Evaluation of Fossil Gas, Carbon Capture, Synthetic Direct Air Carbon Capture, Non-Green Hydrogen, and Electro-Fuels

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Table of Contents

8.3. Why Not Fossil Gas as a Bridge Fuel?

Most fossil gas today is used for electricity generation, building heat, or industrial heat. Because fossil gas is not very dense, it can be stored only in a large container or an underground storage facility. As such, fossil gas is often compressed or liquefied for transport and storage. **Compressed natural gas (CNG)** is fossil gas compressed to less than 1 percent of its gas volume at room temperature. **Liquefied natural gas (LNG)** is fossil gas cooled to minus 162 degrees Celsius, the temperature at which it condenses to a liquid at outdoor air pressure. LNG has a volume that is one six-hundredth of the volume of the original gas.

Both CNG and LNG can be sent through pipelines, although different pipelines are needed for each. Both can also be stored and used in automobiles designed to run on fossil gas. Both can be transported by truck or bus with a special fuel tank and stored at a power plant when a pipeline is not available.

For overseas transport, CNG from a pipeline is often converted to LNG at a marine export terminal, put on a tanker ship with super-cooled storage tanks, then shipped overseas. At the import terminal, it is re-gasified and piped to its final destination -- either a power plant, industrial company, or company that transmits and distributes the fossil gas to buildings for heating or other purposes.

Fossil gas is mined from underground conventional or unconventional wells. Conventional wells are shallow and small in area and produce oil, fossil gas, or both. Unconventional wells are deep and large in area and include shale gas and coal-bed methane wells. **Hydraulic fracturing** (**fracking**) is used in both well types, but mostly in unconventional shale gas wells. **Shale** is sedimentary rock composed of a muddy mix of clay mineral flakes and small fragments of quartz and calcite. Large shale formations containing fossil gas can be found in many areas of North America and worldwide, some close to population centers.

In the United States in 2022, at least 79 percent of all fossil gas mined and 95 percent of new fossil gas mined came from shale rock, thus was extracted by fracking[183]. Fracking requires large volumes of water, laced with chemicals, forced under pressure to fracture and re-fracture the shale rock to increase the flow of fossil gas. As the water returns to the surface over days to weeks, it is accompanied by methane that escapes to the air. As such, more methane leaks during the fracking of unconventional shale wells than from conventional gas and oil wells. About 5 percent of fracked wells leak methane and the other components of fossil gas immediately, 50 percent leak after 15 years, and 60 percent leak after 30 years[183]. Methane, which is a strong atmospheric warming agent[184], also leaks during the transmission, distribution, and processing of fossil gas[185,186,187].

For electricity production, fossil gas is usually used in either an **open-cycle gas turbine** or a **combined-cycle gas turbine**. In an open-cycle turbine, air is sent to a compressor, and the compressed air and fossil gas are both sent to a combustion chamber, where the mixture is burned. The hot gas expands quickly, flowing through a turbine to perform work by spinning the turbine's blades. The rotating blades turn a shaft connected to a generator, which converts a portion of the rotating mechanical energy into electricity.

The main disadvantage of an open-cycle turbine is its exhaust contains waste heat that could otherwise be used to generate more electricity. A combined-cycle turbine routes that heat to a heat-recovery steam generator, which boils water with the heat to create steam. The steam is sent to a steam turbine connected to the generator to generate 50 percent more electricity than with the open-cycle turbine alone. Thus, a combined-cycle turbine produces about 150 percent of the electricity of an open-cycle turbine with the same input fossil gas and the same carbon dioxide emissions.

On the other hand, the ramp rate (rate at which a turbine can produce its maximum electricity from a cold start) is 20 percent per minute for an open-cycle turbine. This is two to four times that of a combined-cycle turbine (5 to 10 percent per minute). In other words, the less efficient open-cycle turbine, which emits 50 percent more carbon dioxide per unit of electricity generated, is more useful for filling in gaps in grid-electricity supply than is a combined-cycle turbine.

It has long been suggested that fossil gas could be used as a **bridge fuel** between coal and renewables[188]. The two main arguments for this suggestion are (1) fossil gas emits less CO_2-equivalent emissions per unit of energy produced than coal and (2) fossil-gas electric power plants are better suited to be used with intermittent renewables than is coal. However, these justifications are incorrect and insufficient. Fossil gas is not recommended for use together with WWS technologies for multiple reasons, as discussed in the following sections.

8.3.1. Climate Impacts of Fossil Gas versus Coal

When used in an electric power plant, fossil gas substantially increases, rather than decreases, global warming compared with coal over a 20-year time frame. Over a 100-year time frame, coal causes more warming than fossil gas, but the difference is small. Also, whereas coal causes more air pollution damage than does fossil gas, both coal and fossil gas cause far more air pollution damage than WWS. As such, spending money on either fossil gas or coal represents an opportunity cost relative to spending the same money on WWS.

Considering only lifecycle emissions, generating 1 kilowatt-hour of electricity with fossil gas using a combined-cycle gas turbine or an open-cycle gas turbine causes 2.3 and 2.8 times, respectively, the warming over a 20-year time frame as generating 1 kilowatt-hour with coal. Over a 100-year time frame, using fossil gas, with the same turbines, may cause only 36 and 19 percent less warming, respectively, than using coal[10]. The fact that fossil gas causes far more warming than coal over a 20-year time frame is a concern because of the severe damage global warming is already causing. More fossil gas emissions in the short term may trigger difficult-to-reverse impacts, such as the complete melting of the Arctic sea ice.

The reasons fossil gas causes more warming than coal over a 20-year timeframe and only slightly less warming than coal over a 100-year timeframe are as follows. First, although fossil gas burned in an open-cycle or combined-cycle turbine produces less carbon dioxide per unit of electricity than burning coal, more methane (a greenhouse gas) generally leaks and is vented to the air during the mining, transport, and processing of fossil gas than of coal. Because methane is a potent short-term greenhouse gas, the emission of more methane contributes to more short-term warming by fossil gas than coal. Second, and more important, burning coal emits more nitrogen and sulfur oxides per kilowatt-hour of electricity generated than does burning fossil gas. Nitrogen and sulfur oxides produce cooling aerosol particles, which offset or mask much of coal's global warming. The cooling impacts of these particles are through their reflection of sunlight to space and their enhancement of cloud thickness. Thicker clouds reflect more sunlight, cooling the ground. As such, coal's emissions of nitrogen and sulfur oxides, which are both short-lived chemicals, cause short-term cooling, offsetting much of the short-term warming caused by carbon dioxide from coal.

Regardless, neither fossil gas nor coal is recommended in a 100 percent WWS world. Considering lifecycle emissions alone and before considering carbon capture, fossil gas causes 56 to 72 times the warming, per unit of electricity generated, of wind, averaged over 100 years[10]. Coal causes about 88 times as much warming as wind. With carbon capture and considering all emissions, fossil gas and coal also cause much more warming than does wind (Figure 8.1).

8.3.2. Air Pollution Impacts of Fossil Gas versus Coal and Renewables

Whereas fossil gas for electricity causes more warming than coal over 20 years and slightly less warming than coal over 100 years, coal emits more health-damaging air pollutants than does fossil gas. Nevertheless, both fossil gas and coal are much worse for human health than are WWS technologies, which emit zero air pollutants during their operation. WWS emits pollutants only during the manufacture and decommissioning of WWS equipment. Such WWS-related emissions will disappear to zero as all energy is transitioned to 100 percent WWS, since at that point, even mining and manufacturing will be powered with WWS.

More carbon monoxide, volatile organic carbon, methane, and ammonia are emitted during fossil-gas production and use than during coal production and use in the US. Coal production and use emit more nitrogen oxides, sulfur dioxide, and particulate matter[189]. Emissions from the mining, transport, processing, and consumption of fossil gas may cause 5,000 to 10,000 deaths each year in the US from air pollution[190]. Coal-related emissions may cause 20,000 to 50,000 deaths per year. Thus, both fuels cause air-pollution deaths, but coal causes more. The reason is that nitrogen oxides and sulfur dioxide from coal convert to particles in the air, and those particles plus the particles emitted directly from coal plants cause severe health damage.

In sum, coal causes more deaths than does fossil gas, but both coal and fossil gas cause far more deaths than do WWS technologies. The combination of the much higher CO_2-equivalent emissions and air-pollution deaths due to fossil gas compared with WWS renders fossil gas neither a bridge fuel nor a safe chemical.

8.3.3. Fossil Gas is Not Needed for Peaking or Load Following

Another argument for using fossil gas as a bridge fuel is that it is useful for load following and peaking. Thus, it prevents blackouts on the electricity grid. The argument continues that WWS technologies are intermittent and need fossil-gas-powered load-following or peaking plants to back them up when wind and solar outputs are low.

Whereas fossil-gas plants do help with peaking and load following, they are not needed. Other types of WWS electric power storage options available include hydroelectric-power reservoir storage, pumped hydropower storage, stationary batteries, grid-hydrogen storage, CSP with storage, flywheels, compressed-air energy storage, and gravitational storage with solid masses.

Transition highlight. By 2024, the costs of wind-battery and solar-battery electricity-generating systems were already much lower than those of fossil-gas peaker plants[191]. In fact, in just 4 years, from 2020 to 2024, California and Texas each installed over 8 gigawatts of batteries (the peak power of about eight 1-gigawatt nuclear reactors) on their main grids, starting from virtually nothing, in addition to installing a lot of solar photovoltaics and, in Texas, wind turbines.

8.3.4. Land Required for Fossil Gas Infrastructure

The continuous use of fossil gas for electricity and heat results in the continuous and cumulative degradation of land for as long as fossil-gas use continues. Wells must be dug, and pipes must be laid every year to supply a world thirsty for fossil gas. When gas wells become depleted after 20 to 30 years, new wells must be drilled. Fifty thousand new fossil-gas wells are drilled each year in North America alone to satisfy fossil gas demand[192]. The land area required for the well pads, roads, and storage facilities for these new wells amounts to 2,500 square kilometers of additional land consumed per year. Once a gas well is depleted, it is sealed and abandoned, and a portion of the abandoned land cannot be used for any other purpose. The United States alone has 1.3 million active oil-and-gas wells and 3.2 million abandoned ones. Worldwide, an estimated 29 million wells are abandoned. Two-thirds of these are estimated to leak methane and other hydrocarbons[193]. The fossil gas infrastructure also requires land for underground and aboveground pipes, power plants, fueling stations, and underground storage facilities.

The flammability of fossil gas further results in explosions with fatal consequences in homes and urban areas. For example, on September 9, 2010, a fossil gas explosion in a San Bruno, California, neighborhood destroyed 38 homes, killed 8 people, and injured 58 others.

Fossil gas blowouts are also a danger to the local and regional community. For example, from October 23, 2015, to February 11, 2016, a major breach in the Aliso Canyon, California, underground fossil-gas storage facility caused 97,100 tonnes of methane, 7,300 tonnes of ethane, and a host of other hydrocarbons to spew into the air. The result was not only damage to the health of nearby residents but also the possible death from air pollution of up to a few dozen people across California[194].

The fossil-fuel infrastructure currently occupies about 1.3 percent of the land area of the United States[10]. This is due, not only to active and abandoned oil-and-gas wells, but also to coal mines, oil refineries; millions of kilometers of pipelines and the clear-cut areas around them, power plants, fueling stations, fossil-gas processing stations, and fossil-gas storage facilities. Whereas all fossil fuels contribute to this land area degradation, fossil gas' share is growing due to the replacement of coal by fossil gas, particularly by hydraulically-fracked gas. The damage due to fracking includes damage, not only to the landscape, but also to groundwater, into which fracked fossil gas often leaks. Additional damage occurs to roads, which must carry heavy trucks associated with fossil-gas development. Gas flaring is another form of damage, as flaring emits soot (particles containing black carbon), which causes health damage, warms the air, evaporates clouds, and melts snow.

8.4. Why Not Carbon Capture With Fossil Gas or Coal?

A proposal to help solve the climate problem that does little more than keep the fossil-fuel and bioenergy industries in business, is to capture carbon dioxide emitted from stationary fossil-fuel, bioenergy, and chemical emission sources before the gas escapes from the exhaust stack of the source. The carbon dioxide is then piped and either stored underground or used by industry. The carbon dioxide is captured with equipment added to the plant.

This solution does not help for 4 reasons. First, carbon capture always increases carbon dioxide, because it always requires equipment and electricity to run the equipment. Even in the best case, where renewable electricity powers the capture equipment, that same amount of renewable electricity will always reduce more carbon dioxide simply by replacing any combustion source of carbon dioxide. Thus, using renewable electricity for carbon capture is an opportunity cost that always increases carbon dioxide. Second, carbon capture always increases emissions of health-affecting gases and particles aside from carbon dioxide because of the additional electricity carbon capture requires. That extra electricity, if dirty, produces more emissions than no capture and, if clean, is no longer able to replace a dirty electricity source, thereby allowing the current plant to continue polluting as well as preventing the elimination of pollution from another plant. Third, again due to its additional need for electricity, carbon capture may increase the land degradation from the mining of fossil fuels compared with no capture. Fourth carbon capture permits fossil-fuel infrastructure to continue and, in fact, may increase it due to the additional energy requirements. In sum, carbon capture diverts funds from lower-cost renewables that reduce even more carbon dioxide and air pollutants and far more effectively than does carbon capture. These issues are discussed in detail next.

Carbon capture and storage (CCS) is the separation of carbon dioxide from other exhaust gases following fossil-fuel or biofuel combustion or chemical release, such as during cement or steel manufacturing. The captured carbon dioxide is then pressurized and transported, via pipeline, to an underground geological formation (such as a saline aquifer), a depleted oil-and-gas field, or an un-minable coal seam. The exhaust gases not captured are emitted to the air or filtered further. Geological formations worldwide may theoretically store up to two trillion metric tonnes of carbon dioxide, which compares with a 2022 carbon dioxide emission rate from fossil-fuel combustion and industrial-process chemical reaction of about 38.5 billion metric tonnes per year[129].

Another proposed CCS method is to inject the carbon dioxide into the deep ocean. Because carbon dioxide is an acid, this method acidifies the ocean. Since the Industrial Revolution, a high fraction of carbon dioxide emitted to the air worldwide has dissolved in ocean water, similarly increasing ocean acidity. Some carbon dioxide injected into the deep ocean will also eventually work its way back to the surface and evaporate to the air. A third proposed sequestration method is to mix captured carbon dioxide with concrete, trapping the gas inside the concrete.

Carbon capture and use (**CCU**) is the same as CCS, except the carbon dioxide isolated during carbon capture is sold to industry to pay back the cost of the carbon-capture equipment and its energy consumption. To date, the major application of CCU has been **enhanced oil recovery**. In fact, by the end of 2023, about 82.1 percent of all carbon dioxide captured worldwide for storage or use had been used for enhanced oil recovery[195]. With this process, captured carbon dioxide is piped to an oil field, where it is pumped underground. There, it binds with the oil, reducing the oil's density and allowing it to rise to the surface faster. Once the oil is extracted, some of the carbon dioxide is separated from it and sent back into the field. However, during transport and separation, and due to the energy needed to inject carbon dioxide into the well, 30 to 40 percent of all carbon dioxide originally captured is released back to the air[196,197].

Enhanced oil recovery also results in about two additional barrels of oil for every tonne of carbon dioxide injected into the oil field. When this is burned, it produces even more air pollution and carbon dioxide emissions.

Transition highlight. Burning two barrels of oil releases 0.86 tonnes of carbon dioxide to the air. Because one tonne of carbon dioxide added to an oil field for enhanced oil recovery produces two barrels of oil, 86 percent of that carbon dioxide is released back to the air upon burning the oil. However, only 20 to 80 percent of the oil produced from enhanced oil recovery is new oil that does not replace oil that would otherwise be produced. Thus, only the emissions from burning 20 to 80 percent of the oil due to enhanced oil recovery can be considered new emissions. Burning such oil releases 17 to 69 percent of the carbon dioxide originally captured. Adding that to the 30 to 40 percent released during enhanced oil recovery gives a total release rate of originally-captured carbon dioxide of 47 to 109 percent.

Another proposed use of carbon dioxide has been to create carbon-based fuels (**electro-fuels**) to replace gasoline, diesel, methanol, and jet fuel. Carbon-based electro-fuels suffer multiple issues, as discussed in Section 8.7.

8.4.1. Air-Pollution and Climate Impacts of Fossil Sources With Carbon Capture

Proponents of carbon capture claim that capture equipment removes 90 percent or more of carbon dioxide from a fossil-fuel exhaust stream. However, real data show that the annually averaged carbon dioxide capture efficiency is only 10 to 80 percent[198]. This is because the carbon-capture equipment runs less efficiently over time; the carbon-capture equipment is down due to unplanned or planned maintenance; and/or the facility taking the carbon dioxide for use (e.g., enhanced oil recovery) or storage is temporarily not taking the carbon dioxide.

The capture efficiency accounts only for carbon dioxide captured from a smokestack. But running carbon-capture equipment requires electricity. The amount of such electricity is embodied in the energy penalty. The **energy penalty** of carbon capture is the percentage of fuel burned in an electricity-producing plant that must be dedicated to carbon capture for a fixed quantity of work output by the plant. It has a theoretical range of 11 to 40 percent[199] and a practical range of 13 to 44 percent[200]. The electricity is used to separate the carbon dioxide from the gas mixture, compress the carbon dioxide for pipe transport, move the carbon dioxide through the pipeline, and store or use the carbon dioxide.

The electricity required for the energy penalty usually comes from fossil fuels. Mining, transporting, and using such fuels produce emissions of carbon dioxide, methane, and air pollutants. If the fossil fuels used to run the capture equipment are from a different power plant from the plant housing the equipment, then none of the emissions associated with the extra fuel used to run the equipment are captured. Otherwise, only 10 to 80 percent are captured. In addition, none of the carbon dioxide, methane, or air pollutants emitted during the mining of the fossil fuels used at the power plant where the capture equipment is housed, are ever captured.

When all carbon dioxide and methane emissions are accounted for from mining, transporting, and combusting fossil fuels for normal electricity production in a fossil-fuel power plant, and the energy penalty associated with carbon-capture equipment is also accounted for, the overall capture efficiency of the plant with carbon capture declines to between zero and 25 percent. Even in the best case of using renewable electricity to run the carbon-capture equipment, that renewable electricity would reduce more carbon dioxide by replacing the fossil fuel in the first place. As such, even in the best case of using renewable electricity to run capture equipment, carbon capture always increases carbon dioxide relative to using that renewable electricity to replace a fossil source

Further, capture equipment captures only carbon dioxide, not health-affecting air pollutants. Also, no health-affecting pollutants are captured during the mining of fossil fuels for normal power plant operations or the additional fuel needed for the energy penalty. Because more fossil fuels are needed to run the capture equipment, carbon capture increases air pollution relative to no capture. In fact, most equipment capturing carbon dioxide from exhaust gas uses a nitrogenbased solvent to bind to the carbon dioxide. The chemical reaction results in the production of some ammonia gas, which is released to the air. Because ammonia is soluble, it dissolves in aerosol particles containing water, producing the ammonium ion, increasing aerosol-particle mass. Aerosol particles cause 90 percent of air-pollution deaths. Thus, a lot of carbon-capture equipment produces a harmful air pollutant released to the local area.

To summarize,

1) Carbon-capture equipment captures 75 to 90 percent of the carbon dioxide in a concentrated exhaust stream when operating at its fullest and best.
2) However, the carbon-capture equipment may be shut down regularly, either due to a lack of demand for the captured carbon dioxide or due to scheduled or unplanned maintenance of the capture equipment. These factors result in the yearly averaged capture rate of the carbon dioxide exhaust stream declining to 10 to 80 percent[198].
3) Carbon-capture equipment does not capture the upstream carbon dioxide or other greenhouse gas emissions resulting from mining, transporting, or processing the fossil fuel used in the plant emitting carbon dioxide. Accounting for these emissions further reduces the overall carbon dioxide capture rate.
4) Carbon-capture equipment does not capture any of the health-affecting air pollutants from the fossil-fuel exhaust stream or from the upstream mining, transporting, or processing of the fossil fuel. Such pollutants include carbon monoxide, nitrogen oxides, sulfur dioxide, organic gases, mercury, toxins, black carbon, brown carbon, and fly ash, all of which affect health.
5) A fossil plant with carbon capture needs 13 to 44 percent more electricity to run the carbon-capture equipment than is needed by a plant without the equipment[200]. If that energy comes from a fossil fuel, the plant then emits even more uncaptured carbon dioxide. If that energy comes from a renewable source, the use of the renewable energy for carbon capture prevents the energy from displacing fossil-fuel energy. In both cases, fossil-fuel mining and infrastructure and air pollution increase 13 to 44 percent relative to no capture.
6) Most carbon-capture equipment releases ammonia, a harmful pollutant, to the air.
7) If the captured carbon dioxide is used for enhanced oil recovery or to produce synthetic fuels, 47 to 109 percent of the captured carbon dioxide is released back to the air.
8) If the captured carbon dioxide is sequestered underground, some of it leaks back into the air over time.
9) Even in the best case of using renewable electricity to power carbon-capture equipment, carbon capture increases carbon dioxide, air pollution, fossil-fuel mining, and fossil-fuel infrastructure because that renewable electricity could otherwise reduce more carbon dioxide and eliminate all air pollution, mining, and infrastructure from a fossil-generating source simply by replacing the source.
10) Thus, the use of renewable electricity for carbon capture is an opportunity cost that increases carbon dioxide, air pollution, fossil-fuel mining, and fossil-fuel infrastructure[68,201,202].

8.4.2. Carbon Capture Projects

By the end of 2023, carbon dioxide was actively being captured in 41 projects worldwide: 15 fossil-gas processing facilities, 3 coal-fired power plants, 2 oil refineries, 4 ethanol refineries, 6 chemical plants, one iron and steel manufacturing plant, 7 facilities for producing hydrogen from fossil gas for ammonia production, 2 multisource carbon dioxide pipelines, and 1 direct-air capture plant[195]. Of all the carbon dioxide captured among these projects, 82.1 percent was used for enhanced oil recovery[195]. The rest was sequestered underground.

The maximum possible capture capacity among these 41 projects was 64.8 million tonnes of carbon dioxide per year[195], which is only 0.17 percent of the 38.5 billion metric tonnes per year emitted in 2022 due to fossil-fuel combustion and chemical reactions[129]. However, of the carbon dioxide going to enhanced oil recovery, 47 to 109 percent is released back to the air (Section 8.4). This leaves the maximum capture capacity at 0.1 percent of world emissions. Further the actual capture rate ranges from 10 to 80 percent of the maximum capture capacity, reducing the capture rate to an average of 0.045 percent of world emissions.

As of 2024, only two fossil-fuel electric-power-generating plants with carbon-capture equipment had sufficient public data to analyze. The carbon-capture equipment of one of the plants was shut off in 2019. In both cases, the separated carbon dioxide was used for enhanced oil recovery. These projects, plus a third, the largest carbon capture project in the world at the time, in which carbon dioxide from a liquefied-natural-gas processing facility was being captured and stored, are discussed. All 3 captured little carbon and increased air pollution and fossil-fuel mining.

8.4.2.1. Boundary Dam Project

The first electric power plant with CCU equipment was the Boundary Dam power station in Estevan, Saskatchewan, Canada. This plant has been operating with CCU equipment on one coal boiler connected to a steam turbine since October 2014. The cost of the retrofit project was $1.47 billion, which included a $240 million subsidy from the Canadian government. The remaining $1.23 billion was paid for by coal-plant electricity customers as an additional charge added to their normal bills. From 2015 through the end of 2023, the average carbon dioxide capture efficiency from the exhaust stream of this plant was 57 percent[203]. Whereas, during some years, the capture efficiency was as high as 66 percent, in others, it was as low as 36 percent. The captured carbon dioxide has all been sold for enhanced oil recovery. Of all carbon dioxide used for enhanced oil recovery, 30 to 40 percent is lost during carbon dioxide transport to and processing within the oil field[196,197]. Another 20 to 80 percent is emitted due to the additional oil produced, depending on whether it is replacing other oil or is new oil. That means that only some or none of the original coal plant emissions are stored underground, on average, and the rest are released to the air. Even that capture rate ignores the fact that the Boundary Dam project required the coal plant to produce 25 percent more electricity to run the carbon-capture equipment, and this resulted in 25 percent more coal mining, combustion, and emissions. In addition, none of the carbon dioxide or air pollution from the mining of the coal was ever captured.

8.4.2.2. Petra Nova Project

The second coal plant with carbon-capture was the W.A. Parish coal power plant near Thompsons, Texas. The plant was retrofitted with carbon-capture equipment as part of the Petra Nova project and began using the equipment during January 2017. The carbon-capture equipment received 36.7 percent of the emissions from a 654-megawatt boiler at the coal plant. The equipment required almost 0.5 kilowatt-hours of electricity to run per kilowatt-hour of electricity produced by the coal plant. An entire fossil-gas turbine with a heat-recovery boiler was built to provide this electricity. A cooling tower and water treatment facility were also added. The retrofit cost $1 billion ($4,200 per kilowatt) beyond the coal plant cost[201]. Due to poor economics, carbon capture was halted at the plant in December 2019.

During operation, captured carbon dioxide was compressed and piped to an oil field, where it was used to enhance oil recovery. Carbon dioxide from the fossil-gas turbine was not captured. The mining and transport of fossil gas also emitted uncaptured carbon dioxide, methane, and air pollutants. Upstream carbon dioxide, methane, and air pollutants from the coal plant itself were also uncaptured. Finally, most of the captured carbon dioxide was released back to the air during enhanced oil recovery.

More specifically, during 2017, only 55.4 percent of the carbon dioxide from the coal-combustion exhaust was captured. When uncaptured carbon dioxide from fossil gas combustion and uncaptured carbon dioxide and methane from mining and processing the coal and fossil gas used are also accounted for, the overall capture rate of CO_2-equivalent emissions was only 10.8 percent over a 20-year time frame and 20 percent over a 100-year time frame[201]. Of the carbon dioxide captured, 47 to 109 percent was then emitted back to the air during enhanced oil recovery (Section 8.4). During the entire 3-year operation of the plant, the capture efficiency from the coal exhaust was a bit higher, 65 percent[198]. However, this does not change the conclusion that this project resulted in virtually no reduction in CO_2-equivalent emissions while increasing fossil-gas mining and air pollution versus no capture.

Using wind instead of fossil gas to power the carbon-capture equipment could have reduced CO_2-equivalent emissions before enhanced oil recovery by 37.4 percent over 20 years and 44.2 percent over 100 years, versus no capture, which is a greater reduction than with gas. The decrease is greater because wind results in no fossil-gas mining or combustion emissions.

However, using the wind electricity that powered the carbon-capture equipment instead to replace coal electricity directly would reduce CO_2-equivalent emissions over both 20 and 100 years by 49.7 percent, more than in the other cases. Thus, it is better to use new WWS electricity to eliminate a carbon dioxide source, and thus prevent carbon dioxide from being emitted in the first place, than to use the same WWS electricity to extract carbon dioxide from the source with carbon capture.

The climate benefit of using WWS electricity to replace fossil-fuel electricity instead of to power carbon-capture equipment is only part of the story. Carbon capture does not reduce any air pollution from the coal plant or coal mine. Instead, it increases air pollution when a fossil fuel is used to provide power for the capture equipment. Even when wind powers the capture equipment, air pollution continues from the coal plant and coal mine. Only when wind replaces the coal plant itself does air pollution from both the coal plant and coal mine decrease.

In sum, the social cost (equipment plus health plus climate cost) of coal-CCU powered by fossil gas is over twice that of wind replacing coal directly and even higher than that of doing nothing. The social cost of using wind to power CCU equipment is also much higher than using the same wind to replace a coal plant. In other words, the best strategy is to use WWS to replace fossil fuels[201]. This conclusion is independent of the fate of the carbon dioxide after it leaves the carbon-capture equipment, and it applies to CCS or CCU with bioenergy or cement manufacturing as well.

When the fate of captured carbon dioxide is considered, the problem deepens. If carbon dioxide is sealed underground, few additional emissions may occur. However, if the captured carbon dioxide is used to enhance oil recovery, its current major application, 47 to 109 percent of the captured carbon dioxide is released back to the air. If the captured carbon dioxide is used to a create carbon-based fuel to replace gasoline and diesel, energy is still needed to produce the fuel, the fuel is still burned in vehicles (creating pollution), and little net carbon dioxide is captured. A fourth application is to use the carbon dioxide to produce carbonated drinks. However, most carbon dioxide in carbonated drinks is released back to the air during consumption.

8.4.2.3. Gorgon Project

A third project is the world's largest CCS plant, which is attached to the Gorgon liquefied natural gas (LNG) facility on Barrow Island, 130 kilometers off the northwest coast of Australia. On March 21, 2016, the facility started converting a portion of the extracted gas to LNG for export and using the rest for local consumption. The raw gas from the Gorgon field near Barrow Island contains about 15 percent carbon dioxide. The Australian government permitted the LNG facility on the condition that 80 percent of the carbon dioxide from the gas be captured and injected two kilometers below Barrow Island, starting the day LNG exports commenced. The CCS equipment cost \$3 billion[Error! Reference source not found.].

Delays prevented capture and injection until August 2019. Inefficiencies and problems limited capture rates thereafter. As a result, over the 5 years between 2016 and 2021, only 32 percent of the carbon dioxide emitted from the LNG facility exhaust stream was captured[198]. The rest was released to the air. Also, a portion of the fossil gas for domestic consumption provided electricity to run the CCS equipment. The burning of this gas emitted enough carbon dioxide to cause the net carbon dioxide emissions from the CCS facility to be positive. Thus, instead of reducing it, the Gorgon CCS plant likely increased carbon dioxide emissions and at a cost of \$3 billion.

In sum, carbon capture is not close to a zero-carbon technology. For the same energy cost, wind turbines and solar panels replacing fossil fuels reduce much more carbon dioxide and also eliminate fossil-fuel air pollution and mining, which carbon capture increases. Using renewables to replace fossils also reduces oil-and-gas pipelines, refineries, gas stations, tanker trucks, oil tankers, and coal trains, oil spills, oil fires, gas leaks, gas explosions, and international conflicts over energy. Carbon capture increases these by increasing energy use.

8.5. Why Not Gray, Blue, or Brown Hydrogen?

In a WWS world, hydrogen should be used primarily for long-distance heavy transport; steel and ammonia manufacturing, grid-electricity storage, and electricity and heat production in microgrids. It should not be used for heating buildings, providing high-temperature heat for industry, or powering passenger vehicles. If it were to be used to heat buildings, it would need to be used either on its own or mixed with fossil gas in existing fossil-gas pipes or run through new hydrogen-specific pipes. However, hydrogen cannot be used in existing gas pipes without high leakage rates, and new pipes are expensive. What is more, burning hydrogen for heat in a building produces air pollutants (oxides of hydrogen and oxides of nitrogen, in particular) and, like burning fossil gas, is much less efficient than using an electric heat pump to provide heat. As such, hydrogen should not be used as a replacement for fossil gas to heat buildings, and proposals to do this have not materialized[204]. Similarly, burning hydrogen for high-temperature heat in industry creates air pollution. Using hydrogen in passenger vehicles can be clean if the hydrogen is produced from wind or solar electricity, but doing so requires up to 3 times the number of wind turbines or solar panels as using the same wind or solar electricity to power battery-electric vehicles.

For its useful applications, hydrogen should be only green hydrogen: produced by electrolysis or photoelectrochemical water splitting, where the electricity comes from WWS in both cases. This section discusses why hydrogen should not be so-called gray, blue, or brown hydrogen.

Three methods of producing hydrogen from fossil gas are steam methane reforming, autothermal reforming, and methane pyrolysis. When not coupled with carbon capture, the hydrogen resulting from steam methane reforming and autothermal reforming is referred to as **gray hydrogen**. When those two methods are coupled with carbon capture, the hydrogen is referred to as **blue hydrogen**. When hydrogen is produced from methane pyrolysis, the hydrogen is referred to as **turquoise hydrogen**. When hydrogen is produced from coal gasification, the hydrogen is referred to as **brown hydrogen**. Each of these techniques is discussed, in turn.

8.5.1. Steam Methane Reforming

Steam methane reforming is a method of producing hydrogen by mixing methane with steam at a high temperature (700 to 1,000 degrees Celsius) and pressure (3 to 25 times atmospheric pressure). Fossil gas is needed for two purposes during steam methane reforming. The first is to provide the energy needed for high temperatures and pressures. The second is to provide the methane used in the chemical reactions that produce hydrogen. During the steam reforming process, methane in fossil gas reacts with two water vapor (H_2O) molecules to form 4 hydrogen molecules (H_2) and a molecule of carbon dioxide. About 96 percent of hydrogen production worldwide in 2019 was from steam methane reforming. This method of hydrogen production consumes about 6 percent of all fossil gas globally[162].

During the mining, transporting, and processing of the fossil gas that arrives at a steam methane reforming plant, gaseous air pollutants, black carbon particles, carbon dioxide, and methane are released to the air. Gaseous air pollutants, black carbon, and carbon dioxide are emitted because mining requires construction equipment, which runs on diesel fuel that pollutes when burned. Mining also requires concrete production for wells, which results in pollution. Trees are also uprooted and land is trenched for pipes. Those processes require diesel and gasoline machinery and vehicles, resulting in even more pollution. Tree-clearing releases stored carbon to the air as carbon dioxide.

Methane leaks from both active and abandoned fossil-gas wells. The United States has 1.3 million active wells and 3.2 million abandoned wells. Worldwide, 29 million oil-and-gas wells have been abandoned, and two-thirds are estimated to leak[193].

Methane leak rates from two of the world's largest fossil gas fields, in Turkmenistan, are estimated by satellite to be 4.1 percent[187]. Leak rates in the US are between 1.2 and 9.4 percent. Methane also leaks from pipes running between gas wells and the fossil-gas processing center (where impurities are removed from fossil gas). More leaks occur at the processing center itself, from pipes running between the processing center and the hydrogen plant, and at the hydrogen plant itself. In addition, electricity from fossil gas is used to compress and transport fossil gas through pipes and to process the fossil gas at the processing station. Generating that electricity results in more emissions. An overall estimate of the worldwide average methane emission rate from fossil-gas mining and transport is 3.5 (1.5 to 4.3) percent[162].

In sum, the production of hydrogen from steam methane reforming results in gaseous air pollution, black carbon particles, carbon dioxide, and methane emissions from mining, transporting, and processing fossil gas and from using the mined fossil gas for energy and as a feedstock[162].

8.5.2. Autothermal Reforming

Another method of producing hydrogen from fossil gas is **autothermal reforming**. With this method, fossil gas is brought to an autothermal reforming facility. However, instead of methane reacting with water vapor, it reacts with pure oxygen to produce a carbon dioxide molecule and two hydrogen molecules. This reaction releases heat, which reduces the need for additional fossil-fuel energy to produce heat for this process

One shortcoming of autothermal reforming is that it produces only two molecules of hydrogen per molecule of methane, whereas steam methane reforming produces 4 molecules of hydrogen per molecule of methane. As such, more methane is needed with autothermal reforming than with steam methane reforming to produce the same quantity of hydrogen. Autothermal reforming also produces carbon monoxide (CO), so additional equipment is needed to react carbon monoxide with steam (H_2O) at high temperature to produce carbon dioxide and one more hydrogen molecule. Even when this is done, though, a maximum of 2.89 molecules of hydrogen can be obtained per molecule of methane[205] (versus 4 molecules of hydrogen with steam methane reforming). Thus, autothermal reforming always requires at least 38 percent more methane mining (resulting in 38 percent more methane leakage) than steam methane reforming to produce the same quantity of hydrogen. A third disadvantage of autothermal reforming is that it requires pure oxygen, which must be separated from air. Separation requires equipment and energy. For these 3 reasons, steam methane reforming is generally preferred by industry over autothermal reforming[206].

The inefficiency and emissions from autothermal reforming can be reduced slightly by using some of the hydrogen produced by the autothermal reforming process in a fuel cell to generate the electricity for oxygen separation from the air. The fuel cell also releases heat that can be used for the autothermal reforming process. However, this means a fuel cell must be purchased and more methane is needed to produce the additional hydrogen needed for the fuel cell. More methane means more fossil-gas mining, transporting, and processing, thus more upstream air pollution, carbon dioxide, and methane emissions. More methane consumption also means more carbon dioxide emitted during the autothermal reforming process.

Some have proposed to capture the carbon dioxide during steam methane reforming and autothermal reforming, resulting in the hydrogen produced becoming blue hydrogen. During steam methane reforming, carbon dioxide emissions occur during two processes: combustion to produce electricity and heat, and chemical reactions to produce hydrogen. Additional emissions arise from powering carbon-capture equipment.

During autothermal reforming (coupled with a hydrogen fuel cell), carbon dioxide emissions arise from the chemical reactions that produce hydrogen but not from combustion to produce energy. That is because heat is provided by both the chemical reaction producing hydrogen and by the fuel cell. So only carbon dioxide from chemical reaction needs to be captured. However, far more carbon dioxide is produced and needs capturing per molecule of hydrogen produced with autothermal reforming than with steam methane reforming. Also, much more equipment is needed with autothermal reforming than with steam methane reforming.

Whereas carbon dioxide capture rates from chemical reaction during steam methane reforming or autothermal reforming can be 90 percent or more when the capture equipment is fully operational, real annually averaged capture rates of pure carbon dioxide streams from steam reforming equipment have been reported as only an average of 78.8 percent[198]. The reasons are that capture equipment is often down for scheduled or unscheduled maintenance; the demand for carbon dioxide is temporarily low; or the capture equipment is less efficient than expected. Capture rates of carbon dioxide from energy production (relevant only to the steam reforming process) are even lower, ranging from 10 to 70 percent[198].

The carbon dioxide that is captured with both steam methane reforming and autothermal reforming must be piped to either an underground storage facility or an industrial facility, where it is used. Piping requires additional energy and results in additional emissions. Of the carbon dioxide that is captured and piped for enhanced oil recovery, for example, 47 to 109 percent is released back to the air (Section 8.4). In addition, neither steam methane reforming nor autothermal reforming reduces upstream emissions or leaks of air pollutants, carbon dioxide, or methane.

Because of the need for additional equipment and energy required for the carbon-capture equipment, steam methane reforming with carbon capture (blue hydrogen) may reduce the warming impact of steam methane reforming with no carbon capture (gray hydrogen) by only 9 to 12 percent over a 20-year time frame[162]. Blue hydrogen, of course, always costs more than gray hydrogen because blue hydrogen requires carbon-capture equipment, pipes, and additional energy not required by gray hydrogen.

8.5.3. Methane Pyrolysis

Methane pyrolysis was discussed in Section 7.2 with respect to converting biological sources of methane to hydrogen. So long as the heat used for methane pyrolysis comes from a WWS source and the methane comes from a biological source, such as landfill gas, methane pyrolysis results in no carbon dioxide emissions, modest methane emissions (depending on the methane conversion efficiency during pyrolysis), and some air-pollution emissions. However, if the methane comes from fossil gas, the upstream emissions of methane, carbon dioxide, black carbon, and air pollutants are significant, just as with steam methane reforming and autothermal reforming[162].

8.5.4. Coal Gasification

Hydrogen can also be produced by **coal gasification**. With this process, coal reacts with oxygen gas and steam under high temperature and pressure to form a mixture of hydrogen gas, carbon monoxide, carbon dioxide, and other chemicals. After impurities are removed, the carbon monoxide reacts with steam to form more hydrogen. Coal gasification results in more carbon dioxide and other pollutant emissions than does steam reforming of methane. Continuous coal mining and transport result in additional fossil-fuel combustion emissions, leaked methane, and land degradation. Additional energy is needed to create the high temperatures and pressures for the gasification process. Hydrogen from coal gasification is referred to as **brown hydrogen**.

In sum, because the steam reforming, autothermal reforming, and coal gasification processes emit carbon dioxide, methane, and other pollutants and degrade land, they are not suitable candidates for producing hydrogen in a 100 percent WWS world. In a WWS world, all carbon and pollution emissions and continuous fuel mining are eliminated. The simplest and cleanest type of hydrogen in a WWS world is green hydrogen.

8.6. Why Not Synthetic Direct Air Carbon Capture?

Synthetic direct air carbon capture and storage (SDACCS) is the removal of carbon dioxide from the air by its chemical reaction with other chemicals followed by sequestration of the carbon dioxide, either underground or in a material. **Synthetic direct air carbon capture and use (SDACCU)** is the same as SDACCS, except that in this case, the captured carbon dioxide is sold for use in industry.

SDACCS/U should not be confused with **natural direct air carbon capture and storage (NDACCS)**, which is the natural removal of carbon dioxide from air by planting trees or reducing permanent deforestation (reducing open biomass burning). Growing a tree removes carbon dioxide and water vapor from the air naturally by photosynthesis and sequesters the carbon within organic material in the tree for decades to centuries while releasing oxygen to the air. Reducing open biomass burning similarly sequesters carbon in trees and eliminates emissions of health-affecting air pollutants and climate-affecting global warming agents (methane, black carbon, and brown carbon, for example) aside from carbon dioxide at the same time. Trees also absorb air pollutants, helping to filter them from the air.

Whereas NDACCS is recommended in a 100 percent WWS world, SDACCS/U is not. SDACCS/U is a cost, or tax, added to the cost of energy generation. As such, it raises energy costs. Because SDACCS/U requires equipment and carbon-dioxide pipelines, and because building and running equipment and pipes require electricity, SDACCS/U also increases carbon dioxide emissions rather than decreasing them. The reason is that the electricity used to run the capture equipment, even if renewable, would otherwise reduce more carbon dioxide by replacing a fossil-fuel or bioenergy carbon dioxide source. Similarly, by not replacing a fossil or bioenergy source with that renewable electricity, SDACCS/U projects increase air pollution, fossil mining, and fossil or bioenergy infrastructure. They also enable the fossil-fuel industry to continue operating by demotivating the need to replace fossils with WWS.

In sum, SDACCS/U will always increase carbon dioxide until all carbon-based electricity sources are eliminated. It will also increase air pollution and allow fossil mining and infrastructure and bioenergy infrastructure to continue.

8.6.1. How Does Air Capture Remove Carbon Dioxide from the Air?

In 1754, Joseph Black isolated carbon dioxide, which he named **fixed air**. He found that heating the odorless white powder magnesium carbonate [$MgCO_3$] released a gas (carbon dioxide) that could not sustain life or fire. The remaining solid, magnesium oxide [MgO] weighed less than the original magnesium carbonate. He similarly found that adding potassium carbonate [K_2CO_3] to magnesium oxide (MgO) in solution produced solid magnesium carbonate [$MgCO_3$]. The mass of $MgCO_3$ exceeded that of MgO by the same amount that was lost when $MgCO_3$ was heated to form MgO. The difference in mass in both cases was the mass of carbon dioxide. As such, Black not only captured carbon dioxide, but he also quantified the mass of carbon dioxide for the first time.

Today, an important air capture technique is to react carbon dioxide from the air with alkali metal oxides (Na_2O or K_2O, among others), alkali metal hydroxides [NaOH or KOH], alkaline Earth metal oxides [MgO or CaO], or alkaline Earth metal hydroxides [$Mg(OH)_2$ or $Ca(OH)_2$][207 207]. For example, a classic method of removing carbon dioxide from the air while recycling the material removing it is to expose the carbon dioxide to a large pool of calcium hydroxide [$Ca(OH)_2$,], also called slaked lime. The products of the reaction are calcium carbonate [$CaCO_3$] and water vapor. Heating the calcium carbonate to 427 degrees Celsius releases a concentrated stream of carbon dioxide that can be captured and used. The leftover calcium oxide [CaO] is then reacted with water to reform calcium hydroxide. The problem with this process is that it needs a continuous electricity input.

8.6.2. Opportunity Cost of Direct Air Capture

By removing carbon dioxide from the air, air capture does exactly what WWS generators, such as wind turbines and solar panels, do. This is because WWS generators replace fossil generators, preventing carbon dioxide from getting into the air in the first place. The impact on climate of removing one molecule of carbon dioxide from the air is the same as the impact of preventing one molecule from getting into the air in the first place.

However, WWS generators also (a) eliminate air pollutants aside from carbon dioxide from fossil-fuel combustion; (b) eliminate the upstream mining, transport, and refining of fossil fuels and the corresponding emissions; (c) reduce the oil-and-gas pipeline, refinery, gas station, tanker truck, oil tanker, and coal train infrastructure of fossil fuels; (d) reduce oil spills, oil fires, gas leaks, and gas explosions; (e) reduce international conflicts over energy; and (f) reduce the large-scale blackout risk associated with centralized power plants by decentralizing/distributing power. Air capture does none of that. Its sole job is to remove carbon dioxide from the air.

Transition highlight. To illustrate how synthetic direct air capture increases carbon dioxide, consider the world's second, and largest at the time, direct-air-capture plant. The plant, built in Iceland by Climeworks, is designed to capture up to 36,000 tonnes per year of carbon dioxide and store it underground. Large fans blow air over an adsorbent. The adsorbent reacts with carbon dioxide in the air, extracting it. Heat then releases pure carbon dioxide from the adsorbent. The released pure carbon dioxide is piped underground to a sequestration site. According to Climeworks, about 5,000 to 6,000 kilowatt-hours of electricity and electricity converted to heat are needed to remove one tonne of carbon dioxide from the air and store it[208]. This is more than twice the 2,000 to 3,000 kilowatt-hours per tonne claimed by industry[208] and translates to 167 to 200 grams of carbon dioxide removed from the air per kilowatt-hour of electricity consumed. In the best case, the electricity used for air capture is WWS electricity.

However, because WWS electricity is limited, if it is used for air capture, it cannot be used to replace a coal or fossil-gas electricity or heat source. Using one kilowatt-hour of WWS electricity to replace coal electricity eliminates about 1,380 grams of carbon dioxide-equivalent emissions over a 20-year time frame (930 from coal combustion and 450 from coal mining)[201]. Thus, using WWS electricity for air capture instead of for replacing coal electricity increases carbon dioxide in the air by a factor of 7 to 8. Using WWS for air capture instead of for replacing coal also prevents the elimination of air pollution, mining, and infrastructure associated with the coal plant.

In the present case, the electricity and heat generated for the Iceland air capture plant are geothermal electricity and heat, and Iceland produces no coal electricity. However, Iceland is increasingly using coal for industrial heat. Coal and fossil gas for heat emit about 440 grams of CO_2-equivalent per kilowatt-hour of fuel energy[162]. Mining of coal and gas produces another 215 grams, for a total of 655 grams of CO_2-equivalent per kilowatt-hour of coal or gas over a 20-year time frame (ignoring the transport of coal or gas overseas to Iceland). Given that one kilowatt-hour of geothermal electricity produces about one kilowatt-hour of high-temperature heat to replace coal, using geothermal electricity for air capture instead of for replacing coal (or gas) for heat increases carbon dioxide emissions by a factor of 3.3 to 4.

On an absolute basis, using equipment and energy to remove carbon dioxide from the air results in little carbon removal. In one air capture plant, for example, electricity for the equipment was provided by a fossil gas combined cycle turbine. Mining, transporting, processing, and burning of the gas produced air pollutants, methane, and carbon dioxide. Such emissions were so large that, averaged over 20 and 100 years, they offset 89.5 and 69 percent, respectively, of all carbon dioxide captured by the plant[201].

The social cost of air capture includes the costs of capture equipment, fossil-gas electricity used to run the equipment, and air-pollution health problems due to the electricity use, less the cost benefit of removing carbon dioxide from the air. The social cost of running the air capture plant in this example is about 8 times that of using the same electricity, but powered by wind, to replace part of a coal plant[201]. The reason is that wind replacing coal eliminates all air pollution and more carbon dioxide than does direct air capture, and incurs no carbon-capture equipment cost. Even when wind, instead of fossil gas, powers the air capture plant, the social cost of using wind to power air capture is still 5 times that of using wind to replace part of a coal plant[201]. In fact, there is no case where wind powering air capture has a social cost below that of using wind to replace a fossil-fuel or biomass power plant[201]. This is because wind-powering-air capture always incurs an equipment cost, never reduces air pollution, and reduces only a modest amount of carbon dioxide. Wind replacing a fossil plant incurs no extra equipment cost, reduces air pollution and mining from the fossil plant, and reduces more carbon dioxide emissions than does air capture.

An argument for using air capture is that it will be needed to remove airborne carbon dioxide once all fossil fuels are replaced with 100 percent WWS. If all energy is provided by WWS at that point, air capture should reduce carbon dioxide without increasing air pollution. However, at that point, the question will be whether growing more trees, reducing open biomass burning; reducing agriculture and waste burning; or reducing halogen, nitrous oxide, or nonenergy methane emissions is more cost-effective for limiting further global warming than is air capture. Thus, air capture may or may not be useful even after fossil fuels are no longer used.

In sum, as with carbon capture, direct air capture is not close to a zero-carbon technology. For the same energy cost, wind turbines and solar panels replacing fossil or biomass combustion sources reduce far more carbon dioxide while also eliminating fossil air pollution, mining, and infrastructure, which air capture increases.

8.7. Why Not Nonhydrogen Electro-fuels?

Electro-fuels are synthetic fuels that replace gasoline, diesel, methanol, ethanol, and jet fuel as transportation fuels. They are made from molecular hydrogen created by electrolysis (hence the prefix, "electro") and carbon dioxide from carbon capture or synthetic direct air capture. The simplest electro-fuel is hydrogen itself. When produced from clean, renewable WWS electricity and used in a fuel cell to power a long-distance aircraft or ship, green hydrogen is a useful electro-fuel. Gray, blue, and brown hydrogen, on the other hand, are not useful or recommended (Section 8.8).

Methanol (CH_3OH) is the next-simplest electro-fuel. It is produced from 3 hydrogen molecules (H_2) reacting with one carbon dioxide molecule (CO_2). A byproduct of this reaction is water (H_2O). Ethanol (C_2H_5OH) is similarly created from 6 hydrogen molecules and two carbon dioxide molecules. A byproduct is 3 water molecules. Synthetic methanol and ethanol are proposed to replace methanol derived from fossil gas and ethanol derived from corn, respectively, for ground transportation. Synthetic ethanol is also competing with other nonpetroleum hydrocarbon-based fuels to replace jet fuel for air travel. Such nonpetroleum fuels are referred to as sustainable aviation fuels (SAFs). Ethanol produced from corn is similarly vying to become an SAF.

Gasoline contains many long-chain hydrocarbons. Such hydrocarbons can be manufactured synthetically as an electro-fuel by first converting many carbon dioxide molecules to carbon monoxide molecules and then reacting the carbon monoxide with molecular hydrogen. The result is a distribution of hydrocarbon with different numbers of carbon atoms, similar to gasoline.

The argument for using these electro-fuels is that they eliminate the reliance on fossil-fuel mining and corn-growing. However, aside from green hydrogen, electro-fuels should not be supported as a solution to air pollution, global warming, and energy insecurity. The reasons are (1) all such fuels are still combusted, creating air pollution, and in the case of SAFs, contrails; (2) since carbon capture and direct air capture are opportunity costs that increase air pollution, carbon dioxide, fossil mining, and fossil infrastructure (Sections 8.4 and 8.9), so are carbon-based electro-fuels; (3) carbon-based electro-fuels all require chemicals and energy, in addition to captured carbon dioxide, causing their emissions to be similar to or higher than the fossil fuels or biofuels they replace; and (4) biofuel-based electro-fuels (e.g., ethanol-based SAF) suffer from the same problems as ethanol with or without carbon capture (Section 8.9).

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