



## GREEN POWER: HOW SUSTAINABILITY IS REVOLUTIONIZING FUEL TECH

**This paper examines how sustainability imperatives have driven transformative changes in fuel technology over the past three years. Ambitious commitments and regulatory frameworks striving towards net-zero emissions, such as the EU's ReFuelEU Aviation mandate and the Belém 4x pledge, have accelerated the shift away from fossil fuels toward cleaner alternatives. The analysis focuses on four aspects of fuel technology: all-solid-state batteries that aim to replace traditional lithium-ion batteries, third-generation biofuels, synthetic aviation fuels produced with carbon dioxide from conversion pathways, and hydrogen fuel cell systems. Each section discusses recent advances, sustainability benefits, manufacturing and deployment challenges, and future outlooks. Across all four technologies, there is a consistent pattern. While these innovations demonstrate strong potential to replace fossil fuels, factors such as cost, scalability, and infrastructure shortcomings remain an obstacle to real-world adoption.**

### Introduction

Policies and commitments towards net zero emissions have played an influential role in advocating for sustainable practices, specifically in fuel technology. Ambitious commitments are pushing for dramatic reductions or even net-zero emission levels in the next two-three decades. ReFuelEU aviation, for example, pushes for the widespread use of sustainable aviation fuels (SAF) to decrease carbon emissions [1]. The policy aims to support climate ambitions of reducing emissions by 55% towards 2030 [1].

Additionally, Brazil and partnering countries such as India, Italy, and Japan have pledged to quadruple their production of sustainable fuel by 2035 [2]. Referred to as "Belém Commitment for Sustainable Fuels," or "Belém 4x," the countries launched an initiative on October 14, 2025, to radically increase production in fuel sources like biofuels, biogases, synthetic fuels, and hydrogen [2].

In parallel, these policies are reshaping the markets. For example, electric cars surpassed 17 million sales in 2024, becoming more than 20% global sales share [3]. New centers of electric vehicle adoption are developing across Asia and Latin America. Electric vehicle sales in these regions grew by over 60% in 2024, a rate comparable to where the European market was about five years prior [3]. Electric vehicles are projected to exceed 40% of global car sales by 2030 [3].

Across multiple industries, fuel technology is undergoing significant overhauls. Shifting away from traditional fossil fuels, innovations in advanced batteries, biofuels, synthetically produced e-fuels, and hydrogen fuel cells all strive to mitigate emissions and other negative impacts from current infrastructure. This paper argues that although sustainability policies have greatly sped up innovation across fuel technologies, the rate of adoption is slower due to economic and infrastructural constraints.

### An Emerging Battery Alternative: All Solid-State Batteries

As of recently, all solid-state batteries (ASSBs) have undergone significant development. Recognized as a "next-generation battery," ASSBs have gained traction as a possible successor to the widely used traditional lithium-ion battery [4]. Specifically, innovations have been made to

address safety concerns and energy density limitations. These accelerated enhancements in the past three years are essential to meet the demands of next-generation lithium battery markets, as large-scale sectors such as electric vehicles, energy storage systems, artificial intelligence, and information technology rapidly expand [4].

A major issue traditional lithium-ion batteries faces safety concerns due to flammable liquid electrolytes, leading to documented electric vehicle fire incidents and posing other potential risks. Sustainability goals, driven by the adoption of renewable energy and the use of electric vehicles, emphasize the need for alternatives. Moreover, conventional lithium-ion technology is nearing its theoretical limit: cathode materials like lithium cobalt dioxide and lithium iron phosphate offer capacities of only 140-170 mAh/g, making further energy density improvements impractical and difficult [4]. Combined, these reasons have led to the transition into solid-state electrolytes from liquid electrolytes, which eliminate the fire risks while enabling the use of lithium metal anodes that offer much higher theoretical capacities than conventional graphite anodes.

From an environmental point of view, the removal of flammable liquid electrolytes decreases risks in production and disposal concerns because of the material's toxicity [5]. Ultimately, ASSBs offer many advantages such as improved safety, higher energy density potential, improved thermal stability, and improved durability and lifespans, with some lab-scale demonstrations achieving up to 5,000 cycles for NMC811-based cells using engineered composite anodes [4]. Further, recent advances in solid electrolyte materials have achieved ionic conductivities up to 8.4 mS/cm for sulfide-based electrolytes such as  $\text{Li}_{5.4}\text{PS}_{4.4}\text{Cl}_{1.6}$  [4]. Sustainability benefits also go beyond operational safety. Solid electrolytes can be recovered and regenerated from a battery that has lost its ability to hold charge, with recycled electrolytes processed through deformation-based resintering showing 89.7% capacity retention after 400 cycles [4].

Still, significant tradeoffs prevent commercialization. Current ASSB production costs are considerably more expensive compared to conventional lithium-ion batteries, driven mostly by the high cost of solid electrolyte materials. As of now, liquid electrolytes make up only about 14% of a conventional lithium ion battery's total cost, suggesting that solid electrolyte prices must fall greatly before ASSBs can be economically viable [4]. Manufacturing ASSBs is energy-intensive, with high-temperature sintering processes for solid electrolytes contributing to a substantial amount of greenhouse gas emissions. A recent life-cycle study of a sulfur-based ASSB found that about 75% of cumulative energy demand comes from clean dry-room operations alone, with positive electrode paste production contributing another 10% [5]. Figure 1 presents the energy demand breakdown.

The past three years have focused greatly on cost reduction strategies. Solution-based synthesis methods have demonstrated potential for up to 92% cost reduction in sulfide-based electrolytes through the utility of low-cost, less-pure precursors. Emerging manufacturing innovations like the cold sintering process enable densification at temperatures below 300°C, rather than traditional high temperature methods, offering potential pathways to lower both energy consumption and production costs [5]. However, these techniques remain at the laboratory scale. Another issue is scaling up in manufacturing, as techniques like thin-film deposition and wet-slurry fabrication must move from the lab to the industrial scale. Interfacial resistance between solid electrolytes and electrodes continue to be a performance limitation, though infiltration fabrication processes and composite electrolyte designs are promising [4]. Performance at room temperature and low external pressure, the conditions required for real-world pouch-cell electric vehicle deployment, also proves a significant challenge. Many high-performance ASSBs are reported to be under impractical high stack pressures during tests [4].



Cumulative energy demand breakdown for sulfur-based ASSB manufacturing

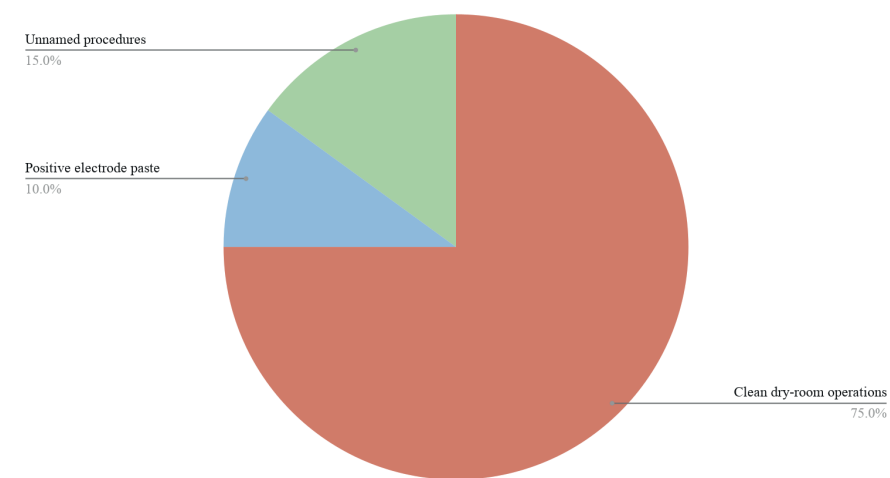


Figure 1: A pie chart demonstrating the cumulative energy demand breakdown for sulfur-based ASSB manufacturing. It should be noted that there is a 15% slice that was unnamed [5].

Lab-tested ASSBs achieve energy densities at the cell-level ranging from 115 Wh/kg in early sheet-type cells to 263 Wh/kg in optimized NMC811-based configurations [4]. These values are competitive with mature lithium-ion batteries, but do not consistently exceed them yet. The theoretical potential is higher if lithium metal anodes can be stabilized against dendrite formation, but the solution is still unresolved [4]. The extended lifespan of ASSBs offers extra environmental benefits by reducing how often they are replaced and subsequent resource consumption and manufacturing emissions [5]. However, there are issues with their end of life management that could offset these gains. The tightly integrated solid electrolytes and electrodes in ASSBs make traditional recycling complicated, necessitating direct recycling, electrohydraulic fragmentation, and closed-loop recovery systems to efficiently retrieve valuable materials [5].

To add on, ASSB recycling infrastructure does not exist at a commercial scale, making this a critical challenge for scaling. Projections claim its full development to be between 2040 and 2050 [5]. Toyota has announced mass production plans to begin in 2027, with broader market share by 2030 [5]. These dates reflect early production instead of mass displacement of lithium-ion technology. Therefore, realistically, ASSBs are not in the position for widespread or even commercial adoption. Again, production costs remain much higher than current lithium-ion batteries, scalable manufacturing processes are still being worked on, and infrastructure lags behind by many years, hindering production even more. ASSB development is a part of a common pattern in fuel and energy technology. Sustainability-driven imperatives have led to up to lab-scale innovations, but the gap between theory and commercialization is a powerful constraint.

Emphasis on Third-Generation Biofuels

In pursuit of a greener future, biofuel production has become a relevant candidate for alternative fuel production and renewable energy solutions. Essentially, biofuels are derived from biomass or organic matter from decomposing substances. Currently, biofuels can be classified into four generations: first-generation biofuels are from food crops (corn, sugarcane, seeds), second-generation biofuels are from non-food crops (agricultural and forest remains, vegetable grasses), and third and fourth-generation biofuels, the most nascent groups, are from algae and cyanobacteria. The production of biofuels over the course of the 21st century has exponentially increased; in 2000, 180 thousand barrels of oil equivalent per day were produced worldwide, which rose to about 1,914 thousand barrels of oil equivalent per day in 2022 [6]. This approximately tenfold increase, however, reflects the scaling of only first and second generation biofuels, not third generation ones. It is noted that microalgae-based biodiesel is still in the laboratory stage, which implies third-generation biofuels and beyond are not scaled into production yet. The figure below is a flowchart of biomass classifications.

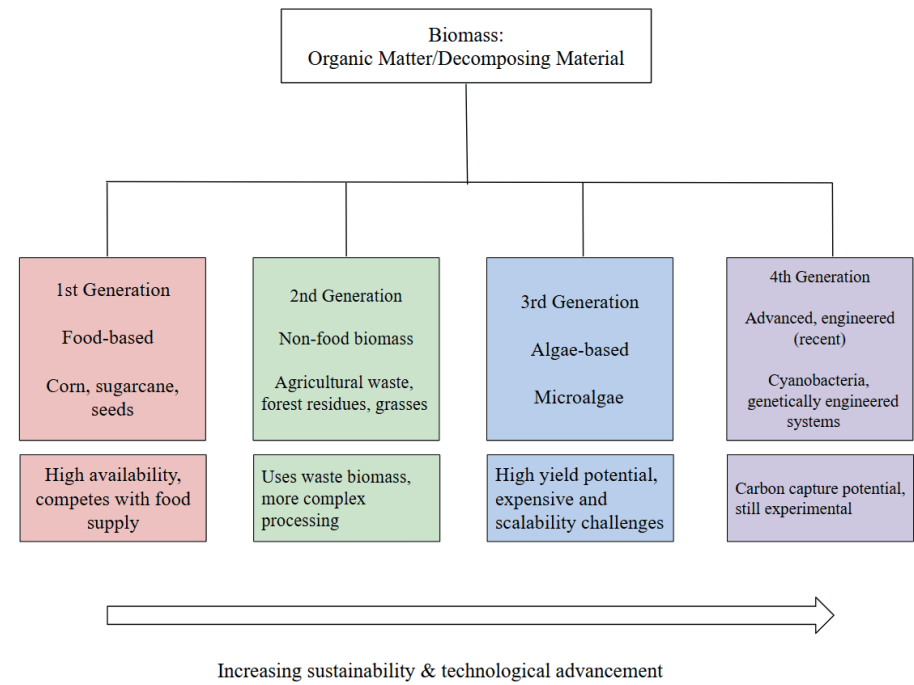


Figure 2: A flowchart summarizing the four generations of biomass [6].

Growing concerns about food security and land use competition have driven shifts and preferences in biofuel feedstock selection. Harvesting first-generation food crop-based biomass faced criticism for competing with food production, prompting a transition into second-generation non-food-crop biofuels. Still, second-generation pathways still relied on arable land or forest resources and they are described as less productive economically because of complex conversion technology compared to first-generation pathways [6]. Each generational shift evidently solves the main issue with the prior generation but creates a new one. This pattern is observable with the third-generation of algae, as it serves as an alternative to escape from land-use but inherits a new issue of economic unviability at the moment.

Originating from microorganisms, they are described to have a “noncompetitive nature for food chains” while being able to produce multiple products such as bioethanol, biogas, and biodiesel [6]. Moreover, the microorganisms can be cultivated under autotrophic conditions (using carbon dioxide, light, and nutrients to create biomass), heterotrophic conditions (where light is not used on organic carbon sources) or mixotrophic conditions (a combination of the previously mentioned metabolic methods) [6]. This metabolic flexibility is an important feature. Autotrophic growth allows algae to act as a sink for carbon dioxide during growth, which is highlighted as a major benefit of the third-generation along with higher lipid content, high energy, and a faster growth rate [6]. The same organism class can be tuned across cultivation modes depending on whether carbon capture or biomass yield is prioritized, an aspect of process versatility that lignocellulosic feedstocks do not possess. The conversion of biomass to biofuels can be performed through a variety of transesterification techniques, involving the reaction of triglycerides with alcohol to produce biodiesel and glycerol [6]. Different methods have been developed for different microalgae species, such as homogeneous catalysis, heterogeneous catalysis, enzymatic transformation, supercritical transesterification, ultrasound-assisted transesterification, and microwave-assisted transesterification. The choice of techniques depends on feedstock quality, production scale, and available resources, with research focused on making these processes optimal and more efficient [6]. It is implied that there is no highly preferred approach or standard, compared to uniform alkali-catalyzed transesterification commonly used in first-generation biodiesel production.

Additionally, algae as a means of biofuel production proves multiple benefits compared to previous generation biofuels: the use of nonfood crops, limited land footprint by using non-arable land, cheap sourcing from waste (food oil, garbage, seawater), the ability to use nonpotable water (sewage, seawater) instead of potable freshwater, and no consumption of chemical fertilizers and pesticides [6]. Microalgae species demonstrate oil contents ranging from 4% to 77% by weight, with high performing species like the Schizochytrium sp. (50-77%) and Nannochloris oleoabundans (35-65%) are frequently cited as evidence for the commercial promise of algal biodiesel. Table 1 below shows the oil content by weight of a variety of microalgae species [6].

Table 1: An adopted table of oil content by %wt of fourteen algal species [6]. The value for parietochloris incisa is represented as “062” in the source table, which may be a typo.

| Species                 | Oil Content (%wt.)                    |
|-------------------------|---------------------------------------|
| Chlamydomonas sp.       | 22.7                                  |
| Chaetoceros muelleri    | 13-24                                 |
| Parietochloris incise   | (appears as “062” in the source used) |
| Tetraselmis tetrathele  | 25-30                                 |
| Nostoc commune          | 22                                    |
| Emiliania huxleyi       | 43.8                                  |
| Choomonas salina        | 12-14.5                               |
| Mesotaenium sp.         | 19-35                                 |
| Spirulina platensis     | 4-11                                  |
| Synechocystis sp.       | 11                                    |
| Nannochloris sp.        | 22-56                                 |
| Neochloris oleoabundans | 35-65                                 |
| Chlorella sp.           | 28-53                                 |
| Schizochytrium sp.      | 50-77                                 |

However, oil content by itself is not the only thing considered for commercial viability, and Table 1 can be a misleading ranking of the best species that ignores underlying economics. Three important factors should be considered before making assumptions based on the percentages. Firstly, oil content describes how much of dry biomass is lipid, not the rate at which biomass is created. A species with high lipids that grows at a slow rate may yield less biodiesel than a species with moderate lipids that grows faster. Ultimately, there are two beneficial variables of faster growth rate and higher lipid content that are independent of each other [6]. Secondly, it is important to note that algal biodiesel research, including cultivation, harvesting, and lipid extraction are at the lab-scale, so values in Table 1 should be taken into account of laboratory conditions compared to possibly different commercial yields. Lastly, picking a species with a higher lipid content does not get rid of the expensive harvesting and extraction processes that follow cultivation, since expenses are tied to cultivation process itself, not the choice of feedstock [6]. A fair interpretation of Table 1 can be a list of candidates for further optimization, not a power ranking of feedstocks.

There is a large economic disadvantage, however. According to IEA 2021 data, advanced biofuels (algal) cost \$1.20-\$2.00 per liter to produce, about two to four times more than the \$0.50-\$0.60 per liter cost of conventional gasoline, and 1.5 to 4 times the cost of soybean biodiesel at \$0.70-\$0.90 per liter or sugarcane ethanol at \$0.45-\$0.65 per liter [6]. By cost per energy, advanced biofuels reach \$34.30-\$57.10 per GJ as opposed to \$14.60-\$19.00 per GJ for conventional gasoline [6]. This tremendous cost penalty is driven by the costly procedures of microalgae harvesting and

lipid extraction, marking these as bottlenecks [6]. It is noted that marine eutrophication is a major environmental risk of the third generation, but this concern is the output problem, not a constraint for cultivation. Moreover, the primary obstacles are economic at the moment.

With everything taken into account, third-generation biofuels occupy a contradictory position. They address most sustainability concerns aimed at the first two generations, like no arable land and portable water requirements, no fertilizers, and no food competition. Still, they are incapable of displacing earlier generations in actual production because of complicated issues that largely pertain to cost, a trend observed in the previous section. For now, the third-generation continues the generational progression of trading one set of limitations for another, specifically trading land usage and food security concerns for economic constraints.

Although third-generation operations continue lab-scale optimization, researchers have also begun advancing fourth-generation approaches; the source describes them as “an extension of the third generation” that utilizes modern biological technology, hinting that the third and fourth-generation are closely related with an added layer of genetic-engineering or modifications [6]. The fourth-generation includes genetically modified photosynthetic microorganisms, such as cyanobacteria. These organisms are capable of converting ambient carbon dioxide to ethanol through photosynthetic bacteria pathways with the goal of overcoming production obstacles [6].

The fourth-generation inherits the same harvesting and extraction bottlenecks as the third-generation which revolve around their complexity and financial cost, while adding a unique risk environmentally: their GMO release in the environment could be a threat [6]. Oil content data highlights the current low viability of cyanobacteria species currently. Table 2 below displays the lipid yields of a few species, which are lower than the higher performing microalgae in Table 1. *Spirulina platensis* maxes out at 11% and *Synechocystis* sp. sits at 11%, compared to *Schizochytrium* sp. at 50-77% [6]. It is implied that cyanobacteria do not currently rest on their natural lipid content; it depends on the potential of genetic modification to increase these values substantially. Currently, genetic engineering efforts aim to increase hydrocarbon output while lowering emissions. Specific performance improvements are still under development as research remains very limited [6].

Table 2: An adopted table of oil content by % wt in three different species of cyanobacteria [6].

| Species             | Oil Content (% wt.) |
|---------------------|---------------------|
| Nostoc commune      | 22                  |
| Synechocystis sp.   | 11                  |
| Spirulina platensis | 4-11                |

Synthetic Fuel's Appeal in the Aviation Sector

As an associated industry with the heavy-emission transportation sector, aviation accounts for 2.5% of global carbon dioxide emissions, with demand growing 4% annually [7]. This growth is also met by strong sustainability ambitions. The industry is aiming for net-zero emissions by 2050; however, sustainable aviation fuel production only reached 0.5 million tonnes in 2023, a quantity extremely short of the 46 million tonnes needed by 2030 to meet this goal [7]. Regulatory drivers such as the EU's ReFuelEU Aviation mandate, requiring gradual sustainable aviation fuel (SAF) blending from 2% in 2025 to 70% by 2050, and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) eligibility requirements are strongly advocating for the transition into SAF [8]. However, unlike ground transportation, which can decarbonize through electrification, the air industry faces unique challenges. Specifically, jet engines need energy-dense liquid fuels that batteries cannot provide because of weight constraints. Current scale production of biofuels cannot meet global demand either because of limited feedstocks. As a result, the fuel technology industry, especially aviation, has pivoted to reimagining where the carbon comes from instead of only the power source. In the past three years, this shift has been urgent as regulatory mandates push the aviation industry to move beyond fossil fuels and traditional biofuels to synthetic alternatives [7].

Synthetic fuel production needs three main inputs: captured carbon dioxide from the atmosphere or industrial sources, hydrogen produced through water electrolysis using renewable energy, and energy to run the chemical conversion process. Further, the conversion follows different pathways depending on which intermediate compound is used, being syngas (a mixture of carbon monoxide and hydrogen), methanol, or ethylene. All compounds aim to create the same end product of liquid hydrocarbons in the C8 to C16 carbon chain range that jet fuel consists of [7]. These synthetic hydrocarbons are chemically the same as petroleum-based jet fuel, subsequently making them “drop-in” replacements. This creates an infrastructural advantage over battery-electric aviation, because they would need entirely new aircraft designs and ground infrastructure. Also, SAF can

achieve up to 80% reduction in lifecycle greenhouse gas emissions compared to conventional aviation fuel, although this does vary significantly by production route and type of feedstock [8]. Moreover, this variation is seen across all major production pathways and their feedstocks, shown by the figure below. Ultimately, the manufacturing of synthetic fuels provides utility for captured dioxide which assists in closing the carbon cycle, while being compatible with current infrastructure effectively reducing costs [7]. Collectively, these properties put synthetic fuels as a near-term option capable of meeting aviation's fuel demands. Synthetic fuels avoid the constraints mentioned by drawing carbon from carbon dioxide and hydrogen from water, inputs that are unlimited given sufficient renewable electricity.

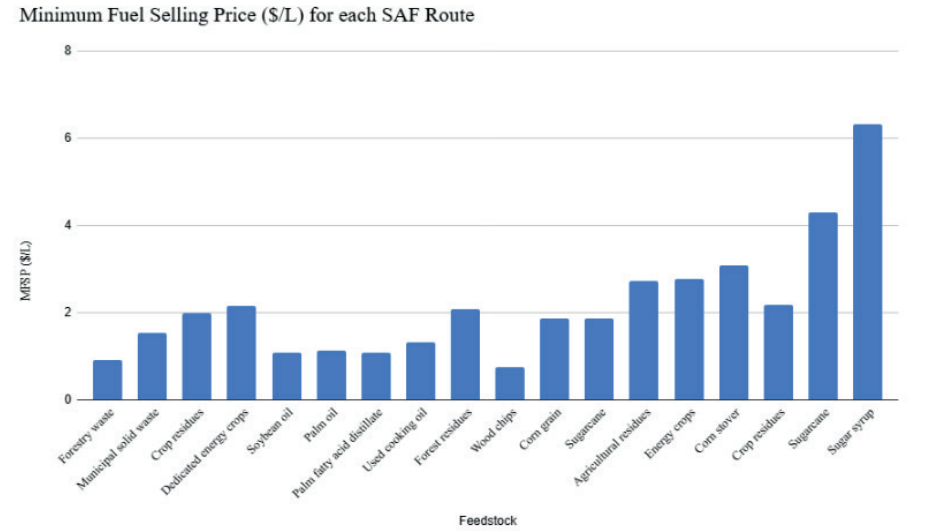


Figure 3: A chart demonstrating the minimum fuel selling price (\$/L) of SAF production routes by feedstock. This data is adopted from a table [8].

However, different pathways have different degrees of sustainability. Recently, research shows how the mentioned three routes have substantial variation. This includes energy intensity differences up to five times, carbon dioxide efficiency ranging from about 70%-90% (with the potential to reach 100%), and technology limitations and readiness spanning from only lab-scale to industrial processes [7]. The minimum fuel selling price also varies by route: the hydroprocessed esters and fatty acids route shows the lowest average minimum fuel selling price at about \$1.2 per liter, while the synthesized iso-paraffins route reaches \$4.26 per liter. Both of these routes cost significantly higher than conventional fuel on average [8]. Another important bottleneck is the feedstock availability; Europe projects production capacity in 2025 includes 7.2 million tons with the hydroprocessed esters and fatty acids route, though scalable feedstocks remain limited as waste cooking oil, a primary feedstock for this route, is a finite resource despite recovery potentials exceeding 5 million tons annually in markets like China [8]. This feedstock limit is a big reason why carbon dioxide-based synthetic fuels are garnering support over regular biofuels [7]. These differences are significant to acknowledge as the aviation industry seeks to increase their scale of production from 0.5 million tonnes to 46 million tonnes by 2030 [7].

Fuel Cell Technology: An Electrochemical Revolution

Although batteries have revolutionized transportation and power sources in general, certain applications face constraints with conventional battery characteristics. This pertains to weight limitations in aviation or extensive cargo, extended charging times for commercial fleets, or range restrictions for long travel. Moreover, transportation accounts for 29% of greenhouse gas emissions in the United States, with heavy-duty and long-range uses contributing largely to this statistic [9]. Fuel cells address these critical shortcomings of batteries: these electrochemical devices convert hydrogen fuel directly into electricity, producing only warm air and water vapor as byproducts. This makes fuel cells zero-emission, adding to its increasing favorability and potential. Research reveals that fuel cell vehicles can reduce greenhouse gas emissions by 50% compared to gasoline vehicles when powered by renewable hydrogen [9].

Fuel cells are electrochemical devices that convert chemical energy into electricity through reduction-oxidation reactions. Unlike batteries that are designed for shorter-term energy storage

| Fuel Cell                    | Material                                                                  | Operating Temperature | Typical Stack Size                            | Electrical Efficiency (LHV)                           | Common Use                                                                                 | Strengths                                                                                                                     |
|------------------------------|---------------------------------------------------------------------------|-----------------------|-----------------------------------------------|-------------------------------------------------------|--------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Polymer electrolyte membrane | Perfluorosulfonic acid polymer membrane                                   | Less than 120°C       | Less than 1 kW to 100 kW                      | 60% with pure hydrogen gas<br>40% using reformed fuel | Backup power, portable systems, distributed generation, transportation, specialty vehicles | Solid electrolyte limits corrosion and simplifies management; low-temperature operation, rapid startup and load response      |
| Alkaline                     | Aqueous potassium hydroxide in porous matrix or alkaline polymer membrane | Less than 100°C       | 1-100 kW                                      | 60%                                                   | Military, space, backup power, transportation                                              | Broad choice of materials allows for cheaper components; low-temperature operation with quick startup                         |
| Phosphoric Acid              | Phosphoric acid held in porous structure or polymer matrix                | 150-200°C             | 5-400 kW (common commercial unit size 100 kW) | 40%                                                   | Distributed generation                                                                     | Usable for combined heat and power systems; improved tolerance to fuel contaminants                                           |
| Molten Carbonate             | Molten lithium/sodium/potassium carbonate salts in porous support         | 600-700°C             | 300 kW modules to multi-MW plants             | 50%                                                   | Electric utility and distributed generation                                                | High efficiency; adaptable to different fuels; usable for combined heat and power systems and hybrid gas turbine cycles       |
| Solid Oxide                  | Ceramic oxide electrolyte                                                 | 500-1000°C            | 1 kW to 2 MW                                  | 60%                                                   | Auxiliary power, electric utility, distributed generation                                  | High efficiency; fuel flexible; solid electrolyte; compatible with combined heat and power systems and hybrid turbine systems |

Figure 4: An adopted table comparing the five main fuel cell technologies [9].



and require recharging, fuel cells continuously generate electricity as long as fuel is supplied. Fuel cells consist of two electrodes, an anode and a cathode, and electrons move through an external circuit to produce electricity [9]. Stated previously, the only byproducts are warm air and water vapor, making it completely clean in terms of power production. There are five main fuel cell systems, distinguished by their electrolyte materials and temperatures during operation. Polymer Electrolyte Membrane Fuel Cells operate below 120°C and are largely present in transportation applications like passenger cars and heavy-duty trucks because of their low operating temperature, quick start-up time, and durability [9].

They possess an electrical efficiency of 60% for direct hydrogen and power outputs ranging from under 1 kW to 100 kW. Solid Oxide Fuel cells and Molten Carbonate Fuel Cells operate at extreme temperatures (500-1000°C and 600-700°C respectively) making them suitable for stationary power generation and grid applications where their 50-60% electrical efficiency and ability to use a variety of fuels provide flexibility [9]. Moreover, these fuel systems' high temperature operation allows these fuel cells to reform hydrocarbon fuels internally, reducing complexity and costs. Lastly, the remaining types, Alkaline Fuel Cells and Phosphoric Acid Fuel Cells, are for specialized utility in space, military, and other heat and power systems [9]. Figure 4 shows a table comparing the fuel cell technologies.

However, the sustainability for fuel cells is not possible without affordable clean hydrogen, an important reason for why this technology's promise fails. Since fuel cells only produce water vapor at the point of use, their lifecycle emissions are determined mainly by how the hydrogen feeding them was produced. Currently, over 90% of hydrogen is generated from fossil fuels with methods such as steam methane reforming, a process that produces substantial carbon dioxide at the production stage, basically displacing emissions rather than completely eliminating them [9]. The reason for the domination of fossil-based pathways is economic. Producing hydrogen from natural gas costs about \$0.50-\$1.70 per kilogram, while renewable pathways cost significantly more at \$3.00-\$8.00 per kilogram [9].

Again, similar to many emerging fuel technologies, the bottleneck for this entire technology is the huge price gap. The market will continue to favor fossil-based hydrogen as long as clean hydrogen remains a much more expensive alternative. Subsequently, deployed fuel cells continue to run mostly on hydrogen which undermines the zero-emission goal. To address this, the United States' Department of Energy (DOE) has set a target of \$1 per kilogram for green hydrogen through net-zero carbon pathways, an 80% cost reduction, which would make renewable hydrogen economically competitive with fossil-based hydrogen [9]. If this happens, the full decarbonization feature of fuel cells would be unlocked. Until this target is met, hydrogen cost remains a limiting factor for this technology's full potential. The figure below portrays the hydrogen cost gap.

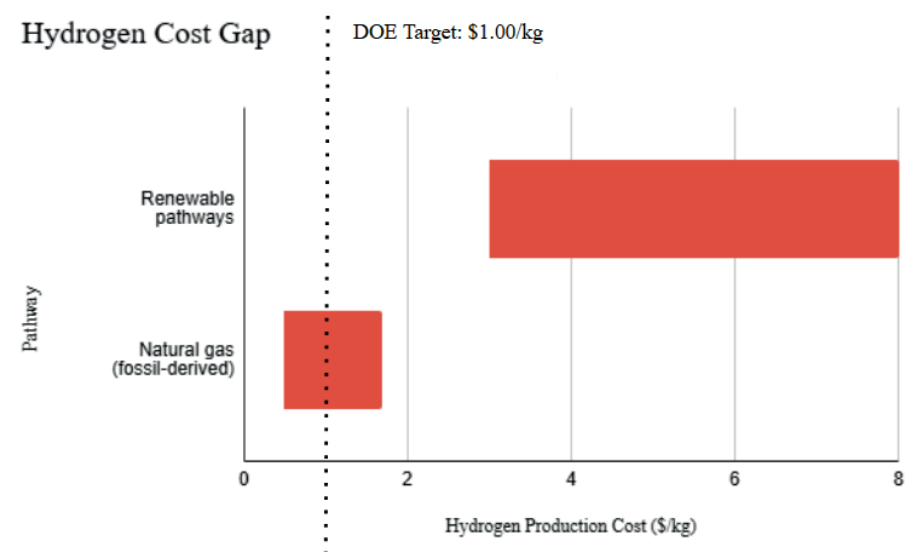


Figure 5: The hydrogen cost gap between fossil-based and renewable production of hydrogen. The dotted line represents the production price the DOE is aiming for [9].

It is widely acknowledged that fuel cell technology is a mature technology that has been developed over decades. Still, the deployment and development of fuel cell technology has been accelerated in the past three years due to sustainability incentives after having been proven viable. For example, in commercial trucking, Nikola Motors produced 42 Class 8 fuel cell trucks by 2023, with 35 wholesaled to customers, while Hyzon Motors deployed 19 trucks across the United States, Europe, and Australia [9]. These fuel cell trucks achieve efficiencies equivalent to 12-15 miles per gallon–188-234% more efficient than the average diesel truck at 6.4 miles per gallon. Fuel cell technology has dramatically reshaped the maritime sector as well: in 2023, Norway's Norled AS, one of the largest ferry companies in Norway, received approval to use the MF Hydra, the world's first hydrogen ferry, equipped with 4 tonnes of liquid hydrogen and two 200-kW fuel cells [9]. Similarly, this was followed by the launch of the MV Sea Change, the first commercial hydrogen-powered ferry in the United States, capable of sailing 300 nautical miles with 360-kW Cummins fuel cells [9].

Conclusion

Fuel technology has undergone accelerated development and usage due to sustainability-driven goals. Most of the world is investing into greener alternatives that will likely define the future of fuel. Importantly, solutions and innovations to conventional fuel technologies are essential to fulfill this vision; transportation depends largely on fossil fuels and is responsible for producing a large share of greenhouse gas emissions as a result (29% of greenhouse gas emissions in the United States are due to transportation) [9]. As governments and national organizations continue to set forth ambitious commitments of reduced emissions to be accomplished in two-three decades, fuel technology has been under immense pressure to align with these demands. Sustainability has effectively reshaped approaches to not only fuel technology, but to energy, resource efficiency, and conservation.

As discussed in this paper, innovations in fuel technology are not immediately translating to real-

world adoption; there are many constraints, most of which are economic, that prohibit deployment or total sustainability. Moreover, these technologies are not equally close to real-world adoption, as there is a clear hierarchy. SAF produced through the HEFA route is the closest to widespread adoption. It has already transitioned into commercial application under the CORSIA Phase I Pilot in 2021, holds ASTM certification, and has reached the highest technology readiness of any SAF route [8]. Recent regulatory action has accelerated its trajectory as well. The EU's ReFuelEU Aviation Regulation, finalized in 2023, necessitates increasing SAF blending shares at EU airports [1], while the UK Jet Zero Strategy requires at least 10% SAF blending by 2025 [8]. SAF production also doubled between 2022 and 2023, reaching 480,000 tons, though high costs, about \$2,860 per ton that is double the cost of conventional jet fuel, remain the main obstacle [8]. Following SAF are hydrogen fuels.

There is commercialization with limited geographical deployment, much of it being from the past few years. The MF Hydra ferry entered service in 2023 and the MV Sea Change launched in July 2024, alongside about 9,500 hydrogen-powered forklifts at Walmart, fuel cell buses in California and China, and Class 8 trucks from Nikola and Hyzon [9, 10]. Again, real-world adoption is present but is still constrained by refueling infrastructure and the cost of green hydrogen [9]. All-solid state batteries and algae-based biofuels are the furthest from deployment. ASSBs are restricted by complex manufacturing and the high cost of materials like lithium sulfide, which costs about \$10,000-\$15,000 per kilogram [4]. Groups such as the China All-Solid-State Battery Innovation Collaboration Platform have set distant dates to target the supply chain only by 2030 [5]. Algae as a biofuel feedstock continues to be hindered by its cultivation costs, efficiency, and scaling barriers that keep it at the lab scale [6].

Works Cited:

[1] European Commission, "ReFuelEU Aviation - Mobility and Transport," 2023. Available: ReFuelEU aviation - Mobility and Transport - European Commission.

[2] International Energy Agency, "Brazil, India, Italy and Japan pledge for quadrupling of sustainable fuels by 2035," IEA Bioenergy, 2024. Available: Brazil, India, Italy and Japan pledge for quadrupling of sustainable fuels by 2035 based on a new IEA report | Bioenergy.

[3] International Energy Agency, "Global EV Outlook 2025," IEA, Paris, France, 2025. Available: Executive summary – Global EV Outlook 2025 – Analysis - IEA.

[4] J. Sung, J. Heo, D.-H. Kim, S. Jo, Y.-C. Ha, D. Kim, S. Ahn, and J.-W. Park, "Recent advances in all-solid-state batteries for commercialization," Mater. Chem. Front., vol. 8, no. 8, pp. 1861–1887, Apr. 2024, doi: 10.1039/d3qm01171b.

[5] A. Machín, M. C. Cotto, F. Díaz, J. Duconge, C. Morant, and F. Márquez, "Environmental aspects and recycling of solid-state batteries: A comprehensive review," Batteries, vol. 10, no. 7, p. 255, Jul. 2024, doi: 10.3390/batteries10070255.

[6] R. El-Araby, "Biofuel production: exploring renewable energy solutions for a greener future," Biotechnol. Biofuels Bioprod., vol. 17, no. 129, 2024, doi: 10.1186/s13068-024-02571-9.

[7] P. Hirunsit, A. Senocrate, C. E. Gómez-Camacho, and F. Kiefer, "From CO2 to Sustainable Aviation Fuel: Navigating the Technology Landscape," ACS Sustainable Chem. Eng., vol. 12, no. 32, pp. 12143–12160, 2024, doi: 10.1021/acssuschemeng.4c03939

[8] B. Wang, Z. J. Ting, and M. Zhao, "Sustainable aviation fuels: Key opportunities and challenges in lowering carbon emissions for aviation industry," Carbon Capture Sci. Technol., vol. 13, p. 100263, Dec. 2024, doi: 10.1016/j.ccst.2024.100263.

[9] D. Manzo, R. Thai, H. T. Le, and G. K. Venayagamoorthy, "Fuel cell technology review: Types, economy, applications, and vehicle-to-grid scheme," Sustainable Energy Technol. Assess., vol. 75, p. 104229, Feb. 2025, doi: 10.1016/j.seta.2025.104229.

[10] "MV Sea Change," FerryRiders.com, 2024. Available: MV Sea Change - FerryRiders.com.

Biographies

**Dr. Raj Shah** is a Director at Koehler Instrument Company in Holtsville, New York. He is an elected Fellow by his peers at ASTM, IChemE, ASTM,AOCS, CMI, STLE, AIC, NLGI, INSTMC, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-awaited Fuels and Lubricants Handbook <https://bit.ly/3u2e6GY>.

He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honorific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Board of Directors at Farmingdale College for Mechanical Technology, as well as the Department of Material Science and Chemical Engineering at Stony Brook University where he is also an Adjunct Professor. Raj has over 875 publications and has spent the past three decades actively in the energy industry.

**Gavin Thomas** is part of a thriving internship program at Koehler Instrument Company in Holtsville, and just graduated with a degree in Chemical and Molecular Engineering from Stony Brook University, Stony Brook, New York. He also works as a process engineer at Mill-Max in Oyster Bay, NY where he becomes hands-on with various production processes to ultimately improve safety, efficiency, and cost-effectiveness.



Gavin Thomas



Mathew Roshan



Joseph Contreras

**Mr. Joseph Contreras and Mathew Roshan**

are a part of a thriving internship program at Koehler Instrument Company in Holtsville and students of Chemical Engineering at Stony Brook University, Long Island, NY, where Dr. Shah is the current chair of the external advisory board of directors.

Author Contact Details

**Dr. Raj Shah, Koehler Instrument Company**  
• Holtsville, NY11742 USA  
• Email: [rshah@koehlerinstrument.com](mailto:rshah@koehlerinstrument.com)  
• Web: [www.koehlerinstrument.com](http://www.koehlerinstrument.com)

