reservoirs and saline aquifers should be used to thoroughly investigate the alternative options and invest in renewable energy sources. ❐

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Coal as a low-carbon fuel?

Dan Schrag

The conversion of coal into liquid fuel is one of the dirtiest ways to produce transportation fuel. But if carbon is captured and stored, and some biomass is added, it could become the cleanest way to power jets, trucks and trains.

Reducing carbon emissions to a level that will prevent the worst consequences of climate change will not be easy. We can make energy usage dramatically more efficient; we can increase the use of non-fossil-fuel energy sources; and we can install carbon capture and storage facilities on all large stationary sources of CO_2, such as power plants. But a handful of uses for fossil fuel that are very difficult to replace will remain. This is particularly true in the transport industry, which consumes roughly 60 million of the 85 million barrels of petroleum produced per day across the globe. In the US, transport is responsible for around 30% of CO_2 emissions. Right now, it will be much cheaper to increase energy efficiency, among many other ways of reducing emissions, than to tackle transportation. But in the long run, it will not be possible to achieve acceptable emissions reductions without curbing petroleum's contribution to climate change.

Half of the petroleum used in the transport industry is refined into petrol and used to run automobiles and light trucks. Much of the remainder is used as diesel, which fuels heavy trucks, trains and ships, or is made into jet fuel. There are numerous proposals aimed at reducing our reliance on petrol. One possibility is plug-in hybrid vehicles, which run off both battery power and petrol, or fully electric automobiles that rely on battery power or hydrogen fuel cells alone. Another option is replacing petrol with ethanol — perhaps generated by cellulosic feedstocks (mainly grasses and trees). But none of these options work well for diesel or jet fuel. The production of biodiesel from crops such as soybean is limited by the amount of available arable land, and the costs associated with biodiesel production using algae in aquaculture are prohibitively high[1].

An alternative solution is an old technology for the conversion of coal into fuel. Suitably adjusted, it has many advantages for use in a low-carbon world. Carbon capture is part of the process, biomass — whose carbon content comes from the atmosphere — can be used at least as part of the energy input, and the resulting fuel is low in contaminants, yet high in energy density.

Coal to fuel

More than 80 years ago, two German chemical engineers named Franz Fischer and Hans Tropsch developed a method for generating synthetic diesel from coal. The method, termed the Fischer-Tropsch process, involves the gasification of coal, and its subsequent conversion into liquid hydrocarbons. The gasification step yields carbon monoxide and hydrogen, together with CO_2 and methane. When the carbon monoxide and hydrogen mixture is passed over a catalyst — usually a form of iron or cobalt — it is converted into liquid hydrocarbons. Varying the temperature and pressure at which this step takes place, along with the composition of the catalyst, renders different hydrocarbons, including jet fuel and diesel fuel. The technology was perfectly suited to coal-rich oil-poor Germany. Indeed, production of synthetic fuels reached more than 120,000 barrels per day during World War II. The same technology was deployed in South Africa during the Apartheid embargo, and Sasol, the South African oil company, remains the largest producer of Fischer-Tropsch fuels in the world (Fig. 1).

Synthetic fuels made by the Fischer-Tropsch process have many qualities that make them attractive for modern transportation systems. The fuels are very low in sulphur, mercury and aromatics, and produce fewer particulates and nitrous oxides when combusted, making them attractive from an environmental health perspective. Synthetic fuels are also more energy-rich than petroleum fuels, raising their attractiveness to the aviation industry because they would allow increased range or payload. Despite these advantages, Fischer-Tropsch fuels have a bad reputation, and not just because of their historical association with the Nazis and Apartheid.

The problem is that converting coal into synthetic diesel or jet fuel using Fischer-Tropsch methods produces large quantities of CO_2. Compared with emissions from petroleum — which includes emissions associated with extraction, refining, distribution and combustion in an engine — Sasol's Fischer-Tropsch plants in South Africa produce twice as much CO_2 per barrel of fuel compared with the average petroleum fuel, even when corrected for the higher energy density. Indeed, these plants in South Africa are among the largest stationary sources of CO_2 in the world. A modern Fischer-Tropsch facility designed with newer engineering and more efficient catalysts would be slightly cleaner, but would still emit at least 50% more CO_2 per barrel of fuel compared with petroleum[2]. It is little wonder, then, that many environmental groups have identified coal-to-liquid plants using the Fischer-Tropsch process as one of the greatest threats to addressing anthropogenic climate change.


BP

Figure 1 | A Fischer-Tropsch plant. The conversion of coal into liquid fuel via the Fischer-Tropsch process could prove to be one of the most environmentally friendly technologies of the future.

Adjustment to a low-carbon world

Ironically, the same technology that produces the most carbon-polluting fuels in the world could be made to produce one of the cleanest fuels. I came to this realization while advising a synthetic-fuel company on how best to adapt to impending carbon regulations and on opportunities for carbon capture and storage. I noticed that the Fischer-Tropsch process has two features that will allow it to compete with petroleum and alternative transportation fuels in a carbon-constrained world.

First, the various catalysts that are used for converting the gasified coal into hydrocarbons are poisoned by CO_2 in the gas stream. This means that Fischer-Tropsch plants have to capture the CO_2 produced during gasification, making them perfectly suited to carbon capture and storage, as they have already paid for the expensive part of the process — the separation of CO_2 from a mixed gas stream. The cost of compressing and storing the CO_2 emitted from large Fischer-Tropsch facilities is very small, and probably lies between $10 and $20 per ton[2].

Thus, even a relatively low price on CO_2 emissions would be enough of an economic incentive to ensure that most of the CO_2 produced in Fischer-Tropsch plants is sequestered away from the atmosphere — as long as they are located near suitable and safe storage facilities, that is (see Commentary on geological carbon storage on page 815 of this issue and Commentary on deep-ocean storage on page 820 of this issue). This would improve the carbon footprint of the Fischer-Tropsch process considerably; a new Fischer-Tropsch plant that converts coal to diesel or jet fuel with more than 80% carbon capture and storage has a life-cycle carbon footprint that is 5% to 12% better than the average barrel of petroleum[2].

The right mix

The second feature of the Fischer-Tropsch process that allows for a reduced carbon footprint is the high-temperature gasification, which allows one to substitute coal with biomass. If one uses roughly 60% coal and 40% biomass as a feedstock, combined with 80% carbon capture, the synthetic diesel or jet fuel would have nearly a zero carbon footprint[2]. In this scenario, one can think of the coal as an energy source that converts biomass to synthetic fuel with nearly 100% efficiency: essentially, an amount of carbon equivalent to that from the coal ends up stored in a geological formation and the carbon-equivalent of the biomass, which came from the atmosphere, ends up in the fuel.

This idea of using both biomass and coal in the Fischer-Tropsch process is not new. Numerous studies outline the many advantages of the Fischer-Tropsch process over the biochemical production of biofuels such as cellulosic ethanol[3–5]. For example, gasification, the first step of the Fischer-Tropsch process, converts biomass to a carbon-monoxide–hydrogen gas mix regardless of the starting material. Thus any biomass, including switchgrass, prairie grass, forest cuttings, agricultural waste and even municipal solid waste, can be used. This makes the process far more adaptable than first-generation biofuel production, which relies on sugar from corn or cane. Furthermore, synthetic fuels produced by the Fischer-Tropsch process have a net energy balance (output relative to inputs) that is more than six times higher than that of corn ethanol and more than four times that of soybean biodiesel[6].

But perhaps the most important advantage of the Fischer-Tropsch process over biochemical biofuel production is the product: diesel and jet fuel with a high energy content and low levels of contaminants such as sulphur, mercury and nitrous oxides. Ethanol, by contrast, whether from sugar or cellulose, cannot be used in jet engines or compression engines of trucks, trains and ships. Even if we were able to eliminate petroleum consumption in passenger cars through the use of plug-in hybrids or fuel-cell vehicles, we would eventually have to replace diesel and jet fuel. Synthetic fuels may be one of the few ways to do this at the scale required and at a reasonable cost — well under $100 per barrel[2].

If biomass alone were used to fuel the Fischer-Tropsch process, and carbon capture and storage technology was used, the whole process could become carbon negative. At least at a small scale, where low-cost biomass is available, pure biomass Fischer-Tropsch plants may be an excellent idea. In fact, two companies have built a small Fischer-Tropsch plant in Germany that uses biomass feedstock to make synthetic diesel fuel. And an American company recently announced plans to build a synthetic fuel plant in Rialto, California, that would use municipal waste as feedstock. CO_2 emissions from these plants will not be stored because they are relatively small-scale operations (producing less than 1,500 barrels per day); storage might be more economical in the future as the price of carbon rises.

The choice of incentives

However, Fischer-Tropsch facilities are very capital intensive, which means that synthetic fuels will best compete with petroleum when one can take advantage of the economies of large-scale factories, where at least 30,000 barrels of fuel are produced per day. A plant of this size, if running on pure biomass as a feedstock, would require more than 50,000 tons of biomass delivered each day — something difficult to imagine given existing infrastructure. Although we do not yet have the capacity to transport and store vast quantities of biomass from seasonal harvests, we do have the infrastructure to deliver equivalent amounts of coal from mines to Fischer-Tropsch plants in most coal-producing countries. This leads to an interesting dilemma.

Environmental groups have legitimate concerns that government subsidies for Fischer-Tropsch facilities could lead to the proliferation of synthetic-fuel plants that use coal without biomass co-feed and without carbon capture and storage. If this were to happen, the broad adoption of Fischer-Tropsch fuels would virtually double the emissions from petroleum. On the other hand, we cannot afford to delay looking into this option: building the infrastructure needed to produce vast amounts of clean synthetic diesel and jet fuel will take a very long time.

One critical step that will ensure that the future of synthetic fuels is a clean one is to put a price on CO_2. A carbon price will not only encourage carbon capture and storage in Fischer-Tropsch plants because of its low cost, but will also encourage the blending of coal with biomass. Some states in the US, such as California and Massachusetts, have already passed low-carbon fuel standards that will create markets for small Fischer-Tropsch facilities that use pure biomass. Subsidies for such fuels, even beyond the current subsidies for biodiesel, will encourage the deployment of cleaner facilities. But given the limitations on how much biomass can be concentrated at one facility, pure biomass facilities cannot make a dent in the diesel and jet-fuel market. For now, a reasonable strategy would be to encourage synthetic-fuel plants that have a carbon footprint better than conventional petroleum, and perhaps even better than corn ethanol, by using mostly coal with a small amount of biomass along with carbon capture and storage. Over time, as the price on CO_2 rises, there will be more economic incentive to invest in new biomass transportation infrastructure, and the fraction of biomass used in the process will grow.

In the long run, perhaps some new fuel, such as ammonia or hydrogen, will replace hydrocarbons altogether. But for the foreseeable future, the world will need diesel and jet fuel — and in huge quantities. Combining biomass with coal in synthetic-fuel plants that capture the carbon and store it in geological repositories could take an old technology with a bad reputation and a terrible environmental footprint and turn it from black to green. ❒

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Triage in the greenhouse

Ralph F. Keeling

The path towards mitigating global warming is going to be tortuous. Capturing carbon dioxide and pumping it directly into the deep ocean to avoid atmospheric build-up is an option that has been dismissed prematurely.

Among those concerned with marine preservation, the idea of reducing global warming by pumping CO_2 into the deep ocean is anathema: the suggestion, which was among the earliest proposals for combating climate change, is regarded as violating a precautionary approach to preventing marine pollution, while disregarding the well-being of marine organisms. But the oceans take up billions of tons of CO_2 from the atmosphere each year anyway; when this CO_2 will enter the deep ocean is just a matter of time. And if the atmospheric build-up of CO_2 proceeds unchecked, its consequences for ecosystems and society could easily trump efforts at marine conservation. Regardless of the merits of direct oceanic CO_2 disposal, its early dismissal as too environmentally damaging illustrates that we are not yet prepared to face the consequences of fossil fuel emissions — or the tough choices that may be required to preserve our planet.

Deep-ocean injection

Ocean disposal of carbon dioxide was introduced by Marchetti[1], who saw global warming as a problem of kinetics. The deep ocean has an enormous capacity for absorbing CO_2 and will eventually take up most of the excess CO_2 from burning fossil fuels. The pace of absorption is very slow, however, because the deep ocean has only indirect contact with the atmosphere, through mixing with ocean surface waters. Marchetti therefore suggested by-passing the surface ocean by collecting CO_2 at power plants or other concentrated sources and pumping it directly into the deep ocean.

Despite complexities, the proposal is basically sound. Although 20% or more of the CO_2 deposited in the deep ocean would inevitably leak back out into the atmosphere within decades to centuries, most would be retained in the ocean indefinitely. Simulations with ocean-circulation models have shown that the amount of leakage is reduced significantly by injecting at depths below 1,000 m in most ocean regions. Pure CO_2 injected at these depths either from offshore pipes or ships will exist as liquid, owing to the high pressure. Down to depths of about 2,750 m, CO_2 is less dense than sea water. Pure CO_2 injected above that level will therefore initially float upwards. In contact