, BiofuelCircle operated 35 Biomass Bank storage depots across five Indian states, with a network of 45,000+ farmers, 1,300 rural partners, and 350,000 tons of annual biomass supply under contract. By September 2025, this had expanded to 60 depots across seven states (120,000 farmers, 3,000 rural partners), with planned near-term expansion to 81 depots across 10 states (150,000 farmers and 5,000 rural partners). BiofuelCircle's current national network goal is 125 Biomass Bank locations with approximately 1 Mt annual capacity, scaled to serve existing demand from compressed biogas plants, briquette and pellet manufacturers, and other industrial customers.

BiofuelCircle provided current price ranges from their platform transactions as of early 2026: baled agricultural residue at \$35–40/t, biomass briquettes at \$60–70/t, and biomass pellets at \$80–90/t. These prices reflect delivered cost to the end customer and embed collection, densification, storage, and transport. The main analysis uses \$90/t as a conservative assumption corresponding to pelletized feedstock—the densified, dehydrated form most suitable for long-distance transport to and use in a gasification facility.

C.2 BIOME INDUSTRIA: DENSIFICATION AND BRIQUETTE/PELLET MANUFACTURING

Biome Industria operates a complementary layer of the residue supply chain: densification of collected biomass into briquettes (70–90 mm) and pellets (6–25 mm) currently sold as solid biofuel replacements for coal in industrial boilers. Biome operates two production units—in Rewari district, Haryana, and Parbhani district, Maharashtra—and sources from farmers across Haryana, Punjab, and Maharashtra. Their products deliver 2,800–4,000 kilocalories of heat per kilogram of biomass depending on the feedstock, with feedstocks including mustard husk, paddy straw, soybean husk, chana husk, groundnut shells, and sugarcane bagasse. Biome has stated a target of utilizing 1 Mt of biomass annually by 2030.

Biome's model illustrates two relevant points for PBtL feasibility. First, the densification step is actively commercializing—multiple companies are producing briquettes and pellets at scale for industrial customers, which is the same physical form most suitable for PBtL gasifiers. Second, the breadth of feedstocks accepted across Biome's operations (six distinct residue types) confirms that India's residue supply chain is being built to handle heterogeneity at the input side, with standardized briquette/pellet output specifications tuned to customer end-use requirements.

C.3 IMPLICATIONS FOR PBTL FEASIBILITY

Together, these examples demonstrate three points relevant to PBtL feasibility. First, the seasonal-to-year-round mismatch that has historically been the central logistical barrier to residue utilization is being solved through dedicated rural storage infrastructure—most directly via the Biomass Bank depot model. Second, densification into pellets and briquettes is occurring at scale through specialized manufacturers like Biome, producing a standardized feedstock form well-suited to gasification. Third, the supply chain is being built around the existing customer base of power plants and industrial facilities, meaning a PBtL facility would plug into an existing aggregation and logistics ecosystem rather than having to build one from scratch.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. “Financing Sustainable Aviation Fuels: Case Studies and Implications for Investment” (World Economic Forum, February 2025), https://reports.weforum.org/docs/WEF_Financing_Sustainable_Aviation_Fuels_2025.pdf.

2. Marisa Garcia, “Sustainable Aviation Fuel: eSAF Found to Be 13 Times the Cost of Regular Aircaft Fuel,” *Aerospace Global News* (blog), November 20, 2025, https://aerospaceglobalnews.com/news/argus-esaf-price-index/.

3. “Previous Price of ATF Prices in Metros (Dollars/Kl) for Domestic Airlines on International Run,” IndianOil, accessed June 10, 2026, https://iocl.com/atf-domestic-airlines-on-international.

4. “Atmanirbhar Bharat: The Foundation of a Strong and Developed India,” *PM India* (blog), August 15, 2025, https://www.pmindia.gov.in/en/news_updates/atmanirbhar-bharat-the-foundation-of-a-strong-and-developed-india/.

5. “India - Countries & Regions,” IEA, accessed January 30, 2026, https://www.iea.org/countries/india/oil.

6. “How Much of the World’s Shipping & Oil Goes Through the Strait of Hormuz? 2025 vs 2026 Percentages of Global Supply,” *Speed Commerce* (blog), March 16, 2026, https://www.speedcommerce.com/insights/how-much-of-the-worlds-shipping-goes-through-the-strait-of-hormuz/.

7. Tsvetana Paraskova, “India’s Oil Crisis Deepens as Hormuz Remains Shut,” OilPrice.com, May 14, 2026, https://oilprice.com/Energy/Energy-General/Indias-Oil-Crisis-Deepens-as-Hormuz-Remains-Shut.html.

8. Smriti Jain, “US-Iran War: From Russia to Middle East - How India Is Managing to Secure Its Crude Oil Supplies amid Disruptions,” *The Times of India*, May 19, 2026, https://timesofindia.indiatimes.com/business/india-business/us-iran-war-from-russia-to-middle-east-how-india-is-managing-to-secure-its-crude-oil-supplies-amid-strait-of-hormuz-disruptions/articleshow/131198401.cms.

9. Sambit Mohanty and Ratnajyoti Dutta, “Jet Fuel, Gasoline Propel India’s 2024 Oil Demand; Trend Set to Spill over into 2025,” S&P Global Energy, January 28, 2025, https://www.spglobal.com/energy/en/news-research/latest-news/crude-oil/012825-jet-fuel-gasoline-propel-indias-2024-oil-demand-trend-set-to-spill-over-into-2025.

10. “India,” *Clean Air Fund* (blog), accessed May 12, 2026, https://www.cleanairfund.org/geography/india/.

11. Ruoyu Lan, Sebastian D. Eastham, Tianjia Liu, Leslie K. Norford, and Steven R. H. Barrett, “Air Quality Impacts of Crop Residue Burning in India and Mitigation Alternatives,” *Nature Communications* 13, no. 1 (November 14, 2022): 6537, https://doi.org/10.1038/s41467-022-34093-z.

12. “Stubble Burning: Delhi’s Toxic Air Crisis Needs Tough Action,” *Policy Circle* (blog), September 24, 2025, https://www.policycircle.org/environment/stubble-burning-delhi-air/.

13. Hannah Ritchie and Pablo Rosado, “CO_2 and Greenhouse Gas Emissions,” *Our World in Data*, December 19, 2025, https://ourworldindata.org/profile/co2/india.

14. “India,” Climate Action Tracker, September 24, 2025, https://climateactiontracker.org/countries/india/.

15. Pallavi Das, Vaibhav Chaturvedi, Joy Rajbanshi, Zaid Ahsan Khan, Satish Kumar, and Akash Goenka, “A New Scenario Set for Informing Pathways to India’s next Nationally Determined Contribution and 2070 Net-Zero Target: Structural Reforms, LIFE, and Sectoral Pathways,” *Energy and Climate Change* 6 (December 1, 2025): 100192, https://doi.org/10.1016/j.egycc.2025.100192.

16. Aman Srivastava and Nikita Shukla, “India’s Second NDC: Revisiting the Intensity of Climate Ambition,” *Sustainable Futures Collaborative* (blog), April 15, 2026, https://www.sustainablefutures.org/blog/indias-second-ndc-revisiting-the-intensity-of-climate-ambition/.

17. Emilia Chojkiewicz, Nikit Abhyankar, and Amol Phadke, “Plummeting Solar+Storage Auction Prices in India Unlock Affordable, Inflation-Proof 24/7 Clean Power” (India Energy & Climate Center, May 20, 2025), https://live-iecc-gspp.pantheon.berkeley.edu/resources/reports/plummeting-solarstorage-auction-prices-in-india-unlock-affordable-inflation-proof-24-7-clean-power/.

18. “India Solar Panel: What Led to the Historic Rs 2/kWh Tariff?,” *JMK Research & Analytics* (blog), accessed January 30, 2026, https://jmkresearch.com/renewable-sector-published-reports/what-led-to-historic-low-solar-tariff-of-rs-2-kwh-in-india/.

19. Aarushi Koundal, “DeepDive: India’s Green Hydrogen Journey Starts at ₹397 per Kg,” ETEnergyworld.com, June 6, 2025, https://energy.economictimes.indiatimes.com/news/renewable/deepdive-indias-green-hydrogen-journey-starts-at-397-per-kg/121676152.

20. Laurie Stone, “How India Can Enhance Global Energy Security Through Green Hydrogen,” *RMI* (blog), January 16, 2026, https://rmi.org/how-india-can-enhance-global-energy-security-through-green-hydrogen/.

21. Dan Slanger, “India Aims to Become a Green Hydrogen Leader,” *RMI* (blog), April 5, 2023, https://rmi.org/india-aims-to-become-a-green-hydrogen-leader/.

22. Leigh Collins, “India Records Lowest-Ever Winning Bid for Green Hydrogen at Auction: Minister,” Hydrogen Insight, February 18, 2026, https://www.hydrogeninsight.com/production/india-records-lowest-ever-winning-bid-for-green-hydrogen-at-auction-minister/2-1-1945518.

23. V. Venkatramanan, Shachi Shah, Shiv Prasad, Anoop Singh, and Ram Prasad, “Assessment of Bioenergy Generation Potential of Agricultural Crop Residues in India,” *Circular Economy and Sustainability* 1, no. 4 (December 1, 2021): 1335–48, https://doi.org/10.1007/s43615-021-00072-7.

24. “Feasibility Study on the Use of Sustainable Aviation Fuels in India” (International Civil Aviation Organization, 2025), https://www.icao.int/sites/default/files/environmental-protection/Documents/ACT-SAF/Feasibility_Study_India.pdf.

25. “Bioresources within a Net-Zero Emissions Economy: Making a Sustainable Approach Possible” (Energy Transitions Commission, July 2021), https://www.energy-transitions.org/wp-content/uploads/2021/07/ETC-bio-Report-v2.5-lo-res.pdf.

26. “BiofuelCircle Market Insights - January 2026” (BiofuelCircle, January 2026), https://www.biofuelcircle.com/wp-content/uploads/2026/01/Market-Insights-January-26.pdf.

27. Ozzy Jegunma, “Flight Path to Net Zero: Aviation’s Fuel Outlook to 2050,” Wood Mackenzie, October 6, 2025, https://www.woodmac.com/news/opinion/flight-path-to-net-zero-aviations-fuel-outlook-to-2050/.

28. Timothy J. Wallington, Maxwell Woody, Geoffrey M. Lewis, Gregory A. Keoleian, Eytan J. Adler, Joaquim R. R. A. Martins, and Matthew D. Collette, “Green Hydrogen Pathways, Energy Efficiencies, and Intensities for Ground, Air, and Marine Transportation,” *Joule* 8, no. 8 (August 21, 2024): 2190–2207, https://doi.org/10.1016/j.joule.2024.07.012.

29. Thomas K. Walker III, Marika Tatsutani, and Jonathan Lewis, “Decarbonizing Aviation: Enabling Technologies for a Net-Zero Future” (Clean Air Task Force, April 2024), https://cdn.catf.us/wp-content/uploads/2024/04/03083920/decarbonizing-aviation-technologies-net-zero-future.pdf.

30. Jayant Mukhopadhaya and Dan Rutherford, “Performance Analysis of Evolutionary Hydrogen-Powered Aircraft” (International Council on Clean Transportation, January 2022), https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf.

31. “ReFuelEU Aviation,” European Commission, accessed February 4, 2026, https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en.

32. Department for Transport, “The SAF Mandate: An Essential Guide,” GOV.UK, December 19, 2024, https://www.gov.uk/government/publications/about-the-saf-mandate/the-saf-mandate-an-essential-guide.

33. “SAF Policies,” International Civil Aviation Organization, accessed February 5, 2026, https://www.icao.int/SAF/saf-policies.

34. “Rajya Sabha Unstarred Question No : 2256, Blending of Aviation Fuel” (Government of India - Ministry of Civil Aviation, December 16, 2024), https://sansad.in/getFile/annex/266/AU2256_68EEIG.pdf?source=pqars.

35. Axel Esqué and Daniel Riefer, “How the Aviation Industry Could Help Scale Sustainable Fuel Production,” McKinsey & Company, July 22, 2024, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/how-the-aviation-industry-could-help-scale-sustainable-fuel-production.

36. Oscar Rosales Calderon, Ling Tao, Zia Abdullah, Kristi Moriarty, Sharon Smolinski, Anelia Milbrandt, Talmadge Michael, et al., “Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process” (National Renewable Energy Laboratory, July 2024), https://docs.nrel.gov/docs/fy24osti/87802.pdf.

37. Rimjhim Singh, “Indian Airlines Warn Govt Soaring Fuel Costs Threaten Ops, Seek Urgent Help,” Business Standard, April 28, 2026, https://www.business-standard.com/industry/aviation/west-asia-conflict-indian-airlines-govt-rising-jet-fuel-costs-atf-flights-126042800653_1.html.

38. Thomas Washington and Daniel Workman, “Volatile Sustainable Aviation Fuel Prices Highlight Scaling Challenges,” S&P Global Energy, January 28, 2026, https://www.spglobal.com/energy/en/news-research/latest-news/refined-products/012826-volatile-sustainable-aviation-fuel-prices-highlight-scaling-challenges.

39. “Sustainable Aviation Fuel (SAF) Fundamentals - July 3, 2025,” GrainFuel Nexus, July 3, 2025, https://www.grainfuel-nexus.com/navigating-trade-dynamics/sustainable-aviation-fuel-saf-fundamentals-july-3-2025.

40. “SAF Deployment” (International Air Transport Association, 2023), https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-policy-2023.pdf.

41. “SAF Production Growth Rate Is Slowing down, Essential to Correct Course Ahead of e-SAF Mandates,” International Air Transport Association, December 9, 2025, https://www.iata.org/en/pressroom/2025-releases/2025-12-09-04/.

42. Lamar Johnson, “Delta Reframes Net-Zero as an ‘Aspiration,’ but Denies Axing 2030 SAF Goal,” ESG Dive, April 17, 2026, https://www.esgdive.com/news/delta-reframes-2050-net-zero-goal-denies-cutting-2030-saf-goal/817835/.

43. “Chart of the Week: Ramping up SAF through Standalone HEFA Facilities” (International Air Transport Association, November 15, 2024), https://www.iata.org/en/iata-repository/publications/economic-reports/ramping-up-saf-through-standalone-hefa-facilities/.

44. “CENA SAF-Outlook 2025-2030: Volumes, Technologies and Markets for Sustainable Aviation Fuels” (CENA Hessen, 2025), https://redaktion.hessen-agentur.de/publication/2025/4461_CENA_SAF_Outlook_2025-2030_EN.pdf.

45. Oscar Rosales Calderon, Ling Tao, Zia Abdullah, Michael Talmadge, Anelia Milbrandt, Sharon Smolinski, Kristi Moriarty, et al., “Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway” (National Renewable Energy Laboratory, July 2024), https://docs.nrel.gov/docs/fy24osti/87803.pdf.

46. “Global Feedstock Assessment for SAF Production: Outlook to 2050” (International Air Transport Association, September 2025), https://www.iata.org/globalassets/iata/publications/sustainability/global-feedstock-assessment-for-saf-production-outlook-to-2050.pdf.

47. “Used Cooking Oil: The Certified Unknown,” Transport & Environment, December 2024, https://www.transportenvironment.org/articles/uco.

48. “2023 Renewable Energy Directive Fact Sheet” (Transport & Environment), accessed February 6, 2026, https://www.transportenvironment.org/uploads/files/RED-III-Fact-sheet-on-RED-targets.pdf.

49. “Policy Nuggets: The UK SAF Mandate,” *SkyNRG* (blog), May 28, 2024, https://skynrg.com/policy-nuggets-the-uk-saf-mandate/.

50. Susan van Dyk and Jack Saddler, “Progress in Commercialization of Biojet / Sustainable Aviation Fuels (SAF): Technologies, Potential and Challenges” (International Energy Agency, April 2021), https://task39.ieabioenergy.com/wp-content/uploads/sites/37/2023/01/Progress-in-commercialization-of-biojet-Sustainable-Aviation-Fuels-SAF-Technologies-potential-and-challenges.pdf.

51. “ReFuelEU Aviation Handbook” (International Air Transport Association, September 2024), https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/refuel-eu-aviation-handbook.pdf.

52. Vivek Waghmode, “India to Set Fresh Target of 30 Per Cent Ethanol Blending in Petrol by 2030: Report” (Advanced Biofuels USA, April 15, 2025), https://advancedbiofuelsusa.info/india-to-set-fresh-target-of-30-per-cent-ethanol-blending-in-petrol-by-2030-report.

53. “Reliance: India’s Gasoline Demand to Peak by 2035, Diesel by 2041,” Hydrocarbon Processing, April 3, 2025, https://www.hydrocarbonprocessing.com/news/2025/04/reliance-indias-gasoline-demand-to-peak-by-2035-diesel-by-2041/.

54. Amulya Charan, “Carbon Capture, Utilisation and Storage (CCUS) in India: Reality or Mirage?,” *Amulya Charan* (blog), October 23, 2025, https://www.amulyacharan.com/2025/10/23/carbon-capture-utilisation-and-storage-ccus-in-india-reality-or-mirage/.

55. N. C. Gupta, Ruchika Tanwar, Dipesh, Anubha Kaushik, Rita Singh, A. K. Patra, Pinaki Sar, and Purvil Khakharia, “Perspectives on CCUS Deployment on Large Scale in India: Insights for Low Carbon Pathways,” *Carbon Capture Science & Technology* 12 (September 1, 2024): 100195, https://doi.org/10.1016/j.ccst.2024.100195.

56. Atanu Mukherjee and Saurav Chatterjee, “Carbon Capture, Utilization, and Storage (CCUS) - Policy Framework and Its Deployment Mechanism in India” (NITI Aayog, November 2022), https://www.niti.gov.in/sites/default/files/2022-12/CCUS-Report.pdf.

57. Yuanrong Zhou, Stephanie Searle, and Nikita Pavlenko, “Current and Future Cost of E-Kerosene in the United States and Europe” (International Council on Clean Transportation, March 2022), https://theicct.org/wp-content/uploads/2022/02/fuels-us-europe-current-future-cost-ekerosene-us-europe-mar22.pdf.

58. “Technology Readiness Levels Definitions and Descriptions” (Australian Government - Department of Defence, n.d.), https://www.dst.defence.gov.au/sites/default/files/basic_pages/documents/TRL%20Explanations_1.pdf.

59. “European Aviation Environmental Report 2025” (European Union Aviation Safety Agency, 2025), https://www.easa.europa.eu/sites/default/files/eaer-downloads/EASA_EAER_2025_Book_v5.pdf.

60. “Questions and Answers about SAF,” Neste, accessed February 9, 2026, https://www.neste.com/en-us/products-and-innovation/sustainable-aviation/questions-and-answers-about-saf.

61. Rituparna Ghosh, "India's IOC Gets ISCC Certification for SAF at Panipat," Argus, August 21, 2025, https://www.argusmedia.com/en/news-and-insights/latest-market-news/2723366-india-s-ioc-gets-iscc-certification-for-saf-at-panipat.

62. Himanshu Ojha, "EIL Partners with CSIR-IIP to Establish 20 KLPD Bio-ATF," Outlook Business, May 29, 2025, https://www.outlookbusiness.com/planet/industry/eil-partners-with-csir-iip-to-establish-20-klpd-bio-atf-plant-for-mrpl.

63. "Freedom Pines Fuels," LanzaJet, accessed February 9, 2026, https://www.lanzajet.com/freedom-pines.

64. Dan Brown, "DG Fuels, Johnson Matthey & Bp Partner for Largest Fischer-Tropsch SAF Plant" (DG Fuels, April 10, 2024), https://dgfuels.com/2024/04/10/dg-fuels-johnson-matthey-bp-partner-for-largest-fischer-tropsch-saf-plant/.

65. Dan Brown, "DG Fuels Advances Plans to Create EU-Compliant E-SAF Market Supply" (DG Fuels, August 25, 2025), https://dgfuels.com/2025/08/25/dg-fuels-advances-plans-to-create-eu-compliant-e-saf-market-supply/.

66. Fayaz Hussain, "Energy China Breaks Ground on SAF Project in Heilongjiang," *SAF Investor* (blog), October 16, 2024, https://www.safinvestor.com/news/146132/china/.

67. "Spotlight on E-SAF," Transport & Environment, accessed February 9, 2026, https://www.transportenvironment.org/topics/planes/saf-observatory/spotlight-on-e-kerosene.

68. "Chart of the Week: The Role of Power-to-Liquid in Expanding SAF Availability" (International Air Transport Association, March 28, 2025), https://www.iata.org/en/iata-repository/publications/economic-reports/the-role-of-power-to-liquid-in-expanding-saf-availability/.

69. Bofan Wang, Zhao Jia Ting, and Ming Zhao, "Sustainable Aviation Fuels: Key Opportunities and Challenges in Lowering Carbon Emissions for Aviation Industry," *Carbon Capture Science & Technology* 13 (December 1, 2024): 100263, https://doi.org/10.1016/j.ccst.2024.100263.

70. Veronika Prykhodko, "UCO Prices Reach Two-Year High in 2024, Increases to Continue in 2025 amid Demand," *Fastmarkets* (blog), January 14, 2025, https://www.fastmarkets.com/insights/uco-prices-reach-two-year-high-in-2024-increases-to-continue-in-2025-amid-demand/.

71. Nidhi Verma, "India State Fuel Retailers Raise Maize Ethanol Purchase Price -Local Media," *Reuters*, January 4, 2024, sec. Energy, https://www.reuters.com/business/energy/india-state-fuel-retailers-raise-maize-ethanol-purchase-price-local-media-2024-01-04/.

72. “Alternative Aviation Fuel Policy in the European Union,” *Climate Catalyst* (blog), March 2026, https://climatecatalyst.org/learning-hub/sustainable-aviation-fuel-policy-in-the-eu/.

73. “CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels” (International Civil Aviation Organization, June 2025), https://www.icao.int/sites/default/files/environmental-protection/CORSIA/Documents/CORSIA%20Eligible%20Fuels/ICAO-document-06-Default-Life-Cycle-Emissions-June-2025.pdf.

74. Liang Jing, Hassan M. El-Houjeiri, Jean-Christophe Monfort, James Littlefield, Amjaad Al-Qahtani, Yash Dixit, Raymond L. Speth, et al., “Understanding Variability in Petroleum Jet Fuel Life Cycle Greenhouse Gas Emissions to Inform Aviation Decarbonization,” *Nature Communications* 13, no. 1 (December 21, 2022): 7853, https://doi.org/10.1038/s41467-022-35392-1.

75. Tim Searchinger, Ralph Heimlich, Richard Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot Hayes, and Tun-Hsiang Yu, “Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change,” *Science* 319 (February 29, 2008), https://doi.org/10.1126/science.1151861.

76. Farzad Taheripour, Steffen Mueller, Isaac Emery, Omid Karami, Ehsanreza Sajedinia, Qianlai Zhuang, and Michael Wang, “Biofuels Induced Land Use Change Emissions: The Role of Implemented Land Use Emission Factors,” *Sustainability* 16, no. 7 (January 2024): 2729, https://doi.org/10.3390/su16072729.

77. “Sustainable Aviation Fuels (SAF) Sustainability Guide for Corporate Buyers” (Transport & Environment, October 2023), https://uploads.transportenvironment.org/production/files/2023-10-Corporate-SAF-Buyers-guide.pdf.

78. “80% of Europe’s ‘Used’ Cooking Oil Now Imported Raising Concerns over Fraud – Study,” T&E (T&E, December 14, 2023), https://www.transportenvironment.org/articles/80-of-europes-used-cooking-oil-now-imported-raising-concerns-over-fraud-study.

79. Chris Malins, “Waste Not Want Not: Understanding the Greenhouse Gas Implications of Diverting Waste and Residual Materials to Biofuel Production,” *International Council on Clean Transportation* (blog), August 24, 2017, https://theicct.org/publication/waste-not-want-not-understanding-the-greenhouse-gas-implications-of-diverting-waste-and-residual-materials-to-biofuel-production/.

80. “Is the Biofuel Industry Approaching a Feedstock Crunch?,” IEA, December 6, 2022, https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch.

81. “ReFuelEU Aviation Regulation – How Does It Affect the Aviation Sector?” (NOW GmbH, May 2024), https://www.now-gmbh.de/wp-content/uploads/2023/11/NOW-Factsheet_ReFuelEU-Aviation-Regulation.pdf.

82. “EU Tightens Rules on UCO Imports: Implications for the Biofuels Market,” ResourceWise, accessed May 22, 2026, https://www.resourcewise.com/blog/eu-tightens-rules-on-uco-imports-implications-for-the-biofuels-market.

83. Aron Bell, Liam Anthony Mannion, Mark Kelly, Robert Parker, Mohammad Reza Ghaani, and Stephen Dooley, “Life Cycle CO2e Intensity of Power-to-Liquid Sustainable Aviation Fuel Scenarios and Specific Use Cases,” *Advances in Applied Energy* 20 (December 1, 2025): 100248, https://doi.org/10.1016/j.adapen.2025.100248.

84. Karin Treyer, Romain Sacchi, and Christian Bauer, “Life Cycle Assessment of Synthetic Hydrocarbons for Use as Jet Fuel: ‘Power-to-Liquid’ and ‘Sun-to-Liquid’ Processes” (Paul Scherrer Institut, February 2022), https://www.psi.ch/en/media/72878/download?attachment=.

85. “Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels,” HSE, accessed May 15, 2026, https://hse.sdu.nl/content/CELEX-32023R1185-20230710-ENG#.

86. Marcel Dossow, Vincent Dieterich, Andreas Hanel, Hartmut Spliethoff, and Sebastian Fendt, “Improving Carbon Efficiency for an Advanced Biomass-to-Liquid Process Using Hydrogen and Oxygen from Electrolysis,” *Renewable and Sustainable Energy Reviews* 152 (December 1, 2021): 111670, https://doi.org/10.1016/j.rser.2021.111670.

87. “Conversion of Sugar Cane Biomass into Ethanol,” CORDIS | European Commission, accessed March 3, 2026, https://cordis.europa.eu/project/id/227464/reporting.

88. Anders S. Nielsen, M. Ostadi, Bjørn Austbø, M. Hillestad, Gonzalo del Alamo, and Odne Burheim, “Enhancing the Efficiency of Power- and Biomass-to-Liquid Fuel Processes Using Fuel-Assisted Solid Oxide Electrolysis Cells,” *Fuel* 321 (August 1, 2022): 123987, https://doi.org/10.1016/j.fuel.2022.123987.

89. Mahsa Mehrara, Sennai Mesfun, Johan Ahlström, Andrea Toffolo, and Elisabeth Wetterlund, “Electrification-Enabled Production of Fischer-Tropsch Liquids – A Process and Economic Perspective,” *Applied Energy* 393 (September 1, 2025): 126083, https://doi.org/10.1016/j.apenergy.2025.126083.

90. Felix Habermeyer, Julia Weyand, Simon Maier, Esa Kurkela, and Ralph-Uwe Dietrich, “Power Biomass to Liquid — an Option for Europe’s Sustainable and Independent Aviation Fuel Production,” *Biomass Conversion and Biorefinery* 14, no. 14 (July 1, 2024): 16199–217, https://doi.org/10.1007/s13399-022-03671-y.

91. “SAF Handbook” (International Air Transport Association, May 2024), https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-handbook.pdf.

92. Franziska Müller-Langer, Katja Oehmichen, Sebastian Dietrich, Konstantin M. Zech, Matthias Reichmuth, and Werner Weindorf, “PTG-HEFA Hybrid Refinery as Example of a SynBioPTx Concept—Results of a Feasibility Analysis,” *Applied Sciences* 9, no. 19 (January 2019): 4047, https://doi.org/10.3390/app9194047.

93. Fredrik Nyholm, Sami Toppinen, and Henrik Saxén, “Sustainable Power-to-Liquids Aviation Fuels: Modelling and Comparison of Two Fischer-Tropsch Upgrading Process Concepts,” *Energy Conversion and Management* 342 (October 15, 2025): 120153, https://doi.org/10.1016/j.enconman.2025.120153.

94. “Ensuring Minimum CUF of 19% for a Solar Power Plant Over 25 Years: A Guide for Developers under PM-KUSUM Scheme” (RenewableWatch, June 2024), https://renewablewatch.in/wp-content/uploads/2024/06/PM-KUSUM-Whitepaper.pdf.

95. “India’s Energy Overview: Yearly Highlights of 2024-25” (Vasudha Foundation, 2025), https://www.vasudha-foundation.org/wp-content/uploads/Indias-Energy-Overview-year-end-report-of-FY-2024-25.pdf.

96. “Reassessment of Solar Potential in India: A Macro-Level Study,” The Energy and Resources Institute, July 15, 2025, https://www.teriin.org/policy-brief/reassessment-solar-potential-india-macro-level-study.

97. “Report of the Comptroller and Auditor General of India on Solar Parks and Ultra Mega Solar Power Projects” (Indian Ministry of New and Renewable Energy, 2025), https://cag.gov.in/uploads/download_audit_report/2025/Report-No.-13-of-2025_Solar-English-0689da599bbca52.63858106.pdf.

98. “Sugar Cane Yields,” Our World in Data, accessed March 4, 2026, https://ourworldindata.org/grapher/sugar-cane-yields?tab=discrete-bar&time=latest&country=Western+Asia~IND~OWID_ASI~OWID_WRL.

99. Partha Sarathi Biswas and Harish Damodaran, “In Ethanol, Govt’s Sugar Solution,” The Indian Express, September 4, 2019, https://www.indiansugar.com/NewsDetails.aspx?nid=42607&.

100. Shrinivas Jadhav, Sahil K. Shah, Vidya Kumbhar, and T. P. Singh, "Quantification of Sugarcane Crop Water Footprint Using Remote Sensing and Machine Learning Techniques: Case Study of Kolhapur District, Maharashtra, India," *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-5-W2-2025 (December 19, 2025): 249–56, https://doi.org/10.5194/isprs-annals-X-5-W2-2025-249-2025.

101. "Sugarcane's Efficiency in Water Utilisation and Ethanol Production Confirmed by ICAR-IISR Report," *ChiniMandi* (blog), August 13, 2024, https://www.chinimandi.com/sugarcanes-efficiency-in-water-utilisation-and-ethanol-production-confirmed-by-icar-iisr-report/.

102. Wolter Scholten, "The Water Footprint of Sugar and Sugar-Based Ethanol" (University of Twente, April 2009), https://essay.utwente.nl/fileshare/file/58701/scriptie_W_Scholten.pdf.

103. M.M. Mekonnen and A.Y. Hoekstra, "The Green, Blue, and Gray Water Footprint of Crops and Derived Crop Products" (UNESCO-IHE Institute for Water Education, December 2010), https://waterfootprint.org/resources/Report47-WaterFootprintCrops-Vol1.pdf.

104. Dan Slanger, "Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption," *RMI* (blog), August 2, 2023, https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/.

105. Terra Nova, "Social Cost of Carbon as a Policy Tool: Challenges in the Indian Context," Observer Research Foundation, June 24, 2024, https://www.orfonline.org/expert-speak/social-cost-of-carbon-as-a-policy-tool-challenges-in-the-indian-context.

106. Katharine Ricke, Laurent Drouet, Ken Caldeira, and Massimo Tavoni, "Country-Level Social Cost of Carbon," *Nature Climate Change* 8, no. 10 (October 2018): 895–900, https://doi.org/10.1038/s41558-018-0282-y.

107. "Indian Carbon Credit Trading Scheme," International Carbon Action Partnership, March 30, 2026, https://icapcarbonaction.com/en/ets/indian-carbon-credit-trading-scheme.

108. "Carbon Credit Price in India 2026: What Will CCCs Cost and How to Plan," CarbonNeeti, March 28, 2026, https://carbonneeti.com/blog/carbon-credit-price-india-2026.

109. "EU Carbon Permits," accessed February 12, 2026, https://tradingeconomics.com/commodity/carbon.

110. "EU ETS II Pricing Scenarios," *BloombergNEF* (blog), September 17, 2025, https://about.bnef.com/insights/commodities/eu-ets-ii-pricing-scenarios/.

111. “Green Wings: India’s SAF Revolution in the Making” (Deloitte, October 2024), https://www.deloitte.com/in/en/issues/climate/sustainability-and-climate/sustainable-aviation-fuel-report.html.

112. Deirdre Fulton, “India’s Domestic Aviation: A Deep-Dive Into a Decade of Growth,” OAG, June 18, 2024, https://www.oag.com/blog/indias-domestic-aviation-market.

113. Kevin Yoo and Siddhant Chauhan, “India and South Asia Airplane Fleet to Quadruple by 2043 in World’s Fastest-Growing Commercial Aviation Market,” Boeing, February 6, 2025, https://www.boeing.co.in/content/theboeingcompany/in/en/news/2025/india-and-south-asia-airplane-fleet-to-quadruple-by-2043-in-worlds-fastest-growing-commercial-aviation-market.

114. “Air Passenger Demand Forecasting: The Future of Global Air Travel (2024-2044),” International Air Transport Association, accessed February 12, 2026, https://www.iata.org/en/publications/newsletters/iata-knowledge-hub/air-passenger-demand-forecasting-the-future-of-global-air-travel/.

115. “Vision 2040 for the Civil Aviation Industry in India” (Federation of Indian Chambers of Commerce and Industry, January 2019), https://static.investindia.gov.in/s3fs-public/2020-02/VISION-2040-FOR-THE-CIVIL-AVIATION-INDUSTRY-IN-INDIA.pdf.

116. “2025 European Aviation Environmental Report,” CLECAT, January 17, 2025, https://www.clecat.org/news/Newsletters/2025-european-aviation-environmental-report.

117. Department for Transport, “Sustainable Aviation Fuel Mandate: Final Stage Cost Benefit Analysis” (GOV.UK, April 2024), https://assets.publishing.service.gov.uk/media/66601969dc15efdddf1a872d/uk-saf-mandate-final-stage-cost-benefit-analysis.pdf.

118. “Aviation Fuel,” IndianOil, accessed November 6, 2025, https://iocl.com/aviation-fuel.

119. “Jet Fuel Price Monitor,” International Air Transport Association, accessed November 6, 2025, https://www.iata.org/en/publications/economics/fuel-monitor/.

120. Rakesh Sharma and Mihir Mishra, “India Doubles Jet Fuel Prices for a Few Hours, Then Reverses - Bloomberg,” Bloomberg, April 1, 2026, https://www.bloomberg.com/news/articles/2026-04-01/india-reverses-huge-jump-in-jet-fuel-prices-to-shield-consumers.

121. Mahima Kapoor, “India News: Jet Fuel Prices Reach Record High amid Iran War,” dw.com, April 1, 2026, https://www.dw.com/en/india-news-jet-fuel-prices-reach-record-high-amid-iran-war/live-76615690.

122. “Index Files for WPI Series (BASE: 2004-05),” Government of India, Office of the Economic Adviser, accessed February 24, 2026, https://eaindustry.nic.in/download_data_0405.asp.

123. Julian Atchison, “SECI Completes Renewable Ammonia Auction Round,” Ammonia Energy Association, September 1, 2025, https://ammoniaenergy.org/articles/seci-completes-renewable-ammonia-auction-round/.

124. “SECI Announces Results of 1.2 GW Solar and 3.6 GWh Energy Storage Auction,” *Renewable Watch* (blog), January 13, 2026, https://renewablewatch.in/2026/01/13/seci-announces-results-of-1-2-gw-solar-and-3-6-gwh-energy-storage-auction/.

125. “Traffic News: Annexure-III-Passengers (March, 2025)” (Airports Authority of India, 2025), https://www.aai.aero/sites/default/files/traffic-news/Mar2k25Annex3_0.pdf.

126. Sanjeev Choudhary, “RIL-BP Jet Fuel Market Share Rises to 7.5% in FY25,” *The Economic Times*, April 17, 2025, https://economictimes.indiatimes.com/industry/energy/oil-gas/ril-bp-jet-fuel-market-share-rises-to-7-5-in-fy25/articleshow/120355741.cms.

127. Dan Esposito, “Evidence Shows Three Pillars Remain Crucial for 45V Hydrogen Tax Credit to Protect Climate, Consumers, Industry” (Energy Innovation, July 25, 2024), https://energyinnovation.org/report/evidence-shows-three-pillars-remain-crucial-for-45v-hydrogen-tax-credit-to-protect-climate-consumers-industry/.

128. “Bioresources Within A Net-Zero Emissions Economy,” *Energy Transitions Commission* (blog), July 2021, https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/.

129. “India’s Green Hydrogen Price Discovery: A Strategic Leap Toward Energy Transition | June | Vol I | 2025,” *Sidebar* (blog), August 7, 2025, https://sidebarlaw.in/indias-green-hydrogen-price-discovery-a-strategic-leap-toward-energy-transition-june-vol-i-2025/.

130. “India’s Ocior Energy Wins HPCL Tender for 5,000 Mt/Year Plant to Supply Renewable Hydrogen at 3.82/Kg,” S&P Global Energy, July 15, 2025, https://www.spglobal.com/energy/en/news-research/blog/energy-transition/070125-et-highlights-india-ocior-renewable-hydrogen.

131. Saurav Anand, “GST on Electrolysers Cut to 5%: What It Means for Green Hydrogen Costs, Industries and India’s Export Ambitions,” The Economic Times, September 4, 2025, https://energy.economictimes.indiatimes.com/news/renewable/gst-on-electrolysers-cut-to-5-what-it-means-for-green-hydrogen-costs-industries-and-indias-export-ambitions/123689132.

132. Vipul Garg, "India's Numaligarh Hydrogen Tender Ends at Record-Low Rupees 279/Kg," S&P Global Energy, February 12, 2026, https://www.spglobal.com/energy/en/news-research/latest-news/energy-transition/021226-indias-numaligarh-hydrogen-tender-ends-at-record-low-rupees-279kg.

133. Nathan Johnson, Michael Liebreich, Daniel M. Kammen, Paul Ekins, Russell McKenna, and Iain Staffell, "Realistic Roles for Hydrogen in the Future Energy Transition," *Nature Reviews Clean Technology* 1, no. 5 (May 2025): 351–71, https://doi.org/10.1038/s44359-025-00050-4.

134. "IOCL Ends First Green H2 Auction at $4.6/Kg," *JMK Research & Analytics* (blog), May 20, 2025, https://jmkresearch.com/iocl-concludes-indias-first-green-h2-end-user-offtake-auction-at-us4-6-per-kg/.

135. Rakesh Sharma and Rajesh Kumar Singh, "India Records Lowest-Ever Price for Green Hydrogen in Tender," *Bloomberg.Com*, February 16, 2026, https://www.bloomberg.com/news/articles/2026-02-16/india-records-lowest-ever-price-for-green-hydrogen-in-tender.

136. Ribhav Pal, Vishal Tripathi, Karan Kothadiya, Prateek Aggarwal, and Deepak Yadav, "Augmenting the National Green Hydrogen Mission: Assessing the Potential Financial Support through Policies in India" (Council on Energy, Environment and Water, May 1, 2025), https://www.ceew.in/publications/augmenting-the-national-green-hydrogen-mission.

137. Jyoti Gulia, Kapil Gupta, Vibhuti Garg, and Charith Konda, "India's $2.1bn Leap towards Its Green Hydrogen Vision," March 7, 2024, https://ieefa.org/resources/indias-21bn-leap-towards-its-green-hydrogen-vision.

138. CFLI India and CEEW, "Financing Green Hydrogen in India: Private Sector Considerations to Strengthen India's Enabling Environment for a Competitive Green Hydrogen Economy" (Council on Energy, Environment and Water, 2024), https://www.ceew.in/publications/how-can-indian-policymakers-boost-investments-for-domestic-green-hydrogen-financing.

139. Parimal Kogekar, Ankur Malyan, and Jagabanta Ningthoujam, "Green Hydrogen Production Pathways for India," *RMI* (blog), July 10, 2025, https://rmi.org/green-hydrogen-production-pathways-for-india/.

140. "India Discovers $0.03 per Unit Solar Tariffs in Two Auctions" (REGlobal, August 14, 2024), https://reglobal.org/india-discovers-0-03-per-unit-solar-tariffs-in-two-auctions/.

141. "Global Solar Atlas," Global Solar Atlas, accessed February 13, 2026, https://globalsolaratlas.info/map.

142. “Electrolysis System Capex by 2050 - Updated Forecast” (BloombergNEF, 2022).

143. “Equations & Variables | Electricity | 2022 | ATB | NLR,” National Renewable Energy Laboratory, accessed February 13, 2026, https://atb.nrel.gov/electricity/2022/equations_&_variables.

144. Alasdair Graham, Marc Farre Moutinho, Rafal Malinowski, and Stephannie Lins, “Unlocking the First Wave of Breakthrough Steel Investments: International Opportunities” (Energy Transitions Commission, April 2023), https://www.energy-transitions.org/wp-content/uploads/2023/04/Unlocking-the-First-Wave-of-Breakthrough-Steel-Investments-International-Opportunities-April-2023.pdf.

145. “Review of Technology Data for Advanced Bioenergy Fuels” (Danish Energy Agency, May 5, 2014), https://ens.dk/media/3514/download.

146. “Carbon Capture and Storage in the United States,” U.S. Congressional Budget Office, December 13, 2023, https://www.cbo.gov/publication/59832.

147. Vivek Kumar, “Biomass Pellet Pricing in India: A Comprehensive Analysis,” RK Systems, May 10, 2025, https://rkwindmast.com/c/biomass-pellet-price-in-india.html.

148. Payal Kaur, Adithya Bhashyam, Martin Tengler, Claire Curry, and Andrew Logan, “2025 Levelized Cost of Blue and Gray Hydrogen: Location and Incentives Matter” (BloombergNEF, November 6, 2025), https://www.bnef.com/insights/37881/view.

149. “Central Excise and Customs Rate on Major Petroleum Products,” Ministry of Petroleum & Natural Gas, Government of India, accessed February 13, 2026, https://ppac.gov.in/prices/central-excise-and-customs-rate-on-major-petroleum-products.

150. “Civil Aviation Ministry Asks Delhi Government to Reduce VAT on ATF or Face Flight Diversion – Here’s Why,” *The Financial Express* (blog), March 26, 2025, https://www.financialexpress.com/business/airlines-aviation-civil-aviation-ministry-asks-delhi-government-to-reduce-vat-on-atf-or-face-flight-diversion-heres-why-3789469/.

151. “Fuel - Fact Sheet” (International Air Transport Association), accessed November 6, 2025, https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-fuel/.

152. “Climate TRACE,” Climate TRACE, accessed February 13, 2026, https://climatetrace.org.

153. “Climate TRACE Releases First Comprehensive, Independent Database of Global Greenhouse Gas Emissions,” Climate TRACE, September 14, 2021, https://climatetrace.org.

154. Stefan Bube, Nils Bullerdiek, Steffen Voß, and Martin Kaltschmitt, "Kerosene Production from Power-Based Syngas – A Technical Comparison of the Fischer-Tropsch and Methanol Pathway," *Fuel* 366 (June 15, 2024): 131269, https://doi.org/10.1016/j.fuel.2024.131269.

155. M. Peacock, J. Paterson, L. Reed, S. Davies, S. Carter, A. Coe, and J. Clarkson, "Innovation in Fischer–Tropsch: Developing Fundamental Understanding to Support Commercial Opportunities," *Topics in Catalysis* 63, no. 3 (July 1, 2020): 328–39, https://doi.org/10.1007/s11244-020-01239-6.

156. Felix Habermeyer, Veatriki Papantoni, Urte Brand-Daniels, and Ralph-Uwe Dietrich, "Sustainable Aviation Fuel from Forestry Residue and Hydrogen – a Techno-Economic and Environmental Analysis for an Immediate Deployment of the PBtL Process in Europe," *Sustainable Energy & Fuels* 7, no. 17 (August 22, 2023): 4229–46, https://doi.org/10.1039/D3SE00358B.

157. Arno de Klerk, "Fischer–Tropsch Fuels Refinery Design," *Energy & Environmental Science* 4, no. 4 (March 29, 2011): 1177–1205, https://doi.org/10.1039/C0EE00692K.

158. "SAF Conversion Processes," accessed February 6, 2026, https://www.icao.int/SAF/saf-conversion-processes.

159. "CORSIA Sustainability Certification Schemes," International Civil Aviation Organization, accessed February 6, 2026, https://www.icao.int/CORSIA/corsia-scs-evaluation.

160. "Enabling the Utilization of SAF Blends up to 100%" (International Energy Agency, April 2025), https://iea-amf.org/app/webroot/files/file/Webinar_series_Task66/WS1_Infosheet.pdf.

161. "Viewpoint: Bio-Based Aromatics Point The Way To Burning 100% SAF | Aviation Week Network," accessed February 6, 2026, https://aviationweek.com/business-aviation/aircraft-propulsion/viewpoint-bio-based-aromatics-point-way-burning-100-saf.