LOW-CARBON ELECTROFUEL SYNTHESIS FOR AVIATION AND FREIGHT TRANSPORTATION: A TECHNO-ECONOMIC ANALYSIS

Evan D. Sherwin, Carnegie Mellon University, (412) 268-7938, esherwin@cmu.edu
W. Michael Griffin, Carnegie Mellon University, (412) 268-2299, wmichaelgriffin@cmu.edu
Inês M. L. Azevedo, Carnegie Mellon University, (412) 268-3754, iazevedo@cmu.edu

Overview

Limiting global warming to 2°C will require massive reductions in greenhouse gas (GHG) emissions across the global economy. The aviation and freight sectors require fuels with high energy density, likely low-carbon liquid fuels. We consider the economic and environmental tradeoffs of three strategies for reducing GHG emissions from these sectors by 80% or more: 1) hydrocarbon *electrofuels* synthesized from carbon dioxide (CO_2) captured from the atmosphere using direct air capture (DAC) of carbon dioxide (CO_2) coupled with hydrogen from electrolysis of water, 2) *biofuels*, and 3) conventional fuels coupled with DAC and sequestration in a geologic formation (*DACS*).

Electrofuels are roughly carbon neutral if the carbon capture, hydrogen production, and fuel synthesis processes are powered by essentially carbon-free electricity, such as wind, solar, and nuclear. Both electrofuel production and DAC are capital-intensive processes, creating an incentive for a high capacity factor. However, electricity costs are also substantial for both electrofuels and DACS. Variable renewable electricity is a relatively inexpensive source of very low-carbon electricity. Thus, there is a tension between capacity factor, capital cost, electricity cost in DACS and electrofuel production.

Established processes exist for production of bio-based diesel (biodiesel) and jet fuel (biojet). Although these fuels are based on carbon captured from the atmosphere by plants, they are associated with an uncertain but likely substantial amount of net GHG emissions. In addition, replacement of an appreciable fraction of jet fuel or heavy freight fuel with biofuel would require conversion of a nonnegligible fraction of the world's arable land to feedstock crops, contributing to additional GHG emissions from direct and indirect land use change and likely raising food prices.

Methods

The future cost and technical characteristics of DAC systems, electrolyzers, low-carbon electricity, and hydrogen and electricity storage create the greatest uncertainty for the future cost of electrofuels and DACS. We use a techno-economic model of electrofuel production and DACS, varying these values parametrically to determine when each of the three strategies considered is preferred for mitigating emissions from aviation and heavy freight transportation.

We consider the effect on the cost of electrofuels and DACS of coupling variable renewable electricity with electricity storage or, in the case of electrofuels, hydrogen storage as well. We treat capacity factor parametrically, as a proxy for a location's renewable production profile and the potential for electricity or hydrogen storage. We simultaneously vary the capacity factor for electrofuels and DACS powered solely by electricity for direct comparison. We consider DAC cost estimates from three separate sources.

In the baseline model we assume renewable electricity is available at 3¢/kWh, assuming modest cost reductions and deployment in high-resource locations. Because we consider electrofuel production and DACS powered entirely by renewable electricity, both methods are able to mitigate nearly all life-cycle emissions from aviation or heavy freight transportation.

Results

We find that if nuclear or grid electricity are used, DACS is always lower cost than electrofuel production even with high capacity factors, assuming conventional fuels cost \$4/gallon of gasoline equivalent (GGE) or less. Unless advanced nuclear and grid electricity costs fall below 6¢/kWh, the cost of hydrogen production alone, assuming a 70% efficient electrolyzer, is higher than the total cost of the conventional fuel. Thus electrofuel production, which requires DAC and amortization of electrolyzer and fuel synthesis infrastructure, necessarily cannot be competitive with DACS even assuming relatively high CO_2 transportation and sequestration costs.

We compare electrofuels and DACS with conventional jet fuel at $2/GGE under the generous assumptions of substantial improvements in electrolyzer cost and efficiency and the ability to meet DAC heat demand using waste heat from the electrolyzer and fuel synthesis, and no system integration costs. We find that electrofuels are less cost-effective than DACS in almost all circumstances, although they are slightly preferred in one DAC cost scenario with capacity factors of 70% and above. The associated price premium for running this electrofuel production system at a 70% capacity factor, likely not achievable at 3¢/kWh with renewable electricity and storage, is $0.9-3.5/GGE, and the implicit carbon price is $110-422/t($CO_2$). The corresponding cost of DACS is $70-350/t($CO_2$). However, compared to fuel price of $3/GGE, electrofuels are competitive for capacity factors of 30-40% or higher. All currency is in 2017 dollars.

Under more conservative electrolyzer cost and efficiency assumptions, assuming DAC heat demand is met with electricity and assuming system integration costs equal to the total capital cost of the electrolyzer and the DAC and fuel synthesis systems, we compare electrofuel costs to diesel prices at $3/GGE. In this case, electrofuels are never competitive, with GHG mitigation costs 1.7-2 times that of DACS at a 70% capacity factor.

Although biodiesel and biojet production costs may be lower than the cost of electrofuels or DACS, these fuels are unlikely to be able to provide an 80% net reduction in GHG emissions at large scales, although the precise figures are highly uncertain (1). In addition, fulfilling global aviation fuel demand with biojet would likely require at least 1% of global arable land, or substantially more if freight fuel demand were included (1, 2).

Conclusions and policy implications

There are no easy answers to deep decarbonization of heavy freight transportation and, especially, aviation. Pursuing electrofuels or DACS to achieve 80-90% GHG emissions reductions could easily increase fuel costs many times over. For electrofuels to be competitive, the cost of high capacity factor variable renewable electricity, including electricity or hydrogen storage, will likely have to fall substantially below 6¢/kWh. Large reductions in the capital cost of DAC infrastructure and electrolyzers, particularly highly efficient solid oxide electrolyzer cells, would render the economics of electrofuels and DACS increasingly favorable.

Biofuels may have the potential to produce jet fuel and diesel substitutes at lower cost than electrofuels or conventional fuels with DACS. However, the life cycle emissions of these fuels are highly uncertain and may fall far short of the desired 80% reduction in GHG emissions intensity (1), requiring additional mitigation efforts in other sectors. In addition, massive land use requirements for feedstock crops will likely displace production of foodcrops, increasing food prices and effectively placing a highly regressive tax on the world's poor.

Although electrofuel production or DACS could massively increase the cost of jet fuel and diesel, jet fuel costs could rise by more than 300% before increasing airfares to average 1980 levels (3, 4). The same price increase would raise freight transport costs by roughly 70%. Although the implicit mitigation cost is high, such cost increases could be politically acceptable as part of a determined effort to limit the worst effects of climate change.

Given existing government support for wind, solar, electricity storage, and biofuels, policymakers interested in deep decarbonization may wish to take additional aggressive measures to promote cost reductions in DAC systems, and perhaps electrolyzers and integrated electrofuel synthesis plants, as well as streamlining policy to facilitate carbon sequestration. Such an effort would likely contain a research and development component, but the largest cost reductions will likely come through aggressive deployment.

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