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References for DAC e-fuels

Please see the article in Joule shared here.

Additional submitted attachment is included below.

Joule

CellPress

COMMENTARY

CO_2-to-Fuels Renewable Gasoline and Jet Fuel Can Soon Be Price Competitive with Fossil Fuels

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Rob McGinnis, PhD, is an inventor and entrepreneur. He is the founder and CEO of Prometheus, a company that is developing technology to remove carbon dioxide from the air and turn it into fuels. He previously founded Mattershift, where he developed large-scale carbon nanotube membranes. Rob was previously founder of Oasys Water, a company focused on developing forward osmosis technologies for water purification. Rob received his PhD in Engineering from Yale University.

Recent breakthroughs in separations and catalysis, along with long-trend reductions in solar and wind electricity costs, have significantly increased the potential for cost-competitive renewable fuels from direct air capture (DAC) of CO_2. This is an important development because there is little time available to reduce CO_2 emissions sufficiently to avoid the worst effects of climate change.[1] Transportation fuels contribute a significant portion of current CO_2 emissions, accounting for 23% of global greenhouse gas (GHG) emissions and up to 40% of GHGs in developed economies, offering significant opportunities for emissions reduction from the decarbonization of such fuels.[2,3]

Electrification of the global vehicle fleet, which now totals over 1 billion cars and trucks, or conversion of vehicles to use novel fuels like hydrogen, cannot proceed quickly enough to address the climate crisis.[4] Replacing fossil-fuel gasoline, diesel, and jet fuels would be able to proceed at a much faster pace, because it does not require the replacement or retrofit of the existing vehicle fleet. In order for this fuel replacement to occur, however, renewable fuels must offer the same or better performance than fossil fuels at the same or lower price. Subsidies and tax incentives can help accelerate adoption or tip the scales on price competitiveness, but to reach the scale necessary to address the climate crisis without creating unsustainable economic and political costs, renewable fuels must be able to stand on their own to compete for market share from fossil fuels. They must be molecularly identical to gasoline, diesel, and jet fuel, and in order to fully or nearly fully replace fossil fuels, they must cost less to produce.

Several technical and economic developments have occurred recently to make this possible. Over the last three years, the conversion of CO_2 to fuels in inexpensive water-based systems (aqueous CO_2 electrolysis) with base-metal catalysts has shown high faradic efficiencies for reduction of CO_2 to C2 fuel products such as ethanol.[5] Previously, CO_2 reduction to CO for syngas production was considered the most promising conversion pathway, based on catalyst performance. This approach, however, occurs at elevated temperatures and pressures and requires a separate electrolysis step to produce H_2. Following this, a Fisher-Tropsch conversion to produce “syncrude” is employed, followed by distillation-based refining to finished fuel products.[6] These processes are energy and capital intensive and require massive scale to become practical. They are also unlikely even at such scale to compete with fossil fuels on price.

Aqueous CO_2 electrolysis offers advantages over this and other previous approaches because it does not require a separate H_2 generation step and can produce liquid fuels like ethanol directly in a single process step. These advantages come with tradeoffs, however, because the cathode current densities of aqueous electrolysis systems can be lower than those of gaseous systems.[5] In order to produce low-cost fuels with such systems, it is therefore important to use low-cost components to allow for larger catalyst areas. The combination of using base-metal catalysts and operating the systems at room temperature and pressure, however, offers significant opportunities to reduce system capital costs, offering potential for a lower fuel cost, at smaller scale, than with previous approaches.

A second development has been in the effective upgrading of alcohols like ethanol to gasoline, diesel, and jet fuels.[7] This upgrading requires an inexpensive catalysis step (oligomerization and dehydration), which is exothermic and compact, operating at moderate temperatures and pressures.

One previous objection to the aqueous CO_2 electrolysis pathway has been that the fuels produced by this means, such as ethanol and other alcohols, are difficult to separate from water. This has until recently required expensive and energy-intensive separations like distillation, which would involve similar costs and tradeoffs to gas phase approaches like Fischer-Tropsch. Thanks to a third recent breakthrough, this problem has also been addressed. The separation of ethanol and other fuel products from water can now be achieved by using a nanotechnology-based separation, operated at room temperature and pressure. This approach does not require a phase change of water and thereby avoids its high latent heat of vaporization. This reduces the energy of alcohol-water separations by more than 90% compared with distillation, previously the only practical means to achieve such separations. This is made possible by using carbon nanotube membranes, which show a near ideal preference for the passage of alcohols, while rejecting the passage of water.[8–10]

An additional advantage of water-based catalysis is that CO_2-capture costs and process complexity could be significantly reduced. In most DAC CO_2-to-fuels approaches to date, pure CO_2 has been required. Energetically, it is quite expensive to take a diffuse CO_2 source (e.g., air at 410 parts per million [ppm]) and separate and compress it to a 100% pure stream. This requires a tremendous decrease in entropy—concentrating CO_2 from 0.04% to 100%, and then subsequently pressurizing it further. By capturing CO_2 directly in the water in which it will be used, much less concentration is required (from 0.04% in air to <2% in a solution of carbonate and bicarbonate salts). This is expected to contribute to energy and capital cost savings. How much this integrated aqueous CO_2 capture approach lowers DAC costs in relation to pure CO_2 approaches on a \$/ton-CO_2 basis will need to be more precisely determined to allow for effective comparisons of CO_2 capture alone. Because the CO_2 capture is integral to the aqueous catalysis process, it is difficult from an accounting perspective to separate its proportional cost. For example, large CO_2/water contact areas (such as cooling towers) similar to those used in more conventional approaches will still be required, and in fact these could be larger than those of pure CO_2 systems, but no CO_2 compressors will be needed, and there are no CO_2-specific process operations such as heating/cooling cycles or calcination/de-calcination processes. Many other aspects of CO_2 utilization in aqueous catalysis systems are multipurpose, making CO_2-specific costs difficult to separate. It is also noteworthy that integrated CO_2 capture cannot supply pure CO_2 for other uses—it can only be used for fuel production, which makes full apples-to-apples comparisons more difficult. It is likely standardized methods for effective comparison of DAC CO_2-capture costs will be developed as aqueous CO_2 electrolysis methods see greater use.

These advances together allow for inexpensive systems that can make true gasoline, diesel, and jet fuels from atmospheric CO_2. These systems can run at room temperature and atmospheric pressure using only electricity rather than the mix of electricity and fossil fuels (such as methane for process heat) typically required by previous approaches. One practical advantage of non-thermal processes using only renewable electricity is that they can be turned on and off quickly to match intermittent supplies of renewable power. This is much better suited to the availability of renewable energy sources than thermal processes that must run 24/7 for stable operation. The low capital costs possible with unpressurized, room-temperature systems are also important in this regard. Such systems might run at low utilization rates—as low as 50% uptime while still hitting their economic goals—allowing them to sit idle during peak electricity-pricing periods, keeping their electricity costs low. Thermal systems with high capital costs must run at the highest possible utilization rates, ideally 24/7 operation for capital-cost reasons and process stability, making them much less flexible for intermittent renewable power. This flexibility is important to keep the price of the electricity, a major input in such fuels, as low as possible to compete with the costs of fossil fuels.

The macro-scale economic trend that enables the use of the technical breakthroughs discussed above is the long-term reduction in the cost of solar and wind power. The cost of electricity from these sources has come down tremendously over the last ten years. Recently, the city of Los Angeles purchased large-scale solar power for less than \$0.02/kWh (kilowatt hours).[11] Having low-cost electricity matters a great deal, because a lot of electricity is needed to make fuel. Gasoline contains approximately 36.3 kWh of energy per gallon.[12] The best electrochemical processes are unlikely to achieve overall efficiencies of over 60% in the near term, meaning that each gallon of gasoline will require at least 56 kWh of electricity. With wholesale solar power being available at \$0.02/kWh, this means the electrical energy input to renewable gasoline from CO_2 costs approximately \$1.12/gallon, low enough to be competitive with fossil fuels if the capital costs of the systems and the cost of CO_2 capture are also low.

We project that by putting all of these advances together, it will be possible to offer renewable gasoline from DAC CO_2-to-fuels within the next two years that is price competitive with fossil gasoline. Once this is demonstrated, the main challenge will be in achieving speed to scale. The scope of the effort required is significant—in order to replace all fossil gasoline in the United

States, assuming 66% resource availability and a 60% conversion efficiency, an additional 1.4 TW (terawatts) of combined solar and wind capacity for the United States alone will be required.

Innovations in renewable project finance will also be required to achieve this scale. For example, high wind and solar-resource geographies that are too far from major cities for cost-effective transmission-line connections will be ideal for fuel generation, particularly to get to TW scale. However, without a transmission line to secondary customers for the power produced, such projects will have to be dedicated to fuel production. Because CO_2-to-fuels production is based on new technologies, technical risk will have to be addressed in such projects. Possible approaches to this could include lines of credit or other such facilities that would be sufficient to pay for transmission lines if needed as insurance against unforeseen reductions in fuel production. Such financial innovations could accelerate these projects, but as with any risk mitigation, they will also have costs. These costs must be kept low enough to be compatible with the competitiveness of the renewable fuels. In order to scale quickly enough to the magnitude necessary for addressing the climate crisis, this challenge must be addressed simultaneously with the challenges of technology scale-up and deployment.

A large number of fuel-making systems will also need to be built and deployed—approximately 150,000 systems rated for one million gallons per year each (MGY) for the United States alone. The existing infrastructure for gasoline, diesel, and jet fuels, however, need not be changed, because renewable CO_2-to-fuel gasoline, diesel, and jet fuel are molecularly identical to their fossil fuel antecedents (although much cleaner, because they do not contain sulfur, benzene, heavy metals, etc.), and could be transported and sold with existing infrastructure. Most importantly, this approach to decarbonizing transportation fuel can happen quickly. This is the kind of solution we need, because we don't have time to waste.

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COMMENTARY

Electric Vehicles Batteries: Requirements and Challenges

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Jie Deng is a research engineer in the Department of Electrification Subsystems and Power Supply at Ford Motor Company. He has extensive experience in computer-aided engineering analysis (structural, fluid, and thermal), battery simulations, and material characterization. He got his PhD in Mechanical Engineering from Florida State University and has published over 30 papers. His current research mainly focuses on battery array design and multi-physics modeling and testing of battery behaviors under various abuse conditions.

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