Carbon Removal from the Atmosphere

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Table of Contents Page

1. Summary

Global warming and climate change are associated with increases in atmospheric carbon dioxide (CO_2) levels caused by the burning of fossil fuels (chiefly natural gas, fuels made from petroleum, and coal). CO_2 concentration had remained essentially constant at 280 parts per million (ppm) for centuries before the industrial revolution began. It is now nearly 430 ppm and has been increasing 5 ppm per year.

Estimated energy-related fossil CO_2 emissions in the United States peaked at 6.0 billion metric tons ("tonnes") in 2005 and had declined to 4.8 billion tonnes in 2023, due primarily to efficiency improvements, more electricity from solar and wind, and lower coal usage. Although large additional reductions are expected in the next two or three decades, reaching the goal of zero fossil carbon emissions by affordable strategies will be very challenging. Further innovations in both technology and governmental actions are needed.

The author joins many others who feel that strategies to affordably remove large quantities of CO_2 from the atmosphere should also be implemented, leading to the replacement of annual additions by annual subtractions. This essay discusses two proposed strategies to remove an annual total of 5.0 billion tonnes from the atmosphere. He does believe that fossil emissions can be reduced to near zero by the 2050s, giving a combined reduction below 2023 approaching 10 billion tonnes per year.

The recommended removal strategies use permanent underground sequestration of captured CO_2. Most of the capture would use Direct Air Capture (DAC) systems, which contact ambient air with alkaline water solutions. The systems are fueled by natural gas or coal (with total capture and sequestration of their fuel carbon in addition). The balance of the capture would occur during the manufacture of biofuels from biomass crops and wastes.

Moderate fees paid by all energy buyers would fund DAC-system capital and operating costs. The selling prices of biofuels would include an increment for carbon capture and sequestration costs.

2. Introduction

The concentration of carbon dioxide (CO_2) in the atmosphere has already risen by over 50% above pre-industrial levels due to emissions from burning fossil fuels (coal, petroleum, and natural gas) and continues to increase each year. This higher CO_2 concentration has been linked to increases in global warming, which contribute to sea-level rise and more extreme weather. Severe economic costs, loss of life, and other adverse impacts result. Atmospheric CO_2 acts as a greenhouse gas which reduces heat losses from the earth to space, causing higher average surface temperatures.

Numerous programs are underway worldwide which seek to significantly reduce CO_2 emissions from future fossil fuel uses.

Considerable ongoing CO_2 emissions come from biomass, which have no adverse impact on atmospheric CO_2 levels since they merely recycle carbon removed from the air by photosynthesis. Fossil CO_2 emissions, on the other hand, emit carbon which was stored by plants which grew tens of millions of years ago.

It is customary to quote CO_2 emissions in metric tons (one metric tonne ("te") = 1000 kilograms or 2205 pounds). Reference (2) shows that U.S. energy-related fossil CO_2 emissions declined from their peak of 6.0 billion tonnes in 2005 to 4.8 billion tonnes in 2023. Reference (1) forecasts (extrapolated base case) 2055 emissions at 4.0 billion tonnes. Such values far exceed desirable 2055 totals, which are below zero.

This essay summarizes two types of proposed technologies which would annually remove billions of tonnes of CO_2 from the atmosphere. If these were combined with programs to largely eliminate fossil CO_2 emissions, significant annual net CO_2 atmospheric reduction is believed possible (and affordable) by the 2050s. Both proposed new technologies employ permanent underground storage ("sequestration") of very large annual quantities of CO_2 as discussed in Chapter 3. The stored CO_2 will be captured during biofuels manufacture (Chapter 4) or using direct air capture (Chapter 5).

Major improvements in the United States will add to the needed large improvements in the rest of the world, beginning a continual gradual reduction in atmospheric CO_2 concentrations.

3. CO_2 Sequestration

The proposed technologies in Chapters 4 and 5 require the permanent sequestration of carbon dioxide. Sequestration is the term used for safe and effective storage for unlimited durations.

3.1 CO_2 Properties

Depending upon its temperature and pressure, CO_2 can exist in any of four different phases: solid, liquid, gas, or supercritical fluid.

Solid carbon dioxide is called dry ice. It only occurs below -57°C (-70°F) and is not of interest here.

Liquid CO_2 can exist only at elevated pressures, whose lower limit varies with temperature. Example limits are 30 bar at -6°C, 51 bar at 15°C, and 72 bar at 30°C (1 bar = 10^5 Pascals or 14.51 psi).

Supercritical fluid exists at temperatures above its critical temperature of 31°C and pressures above its critical pressure of 73.8 bar. Such fluids exhibit no liquid/gas transition.

The gas phase occurs at all conditions outside the above ranges.

Liquid CO_2 has a density of 0.82 kg/liter at 15°C.

3.2 CO_2 Transport and Temporary Storage

Specialized tank trucks are commonly seen on roads today, delivering pressurized liquid CO_2 for carbonated beverages and other uses.

The proposed annual quantities to be sequestered far exceed total CO_2 captured and used today. It will be highly desirable to minimize transport and storage costs (as well as leakages). Preferred conditions for its handling, transport, and temporary storage as liquid are expected to be close to 15°C and 51 bar. Tanks and pipelines will be well insulated, with small active cooling systems. Safety pressure-relief values would operate very rarely.

Costs can be minimized by siting the larger capture facilities close to sequestration sites, enabling pipeline transport to be used in many cases. Truck or rail transport will be employed in other cases. By the 2050s, all energy used for transport and storage (to operate pipelines, trucks, locomotives, and refrigeration) will have no fossil emissions.

3.3 Sequestration

Reference (3) presents the results of extensive DOE studies which have identified numerous sites throughout the United States believed suitable for safe permanent CO_2 storage very deep underground. They occur in rock formations similar to those which have stably held extensive deposits of natural gas for tens of millions of years. The identified total storage capacity of these sites is extremely large: suitable to handle expected sequestration quantities for over a century (before 2100, practical fusion energy sources and other new technologies should take over).

Suitable pressures for liquid injection to the storage formations can easily be reached using booster pumps requiring moderate power. Expected sequestration sites will have underground temperatures hotter than the CO_2 critical temperature and thus injected liquid will immediately become a supercritical fluid.

Injection wells will have redundant check valves to prevent back flow. Automated monitoring will quickly identify any new sites exhibiting problem leakages, enabling their prompt draining and abandoning.

CO_2 captured from fossil fuels is chemically identical to that from biomass or captured from the air. When desired, fossil CO_2 may be distinguished by its lack of any carbon-14 isotope. Liquid CO_2 from multiple sources can be combined in any proportions for handling and sequestration. Section 6 cites proposed example annual CO_2 quantities sequestered.

3.4 National Carbon Administration

By about the early 2030s, the federal government must create an effective new organization which might be called the National Carbon Administration (NCA). It will purchase all liquid CO_2 to be sequestered and fund required licensing, transport, sequestration, and monitoring. CO_2 purchase prices will vary based on its capture and transport costs. The NCA will use many well-qualified private corporations to perform most of the required functions.

The NCA will be fully funded by user fees collected on all purchased grid electricity and fuels (except those used in the Chapter 5 direct air capture systems). User fees are expected to average less than 20% of energy prices when the recommended technologies are in large-scale use.

4. Biofuels

It is proposed to manufacture and sell large annual quantities of biofuels in future decades, significantly reducing consumption of fossil fuels. Four new biofuels would be manufactured: bio-natural gas (BNG), biopropane, biogasoline, and biokerosene. The proposed hydrocarbon biofuels would obtain all their carbon from the atmosphere via photosynthesis and contain no fossil carbon. The manufacture of most of today's liquid biofuels (chiefly ethanol and biodiesel esters) would be discontinued, due to their higher cost and inferior properties.

Two types of converters would be installed at numerous sites throughout the United States. One type would manufacture three different bio-liquid fuels (Section 4.1). The other type would produce bio-natural gas (Section 4.2).

4.1 Liquid Biofuels Manufacture

Novel new converters will be fed solid biomass and air and produce three premium-quality liquid hydrocarbon biofuels: propane, gasoline, and kerosene. Converter outputs will also include three byproducts: pure liquid CO_2 for sequestration and/or conversion to BNG, excellent organic fertilizer, and extremely clean warm air. The converters will be energy self-sufficient and produce no wastes.

4.1.1 Biomass Feeds

Suitable biomass feeds include many types of wastes and crops. The expected overall U.S average consumption for biofuels manufacture is roughly one-fourth wastes and three-fourths crops.

Biomass wastes will originate from farms, forests, food-processing, yards and gardens, sewage treatment, municipal solid wastes, any types of plastics, and other sources. They will be sorted when necessary to remove most non-organics such as metals and glass.

Crops will be grown to produce hay, wood chips, and other shredded types of biomass. Biodiversity is very desirable to allow staggered harvesting and minimize vulnerabilities to pests, diseases, etc.. Preferred crops will be perennial, have deep roots, tolerate wide ranges of precipitation, and be fast growing. Many will incorporate the C4 type of photosynthesis. Weeds growing amongst the crops may be included in the harvest. Some crops will yield more if harvested more than once annually.

Biomass crops will benefit from fertilizers (Section 4.4). Most crops will benefit from drip irrigation during droughts.

No-till farming will minimize methane emissions, reduce costs, and provide other benefits. Many woody plants can have part or all of their tops harvested, leaving their roots undisturbed (coppice practice). New designs of semi-automated, zero-pollution equipment will make harvesting of crops grown on (presently unusable) uneven and/or rocky terrain safe and cost effective.

Reference (4) summarizes extensive DOE studies which concluded that well over one billion annual dry tons of biomass could be grown or collected in the U.S. without adverse effects on food production or prices.

4.1.2 Feed Preprocessing, Transport, and Storage

All biomass feeds require preprocessing to reduce the maximum size of individual pieces to under one inch and reduce their moisture content. These steps will facilitate use of conveyors and silos. Temporary storage will be used at both production and converter sites, with transport by large trucks or rail cars. Feed processing will be performed either at the source or at third-party facilities. Feed storage will allow continuous 12-month converter operation at constant rates. All preprocessing, transport, and storage equipment will be designed to minimize unpleasant odor emissions.

4.1.3 Liquid Biofuels Properties

The proposed saturated-hydrocarbon (alkane) fuels will be of premium quality with negligible contents of sulfur, olefins, aromatics, and oxygenates.

The biopropane will meet all existing fossil propane specifications and contain the standard few parts per million of odorant for safety purposes. It will consist of nearly all propane (C_3H_8) with several percent butane (C_4H_{10}).

The 99-octane biogasoline will consist mostly of “isooctane” (2,2,4-trimethyl pentane, C_8H_{18}) with sufficient dissolved butane (C_4H_{10}) to achieve the seasonally-desired Reid Vapor Pressure (RVP) for ease of engine starting. Its superior composition will minimize engine emissions of CO, hydrocarbons, particulates, and NO_x. It will contain no sulfur or nitrogen.

The biokerosene will be a blend of alkanes from hexane (C_6H_{14}) to hexadecane ($C_{16}H_{34}$). Minor variations will optimize its properties for use as jet fuel, diesel fuel, heating oil, or JP-8 military fuel.

4.1.4 Converters

The automated bio-liquids converters will be fed only prepared biomass and ambient air (no electricity or water inputs are needed). Feeds will be a variable blend from crops and/or wastes.

Biofuel output temperatures will be slightly above ambient, pressurized liquid CO_2 temperature 15°C, and the other streams near 50°C. Within limits, biofuel proportions can be varied to accommodate market demands. The CO_2 is piped to on-site tanks before being transported to either sequestration sites or BNG converters (Section 4.2). The fertilizer (about 4% of dry feed weight, Section 4.4) is conveyed to a nearby silo. Warm air is either vented or utilized to heat adjacent greenhouses, etc.

Each converter is comprised of a number of subsystems. Most operate at 10 bar internal pressure with the cold section at 30 bar and the liquid CO_2 pumped to 51 bar. Subsystems include the following.

The gasifier section operates at 700°C and is fed biomass, steam, and gaseous oxidizer (90% O_2, 10% N_2). Outputs are solid fertilizer and a synthesis gas mixture consisting of H_2, H_2O vapor, CO, CO_2, CH_4, and N_2. The section includes heat exchange and solids handling.

The electrochemical section operates at 900°C and is fed fuel gas from the reactor section below, steam, and oxidizer. Its outputs are nearly pure hydrogen, exhaust (H_2O vapor, CO_2, and N_2), a 900°C steam/oxidizer mix for the gasifier, and electricity for all converter needs.

The reactor section includes several catalytic reactors operating at 200 to 300°C, which convert synthesis gas into mixed hydrocarbons and intermediate compounds. A hydrocracking reactor reacts hydrogen with the heaviest hydrocarbons to produce more kerosene.

A distillation column separates the desired products from reaction intermediates and the fuel gas mixture for the electrochemical section.

An oxidizer section uses compressors and pressure-swing absorption (PSA) beds to obtain oxidizer gas from ambient air.

A cold section uses heat exchange, refrigeration, PSA, and an intercooled compressor to separate pure liquid CO_2 from exhaust gas, with its the tail gas added to the warm air byproduct.

Other subsystems provide conditioning of electric power and control functions. Detailed material and energy balances predict overall conversion efficiencies of 65% to 70% (lower heating value basis).

Most converter sites will have multiple converters installed, with a shared facility for maintenance, personnel, controls, and support needs. Most will hold open houses for students and the public.

4.2 Bio-Natural Gas (BNG) Converters

These converters will be installed at sites usually some distance from the bioliquids converters.

They will purchase a fraction of the bio-CO_2 from the above converters (delivered by truck and temporarily stored on site). They will also purchase water from a connected pipeline and electric power from a connected grid when prices are low (when grid supplies tend to exceed demand). Their BNG product will be immediately delivered into a connected natural gas pipeline, where it will “co-mingle” with flowing fossil natural gas.

The BNG will meet all specifications for fossil natural gas, including heating value and added odorant for safety. Its composition will be approximately 95% methane, 4.5% ethane, and 0.5% CO_2.

The BNG converters will frequently start and stop operating in response to grid prices. Natural gas pipeline networks incorporate on-line gas storage to balance supply and demand.

The converters will use solid-oxide electrolysis to split steam into hydrogen and oxygen. The hydrogen will be catalytically reacted with CO_2 feed to synthesize methane, ethane, and water for recycling. They include heat exchangers, units to remove virtually all water vapor from the product, and systems to purify feed water. Pumps will maintain systems at desired gas delivery pressure, making compressors unnecessary. Oxygen gas from electrolysis is vented after cooling. Expected lower heating value energy efficiency of these converters is 75 to 80%.

4.3 Biofuel and Fossil Fuel Sales 2050s and Later

Once sufficient biofuels manufacturing capacity is available, biofuels and/or fossil fuels will be sold to all customer classes as follows.

Natural gas pipelines will transport co-mingled BNG and fossil natural gas. Customers able to prove they are capturing and delivering liquid CO_2 will pay a lower price (based on the quantity of CO_2 delivered to a collection company).

Biopropane and biogasoline will replace fossil propane and gasoline, which will no longer be sold for fuel applications.

Biokerosene and fossil kerosene will be delivered in separate trucks or rail cars. Lower-priced fossil fuel will be sold only to customers delivering the appropriate quantity of captured liquid CO_2.

Fossil petroleum and natural gas liquids will be sold only for processing in facilities which capture and deliver for sequestration all carbon not converted to fossil kerosene, chemicals, or materials.

Coal will be sold only to users who can prove 100% capture and sequestration of all contained carbon. The great majority of coal is expected to be used in direct air capture systems (Chapter 5).

4.4 Organic Fertilizer

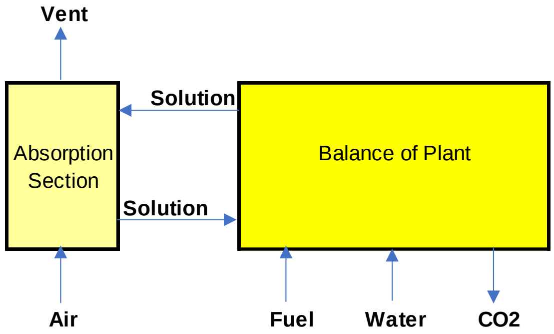
The converter gasifiers cited in Section 4.1.4 produce a solid organic fertilizer containing the phosphorus, potassium, sulfur, and trace elements present in the biomass. However, all nitrogen in the feed is converted into N_2 gas and vented. The fertilizer can be enhanced by downstream companies, who can add suitable nitrogen compounds and convert the product into a granular form. Nitrogen additions could use ammonia made from natural gas with 100% carbon capture and sequestration. The enhanced fertilizer will be ideal for use on biomass crops and most other crops.

5. Direct Air Capture

The biofuels process summarized in Section 4.1 indirectly captures CO_2 from the air after it had been recently stored in plants via photosynthesis. This chapter describes a process which directly removes CO_2 from the atmosphere with zero pollution or fossil carbon emissions. The Chapters 4 and 5 removal benefits are additive.

Quite a few processes for direct air capture have been demonstrated (at small to moderate scale) or proposed. The type proposed herein uses modifications of demonstrated processes believed to have low technical risks. Its expected key advantages are minimized costs, scalability to very large capacities, and preservation of large fossil fuel sales.

The simplified figure below shows major streams:



Proposed variants of the process will use either of two fossil fuels to supply the required energy input: natural gas or coal. Some natural gas systems would also use low-priced grid power when available. All of the fossil CO_2 produced from use of these fuels will also be fully captured and sequestered along with the direct-air-capture CO_2. A brief description of proposed equipment follows.

5.1 Absorption Section

By the 2050s, the expected atmospheric CO_2 concentration might be about 520 parts per million. The absorption section could be designed to remove three-fourths of this CO_2 from incoming air, thus requiring air flow of 2600 volumes per volume of CO_2 gas absorbed. An input water solution of potassium hydroxide (KOH) would be brought into intimate contact with the flowing air to chemically absorb CO_2 by the following exothermic reaction:

$$2\ KOH + CO_2 \rightarrow K_2CO_3 + H_2O$$

The air would also evaporate some of the water from the KOH solution, increasing the humidity of exit air (the incoming solution contains excess water as needed to maintain system water balance). The heat absorbed by humidification is usually greater than released by the absorption reaction, resulting in a reduction in vented air temperature. The exit solution would contain K_2CO_3 close to its solubility limit. Both liquid streams would also recycle small dissolved levels of the other potassium salt.

The absorption equipment would be designed to minimize air pressure drop and hence required fan power. It could operate over a considerable range of ambient air conditions. Demisting features would minimize any carryover of solution by the exit air flow. The absorption section uses numerous modules connected in parallel, enabling factory manufacturing of these bulky assemblies.

Potassium salts are preferred over sodium counterparts due to the value as a fertilizer of their very small entrainment by exit air to surrounding lands. They are also moderate in cost and highly soluble.

5.2 Balance of Plant

This interconnected assembly includes the following major subsystems. Unless noted, most systems operate at about 3 bar absolute pressure. The descriptions below are simplified.

5.2.1 Fuel Processing

Completely different designs are used for natural gas or coal systems. Each produces a clean fuel gas mixture completely suitable for use in the connected fuel cell system.

The natural gas reforming subsystem vaporizes added water, mixes and preheats fuel and steam, and uses a hot granular catalyst bed to produce a fuel gas mixture (containing H_2, steam, CO, CO_2, CH_4, and N_2) without forming any solid carbon. Some natural gas systems will contain additional components enabling very low-cost electricity (when available) to be used alternately with natural gas.

Suitable coals include high sulfur types and lignite. The coal gasification subsystem operates at 10 bar pressure. It vaporizes added water and then reacts fine coal particles with steam and oxygen-enriched air at 700°C to form a gas mixture containing H_2, steam, CO, CO_2, CH_4, N_2, and H_2S. A multi-step sulfur section removes the H_2S (containing all sulfur from the coal) and converts it into pure liquid sulfur salable byproduct. Inorganics present in the coal are recovered as a salable ash byproduct (the above diagram does not show the byproducts). The clean (sulfur-free) fuel gas will not form solid carbon at any temperature subsequently used.

5.2.2 Fuel Cell System

A solid-oxide fuel cell system operating at 900°C is fed air and fuel gas from the above subsystem. It produces DC electric power for complete system operation (no grid connection is required). The air oxidizes less than half of the fuel heating value, yielding an output fuel stream containing only H_2, steam, CO, CO_2, and N_2 (including all nitrogen in the added air). The hot output fuel is fed to the attached calcining section (5.2.4).

5.2.3 Conversion Subsystem

This multi-step section performs the following (slightly endothermic) chemical reaction:

$$K_2CO_3 + H_2O + CaO \rightarrow 2\ KOH + CaCO_3$$

The potassium compounds are in aqueous solution, while the calcium compounds are granular dry solids. Makeup water (condensed from exhaust) or from the purification subsystem (5.2.7)) is added to the KOH solution as needed to supply humidification losses in the absorption section. Required heat is added to the conversion system from exhaust cooling.

5.2.4 Calcining Subsystem

The highly endothermic calcining reaction is performed at 900°C (and 3 bar pressure):

$$CaCO_3 \rightarrow CaO + CO_2 \text{ (gas)}$$

Fuel gas (from 5.2.2) and excess air are both fed at 900°C, reacting to maintain constant operating temperature. Exhaust from the calciner contains steam, CO_2 (from both fuel oxidation and $CaCO_3$), excess O_2, and N_2. The partial pressure of CO_2 in the exhaust is roughly three-fourths the equilibrium value at these conditions.

5.2.5 Power Conditioning

The DC electric power produced by the fuel cell system (5.2.2) is inverted to 60 Hz AC at voltages appropriate for all system power uses. Fan cooling by ambient air removes heat.

5.2.6 Rotating Equipment

The system uses many types of motor-driven equipment power from the above section.

Numerous large fans move ambient air through the absorber section modules.

An air compressor produces 3-bar air for the fuel cell and calcining subsystems. A two-stage intercooled CO_2 compressor increases its pressure from near ambient to 30 bar. A refrigeration compressor is used to obtain temperatures near -25°C for CO_2 liquefaction.

Various small pumps, fans, and compressors perform other tasks.

5.2.7 Water Purification

Makeup water obtained from a local source (ocean, lake, river, or groundwater) is thoroughly purified using highly efficient multi-stage flash distillation. The required input heat is obtained from system losses (exhaust cooling, condenser, intercooling, etc.). The required cooling uses ambient-air fans.

5.2.8 Heat Exchangers

Heat exchangers in use operate at temperatures from -25°C to 900°C and pressures up to 30 bar.

Two direct heat exchangers connected to the calciner transfer heat from moving solid particles to counterflowing gas through their bed. One cools CaO by input air. The other heats $CaCO_3$ using a fraction of calciner exhaust. Flows are adjusted to achieve equal hot and cold temperatures for both solid and gas streams.

A condenser recovers water from calciner exhaust for use in natural gas reforming or coal gasification, with the surplus contributing to KOH solution makeup.

Other units are employed in various other parts of the balance of plant.

5.2.9 Cold Section

Saturated exhaust from the condenser at 25°C enters this section, which uses refrigeration, intercooled CO_2 compressor, heat exchange, and a pressure-swing absorption bed to yield pure liquid CO_2, water, and tail gas (mostly N_2 plus a little O_2), which is vented.

5.3 Summary

Systems fueled by natural gas are predicted to require about 1450 kWh of fuel lower heating value (LHV) per tonne direct-air-capture (DAC) liquid CO_2 for sequestration. They would also capture all fuel carbon to yield about 0.29 tonnes liquid fossil CO_2 for sequestration per tonne DAC CO_2.

Natural-gas systems operating on input electric power would use 1570 kWh per tonne DAC CO_2 and produce no fossil CO_2 when not using gas.

Coal-fueled systems would need a LHV of about 1810 kWh per tonne DAC CO_2 and capture all fuel carbon to co-produce 0.63 tonnes liquid fossil CO_2.

Coal systems would yield saleable byproducts of about 1% liquid sulfur and 6.8% ash, based on coal weight. The sulfur can be added to asphalt paving to enhance its properties or used in phosphate fertilizer manufacturing. The ash can be converted by highly efficient downstream equipment to slag for use as additives to construction materials.

Coal is forecast to sell in 2050 for about half the price of natural gas per unit of heating value. Known domestic reserves of coal are much greater than the large known natural gas reserves. However, coal-fueled DAC systems will require larger capital investments, maintenance, and personnel costs compared with natural gas systems.

6. Example

By the mid-2050s, it is believed possible and affordable to remove and permanently sequester about **5.0 billion tonnes** per year of CO_2 from the atmosphere in the United States using the processes outlined in Chapters 4 and 5.

The DOE uses "Quads" to quantify United States annual energy quantities. This archaic unit is defined as one quadrillion (10^{15}) British Thermal Units (BTU). The author instead uses Exajoules (EJ) for such quantities: 1 EJ = 10^{18} Joules. Useful conversions are 1.00 Quad = 1.054 EJ and 1 kilowatt-hour = 3.6 Megajoules (MJ).

The author uses lower heating values (LHV) instead of the higher heating values(HHV) used by DOE. Average LHV/HHV ratios are 90.1% for natural gas, 91.9% for propane, 93.2% for gasoline, 93.3% for kerosene, 93.4% for "steam" coal, and 93.1% for dry biomass.

6.1 Biofuels Manufacture

By the 2050s, fossil fuels will be sold domestically only to users who capture all their carbon and arrange its sequestration. Remaining fuel users will be able to purchase only biofuels (at higher prices). Example biofuels manufacture and U.S. consumption in the mid-2050s has a total LHV of 15.0 EJ, comprised of 4.5 EJ BNG, 0.6 EJ biopropane, 2.4 EJ biogasoline, and 7.5 EJ biokerosene.

Detailed modeling of the proposed manufacturing processes gives sequestered CO_2 of **560 million tonnes** (captured indirectly from the atmosphere). Process feeds are 980 million tons dry biomass (with LHV of 15.4 EJ) plus 5.9 EJ zero-carbon electric power. Saleable byproduct is 36 million tons dry organic fertilizer.

6.2 Natural-Gas DAC Systems

A total of **2000 million tonnes** of DAC CO_2 might be captured using systems powered by fossil natural gas. The required natural gas LHV is 10.44 EJ. Additional sequestered fossil CO_2 would be 580 million tonnes. In 2022, total U.S. natural gas consumption was about 35 EJ. The example uses no electric power from external sources.

6.3 Coal-Fueled DAC Systems

These systems would capture **2440 million tonnes** DAC CO_2, bringing total CO_2 capture from the atmosphere to 5.0 billion tonnes per year. Additional sequestered fossil CO_2 from the coal is 1540 tonnes. Required coal LHV is 15.90 EJ. In 2022 U.S. coal consumption had declined to 9.5 EJ. Coal production in the U.S peaked in 2006 at 23.4 EJ and could be significantly increased for the proposed new use. At an average coal LHV of 18.86 GJ/ton, coal weight for the above capture is 840 million tons. Saleable byproducts would be 8.4 million tons sulfur and 57 million tons ash.

6.4 DAC Fuel Costs

2022 U.S. fuel costs for large electric power plants were \$0.0266/kWh for natural gas and \$0.0078/kWh for coal (LHV basis, based on Reference 1). Using predicted efficiencies, 2022 costs would be about \$39/DAC CO_2 tonne for natural gas systems and \$14/tonne for coal systems. By 2050, Reference 1 predicts coal prices are to increase somewhat while natural gas prices remain nearly unchanged (in inflated dollars).

7. Discussion

The strategies outlined in this essay should be implemented concurrently with programs to eliminate the U.S. existing (fossil) CO_2 emissions, now about 4.8 billion tonnes per year. The combined reduction would thus total some 9.8 billion annual tonnes.

7.1 Zero Carbon Emissions

A combination of four major programs is recommended to eliminate existing fossil CO_2 emissions:

(1) Significantly improve energy usage efficiencies

(2) Increase power generation from solar photovoltaic and wind systems

(3) Install technology to capture and sequester all carbon from fossil fuel uses

(4) Manufacture and sell biofuels to replace a large share of fossil fuels (per Chapter 4)

Section 7.6 cites a planned essay which will include recommendations for reaching zero carbon emissions ("ZCE") by the early 2050s.

7.2 Financial

By the 2050s, total U.S. energy consumption is expected to be significantly lower, in spite of population growth and significantly larger GDP. Although user energy purchase prices (including the fees cited in Section 3.4) proposed by the author would be considerably higher, expected user energy expenditures would be a considerably smaller share of GDP than the present 7.0% (from Reference 1). The planned essay will include cost estimates.

7.3 Timeline

Progress is already being made on reducing fossil CO_2 emissions. Reductions of emissions are expected to accelerate well before 2050. DAC systems could reach higher removal levels than the example given. New zero-carbon alternatives could later emerge, possibly including nuclear fusion systems.

7.4 International

Worldwide actions are needed to achieve the needed CO_2 atmospheric reductions. The United States can benefit both the planet and its economy by licensing many of its new technologies, and by export sales of consulting, equipment, biofuels, and fossil fuels (the latter only for uses with full carbon capture).

7.5 Fossil Fuels Production

The natural gas and coal proposed to power the DAC systems will be produced under strict regulations which virtually eliminate methane leakages and greatly reduce other adverse environmental impacts from existing production practices. Their pre-processing and transportation to DAC facilities will emit no fossil CO_2 to the atmosphere.

7.6 Next Essay

The author plans to post another essay entitled “United States Energy 2050s” by summer 2025 on his Reference 5 website, summarizing recommendations for eliminating existing fossil carbon emissions and giving example overall cost and financial estimates.

8. References

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