

Combating Global Warming

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June 2020

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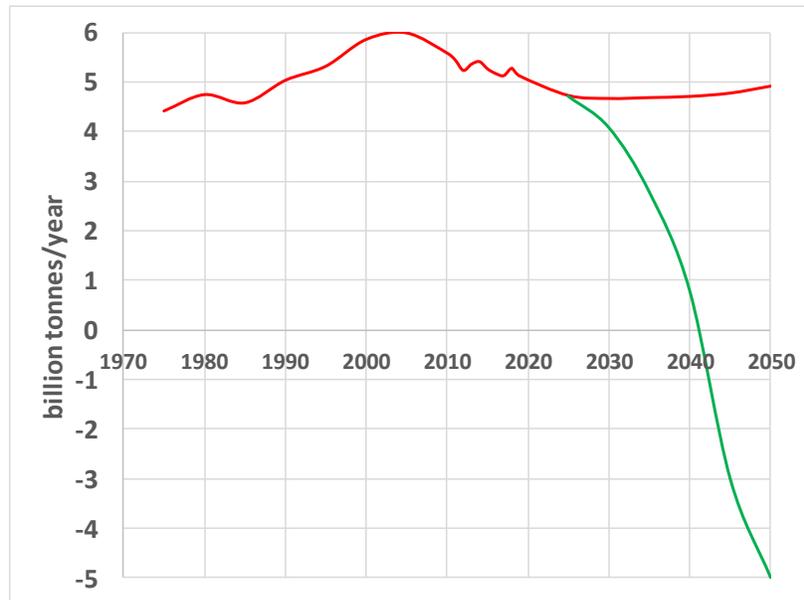
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1. Summary

Global warming is caused primarily by CO₂ emissions from fossil fuel use. This article cites quantities for the United States, with suggestions about applying the recommendations to the rest of the world. Energy-related fossil CO₂ emissions are shown below (tonnes are metric tons).

Figure 1.1 U.S. CO₂ Emissions



The red line shows actual emissions and DOE forecast emissions (5.12 billion tonnes in 2019 and 4.92 billion tonnes in 2050) based on continuation of existing trends and regulations. The green line shows proposed emissions, which become negative (net removal from the atmosphere) shortly after 2040. The proposed 2050 negative emissions result from an affordable program of seven interrelated elements as follows.

Efficiency Improvements Energy use is decreased by 40% by more efficient buildings, transportation equipment, and industrial processes.

Solar and Wind Electricity from solar and wind is significantly increased, enabled by higher prices, more economical energy storage, and grid improvements.

Fuel Cell Systems Cost-effective equipment fueled by natural gas or liquid fuels are extensively used in both buildings and transportation (chiefly trucks, buses, locomotives, and ships). They generate electricity at excellent efficiency plus useful heat. Most include CO₂ capture.

Carbon Capture and Sequestration (CCS) 7.9 billion annual metric tons of CO₂ (5.0 billion from the atmosphere, balance from fossil fuels) are economically captured, transported, and permanently stored deep underground.

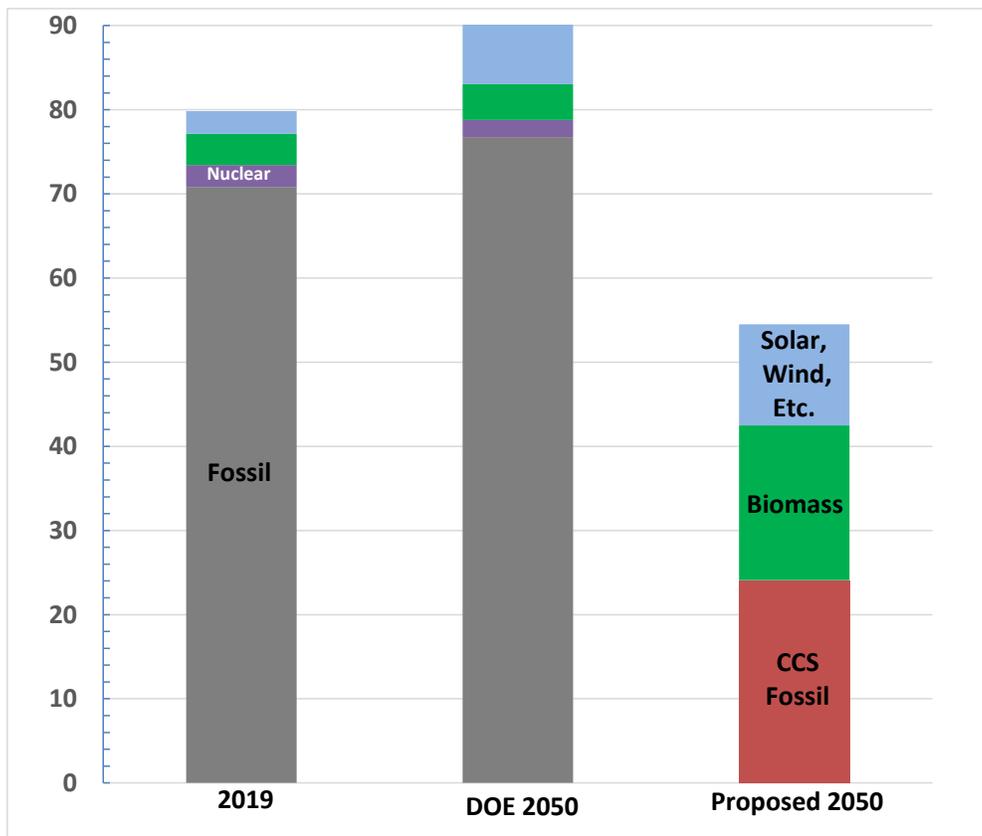
Biomass Farming 1.2 billion tons per year of biomass crops are grown on land not used for food. These crops are fast-growing perennial grasses and trees with moderate water needs.

Bio-Energy Converters Biomass crops and wastes are gasified and converted into gaseous and liquid hydrocarbon biofuels plus electricity. The converters also perform virtual electricity storage by sometimes making electricity from biomass or using surplus grid power to produce additional biofuels. All carbon not transferred to the biofuel products is captured for sequestration.

Direct Air Capture These systems economically remove CO₂ from the atmosphere using coal as the energy source, with total carbon capture, zero pollution, and no wastes.

The proposed elements include known, emerging, and new technologies. Although development and demonstrations are needed, risks are moderate. Necessary governmental roles include the supervision of CO₂ sequestration. The program would enhance GDP, create many net full-time jobs, and increase exports. Figure 1.2 compares sources of energy with the DOE 2050 forecast.

Figure 1.2 Delivered Energy
(exajoules)



The topmost layers include hydroelectric and geothermal renewables. The proposed case omits nuclear power and captures all CO₂ from fossil fuels for sequestration.

2. Introduction

This article uses technical terms and units listed in Chapter 20, with conversion factors. Energy quantities are given in exajoules (EJ), rather than archaic quads (10^{15} BTU). Carbon dioxide quantities use metric tons (“tonnes”). All financial figures are given in constant 2019 dollars. Both future and present verb tenses are used interchangeably in this article: no significance should be attached to their selection. This paper, prior papers by the author (list in Chapter 21), and his background are available at www.robertruhl.com.

This article recommends a program of energy system improvements which could be implemented by 2050 and gives example results for that year. The expected benefits will accumulate between now and then (example in Figure 1.1), with greater annual benefits likely after 2050. Chapter 14 summarizes example 2050 values.

Although this document is focused on the United States, its recommendations are largely also applicable to the rest of the world, as discussed in Chapter 17.

2.1 Idea Sources

Chapter 21 gives DOE references used. The ideas herein originate from a wide variety of sources. Some (not specifically identified) are original from the author. Others are non-proprietary from his long-time employment (Standard Oil, British Petroleum, Technology Management Inc., and AnywherEnergy L3C). Still others are from the internet.

2.2 Background Information

Ref. 1 lists 2019 U.S. population as 328 million and predicts 2050 population at 389 million (19% increase). Our gross domestic product in 2019 was \$21.35 trillion, predicted to grow 77% to \$37.81 trillion in 2050 (both in 2019 dollars). DOE figures used in Chapter 1 are from Ref. 1.

2.3 Grid Balancing

The electric power grid must remain balanced at all times: total input power minus operating losses must always equal output power. Expected future changes to consumption patterns and major additions of highly-variable wind and solar generation will make balancing more challenging. Grid balancing may use combinations of the following (all but number 8 are now used):

1. Time of Use (TOU) Rates User consumption patterns are altered by varying rates per kilowatt-hour: expected to be employed far more in the future.

2. Voltage Variations Grid voltages are allowed to vary about $\pm 10\%$ from nominal, slightly altering consumption.

3. Wheeling Power is bought or sold to other interconnected utilities.

4. Load Following Power output of generating plants is varied. In large existing plants, load following usually reduces efficiency and can be performed only slowly. The proposed fuel cell systems (Chapter 6) will have superior load-following characteristics.

5. Peaking Generation Gas-turbine peaking generators are extensively used today to provide occasional additional power. Their low average capacity factors and moderate efficiencies make their electricity relatively expensive.

6. Curtailment When renewable generation exceeds demands, solar power can be temporarily disconnected (using contactors) and/or wind turbines furlled. Curtailment reduces sales revenue, thus increasing cost per kWh.

7. Grid-Scale Storage Batteries are discussed in Section 2.4 and alternatives in Section 16.11.

8. Virtual Batteries Section 2.5 describes these proposed new grid-connected systems.

2.4 Large Stationary Batteries

Lithium-ion, lead-acid, and other types of conventional secondary battery systems are in service. Many types of flow batteries (which separate reactant storage from reaction hardware) are also under development. All of these systems have the following attributes. Discharge AC output energy is lower than charging energy by at least 7%. Typical cycle times are short (10 to 60 hours typical). Total storage cost (capital amortization, maintenance, energy losses, and other) per kWh delivered is high (usually above 20 cents per kWh), with limited potential for significant future reduction. Existing capacity of these systems is small. They are not expected to play a large future role.

2.5 Virtual Batteries

Virtual battery systems import surplus (low cost) grid power, which is consumed in real time for a valuable purpose. At other times (when grid prices are high and extra power needed), they generate power from fuel for export to the grid. Thus, they accomplish apparent storage without performing actual storage.

Virtual batteries have three outstanding advantages over conventional batteries. Their output energy is independent of their input energy (and hence may be significantly higher or lower). Timing of input energy is independent of outputs, allowing for additive storage cycles which are less than daily, daily, weekly, monthly, and seasonal. Since the proposed virtual battery systems are part of equipment also performing other valuable functions, their effective apparent energy storage costs are far lower than secondary batteries (typically under 5 cents per kWh).

This paper proposes virtual battery functions built into both stationary fuel cell systems (Section 6.5) and biomass converter systems (Section 8.5).

PART ONE: COMPONENTS OF PLAN

The next seven chapters briefly describe the recommended approaches and technologies which could affordably achieve fossil CO₂ emissions reduction of about 10 billion tonnes per year while providing large economic and other benefits. Most of the innovative technologies proposed have been subjects of extensive calculations by the author, whose results are summarized only briefly in this paper. The new ideas are based firmly on known science but will require significant engineering and manufacturing development to reach profitable commercialization. Readers who are less interested in the included technical details may gloss over these without losing the principal messages.

3. Energy Usage Efficiency

The proposed plan reduces 2050 delivered energy use by 40% from the DOE forecast. Perhaps one-tenth of the reduction would result from conservation actions to reduce energy waste (such as lowering the intensity and duration of most electric lighting). The great majority of the consumption savings would result from a wide range of energy efficiency improvements, some of which utilize the fuel cell systems described in Chapter 6. This chapter cites some of the expected types of improvements, but many others are also expected. Chapters 10 through 13 mention sector-specific efficiency improvements.

3.1 Infrastructure

Major improvements will be made to the U.S electric power grid, natural gas pipeline network, and public roadways. The improvements will save energy, improve safety, and help enable the proposed plan components. Chapter 14 contains examples of proposed funding.

Grid and pipeline systems will be modernized, upgraded, and extended to serve new locations. New cost-effective micro-tunneling machines will assist installation of new underground electric and gas lines. Components and systems will be added to divide the grid into numerous interconnected microgrids, reducing the number of customers affected by grid outages. Grid and pipeline improvements will be funded using revised rate structures, billing each customer for energy use plus a fixed monthly charge which accurately reflects the costs of connected infrastructure.

Public roads, bridges, and tunnels will also be modernized, upgraded, and slightly expanded. Traffic sensors, communications, and control systems will be significantly upgraded. The improvements will reduce travel delays, saving fuel, and facilitate increased truck traffic to serve the proposed new energy systems. Roadway improvements and maintenance will be funded by new travel fees per ton-mile, which will replace existing taxes on gasoline and diesel fuel (which are inadequate and do not properly share costs with plug-in and energy-efficient vehicles).

3.2 Buildings

Buildings consume a major share of energy in three sectors: residential, commercial, and industrial. Many types of improvements will reduce energy usage in buildings.

The largest share of building energy consumption is for heating, ventilation, and air conditioning (HVAC). Major savings can be made in most buildings by significantly improving doors, windows, and insulation. Installation of highly efficient ductless heat pump systems (which use outdoor air as a source of heat) for space heating and cooling can reduce required energy purchases. Advanced energy-recovery ventilation (ERV) systems can improve indoor air quality and comfort while saving energy.

By 2050, a great many buildings will have fuel cell systems (Chapter 6) which can improve energy efficiency of fuel conversion to electricity and useful heat.

Incremental improvements are also expected in the efficiencies of refrigeration equipment and LED lighting.

3.3 Transportation

Major efficiency improvements in most types of transportation are proposed by 2050, including the following.

Plug-in vehicles (both pure electric and engine hybrid) are expected to become dominant for both light-duty and short-range commercial transportation. Most plug-in vehicles use less than half the delivered energy of their engine-only counterparts.

Most freight trucks, buses, and locomotives with long daily travel are expected to convert to on-board fuel cell systems (Chapter 6), cutting energy use by roughly two-thirds. Fuel cell systems will also begin to appear on ships.

Many natural gas pipelines will replace their compressor power sources (grid or gas turbines) with more efficient fuel cell systems. Little improvement is expected in the forecast efficiencies of aircraft, recreational boats, and most military equipment.

Chapter 13 contains additional details.

3.4 Manufacturing

Nearly all 2050 manufacturing operations can achieve higher energy efficiencies, aided in many cases by on-site fuel cell systems (Chapter 6). Some processes now burning fuels will switch to more efficient and emissions-free electricity. Chapter 12 gives examples of manufacturing improvements.

4. Renewable Energy

Renewable energy includes bio-energy, solar, wind, hydroelectric, and geothermal. Bio-energy is discussed in Chapter 8: it is proposed to contribute over 60% of 2050 delivered renewable energy.

Solar energy systems include photovoltaic (PV: electricity obtained using semiconductors), mirror/steam-generator assemblies, water heating, and passive space heating. PV systems have already become less expensive than mirror/steam alternatives, which are expected to be retired in the next two decades. By 2050, solar water heating installations are expected to become unimportant due to emerging alternatives (especially fuel cell cogeneration) which have lower total costs. Passive solar features in buildings will reduce required space heating duty. The vast majority of usable solar energy, however, is expected to be photovoltaic.

Table 4.1 compares proposed 2050 consumption with 2019 actual and the DOE forecast. Share values refer to total user consumption.

Table 4.1 Renewable Electricity Consumption
(exajoules)

	2019	2050	
		DOE	Proposed
Hydroelectric	0.94	0.92	0.92
Geothermal	0.05	0.17	0.17
Large Solar	0.37	3.00	4.00
On-Site Solar	0.37	1.53	4.00
Wind	0.97	2.16	2.91
Sum	2.70	7.78	12.00
Share	3.4%	8.6%	22.0%

The large proposed increases in solar and wind are enabled by higher proposed prices, grid upgrades, and chiefly by the virtual battery systems discussed in Sections 2.5, 6.5, and 8.5.

4.1 Solar Photovoltaic Systems

Solar panels generate DC electricity, which is inverted to 60 Hertz AC and synchronized with the connected power grid (single phase or three phase). Systems include switchgear, overcurrent, and overvoltage protection. When grid voltage exceeds 480 Volts, transformers are added.

Individual PV systems vary greatly in size, from residential rooftop systems of a few kilowatts up to large solar farms having tens of megawatts. Installed costs per kW are lower for larger system capacities and have been declining with time. A large share of today's installed capacity has enjoyed federal and state tax incentives, which have an uncertain long-term future. Installed capital costs of future rooftop PV systems (residential, commercial, and industrial) will benefit from sharing of grid interfacing and inverters with fuel cell systems (Chapter 6).

Annual total electricity production from a PV installation depends on its location. The desert southwest yields the greatest output, while some northern sites average as little as one-third of the best. At a St. Louis example rooftop site (with 10% example total system losses), Ref. 6 gives an annual average of 1460 AC kWh per rated kilowatt of PV panels. Hourly electricity AC production varies also varies with the day of the year, hour of the day, and the weather. In St. Louis, monthly AC kWh production varies from 63% of annual average (December) to 128% (July).

4.2 Wind Turbines

Wind turbine designs have improved significantly over the past decade and are expected to further evolve. Emerging new systems have larger single-unit capacity (up to more than 5 MW), lower installed cost per kW, and lower maintenance costs. As with solar systems, capital cost per kW is typically lower for larger systems.

Wind farm electricity generation varies greatly with the weather, from zero to a maximum value (turbines automatically stop rotating in very high winds to avoid damaging the equipment). Average annual production varies considerably with the site: many sites are much windier than others. The best sites are near hills, mountains, or large bodies of water. Good sites are also found in large flat areas with few trees.

4.3 Hydroelectric Systems

Electricity is generated at large dams plus a little from small systems. Due to their large environmental impact and high installed cost, no significant new capacity is expected in the United States (some small systems are being removed).

4.4 Geothermal Systems

At sites with hot underground thermal sources close to the surface, steam turbine-generator systems can generate electricity. As Table 4.1 shows, this energy is forecast to more than triple by 2050. Since the U.S. has very few suitable sites for such installations, however, this type of generation will contribute only a small share.

Some heat pumps have also used shallow underground loops in space heating/cooling systems. Recent advances in (far more common) air-source heat pumps have made the latter more cost effective and thus very few geothermal heat pumps are expected in the future.

4.5 Grid Infrastructure

The large increases in the proposed use of renewable electricity will require significant upgrading of existing U.S electric grid infrastructure. The present grid includes many elements which are too old and/or poorly designed. Maintenance has also been insufficient. Increased capacities of both transmission and distribution equipment are needed. New feeders will be required in many cases to connect new generation capacity. Far better sensing and control features will help to minimize outages (including the addition of contactors to create “microgrids”).

5. Carbon Capture and Sequestration

Global warming is chiefly caused by the atmospheric accumulation of fossil CO₂ from human (anthropogenic) uses of fossil fuels and deforestation. Carbon dioxide concentration in the air has risen from its steady pre-industrial level of 280 parts per million (ppm) to over 410 ppm today and continues to increase. Smaller human contributions to global warming are due to emissions of methane (Section 5.5) and other gases (Section 19.1).

The actions and processes described herein propose to capture and permanently sequester virtually all CO₂ from continued fossil fuel use. In addition, large quantities of CO₂ will be continually removed from the atmosphere and also sequestered. The expected result is a significant net removal from the air of five billion tonnes CO₂ per year by 2050 (Fig. 1.1). A new federal agency called the National Carbon Administration (NCA) will finance and supervise carbon capture and sequestration (CCS), as discussed in Sections 14.4 and 18.6.1.

5.1 Properties

CO₂ is a gas, liquid, or solid depending upon its temperature and pressure. It is colorless and (in low concentrations) odorless and tasteless. It has many industrial uses, including production of carbonated beverages (it is quite soluble in water).

It becomes a liquid at elevated pressure when its temperature is between -57°C (triple point) and 31°C (critical temperature). The liquid boils at 24 bar at -13°C, 35 bar at 0°C, 53 bar at 17°C, and 74 bar (critical pressure) at 31°C. Below -57°C, CO₂ is a solid called dry ice. Above 31°C, it is a supercritical fluid with no liquid/gas transition.

Liquid density at 17°C is 81% of water. Gas density is 1.53 times air.

5.2 Capture

The CO₂ capture and sequestration (CCS) proposed herein require its virtually-complete separation from gas mixtures followed by its condensation. The desired liquid has minimal dissolved oxygen and water to minimize corrosion of contacting materials. Minimization of separation costs is of major importance. The proposed capture strategies depend upon the nature of the gas mixture and not the CO₂ source. Two categories of gas mixture are targeted: exhausts with high (over 25%) initial CO₂ concentrations and ambient air with low (slightly over 400 ppm) initial concentration.

Costs of CO₂ capture from exhaust gas mixtures can be minimized when such mixtures are present at elevated pressure and contain low percentages of nitrogen and oxygen (and hence have high concentrations of CO₂ and easily-condensed water vapor). The exhausts proposed for capture are mostly from medium-to-large fuel cell and other electrochemical systems (with a small share from specialized new industrial systems). These exhausts achieve low oxygen concentration by operation at very high fuel utilization (facilitated by heat exchange) and low nitrogen concentration by employing molecular-sieve (pressure swing adsorption) oxygen concentration. High exhaust pressures are facilitated by the use of oxygen-enriched oxidant gas

and process benefits of elevated-pressure operation. Chapters 6 and 8 describe the proposed CO₂ capture methods.

Direct CO₂ capture from the air requires a completely different approach, which is described in Chapter 9.

5.3 Transport

Liquid CO₂ has been transported in fairly large quantities in the U.S. for decades to supply industrial and commercial customers and for enhanced oil recovery. The liquid is typically at ambient temperature and maintained at sufficient pressure to prevent its venting to the atmosphere. In some cases, refrigeration is employed to minimize required pressure. Transport employs specialized equipment designed to safely contain the maximum pressures. Temporary storage tanks will be used at both capture and sequestration sites. Transportation may use trucks, rail cars, pipelines, barges, and ships. The expected costs of CO₂ transport are moderate.

5.4 Sequestration

It is proposed to permanently sequester nearly 8 billion tonnes of CO₂ annually by 2050 (5 billion from the air and almost 3 billion from fossil fuels). It will be injected as pressurized liquid into suitable sites deep underground for permanent storage. The required injection pressures will vary with location but will typically be near 100 bar (about 1500 psi). Injection depths will also vary but will usually exceed one-half mile.

Extensive studies of U.S. geological formations suitable for permanent CO₂ sequestration are summarized in the NETL Carbon Storage Atlas (Ref. 3). Identified sites exist in every state and have an estimated storage capacity of over 500 years at the proposed annual rates.

Huge quantities of natural gas have remained underground for tens of millions of years. Since natural gas is lighter (and more chemically stable) than CO₂ but escapes very little from underground reservoirs, the outlook for permanent carbon dioxide storage is bright.

As soon as the liquid CO₂ is injected, it will be heated by the warm surrounding rock or brine to become a supercritical fluid. At an example underground temperature of 80°C and pressure of 100 bar, 8 billion tonnes of supercritical CO₂ has a volume of about 15 cubic miles. The land area of the 48 states is about 3 million square miles and so this annual volume is equivalent to an average depth of one-twentieth of an inch. Of course, actual injection sites will be a small fraction of total land area, but the cited quantities are useful for visualization.

Much of the injected CO₂ is expected to very slowly chemically react with underground rock formations to form stable solid carbonate minerals from oxides present.

Two concerns must be properly addressed to ensure proper safety of the storage. There are potential risks of causing seismic activity (earthquakes) or of sudden large leakage posing a suffocation threat. Both of these risks must be minimized by thorough geologic studies and ongoing monitoring of the sites used. Rare very minor tremors or very small leaks should be tolerable.

5.5 Methane

Anthropogenic CO₂ emissions are believed to be responsible for well over 80% of the annual emissions increasing global warming. Methane (CH₄) emissions are the principal additional problem. Each volume of methane has a global warming effect about 23 times that of carbon dioxide.

Anthropogenic methane emissions occur from diverse sources. Leakages from natural gas production, transport, refineries, and industrial plants are considerable. The burial of organic matter by plowing and at landfills produces anaerobic digestion (yielding methane and CO₂). Livestock, chiefly cattle, also emit methane.

By 2050, methane emissions should be significantly reduced. Natural gas leakages can be greatly reduced by applying existing knowledge (made cost-effective by higher prices and fines). Much farming can be converted to “no till” methods to minimize burial of green plant matter (Chapter 7). As discussed in Section 8.6, landfills will be harvested, and no new ones created. Fewer cattle will be raised due to expected shifts in diets.

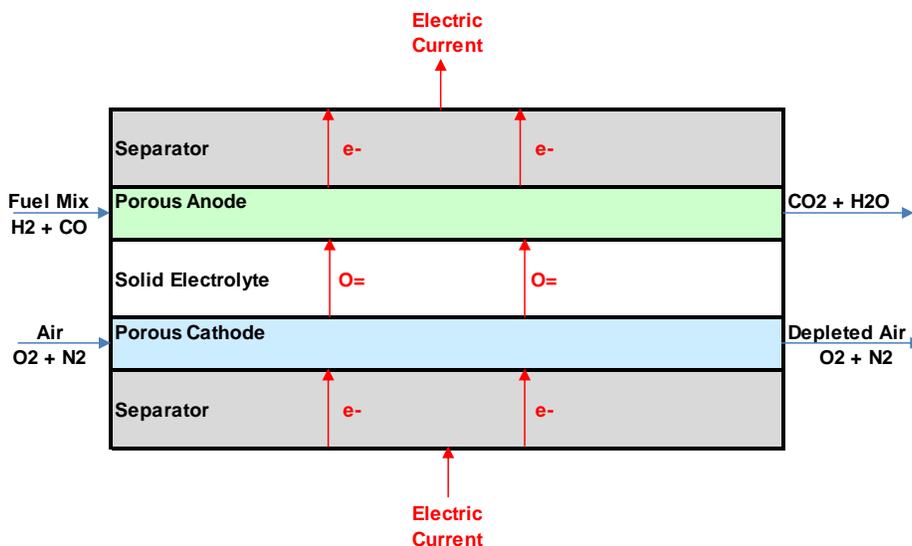
6. Fuel Cell Systems

At present, nearly all electricity made from fuels is produced using heat engines: steam engines, gas turbines, or piston engines. An emerging alternative is fuel cell systems, which instead use electrochemical cells to generate electricity from fuels and oxidizers (usually air). The principal types of fuel cells are called polymer electrolyte (PEM), phosphoric acid, alkaline, molten carbonate, and solid oxide (SOFC). The latter type is expected to become the dominant technology for electricity production from fuels well before 2050 and are the subject of this chapter. The other types are not expected to be economically competitive when used in systems fed by hydrocarbon fuels. Section 6.3 discusses fuel choices.

6.1 Solid-Oxide Fuel Cells

A simplified schematic of an SOFC is shown here. One separator is used between each pair of cells.

Figure 6.1 Solid-Oxide Fuel Cell



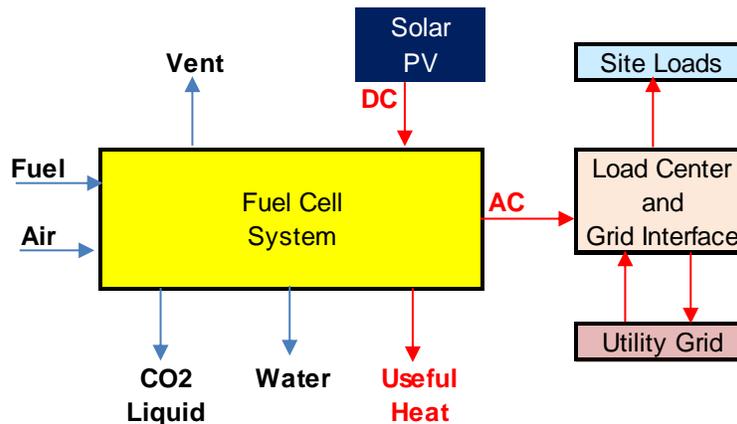
These cells operate at high temperatures: typically, near 900°C (1650°F). A fuel gas mixture from a fuel processing section (described below) contains fuel components (H₂, CO, and a little CH₄) in addition to H₂O vapor, CO₂, and sometimes a little N₂. As the fuel mix flows through the anode layer, the fuel components electrochemically react with oxygen ions (O⁻) to produce electrons (e⁻), water vapor, and CO₂. Air flows through the cathode, which produces oxygen ions using incoming electrons. The solid ceramic electrolyte (made of yttria-stabilized zirconia, YSZ) is a good oxygen-ion conductor but does not conduct electrons. The separators between each cell are excellent electron conductors but do not conduct ions. Each cell generates between 0.6 and 0.8 Volts DC, depending upon current density and average reactant partial pressures. Since the net oxidation reaction liberates more energy than is electrically removed, heat (not shown) is also released. The figure does not show the required seals, which isolate the fuel and air circuits from each other.

Example production cells will be circular discs with diameter less than 70 mm and thickness under 1.0 mm (including one separator). Typical electric power generation will be near 5 Watts.

6.2 SOFC Systems

The figure shows inputs and outputs for a stationary grid-connected system with optional CO₂ capture (Section 6.4) and optional solar photovoltaic array. Blue arrows are material and red are energy streams.

Figure 6.2 Proposed Fuel Cell System



The Vent gas will be mostly nitrogen and oxygen plus CO₂ (if not captured) and a little water vapor not condensed during heat recovery. It will be odorless and completely free of pollutants. Input air may originate indoors or out.

SOFC systems are produced for both stationary and transportation applications, with rated power outputs from under 3 kW to 3 MW (maximum size limited by standard highway truck capacity). The hot-swappable systems can be ganged for larger capacities and redundancy. They are reliable (designed for continuous duty), capable of load following from zero to rated maximum power, non-polluting, quiet, and safe. Cold starts require 20-30 minutes, but systems may be hot idled for instant power availability.

Their efficiencies will be excellent. AC Output/Fuel HHV will be 50% to 60% for systems with CO₂ capture. Including maximum heat recovery, total HHV energy efficiency can reach 100%. Sections 6.4 and 6.7 give efficiencies for other configurations. Practical SOFC systems are compact and contain many integrated subsystems inside a protective safe-to-touch enclosure. Simplified descriptions are given below.

6.2.1 Hot Subassembly

Multiple stacks of numerous cells are connected in series and parallel to generate the desired DC voltages and power. The stacks are clamped inside a well-insulated hot subassembly, which also contains a thermally-integrated fuel processing system. Incoming fuel (Section 6.3) is catalytically reacted with steam to yield a fuel gas mixture. The fuel gas is routed through more

than one set of anodes in series to completely oxidize all fuel components, producing a spent fuel exit stream with typically 0.2% free excess O₂. Heat exchange within the hot zone maintains constant stack and fuel processor temperatures. Air and fuel gas flows are varied to follow the desired power output and control temperatures.

6.2.2 Power Conditioning

This subsystem converts stack DC (plus optional solar DC) into control power for on-board equipment and the desired main power output(s). Typical stack voltages are ± 180 to ± 400 VDC (depending upon kW size and desired AC output voltage). Common 60 Hertz AC outputs are 120/240 Volts, single phase and 208Y/120 or 480Y/277 Volts, 3 phase. Some systems (chiefly used in transportation) will have DC main outputs. Suitable protective devices are included. AC Voltage and phasing is synchronized to the grid when so connected. Most will also include a small lithium-ion battery bank (of much lower working voltage) for load following (and sometimes also for load leveling and/or cold starts).

6.2.3 Balance of System

Rotating equipment includes fans, blower(s), compressor(s), and pumps. Control valves are the remaining items with moving parts. An absorbent bed removes parts-per-million sulfur odorants when present. Heat exchangers, filters, control system, connectors, sensors, manifolds, and wiring harnesses are included.

6.3 Fuels

The systems are designed to operate on clean gaseous or liquid hydrocarbon fuels. Fossil fuels (natural gas or diesel) are used only on systems with CO₂ capture. Biofuels (bio-natural gas, bio-propane, or bio-kerosene) are used either with or without CO₂ capture (since their CO₂ has atmospheric origin).

Stationary systems will use piped natural gas or bio-natural gas (when available) due to their excellent convenience and cost advantage over liquid fuels. Stationary systems without piped gas service will use bio-propane (from large on-site tanks refilled by trucks as needed), which is also suitable for ranges, cooktops, grilles, and other applications using burners.

Transportation fuel cell systems will use liquid hydrocarbon fuels, due to their excellent energy per gallon and ability to be stored in light weight tanks. Systems not using CO₂ capture will use bio-kerosene, while those with CO₂ capture will use fossil diesel for its lower production cost, wide availability, and much larger potential supply.

6.4 Carbon Dioxide Capture

These optional add-on systems capture over 99% of the carbon in the fuel, yielding pressurized liquid CO₂ (at temperatures near ambient) for local storage followed by its transport and sequestration. Systems without CO₂ capture have slightly higher AC/HHV efficiencies of 52% to 62% and slightly lower maximum total energy efficiencies of 99% HHV. Input to capture systems is a saturated spent fuel stream consisting mainly of CO₂ and water vapor with very small percentages of O₂ and (when present in the fuel) N₂. Its water vapor content depends upon the nature of the prior heat recovery system. The capture system has a two-stage intercooled compressor, which delivers 25 bar impure CO₂ from 1 bar feed (example pressures). Other

equipment includes heat exchangers, refrigeration system, desiccant system, pressure-swing absorbent beds, and a liquid CO₂ pump. System output streams are liquid CO₂ near 15°C and 50 bar, pure liquid water, and a very small flow of vent gas (O₂ plus N₂).

6.5 Grid Interface

Nearly all stationary systems will be connected to the grid via a smart grid interface. This assembly will contain overvoltage (including lightning) protection, overcurrent protection, and a contactor to quickly disconnect the grid when appropriate. It will also contain time-of-use metering of both export and import power for billing and control purposes. In many cases, the fuel cell system will be connected to a microgrid of nearby users. During some grid outages, the microgrid will be isolated by utility contactor(s) and the fuel cell system will help supply neighboring power users (a valuable function).

6.5 Virtual Battery Operation

Most grid-connected fuel cell systems will sometimes be operated as virtual battery systems. When grid prices are low, the fuel cell systems are hot idled (still capable of producing hot water) and site power needs imported (purchased) from the grid. At somewhat higher prices, the fuel cell supplies varying site loads (“load following”) with no grid power flow in either direction. At higher prices, the fuel cell system will operate at its maximum cost-effective power, with surplus beyond site needs exported (sold) to the grid.

6.6 Surplus Heat Utilization

The difference between the cited maximum energy efficiency and AC efficiency is potentially recoverable useful heat. Most of this heat is available at a temperature of at least 120°C as is thus capable of driving an absorption heat pump system (Section 10.3). The sum of AC output and 120°C heat is 85% (with CO₂ capture) or 87% (without CO₂ capture). Half the remaining heat is available at 60°C minimum and is thus suitable for water heating and ductless heat pump refrigerant vaporization. The balance is available at 30°C, suitable for makeup air heating. Add-on heat recovery systems external to the fuel cell system are needed to utilize this valuable thermal energy.

6.7 Turbocharging

Many larger (about 300 kW and up) stationary and mobile systems will benefit from the addition of turbocharging. By allowing stack operation at 3 bar (typical) pressure, stack electrochemical efficiencies are increased. Dual turbines (expanding spent fuel and depleted air separately) drive both the cathode air compressor and a generator. Turbine exhausts preheat hot zone input gases. Resulting AC/HHV efficiency is 70% to 75% with CO₂ capture and 2% higher without capture. Maximum energy efficiencies are unchanged from non-turbo counterparts.

6.8 Costs

Installed capital costs of fuel cell systems are expected to decline with increased manufacturing volume from 2025 to 2050. They will also decline as system kW size increases. Systems having lower rated AC/HHV efficiencies will have somewhat lower capex. Example average installed costs are given in Table 14.4. Maintenance costs are expected to depend primarily upon annual kWh electricity output and to decline slowly with time. Fuel costs are discussed in Section 14.3.

7. Biomass

The proposed plan greatly increases the utilization of biomass as a primary fuel. The original source of all biomass energy is plants using photosynthesis to convert CO₂ removed from the atmosphere plus water into carbohydrates (sugars and starches) and celluloses. Subsequent biological processes in the plants produce numerous other energy-storing organic compounds, including lignin, proteins, and fats.

Usable energy produced in the U.S. from biomass today chiefly consists of heat from combustion of wood and various wastes, ethanol fermented from corn, and a tiny amount of biodiesel esters from vegetable oils. The proposed plan phases out these uses (except for wood burned in fireplaces) in favor of much more efficient processes.

Chapter 8 describes proposed new systems to convert biomass crops and wastes into biofuels and electricity.

7.1 DOE Report

The U.S. Department of Energy has published a major report entitled 2016 Billion-Ton Report (Reference 4), which updates and enhances two earlier reports. Without harming expected production of foods, feeds, fiber, and timber, they estimate potential dry biomass production up to 1147 million tons in 2030 and 1520 million tons in 2040. Using linear extrapolation, 2050 dry biomass is up to 1893 million tons.

The largest component in the potential totals are farmed dedicated perennial energy crops, including switchgrass, miscanthus, energy cane, biomass sorghum, willow, poplar, and pine. Also included are forest, agricultural, and municipal biomass wastes (including a small percentage of animal biomass wastes). Liquid biomass wastes include used cooking oils.

7.2 Production Enhancement

Many factors could further increase possible 2050 biomass production, including the following.

A genus of trees called paulownia is native to China and includes paulownia tomentosa, which is said to be the world's fastest growing tree. It employs more efficient C₄ photosynthesis (rare in trees, but present in many grasses) and thus uses less water than most plants, which use C₃ photosynthesis. These trees sprout anew from their stumps after harvesting. Their annual dry biomass production is at least several times that of other fast-growing trees. Many are grown in Japan as well as China. They are starting to be marketed in the U.S. as a source of lumber. Types of paulownia are believed suitable for growing in every state. Their extensive farming would boost available biomass for energy uses.

Genetic engineering is rapidly progressing today and is expected to lead to many improvements in important crops, including enhanced resistance to diseases, pests, and environmental stresses.

Organic fertilizers from biomass converters (Chapter 8) can be applied to biomass crops to enhance growth. Drip irrigation using rainwater collected and stored by improved methods can increase growth during dry spells and minimize wildfire dangers.

New types of semi-automated harvest equipment can facilitate utilization of (presently non-farmed) unlevel land, reduce costs, and improve safety.

7.3 Other Improvements

Expected improvements in American diets and elimination of ethanol use as a fuel will free much land now used for corn and soybean farming for biomass crops, increasing net farm incomes per acre.

No-till farming (enabled by greater use of perennial instead of annual crops) will reduce methane emissions and lower costs.

Biodiversity can be increased by converting many farms to a combination of fields and woodlands and growing a greater variety of crops (foods as well as biomass energy crops). Woody crops can be harvested in winter and other crops in summer, allowing full-time employment of workers. Biodiversity will benefit wildlife and reduce vulnerability to diseases and pests.

Most farms producing biomass for energy will perform mechanized size reduction (example average size 1 cm) of harvested biomass to facilitate its temporary storage and transport. Such storage will also minimize unwanted rainwater absorption after harvest.

7.4 Conclusions

Most plant-derived and mixed-waste dry biomass has quite similar composition ratios. Its organic content may be approximated by the formula $\text{CH}_{1.44}\text{O}_{0.67}\text{N}_{0.01}$. Its higher heating value is about 18.6 MJ/kg and lower heating value about 17.3 MJ/kg. Its carbon content is about 47.5% by weight and ash content about 3.7%. This ash contains an average of about 2% sulfur and 1% chlorine (as sulfates and chlorides). It also contains essential phosphorus, potassium, and trace minerals.

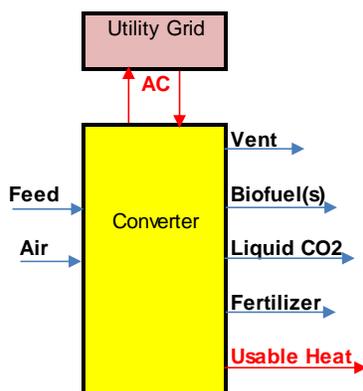
The United States is one of the most advantaged countries in the world to sustainably produce massive annual quantities of biomass for energy uses. The total land area in the 48 contiguous states is nearly three million square miles. If the Chapter 14 example 2050 quantity of 1700 million dry tons of biomass included 1200 million farmed tons (the balance being wastes) and enhanced average yields reached 10 tons per acre, the required farmed area would be 6.3% of the 48-state total.

The factors cited above are expected to enable total 2050 dry biomass production up to at least 2000 million dry tons, allowing an excess to manufacture biofuels for export to the many countries lacking sufficient available and suitable land.

8. Bio-Energy

Biomass (and/or municipal solid waste) is fed to converters as shown below:

Figure 8.1 Biomass Converter



Each automated converter will be a complete factory-built system transportable on a standard flatbed trailer and installed near a biomass source.

8.1 Feeds

Most of the converters are fed 100% biomass (crops and/or wastes). Feeds are pre-processed into pieces under 1 cm each and dried using surplus heat from converter operation. A water tank (not shown) stores water condensed from drying to be fed as needed to achieve hydrogen balance in the biofuel product. Some converters will process feeds also containing a little fossil carbon, as discussed in Section 8.6. Biomass liquids (e.g. used cooking oil) may be co-fed if desired.

8.2 Biofuels

Each converter will produce one of the four biofuels below. 100% of the carbon in each fuel will be renewable from biomass. A few parts per million of a conventional sulfur-bearing odorant will be added to BNG and bio-propane.

8.2.1 Bio-Natural Gas (BNG).

This product will consist of approximately 99% CH₄, 0.3% CO₂, and 0.7% N₂. Its heating values will be 2% lower than average fossil natural gas due to an absence of higher hydrocarbons. BNG will be compressed to the pressure of an attached pipeline and co-mingled with fossil natural gas in distribution systems (co-mingling is discussed in Section 8.9).

8.2.2 Bio-Propane

This fuel will contain no butane (unlike fossil counterparts), enhancing its cold weather characteristics but slightly lowering its heating values (co-mingling with fossil propane is discussed in Section 8.9).

8.2.3 Bio-Gasoline

This super-premium 100-octane fuel will contain no aromatics, olefins, or sulfur. Its Reid vapor pressure (RVP) will be seasonally adjusted to balance cold weather engine-starting performance with evaporative losses.

8.2.4 Bio-Kerosene

This premium fuel will contain no aromatics or sulfur. It will be highly suitable as jet fuel, all-purpose military fuel, and for transportation fuel cell systems using liquid fuel.

8.3 Carbon Dioxide Capture

All of the carbon in converter feed not present in the biofuel product will be captured as liquid CO₂ at typically 15°C and 50 bar pressure. Thus, the converters will emit no gaseous CO₂. The liquid bio-CO₂ is temporarily stored on site in tanks and sold for sequestration (thus achieving net removal of CO₂ from the atmosphere).

8.4 Fertilizer, Usable Heat, and Vent

All biomass contains a mixture of minerals (typically 3 to 4% of dry weight), which are retained in a solid organic fertilizer rich in phosphorus, potassium, and desirable trace elements. This can be sold or returned to associated farms. Nitrogen can be optionally added using ammonia (see Sections 12.2.2 and 16.6).

The usable heat can be used to pre-dry feeds and heat nearby buildings (including greenhouses: Section 8.8).

The vent gas consists of clean air with slightly depleted oxygen.

8.5 Virtual-Battery Operation

Converters are connected to the grid (usually through a transformer). Section 2.5 cites key advantages of virtual batteries. The converters alternate between three different modes based on grid pricing, as follows. Mode transfers can be performed in about ten minutes.

8.5.1 Zero-Power Mode

At intermediate grid prices, converters neither import nor export power, producing as much biofuel as possible under these conditions. HHV efficiency is about 72% for each biofuel. Carbon yield ranges from about 39% for BNG to 51% for biokerosene (balance of the feed carbon becomes bio-CO₂ for sequestration).

8.5.2 Power Export Mode

At high grid prices, the converters produce maximum export electricity and no biofuel. HHV efficiency is about 50%. All carbon in the feed is captured as liquid bio-CO₂.

8.5.3 Power Import Mode

At low grid prices, converters can convert all feed carbon into biofuel with no liquid CO₂. HHV efficiency varies from about 85% for BNG to 80% for biokerosene.

8.6 Municipal Solid Waste (MSW)

MSW is collected from residential, commercial, and industrial sources. By 2050, much more effective sorting of wastes is expected by users and at depots with advanced automated sorting equipment. Considerably more recycling of metals, glass, plastics, and paper products is expected.

However, a large quantity of mixed waste is expected to remain: material now mostly being dumped in landfills. While the majority of this waste has biomass origin, it also includes materials made from fossil fuels (mostly plastics). The converters will process this mixture into the same products. The small share of fossil components can be tracked, and its associated carbon accounted for in the liquid CO₂ for sequestration (which becomes a blend of mostly bio-CO₂ and some fossil CO₂). Since all CO₂ is chemically identical, accounting can properly keep track of both sources. The conversion of MSW into valuable fuels and electricity thus provides a major economic advantage over landfills, removes CO₂ from the air, and helps reduce litter. Some converters will be fed both biomass and MSW, either mixed or alternating.

Accumulated landfills can gradually be mined to recover buried carbonaceous materials (of mixed biomass and fossil origin) for conversion to saleable products, reducing methane emissions from the landfills, and freeing land for other uses.

8.7 Converter Design

Each converter is comprised of four principal sections. Typical internal operating pressure for most of the equipment is 30 bar. Temperatures cited are examples. Converters operate continuously at a constant feed rate, switching among the three operating modes as desired.

8.7.1 Gasifier Section

Dried feed is fed into a gasifier hot zone maintained at 800°C together with a 900°C input mixture of steam and pure oxygen from the electrochemical section. Adiabatic gasification occurs, yielding synthesis gas (“syngas”) consisting of H₂, H₂O vapor, CO, CO₂, CH₄, and N₂ plus carbon-free solid ash. Trace impurity gases such as H₂S and HCl react with the ash, forming sulfates and chlorides. Syngas and ash are cooled by heat exchange, with the ash becoming premium solid organic fertilizer. Section 16.8 discusses possible production of ash containing biochar.

8.7.2 Electrochemical Section

This adiabatic hot zone operates at 900°C with its temperature maintained by adjusting feed temperatures of its inlet gas streams. It contains multiple sets of solid-oxide stacks whose gas flows are isolated from one another, but which exchange heat. Some of these stacks reverse their operation when operating modes change.

The section is fed one or three preheated gas streams. Steam is always fed. Except in power import mode, oxidant and fuel gas are also fed. Oxidant gas is enriched to at least 70% O₂ from air by pressure swing adsorption (PSA). Fuel gas is reactor tail gas (in zero-power mode) or gasifier syngas (in power-export mode).

Output gases from this section are (1) the steam-oxygen mix to the gasifier, (2) hydrogen for biofuel synthesis (except in power export mode), (3) spent fuel mix of steam and CO₂ with a little N₂ and O₂ (except in power import mode), and (4) vent gas of O₂ and N₂.

The stacks generate required electric power for the balance of plant in zero-grid mode. In power-export mode they generate maximum power. In power-import mode, considerable power is fed to stacks which electrolyze steam into hydrogen.

8.7.3 Reactor Section

Each reactor section is dedicated to the synthesis one of the four biofuels from syngas from the gasifier and hydrogen from the electrochemical section.

Bio-natural gas requires the simplest reactor section. A well-known methanation catalyst produces methane at very high conversions from H₂, CO, and CO₂. Water is removed by condensation and a final desiccant. The product contains about 0.3% residual CO₂.

Various reaction pathways are possible for the other biofuels. The example paths below cite one set of alternatives. A common first step might be to use a well-known catalyst to make methanol from the syngas. Methanol can be dehydrated to ethylene.

Bio-Propane might be made by reacting ethylene with methanol to make propylene, following by hydrogenation to propane.

Bio-gasoline can consist of isooctane blended with a little isobutane to adjust its vapor pressure. Ethylene can be dimerized into isobutylene. Isobutylene can be dimerized to isooctenes. Hydrogenation of these olefins yields the bio-gasoline mixture.

Bio-kerosene can consist of normal paraffins: dodecane plus a little octane to lower its minimum use temperature. Ethylene dimerization to butylene can be followed by butylene trimerization and dimerization to dodecene and octene for subsequent hydrogenation to dodecane and octane.

The reactor section will also include heat exchange and other equipment.

8.7.4 Balance of Plant

This section includes outer enclosure, power conditioning, compressors, pumps, fans, PSA oxygen concentrator, solids handling, valves, manifolds, connectors, and control system.

8.7.5 Example Rates

An example converter designed to produce bio-kerosene has the following projected operating rates using switchgrass feed. Dry biomass constant feed rate is 850 lb/hr (HHV 2000 kW, annual rate 3720 tons/year) and fertilizer production is 138 tons/year.

In zero-grid mode, bio-kerosene production is 38.5 gal/hr (72% HHV efficiency). In grid-import mode, 1530 kW is input, and biofuel is 75.4 gal/hr (80% HHV efficiency). In grid-export mode, 1000 kW of AC power is sold (50% HHV efficiency). Usable heat averages about 600 kW.

8.8 Greenhouses

The surplus heat from converter operation greatly exceeds that required to pre-dry typical biomass feeds. It is ideally suited for heating adjacent greenhouses, significantly reducing their annual operating costs. If absorption heat pumps were used, additional heating would occur as well as desirable cooling in hot weather. Greenhouses could grow valuable produce (such as tomatoes, salad greens, and strawberries) of superior quality for local sale, creating additional full-time jobs.

A converter with the above example size could supply most of the annual heat for a well-designed greenhouse in Ohio of perhaps two acres, creating about seven greenhouse jobs.

8.9 Biofuels Delivery

BNG will be co-mingled with fossil natural gas in the existing pipeline and storage network (with upgrades and expansions). All users will receive the same blended product, but their BNG usage will be billed at a somewhat higher price. User BNG share will depend upon their CO₂ capture and whether they elect to buy 100% BNG regardless. System-wide blends will be adjusted to match aggregate user demands, with BNG premiums reflecting its available supply.

Bio-propane will also be co-mingled with fossil propane in storage and delivery trucks, with the same considerations as for natural gas.

Bio-gasoline will be the only type of gasoline sold. Bio-kerosene will be the only type of kerosene sold. Fossil diesel will be sold only to users with 100% CO₂ capture.

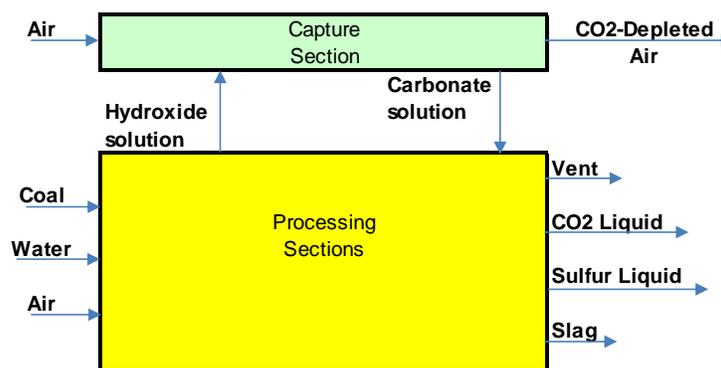
9. Direct Air Capture

Biomass growth captures CO₂ from the atmosphere, leading to the possibilities described above. This chapter describes another type of process which can affordably remove additional CO₂ from the atmosphere for sequestration. In order to isolate pure atmospheric CO₂ for liquefaction, it must be concentrated by a factor of about 2400 (a considerable challenge).

9.1 Process Description

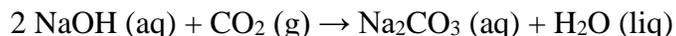
The modular capture equipment is fed ambient air, makeup water, and low-cost coal. Its saleable outputs are liquid CO₂ (containing all carbon from the coal plus that captured from air), pure sulfur (or sulfuric acid), and slag. The process is pollution free. A simplified schematic of the grid-independent process is shown below.

Figure 9.1 Direct Air Capture System



9.1.1 Capture Section

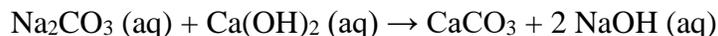
Large fans bring ambient air into intimate contact with small droplets of concentrated aqueous alkali (NaOH or KOH) solution. About two-thirds of the CO₂ in the air reacts with the alkali:



Exiting CO₂-depleted air is slightly cooler and has slightly higher humidity (thus requiring the makeup water). The design of this section minimizes fan power consumption and includes effective mist capture. The processing sections recover pure liquid CO₂ and byproducts as follows.

9.1.2 Calcium Conversion Section

The carbonate solution from the capture section is reacted with lime solution to form precipitated solid calcium carbonate, regenerating the absorbent.



The solid carbonate is then rinsed and dried by energy-efficient equipment.

9.1.3 Coal Gasification Section

Low-cost “steam coal” is used as the energy source. This pressurized section gasifies the coal with steam and 90% oxygen (made from air using PSA). All sulfur is removed and converted into liquid elemental sulfur (or alternatively into sulfuric acid) for sale. Ash is separated and then fused into slag to be sold for construction. Clean fuel gas (consisting of H₂, H₂O vapor, CO, CO₂, CH₄, and N₂) is piped to the fuel cell/calcining section.

9.1.4 Fuel Cell/Calcining Section

An integrated section with a hot zone operating at 8 bar and 1000°C is fed three streams: the above fuel gas, more 90% oxygen, and dried calcium carbonate. Fuel cell stacks generate all the electric power required for the complete process (using about 15% of the coal HHV). The calcining reaction proceeds to completion:



Required heat for the large endotherm is obtained from staged fuel gas oxidation plus surplus heat from fuel cell operation, yielding an exhaust of 57% CO₂, 40% steam, balance nitrogen and oxygen. The hot exhaust directly contacts the solids. Its CO₂ content is about two thirds from the carbonate and the remainder from the fuel gas.

The exiting quicklime and exhaust are heat exchanged with the incoming streams. Cooled CaO is slaked and dissolved in water for recycling to the calcium conversion section.

9.1.5 Balance of Plant

Other equipment includes heat exchange, compressors, refrigeration to liquefy CO₂, PSA (to produce 90% O₂/10% N₂ from air and to purify CO₂), pumps, smaller fans, power conditioning, control system, solids handling, and temporary storage.

9.1.6 Summary

Each modular converter is factory built and transported to the installation site on several flatbed trucks. Sites are selected near sequestration sites and have rail and road access (some are former coal power plant sites). Sites have multiple converters, supported by a maintenance and management building. The preferred size of a single converter is not yet obvious: it might be about 3 MW (net usable power employed, mostly for calcining).

A coal HHV of 19.4 GJ (\$10 in 2019 dollars per Ref. 1 in 2050) will remove one tonne of CO₂ from the atmosphere (together with 0.48 tonne fossil CO₂). Typical weights per atmospheric tonne CO₂ are 1930 lb coal, 18 lb liquid sulfur, and 130 lb slag.

Similar processes (powered by natural gas or electricity instead of coal) have been demonstrated at large pilot scale by at least two companies worldwide. Their use of more expensive energy sources greatly increases their operating cost.

PART TWO: CONSUMPTION SECTORS

The DOE divides delivered energy consumption into four sectors (listed with their 2019 shares, expected to change little in 2050):

Residential	15.4%
Commercial	12.3%
Industrial	35.0%
Transportation	37.3%

The first three of these (discussed in the next three chapters) will share proposed 2050 pricing structures for grid electricity and gaseous fuels as follows.

Fixed monthly fees will be charged for grid connection, based on annual peak kilowatt power demand. Electricity variable prices per kWh will vary with time of use, sometimes changing hourly at short notice (mainly due to the unpredictability of wind and solar generation). Electricity variable export prices (sales to the grid) will be slightly lower than import prices. Variable pricing will decline somewhat as quantities increase, but not vary by sector.

Fixed monthly fees will also be charged for piped natural gas (comingled BNG and fossil gas), based upon annual peak flow. Variable prices for BNG will be slightly higher than for fossil natural gas. Fossil gas will be sold only for use in equipment (primarily fuel cell systems) with CO₂ capture. Variable prices will be slightly lower for larger users.

Comingled propane (bio and fossil) will be delivered by truck (rail car to very large users). As with natural gas, bio-propane will cost slightly more, with fossil propane sold only for CCS equipment.

The 2050 ratio of natural gas to grid variable prices will be much higher than DOE forecasts in order to support the desired mix of energy sources and financial results. 2050 example prices are given in Chapter 14.

10. Residential

Various future options for lowering consumption of residential energy (and CO₂ emissions) are discussed below. Somewhat over half of U.S. residences have piped natural gas service (which will carry comingled BNG and fossil gas in 2050). Of the remainder, some will purchase comingled propane (stored in either permanent on-site or portable tanks), and many will use electricity only.

10.1 Conservation

Increased use of the four R's can be beneficial: reduce, recycle, repair, and reuse. Elimination of waste can reduce residential energy consumption as well as the embedded energy in purchased goods. Recycling of metals, glass, plastics, and paper can be increased. Selection of higher-quality purchased items which can be repaired can lengthen replacement intervals. Reuse of items such as shopping bags can avoid disposal alternatives. Many single-use plastic items can be replaced by paper equivalents. Conservation can also be practiced by using sensible thermostat settings, assisted by better humidity and ventilation controls.

10.2 Efficiencies

Space heating and cooling consumes the most annual energy in most homes. Major savings are often possible with enhanced insulation and superior windows and doors. Shade trees and seasonal awning use can reduce hot weather cooling needs.

Advanced appliances will become available in the future with higher efficiencies. Condensing electric clothes driers with vapor compression will be faster and consume less energy. Heat-pump water heaters will become cost effective for some users. Refrigerator-freezers will use less energy.

LED lighting systems can be equipped with new types of smart switches to minimize unnecessary on time. Entertainment and other electronic equipment will have much lower total power consumption.

More efficient plug-in personal transportation is discussed in Chapter 13. Electric outdoor tools are quieter, less polluting, and use much less energy than gasoline types.

10.3 HVAC Systems

Most homes can replace worn-out furnaces or central air conditioning systems with higher-efficiency equivalents.

The emerging ductless heat pump systems, however, can achieve considerably higher energy efficiencies. In space-cooling mode, they typically cut power consumption in half. In space-heating mode, they use far less energy than furnaces or resistance heating (but at today's very low natural gas prices, they offer little cost savings over natural gas furnaces). By 2050, such heat pumps are expected to have considerably lower operating costs than natural gas furnaces.

Another newly-emerging technology is energy-recovery ventilators (ERVs). These use fans to heat-exchange stale indoor exhaust air with incoming outdoor fresh air. In cold weather, water is condensed from exhaust air for use in humidification (and recovering more heat). Filtering of the fresh air is usually included. ERVs can improve indoor air quality while saving energy.

An expected future option will be the addition of advanced high-efficiency **absorption heat pump** subsystems to the ductless systems. Such combined systems can further enhance energy efficiencies, reduce operating costs, and allow full heating and cooling during extended grid outages. The add-on systems will contain gas burners and have sufficient capacity to use fuel instead of electricity for space cooling and heating when power prices are very high or during grid outages. A useful synergy exists between absorption heat pump and fuel cell systems.

HVAC equipment operation timing can be shifted somewhat by the use of thermal storage. Passive storage occurs when indoor temperatures are allowed to vary (within comfort ranges) so that more heating or cooling can be performed when grid prices are lower. Although active storage systems are also possible (using tanks containing melting/freezing water or wax), they often reduce overall energy efficiencies and are costly.

10.4 Solar Photovoltaic Systems

Even though annual energy production from PV systems depends on location, all 50 states will have potentially cost-effective residential opportunities well before 2050. Solar arrays are usually mounted on roofs, but sometimes on ground-based racks. An important siting consideration is a minimal amount of shading from buildings or trees between about 8 am and 5 pm and a roughly south orientation (within 45 degrees). Arrays which are tilted (e.g. at pitched-roof angle) produce more energy than horizontal ones.

Significant cost components for an installed solar system are an inverter, grid interface, disconnect switches, and electrical protective items. This equipment can be designed to be shared with an existing or future fuel cell system, thereby making the combination more cost effective. Surplus electricity from PV systems is fed to the utility grid, offsetting purchase costs (large systems can yield annual net revenue).

10.5 Backup Power Systems

Residences without fuel cell systems will have no electric service (and hence usually no space heating) during grid outages unless they have a backup power system. Solar PV systems are seldom configured to supply any power during grid blackouts. Backup options are battery and engine-generator systems.

Battery backup systems use banks of lithium-ion (or other types of) storage batteries together with charging and inverter circuits, manual or automatic switching, and protective devices. They can be wired to power priority loads (e.g., refrigerator-freezers, selected electronics and lighting, and HVAC equipment types which use minimal power. Since the installed cost of these systems per kWh of usable capacity is quite high, systems are limited in their duration of operation.

Permanently installed engine-generators are available for operation on gaseous or liquid fuels. They can be used with or without battery banks. Available capacities can power priority loads or

complete homes. They are very noisy and have safety and reliability concerns. Their installed cost can be considerable, approaching that of fuel cell systems.

Portable gasoline or diesel engine-generators are also available. They are quite dangerous and inconvenient.

10.6 Fuel Cell Systems

The great majority of residential fuel cell systems will use BNG or bio-propane fuel (BNG is considerably cheaper if available). A small percentage (chiefly but not exclusively apartment buildings) will install more costly fuel cell systems with CO₂ capture (CCS, described in Chapter 6). Fossil natural gas or propane is available at lower cost for CCS systems. Sale of liquid CO₂ for sequestration will reduce the net cost of BNG or bio-propane.

Steady-state AC output capacities will be available from 1 kW upwards, with most single-family homes installing 3 to 6 kW. Their power conditioning circuits will deliver short-time surge power up to about three times continuous rating (from attached batteries and/or PV systems). Output voltage is 120/240 VAC, 60 Hertz, synchronized with the connected grid. These systems can supply uninterruptible whole-house power throughout grid outages of any duration. Multifamily homes and apartment buildings can install larger systems of appropriate capacity (up to over 100 kW).

Various thermal attachments utilize surplus heat for water heating and to assist space heating. Higher-temperature surplus heat is also available for absorption heat pumps (Section 10.3). Typical hot water subsystems hold 100 gallons, with heat recovered continuously until the entire tank is hot.

Fuel cell systems will normally be operated in virtual-battery mode. When grid prices are very low, the system is hot idled with electricity imported from the grid. At somewhat higher prices, the system load follows site needs, with zero grid power exchange. When grid prices make it profitable, the system operates continuously at maximum power and exports (sells) the surplus. Transition prices for virtual-battery modes will vary with fuel price and surplus heat utilization.

In some neighborhoods, smart local grid switching will sometimes desirably allow the system to help power a microgrid of neighbors during grid outages.

10.7 Autonomous Homes

A small percentage of homes on one acre or larger lots will invest considerable sums (and labor) to achieve autonomous status. Many will include vegetable and flower gardens.

An autonomous home is here defined as one able to operate conveniently without connected or delivered supplies of fuel, electricity, cable communications, or water and with no sanitary discharge to a sewer or septic system. All its communications will use advanced wireless technology. Its vehicles and outdoor tools will be plug-in (pure electric and/or gasoline hybrid).

The owner will annually grow sufficient biomass for on-site conversion to supply all electricity and fuel needs. The biomass will be a diverse mix of types cited in Chapter 7. It will be

harvested, shredded, dried, and stored in a silo for 12-month conversion in a miniature converter using technology similar to that described in Chapter 8. The converter produces bio-propane, bio-gasoline (if needed), and electricity. Its ash (enriched by a little bio-ammonia also produced) is used to fertilize biomass crops and gardens. A battery bank is attached. A rooftop PV array will sometimes add supplemental energy input.

Solid wastes will be carefully sorted, with all recyclables driven to a suitable off-site collection depot. An automated system will process household sanitary effluent to yield safe purified water suitable for irrigation and dried solids, which are added to biomass converter feed.

Rainwater will be collected from roof and driveway. Some will be thoroughly purified for household drinking, cooking, and washing. Most will be stored in a properly-maintained on-site pond for crop irrigation (and available for firefighting).

The owner will enjoy the satisfaction of producing all residential energy needs and of generating no wastes needing external disposal. The home will have zero carbon footprint and pay no utility bills (other than for communications and possibly for roadway storm sewer). If optional CCS is added, the home will become carbon-negative.

10.8 Residential Summary

The table below summarizes options for homes with and without gas fuel available. Abbreviations in the table include BP for bio-propane, HP for heat pump, FC for fuel cell system, AC for air conditioner, AHP for absorption heat pump, and na for not available.

Table 10.1 Residential Options

	With BNG or BP		No Fuel	
	Basic	Preferred	Basic	Preferred
Essentials				
Range	Gas	Gas	Electric	Electric
Drier	Gas	Compressor	Resistance	Compressor
Water Heating	Gas	Fuel Cell	Resistance	Heat Pump
Space Heating	Furnace	Ductless HP	Central HP	Ductless HP
Space Cooling	Central AC	Ductless HP	Central AC	Ductless HP
Desirable Options				
Backup Power	none	Battery or FC	none	Battery
AHP Add-On	none	Yes	na	na
Fuel Cell System	none	Yes	na	na
Solar PV System	none	Yes	none	Yes

11. Commercial

The commercial sector includes wholesale, retail, and service companies of all sizes. It also includes government facilities, health care, schools, hotels, restaurants, and office buildings. Smaller commercial sites have energy use similar to residential. Some small facilities can share HVAC and fuel cell systems with each other. The largest commercial sites (often with multiple buildings) have tens of thousands of employees and use many megawatts of electric power.

11.1 Efficiencies and Conservation

Improved insulation, windows, and doors can reduce HVAC needs. More efficient refrigeration systems will become available. Kitchen facilities can benefit from various improvements.

Most sites can conserve electricity by lowering illumination levels, using less lighting when closed, and slightly adjusting inside temperatures. Recycling can be increased, and many types of waste reduced.

11.2 HVAC Systems

Most sites will use high-efficiency ductless heat pumps. Many with fuel cell systems will add absorption subsystems to further boost efficiency and operating flexibility. Energy-recovery ventilators will also be desirable. A small share of commercial facilities will use active thermal storage systems (usually ice/water type) to exploit TOU pricing.

11.3 Solar PV Systems

A considerable fraction of commercial buildings can install rooftop solar arrays, either horizontal or tilted. Such arrays will often have lower installed cost than residential PV due to economies of scale for larger capacities.

11.4 Fuel Cell Systems

A sizeable number of commercial buildings will install fuel cell systems (the majority using natural gas and the remainder propane), which will produce operating cost savings and supply uninterrupted power (avoiding the need for backup power systems). Nearly all will include CO₂ capture (CCS), reducing net fuel cost after CO₂ sales credits. Surplus heat from the fuel cell systems can assist space heating, provide hot water, and partly supply thermal inputs to the absorption subsystems cited in 11.2.

The fuel cell systems will operate as virtual batteries: hot idling when grid prices are low, load following at moderate prices, and generating full power when prices are higher (allowing significant export sales). Most sites will operate fuel cell systems on lower-cost fossil fuel, but some will use biofuel in order to achieve greater net carbon removal from the atmosphere (which can be touted in advertising). The utilities in some locations will establish microgrids, with fuel cell systems powering nearby customers during most grid outages. Some large commercial sites with high (300 kW and larger) electrical needs will install higher-capex turbocharged fuel cell systems (Section 6.7) for higher electrical efficiencies.

12. Industrial

Included in this sector are mining, fossil energy exploration and production, manufacturing, and refining. By 2050 this sector will reflect growth in domestic manufacturing (displacing some imports). Expected production of fossil fuels will change significantly: less natural gas, much less petroleum, and more coal.

12.1 Similarities to Commercial

All the improvements cited in Chapter 11 are applicable to most manufacturing facilities. Many large installations will use multiple megawatt-scale turbocharged natural gas fuel cell systems with CCS. Industrial fuel cell systems will furnish major virtual battery capacity to the grid.

12.2 Manufacturing

Nearly all 2050 manufacturing operations can achieve higher energy efficiencies. They can all be modified to emit zero fossil CO₂ through the combined use of CCS, biofuels, and (carbon-negative) grid power.

Three specific large-scale industrial processes now consume large quantities of energy and emit considerable fossil CO₂. By 2050, each can be replaced with more efficient new processes with zero CO₂ emissions and no pollution. All fossil CO₂ from the proposed new processes would be captured and permanently sequestered. Each would use natural gas fuel and include molecular sieves, heat exchangers, and compressors.

12.2.1 Cement

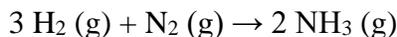
Portland cement manufacture requires endothermic calcining of limestone to lime:



Conventional kilns emit fossil CO₂ from both the limestone and combusted natural gas fuel. The more efficient new process would perform the same chemical reaction while capturing all CO₂ from both feed and natural gas.

12.2.2 Ammonia

Ammonia is made by catalytically reacting hydrogen and nitrogen, typically above 300°C and 30 bar:



It is made using natural gas, water, and air. Ammonia is the leading type of farm fertilizer (applied as pure anhydrous liquid or a derivative).

Proposed new processes would incorporate reaction systems with modified fuel cell technology (Chapter 6). Steam-reformed natural gas fuel would be fully oxidized by two oxygen streams: one from steam (producing the required hydrogen) and one from oxygen-enriched air. All carbon would be captured and sequestered.

12.2.3 Iron

Nearly all iron from iron ore is promptly converted into steel. The vast majority of the iron produced in the U.S. today uses coke as the energy source and reducing agent in blast furnaces. Both the coke ovens (which produce coke from metallurgical coals) and the blast furnaces emit large quantities of fossil CO₂ together with many air pollutants.

New direct-reduction processes are proposed to reduce the ore to iron using hydrogen made electrochemically from steam. Natural gas (with all its carbon captured and sequestered) would supply the energy to produce the hydrogen, using systems resembling the fuel cell systems described in Chapter 6.

12.3 Fossil-Fuel Refining

Refineries are fed three types of fossil fuels: petroleum (crude oil), natural gas, and natural gas liquids (NGL). They produce liquid fuels, asphalt for paving, and numerous chemicals (including intermediates). Existing refineries emit large quantities of fossil CO₂ and pollutants, while consuming considerable energy.

Major changes to these refineries by 2050 are proposed. Modified fuel cell technology (Chapter 6) is combined with process changes to capture all CO₂ from carbon not present in the products. Refineries would continue to produce the same chemicals and asphalt, but the only fuels produced for sale would be propane and a superior type of diesel (both used only in fuel cell systems with CO₂ capture). The propane would contain a few parts per million sulfur-bearing odorant (captured during use). The new non-toxic diesel would contain no aromatics or sulfur, thus emitting no SO₂ when used. Fossil fuel exports will be sold only to users who capture CO₂.

12.4 Chemicals Production Notes

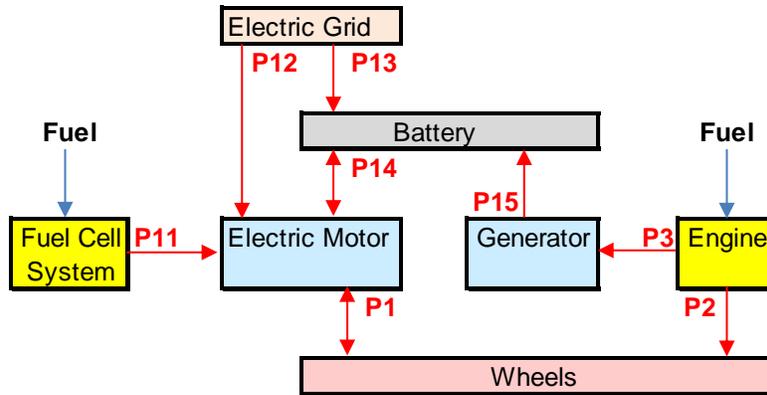
Ammonia and some chemicals (including monomers such as ethylene and propylene) could be produced from biomass rather than fossil fuels. Although biomass-derived products will sell at higher prices, they are expected to capture some market share.

Plastics and other chemicals containing fossil carbon are expected to not result in net fossil CO₂ emissions, due to the combination of recycling and CCS of municipal wastes (with a little extra bio-CO₂ sequestration to offset minor losses).

13. Transportation

Figure 13.1 is a simplified view of alternative power paths for wheeled transportation (road vehicles and railroads).

Figure 13.1 Transportation Power Paths



Paths P1 through P3 are mechanical power (torque times rotational speed) and the other paths are electrical power. Traditional systems use P2 and P3 (with a battery powering auxiliary systems only). Existing hybrid systems usually employ P1, P2, P3, P14, and P15, with a fraction also sometimes using P13 (plug-in option). Double arrows show the use of regeneration during deceleration to return energy to the battery. Path P12 is used only by electric trains. Pure electric plug-in vehicles use P1, P13, and P14. P11 is a proposed major path in the future, which would be combined with various combinations of the other paths.

Types of transportation other than wheeled use propellers (ships, boats, some planes), fans (fanjet planes), or compressors (pipelines). None of these use regeneration.

All types of transportation equipment include at least small rechargeable batteries (mostly lead-acid or lithium-ion). Some also have larger batteries to implement hybrid traction functions, including storing deceleration energy and providing peak power.

The forecast 2050 transportation totals from DOE (Ref.1) are 3564 billion light-duty vehicle miles traveled, 415 billion freight ton-miles, and 2047 billion available aircraft seat miles.

Table 13.1 gives DOE forecast and proposed quantities.

Table 13.1 Transportation 2050
(Exajoules)

	DOE	Proposed					Sum	ratio
	Ref.1	Electricity	BNG	Bio-Gasoline	Bio-Kerosene	Diesel CCS		
Light-Duty Vehicles	12.76	4.00		1.50			5.50	43%
Commercial Light Trucks	1.13	0.15				0.30	0.45	40%
Buses	0.28	0.05				0.10	0.15	53%
Freight Trucks	6.42	0.30				4.08	4.38	68%
Rail	0.55	0.05				0.35	0.40	73%
Shipping	0.94				0.58	0.22	0.80	85%
Boats	0.25			0.20	0.05		0.25	99%
Aircraft	4.30			0.05	3.87		3.92	91%
Military	0.51				0.50		0.50	99%
Lubricants	0.14				0.10		0.10	73%
Pipelines and Distribution	0.84		0.25			0.15	0.40	47%
Total	28.12	4.55	0.25	1.75	5.10	5.20	16.85	60%

The three biofuels are produced in carbon-negative processes and emit (carbon-neutral) bio-CO₂ back into the atmosphere during transportation uses. The fossil diesel is used only in fuel cell systems with CCS. Proposed energy consumption is 60% of DOE forecast. The following sections describe the major expected types of traction power systems in 2050.

13.1 Electricity

The above table shows electricity as 27% of proposed energy. A small fraction powers electric trains, but the great majority is plug-in power. Most of these vehicles recharge at low TOU prices when practicable. Light-duty vehicles obtain the great majority of their electricity at residences. Trucks and buses mainly recharge at overnight depots and lots. Workplace recharging stations will be widespread, as will public rapid-recharge boxes (with universal compatibility, automatic billing, and reservation capabilities). Electric range between recharging will vary by intended use, from under 50 miles to over 400 miles. Some of the light duty vehicles will have two or three wheels, but most will be four-wheel sedans, SUVs, vans, or pickups.

Over half the plug-in vehicles are pure electric. The remainder are engine hybrids using bio-gasoline. Their engines operate mainly on long trips. Their ability to quickly refuel with gasoline at many locations is desirable.

13.2 Engines

Most bio-kerosene is used in gas turbine engines on aircraft and military equipment. Some powers diesel engines on ships, other military equipment, and boats. A small amount fuels steam turbines on ships. A heavier version of bio-kerosene is used to make lubricants (used in smaller quantities due to reduced total engine use).

Bio-gasoline is used in the hybrid light-duty vehicles cited above, in recreational boats, and in small general-aviation planes.

The bio-CO₂ in engine exhaust is all returned to the atmosphere.

13.3 Fuel Cell Systems without CCS

Some of the proposed transportation fuel cell systems will use biofuels and perform no CO₂ capture. Systems on natural gas pipelines will use BNG fuel cell systems to power their compressors and auxiliary equipment. Bio-kerosene fuel cell systems will generate all (or most) electric power on many commercial aircraft and at military bases.

13.4 CCS Fuel Cell Systems

Most of the fuel cell systems used in transportation will use fossil diesel fuel and capture all its carbon for sequestration. Pressurized on-board tanks with flexible internal dividers will store both liquid CO₂ and fuel. Although the carbon dioxide occupies considerably more volume than the fuel, the excellent efficiency of fuel cell systems requires combination tanks similar in size to those needed for engines on vehicles having the same travel range.

Individual transportation fuel cell systems will range in size from under 100 kW (in some small commercial trucks) to perhaps 3000 kW, with multiple systems in many of the larger applications. Most fuel cell systems will be hybridized with lithium-ion battery packs to supply higher peak power (but limited energy storage). The systems will be used on trucks, buses, locomotives, ships, and liquid-fuel pipelines. Many systems of 300 kW and larger will be turbocharged for higher efficiency.

CCS systems could alternatively operate on higher-priced bio-kerosene to remove CO₂ from the atmosphere (not assumed in the Chapter 14 example).

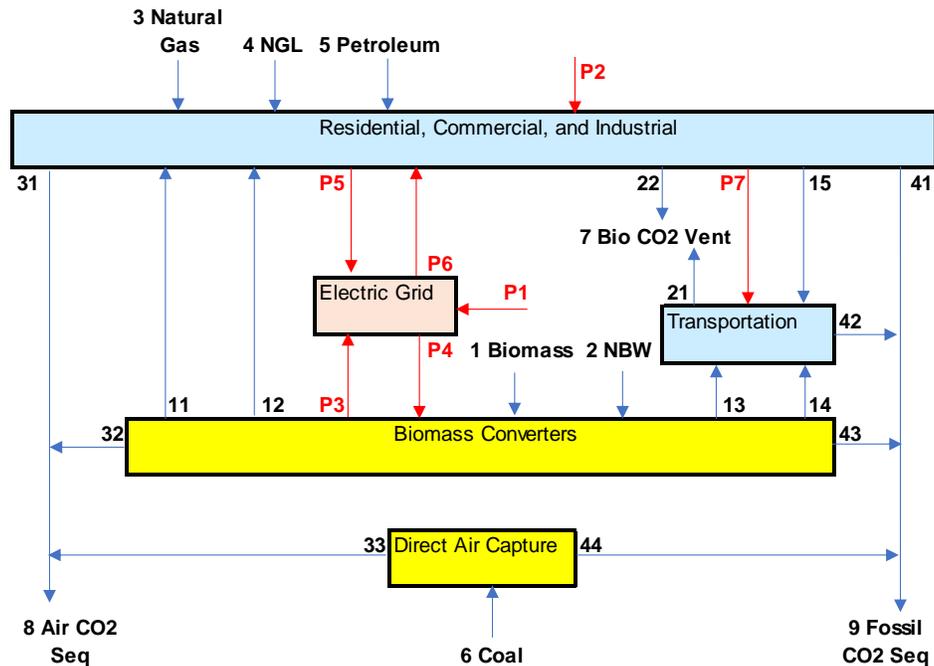
PART THREE: DISCUSSION AND CONCLUSIONS

14. Example

This chapter contains an example 2050 material and energy balance, example energy cost summary, comparisons with the 2050 DOE forecast, and other financial estimates. Constant 2019 dollars are used. It is emphasized that all estimates in this chapter are likely to significantly differ from actual results (which might be either higher or lower).

14.1 Material and Energy Balance

The proposed 2050 simplified balance is shown below (Figure 14.1).



Energy and Fuels	EJ	Carbon Dioxide	million tonnes	Electricity	EJ
1 Biomass	28.72			P1 Renewables to Grid	8.00
2 Non-Biogenic Wastes	2.13	7 Bio-CO2 Vented	666	P2 User-Site PV	4.00
3 Natural Gas	16.51	8 Atmospheric CO2 Seq	5000	P3 Converters to Grid	8.00
4 Natural Gas Liquids	2.50	9 Fossil CO2 Seq	2845	P4 Grid to Converters	3.00
5 Petroleum	6.00	21 Transportation	446	P5 Users to Grid	2.00
6 Coal	15.79	22 Stationary Users	221	P6 Grid to Users	13.80
11 Bio-Natural Gas	5.80	31 Stationary Users	111	P7 Transportation	4.55
12 Bio-Propane	0.75	32 Converters	1904		
13 Bio-Gasoline	1.75	33 Direct Air Capture	2985		
14 Bio-Kerosene	5.10	41 Stationary Users	914		
15 Fossil Diesel	5.20	42 Transportation	363		
		43 Converters	141		
		44 Direct Air Capture	1426		

Stream (1) is 1700 million tons biomass dry weight: a sustainable quantity as discussed in Chapter 7. Stream (2) is 50 million tons of non-biogenic wastes, comprised mostly of plastic and rubber (mixed with biomass wastes) and also discussed in Chapter 7.

Stream 6 is 790 million tons of coal. Although higher than the 706 million tons U.S. production in 2019, it is well below average production from 1990 to 2014 of 1070 million tons per year and only slightly above 2017 production of 775 million tons. The recent lower production reflects power plant shutdowns rather than production limitations.

An outstanding result in this example is Stream 8: net removal of 5.0 billion tons of CO₂ from the atmosphere. The great majority of the fossil carbon feeds (Streams 3 through 6) is sequestered (Stream 9). A small fraction is converted to recyclable products such as asphalt and plastics (not shown).

14.2 DOE Forecast for 2050

Table 14.1 lists selected values from Tables A2 and A3 in Ref. 1, using 2019 dollars and converting their energies listed in Quads to exajoules (EJ). Their LPG is listed here as Propane and their distillate fuel oil listed as Diesel.

Table 14.1 DOE Delivered Energy 2050

	EJ	Cost/GJ	Billions
Natural Gas	26.58	\$5.71	\$152
Propane	5.74	\$27.45	\$158
Gasoline	15.01	\$27.17	\$408
Jet Fuel	4.92	\$20.73	\$102
Diesel	8.73	\$25.90	\$226
Grid Electricity	17.21	\$27.52	\$474
Totals	78.19	\$19.43	\$1,519

The \$1519 billion is 98.4% of their total of \$1543 billion, since Table 14.1 excludes residual oil, industrial coal, and miscellaneous (which are phased out in the proposed case). The 78.19 EJ is 87.6% of their total of 89.30 EJ, which includes other categories without listed costs (such as refinery and chemical plant feedstocks). The costs include both fixed and variable components (where applicable) and most of the applicable taxes. GDP was \$21.3 trillion in 2019 and is forecast to increase to \$37.8 trillion in 2050 (both 2019 dollars).

14.3 Proposed 2050 Delivered Energy

The following table lists proposed delivered energy, mean prices per GJ, and annual user costs. The CO₂ produced by fuel use is either vented or captured and sequestered (CCS) where listed.

Table 14.2 Proposed Delivered Energy

	EJ	Cost/GJ	Billions
Bio-Natural Gas Vented	3.80	\$26.20	\$100
Bio-Natural Gas CCS	2.00	\$23.70	\$47
Natural Gas CCS	16.51	\$21.55	\$356
Bio-Propane Vented	0.55	\$36.00	\$20
Bio-Propane CCS	0.20	\$33.00	\$7
Bio-Gasoline Vented	1.75	\$35.00	\$61
Bio-Kerosene Vented	5.10	\$28.00	\$143
Diesel CCS	5.20	\$37.40	\$194
Grid Electricity	11.80	\$35.00	\$413
Piped Gas Fixed			\$60
Grid Fixed			\$120
Road Use Fees			\$150
Totals	46.91	\$35.62	\$1,671
Ratio to DOE Forecast	60%	183%	110%

The total is 4.4% of 2050 GDP: higher than DOE forecast ratio of 4.0% but lower than 2019 actual (5.5%). This total is believed to be appropriate and affordable, with some assistance being provided to low-income families (Section 14.4). The fixed charges and road use fees will fund the significant improvements to infrastructure discussed.

The much higher unit costs will provide enhanced incentives for users to invest in more efficient equipment and systems. The proposed fossil natural gas variable cost (much higher than DOE forecast) will support the energy mix assumed in Section 14.1. The average cost of bio-kerosene is low because its principal use is for aircraft and other uses supplied by large tank trucks, where handling costs are low. The sum of the variable costs in Table 14.2 is \$1341 billion or \$28.59/GJ. Thus, the proposed 40% energy savings has a value of \$894 billion in 2050.

14.4 National Carbon Administration

Proposed 2050 expenditures for the NCA are summarized in the following table. This agency is discussed in section 18.6.1.

Table 14.3 NCA 2050 Expenditures

	million tonnes	Cost tonne	billions
Bio-CO ₂ from Users	111	\$50.00	\$6
Bio-CO ₂ from Converters	1904	\$30.00	\$57
Air CO ₂ from Direct Capture	2985	\$20.00	\$60
Total Purchases CO ₂ from Air	5000	\$24.47	\$122
CO ₂ Transport and Sequestration	7845	\$12.00	\$94
Assistance Programs			\$50
Overhead			\$15
Total Expenditures			\$282

The 2845 million tonnes of fossil CO₂ have zero purchase cost, since proposed fossil fuel selling prices are net of this CO₂ being collected. The NCA budget is funded entirely out of the \$356 billion natural gas revenue (Table 14.2), which far exceeds its adjusted total production cost of \$74 billion.

The \$50 billion for assistance programs are paid to low-income energy users to help them pay for enhanced-efficiency equipment and partially offset their energy bills.

14.5 Primary Inputs 2050

Streams 1 through 6 in Section 14.1 have a combined total cost of \$436 billion, after allowing for desirable environmental upgrades to fossil fuel extraction. Total user energy costs in Table 14.3 are \$1671 billion. After subtracting the \$60 and \$120 billion fixed utility costs, \$150 billion road use fees, and \$282 billion NCA costs, the difference is \$1059 billion, which should easily pay for all other delivered energy expenses (return on investment, personnel, maintenance parts and supplies, taxes, insurance, and other). The assumed average biomass cost is \$90 per dry ton: an average believed not to threaten food and fiber production.

14.6 Capital Expenditures

The new systems described in Chapters 6, 8, and 9 will begin large-quantity installation in about 2025 and continue past 2050. Their installed cost per kW of nominal capacity will decline significantly over time as manufacturing volumes rise and improvements are phased in. Table 14.4 estimates cumulative capital expenditures for the proposed systems. Biomass converter capacity is based on biofuel products HHV. Direct air capture capacity is based upon net power used in the process. The lower average cost per kW of transportation systems is due to their much larger average size.

Table 14.4 Cumulative Capital Expenditures 2025-2049

	Capacity	Capital Expenditure	
	GW	per kW	billions
Stationary Fuel Cell Systems	526	\$800	\$421
Transportation Fuel Cell Systems	470	\$400	\$188
Biomass Converters	589	\$1,600	\$943
Direct Air Capture Systems	389	\$1,200	\$467
Totals	1974	\$1,022	\$2,018

The 25-year total averages about \$81 billion per year (for comparison, General Electric 2019 revenues were \$95 billion).

In addition to the above, very large capital expenditures will fund other efficiency improvements, infrastructure upgrading, and other installations.

15. Hydrogen

Hydrogen plays essential roles in the recommended plan (Sections 15.1 and 15.2). It also has possible uses which are not assumed (Sections 15.3 through 15.5).

15.1 Hydrogen in Fuel Mixtures

All of the fuels recommended in this report are hydrocarbons: some of biomass origin and others of fossil origin. For use in solid-oxide fuel cell systems (Chapter 6), these fuels are mixed with steam or steam mixtures and catalytically reformed at high temperature, producing a fuel gas mixture with significant percentages of H₂, H₂O vapor, CO, and CO₂, plus a little CH₄ and sometimes N₂.

15.2 Hydrogen for Chemical Reactions

The biofuel production methods summarized in Chapter 8 use hydrogen in synthesis reactions. The gasifier output contains the same gases listed in Section 15.1. Additional hydrogen is produced from steam electrochemically by solid-oxide stacks.

Hydrogen made electrochemically from steam is also used in the manufacture of ammonia, iron, and in fossil-fuel refineries (Chapter 12).

15.3 Hydrogen as a Transportation Fuel

Hydrogen (of relatively high purity) has been successfully demonstrated in all major types of engines and fuel cell systems. Its use produces no CO₂. Its potential future utilization, therefore, depends upon other factors: storage and transport, costs, and environmental aspects of its production.

15.3.1 Storage and Transport

Hydrogen gas has a very low energy content per unit volume (CNG used in fuel cell systems yields about four times the energy per unit volume). Therefore, it is commonly stored and transported at very high pressures (typically near 350 bar or 5000 psi and sometimes higher). Energy is needed for compression. Alloy steel tanks are used (with special features to limit embrittlement) for storage, while high-performance carbon-fiber composite tanks are used on vehicles. The tanks weigh considerably more than the fuel, so the combination weighs considerably more than the proposed liquid hydrocarbons in their tanks (and occupies considerably more volume).

Hydrogen can be liquefied, but this requires considerably more energy and capital cost than gas compression to high pressure. Its very low critical temperature leads to boiloff losses. Liquid hydrogen is practical mainly for space launch rockets.

Hydrogen can also be stored in hydride compounds. However, these require considerable energy to liberate the hydrogen, harming system efficiency and are also quite heavy.

15.3.2 Costs

The lowest cost hydrogen is made from natural gas. The traditional method uses steam reforming, shifting, CO preferential oxidation, and separation processes. A possible future alternative would employ a simpler process using solid-oxide electrochemical systems.

Hydrogen can also be made by steam electrolysis using electric power (preferably off peak).

Future production systems are possible fueled by natural gas with complete CO₂ capture (zero carbon emissions), configured as virtual-battery electrochemical systems. Grid power would be imported to make extra hydrogen when prices are low, electricity exported when prices are high, and hydrogen made with zero grid power at intermediate prices. Natural gas systems could be installed at truck stops, eliminating hydrogen transportation.

Another future option would be biomass converters with 100% CCS of bio-CO₂ (maximum negative carbon) operating as virtual battery systems and making high-pressure “bio-hydrogen”. Such hydrogen, however, would usually require transportation to the point of sale and additional storage tanks.

All of these alternatives would have higher total costs than the recommended plan, which uses liquid hydrocarbon biofuels and fossil diesel with CCS.

15.3.3 Environmental

Traditional hydrogen production from natural gas emits all the carbon as fossil CO₂. Advanced natural gas (or steam electrolysis) methods could achieve zero fossil CO₂ emissions. Hydrogen from biomass would have maximum CO₂ benefit (but be more costly than other biofuels).

15.4 Water Batteries

Demonstrations have been made and alternative concepts explored for sealed solid-oxide secondary battery systems using water, hydrogen, and oxygen at high pressures. Some of the designs would maintain the water always as vapor (“steam batteries”). Thermal storage (with temperature cycling) could improve efficiencies when time cycles are short.

Water batteries have the potential for significantly higher specific energy (Watt-hours per kilogram) than lithium types. They could also be less costly for some applications. They could be advantageous for some plug-in trucks or buses. They might also be attractive in some stationary applications. Their round-trip storage efficiencies would be lower than lithium types in most cases.

15.5 Ammonia-Air Batteries

Stationary storage batteries of medium to large size might use solid-oxide stacks with hydrogen, air, water, and ammonia (stored as liquid). Vaporized ammonia can be used directly as a fuel cell fuel. Capital costs could be well below lithium systems, but storage efficiencies significantly lower.

16. Alternatives

This chapter briefly mentions some alternatives to the ideas proposed. Alternatives using hydrogen were discussed in Chapter 15.

16.1 Quantities and Efficiencies

The 2050 quantities listed in Chapter 14 are examples only. Actual quantities will likely differ from this example in both timing and proportions. The example efficiencies of systems will depend on capital costs: lower capex is often possible at lower efficiency. A significant potential for more exports exists (discussed in Chapter 17).

16.2 Financial

The Chapter 14 price examples were selected to be affordable, completely cover all expected costs, provide incentives for efficiency and conservation, fund infrastructure enhancements, and supply financial assistance to lower income families. The proposed energy expenditures as a fraction of GDP remain lower than now and could be somewhat higher if necessary.

16.3 Renewable Electricity

All of the proposed increases in 2050 renewable electricity are from solar photovoltaic and wind. The 2050 DOE forecasts of hydroelectric and geothermal power generation are adopted. Very few domestic sites are suitable for added hydroelectric capacity, while many small installations are being removed due to worn-out equipment and the harm they cause to ecosystems. Few domestic sites will be cost effective for added geothermal generation.

Other known renewable technologies include solar generation using steam and various ocean systems. None of these are expected to be significant in 2050.

16.3 Alternative Fossil-Fuel Power Plants

In 2019, 62% of domestic electricity was generated by fossil-fuel power plants, which emitted all their resulting CO₂ (accounting for 32% of U.S. total energy-related emissions). Most of this electricity had low production cost (using coal or natural gas) and was generated using steam turbines and/or gas turbines. By 2050, it is proposed to operate no plants of this type, since it would cost far more to reach zero fossil CO₂ emissions with these technologies than by using the proposed combination of renewable and fuel cell systems.

16.4 Nuclear-Fission Power Plants

In 2019, 19% of domestic electricity was generated by nuclear-fission power plants. Fission plants emit zero CO₂. New designs are under development which promise lower costs and improved safety. However, all these plants generate radioactive wastes, which remain dangerous for over 100,000 years and for which so satisfactory storage solution has yet been selected. They are also potentially vulnerable to terrorist threats, which could release radioactivity. By 2050, it is proposed to operate no nuclear fission power plants.

16.5 Alternative Biofuels

The major biofuel used in the U.S. today is ethanol, made from corn. A small amount of biodiesel ester is also used, made from new or used vegetable oil and methanol (made from natural gas). These oxygenated fuels have little or no net environmental benefit, are usually more expensive, and contain less energy per gallon than their fossil counterparts. Many other types of biofuel are now being considered, including other alcohols, ethanol from cellulose, and oxygenates from algae. Since the proposed hydrocarbon biofuels have superior properties, costs, and environmental benefits, the 2050 plan includes no oxygenated fuels. Used cooking oils and other oxygenated biomass wastes can be fed to the proposed biomass converters along with the proposed solid feeds.

Biomass-sourced propane, ammonia, or hydrogen could potentially be used as vehicle fuel. Bio-propane is less convenient than biogasoline or biokerosene. Either ammonia or hydrogen from biomass could be completely carbon negative: a desirable attribute. However, ammonia is poisonous and has multiple other disadvantages as a vehicle fuel. Hydrogen fuel disadvantages are cited in Chapter 15.

16.6 Bio-Ammonia Fertilizers

Another type of converter can convert biomass to ammonia. All of the carbon in the feed would be converted to bio-CO₂ and sequestered. This ammonia can be chemically reacted with the organic fertilizers cited in Section 8.3 (as well as from its own operation) to create balanced complete fertilizers with a preferred nitrogen content. It can also be used in pure anhydrous form as a fertilizer (or chemical intermediate). This negative-carbon ammonia would command a premium price over the zero-carbon ammonia described in Section 12.2.2.

16.7 Bio-Chemicals

Converters which convert biomass to various major organic chemicals are also possible. Part of the bio-carbon would appear in the product and the remainder as liquid bio-CO₂ for sequestration. High-tonnage monomers include ethylene and propylene. Major alcohols are methanol, ethanol, and iso-propanol. Another possibility is ethylene glycol. Such products would cost somewhat more than their conventional counterparts but would be preferred by some customers. For example, a high-yield acre of switchgrass could be converted to considerably more ethanol than fermentation of corn by using converters to those described in Chapter 8.

16.8 Biochar

The gasifiers described in section 8.7.1 would completely gasify all the carbon in the feed for producing biofuels and electricity, yielding a carbon-free ash. Alternative gasifier designs could partially gasify feeds, producing ash containing high-carbon solid biochar. If this mixture were mixed into farm soils, it could supply nutrients, enhance soil structure, and sequester its carbon (chars can persist for many thousands of years). However, biochar production would reduce the yield of biofuels. The example case in Chapter 14 does not assume any biochar production.

16.9 Alternative Fossil Fuels

The only fossil fuels proposed for users in 2050 are natural gas and diesel (both used with full CO₂ capture). All other fossil fuels will be phased out before 2050, with preferred types replaced by superior biofuels.

16.10 Natural Gas as Transportation Fuel

At present, high-pressure compressed natural gas (CNG) is being widely used as an engine fuel in many trucks and buses, which have been built to use this fuel or converted as necessary. Its attractions are considerably lower fuel cost, lower CO₂ emissions, and lower pollution. It does, however, require expensive high-pressure components and tanks and the addition of spark-ignition subsystems. Although the 2050 transportation fuel cell systems could be designed to work well with bio- or fossil-CNG (with no pollution or fossil CO₂ emissions), its proposed much smaller 2050 cost advantage over diesel fuel would not justify the added required expenses. Fuel tanks for ample range using diesel would cost far less and occupy considerably less volume. Diesel fuel is also less dangerous than high-pressure CNG.

16.11 Alternative Electricity Storage

Hydroelectric storage systems are in use today, using either gravity or pumped water. Compressed air energy storage (CAES) systems use underground caverns to store compressed air for use in gas turbine-generator systems. Both of these generate only a tiny share of U.S. electricity and are expected to remain negligible in 2050.

A great many different types of rechargeable (secondary) battery systems are in use today. Lead-acid SLI (starting/lighting/ignition) batteries are standard for engine starting. Deep-cycle lithium-ion and nickel-metal hydride batteries are extensively used in hybrid vehicles. Many alternatives are under study for large systems, including flow-battery systems (which decouple reactant storage from reaction systems). Sections 15.4 and 15.5 cite hydrogen flow battery possibilities. No known battery system appears to offer attractive costs and operating characteristics for grid-scale storage.

Demonstration systems have used flywheels, superconducting magnetic energy storage (SMES), reversible hydrogen-oxygen fuel cell systems, and many other ideas. None of these appear likely to be competitive in cost or efficiency with the recommended systems.

16.12 Alternative Heat Pumps

Geothermal heat pumps use buried pipes to exchange heat with underground soil and/or rock. Although they are more energy efficient, they have much higher installed costs.

Heat pumps using ducts rather than the proposed ductless systems have lower energy efficiency and are vulnerable to mold problems. However, they can have lower capex when retrofitting existing homes.

16.13 Alternative Direct Air Capture

Alternative energy sources (natural gas or electricity) have been used with most early direct capture systems. Although the proposed coal systems are more complex and require development, they promise far lower operating cost.

Other chemical paths have also been studied which use alternatives to lime carbonation and calcining. Their economics are quite uncertain.

16.14 Alternative Exhaust Capture

Direct air capture requires increasing CO₂ concentration some 2400 times from air to pure carbon dioxide. The exhaust from existing power plants and industrial plants typically contains 4% CO₂ or higher, thus requiring a concentration factor of 25 or less. However, the exhaust precooling and makeup water needs (to adapt the proposed capture process) would offset the savings in lower fan power. Also, many of the large existing plants emitting CO₂ will have been replaced before 2050.

16.15 Nuclear Fusion

The diverse and very expensive ongoing projects which seek to develop practical fusion power plants may result in commercial success by 2050 or shortly thereafter, generating affordable carbon-free power from hydrogen isotopes. Questions remain, however, about the radioactivity created in materials surrounding the reaction zones.

17. Rest of World

Global warming and energy supplies are global issues, with the United States currently responsible for an important fraction of world fossil CO₂ emissions and energy consumption. The U.S. can assist the rest of the world in multiple ways in the coming years, as follows.

17.1 DOE Forecasts

The DOE U.S. forecast for 2050 (Ref. 1) includes fossil fuel exports and imports valued in 2019 dollars, and total domestic production.

Natural gas imports are 2.1 EJ worth \$8 billion and LNG exports are 10.7 EJ worth \$59 billion, giving net exports of 8.6 EJ worth \$51 billion. Total domestic production is 49.2 EJ.

Petroleum and other liquids imports are 22.5 EJ worth \$297 billion and exports are 14.5 EJ worth \$267 billion, resulting in net imports of 8.0 EJ and \$30 billion. Total domestic production is 34.8 EJ.

Coal exports are 2.9 EJ worth \$13 billion. Domestic production is 11.3 EJ.

The sum of the above is net exports of 3.5 EJ worth \$34 billion: quite small compared with DOE forecast 2050 domestic consumption (89.3 EJ) and expenditures (\$1543 billion).

17.2 Proposed Exports of Fossil Fuels

2050 exports of fossil fuels should be limited to buyers who capture and sequester all the carbon. Exports might be the difference between DOE forecast domestic production and Chapter 14 example uses. Example prices use DOE forecasts.

LNG exports would be 32.9 EJ, worth \$182 billion. Petroleum and other liquids exports would be 25.8 EJ, worth \$375 billion. No coal would be exported since consumption would equal planned (increased) domestic production. Proposed fossil fuel exports would total \$557 billion.

Some of the forecast exports might be used in the United States for manufacturing value-added products before exporting them. Such products could include ammonia, iron, cement, and organic chemicals as described in Chapter 12.

17.3 Exports of Biofuels

Growing the large quantity of biomass needed for the recommended plan (Chapter 7) will require major land use changes. However, it is likely that domestic capacity for biomass production could exceed forecast consumption by 2050 (or shortly thereafter). Exports of biofuels (which are far easier to ship long distances than biomass) can help support attractive farm prices while supplying the numerous countries unable to grow enough themselves.

17.4 Exports of Technology

The proposed new types of highly innovative processes and equipment (especially fuel cell systems, biomass converters, and coal-fueled direct air capture systems) will be valuable exports. The new technology will incorporate some imported materials, components, and subsystems (with licensing where appropriate). Large-scale manufacturing of equipment can be performed in factories throughout the world: many by joint ventures and others using licensed patents and know-how from the U.S. (and from successful international competitors). Where the United States is the technology pioneer, it will enjoy competitive advantages and lower manufacturing costs versus most competitors. The high degree of automation expected in manufacturing will minimize the benefits of lower labor costs elsewhere.

18. Implementation

Implementation of the proposed plan (with expected future modifications) will produce very large benefits to the economy, the environment, and the public. These benefits can be realized without net costs to federal and local governments. This chapter outlines key elements in a proposed possible plan for implementation.

18.1 Attitudes

U.S. attitudes towards global warming have been slowly shifting towards a desire for improvements by an increasing fraction of the public. This shift is expected to gain momentum, with more supporters from all political parties. Major energy corporations have recently been modifying their attitudes and public statements in favor of seeking reduced global warming and new profit opportunities for themselves. Congress and the President are expected to soon begin responding to the changing opinions.

Proposals such as this one, which identify pathways to major economic benefits in conjunction with major global warming initiatives, should help convert those who sensibly fear the high costs and inconveniences of many previous proposals.

18.2 Major New Technologies

Three of the Part Two technologies require major innovations: fuel cell systems, biomass converters, and direct air capture systems. While each is firmly based on known science, considerable engineering development is needed.

The private sector can develop and implement these technologies more rapidly without direct governmental financial assistance. It can assemble the required technical expertise, management skills, and financing needed to reach profitability. Success in these efforts will be facilitated by initiating the governmental programs described in Section 18.6. Investors in this technology must be patient, but the rewards will be huge benefits to the environment coupled with excellent profitability.

18.2.1 Technology Development

Early development work can be performed at very small scale to minimize early expenditures, enable fast timelines, and allow parallel paths to be economically explored. Extensive cost studies and simulations will support hardware design and experimentation. Early work should focus on reducing technical risks of key process elements, leading to small-scale demonstrations of complete systems. Subscale systems operating reliably for extended times will follow and attract sufficient additional financing for subsequent full-scale demonstrations (which are still relatively small: fuel cell systems rated 3 to 300 kW, biomass converters at 1 MW, and direct air capture systems at 3 MW).

Fairly small companies (startup or existing) are best suited to perform this work. Components, subsystems, and technical consulting can be purchased from various domestic and international sources. The three technologies could be pursued by a single company, since they have common subsystems. Demonstrations will probably occur first with fuel cell systems, followed by

biomass converters, and finally air capture systems. It would be desirable for multiple companies to complete in these programs, with possible cross-licensing later.

The management team in charge of technology development is the most important factor in determining its success. It must be small, have multidisciplinary expertise, energetic, focused, and possess good people skills. Ample, patient funding together with realistic schedules are essential.

18.2.2 Equipment Design and Manufacturing

The designs of complete fuel cell, biomass converter, and direct air capture systems will begin with field-test assemblies (where allowable unit costs are high) and progress through many successive generations with progressively manufacturing lower costs, improved reliability, and incremental improvements. The largest equipment will be designed to be shipped on standard trucks (using more than one for some systems).

While early field test systems will be manufactured using considerable labor, more and more automation will be phased in as quantities increase. At very high manufacturing volumes, numerous high-capacity plants will be sited throughout the U.S., with each having no more than a few hundred highly-skilled employees. The plants will also manufacture replacement parts and subsystems.

18.2.3 Sales and Service

A large number of licensed firms with factory-trained experts will sell the new systems, provide or oversee installations, and offer various field-service plans. In the case of transportation fuel cell systems, an OEM sales organization will interface with vehicle and equipment manufacturers. The sales and service organization will manage the responsible recycling of used components and equipment, with no use of landfills. Various financing and leasing options will be offered via partnerships.

18.3 Carbon Dioxide Sequestration

Numerous private companies will be funded by the National Carbon Administration (Section 18.6.1) to collect liquid CO₂ in dedicated trucks to be transported to sequestration sites. Special railroad cars will be used with some large sources. Short-term storage tanks will be employed at collection and sequestration sites.

Permanent underground sequestration will also be performed by private companies (most of them also being in the collection business) at government-approved sites throughout the U.S. The sequestration companies will drill injection and monitoring wells, supervise transfer of arriving CO₂ to large on-site tanks, operate injection pumps, and perform continuous monitoring.

18.4 Infrastructure Improvements

Major improvements will be made to three types of infrastructure: electric grid, natural gas pipeline grid, and public roadways. Three types of improvements will be made to each: much better maintenance, capacity increases, and extension of service to new locations.

18.4.1 Electric Grid

Improvements will be funded by the new fixed charges paid by all connected users and generators (Section 14.3). Maintenance will include replacement of aged or defective equipment, improving safety, and reducing fire risks. New types of automated tunneling equipment will facilitate the replacement of some overhead lines by underground service. All meters will be replaced by advanced types with continuous wireless communication, measuring bidirectional currents. Microgrid components will be installed in an increasing number of locations, reducing the likelihood and frequency of outages for many grid users. Transmission and distribution capacities will be increased in many cases to handle the expected large additions in distributed generation (including renewables) and to reduce line losses. The grid will be expanded as needed to serve new sites.

18.4.2 Natural-Gas Pipeline Grid

Improvements will be paid by fixed charges from users and BNG producers. The grid will carry comingled fossil natural gas and BNG, with the natural gas proportion continually varied to balance supply and demand (using existing natural gas cavern storage as needed). Although BNG will have nearly the same properties as the fossil gas, it will be sold at somewhat higher price. Fossil natural gas will be sold only for use in CCS equipment (fuel cell or some industrial systems). Users who sequester all or some of the CO₂ from BNG use will enjoy lower net costs. A minority of users performing CCS will elect to buy the more expensive BNG to increase their negative-carbon footprint.

Pipeline maintenance improvements will include replacement of aged and defective lines and equipment. New types of automated tunneling equipment will enable affordable expansion of service to new customers. Most of the new BNG producers will need new pipelines. Some of the new larger distributed fuel cell systems will need larger lines and prefer higher supply pressure.

18.4.3 Public Roadways

Major improvements will be funded by the Federal Roadways Administration (18.6.2). Maintenance of bridges and roadways will be greatly enhanced to reduce transportation fuel consumption, enhance safety, and reduce travel times. Obsolete bridges will be replaced. Capacities of some roads and bridges will be increased. A limited number of new roads and bridges will be built, including some needed to serve new facilities described herein. Any new rail spurs needed will be funded by freight charges.

18.5 Other Technology Developments

Many evolutionary improvements (with low technical risk) to energy-related systems are assumed and expected, with many implied in the above chapters. Transportation equipment will require significant redesign to utilize the new fuel cell systems. HVAC systems will require modifications to optimize utilization of fuel cell system surplus heat. New and improved designs of heat pump systems and clothes driers are assumed. Significant changes to refinery and industrial systems are necessary to capture all fossil carbon or replace fueled heating with electrical. Much of the new equipment can replace aged conventional equipment, with its cost partly justified by energy cost savings.

18.6 Governmental Roles

General governmental revenues are not needed to fund the proposed plan, which will be paid for by energy users and their cost savings. Although example total 2050 user energy expenditures are 110% higher than the baseline DOE forecast, they are a smaller share of forecast GDP than at present (Section 14.3). Each of the following key organizations can be operated at zero net annual cash flow.

18.6.1 National Carbon Administration (NCA)

This new organization will be funded initially by a tax (which might alternatively be called a fee or charge) on each tonne of fossil CO₂ emitted. The tax would begin at a low level and gradually increase to very high levels (effectively eliminating any significant fossil carbon emissions by 2050). In later years, gradually increasing fees on all carbonaceous fuels (biofuels as well as fossil fuels, regardless of their emissions) would fund this administration. Section 14.4 gives an NCA financial example.

The agency would fund the extension of previous sequestration studies (many cited in Ref. 3) to identify suitable sites for permanent CO₂ sequestration, establish regulations for their safe operating and monitoring, and license operating companies. It would also license companies to collect, transport, and temporarily store liquid CO₂ for delivery to sequestration sites.

The largest expenditure in years approaching and after 2050 would be purchasing collected CO₂ from CCS users, thereby providing them an ongoing return on their incremental investment, and offsetting their added CCS operating and maintenance costs.

The NCA will also monitor compliance with regulations on fossil fuel uses and publish monthly reports on energy and CO₂ flows.

18.6.2 Federal Roadways Administration (FRA)

The FRA will be funded by a tax or fee on each ton-mile traveled by road vehicles (light-duty vehicles, trucks, vans, and buses). Each vehicle will have an installed transponder which will wirelessly transmit travel data to hubs, enabling the FRA to collect the fees. Larger freight trucks will also have load cells installed to measure their loads in real time. The road use taxes now attached to fuels for road vehicles will be replaced by the new charges, which will properly reflect plug-in travel, varying fuel efficiencies, and impact on roadways.

Funds collected by the FRA will fund the roadway programs listed in 18.4.3 and also subsidize public transportation (helping to reduce traffic congestion and save fuel). State and local transportation departments will play major roles in implementing the improvements.

18.6.3 Utility Rates

Major changes to utility rate structures and the agencies which regulate these rates are assumed. Both electricity and gas rates will consist of a significant monthly fixed charge (based upon maximum annual current or flow) and a variable charge.

Fixed electrical charges will be paid by both power generators and users. Variable electrical charges will depend on both real and reactive power, vary hourly (time of use, TOU) based on

local supply and demand, and have differentials (import prices will be higher than export prices). Variable rates need not differ between sectors (residential, commercial, or industrial) and will decline only modestly with consumption (quantity effects are largely reflected in fixed charges).

Variable gas rates will depend slightly with usage and may vary seasonally where significant cost differences exist. A premium for BNG over fossil gas will be varied to balance its use with available supply (the example assumes a 10% premium).

18.6.4 Permits and Regulations

Existing regulations and permit requirements for businesses must be simplified, streamlined, and modified to enable the timely and cost-effective installation of the new equipment and systems assumed in the plan.

19. Conclusions

The proposed plan will yield major benefits to the environment and to energy users. It will create millions of new well-paying jobs, significantly expand exports, and eliminate energy imports. Depletion of fossil fuel reserves will be slowed. Farm incomes will rise significantly. Production of superior local produce will increase to the benefit of consumers as well as growers. Grid power reliability and public roadways will be improved.

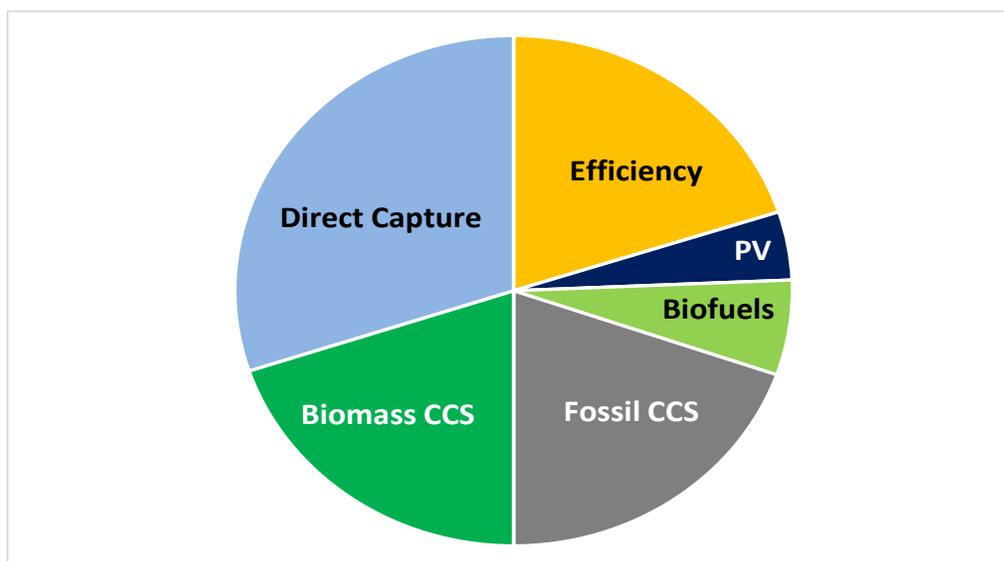
19.1 Environmental Benefits

Fossil CO₂ emissions in 2050 will decrease from the DOE predicted level of 4922 million tonnes to minus 5000 million tons (net CO₂ removal from the atmosphere): a reduction of 9922 million tonnes per year. The increased delivered energy costs (Table 14.2 less 14.1) is \$152 billion or about \$15 per tonne of CO₂ reduction (without considering other considerable benefits).

Other types of airborne emissions will be greatly reduced, reducing smog significantly. Emissions contributing to global warming (methane and NO_x) will be significantly lowered. Particulates, CO, SO_x, and many types of organic emissions (including compounds proven to cause cancer) will also be considerably reduced from transportation, buildings, and industry. Fertilizer runoff will be reduced by increased use of solid organic fertilizers. Many types of water pollution will also decrease.

The chart shows the causes of the proposed reduction.

Figure 19.1 Proposed 2050 CO₂ Reduction



The slice labeled PV represents increases in both wind and solar PV production. The slice labeled Biofuels are uses without CCS: uses with CCS are included in the Biomass slice.

19.2 Benefits to Energy Users

The proposed plan will greatly improve the reliability of electricity supply to most users, with uninterrupted power supplied to many.

User energy efficiencies will be improved significantly. At example 2050 prices, the 40% savings in energy consumption has a value of nearly \$900 billion per year (Section 14.3).

19.3 Employment

The proposed plan would create millions of net new jobs. Employment reductions would occur in oil and gas exploration and production, oil refining, and their support operations. These would be far exceeded by new jobs in biomass production, bioenergy, and greenhouses. Many additional net jobs would be created by the manufacturing, installation, and servicing of all the proposed new equipment and systems. Additional infrastructure spending would support still more jobs. Over ten million net new well-paying full-time jobs are probable, without considering the potential for new exports.

19.4 Farming Impacts

Over 100 million acres of presently unfarmed land will be used to grow the proposed 1.2 billion tons per year of biomass crops, worth over \$100 billion. Additional revenues will result from collecting biomass wastes and processing all of the biomass. Improvements in farming practices will reduce fertilizer costs, conserve water, and reduce tilling (thus improving the environmental impact of farming).

19.5 Fossil Fuels Extraction

Before consideration of probable export increases, domestic natural gas production will decrease by 66% and petroleum production by 77% from 2050 forecasts. The reduced production will prolong the life of proven reserves. Coal production will approximate recent levels. All fossil extraction will be performed with reduced environmental impacts.

19.6 International

In order to halt the rise of atmospheric CO₂ levels and begin its reduction, the types of action outlined here must also be implemented throughout the world (with allowances for differing potential for biofuels production). Wealthy nations (including the U.S.) should provide investment financial assistance and technology advice.

United States fossil fuel imports will cease and exports of LNG and petroleum increase by up to \$560 billion if domestic production were to equal DOE predictions. Biofuel exports might begin before 2050. Technology exports could include licensing and joint-venture revenues for manufacturing the new equipment and systems. Technology-related export revenues could exceed \$40 billion annually.

19.7 Before and After 2050

Between now and 2050, taxes on fossil CO₂ emissions (starting low and steadily rising to very high rates) will add financial incentives for the proposed actions. Revenue from this source will fall to zero as these emissions cease. The proposed NCA will collect this tax and direct its proceeds to assist efficiency improvements and other appropriate expenditures.

Various alternatives will likely play interim roles while some of the proposed technologies are still being developed, installed, and becoming more cost effective. These could include multiple types of flow battery systems.

Figure 1.1 plots expected CO₂ emissions before 2050. Subsequent U.S. net removal will continue to increase due to further improvements in usage efficiency, increases in renewables, and more removal from the air by both biomass and air capture systems (possibly using surplus renewable electric energy to supplement coal).

Financial benefits of all kinds are expected to slowly improve to 2050 levels, with additional improvement afterwards.

19.8 Implementation

The private sector can manage and fund the required technology development and manufacturing programs, creating excellent profits after 2025.

Federal and state governments must revise regulations and create new revenue-neutral agencies to manage carbon dioxide purchase and sequestration and fund infrastructure enhancements.

19.9 Contacts

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20. Glossary, Abbreviations, and Conversions

AC	Alternating current (60 Hertz in U.S.)
aq	Aqueous (dissolved in water)
biofuel	Fuel made from biomass
biomass	Plant and/or animal materials (alive recently)
BNG	Bio-natural gas
BTU	British thermal unit (1 BTU = 1054.4 J, 3414 BTU = 1 kWh)
capex	Capital expenditure (installed cost)
CCS	Carbon capture and sequestration
cm	Centimeter (2.54 cm = 1 inch)
CNG	Compressed natural gas
cogeneration	Generation of electric power plus usable heat
CO ₂	Carbon dioxide (weight 44.01 grams/mole)
DC	Direct current
DOE	United States Department of Energy
EJ	Exajoule = 10 ¹⁸ Joules = 0.9484 Quad
ERV	Energy-recovery ventilation
FRA	Federal Roadways Administration (proposed)
g	Gaseous state
GDP	Gross domestic product of the U.S.
GJ	Gigajoule = 10 ⁹ Joules = 277.8 kWh
GW	Gigawatt = 1000 MW or 1 million kW
ha	Hectare = 10,000 m ² or 2.47 acres
Hertz	cycles per second
HHV	Higher heating value, water vapor condensed
hydrocarbon	compound of carbon and hydrogen
J	Joule. The SI unit of energy = 1 Watt-second
kg	Kilogram = 1000 g = 2.2046 pounds
kJ	Kilojoule = 1000 Joules
kW	Kilowatt = 1000 Watts (unit of true power)
kVA	Kilovolt-amperes (unit of apparent power)
kVAR	Kilovolt-amperes reactive (unit of reactive power)
kWh	Kilowatt-hour (one kW for one hour = 3.6 MJ)
lb	Pound (1 kg = 2.2046 lb)
LHV	Lower heating value, water vapor not condensed
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas (high-propane mixtures)
mcf	Thousand standard cubic feet (scf)
MJ	Megajoule = 10 ⁶ Joules
Microgrid	Group of adjoining customers configured for occasional grid isolation
MMBTU	Million BTU higher heating value
MSW	Municipal solid waste
MW	Megawatt = 1000 kW
NCA	National Carbon Administration (proposed)
NGL	Natural gas liquids (chiefly ethane, propane, and butanes)
NO _x	Nitrogen oxides (including N ₂ O, NO, and NO ₂)
oxygenate	Compound of carbon, hydrogen, and oxygen (e.g., alcohols, esters)
PJ	Petajoule = 10 ¹⁵ Joules

Power	Energy per unit time. Basic unit is the Watt.
PSA	Pressure-swing adsorption system (zeolite molecular sieve)
PV	Photovoltaic (solar)
psig	pounds per square inch gage (above atmospheric)
Quad	Quadrillion BTU = 10^{15} BTU = 1.0544 EJ
Ref	Reference (see Chapter 21)
ROI	Return on Investment (annual)
scf	Standard cubic feet (cubic feet of gas at 1 atmosphere and 60°F)
sec	second
sequester	To permanently store underground
SO _x	Sulfur Oxides (SO ₂ and SO ₃)
SI	Systeme International, the international metric system of units
TMI	Technology Management Inc.
ton	Short ton = 2000 pounds
tonne (te)	Metric ton = 1000 kg = 1.1023 tons
TOU	Time-of-Use electricity pricing
W	Watt (1W = 1 Joule per second)
yr	Year

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