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E-Fuels as Reduced Carbon Emission Options

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Synthetic "E-fuels," or electro-fuels, have been introduced as a potential reduced carbon emissions energy source for power generation and vehicle propulsion applications. Environmental change is needed, with the transportation sector alone producing approximately a quarter of global greenhouse gas (GHG) emissions. Hydrogen, produced from electrolysis to avoid GHG production, is used along with CO_2 or nitrogen to generate these electro-fuels, through the Fischer–Tropsch process. Direct air capture (DAC) of atmospheric carbon dioxide or biomass combustion effluents can provide sources for these gases to be combined with hydrogen to generate synthetic methanol, methane, or ammonia—the three most widely discussed E-fuels. In addition, "ER-fuels," or electrically reformed fuels, are a similar option to E-fuels, where refinery fuel gases, such as ethane or propane, are reformed before synthesis to produce the final fuel. E-fuels, on the other hand, are generated from hydrogen and carbon either captured or produced, not from existing fuels. Redox couples, such as vanadium, can additionally be used as zero emission fuels; they are "electrically rechargeable" in that, through electrolysis, the reducing agent is produced, and then using a fuel cell (FC), the reverse occurs, and electrons plus the oxidizing agent are produced. These synthetic fuels are approximately carbon neutral when the hydrogen is sourced from renewable powered electrolysis, mainly solar and wind energy, as the amount of carbon dioxide consumed is roughly equivalent to the amount produced upon their combustion or FC energy conversion. Combustion in gas turbines or reciprocating piston-cylinder engines and FC electricity generation are the two main uses for extracting energy from E-fuels. Fuel cells are shown to have higher efficiency, but combustion provides fewer infrastructure changes and easier implementation. Both options provide a method for controlling carbon emissions using E-fuels as opportunities for energy storage. [DOI: 10.1115/1.4065731]

Keywords: alternative energy sources, carbon neutral, clean energy, climate change, electrolyzers, energy, environment, fuel cells, fuel combustion, renewable energy

1 Introduction and Background

Increased greenhouse gas (GHG) emissions and rising temperatures have encouraged environmental policies across the globe. The Paris Agreement enforces a global temperature increase limit of 2 °C and a goal of zero emissions between 2050 and 2060 [1]. Achieving this goal requires worldwide reduction of carbon emissions. The transportation sector makes up over 22% of all GHG emissions and approximately 26% of the total global energy demand, thus requiring focus on reducing its energy consumption and carbon production [2]. There have been additional plans and agreements made by governments to expedite the reduction of emissions: the Europe 2030 Climate Package outlines a goal of reducing emissions by 40%, compared to 1990, and shifting to at least 27% renewable energy sources overall [3]. Additionally, the European Commission is targeting 6000 MW of electrolyzer electricity generation by just 2025, with additional increases in the years after [4]. Across the globe, nations are pushing for cleaner energy sources and reduced GHG emissions.

To focus on reducing the emissions from the transportation sector, fossil fuel consumption and combustion in automobile engines must be targeted. Synthetic "E-fuels" provide a promising option for potentially eliminating fossil fuel use in vehicles and reducing carbon emissions without the need for battery power. "E-fuels" are electro-fuels that are produced using a combination of hydrogen and another element, commonly carbon or nitrogen. Hydrogen is generated using water electrolysis, with energy sourced from intermittent renewable sources, such as wind or solar power. There are various types of electrolyzers that can perform this conversion: alkaline, polymer electrolyte membrane, and solid oxide. These have various properties, but all break water apart into hydrogen and oxygen, with an additional byproduct of thermal energy. This process can reach efficiencies of up to 80% and is the most common method for hydrogen production [3]. Additionally, there are multiple options for acquiring the carbon required for the fuel synthesis process. The main methods are referred to as post-combustion, pre-combustion, and oxyfuel combustion [5]. Post-combustion consists of separating the desired gas from the flue gas stream from power plants, whereas pre-combustion uses energy from a partial oxidation process to decompose fuel and produce syngas. Oxyfuel combustion uses the oxygen-fired combustion of fuel and captures the byproducts by condensing water

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Table 1 CCS methods [6]

CCS method	Post-combustion	Pre-combustion	Oxyfuel combustion
Technological maturity	Commercial	Commercial	Development
Applications	Commercial and industrial power plants	Natural gas power plants and processing	Some types of coal fuels
Advantages	Good for reconstruction of existing power plants that helps in consistent usage, more mature than other CCS technology	Low gas volume, high pressure, high CO_2 concentration, less energy intensive, easy CO_2 separation, relatively low water combustion	Uses pure O_2 (reduces nitrogen quantities), more sustainable and environmentally friendly, high efficiency, no chemical operation required, easy to capture
Disadvantages	Low CO_2 partial pressure in flue gas	High energy loss	Low net power output
Cost	Excessive system operation cost	High cost of integrated gasification combined cycle	Excessive cost of air separation system

in the exhaust stream. The advantages and disadvantages are outlined in Table 1.

These methods for providing the components of synthetic fuels lead to three main E-fuels: e-methane (CH_4), e-methanol (CH_3OH), and e-ammonia (NH_3) [6]. These fuels are produced using hydrogen, from electrolysis, and captured carbon (from carbon dioxide) or nitrogen, and their naturally occurring counterparts are often used in industry for fuel and in gas turbines. While these are the most well-known fuels that can be created synthetically, additional fuels are shown in Table 2, classified as carbon-, hydrocarbon-, oxygenate-, or hydrogen-based fuels. These fuels are not discussed in depth due to their significant disadvantages, such as high emissions or high cost. Similarly, "ER-fuels" or electrically reformed fuels are a form of E-fuel or synthetic fuel that is nearly identical to these fuels described above, but the process to produce them is slightly altered since the syngas used is reformed before producing the fuel [8].

To summarize the elements required to produce E-fuels, Fig. 1 illustrates the renewable energy that provides electricity for electrolysis and fuel synthesis, in addition to thermal energy, the electrolyzer that produces hydrogen gas, carbon capture and storage (CCS) that provides carbon, and finally, fuel combustion that can act as another source for carbon and thermal energy.

Additionally, synthetic fuels are all not from naturally occurring gases. Electrically rechargeable redox couples provide another source of energy in the form of an electro-fuel. These redox couples can be charged with an electrochemical energy conversion device, such as an electrolyzer, giving it stored electrical energy to be converted using a fuel cell [9]. The fuel cell reaction for the vanadium redox couple is given in Eq. (1):

$$V^{2+} + H^{+} + \frac{1}{4}O_2 \rightarrow V^{3+} + \frac{1}{2}H_2O \tag{1}$$

The standard electrical potential of this process is about 1.49 V, and the redox couple can be recharged using the reverse of the process, again using an electrolyzer. This fuel provides the potential for a completely electric E-fuel, with no combustion needed.

2 E-Fuel Properties

Each fuel has its own properties, as well as advantages that make it an alternative to traditional fuels. The most significant of their attributes is their efficiency in producing energy. The various efficiencies (Carnot, round-trip, and combined cycle) are compiled in Table 3 for hydrogen, methane, methanol, and ammonia. The Carnot efficiency represents the maximum theoretical efficiency for the use of the fuel in a heat engine, while the round-trip efficiency represents the ratio of energy output to energy input for energy storage purposes. The combined cycle efficiency represents when a gas and steam turbine are used together to produce electricity from fuel. All values are given in percent and represent the findings of literary research from *Advances in Applied Energy* [5].

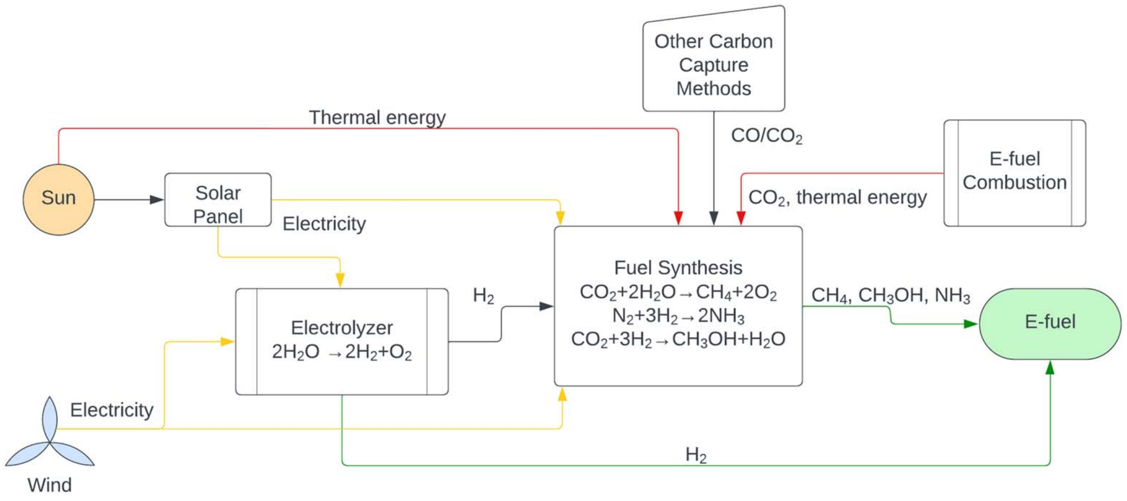
The adiabatic flame temperature values are taken from the methodology in *Theory of Aerospace Propulsion*, Sec. 4.15 [10]. For methane, the round-trip and combined cycle efficiencies, where exhaust gas produced is used to generate steam to produce electricity in a steam turbine, were found for a 571-MW combined cycle gas turbine from General Electric (type 9HA.02) [5]. These efficiencies for methanol, hydrogen, and ammonia were estimated based on the ratio of electrical efficiency of the Brayton cycle and the calculated ideal Carnot efficiency for methane. The ratio for methane was assumed to be equal to that of the gases. The formula for ideal Carnot efficiency is given below in Eq. (2). This study uses a T_c of 298 K and a T_H of the adiabatic temperature calculated of the gas flames, shown in the first row of Table 3.

$$\eta = 1 - T_c/T_H \tag{2}$$

Hydrogen has the highest Carnot and round-trip efficiencies, which would make it a great option for fuel, but is too reactive to be used in combustion engines; storage and transportation of hydrogen is difficult as well and would require major infrastructure changes to do so effectively [11]. However, methane has only slightly lower Carnot and round-trip efficiencies and has the highest combined cycle efficiency of the four fuels in Table 3. Methanol and ammonia have lower efficiencies than hydrogen

Table 2 Extensive list of common E-fuels, sorted by source element [7]

Carbon	Hydrocarbon	Oxygenate	Hydrogen
Coal	Natural gas	Methanol	Hydrogen
Biomass	Coal bed methane	Ethanol	
Oil residue	Landfill gas Coke oven gas Bottled gas Gasoline Diesel Aviation oil Fossil oil	Formic acid Acetic acid Dimethyl ether	



Outline of E-fuel production process

Fig. 1 Outline of the E-fuel production process

and methane in all categories, with ammonia being the lowest; still, the efficiencies of all four fuels do not vary greatly.

The fuels can also be combined into a mixture of multiple gases, which, at a desirable ratio, can be even more efficient. A mixture of ammonia, methane, and hydrogen gas, with around 5% hydrogen and a maximum of 15% ammonia, produces a fuel that has a lower normalized heat rate, referring to the thermal energy required to generate 1 kW of electricity, than individual fuels. With the addition of hydrogen to the mix, there is a lower production of carbon dioxide per mass of fuel. The hydrogen–methane combination also creates a higher temperature flame than methane flame when used for combustion [12]. Thus, this presents another option for the potential use of synthetic fuels.

Electrically rechargeable fuels, such as the vanadium redox couples discussed previously, also provide another viable option, with a charge efficiency of about 94% [5]. This can be done with any redox couple, but the process must be almost reversible, with minimal energy loss. This is a large tradeoff for energy density; elements with higher energy densities are not able to go through both the charging and discharging processes required. Additionally, this type of fuel cannot be used in traditional gas turbines or combustion engines, only in fuel cells, which greatly restricts its use in current vehicle infrastructure [9]. ER-fuels are yet another synthetic fuel option for reducing carbon emissions. As mentioned before, refinery fuel gas undergoes electrified reforming before being converted to synthetic fuels; according to research from Energy Conversion and Management, the ER-fuel process is more efficient than E-fuel production [8].

Figure 2 outlines the differences between the two processes. E-fuels use hydrogen generated from electrolysis and carbon dioxide captured, which are put through reverse water gas shift (RWGS), where H_2 and CO_2 are converted to H_2O and CO, as shown in Eq. (3):

$$H_2 + CO_2 \rightarrow H_2O + CO \tag{3}$$

Table 3 Efficiencies of hydrogen, methane, methanol, and ammonia [5]

Quantity	Hydrogen	Methane	Methanol	Ammonia
Adiabatic flame temperature (K)	2431	2246	2231	2084
Ideal Carnot efficiency (%)	88.00	86.59	84.40	83.89
Round-trip efficiency (%)	44.48	43.97	43.93	43.45
Combined cycle efficiency (%)	64.10	64.85	64.03	63.34

The products are used to create syngas (synthesis gas), a mixture of H_2 and CO, which can then be used for the synthesis of the E-fuel. ER-fuel takes existing fuel and undergoes a reforming process, which is then put through RWGS to generate the new syngas and create the synthetic fuel. The main difference, highlighted in Fig. 2, between these two processes is that E-fuels are generated from pure elements rather than existing, reused fuel. According to *Energy Conservation and Management* [8], given a fuel input of 1.00 MW, 0.82 MW is produced from E-fuels, while 1.25 MW is generated from ER-fuels.

3 E-Fuel Usage Methods

The raw fuel matters little without a method to convert that to electricity. The two main routes for utilizing fuels are from turbines/engines or fuel cells. The traditional gas engine can be used for synthetic fuels and allows easy migration of common fossil-based fuels to E-fuels. Fuel cells, while harder to implement and less commonly used, have their own advantages. Hydrogen provides the highest energy output in a fuel cell, but other fuels still can generate electricity at relatively high efficiencies [13]. In general, fuel cells have the best output with non-alcoholic fuels, such as electrically rechargeable fuels based on redox couples [14]. Conventional centralized power systems have been shown to average less than 33% efficiency. On the other hand, combined heat and power systems, like fuel cell systems that utilize waste heat to warm homes, can provide up to between 80% and 90% efficiency. In this case, this efficiency is the comparison of energy used to energy supplied [15]. The maximum efficiency for fuel cells is determined by the change in Gibb's free energy, not Carnot's efficiency. The use of the thermal energy (heat) generated in addition to the electricity increases the overall yield of the fuel cell as well [16]. Thus, fuel cells provide a possible second option for fuel-to-energy conversion.

4 Fossil Fuel Comparison Overview

For synthetic fuels to provide an alternative, or an addition, to traditional, fossil-based fuels, they must demonstrate equal or better performance. Synthetic fuels provide a lower carbon or carbon neutral option; since they utilize captured gases in their synthesis, emissions produced are approximately equal to those consumed. If used in a fuel cell, the process to convert to electrical energy has even fewer byproducts. A study from Saudi Arabia predicts that E-fuels would reduce transportation emissions by at least

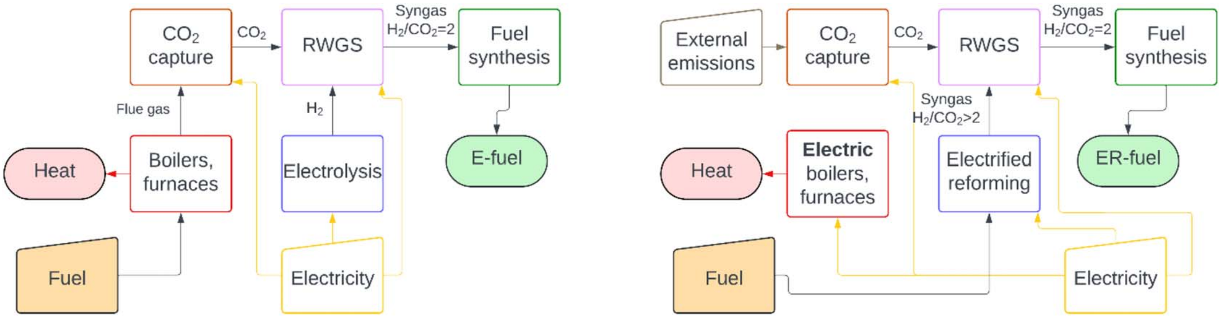


Fig. 2 Comparison of E-fuel and ER-fuel syntheses [8]

50% [17], making them worthwhile from an environmental standpoint.

However, prices for producing synthetic E-fuels were over two times higher than the cost for acquiring fossil fuels as of 2015, from a study that analyzed E-fuel production from the use of wind energy, multiple electrolysis methods, and Fischer–Tropsch synthesis [2]. Additionally, with infrastructure setup to only handle fossil fuels, implementing a change in fuel may require redesigning vehicles, engines, power plants, and fuel transportation methods, especially if fuel cells were desired. While there might be setbacks that could prevent the implementation of synthetic fuels, in the long term, these disadvantages taper off. Electric vehicles and synthetic-based hybrids last around 15% longer than conventional vehicles [18], suggesting that their setbacks could pay off.

5 Cost and Infrastructure

While prices for E-fuels are high in the present, future models suggest that the prices will decrease. Electrolysis is a large portion of the cost of producing E-fuels, and that will decrease as technology advances and electrolyzers become cheaper and more efficient. Life cycle costs for zero emission vehicles (ZEVs), as mentioned above, make the long-term cost of the vehicle lower than conventional vehicles. Additionally, price projections for hydrogen, methanol/methane, and ammonia suggest that they will vastly decrease by 2030, with an estimated price in USD per kilogram of 2.33, 0.69, and 0.50, respectively [4]. Other studies have determined that electric buses are ideal for short-range travel, while fuel cell-powered buses are better for long range, meaning that there are different types of ZEVs that can work in various situations [19]. These trends suggest that ZEVs provide a valuable alternative to traditional vehicles and can likely be implemented in the near future, as hydrogen prices decrease, and electric vehicle infrastructure develops further.

The market for ZEVs is also rapidly increasing, both by consumer demand and by government mandates. In California, Massachusetts, and New York, there is a 10% electric vehicle sale mandate in effect, and other states will likely join as well [18]. Large corporations, such as Amazon, have pledged to reduce their carbon emissions and have in turn invested in the electrolyzer, fuel cell, and electric vehicle companies to fulfill their promise. While pure electric vehicles and hybrids increase in demand, there are also methods to use synthetic fuels in traditional or conventional gasoline vehicles. Up to 30% hydrogen gas can even be mixed with natural gas without having to modify burner nozzles and boiler control parameters [1], allowing for carbon reduction with minimal required infrastructure changes.

While there is hope for E-fuels to overtake fossil fuels as a source of vehicle power and electricity generation, there are still unknowns and potential issues that might prevent immediate change. First, for the oxidation of the fuels in fuel cells, pure oxygen is desired, which can be expensive and difficult to obtain for fuel cells or combustion [20]. Some studies also show that there is minimal difference in non-carbon emissions, such as nitrogen-based emissions, with respect to fossil fuels which may still pose a problem for global warming [21]. Additionally, some ZEVs cannot last for longer trips, so some consumers may still favor traditional gas-powered vehicles [22]. Some E-fuels also have more desirable traits than others, with one Danish study suggesting that e-methanol is the best business case [4]. These factors may slow down the progression of different E-fuels into the current infrastructure, but they still have the potential as a comparable cleaner solution.

6 Conclusions

E-fuels provide an environmentally friendly, low carbon emissions alternative to power vehicles instead of fossil fuels, and different types can be used in traditional gas engines, in fuel cells, or as a source of electricity for battery-operated electric vehicles. These power generation methods additionally have applications in reducing emissions for electricity generation and power plants. With decreasing prices and high durability, they have the potential to lower fuel costs and create longer-lasting vehicles. However, they do have setbacks that could prevent society's transition to synthetic fuels, from difficulty integrating into current consumer vehicles to high initial costs for production sites. Despite these setbacks, engineers and scientists are hopeful, based on technological projections that ZEVs and E-fuels will become the fuels of the future, for cleaner, lower GHG emission energy generation in both transportation and the power sector.

Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent is not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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