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Evaluating the Commercialization Factor and Functionality of an E-fuel-Biofuel Blend in Internal Combustion Engines

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ABSTRACT

The world is currently facing an environmental dilemma. Industries and governments globally must decide between maintaining relatively low transportation prices at the expense of atmospheric CO2 emissions, and upheaving current transportation infrastructure to pave the way for environmentally friendly alternatives, like electric vehicles. Electrofuels (e-fuels) are synthesized hydrocarbon chains, produced through the Fischer-Tropsch process, and have the potential to be carbon-neutral when produced using green energy sources. E-fuels function in internal combustion engines without modification, and are therefore deemed “drop-in fuels.” Due to the energy-intensive nature of the Fischer-Tropsch process, electrolysis, and carbon capture, e-fuels are economically unviable. Blending e-fuels with biofuels, combustible materials derived from organisms, alleviates the energy and cost burden of using e-fuels. An electrofuel biofuel blend (e/biofuel) has the potential to overcome economic shortcomings while maintaining the carbon neutrality of the fuel and compatibility with current combustion engines. However, biofuel’s characteristics differ from e-fuels, creating blending limits based on the acceptable deviation for viscosity, density, octane/cetane rating, and flash point. Calculating the cost of e/biofuels using renewable energy, examining blending limits, and assessing the advantages and disadvantages of this fuel are requisite to understanding the commercial and functional viability of this promising technology.

1. INTRODUCTION

A typical American passenger vehicle emits roughly 4.6 metric tons of CO2 annually, or 8,887 grams of CO2 for every gallon of gasoline burned.[1] This equates to a total of 4.74 million tons of CO2 in passenger vehicle emissions per year in the United States alone.[2] All-time high rates of CO2 emissions and fossil fuel consumption have contributed to a 1.28ºC increase in global average surface temperature from pre-industrial era levels.[3,4] With 2024 being the warmest year on record,[5] scientists worldwide have been developing renewable and sustainable fuels to replace fossil fuels in internal combustion engines and mitigate the adverse environmental impacts of travel and transportation. In particular, electrofuels (e-fuels) and biofuels provide promising pathways for carbon neutrality in the transportation sector, as they are compatible with current internal combustion infrastructure. However, many of these fuels face issues with scalability and energy efficiency.

E-fuels are hydrocarbon chain fuels such as e-gasoline, e-kerosene, and e-diesel synthesized using CO2 and H2. Green hydrogen gas, produced through electrolysis of H2O, is combined with carbon dioxide, typically obtained through carbon capture, using high heat and pressure to create hydrocarbons and water. Because e-fuels are molecularly indistinguishable from conventional fossil fuels,[6] they can be integrated into existing engine infrastructure without modification. Given their compatibility with current combustion engines, these "drop-in fuels" continue to emit CO2 upon consumption. However, overall carbon neutrality can be achieved through the capture of atmospheric carbon during the production process. Though e-fuels provide a promising pathway for renewable fuels, not requiring an upheaval of current infrastructures, they are only carbon neutral if the energy used in their production comes from renewable sources, such as solar and wind power.[7] Further, e-fuels are paramount to decarbonizing the aviation and maritime sectors. Though many argue that electric vehicles should be the primary means of decarbonizing transportation, planes and large ships cannot function on electric energy due to limitations in battery technology. Therefore, e-fuels are imperative to creating environmental sustainability in sectors where infrastructure is solely built around fossil fuels.[8] Biofuels are combustible materials derived from or produced by living organisms.[9] Currently, commercially produced biofuels include bioethanol, biodiesel, and n-butanol.[9]

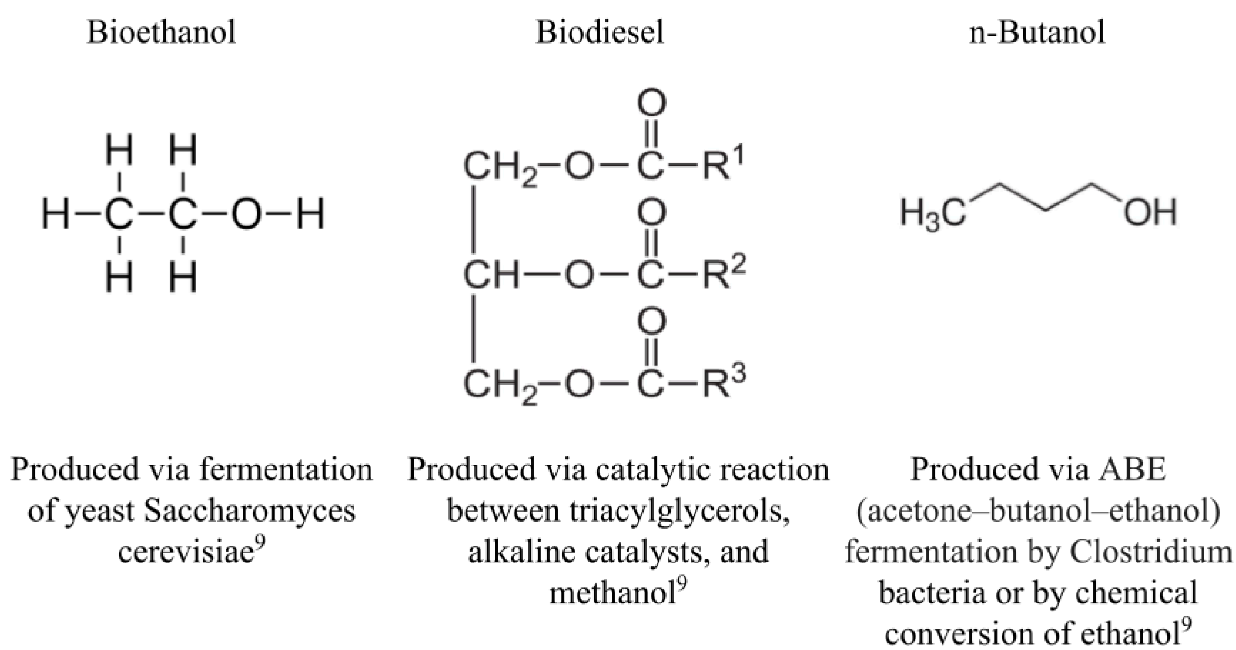

Figure 1. Common commercially produced biofuels and their production pathways.

These biofuels are blended with fossil fuel gasoline for cost efficiency and functionality in combustion engines, as their energy contents are too low and their viscosities too high to perform independently in unmodified ignition engines.[10, 11] Biofuels have three generations, or sources, from which they are derived. First-generation biofuels are sourced from carbohydrate-rich crops, planted for the express purpose of producing biofuels, while second-generation biofuels are sourced from waste biomass, and third-generation biofuels are sourced from microalgae and oleaginous microbes.[9]

First-generation biofuels have become controversial, as crops are grown purely to produce fuel, diverting agricultural land and irrigation systems previously used for food production.[12] Additionally, increased land demands incur the risk of deforestation, while using freshwater, fertilizers, and pesticides to cultivate land adversely affects the environment.[12] While second generation biofuels address some of these issues, they are less economically viable. Second generation biofuels are derived from lignocellulosic materials, which are more complex and challenging to ferment.[13] Therefore, these lignocellulosic materials require pre-treatment to break down the cellulose and lignin, which requires a high up-front capital cost.[14] Third-generation biofuels could resolve the environmental impacts of producing biofuels, as microalgae can be grown in wastewater on non-arable land.[8] However, the energy-intensive process of producing microalgal biofuels and the capital cost of microalgal bioreactors make third-generation biofuels economically unviable.[12]

Despite promising scientific progress in biofuel and e-fuel development, these fuels lack commercial competitiveness, as their energy-intensive production processes cause their final costs to exceed those of fossil fuels.[15] Additionally, biofuels may not be as ecologically clean as they superficially appear. The conversion of natural vegetation to biofuel feedstocks emits a large amount of carbon from the soil and biomass,[12] while the water used to cultivate feedstocks may divert water used for other purposes, potentially exacerbating the environmental impacts of biofuel production in water-scarce areas.

The upfront capital expenses of suitable land and bioreactors used to ferment yeasts and microalgae, specifically for third-generation biofuels, pose challenges to commercial-scale production. While the production of biofuels necessitates steep upfront investment, e-fuel production requires additional continual investment to support processes such as direct air capture of CO2 and the Fischer-Tropsch synthesis process. The energy input needed to synthesize e-fuels is significant due to the energy required to create high-temperature and high-pressure conditions to synthesize hydrocarbon chains.[7] The scalability issues these fuels face hinder their commercial potential. Though this challenge has been remedied by blending these fuels with fossil fuels, doing so degrades the environmental integrity and carbon-neutral intent behind these fuels.

However, blending e-fuels and biofuels may provide a more cost-effective and carbon-neutral alternative to fossil fuels. Since biofuel infrastructure is already fairly developed and biofuel fossil fuel blends are ubiquitous, the necessary infrastructure already exists to create biofuel-e fuel (hereafter referred to as e/biofuel) blends if ratios remain the same. An e/biofuel blend would also enable e-fuels an opportunity for commercial expansion, as they would not need to support the fuel sector fully, therefore being able to gradually scale and gain ubiquity as a renewable fuel source. Introducing e/biofuel blends would save land and water used to cultivate feedstocks if the fuel industry leaned into biofuels. The e-fuel production process can also be streamlined by using the byproduct of CO2 from biofuel bioreactors to produce e-fuels.[16]

Assessing the viability of an e/biofuel blend in internal combustion and compression engines requires examining molecular compatibility, production energy consumption, production capacity, and the challenges and advantages of large-scale production.

2. METHODS

A systematic approach was employed to evaluate and utilize existing sources to determine the economic and chemical viability of e-fuels and biofuels in internal combustion engines. The methodology focused on gathering reliable technical data on fuel properties, production processes, costs, and environmental implications. Fuel property data primarily centered on viscosity, density, flash point, and octane/cetane rating. Production energy requirements, capital costs, operational costs, and renewable energy costs for e-fuels and biofuels were documented from governmental and industry sources.

Literature was gathered from multiple databases and sources to ensure comprehensive coverage. Google Scholar was used for broader academic resources on renewable fuel technology, while PubMed was used for chemical and technical data on molecular characteristics. Industry reports from companies such as Aramco and Shell Company provided statistics on fuel properties, production capacity, and energy consumption. Government sources on environment and transportation were used to assess and project future effects of e-fuels, biofuels, and e/biofuel blends on the atmosphere and economy.

Sources were limited to those published from 2016 onward to evaluate the current state of the biofuel and e-fuel industries, which are constantly evolving due to infrastructural expansion and increased investment. This temporal focus was also essential for understanding the current fuel standards and engine compatibility requirements. However, earlier sources were included selectively to establish foundational knowledge on fuel property limits. Credible sources included peer-reviewed articles with empirical data on fuel properties, production processes, or costs, government reports and statistics from authoritative agencies, and industry data with verifiable claims. Sources with insufficient statistical merit, unsupported by a peer-review process, or lacking methodological transparency were deemed unreliable for the purposes of this article.

While this article provides a comprehensive foundation for assessing e/biofuel viability, several factors limited the scope of analysis. Economic calculations for e-fuel and biofuel production may lose validity over time due to fluctuating costs of renewable energy, unpredictable technological advancements, the uncertainty of investment levels, and policy changes. Furthermore, the rapidly evolving nature of the alternative fuel sector may advance beyond the scope of currently available literature. Thus, the figures presented are subject to change and should be interpreted as estimates rather than definite projections.

Despite these limitations, the methodology applied provides an accurate assessment of the technical feasibility, economic viability, and environmental implications of e/biofuel blends as carbon-neutral alternatives to fossil fuels.

3. COMPARING MOLECULAR PROPERTIES OF E-FUELS AND BIOFUELS

3.1 E-fuel and biofuel properties

The most prominent biofuel blends for automobiles are E10, E15, E85, B2, B5, and B20.[17]

Fuel	**Ethanol content**	Fuel	**Biodiesel content**
E10	10% (blended with gasoline)	B2	2% (blended with diesel)
E15	10.5%-15% (blended with gasoline	B5	5% (blended with diesel)
E85	51%-83% (blended with gasoline)	B20	20% (blended with diesel)

Table 1. Biofuel/fossil fuel blend proportions of commonly produced biofuel blends. Data from ref. 17.

Given the structure of their hydrocarbon chains, the chemical composition of e-fuels is identical to that of fossil fuels. Because of this, both conventional and e-diesel, and conventional and e gasoline have the same physical properties, as shown in table 2, and are therefore both compatible in internal combustion engines.

However, the introduction of biofuels must be limited, as the hydrocarbons produced via biofuel processes have different properties from those of fossil fuels and e-fuels. Thus, high concentrations of biofuels may cause properties to deviate beyond regulatory limits of viscosity, flash point, density, and octane/cetane rating. For example, bioethanol, which is chemically identical to ethanol,[10] does not share physical properties with e-gasoline and gasoline, as shown in table 2, and therefore does not function independently in internal combustion engines.

	E-diesel	**E-gasoline**	**Bioethanol**	**Biodiesel**
Viscosity at 40ºC (cSt)	1.9-3.8[18]	0.69-0.72[21]	1.525[25]	3.6-5.0[18]
Density g/mL	0.834[19]	0.736[17]	0.789[25]	0.845[28]
Flash point (ºC)	57[19]	-45[23]	13[26]	55[14]
Cetane/Octane rating	49[19]	84[24]	110[27]	70.6[19]
Energy density (Btu/gal)	138,700[20]	125,000[20]	76,330[27]	136,339[29]

Table 2. Properties of various e-fuels and biofuels.

3.2 Analysis of blend limits

Using the data above, the change in the parameter of interest was calculated as more biofuel is added to e/biofuel blends. Blend limits were then determined based on the viscosity, density, flash point, and cetane rating of blends, and where numbers fell within acceptable ranges. Approximations assume ideal linear mixing behavior. While this evaluation approach simplifies actual blending behavior, it serves as a suitable method for first-order analysis.

Ethanol is most commonly blended with gasoline for automotive internal combustion engines.[17] Although pure ethanol has the potential to function independently in internal combustion engines, various factors hinder its efficiency.[30] Therefore, if ethanol levels affect crucial fuel properties, engine modifications would be necessary to enhance fuel performance.[31] Viscosity levels that exceed parameters hinder atomization, as the thicker fuel cannot separate into fine droplets, thus preventing complete combustion.[11] Gasoline functions with a viscosity of 1 centistoke (cSt) or below.[21] As shown in Figure 2, ethanol, with a viscosity of 1.525 cSt, can be blended with e-gasoline in ratios up to 35%, with a viscosity of 0.99 cSt.

Furthermore, gasoline density that exceeds the upper limit contains more heavy hydrocarbons, which can lead to incomplete vaporization and poor combustion.[33] A gasoline density that falls below the lower limit may vaporize too rapidly, causing vapor lock, which disrupts fuel delivery.[34] The limits for the density of unleaded petrol are 0.720-0.775 g/mL.[35] Therefore, ethanol, with a density of 0.789 g/mL, should be blended in amounts that keep the overall density within the range to ensure performance in automotive internal combustion engines. A 75% ethanol-e-biofuel gasoline blend, with a density of 0.776 g/mL, is the upper limit for ethanol proportions. Although higher ethanol levels may function in engines, heavy hydrocarbons and poor combustion may significantly impact the efficiency of higher ethanol content fuels.

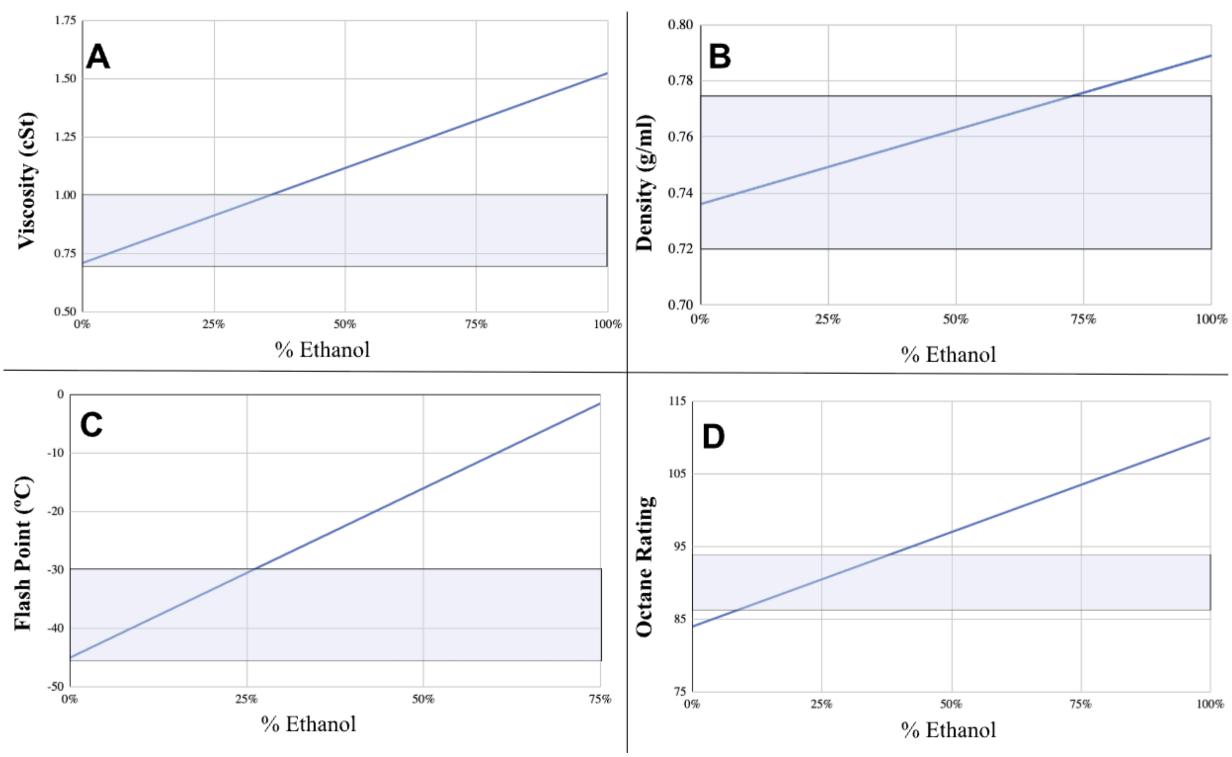

Figure 2. Mixing plot of an ethanol/e-gasoline blend measuring various properties, with the blue box representing the property range necessary to function in an unmodified internal combustion engine. A) Relationship between viscosity and percent ethanol content. B) Relationship between density and percent ethanol content. C) Relationship between flash point and percent ethanol content. D) Relationship between octane rating and percent ethanol content.

The flash point of gasoline must remain below -30ºC for proper ignition.[32] A flash point above this limit requires a higher temperature to ignite. Gasoline's flash point is very low, as the fuel needs to vaporize easily and ignite quickly in cold climates. The flash point of ethanol is 13ºC, while the flash point of e-gasoline is -45ºC. An ethanol/e-gasoline ratio of around 25%, -30.5ºC is the upper limit for ethanol proportions to function in a standard ignition engine without modifications.

Another crucial property of gasoline is octane. The lowest octane fuel sold in the U.S. has an octane rating of 87, while the highest has an octane rating of 94.[36] Gasoline is typically blended with ethanol to achieve higher octane ratings.[10] Higher octane ratings indicate higher resistance to heat and pressure without self-igniting.[37] Pure ethanol's high octane rating requires more energy to ignite, and is therefore incompatible with unmodified ignition engines. 10% ethanol content is the lower limit for an e-gasoline/ethanol ratio, with an octane rating of roughly 86.6, while a 40% ethanol ratio is the upper limit, with an octane rating of approximately 94.4.

Ethanol and e-gasoline's vast discrepancy in flash point is the limiting factor in how much ethanol can be blended while maintaining the fuel's efficiency and properties. Therefore, ethanol should be blended with e-gasoline to produce a maximum of 25% ethanol content blend to ensure function in internal combustion engines.

Progress in the biofuels industry has led to the development of biodiesel. Esters from vegetable oils are processed using transesterification to produce biodiesel, which does not function independently in compression ignition engines, mainly due to its high viscosity, which inhibits atomization.[38]

Biodiesel has a viscosity of 3.6-5.0 centistokes,[18] exceeding e-diesel's 1.9-3.8 cSt viscosity rating. Based on the average viscosity of biodiesel and e-diesel, 65% biodiesel in an e-biodiesel blend is the highest biodiesel ratio that complies with requirements, with a viscosity of 3.8 cSt.

The maximum density for e-diesel in compression ignition engines is 0.845 g/mL,[39] while biodiesel and e-diesel have densities of 0.880 g/mL and 0.834 g/mL, respectively.[19] Thus, the maximum biodiesel ratio in an e/biodiesel blend is 25%, with a density of 0.845 g/mL.

E-diesel's minimum flash point is 55ºC,[19] whereas biodiesel has a flash point of 76ºC.[19] Therefore, any amount of biodiesel can be blended with e-diesel, given the parameters of flash point.

Similarly, biodiesel can be blended in any amount, considering cetane rating. For instance, as of May 2025, E-diesel carries a minimum cetane rating of 49,[19] while biodiesel offers a much higher rating of 70.6,[19] which can improve combustion quality when blended.

The limiting factor in biodiesel's blending capacity is its high density. Therefore, biodiesel should be blended with e-diesel to produce a maximum of 25% biodiesel content fuel to maintain functionality in compression ignition engines.

4. ENERGY AND COST COMPARISONS

4.1 Production energy and cost requirements

The cost to produce one gallon of e-fuel using onshore wind power is $6.89,[33, 34] while the cost to produce one gallon of bioethanol is $1.88,[41] and biodiesel $2.81.[42] Conversely, the cost to produce gasoline derived from fossil fuels is $1.98,[41] and the cost to produce diesel derived from fossil fuels is $2.04.[43, 44] According to these numbers, ethanol is 5.05% cheaper than gasoline, while e-fuels are 249% more expensive than gasoline and 238% more expensive than diesel, and biodiesel is 37.8% more expensive than diesel.

Bioethanol	**Production cost per gallon (USD)**	**Cost compared to fossil fuel gasoline ($1.98)**	**Cost compared to fossil fuel diesel ($2.04)**
Bioethanol	1.88[41]	-5.05%	N/A
E-fuel (using onshore wind power)	6.89[33, 34]	+249%	+238%
Biodiesel	2.81[42]	N/A	+37.8%

Table 3. Cost comparison of bioethanol, e-fuel, and biodiesel against fossil fuel gasoline and fossil fuel diesel.

Though ethanol appears nominally cheaper than gasoline, ethanol contains 30% less energy than gasoline; therefore, this valuation may be misleading.[45] Additionally, these are merely the continual costs of producing fuels, as production requires initial capital investment to construct plants. The cost of constructing an e-fuel plant is roughly $1.67 billion ($1.26 billion in 2016, Consumer Price Index (CPI) increase of 74.4),[46] with an annual operating cost of $122 million ($91.7 million in 2016, CPI increase of 74.4).[47, 48] The median capital cost of a corn-to-ethanol plant with a capacity of 189 kt/yr is $191 million ($143 million in 2016, CPI increase of 74.4),[49] and the median capital cost of a biodiesel plant with a capacity of 200 kt/year is $124 million ($93 million in 2016, CPI increase of 74.4).[49]

The main reason for e-fuel's exorbitant price is the energy needed to extract H2 via electrolysis, carry out carbon capture, and synthesize hydrocarbon chains. In total these processes require 205.684 kWh to produce one gallon of e-fuel.

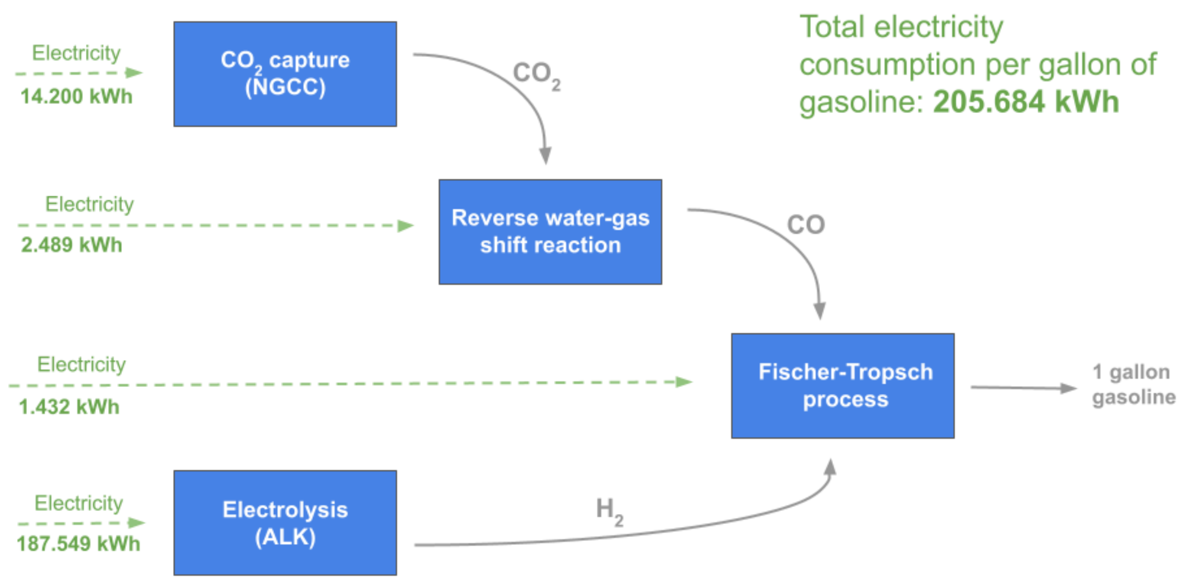

Figure 3. Production pathway and energy consumption of e-fuel via the Fischer-Tropsch process. Data from ref. 40.

Another factor in the high energy consumption of e-fuels is their low energy efficiency. E-fuels have an energy efficiency rate of 37.9%.[40] These losses are due to energy inefficiency during electrolysis, CO2 capture, and the Fischer-Trospch process.[8, 50] Therefore, much more energy is required to produce e-fuels. However, the monetary and energy costs of e-fuels have the potential to decrease as methods and technologies improve the energy efficiency of e-fuel production.

It is important to note that future cost and efficiency projections are subject to significant uncertainty, as these figures rely on technological advancements, economies of scale, and renewable energy costs that are challenging to accurately predict. For example, breakthroughs in electrolysis efficiency or carbon capture technologies could substantially reduce e-fuel production costs, while renewable energy prices may fluctuate based on market conditions and governmental policy. Additionally, sensitivity analysis using different economic conditions could aid future assessments, though the qualitative figures discussed here provide a reliable framework for understanding the relative cost and energy requirements of bioethanol, biodiesel, and e-fuel.

4.2 Production capacity of e/biofuels using renewable energy

To ensure true carbon neutrality in production, fuels must be produced using sustainable energy sources, such as wind and solar. The U.S. uses 376 million gallons of gasoline daily, or 137 billion gallons annually.[51] Additionally, the U.S. consumes roughly 125 million gallons of diesel daily, or 45.6 billion gallons of diesel annually.[52] Cumulatively, America consumes around 183 billion gallons of gasoline and diesel annually. Based on the statistics above, the energy required to produce 183 billion gallons of e-fuel would be 37.6 trillion kWh.

Using onshore wind energy, the cheapest sustainable energy source at 3.3 cents/kWh,[53] to produce 183 billion gallons of e-fuel would cost $124 trillion. However, the amount of energy required to produce e-fuels is projected to drop to 121 kWh/g, or $4.00 per gallon, by 2050,[54] which would bring the annual cost to supply America's fuel needs down to $73.1 trillion.

However, the production possibility of e-fuels is contingent upon how much energy America’s renewable energy sector can sustain. Currently, America produces 2.58 trillion kWh of renewable energy annually.[55] If the renewable energy grid were used at full capacity, 12.5 billion gallons of e-fuels could be produced annually, 6.85% of America’s annual fuel needs.

Given current capacity, the U.S. cannot make an e/biofuel blend that could fully replace conventional fossil fuels. However, e-fuel and biofuel infrastructure are continuing to grow, while labs develop means of decreasing the energy consumption of production. By 2040, U.S. commercial e-fuel plants are projected to produce 4.7 billion to 27.5 billion gallons annually.[56]

The upper end of this figure exceeds the energy usage at which renewable energy infrastructure can be sustained. Therefore, energy consumption, rather than e-fuel infrastructure, will likely be the limiting factor in e-fuel production.

Even so, the prospect that all renewable energy would be channeled into the production of sustainable fuels is highly implausible. Therefore, because the above-mentioned capacity for e fuel production is currently unfeasible, e-fuels must be blended with biofuels to alleviate the energy and monetary cost of the synthetic fuel and increase its commercialization factor to produce enough fuel to meaningfully contribute to the withdrawal from fossil fuels.

Blending with biofuels would allow for the commercial use of e-fuels without exceeding America’s renewable energy capacity. In keeping with the biofuel capacities in e-biofuel blends described in section 2, bioethanol should be blended with e-gasoline to produce a maximum of 25% ethanol content fuel, while biodiesel should be blended with e-diesel to produce a maximum of 25% biodiesel content fuel.

The production of 1 gallon of bioethanol requires 15.76 kWh of energy input.[57] Therefore, according to calculations, 1 gallon of an e-gasoline/ethanol blend with a 25% ethanol content would require 158.203 kWh to produce, compared to the 206 kWh/gal required for e-gasoline alone.[40] 28.9 trillion kWh of energy would be necessary to fulfill America's fuel needs for one year, totaling $95.4 trillion, lowering the cost and energy usage by 23.1% compared to pure e-fuel. The production of 1 gallon of biodiesel requires 16.528 kWh to produce.[58] Therefore, producing 1 gallon of an e-diesel/biodiesel mix with a 25% biodiesel concentration would require 158.395 kWh, lowering cost and energy usage by 23.0%. With these blends, the renewable energy grid could sustain 16.3 billion gallons of e-gasoline/ethanol or 16.3 billion gallons of e-diesel/biodiesel, supplying 8.89% of America's annual diesel and gasoline needs. While this would still be considerably less than the amount needed to fully replace fossil fuels, it would act as a valuable carbon-neutral intermediary as society transitions to new methods of energy storage and transportation.

5. CHALLENGES AND ADVANTAGES

Though e/biofuels show promise for their molecular compatibility with internal combustion engines, the fuels face a slew of hurdles that impact their potential for implementation on a macro scale.

As referenced previously, considerable hurdles in the production of biofuels include the acquisition of land and resources for crop production, and the steep capital costs of equipment to pre-treat lignin and cellulose and produce microalgal bioreactors.[12, 14] However, significant biofuel infrastructure already exists, with most fuels sold in America containing at least 10% ethanol.[59] Therefore, the primary factor limiting the possibility of e/biofuels is e-fuel infrastructure.

As demonstrated above, the energy and cost requirements and the capital cost of producing e-fuels and biofuels are incredibly steep. With today's infrastructure centered around fossil fuels, conventional diesel and gasoline are more economical and commonplace, with price valued over environmental effects. A transition to e/biofuels would require heavy investment in renewable energy systems, diverting resources to constructing electrofuel and biofuel plants and sustainable fuel production. The high costs and inefficiencies of producing e/biofuel compared to other carbon-neutral sources, like electric power, suggest that e/biofuels may be a less effective use of limited decarbonization capital, even if they benefit existing fossil-fuel consuming vehicles.

The limited capacity of America's renewable energy grid also restricts e-fuels' scalability, which, by extension, limits the production capacity of an e/biofuel blend. As discussed in section 3, the entirety of America's renewable energy would only be able to supply enough e-fuel for 6.85% of annual gasoline and diesel usage. Therefore, with current infrastructure, e-fuels do not appear to be close to being able to sustain the commercialization of e/biofuels. However, e-fuel and renewable energy infrastructure are currently scaling, with 45 new plants projected to open in Europe alone,[60] and the American renewable energy grid projected to have the capacity to supply 44% of overall energy needs by 2050.[61] However, the timeline for e-fuel expansion notably falls behind the immediate need for emissions reductions. Scaling e-fuel production to impactful levels will require decades of investment and construction. This timing disparity suggests that e/biofuels may, in the short-term, be better suited as targeted solutions for sectors with limited electrification alternatives, like aviation and maritime shipping, rather than as a primary strategy for decarbonizing the broader transportation sector.

E-gasoline/bioethanol and e-diesel/biodiesel blends lower the cost and energy usage by 23.08% and 23.01%, respectively, from pure e-fuels. These cheaper production costs enable increased production capacity and consumer accessibility. Furthermore, if blended with biofuels, less e-fuel production would be necessary to produce the same amount of fuel. Therefore, less e-fuel infrastructure would be required to commercialize the fuel, enabling imminent e-fuel incorporation into the transportation sector. Since e-fuel infrastructure currently lags behind that of biofuels and needs more time to expand, e/biofuel blends would incentivize plant construction as e-fuels could be used without fully developed infrastructure, and actual implementation increases the incentive for e-fuel investment, allowing infrastructure to expand further. Biofuel plants would need to maintain current production levels, as they produce enough to fulfill gasoline and diesel blending requirements, which are similar to the upper-limit blending ratios of e/biofuels. Though biofuel blending decreases fuel costs, biomass production competes with food crops for agricultural resources. Therefore, large-scale biofuel production can be socially irresponsible and unsustainable, particularly in regions facing food insecurity.

A promising means of increasing the efficiency of e-fuel production is combining the process of producing biofuels with that of producing e-fuels. Bioreactors, used to ferment microorganisms to produce biofuels, yield CO_2 as a byproduct. CO_2 captured as a byproduct can be used to produce e-fuels via the Fischer-Tropsch process.[62] Additionally, combining these processes can boost power output by 50% to 100%, allowing for the production of more usable fuel.[62] Combining the processes further decreases the energy and cost input of producing e-fuels, as plants rely less on carbon capture, which consumes a significant amount of energy per ton, streamlining the production of e/biofuels. However, this integration creates a dependency on reliable biofuel production. If biofuel production faces crop failures or land-use constraints, then e-fuel production at integrated facilities would be similarly disrupted, creating supply-chain liabilities that would not exist at standalone facilities.

This combination of processes also aids the carbon-neutrality of e/biofuels, as the vast majority of ethanol biorefineries release CO2 byproduct into the atmosphere, with only 40 of America's 192 operating ethanol plants having the capacity to capture CO2 and supply it to a nearby processing partner.[63, 64] This method is sparsely implemented despite the evident benefits of combining e-fuel and biofuel production processes. Therefore, increased connectivity between sustainable fuel plants is necessary to create true carbon neutrality in the transportation sector.

E/biofuels provide a more accessible, truly carbon-neutral fuel. Though e/biofuels increase the commercial viability of sustainable fuel options, their cost remains significantly higher than fossil fuels, requiring further advancements and infrastructure expansion, particularly in e-fuel production, to achieve competitive prices. Much like how biofuels gained ubiquity, commercial competitiveness would further rely upon government subsidies, policy support, and private investment in the e-fuel industry.[65] One way governments could incentivize the use of e/biofuels and make them more economically viable would be to include the environmental costs and property damage costs from climate change-induced phenomena into fossil fuel prices.

6. CONCLUSION

Despite global efforts to decrease the rate of carbon emissions and global warming, climate threats remain prevalent, as many governments fail to uphold pledges to adopt carbon-neutral infrastructure. With a large portion of carbon emissions coming from the transportation sector, a carbon-neutral alternative to fossil fuels is imperative to achieving climate change goals. E-fuels present a promising solution. However, the commercialization factor of such fuels is greatly diminished compared to fossil fuels, and is, therefore, widely regarded as an unviable, inaccessible alternative to fossil fuels. Though capital and input costs for producing e-fuels are currently high, blending e-fuels with biofuels maintains the carbon-neutral integrity of e-fuels while lowering costs. While biofuels are cheaper, carbon-neutral fuel alternatives, they do not function independently in combustion and ignition engines without modification and must be supplemented with other fuels.

Despite the limitations of fuel blending, mixing biofuels with e-fuels can decrease cost and energy consumption by roughly 23%. Given the current capacity of America's renewable energy grid, e/biofuels could sustain 8.89% of the country's diesel and gasoline consumption while maintaining carbon neutrality. Provided the insufficient state of current e-fuel infrastructure, this figure is not currently achievable, but plausible in the future as e-fuel technology develops and infrastructure expands. Mixing e-fuels with biofuels would also allow for a broad rollout of e fuels in the near future, converting the fuels from a lab-focused hypothetical to a reality, as less infrastructure could supply the same fuel demands. E/biofuel production can be further streamlined by using the CO2 byproduct from biofuel bioreactors in the Fischer-Tropsch process to produce hydrocarbon chains used in e-fuels. Combining the processes would doubly preserve the carbon-neutral integrity of e/biofuels.

Future work should focus on physical experimentation of mixing limits to validate blend property calculations and engine tolerance under varying climate conditions. Sensitivity analysis and economic modeling of production and market feasibility under different policy scenarios are also necessary to determine the possible scale of e/biofuel implementation. Alleviating the economic and environmental impact of biofuels by improving the energy efficiency of microalgal biofuel production or investigating alternative feedstocks may address sustainability concerns associated with first-generation biofuels and increase e/biofuel viability. More efficient electrolysis and carbon capture technologies could substantially reduce the energy intensity of e-fuel production, bringing costs closer to fossil fuel parity. Ultimately, these investigations, combined with strategic infrastructure investment, could enable widespread access to carbon-neutral fuel alternatives and represent a significant step towards decarbonizing the transportation sector.

REFERENCES

[1]Environmental Protection Agency. (2025, March 31). Greenhouse Gas Emissions from a Typical Passenger Vehicle. Retrieved May 6, 2025, from https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger vehicle
[2]Bureau of Transportation Statistics. (2021). National Transportation Statistics. Retrieved May 6, 2025, from https:// www.bts.gov/content/automobile-profile
[3]U.S. Energy Information Administration. (2025, April 30). U.S. Natural Gas Total Consumption. Retrieved May 6, 2025, from https://www.eia.gov/dnav/ng/hist/n9140us2a.htm
[4]Lindsey, R., & Dahlman, L. (2024, January 18). Climate Change: Global Temperature. Retrieved May 6, 2025, from https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperatu re
[5]National Oceanic and Atmospheric Administration. (2025, January 10). 2024 was the world's warmest year on record. Retrieved May 6, 2025, from https://www.noaa.gov/news/2024-was-worlds-warmest-year-on-record
[6]Ringle, E. (2023, March 30). New Consortium Advances Technologies That Use Renewable Electricity To Turn Carbon Dioxide Into Fuel. National Renewable Energy Laboratory. https://www.nrel.gov/news/detail/program/2023/ new-consortium-advances-technologies-that-use-renewable-energy-to-turn-carbon-dioxide-into -fuel [7]Dell'Aversano, S., Villante, C., Gallucci, K., Vanga, G., & Di Giuliano, A. (2024). E-fuels: a comprehensive review of the most promising technological alternatives towards an energy transition. *Energies*, *17*(16), 3995. https:// www.mdpi.com/1996-1073/17/16/3995
[8]International Energy Agency. (2023, December). The Role of E-fuels in Decarbonising Transport. https://www.iea.org/reports/the-role-of-e-fuels-in-decarbonising-transport
[9]Love, J. (2022). Microbial pathways for advanced biofuel production. *Biochemical Society*

Transactions, *50*(2), 987-1001. https://pmc.ncbi.nlm.nih.gov/articles/PMC9162456/
[10]Alternative Fuels Data Center. (n.d.). Ethanol Fuel Basics.
https://afdc.energy.gov/fuels/ethanol-fuel-basic [11]Krause, P., & Labuda, R. (2018). The influence of liquid viscosity on atomized fuel mean droplet size determined by the laser diffraction method. *New Trends in Production Engineering*, *1*(1), 435-441. https://www.researchgate.net/publication/329421439_The_Influence_of_Liquid_Viscosity_on_Atomized_Fuel_Mean_Droplet_Size_Determined_by_the_Las er_Diffraction_Method
[12]Jeswani, H. K., Chilvers, A., & Azapagic, A. (2020). Environmental sustainability of biofuels: a review. *Proceedings of the Royal Society a*, *476*(2243), 20200351.
https://pmc.ncbi.nlm.nih.gov/articles/PMC7735313/ [13]Igwebuike, C. M., Awad, S., & Andrès, Y. (2024). Renewable energy potential: Second-generation biomass as feedstock for bioethanol production. *Molecules*, *29*(7), 1619. https://www.mdpi.com/1420-3049/29/7/1619 [14]Losordo, Z., McBride, J., Van Rooyen, J., Wenger, K., Willies, D., Froehlich, A., ... & Lynd, L. (2016). *Cost competitive second-generation ethanol production from hemicellulose in a Brazilian sugarcane biorefinery. Biofuels, Bioproducts and Biorefining 10: 589–602*.
https://scijournals.onlinelibrary.wiley.com/doi/full/10.1002/bbb.1663
[15]D'Adamo, I., Gastaldi, M., Giannini, M., & Nizami, A. S. (2024). Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen. *Environmental Research*, *246*, 118163.
https://www.sciencedirect.com/science/article/pii/S0013935124000677
[16]Gray, N., O'Shea, R., Smyth, B., Lens, P. N., & Murphy, J. D. (2022). What is the energy balance of electrofuels produced through power-to-fuel integration with biogas facilities?. *Renewable and Sustainable Energy Reviews*, *155*, 111886.
https://www.sciencedirect.com/science/article/pii/S1364032121011539
[17]Alternative Fuels Data Center. (n.d.). Fuel Blends. https://afdc.energy.gov/fuels/blend
[18]Verduzco, L. F. R. (2013). Density and viscosity of biodiesel as a function of temperature: Empirical models. *Renewable and Sustainable Energy Reviews*, *19*, 652-665.
https://www.sciencedirect.com/science/article/abs/pii/ S1364032112006338
[19]Guo, S., Yang, Z., & Gao, Y. (2016). Effect of adding biodiesel to diesel on the physical and chemical properties and engine performance of fuel blends. *Journal of Biobased Materials and Bioenergy*, *10*(1), 34-43. https:// www.researchgate.net/publication/307547973_Effect_of_Adding_Biodiesel_to_Diesel_on_the_Physical_and_Chemical_Properties_and_Engine_Performance_of_Fuel_Blends
[20]Bureau of Transportation Statistics. (2022). Energy Consumption by Mode of Transportation. https://www.bts.gov/ content/energy-consumption-mode-transportation
[21]Taylor, R. I. (2021). Fuel-lubricant interactions: critical review of recent work. *Lubricants*, *9*(9), 92. https://www.researchgate.net/publication/353798491_Fuel-Lubricant_Interactions_Critical_Review_of_Recent_Work [22]Environmental Protection Agency. (2017, February). Density of EPAct Study Test Fuels vs Market Fuel. https://

www.epa.gov/sites/default/files/2017-02/documents/exhibit-h.pdf
[23]Al-Abdullah, M. H., Kalghatgi, G. T., & Babiker, H. (2015). Flash points and volatility characteristics of gasoline/ diesel blends. *Fuel*, *153*, 67-69. https://www.sciencedirect.com/science/article/abs/pii/S0016236115002239
[24]Oak Ridge National Laboratory. (2016, July). Summary of High-Octane, Mid-Level Ethanol Blends Study. https:// info.ornl.gov/sites/publications/files/pub61169.pdf
[25]Muhaji, & Sutjahjo, D. H. (2018, January). The characteristics of bioethanol fuel made of vegetable raw materials. In *IOP Conference Series: Materials Science and Engineering* (Vol. 296, p. 012019). IOP Publishing. https:// iopscience.iop.org/article/10.1088/1757-899X/296/1/012019/pdf
[26]National Fire Protection Association. (2010). Fire Protection Guide to Hazardous Materials (14th ed.). [27]Alternative Fuels Data Center. (n.d.). Fuel Properties Comparison. https://afdc.energy.gov/fuels/properties [28]European Committee for Standardization. (2022). *EN 590:2022 – Automotive fuels – Diesel – Requirements and test methods*. https://dieselnet.com/standards/eu/fuel_automotive.php
[29]Ozsoz, M., Ibrahim, A. U., & Coston, P. P. (2019). Application of CRISPR technology for the generation of biofuels: a review. *J Fundam Renewable Energy Appl*, *9*(278), 2. https://www.researchgate.net/profile/Assoc-Prof-Dr-Abdullahi-Ibrahim/publication/342000174_Journal_of_Fundamentals_of_Renewable_Energy_and_Applications/links/5edde5ff92851c9c5e8fa87b/ Journal-of-Fundamentals-of-Renewable-Energy-and-Applications.pdf
[30]Alternative Fuel Data Center. (n.d.). Ethanol Benefits and Considerations. https://afdc.energy.gov/fuels/ethanol benefits
[31]Poudel, S., & Deb, D. (2017). Study of Modified Internal Combustion Engine to Run with Ethanol. *International Journal of Engineering and Applied Sciences*, *4*(8), 257403. https://www.researchgate.net/profile/Sajag-Poudel/publication/320736411_Study_of_Modified_Internal_Combustion_Engine_to_Run_with_%27Ethanol%27/links/5c5cabe6299bf1d14cb348ed/Study-of-Modified-Internal-Combustion-Engine-to-Run-with-Ethanol.pdf
[32]Shell Company LP. (2024, March 25). Safety Data Sheet According to OSHA Hazard Communication Standard, 29 CFR 1910.1200. https://msdsstorageaccount.z13.web.core.windows.net/SDS/000000000673_US_EN.pdf
[33]Tyagi, U., Aslam, M., & Sarma, A. K. (2023). Green Anti-knock Agents for Enhancement of Gasoline Performance. https://doi.org/10.1039/BK9781837670079-00238
[34]Bridgeman, O. C., & White, H. S. (1932). Automobile Fuel-System Design and Vapor Lock. *SAE Transactions*, 129-184. https://www.jstor.org/stable/44436651?casa_token=-1hNrrzy250AAAAA%3Aqy4yKeGuMFbtRdQ7pKvbTL9HwjbC5Q79WIMaBGPifzx8PzX1ySKHl4Is PJTJng-inbADhZclLAQ5Hwdt9zDf-39QKrUg7ARXfnxRf8pgEyVZ-thtoMcZ&seq=1
[35]European Committee for Standardization. (2017, November 1). EN 228 - Automotive Fuels - Unleaded Petrol - Requirements and Test Methods.

https://cdn.standards.iteh.ai/samples/64611/73418e35d0bd40e2a6fef14de63af10d/SIST-EN-228-2012-A1-2017.pdf
[36]U.S. Energy Information Administration. (n.d.). Gasoline explained. https://www.eia.gov/energyexplained/ gasoline/octane-in-depth.php
[37]Heywood, J. (2018). Internal combustion engine fundamentals.
[38]Pinto, A. C., Guarieiro, L. L., Rezende, M. J., Ribeiro, N. M., Torres, E. A., Lopes, W. A., ... & Andrade, J. B. D. (2005). Biodiesel: an overview. *Journal of the Brazilian Chemical Society*, *16*, 1313-1330. https://www.scielo.br/j/ jbchs/a/XjvNVsBFJgJH3cbRvCJDdBS
[39]Hira, A., & Krishnan, P. (2024). The macro view of solar policy: The case for supporting utility-scale power. *Solar Compass*, *12*, 100096. https://www.sciencedirect.com/science/article/pii/S2772940024000304
[40]Soler, A., Dekeyser, J., Ramasary, A., Gordillo, V., Lilley, W., Schmidt, P., Weindorf, W., Raksha, T., Failer, S., Astono, Y., Houghton, T., Dell'Orco, S., & Armann Feroz. (2024, March). E-Fuels: A technoeconomic assessment of European domestic production and imports towards 2050 – Update. Concawe. https://www.efuel-alliance.eu/ fileadmin/Downloads/Rpt_24-4-1.pdf
[41]U.S. Grains Council. (2025, January 22). Ethanol Market and Pricing Data – January 22, 2025. https://grains.org/ ethanol_report/ethanol-market-and-pricing-data-january-22-2025/
[42]Iowa State University Central for Agriculture and Rural Development. (2025, January). Historical Biofuel Operating Margins. https://www.card.iastate.edu/tools/operating-margins/?b=biodiesel
[43]Statista Research Department. (2025, May 2). Distribution of diesel fuel prices in the United States in select months from 2020 to 2025, by cost component. https://www.statista.com/statistics/653066/breakdown-of-the-united states-diesel-price-by-expense/
[44]U.S. Energy Information Administration. (2025, May 6). Gasoline and Diesel Fuel Update. https://www.eia.gov/ petroleum/gasdiesel/
[45]Lynch, M. (2022, June 6). Though Ethanol Might Appear 'Cheaper' Than Gasoline, Let's Do The Math On Energy Content. Forbes. https://www.forbes.com/sites/michaellynch/2022/06/06/ethanol-is-cheaper-than-gasoline-well-5 -of the-time/
[46]Federal Reserve Bank of Minneapolis. (2024). Consumer Price Index, 1913-. https://www.minneapolisfed.org/ about-us/monetary-policy/inflation-calculator/consumer-price-index-1913-
[47]Penev, M. (2020). *Techno-Economic Modelling with H2A and H2FAST* (No. NREL/PR-5400-75588). National Renewable Energy Lab.(NREL), Golden, CO (United States). https://www.osti.gov/biblio/1604304
[48]Delgado, H. E., Cappello, V., Zang, G., Sun, P., Ng, C., Vyawahare, P., ... & Marcinkoski, J. (2023). Techno economic analysis and life cycle analysis of e-fuel production using nuclear energy. *Journal of CO2 Utilization*, *72*, 102481. https://www.sciencedirect.com/science/article/pii/S2212982023000926#tbl0005

[49]Tsagkari, M., Couturier, J. L., Kokossis, A., & Dubois, J. L. (2016). Early‐stage capital cost estimation of biorefinery processes: a comparative study of heuristic techniques. *ChemSusChem*, *9*(17), 2284-2297. https:// pmc.ncbi.nlm.nih.gov/articles/PMC5129486/
[50]Ellis, T., Gerrish, R., & Michel, G. (2024, March 25). E-fuels: A Challenging Journey To A Low-Carbon Future. S&P Global Ratings. https://www.spglobal.com/_assets/documents/ratings/research/101595057.pdf
[51]U.S. Energy Information Administration. (2025, April 30). U.S. Product Simplified of Finshed Motor Gasoline. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mgfupus2&f=a
[52]U.S. Energy Information Agency. (2023, September 14). Diesel fuel explained. https://www.eia.gov/ energyexplained/diesel-fuel/use-of-diesel.php
[53]Hira, A., & Krishnan, P. (2024). The macro view of solar policy: The case for supporting utility-scale power. *Solar Compass*, *12*, 100096. https://www.sciencedirect.com/science/article/pii/S2772940024000304
[54]Zhou, Y., Searle, S., & Pavlenko, N. (2022). Current and future cost of e-kerosene in the United States and Europe. *I: International council on clean transportation Working paper*, *14*. https://theicct.org/publication/fuels-us-eu-cost ekerosene-mar22/
[55]U.S. Energy Information Administration. (2025, April 24). Monthly Energy Review April 2025. https:// www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf
[56]Transport Energy Institute. (2024, November 19). E-fuels: Evaluating the Viability of Commercially Deploying E fuels in Road Transport. https://www.transportationenergy.org/research/reports/e-fuels-evaluating-the-viability-of commercially-deploying-e-fuels-in-road-transport/
[57]Chapin, B. (2010, September 21). USDA Report Shows Improving Corn-Ethanol Energy Efficiency. U.S. Department of Agriculture. https://www.usda.gov/about-usda/news/blog/usda-report-shows-improving-corn-ethanol energy-efficiency
[58]Institute for Local Self-Reliance. (1994). How Much Energy Does It Take to Make a Gallon of Soydiesel?. https:// afdc.energy.gov/files/pdfs/3229.pdf
[59]Anderson, J. E., DiCicco, D. M., Ginder, J. M., Kramer, U., Leone, T. G., Raney-Pablo, H. E., & Wallington, T. J. (2012). High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States. *Fuel*, *97*, 585-594.
[60]Transport and Environment. (2024, January 24). E-fuels for planes: with 45 projects, is the EU on track to meet its targets? https://www.transportenvironment.org/articles/e-fuels-for-planes-with-45-projects-is-the-eu-on-track-to meet-its-targets
[61]U.S. Energy Information Administration. (2022, March 18). EIA projects that renewable generation will supply 44% of U.S. electricity by 2050. https://www.eia.gov/todayinenergy/detail.php?id=51698#
[62]Gray, N., O'Shea, R., Smyth, B., Lens, P. N., & Murphy, J. D. (2022). What is the energy balance of electrofuels produced through power-to-fuel integration with biogas facilities?.

Renewable and Sustainable Energy Reviews, *155*, 111886.
https://www.sciencedirect.com/science/article/pii/S1364032121011539
[63]Hossain, T., Burli, P., Pin, J., Jones, D., Hartley, D., & Hess, R. (2023, January). Deployment of BECCUS value chains in the United States: A case study of sequestering CO2 from ethanol production. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2023/03/BECCUS-1.0_US-Case-Study_final_update.pdf
[64]Bryan, T. (2024, October 11). The CO2 Report. Ethanol Producer Magazine. https://ethanolproducer.com/articles/ the-co2-report
https://www.sciencedirect.com/science/article/abs/pii/S0016236112002268
[65]Kiran, B., Kumar, R., & Deshmukh, D. (2014). Perspectives of microalgal biofuels as a renewable source of energy. *Energy conversion and management*, *88*, 1228-1244. https://www.sciencedirect.com/science/article/abs/pii/S0196890414005470