E-Fuel

Decarbonizing Aviation with Sustainable Drop-In Fuel Alternatives

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About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

About Third Derivative

Founded by RMI and New Energy Nexus in 2020, Third Derivative (D3) is an open, collaborative climate tech ecosystem that accelerates startups and moves markets. By guiding and supporting climate tech entrepreneurs who are bringing new ideas and innovation to market, D3 is accelerating the clean future worldwide. Through a vast global network of deep experts, corporate partners, and investors, D3 helps startups go to market faster with their breakthrough ideas, create real impact, and transform markets.

Executive Summary

Aviation is the backbone of today's globalized economy, but it's also a major contributor to climate change. Burning jet fuel accounts for **2%–3%** of global greenhouse gas emissions today, and consumption is expected to more than **double by 2050** as the industry continues to expand.

Efforts are under way to find cleaner technologies for powering aircraft, but the sector is proving stubbornly expensive and difficult to decarbonize. Specifically for medium- and long-haul aviation (which accounts for two-thirds of aviation emissions), there are challenges with potential solutions, such as:

- **Batteries, hydrogen, and ammonia** have low energy densities that are incompatible with aviation's weight and space constraints and would require trillions of dollars of investment to build new airplanes, engines, and infrastructure that can work with these fuel types.
- Hydroprocessed esters and fatty acids **(HEFA) biofuels** are sourced from waste oils and fats that exist in short supply.
- **Cellulosic and algae biofuels** incur high costs through the growth, collection, and transport of biomass.
- **Electrofuels (e-fuels)** are too costly because of significant electricity usage.

Although innovation will drive down the cost of all these fuels, only "drop-in" replacements that work with existing airplanes — biofuels and e-fuels — can scale up to decarbonize the industry in accordance with **pledges by almost 300 airlines** to achieve net-zero carbon emissions by 2050.

Based on our technoeconomic review, we found that e-fuels have a clear pathway to achieving <$4/gallon, which can be cost competitive with conventional fuels:

- **Clean electricity** has already reached $15/MWh in some geographies.
- **Low-carbon hydrogen** is on track to be <$1/kg with technology improvements and inexpensive renewable power.
- **Carbon capture** from high-purity point sources is already <$30/ton.
- **Co-electrolysis** is a novel technique in e-fuel synthesis that can improve efficiencies by producing syngas — a mixture of hydrogen and carbon monoxide (CO) — in a single step.
- Depending on the fluctuating price of petroleum, it's possible that a sustainable aviation fuel incentive or subsidy will be required to make such fuels cost competitive.

The **Sustainable Aviation Buyers Alliance**, composed of Boeing, United Airlines, Amazon, and other key stakeholders, has formed to cultivate demand for sustainable aviation fuel (SAF), while startups such as SeeO2, Twelve, Prometheus, Infinium, and many others are working to bring down costs and catalyze supply. But these startups will need broad support to scale up rapidly.

Accordingly, we have a series of recommendations for different groups:

- **Investors:** Make seed investments in startups that are working on breakthrough developments for drop-in fuels.
- **Corporations:** Support pilot projects with startups to help test and validate their technologies.
- **Policymakers:** Provide grant funding for startups and push for SAF mandates.
- **Project developers:** Deploy SAF technology in locations with cheap renewables.

Multistakeholder support is critical for the advancement of SAF technologies to save them from falling into the notorious climate tech "**valleys of death**." This why at Third Derivative, we're focused on building bridges and collaborative ecosystems that can provide the support necessary to rapidly scale up these nascent and necessary technologies.

Aviation's Decarbonization Challenge

Aviation is the backbone of the globalized economy, but it's also a major contributor to climate change. Burning jet fuel accounts for **2%–3%** of global greenhouse gas emissions today, and consumption is expected to more than **double by 2050** as the industry continues to expand.

Slashing CO_2 emissions from aviation will be crucial in the fight against climate change. Yet, as with most hard-to-abate sectors, the pathway to decarbonizing aviation is complex and lengthy, and it requires significant capital investment. The industry is aware of the challenge; a group of almost **300 airlines** has committed to zero carbon emissions by 2050. Governments, such as France and Norway, have already instituted minimum SAF mandates for flights that depart their countries. Even so, sustainable aviation fuels make up just **0.1% of the market** and **cost two to three times** more than fossil fuels today.

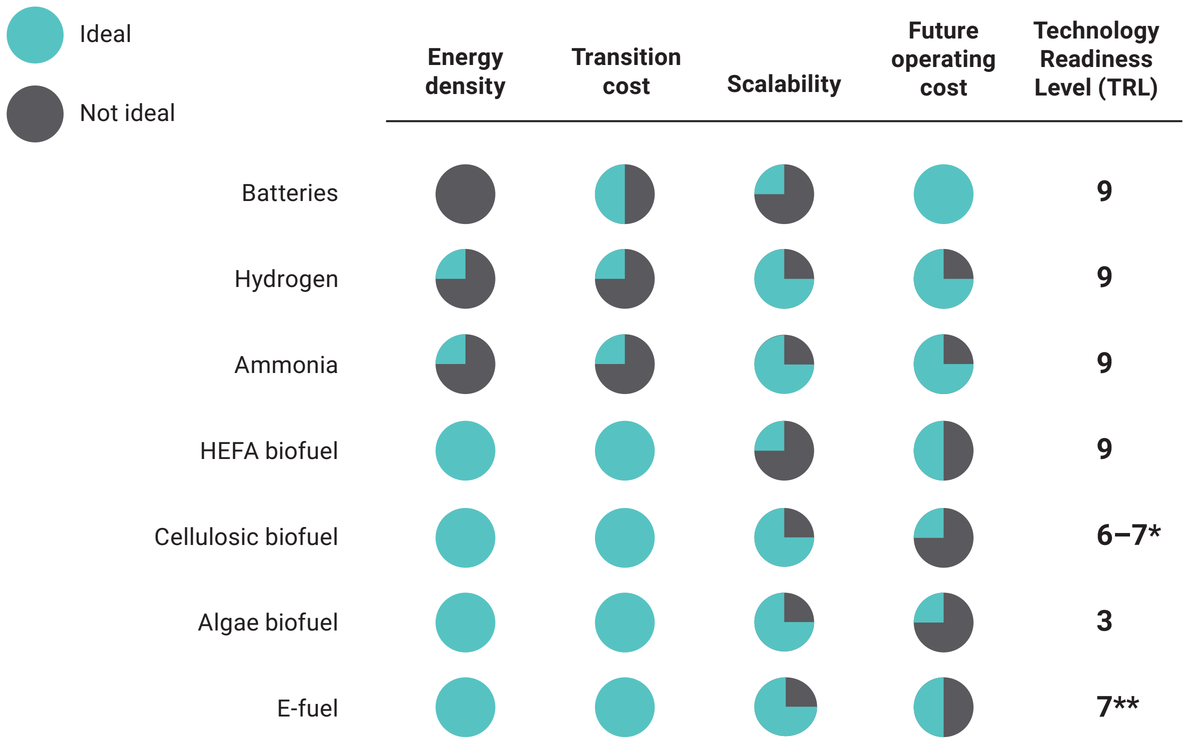
There are several options for decarbonizing medium- and long-haul aviation, which represents **over 60% of aviation emissions**. The leading contenders are:

- **Batteries:** For propeller-driven aircraft
- **Liquid hydrogen:** For propeller aircraft or hydrogen combustion jet engines
- **Liquid ammonia:** For propeller aircraft or ammonia combustion jet engines
- **Biofuels:** Drop-in fuels derived from bio-based sources, such as waste vegetable oils, energy crops, cellulosic biomass, or algae
- **E-fuels:** Drop-in fuels derived from electricity, water, and CO_2, also known as power-to-liquids

To be viable at scale, these options ought to: (1) have high energy density, (2) minimize infrastructural and operational switching costs, (3) be scalable, and (4) be cost competitive with fossil fuels (see Exhibit 1, next page). The rest of this paper will evaluate the potential solutions against these criteria.

Exhibit 1

Across Key Criteria, E-Fuels Are One of the Most Promising Pathways to Decarbonizing Aviation



* Cellulosic biofuels can be derived from many processes including pyrolysis, alcohol-to-jet (ATJ), Fischer-Tropsch (FT), etc. Many of these processes are TRL-7, but only for specific feedstocks.

** E-fuel can be derived from ATJ or FT, both of which are at TRL-7. These processes are further described later in the paper.

Weight and Space Are Key Limiting Factors

One critical consideration when looking at alternatives to jet fuel is their energy density, a measure of how much energy is packed into each pound or gallon of fuel. This is critical for aircraft that travel significant distances without refueling and need to be as lightweight and efficient as possible.

Although batteries may be an option for decarbonizing short-haul flights, battery energy density is likely to be an insurmountable barrier for medium- and long-haul aviation. Today's most advanced commercial lithium-ion batteries have an energy density **60 times lower** than jet fuel. Put into perspective: a Boeing 787 airliner would require 6,000 tons of onboard batteries to match the energy of 100 tons of jet fuel (a 787's maximum takeoff weight is **250 tons**). Next-generation battery chemistries such as lithium-air are projected to have only **double the energy density of lithium-ion**, falling far short of the required threshold.

Liquid hydrogen and ammonia are four and three times less energy dense, respectively, than jet fuel on a volumetric basis. One potential workaround would be to **redesign aircraft** to have elongated fuselages that could accommodate extra fuel storage. But they would be considerably heavier than conventional planes, significantly affecting their performance. On a mass basis, hydrogen has a better energy density than jet fuel, but that doesn't account for the expensive and heavy cryogenic tanks and equipment required to keep liquid hydrogen below −420°F (liquid hydrogen is one of the coldest known substances).

Biofuels and e-fuels don't require any changes to engines or fueling infrastructure as they are drop-in solutions that can replace conventional jet fuel today.

Fuels Should Fit Existing Infrastructure

Today's jet engines and turboprops cannot be powered by batteries, hydrogen, or ammonia. Consequently, adopting these energy sources at scale would require an overhaul of air fleets, distribution and fueling infrastructure, and operations.

A transition to battery-, hydrogen-, or ammonia-powered aviation would require replacing the **35,000 aircraft** expected to be operational globally in 2027, retrofitting manufacturing facilities to build new kinds of planes, and building new fueling infrastructure at over **40,000 airports**, not to mention establishing a global hydrogen distribution network that doesn't exist today. We estimate that the switching costs for battery, hydrogen, or ammonia aviation are in the ballpark of $3 trillion to $6 trillion.[i]

It's also important to recognize the R&D costs associated with novel aircraft programs. Developing a new aircraft model costs billions of dollars (the Boeing 787 reportedly cost **$32 billion to develop**), and certifying it to fly with the Federal Aviation Administration can take **almost a decade**. Airlines are also unlikely to scrap working aircraft, so planes will be replaced only at the end of their operational lives. As commercial planes typically have life spans of around **30 years**, and many airlines have purchasing agreements with manufacturers into the 2030s, it is unlikely that decarbonizing aviation with stock turnover is feasible by 2050.

Drastic, systemic transitions also suffer from a "chicken and egg" predicament. Airlines and aircraft manufacturers won't act until airports around the world can fuel their planes; airports won't act unless the aircraft and fuel distribution infrastructure is in place; and fuel producers and pipeline builders won't act without the demand. Coordinating the simultaneous, binding, and global commitments required to solve this problem across public and private actors would be incredibly challenging.
In contrast, biofuels and e-fuels don't require any changes to engines or fueling infrastructure as they are drop-in solutions that can replace conventional jet fuel today (see Exhibit 2, next page).

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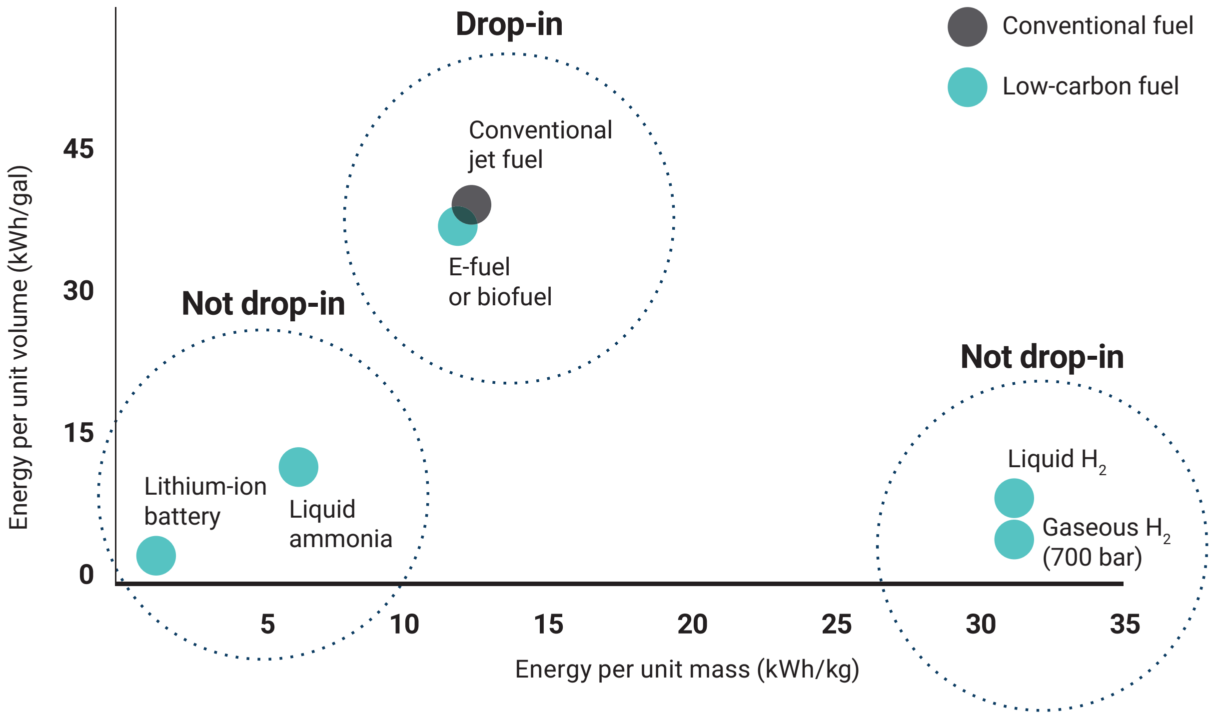
i Assumes $100 million for a 737 (as a midsized plane) with 35,000 airplanes in the global fleet that need to be gutted and remanufactured. Airplane stock turnover is then assumed as ~50% of the total switching cost in the high-transition cost case ($6 trillion total); see Exhibit 3, page 11.

Exhibit 2

E-Fuel and Biofuel Have Comparable Energy Densities to Petroleum and Can "Drop In" to Existing Infrastructure



Supply of HEFA Biofuels Is Limited

Most sustainable aviation fuel (SAF) currently in use is hydroprocessed esters and fatty acids (HEFA) biofuel produced from waste cooking oil from the food processing or restaurant industries. HEFA can also be made from dedicated energy crops such as jatropha, palm oil, and rapeseed.

However, only about 4 million gallons of HEFA biofuels are produced every year, and there are significant constraints to producing more. The Energy Transitions Commission estimates that the global supply of waste cooking oils could deliver less than 200 million gallons of fuel each year, the bulk of which is already collected for use in biodiesel for ground transportation.

Making HEFA jet fuel from energy crops instead would require unsustainably large amounts of land. Satisfying the demand for **230 billion gallons** of jet fuel by 2050 using only jatropha-derived HEFA may require as much as **2 billion hectares** — 20 times more than all the **farmable land in China**. Dedicated energy crops have food-versus-fuel and ecological concerns, such as palm oil to produce HEFA having caused significant **deforestation in the tropics**.

Although HEFA is a relatively cheap and technically ready option being used to make SAF today, it is an insufficient option to meet global demand.

Newer approaches are opening the door to making biofuels from far more abundant materials.

Cellulosic and Algae Biofuels Are Promising but Expensive

Newer approaches are opening the door to making biofuels from far more abundant materials. Rather than extracting oil from the fruit or seed of crops, these technologies work with algae or cellulose (the stringy, fibrous parts of plants). This makes it possible to convert biomass like energy crops, seaweed, the organic portions of municipal waste, agricultural by-products, or forest residues into fuels.

The challenge is the costs and complexity of supplying and processing these raw materials. Agricultural and forest residues are widely dispersed and can be **expensive to gather and transport**. Municipal solid waste contains food waste with high water content and low energy value. With algae, the most significant cost comes from **growing the biomass**; open pond systems experience high levels of contamination, whereas enclosed algae bioreactors are costly to build and operate.

The fundamental challenge with biomass is that it is relatively low in energy density both by weight (especially if wet) and by the amount that is harvestable per acre (exceptions include algae and wastes, like municipal waste or sawmill residues, that are already collected in centralized locations). For example, the sustainable harvest of corn stover is about 1.5 tons per acre per year. It is therefore logistically and energetically expensive to collect large quantities (>100,000 tons per year) at a central processing plant.

Accordingly, successful cellulosic biofuel technologies should have one of two characteristics. The first, and obvious, option is to have strong economics at small scales (that is, have low capital expenditures). Alternatively, if their economics depend on economies of scale (like most thermochemical processes), then the technologies have to be relatively agnostic to multiple and variable biomass feedstocks, since it is difficult to collect large quantities of inexpensive, consistent feedstock in a single location. Historically, both thermochemical processes (gasifiers) and enzymatic/cellular approaches to biomass conversion have had challenges with variable feedstocks.

Nonetheless, several startups are working to lower the cost of next-generation biofuels. One example is the Third Derivative (D3) portfolio startup **Enchi**, which is developing bacteria that break down cellulose to glucose and ferment it to ethanol, which can then be upgraded to jet fuel. Enchi's core innovation eliminates the pretreatment step, which should lower costs while accepting a greater variety of feedstocks. Another startup, **Viridos**, is using genetic engineering to cultivate an algae strain with five times greater productivity.

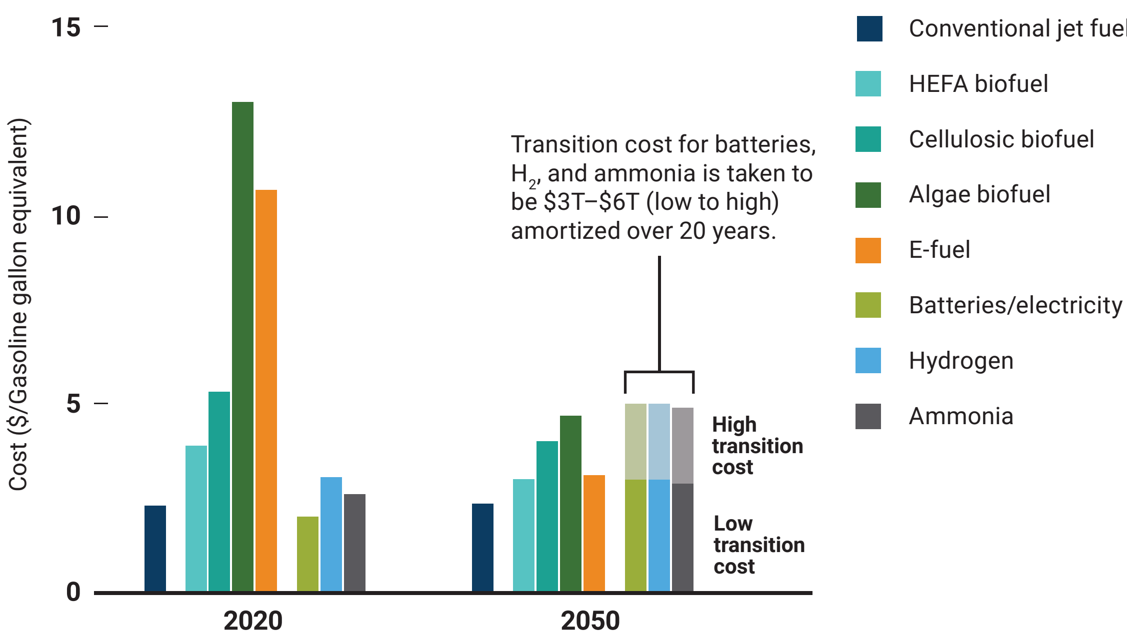
E-Fuel: Promising Pathways to Lower Costs

As noted above, while HEFA, algae, and cellulosic biofuels will be important contributors to decarbonizing aviation, the practical economic availability of bio-based feedstocks may not be sufficient for the **230 billion gallons** of aviation fuel needed annually by 2050.

Accordingly, e-fuel made from water-derived hydrogen (H_2), CO_2, and renewable electricity should also be pursued. While prohibitively expensive today (see Exhibit 3, below, and Exhibit 6, page 15), rapidly dropping prices of low-carbon H_2, carbon capture, and renewable electricity present an exciting pathway for e-fuel to become cost competitive. In the next section, we will dig deeper into the developments that can scale e-fuel to billions of gallons by 2050.

Exhibit 3

Cost of E-Fuel in 2020 and Projected to 2050



Sources: S&P Global, Ammonia Energy Association, McKinsey, and US Department of Energy

The Road to Affordable E-Fuel

E-fuel is still at the proof-of-concept stage with few production facilities. That said, it represents one of the most promising solutions to reduce aviation emissions thanks to dropping prices of H_2, CO_2, and electricity.

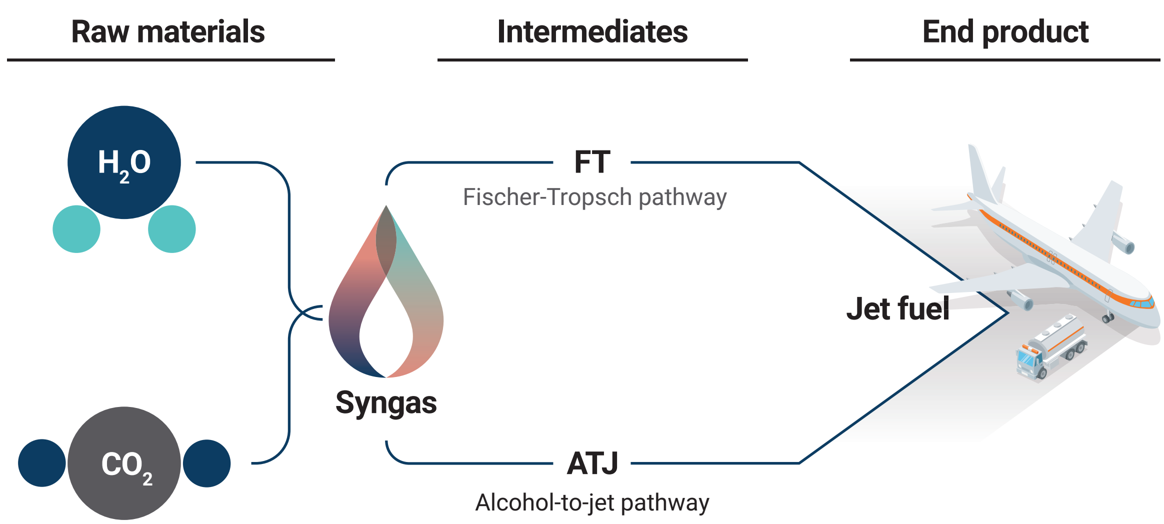
There are currently two primary pathways to produce e-fuel (see Exhibit 4):

1. The Fischer-Tropsch (FT) pathway is a reaction that converts syngas (a mixture of CO and H_2) into jet fuel, diesel, and other products.

2. The alcohol-to-jet (ATJ) pathway is typically a three-step process that converts alcohols (methanol, ethanol, or others) to jet fuel. Alcohols can be produced via fermentation of bio-feedstocks, but for e-fuels, the alcohols are produced from electricity-derived syngas.

Exhibit 4

E-Fuel Pathways

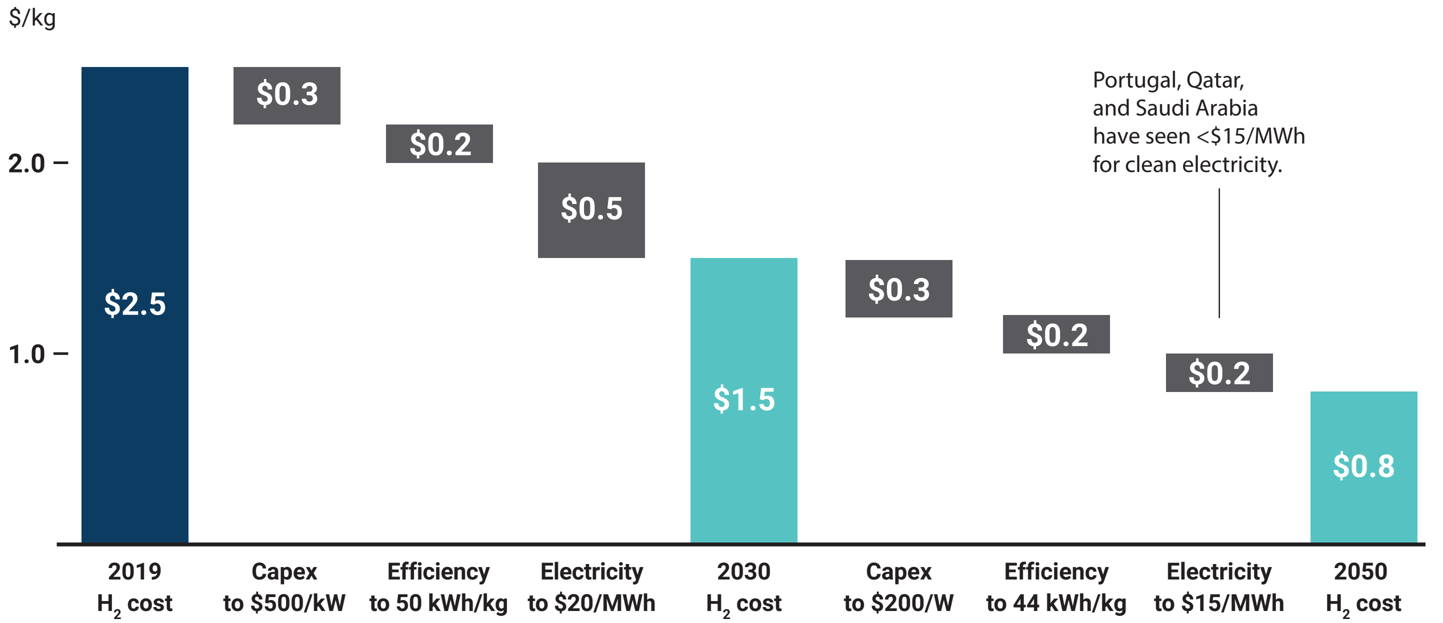


The Falling Costs of Hydrogen and Carbon

Hydrogen is the dominant ingredient in e-fuel synthesis. Green hydrogen is typically produced via electrolysis, which is an electricity-intensive process of splitting water into its hydrogen and oxygen constituents. Green hydrogen accounts for roughly 70% of the levelized e-fuel cost (see Exhibit 6, page 15).

Today, hydrogen produced via electrolysis costs **$3–$7/kg**, but this is expected to drop to $1/kg or less by 2050 in regions with abundant renewable energy. Improvements in the capital cost of electrolyzers and in electrolyzer efficiency, as well as dropping costs of renewable electricity, will help reduce the cost (see Exhibit 5, next page).

Exhibit 5 **Cost of Low-Carbon Hydrogen Is Expected to Drop Significantly with Technology Improvements and Cheaper Electricity**



Note: The 2019 cost assumes $800/kW capex, 55 kWh/kg efficiency, and $30/MWh electricity.
D3 model, assumptions consistent with IRENA and RMI Green Hydrogen Catapult.

The other major input for e-fuel production is CO, which is derived from CO_2 captured either directly from the atmosphere (direct air capture, or DAC) or from the exhausts of industrial facilities (point-source capture). The cost of the CO_2 varies dramatically, depending on its source.

Several industrial sources, such as ethanol, ammonia, and natural gas processing plants, already generate >90% pure CO_2 streams that can be further purified for **$30/ton or less**. In the United States alone, roughly 75 million tons of these high CO_2 concentration flue gases are produced annually, enough for about 15%–20% of US aviation fuel demand today. Affordable CO_2 from these industrial sources could support the early development of e-fuels while more carbon capture facilities come on line.

For e-fuel to be truly carbon neutral requires using DAC, which removes CO_2 from the atmosphere. DAC CO_2 currently costs hundreds of dollars per ton, but we see pathways for that to drop to $50–$100 per ton by 2050, as covered in a previous **insight brief**.

New Ways to Turn CO_2 into CO

The first step in the production of e-fuel is to reduce CO_2 to CO. This can be a complex and expensive process, but new techniques are emerging that could lower costs. Pathways include:

1. The reverse water gas shift (RWGS) reaction: This is a relatively mature thermochemical process that reacts CO_2 with H_2 to produce water and CO at atmospheric pressure and ~750°C.

2. Electrochemical CO_2 reduction: This is a relatively new approach that uses electricity to directly reduce CO_2 to CO.

3. Co-electrolysis: This path uses one electrolyzer to simultaneously reduce both water to H_2 and CO_2 to CO. This single-step production of CO is simpler and potentially more efficient than the two-step alternative of producing green hydrogen via electrolysis followed by the RWGS process.

Co-electrolysis is particularly attractive because simultaneously producing both hydrogen and CO using the same equipment could significantly reduce capital and operational expenditures and improve energy efficiencies. The technology is still immature, though technical advances are on the horizon with startups such as **Sunfire** and **SeeO2** (a D3 cohort company) working to improve co-electrolyzers. Indeed, recently announced **e-fuel demonstration projects**, such as Nordic Blue Crude and the Hague Airport project, plan to use co-electrolysis instead of RWGS.

Fischer-Tropsch: Mature Technology Gets a Revamp

There are two major pathways to convert syngas into liquid fuels: the FT process or alcohol production followed by ATJ. The FT process was developed in 1925 to convert coal-derived syngas into liquid fuels. Today, there are several commercial plants in operation using methane or coal as feedstocks, such as the Shell plants in Malaysia and Qatar. In South Africa, a country with large coal reserves and little oil, the world's largest FT plant, operated by Sasol, provides the country with 40% of its transportation fuel.

Despite the technology's relative maturity, there is still plenty of room for innovation. Several companies, including Johnson Matthey, BP, Velocys, and Ineratec, are developing **modular, smaller scale, and less expensive FT reactors**. Some of these designs use techniques like 3D printing to create networks of microchannels rather than a single large reactor vessel, significantly increasing the surface area available for reactions, as well as enhancing heat transfer and improving temperature control. Velocys has partnered with Shell and British Airways on a demonstration project in the United Kingdom.

Alcohol-to-Jet: Another Shot on Goal

The leading alternative to the FT process first converts syngas into alcohols like methanol, ethanol, and butanol before further processing them to create e-fuels. The ATJ route typically involves three separate steps (dehydration, oligomerization, and hydrogenation) that are mature as separate process steps but have not been demonstrated extensively together.

However, several demo projects are in development, and the **cost and efficiency are projected to be comparable** to the FT route. Both pathways should be pursued with research and development.

Prometheus Fuels, the world's first electrofuels "unicorn" (with a valuation over $1 billion), has developed a nanotechnology-based system that can separate ethanol and other fuel products from water. Normally the separation requires energy-intensive distillation, but Prometheus uses carbon nanotube membranes to selectively filter out alcohols at room temperature and pressure, **reducing energy requirements by up to 90%**.

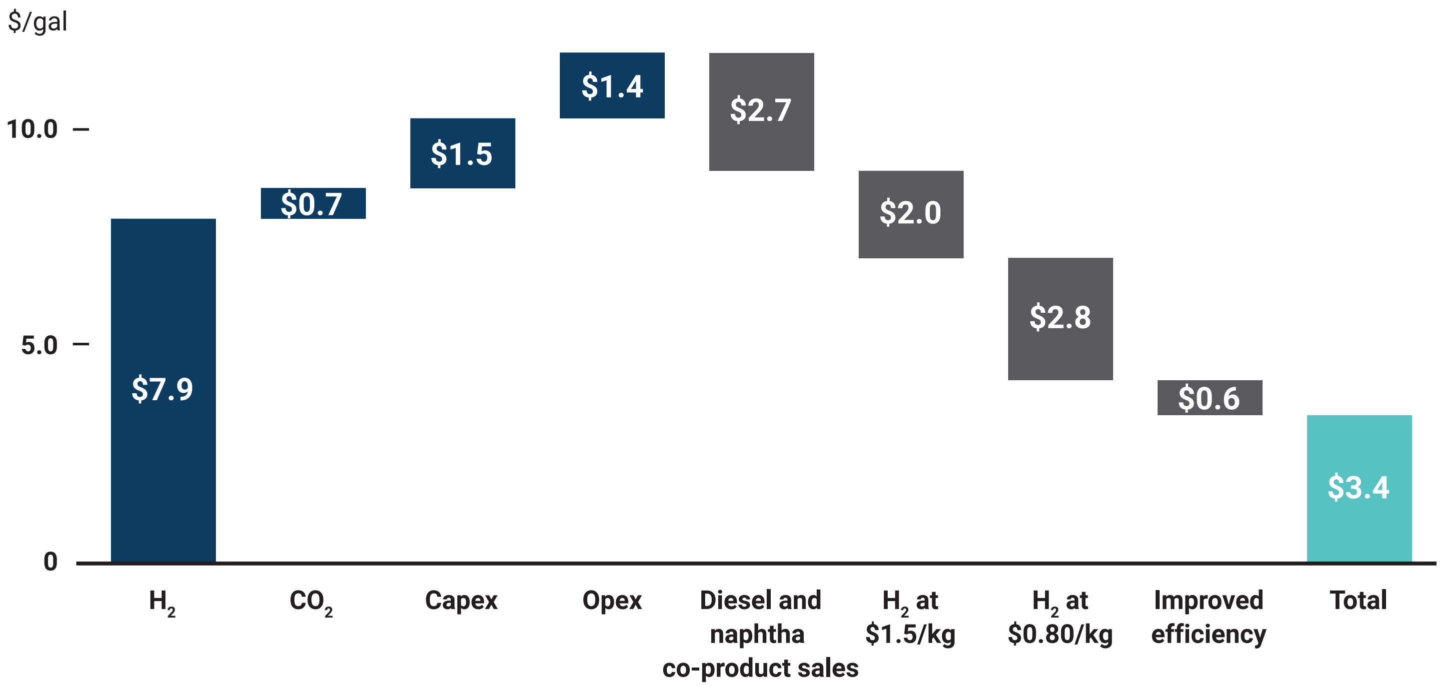
Highly Innovative Fuels, a joint venture of Siemens, ExxonMobil, Porsche, Enel, and others, is working to build several e-fuel plants via alcohol-to-jet in Australia, Chile, and Texas — all locations with ample low-cost renewable electricity. It's targeting first delivery of fuel by the end of 2022.

<$4/gallon

E-fuels today cost about $9/gallon, which is roughly four to six times the price of kerosene aviation fuel. However, the main cost driver is the price of renewable hydrogen, which we expect to drop significantly in coming years. Lower hydrogen costs, coupled with additional improvements in carbon capture and conversion efficiency, pave a clear pathway for e-fuel to fall below $4/gallon (see Exhibit 6). Tax incentives can drive down the cost to even less than jet fuel at around $2/gallon.

Exhibit 6

E-Fuel Cost Breakdown



Assumptions: In the base case, hydrogen is taken at $2/kg and CO_2 is taken at $30/ton. Diesel and naphtha are sold as co-products in the wholesale market for $3/gal and $600/ton, respectively. In the improved efficiency scenario, hydrogen conversion efficiency is taken at 75%, instead of ~60% in the base case scenario. Discount rate is taken as 8% for capex.
Source: Argonne National Laboratory

The Opportunity for Startups, Investors, Corporations, and Policymakers

The world needs to decarbonize the hard-to-abate aviation sector, but the technology pathways are nascent and require significant, multistakeholder support to scale.

Because of concerns around energy density, transition costs, and the time line for a fleet transition, drop-in fuels are the most viable solution for decarbonizing medium- and long-haul aviation. As a result, sustainable fuels will likely be both an enormous new market and the leading opportunity to reduce gigatons of CO_2 emissions. The **Sustainable Aviation Buyers Alliance**, composed of Boeing, United Airlines, Amazon, and other key stakeholders, has already joined together to cultivate demand for SAF.

E-fuel is the missing piece of the puzzle, in short supply today but projected to provide **50% of aviation fuel by 2050**. Exciting new startups, including SeeO2, Twelve, Prometheus, Infinium, and others, are developing novel electrolyzers, reactors, and catalysts that can significantly reduce the cost of e-fuel to $4/gallon or below (see Exhibit 7). Tax incentives can drive down the cost to even less than jet fuel at around $2/gallon.

Additionally, while other technologies are in consideration for decarbonizing marine shipping and long-haul trucking, e-fuels could tap into the larger market and help decarbonize those transportation segments as well.

Although the current high price of e-fuels may deter buyers, policymakers, and investors, it's important for them to know that the main component of its cost, renewable H_2, is expected to drop significantly as the price of solar and wind power continues to decline. Indeed, in certain geographies with inexpensive renewable power, such as Australia and Saudi Arabia, e-fuel can leverage advantageous economics today, presenting a near-term opportunity for corporations, governments, and investors.

At D3, we're focused on building bridges to help startups with novel technologies cross the valleys of death and more rapidly scale their solutions. If you're a startup founder, investor, corporate leader, or policymaker, we would love to work with you to help support this vital technology.

Exhibit 7 **E-Fuels Competitive Landscape**