# CO₂ Removal from the Atmosphere

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# 1. Summary

**1.1 Results**

This paper recommends and describes a strategy for U.S. energy which would replace our large annual fossil CO$_2$ emissions with major annual net removals by 2060, as shown below.

**Figure One. CO$_2$ Emissions**
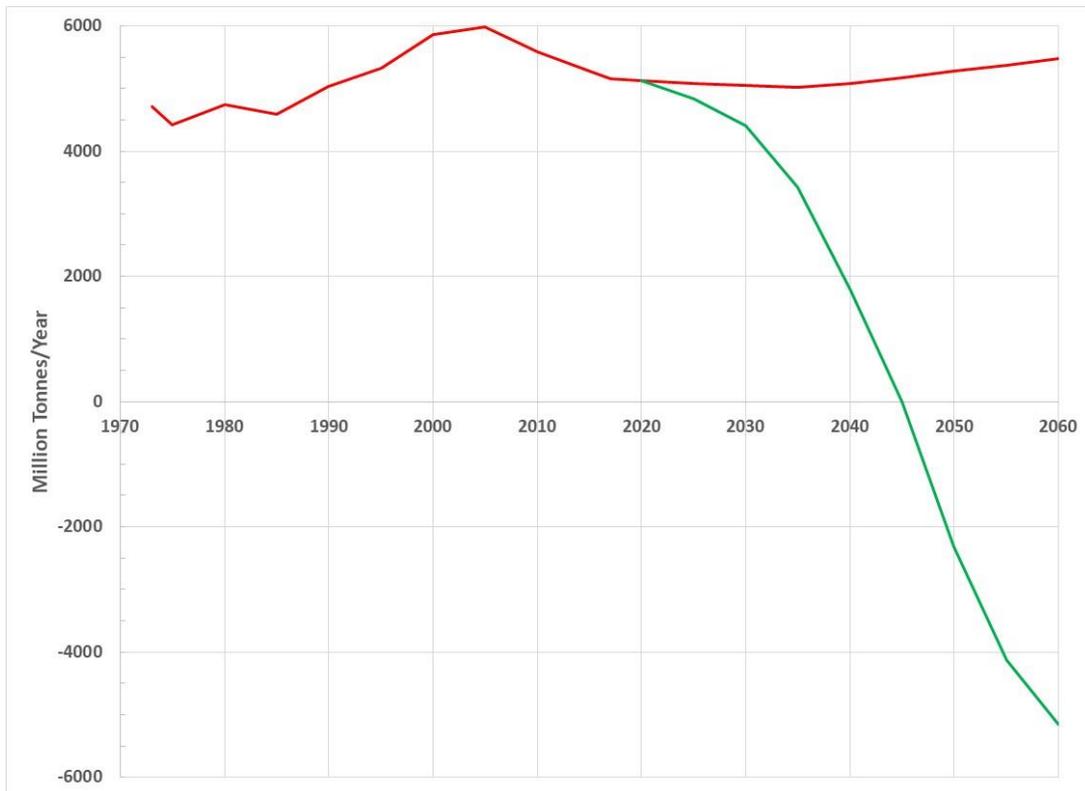


The top line shows historic and forecast U.S. energy-related CO$_2$ emissions from References 1 and 2, while the lower line shows the proposed result. Energy-related CO$_2$ emissions are in millions of metric tons (tonnes, te) per year. Chapter 16 gives definitions and conversion factors. Table 1.1 shows some of the other projected benefits. The first two columns use DOE figures (from Ref. 1) extrapolated to 2060. Liquids are petroleum and its derivatives. Net Energy Expenditures exclude road taxes on gasoline and diesel fuel of $110 billion in 2017 and $142 billion in 2060. Constant 2018 dollars are used throughout this paper.

**Table 1.1 Benefits**

|  |  | Actual 2017 | Extrapolated 2060 | Proposed 2060 |
|---|---|---|---|---|
| Net Energy Expenditures | billion | $1,006 | $1,567 | $1,410 |
| Net Liquids Imports | billion | $124 | $298 | |
| CO2 Emissions | million te | 5151 | 5478 | (5151) |

Proposed 2060 net energy expenditures would decline by 10%, imports of liquid fuels would end, and millions of net new jobs would be created. Energy systems in 2060 would annually remove the same amount of CO$_2$ from the atmosphere as was emitted in 2017: an improvement of 10.6 billion tonnes over forecast emissions. Permanent underground sequestration of CO$_2$ (from fossil fuels and captured from the air) will be utilized. Even larger annual removals could be achieved after 2060.

### 1.2 Energy Sources

Table 1.2 compares proposed 2060 primary domestic energy sources with 2017 and DOE projected values. Annual energy quantities are listed throughout this paper in exajoules (EJ). One Quad ($10^{15}$ BTU) equals 1.0544 EJ. Higher heating values (HHV) of energy sources are used herein, which include the latent heat of water vaporization.

### Table 1.2 Primary Sources
EJ HHV

|  | Actual 2017 | Extrapolated 2060 | Proposed 2060 |
|---|---|---|---|
| Petroleum | 39.54 | 41.17 | 3.70 |
| Natural Gas | 29.14 | 39.75 | 20.07 |
| Coal | 14.97 | 13.88 | 17.34 |
| Nuclear | 8.74 | 6.66 | |
| Hydro Etc. | 1.07 | 1.28 | 1.30 |
| Wind | 0.85 | 1.62 | 3.50 |
| Solar | 0.26 | 3.55 | 8.70 |
| Biomass | 0.18 | 0.22 | 27.95 |
| Total | 94.76 | 108.14 | 82.56 |

Proposed total primary energy is 76% of extrapolated DOE forecast, with fossil fuels totaling only 43% of forecast. Proposed 2060 renewables supply half of the total primary energy and total more than six times the 2060 DOE forecast.

In the proposed strategy, petroleum will be used only for manufacturing chemicals and materials (with zero carbon emissions). Natural gas will be used with total carbon capture primarily for electric power generation and also for certain industrial processes. Coal will be employed to power new plants which will directly remove CO$_2$ from the air, with sequestration of all the carbon from both air and fuel. Nuclear electric power will be discontinued before 2060.

Electricity production from solar and wind will increase considerably over DOE 2060 projections, while energy from hydroelectric and geothermal systems will be unchanged. The proposed use of biomass increases to a very large 2060 value which is 80% of the maximum estimated U.S. sustainable production rate. This biomass will be used to produce electricity and new types of biofuels.

**1.3 Delivered Energy**

Table 1.2 summarizes energy delivered to domestic users (residential, commercial, industrial, and transportation). A fraction of primary energy is consumed by energy conversion, electricity transport, and used for $CO_2$ capture and sequestration.

**Table 1.3 Delivered Energy Summary**
EJ HHV

|  | Actual 2017 | Extrapolated 2060 | Proposed 2060 |
|---|---|---|---|
| Natural Gas | 19.32 | 26.45 | 6.30 |
| Propane | 3.56 | 5.02 | 1.00 |
| Gasoline | 18.18 | 13.37 | 0.50 |
| Kerosene and Diesel | 12.29 | 15.74 | 11.50 |
| Other Liquid Hydrocarbons | 3.67 | 5.32 | 3.70 |
| Liquid Oxygenates | 1.63 | 1.63 | |
| Coal | 1.23 | 1.30 | |
| Electricity | 13.24 | 17.55 | 28.80 |
| Total | 73.13 | 86.39 | 51.80 |

In 2060, proposed natural gas consists of 2.5 EJ of bio-natural gas plus 3.8 EJ of fossil natural gas used by industry with carbon capture. The 2060 propane, gasoline, kerosene, and diesel are biofuels. "Other Liquid Hydrocarbons" in the first two columns consist of jet fuel, diesel fuel, heating oil, and residual oil. In the proposed case, this category is petroleum used to manufacture materials and chemicals. The proposed case uses no oxygenates (such as ethanol: see explanation in Section 12.6) or delivered coal.

**1.4 Proposed 2060 Energy Consumption**

The proposed 40% reduction in delivered energy will result from the installation of very high efficiency fuel cell systems, use of much more efficient user electrical equipment, and other improvements.

**1.5 Economic Benefits**

The sum of user fuel cost savings and imports elimination (Table 1.1) totals $455 billion per year. When other expected financial benefits are added, the total exceeds one trillion dollars per year. The net creation of many millions of new jobs is expected.

**1.6 Solar Power**

The proposed strategy uses solar power to provide (directly or indirectly) most of U.S. energy needs and to help remove $CO_2$ from the atmosphere. Solar power is responsible for the recommended renewable energy sources: biomass growth, solar photovoltaic power, and wind power.

The proposed large increases in solar photovoltaic and wind power will be facilitated by the incorporation of a ***virtual-battery*** function in the biomass converters. Whenever surplus

renewable power is available, it will be used to produce additional biofuels (eliminating the need for conventional batteries or other expensive storage systems).

### 1.7 Major Elements of Proposed Strategy

The proposed U.S. energy strategy for implementation by 2060 is based upon the following major elements, with new technologies playing significant roles.

(1) Major efficiency improvements in energy utilization

(2) Replacement of much fuel usage by zero-carbon-emissions electricity

(3) Very large production of biomass and its conversion to fuels and electricity

(4) Extensive, cost-effective capture and permanent sequestration of CO$_2$

(5) Elimination of CO$_2$ emissions from fossil fuels

# 2. Introduction

## 2.1 Atmospheric Carbon Dioxide
Throughout the 10,000 years before the industrial revolution, the concentration of $CO_2$ in the atmosphere remained close to 280 parts per million. Due to the use of fossil fuels, it has increased 45% to its present value of 407 parts per million. Further increases are unavoidable in coming years. Higher $CO_2$ causes global warming, alteration of global weather patterns, and sea level rise.

The United States is now the world's second largest fossil $CO_2$ emitter (behind China, which has far more people). In 1975, U.S. energy-related fossil $CO_2$ emissions were 4421 million tonnes (metric tons: see Section 2.4 regarding units). They peaked at 6005 million tonnes in 2007 and then declined to 5151 million tonnes in 2017 (due chiefly to lower coal use). The DOE forecast (Ref.1 ) predicts a slight decline to 5024 million tonnes in 2035 before rising to 5279 million tonnes in 2050. Their figures extrapolate to 5478 million tonnes in 2060 (Fig. 1 and Table 1.1).

## 2.2 Objectives
This paper describes an energy strategy which combines many ideas advocated previously by others with numerous new recommendations. It seeks to combine maximized $CO_2$ emissions reduction (to large negative annual rates) with major U.S. economic benefits, which should make its implementation more likely. These benefits include significant user energy cost savings, replacement of imports by exports, and considerable job creation.

The present federal government practice giving large subsidies to various energy businesses and paying for them by increasing budget deficits should be phased out over the next decade or two. New federal roles should include the supervision of a National Carbon Administration (Section 4.6) and passage of laws regulating use of fossil fuels.

This report is limited to the United States, but contains remarks about how the proposals could also be applied to the rest of the world and hence benefit the entire planet.

## 2.3 Timing
The example year of 2060 was selected to allow time for required technology developments, manufacturing ramp-ups, very large capital investments, and other changes to be phased in. Considerable reductions in $CO_2$ emissions and enhanced financial benefits are expected to begin much earlier (Figure One).

## 2.4 Financial and Engineering Units
This paper uses constant 2018 dollars for all prices and financial totals. When needed, the GDP deflator from Ref. 1 (table A20) was used for timing adjustments.

The SI system of units is employed, with equivalents in customary U.S. units given occasionally. Conversion factors are given in Chapter 16, which also includes abbreviations and a brief glossary. Carbon quantities are given in tonnes (metric tons) of $CO_2$ as is customary. Each tonne of $CO_2$ contains 273 kg of carbon and 727 kg oxygen.

**2.5 Appendix**
The Chapter 14 Appendix includes a material and energy balance for the 2060 proposed strategy, fuel heating values table, and a summary of CO$_2$ properties. Higher heating values (HHV, which include the latent heat of water vapor in oxidized fuel) are used for fuels and efficiencies. Table 14.3 gives HHV for various fuels.

**2.6 DOE Projections**
The 2018 Annual Energy Outlook by the Energy Information Administration of the U.S. Department of Energy (Ref. 1) uses extensive computer models to forecast energy quantities through 2050 (assuming evolutionary changes only). Their forecasts were linearly extrapolated to 2060 from 2040 and 2050 values.

**2.7 Population and GDP**
Table 2.1 shows projected U.S. 2060 values (Ref. 1). Population is expected to increase 28% and GDP to reach 2.29 times its 2017 value.

**Table 2.1 Population and GDP**

|  |  | 2017 | 2060 |
| --- | --- | --- | --- |
| Population | million | 326 | 417 |
| Gross Domestic Product | billion 2017 $ | 19,295 | 44,131 |

Energy expenditures in 2017 shown in Table 1.1 were 5.2% of GDP. The proposed 2060 expenditures decline to 3.2% of GDP.

**2.8 Prior Reports**
Three reports from the author are freely available on the website robertruhl.com:

United States Energy 2050 (Ref. 5, March 2016, 64 pp) describes in some detail a proposed strategy to reach zero fossil carbon emissions by 2050, with excellent economic benefits. The present paper modifies many of the assumptions and recommendations from the prior report.

Virtual Batteries (Ref. 6, April 2017, 27 pp) describes many possible variants of the virtual battery systems cited in Section 4.1 below. Virtual batteries perform the equivalent of electricity storage at lower cost than ordinary rechargeable batteries.

Very High Efficiency Fuel Cell Systems (Ref. 7, September 2017, 27 pp) proposes natural gas fuel cell systems of advanced design which could exceed 80% LHV efficiency at capacities of 300 kW and larger.

**2.9 Technology Descriptions**
This document includes only brief technical and cost summaries of the various proposed new technologies. Although most of these proposed processes and equipment have been studied fairly extensively (with numerous calculations) by the author and others, proprietary considerations plus a desire to limit the length of this paper have led to exclusion of details.

# 3. Biomass

## 3.1 Introduction and Summary

By 2060, domestic biomass could furnish primary 34% of U.S primary energy (Table 1.2) in addition to ample foods for consumption and export. The United States is one of the world's most advantaged countries for its very high ratio of arable (and potentially arable) land to population. Its arable land includes an insignificant fraction of tropical rainforest (whose conversion to farms is undesirable).

A major U.S. Department of Energy report (Ref. 3), calculates potential domestic biomass production (for energy uses) in 2040 to be as high as 1.38 billion dry tonnes. If their forecasts versus time are linearly extrapolated, the potential becomes 2.06 billion annual tonnes in 2060. The quantity needed in 2060 for the proposed scheme is 1.65 billion tons (1.50 billion tonnes) or 73% of the potential supply.

At present, U.S. farms total about 365 million hectares (900 million acres). If 2060 biomass were obtained only from farming (not counting the considerable quantity to be obtained from waste streams) with an average annual (enhanced) yield of 20 dry tonnes per hectare, the required 1.5 billion tonnes ( would require 75 million hectares or 21% of today's farm area. Considering that much of the 2060 biomass would be grown on forested land or land not presently being farmed, yields of food crops will rise, and production of ethanol from corn will cease, and some biomass will be obtained from wastes, the farm area needed appears very reasonable.

This paper proposes the use of novel converters (described in Section 4.1) to convert biomass into electricity and biofuels, with most of its carbon captured and permanently sequestered (net removal of CO$_2$ from the atmosphere). The expected value of the energy products will support higher biomass prices than assumed in Ref. 3, allowing for higher growing expenses and increasing the potential harvest above DOE forecasts. Food prices would also be expected to slightly increase, which should help combat obesity (economic benefits from the proposed scheme can also finance food-purchase assistance for the poor).

The proposed 2060 scheme would produce no fuel ethanol from corn (or other biomass) nor any biodiesel esters from oilseeds. It would burn no biomass for heat (other than a trivial amount used in fireplaces).

## 3.2 Farming

The present food crops will continue to be farmed in 2060, with somewhat smaller acreage. Farming of corn and soybeans for fuel production will be discontinued. Major production of new biomass energy crops will occur, some of which grown on land not presently farmed. Expected energy crops will include switchgrass, miscanthus grass, energy cane, sorghum, poplar, willow, eucalyptus, and pine. Biodiversity of farms will minimize vulnerability to disease and insects while providing habitat for diverse wildlife. Most farms are expected to grow both food and energy crops.

Significant investments will be made to capture and store excess rainwater on site to minimize fertilizer runoff and provide irrigation during droughts. Advanced buried drip systems will utilize water very efficiently. Deep-rooted, mainly perennial (no-till) plants will require less water than many food crops (enabling additional energy-crop farming on land too dry for foods). Near-optimum supply of water will boost yields of all crops. Any weeds amongst energy crops can be harvested as additional biomass.

Ample applications of organic and other fertilizers will enhance yields. New types of mechanized equipment for harvesting woody energy crops will minimize worker injuries and facilitate winter operation. The flexible harvest timing of all energy crops will enable sharing of harvesting equipment amongst neighbors.

Advanced plant breeding methods are expected to result in faster growing and more robust strains of both food and energy crops, with minimized water needs. Net farm incomes per acre will increase.

### 3.3 Biomass Wastes
Biomass wastes are desirable as additions to the farmed crops for conversion into advanced biofuels. These wastes can include farm wastes of all types (including animal wastes), food and forest-product processing wastes, yard and garden refuse, municipal solid wastes (after automated removing of recyclables), sewage-treatment plant wastes, and any other available organic materials. Waste conversion can lower average biomass costs, avoid disposal costs, reduce odor generation, and reduce unwanted insect breeding. Ref. 3 discusses example biomass wastes and annual quantities.

### 3.4 Storage and Processing
Harvested biomass requires storage, comminution (size reduction), and drying. In most cases, biomass converters will be installed on the farms, enabling their surplus heat to supply both the driers and also greenhouses (see below). Separate storage will be provided for as-harvested (wet) and dried biomass. Comminution will often be performed on the wet material, speeding its rate of drying. Dry biomass will typically be stored in silos with integrated handling equipment. The average particle size of shredded biomass is expected to be near one centimeter. Installation of converters, processing, and storage equipment on farms will minimize transport costs of the biomass. It will also maximize overall energy utilization efficiency.

### 3.5 Greenhouses
Although the biomass converters (Section 4.1) are quite efficient, their considerable size will lead to significant surplus heat production. About 10% of this heat is needed for feed drying. A small fraction can heat farm buildings in cold weather. The majority is available for heating adjoining greenhouses, thereby removing a significant cost of their cold-weather operation. Greenhouses can grow high-value perishable crops such as tomatoes and vegetables for local sale with superior flavor and freshness. They can also grow flowers and ornamental plants. Added supplemental heaters (used only in very cold weather) will allow a given quantity of heat to heat larger greenhouses. The usable surplus heat from any given converter is about one-half its net output (fuel HHV or AC power). Thus a converter producing 1000 kW of power or fuel

would also yield 500 kW (1.7 million BTU/hour) of heat. This heat might support roughly one hectare (2.47 acres) of greenhouses, depending upon their location and design.

### 3.6 Biomass-Related Jobs
A net increase of millions of biomass-related jobs is predicted from the proposed new energy scheme, since expanded farming, converter operation, and greenhouse operation are considerably more labor intensive than oil refinery and large power-plant operation. Many of these on-farm jobs will have considerable variety and thus be more enjoyable. Working conditions will be quite healthy. The favorable economics will enable well-paying full-time jobs with attractive benefits. Employees can be shifted from some cold-weather tasks (woody biomass and greenhouse operations) to and from warm-weather tasks (herbaceous biomass and outdoor farming operations). Employees can be encouraged to carpool in plug-in vehicles, with free on-site recharging. Healthy free lunches using produce grown on site could be provided.

### 3.7 Financial
The expected selling prices of electricity, biofuels, and food crops are expected to be considerably higher than the sum of labor, debt payments, and other costs. Converter operation will supply the farm with all its electricity (even throughout grid outages) and thermal needs as well as most of its fertilizer needs. The attractive annual net income will enable farmers to retire debt (used for capital investments) at a rapid rate. In some cases, farmers may elect to partner with corporations who will pay for equipment and share annual profits. Chapter 11 gives example prices.

### 3.8 Environmental
The farms are economically converting sunlight into valuable forms of energy as well as foods. They are participating in the permanent removal of significant amounts of CO$_2$ from the atmosphere each year while minimizing other emissions (no-till farming and no herbicides). The rare fungicides or insecticides needed can be natural in origin. Vigorous, bio-diverse crops will host many species of birds and other wildlife.

### 3.9 Possible Biomass Options
Ongoing studies are examining possibilities for the low-cost farming of other types of biomass, including algae and "artificial leaves". The attractive costs and quantities proposed in this paper do not assume the use of such options.

# 4. Energy Supply

Tables 1.2 and 1.3 summarize primary and delivered energy quantities in 2017 and 2060. Fossil fuel use would be allowed only by licensed facilities, who would convert most feed carbon into liquid $CO_2$ for sequestration. A small fraction of the fossil carbon would be contained in manufactured chemicals and materials (chiefly recycled after use).

The proposed 2060 energy supply would discontinue all fossil fuels uses which produce $CO_2$ emissions. Nuclear power generation and oxygenated biofuels production would also have been previously phased out. Chapter 12 discusses excluded energy sources.

## 4.1 Biomass Virtual-Battery Converters

The large quantity of biomass described in Chapter 3 would be fed to new types of converters, which would efficiently convert it into the four hydrocarbon biofuels described in Section 4.2 plus electric power. The converters will completely gasify pre-dried biomass at elevated temperature and pressure, using steam and enriched air (from an integrated molecular-sieve subsystem). Gasifier-section output will be synthesis gas (steam, $H_2$, CO, $CO_2$, $CH_4$, and $N_2$) plus a solid organic fertilizer containing phosphorus, potassium, and important trace nutrients.

The synthesis gas will be used for bio-fuels synthesis (using novel pathways) and as fuel for an integrated electrochemical section which produces electric power (for auxiliary needs and sale) plus some pure hydrogen also used in the synthesis. Integrated systems will capture all carbon not contained in the product fuel as pure liquid $CO_2$ for sequestration. Most converters will be installed at farms or at major biomass waste-producing sites. Many sites will have multiple converters.

Each converter will be complete and fully integrated (transportable on a single standard flatbed truck), automated, pollution free, and fairly quiet. By operating at high temperatures (up to 900ºC) and pressures, feed is converted into product in minutes, rather than the days or weeks required by biological processes. Chapter 11 provides financial estimates.

These converters will have three operating modes:

> Mode 1: Biomass to Grid Power and Liquid $CO_2$
> Mode 2: Biomass to Biofuels and Liquid $CO_2$
> Mode 3: Grid Power and Liquid $CO_2$ to Biofuels

Mode 3 operation will use the solid-oxide electrochemical stacks in reverse, performing electrolysis of steam and $CO_2$ to produce synthesis gas using grid power input. The share of time in each mode can be varied at will in response to grid supply and demand. Modes 1 and 3 will be used less than Mode 2. On-site tanks will store liquid $CO_2$ and byproduct water for use in Mode 3, with a large weekly excess of $CO_2$ removed by trucks for transport and sequestration. The attractive economics of Mode 3 operation when excess renewable power is being produced enables higher installed capacity of solar and wind power to be practical.

The three-mode converter operation is called a **virtual battery**, since the converter accepts grid power some of the time and delivers power to the grid at other times. Unlike conventional batteries or other existing energy storage systems, these virtual batteries can deliver far more electrical energy than is input. The timing of grid power inputs and outputs is completely flexible: large seasonal variations are practical (e.g., excess solar electricity can be consumed in summer and extra electricity delivered to the grid in winter). Virtual batteries avoid the considerable capital and operating costs of conventional storage systems (see Chapter 6 for more on electricity storage). Ref. 6 discusses virtual battery systems in more detail.

## 4.2 Biofuels
Four different hydrocarbon biofuels are proposed for 2060, as follows.

### 4.2.1 Natural Gas
Bio-natural gas (BNG) will be mostly methane, with some ethane and nitrogen. Its heating value and other properties will match fossil natural gas. It will be co-mingled in existing pipelines with larger flows of fossil natural gas. Some BNG will also be sold as high-pressure compressed natural gas (CNG). BNG will be used mostly for cooktops and specialized commercial and industrial heating equipment (it will be more costly than electricity in 2060).

### 4.2.2 Propane
Bio-propane will be very similar to today's fossil propane: stored as pressurized liquid and used as vapor. It will be delivered and sold the same as now, in portable tanks and via bulk deliveries. It will be used for cooktops, grilles, and other purposes. In bulk it will be priced similar to BNG per unit of heating value.

### 4.2.3 Gasoline
Bio-gasoline will be superior to today's gasoline from petroleum. It will be 99 octane and free from aromatics and sulfur. Its principal component will be isooctane (2,2,4 trimethylpentane). Its vapor pressure will be adjusted seasonally (by adding isobutane) as is done today. Due to its expected high selling price, it will be used mainly in small aircraft engines, motor scooters, pleasure boats, and portable equipment.

### 4.2.4 Kerosene
Bio-kerosene will be manufactured in considerable quantity as shown in Table 1.3. It will be a mixture of alkanes (saturated linear hydrocarbons), free from aromatics and sulfur. It will be used almost exclusively as a transportation fuel, used with and without $CO_2$ capture. Some 52% will be consumed by equipment without $CO_2$ capture: chiefly jet aircraft, some light-duty vehicles, and military. The remainder will be used in systems with $CO_2$ capture, including many trucks, buses, locomotives, and ships. $CO_2$ capture will be performed in non-flying transportation systems using advanced fuel cell systems. Very small amounts will also be used for stationary purposes, including standby generators. Chapter 7 discusses proposed systems using this fuel.

### 4.3 Electricity Generation

Table 4.1 compares proposed 2060 electricity generation with actual 2017 values and extrapolated DOE projections. The 8.74 EJ of nuclear heat (Table 1.2) yielded 2.85 EJ of electricity in 2017.

### Table 4.1 Electricity Generation
Exajoules

|  | Actual 2017 | Extrapolated 2060 | Proposed 2060 |
|---|---|---|---|
| Hydro and Geothermal | 1.13 | 1.35 | 1.35 |
| Solar | 0.27 | 3.74 | 8.55 |
| Wind | 0.90 | 1.71 | 3.60 |
| Biomass Net | 0.19 | 0.24 | 4.08 |
| Renewable Subtotal | 2.49 | 7.04 | 17.58 |
| Coal and Misc | 4.56 | 4.30 | |
| Natural Gas | 4.51 | 7.71 | 12.39 |
| Nuclear | 2.85 | 2.17 | |
| Total Generation | 14.41 | 21.23 | 29.97 |

The 2017 difference between electricity generation and consumption (Table 1.3) results from power plant use, imports, and grid losses. The 2060 difference is grid losses (1.17 EJ).

The large increases in solar and wind production are significantly assisted by their expected cost declines together with the new biomass virtual battery systems (Section 4.1) and the operating flexibility of the new natural gas fuel cell systems (Section 4.4). The 2060 solar generation consists of 3.5 EJ at user sites plus 5.05 EJ at utility sites. Some of the 3.5 EJ will be exported by users to the grid.

### 4.4 Natural Gas Fuel Cell Systems

Very high efficiency natural gas fuel cell systems will generate electric power with total capture of all (fossil) carbon as liquid $CO_2$ for sequestration. These distributed systems will be installed at many residential, commercial, and industrial sites to supply uninterruptible power, with some 5.39 EJ annually exported to the grid. The systems will be modular, with expected module sizes ranging from 10 to 3000 kW. Any number of modules may be connected in parallel as needed. The modular design will allow factory mass production, transport to sites on standard trucks, and operating flexibility (load following in response to grid needs or during grid outages). Part or all of the available surplus heat from operation of these systems can be captured and utilized.

### 4.5 Carbon Sequestration

In 2060, proposed liquid $CO_2$ capture and sequestration totals 8212 million tonnes (5151 million tonnes from the air plus 3061 tonnes from fossil fuels: details shown in Chapter 14).

Permanent underground sequestration is extensively discussed in Ref. 4, which cites identified suitable $CO_2$ sequestration sites throughout the U.S. with combined capacity for hundreds of years collection at the proposed rates.

### 4.6 National Carbon Administration

The creation of a new federal agency, possibly called the National Carbon Administration, is proposed. The agency could operate at financial breakeven. Its revenue sources would be fees included in the selling prices of all types of marketed energy (grid electricity, biofuels, and energy feeds to industrial processes). The collected funds would be used to purchase liquid CO$_2$ from stationary and mobile sources (yielding a net financial advantage for energy users who capture CO$_2$). The funds would also pay for its transport, temporary storage, and permanent underground sequestration (with monitoring). Section 5.4 discusses CO$_2$ temporary storage, transport, and sequestration.

### 4.7 Standby and Uninterruptible Power

Uninterruptible standby power systems will be available for users without on-site fuel cell systems as described in Section 4.4. Standby systems would use engine-generators or fuel cells operating on available biofuel (natural gas, propane, gasoline, or kerosene) plus a small battery subsystem. Since their cost of electricity would be higher than grid power, they would operate only during grid outages (with negligible annual use).

# 5. Energy Transport

By 2060, significant changes in the U.S. energy transport infrastructure are expected, as summarized below.

## 5.1 Electricity Grid

The proposed total electricity delivered from the grid in 2060 will increase by 68% over 2017, with some of the solar and wind power travelling considerable distances. Considerable expansion of transmission and distribution networks will thus be required.

Major improvements in grid reliability are also desirable. Aged wiring and equipment should be replaced. Vulnerability to storm and traffic damage should be reduced (using underground lines where possible). Additional redundant paths are desirable. The addition of many more sensors to the grid will enable much more intelligent power control systems.

Grid energy efficiency can also be improved. Greater use of DC transmission lines will contribute. Active power factor control can be expanded, assisted by the new distributed generation systems. Larger conductors will reduce voltage drops. More efficient transformers can be installed.

## 5.2 Natural Gas Pipeline Network

The proposed 2060 combined flow of co-mingled bio-natural gas and conventional natural gas is about 70% of the 2017 flow, and hence the existing network should be suitable (with proper maintenance). New users can be added. The much lower fossil natural gas prices will be charged only to licensed users who capture its carbon for sequestration.

## 5.3 Filling Stations for Road Vehicles

The significantly higher efficiencies of the proposed 2060 road vehicles and the use of private facilities for recharging many plug-in types will require fewer filling stations. Chapter 7 discusses the proposed power conversion equipment for road vehicles. Filling stations will sell primarily bio-kerosene plus a small quantity of biogasoline (some of which will be used off-road for gardening tools, etc.). They will be equipped to offload liquid $CO_2$ from vehicles (mostly trucks) while they are refueling. Many will also offer high-power electric rapid recharging stations for plug-in vehicles.

Private filling stations or depots for fleet vehicles (buses, local trucks, and taxis) will usually be configured for a single energy source: electric plug-in or biokerosene. Plug-in outlets will deliver moderate power for overnight charging (resulting in higher efficiency versus fast recharge). Biokerosene will be dispensed in a manner similar to truck stops, with liquid $CO_2$ offloading where appropriate.

## 5.4 $CO_2$ Storage, Transport, and Sequestration

Selected properties of $CO_2$ are given in Section 14.3. Liquid $CO_2$ has been commercially stored and transported for many decades, using mature technologies. Tanks are typically designed for maximum pressures slightly above 1000 psig, with safety relief valves. Tanks may be insulated or

refrigerated to increase their capacity (liquid density decreases at higher temperatures) and minimize possible venting. Tanks can be designed to safely contain supercritical CO$_2$ without venting (under all but highly unusual conditions), by specifying higher allowable pressures.

Liquid CO$_2$ will be transported to sequestration sites using rail cars, trucks, barges, and ships. In some cases, intermediate storage depots will accumulate liquid from smaller sources.

Once CO$_2$ is injected into permanent underground sequestration sites (pumped to higher pressures than used for transport and temporary storage), it will rapidly be heated by the ground to supercritical temperatures. Some of the sequestered CO$_2$ will slowly react with surrounding rocks to form carbonate minerals.

### 5.5 Other
Exports of coal, petroleum, and liquefied natural gas (LNG) will continue to use existing facilities and types of ships (with the ships being increasingly converted to fuel cell system propulsion with CCS). Some transport of fuels will continue to use rail or river barges.

Some of the existing pipelines for liquid fuels will continue to be used, along with continued use of trucks, rail, and barges for liquid fuel transport.

# 6. Grid-Scale Energy Storage

The electric power grid must always match instantaneous electricity supply to demand. Aggregate demand varies with time of day, day of the week, season, and weather. The proposed large additions of solar and wind power to grid supplies will considerably increase the challenges of matching. Average annual capacity factors (average power/rated power) of most solar PV systems is below 20%. Most wind systems have average capacity factors under 25%.

Most large existing power plants are quite limited in their ability to load follow (adjust output rapidly). A large quantity of gas turbines fueled by natural gas are presently used whenever needed to augment supplies from other sources, but power from these "peaking turbines" has relatively high total cost (often $0.20/kWh or more). Utilities also employ time-of-use pricing to alter user demand timing. Although solar arrays can be taken off line and wind turbines can be furled, such operation increases their average cost of generation.

Low-cost electricity storage at grid scale (megawatt-hours of capacity per cycle) would be increasingly useful in the future as solar and wind capacity grows. Various possible technologies for grid-scale energy storage are summarized below. Each has a delivered cost of output electricity (per kWh), which is the sum of charging electricity, operating and maintenance costs, and capital amortization. Capital amortization depends upon average capacity factor (annual output kWh per kW rated power).

## 6.1 Hydroelectric Systems
Hydroelectric storage systems presently comprise well over 90% of domestic storage capacity. They employ turbines to generate power from water drawn from a water reservoir. The reservoir is filled either by pumping from a lower level (using the turbine-generators in reverse when grid prices are low) or by diverting part of the water from a higher-elevation river (as practiced at Niagara Falls). Their delivered cost of electricity is quite low: generally well below $0.10 per kWh. Their combined capacity is well under 1% of U.S. daily electricity use. Few suitable sites remain for new installations.

## 6.2 Compressed-Air Systems
Compressed-air energy storage (CAES) systems use low-cost grid power to compress large volumes of air for storage in underground caverns. When power prices are high, the air is used to burn natural gas to spin a gas turbine-generator. Some systems can achieve slightly lower costs than the $0.20/kWh cited above, but there are very few suitable sites in the U.S. and thus capacity is small.

## 6.3 Battery Systems
A small number of utility-scale demonstration rechargeable-battery storage systems have been installed, using either deep-cycle lead-acid or lithium-ion batteries. They employ numerous batteries connected in both series and parallel, charging systems, inverter systems, mounting racks, cooling systems, safety systems, and an enclosure. Most are designed for battery replacements every two to eight thousand cycles. Delivered electricity from large battery systems now costs roughly double the cited average for peaking turbines and are expected to remain above peaking cost in the future.

### 6.4 Plug-In Electric Vehicles

The use of plug-in electric vehicles (which use lithium-ion batteries) to perform grid-connected storage has been proposed. Since the expected life of these batteries will sometimes exceed the useful life of the vehicle, it could be valid to consider their capital amortization to be zero when performing storage for the grid. With expected future improvements in power electronics, AC-to-AC round-trip energy efficiencies might average about 85%. When grid time-of-use and buy-versus-sell prices are favorable, such storage could have an attractive delivered electricity cost near $0.10/kWh. If discharge power can be utilized by a residence or commercial building, its value would be greater than exports to the grid. The forecast large use of plug-in vehicles by 2060 is expected to enable many opportunities for their grid-interactive operation to achieve slight reductions in net vehicle annual electricity costs.

### 6.5 Flow Batteries

These batteries use large quantities of liquids and/or gases flowing to and from storage tanks through electrochemical systems which perform charging and discharging. These systems have round-trip storage efficiencies lower than batteries. Their future delivered cost of electricity is uncertain, but their charging/discharging flexibility will not begin to approach the virtual battery systems cited below.

### 6.6 Virtual Batteries

Virtual batteries accept electricity at some times and deliver it at other times, as do conventional rechargeable batteries. However, the electricity is not actually stored. Instead, input power is used for a chosen purpose and later output power is generated when desired.

Virtual battery systems can have important advantages over conventional batteries. Their daily, weekly, or annual total output energy can be far higher or lower than input energy. Timing of input and output energy flows is completely flexible. For example, some of the grid energy can be accepted in summer and delivered in winter. Capital amortization per output kWh is small because the systems are also performing other valuable functions.

The widespread use today of grid-connected solar systems is one type of virtual battery operation: excess solar power is exported to the grid sometimes and power is imported from the grid other times.

The biomass converter systems described in Section 4.1 use grid power to synthesize extra quantities of biofuels when grid prices are low. At high grid prices, biomass is used to generate export power for the grid.

Future distributed fuel cell systems (described in Section 4.4) can operate as virtual batteries. When grid prices are very low, grid power can be imported for site needs and fuel cell systems hot idled. At higher grid prices, surplus power can be exported to the grid.

Both the fuel cell and biomass converter systems can deliver power to the grid at a total cost below $0.10/kWh. Ref. 6 further discusses virtual batteries.

### 6.7 Load Following

The grid-connected natural gas fuel cell systems described in Section 4.4 can rapidly and economically load follow in response to grid supply/demand, unlike many of today's large base-load power plants. This capability, when combined with the virtual battery systems described above will eliminate the need for peaking gas turbines (and their high-cost power) before 2060.

### 6.8 Grid Storage Summary

The proposed 2060 large capacity of virtual battery and load-following systems will facilitate the proposed cost-effective addition of very large additional solar and wind capacity. Existing hydroelectric storage will continue its small contribution. The other storage methods mentioned in this chapter are expected to play very little role due to their higher costs.

# 7. Energy Utilization

By 2060, advances in existing technologies will be combined with widespread deployment of new technologies to significantly increase energy utilization efficiencies. The result will be the ability to provide enhanced energy services to a larger U.S. population and economy at attractive costs. The sections below mention major energy utilization technologies expected to be in use in 2060. Additional options will probably emerge in the intervening years.

Energy users will be encouraged to improve usage efficiency in order to save money (unit prices are predicted to increase: see Chapter 11). Table 7.1 summarizes proposed transportation use. All listed fuels are biofuels. An additional 0.05 EJ of gasoline is forecast for uses other than transportation (such as portable tools). Nearly half of the kerosene will have its $CO_2$ captured on the vehicle for sequestration (CCS column).

### Table 7.1 Proposed 2060 Transportation
EJ HHV

|  | Electricity | Natural Gas | Gasoline | Kerosene CCS | Kerosene no CCS | Total |
|---|---|---|---|---|---|---|
| Light-Duty Vehicles | 2.90 |  | 0.20 |  | 1.40 | 4.50 |
| Commercial Light Trucks | 0.15 |  |  | 0.15 |  | 0.30 |
| Buses | 0.05 |  |  | 0.10 |  | 0.15 |
| Freight Trucks | 0.20 |  |  | 4.40 |  | 4.60 |
| Rail | 0.10 |  |  | 0.30 |  | 0.40 |
| Shipping |  |  |  | 0.55 | 0.15 | 0.70 |
| Boats |  |  | 0.20 |  |  | 0.20 |
| Air |  |  | 0.05 |  | 3.50 | 3.55 |
| Military |  |  |  |  | 0.85 | 0.85 |
| Lubricants |  |  |  |  | 0.10 | 0.10 |
| Pipelines |  | 0.10 |  |  |  | 0.10 |
| Totals | 3.40 | 0.10 | 0.45 | 5.50 | 6.00 | 15.45 |

### 7.1 Light-Duty Vehicles
Light-duty vehicles include cars, SUVs, minivans, and pickup trucks. Ref. 1 predicts light duty vehicle (LDV) travel extrapolating to 3518 billion miles in 2060. Computer-assisted semi-autonomous driving features standard on all vehicles will help improve energy efficiencies. Added intelligence on traffic signals will also help. An expanded market for vehicle rentals will encourage vehicle owners to own smaller vehicles for everyday use and rent larger types for occasional trips. The expected on-road LDVs in 2060 will consist of the following three types:

7.1.1 Plug-in Vehicles
These vehicles will use rechargeable advanced lithium-ion batteries as their sole on-board energy source, with available driving ranges up to 400 miles. Recharging will be mainly at home, with (more costly) fast recharge options at filling stations (requiring 20-30 minutes for 250 miles additional range). Energy efficiency is expected to average 3 to 4 miles per kWh, depending

upon vehicle weight. These pure electric vehicles might account for one-fourth of LDV annual travel.

### 7.1.2 Plug-in Hybrids with Fuel Cell Systems

These will combine lithium-ion battery packs (usually smaller than described above) with advanced fuel cell systems using biokerosene. They will have driving ranges up to 1000 miles (100 miles/gallon of kerosene and typically 100-200 miles plug-in range). Most 2060 LDVs are expected to be this type, with fuel usually being consumed only on long trips. CO$_2$ capture will be an available option on some models (cost effective for high annual travel).

### 7.1.3 Engine Vehicles

These will be mostly two-wheel types using (expensive) gasoline. Their improved engines and the new biogasoline will burn cleaner than today's types. Engine vehicles will account for a small share of miles traveled in 2060, with fuel usage as shown in Table 7.1.

## 7.2 Trucks and Buses

Ref. 1 predicts freight truck travel to extrapolate to 455 billion miles in 2060. Commercial light truck travel extrapolates to 172 billion miles in 2060. Bus mileage is not cited, but bus energy use is about 40% of commercial light trucks. Combined 2060 truck and bus travel is estimated to be 700 billion miles. Their combined energy HHV of 5.05 EJ equals an average mileage of 0.50 miles per kWh.

The majority of these vehicles are expected use advanced, turbo-charged, solid-oxide fuel cell systems hybridized with lithium-ion batteries. Their fuel would be kerosene, with all carbon captured on board as liquid CO$_2$. The remaining travel would use plug-in electricity (mostly for local travel in smaller vehicles).

## 7.3 Aircraft and Military

State-of-the-art high-power gas turbine engines offer power/weight ratios far higher than believed possible with future advanced fuel cell systems. Such engines will therefore be used in commercial aircraft, military aircraft, and other high-power military applications. By 2060, many commercial planes are expected to employ (comparatively low-power) fuel-cell auxiliary power units, fueled by the same biokerosene as their engines. CO$_2$ capture will not be included in aircraft or the great majority of military applications.

Ref.1 predicts commercial air travel to be 2700 billion seat miles (extrapolated to 2060). Airline 2060 average energy efficiency is projected to be 25% better than 2017.

## 7.4 Other Transportation

By 2060, multi-megawatt kerosene fuel cell hybrid systems of the type used on trucks are expected to be in wide use for ships and locomotives. The lubricants in Table 7.1 are shown as kerosene, but will actually consist of heavier bio-paraffins with the listed energy content (far less lubricant are needed for the proposed vehicles, which use far fewer engines).

### 7.5 HVAC in Buildings
The majority of the energy used today in residential and commercial buildings is for HVAC systems. Most of these buildings now have relatively ineffective insulation, windows, and doors. They use large quantities of heat in furnaces and operate relatively inefficient air conditioners.

Future buildings can slash HVAC needs by improving insulation, windows, doors, and fresh-air ventilation systems. Advanced air-source heat pump systems can perform heating and cooling at superior energy efficiencies over today's systems. Where on-site natural gas fuel cell systems are installed (Section 4.4), their surplus heat can operate advanced ammonia-water absorption heat pump systems. Other buildings can use electric compressors to power their heat pumps.

### 7.6 Other Residential and Commercial
Lighting energy use will decrease due to nearly universal use of LED lighting (which will gradually become slightly more efficient) together with smart controls, better lighting focus, and greater use of natural light. Electronic equipment will become more efficient from continuing advances in technology, with the side benefit of lower fan noise. Refrigerators will become more efficient from improved insulation and cooling systems. Cooking equipment will use less energy due to many small changes, plus a greater use of electricity to replace gas.

### 7.7 Industrial
Much industrial heating will shift from burner systems to advanced electrical systems, which will use less energy. Higher prices will provide incentives to enhance efficiencies of many processes, using better recuperation. Chapter 8 discusses specific industrial processes where major changes are expected.

# 8. Manufacturing

Significant changes in major manufacturing operations are recommended to eliminate fossil $CO_2$ emissions. All electricity used will either come from the (carbon-negative) grid or on-site (zero-carbon) generation (solar photovoltaic or natural gas fuel cell). The major processes described below will use petroleum and/or natural gas (sold under licenses for specific uses only, with CCS of all carbon not present in the product). The carbon in product chemicals and materials is expected to be mostly later recycled or else used in waste gasification systems equipped with CCS. This chapter summarizes expected changes in major industrial processes. Example 2060 natural gas and petroleum inputs are given in Table 8.1 below, along with estimated fossil $CO_2$ to be sequestered.

## 8.1 Chemicals

Nearly all organic chemicals are manufactured from natural gas and/or petroleum. Monomers for plastics comprise a large majority of chemicals tonnage. In 2016, plastics production in the U.S. totaled 112 billion pounds. By 2060, it is expected to be twice this amount. Many different plastics are manufactured, both thermoplastics and thermosets. Expected 2060 recycling will reduce the required input hydrocarbons. The largest single monomer is ethylene, currently 37% of the total weight. Although it is technically feasible to produce many monomers from biomass, significant production of this kind is not assumed in this report.

Many thousands of other organic chemicals are also made, with annual quantities ranging from very large (e.g., industrial methanol, ethylene glycol) to very small (e.g., expensive drugs).

## 8.2 Asphalt

Asphalt for road paving and related materials used 0.88 EJ of fossil inputs in 2016. By 2060, the value is expected to total 1.50 EJ.

## 8.3 Ammonia

Production of anhydrous ammonia (chiefly for direct use as a fertilizer) is expected to increase, mostly to enhance biomass growth. In 2017, domestic ammonia consumption was about 16.5 million tonnes (with 28% of this being imported). By 2060, consumption could double.

An advanced process could manufacture ammonia from water and air using fossil natural gas as the energy source, with complete capture of the carbon as liquid $CO_2$ for sequestration. Table 8.1 assumes the use of such a process.

## 8.4 Ironmaking

At present, primary iron (called "pig iron") is made in the U.S. from iron-oxide ore in blast furnaces. These furnaces are also charged with limestone and coke (made from expensive types of coal in coke ovens). Both the coke ovens and blast furnaces emit large quantities of fossil $CO_2$, as well and many other air pollutants. Present U.S. pig iron consumption is about 40 million tonnes per year (with imports about 26% of the total). By 2060, consumption could rise to 60 million tonnes. A new advanced, pollution-free process is proposed, using natural gas as

the energy source and reducing agent, with complete capture of all the carbon as $CO_2$ for sequestration.

## 8.5 Cement

Production of Portland cement (named for the town of its invention in England) currently emits considerable fossil $CO_2$ which arises from both its fuel (usually natural gas) and the calcining of $CaCO_3$ to $CaO$. In 2016, U.S. cement consumption was 96 million tonnes. By 2060, annual demand might reach 145 million tonnes. Cement averages about 64% $CaO$ by weight, with the balance mostly $SiO_2$ plus small percentages of $Al_2O_3$, $Fe_2O_3$, and $SO_3$ (as sulfates). An advanced process is proposed, which will capture as liquid all the $CO_2$ from both natural gas oxidation and limestone calcining.

## 8.6 Manufacturing Fossil-Fuels Summary

The 2060 fossil energy used for manufacturing the above products is summarized below. All the $CO_2$ shown will be sequestered. The great majority of other industrial energy requirements will be supplied by electricity from the grid or produced by on-site PV systems. Small amounts of biofuels (not shown) will also be used.

### Table 8.1 2060 Manufacturing Inputs and CO$_2$

|  | EJ HHV | | CO2 |
| --- | --- | --- | --- |
|  | Natural Gas | Petroleum | million te |
| Chemicals | 1.67 | 2.50 | 70 |
| Asphalt | 0.30 | 1.20 | 15 |
| Ammonia | 0.84 | | 42 |
| Iron | 0.56 | | 28 |
| Cement | 0.44 | | 95 |
| Sum | 3.80 | 3.70 | 250 |

## 8.7 Sulfur and Phosphate Fertilizers

The manufacture of phosphate fertilizers from quarried phosphate rock requires sulfuric acid. While a small percentage of current acid demand is met by byproduct acid from industrial processes, most $H_2SO_4$ is produced from elemental sulfur recovered from petroleum refining and natural gas processing plants.

In 2017, total sulfur consumption in the U.S was about 10 million tonnes, with slightly over 6 million tonnes used for phosphate fertilizer production (from about 28 million tonnes of phosphate rock). By 2060, major efforts to reduce fertilizer runoff are expected to combine with the large use of organic fertilizers from biomass gasification (Chapter 4) to reduce total phosphate fertilizer needs to perhaps one-half of today's. The resulting 2060 annual sulfur demand will be roughly 7 million tonnes. The forecast coal use (Chapter 10) would easily supply this requirement (with excess sulfur available for improving road paving asphalt).

**8.8 Recycling**

Recycling of paper products and polymers has been increasing in the U.S. and is expected to rise further through 2060. Manufacturers also recycle many materials within their plants. However, very large quantities of both biomass-derived materials and items made from fossil fuels are currently being deposited in landfills or incinerated. Such mixed organic wastes can be blended with the biomass feeds for the converters described in Section 4.1, avoiding carbon emissions and reducing the average cost of the converter feeds.

# 9. Exports

The United States is expected to export large quantities of energy-related products in 2060 for both financial and environmental reasons, as summarized below.

## 9.1 Fossil Fuels

By 2060, coal exports are expected to be very small due to coal's large domestic usage for $CO_2$ capture plants.

Exports of a variety of products made from natural gas (with CCS of all surplus carbon) and liquefied natural gas (LNG) will both become quite large by 2060. Priority sales will be made to users who will practice CCS. Some LNG could be used in direct air capture plants where coal is unavailable. Based on the Ref. 1 forecasts of domestic production and prices, potential exports of natural gas (as LNG or products made from gas) could reach 30.1 EJ in 2060, with a value over $175 billion.

Based upon Ref. 1 domestic production and price forecasts, some 90% of domestic petroleum production might be exported (as crude or refined products). As with natural gas, buyers using CCS will be preferred. The 27.6 EJ of exports would have a value over $600 billion.

## 9.2 Biofuels

Limited quantities of the biofuels described in 4.2 could be sold to countries having insufficient biomass resources (BNG as liquid). The biofuels sold in the U.S. (in Table 11.1) have a total value of $446 billion in 2060. If an additional 15% were exported, their value would be $67 billion.

## 9.3 Equipment and Licensing

Equipment exports will include all of the equipment types cited in Chapters 4, 7, and 8 for clean energy conversion, utilization, and manufacturing. In many larger countries, licenses will be established for local manufacturing of the same types of equipment. In some cases, overseas divisions or joint ventures of parent U.S. companies will manufacture equipment.

## 9.4 Consulting

A wide range of energy consulting services will be provided to other countries to enable them to enhance both their environmental and financial results.

## 9.5 CO₂ Services

U.S. companies will offer $CO_2$ transport (via dedicated ships) to the U.S., followed by sequestration. These services can be used by small nations with no suitable sequestration sites.

## 9.6 Foods

The proposed very extensive use of greenhouses to grow fresh produce for local markets, will free large quantities for exports after value-added processing.
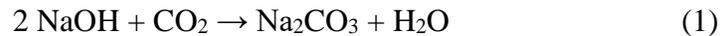
# 10. Direct $CO_2$ Capture

The previous chapters have outlined proposed strategies for the elimination of virtually all energy-related fossil $CO_2$ emissions. Major net removal of $CO_2$ from the atmosphere is also proposed using permanent underground sequestration of the majority of biomass carbon used for energy purposes. This chapter summarizes proposed additional specialized facilities which would affordably capture and sequester an even larger annual quantity of $CO_2$ directly from the atmosphere.

The average concentration of $CO_2$ in the atmosphere is approaching 410 parts per million, which is more than 50% above pre-industrial levels. However, this level is only one part $CO_2$ in 2440 parts air. The direct removal of a gas from a mixture at this low a starting concentration is a major technical challenge. The $CO_2$ must also be compressed far above atmospheric pressure and liquefied for transport. When the additional requirements of affordable capital and operating costs, no pollution, and no use of scarce inputs are added, the challenges increase.

The process outlined below is believed to offer superior economics and environmental performance versus known alternatives.

## 10.1 Process Description
It is proposed to utilize the following three chemical reactions:

$$2\ NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \qquad\qquad (1)$$

$$Na_2CO_3 + CaO + H_2O \rightarrow CaCO_3 + 2\ NaOH \qquad (2)$$

$$CaCO_3 \rightarrow CaO + CO_2 \qquad\qquad (3)$$

Equation (1) reacts an aqueous solution of sodium hydroxide at ambient temperature with a very large flow of ambient air to produce aqueous sodium carbonate. Although this reaction is quite exothermic, an increase in humidity of the air will usually also occur from evaporation of a small fraction of the water present, and thus the discharge air will commonly be slightly cooler than ambient. Equipment designed for performing this step might be designed to reduce ambient $CO_2$ by half (i.e., from 410 ppm to 205 ppm) on average. Good equipment design will minimize power used for the fans moving the air and restrict the loss of sodium to negligible rates.

The solution exiting the above step might have most of its hydroxide converted to carbonate. Reaction (2) will yield a calcium carbonate precipitate while regenerating the sodium hydroxide. Step two will include several functions, including filtering and drying of the precipitate, heat exchange, addition of makeup water to replace losses in step 1, and filtration of incoming solution to remove particles captured from ambient air. Step two is exothermic, which is useful to warm the aqueous solution. The reaction might be performed at a temperature in the vicinity of 60ºC. Calculated pumping power is small.

Reaction (3) is the calcining of solid carbonate. This is a highly endothermic reaction and is desirably performed at high temperature and pressure, for example at 1100ºC and 25 bar.

Calciner system design will include airlocks operating at moderate temperatures for the solid streams, direct-contact heat exchangers for gases and solids, distributed combustion of fuel gas, and ancillary subsystems. Hot steam will also be added to the calciner to dilute the CO$_2$, allowing the calcining reaction to approach equilibrium. The steel pressure vessel will operate at moderate temperature due to effective internal insulation.

## 10.2 Energy Subsystem

The proposed systems will use "steam coal" as their energy source because if its low cost and extensive domestic reserves. The proposed subsystems will emit zero pollution and capture all of the carbon from the coal in addition to removing carbon from the air. A molecular-sieve system will process air to give a gaseous oxidizer mix containing 90% O$_2$. An autothermal gasifier system will react coal, steam, and oxidizer to produce a clean fuel gas mixture, with all sulfur removed and converted to saleable sulfuric acid and/or elemental sulfur. The fuel gas will be oxidized in the calciner to supply the endotherm. The gasifier and calciner systems will operate near 25 bar pressure. An expansion turbine will generate required power.

## 10.3 Other Subsystems

Compressors will be employed for air, oxidant, and refrigeration. Numerous heat exchangers will be utilized, including condensers for water vapor, refrigerant, and CO$_2$. Fans will be used to move air for reaction (1) and for cooling. A small molecular sieve will remove the small percentages of O$_2$ and N$_2$ from the concentrated CO$_2$ gas mixture. Pumps will be used for water, aqueous solutions, and liquid CO$_2$. Liquid CO$_2$ pressure for transportation may be near its critical pressure of 74 bar (1060 psig).

Storage will be provided for coal, CO$_2$ liquid, and salable gasifier byproducts (sulfur or sulfuric acid and ash). Rail transport will be used for inputs and outputs (with CO$_2$ pipelines used in some cases).

## 10.4 Quantities

The proposed Direct Air Capture plants will remove 3174 million tonnes per year of CO$_2$ from the air (about 62% of proposed total removal). They will also capture for sequestration 1573 million tonnes per year fossil CO$_2$ from the coal. Coal HHV required is 17.34 EJ (equals average coal used to generate electric power in 2013-2014). At 20 GJ/ton HHV, coal weight is 864 million tons per year. The ratio of coal HHV to CO$_2$ removed from the air is 1517 kWh/tonne. The partial pressure of gaseous CO$_2$ is increased by this process by a factor of 61,000 from its value in ambient air to pure gas at 25 bar, from which it is condensed (together with the CO$_2$ from the coal).

## 10.5 Alternative Direct-Air Capture Methods

Studies of alternative processes for direct capture from air have generally predicted very high capital and operating costs. Nevertheless, several companies worldwide are actively exploring process candidates, some of which have features in common with the above.

If surplus low-cost natural gas or electricity were available, they could be used to replace some or all of the coal energy source.

# 11. Financial

This chapter gives example prices, costs, and financial totals for the proposed 2060 case (all in 2018 dollars).

## 11.1 Flows
The proposed 2060 material and energy flows cited in the previous chapters are summarized in Section 14.1.

## 11.2 Example User Prices and Costs
Table 11.1 gives example 2060 average user prices and total energy expenditures. Unlike present and forecast prices from Ref. 1, the proposed user prices and expenditures exclude taxes for the maintenance of roads, bridges, etc. (see Section 1.1), since user fees will be collected separately. The Kerosene CCS Net price reflects a credit for CO$_2$ sold by the user.

### Table 11.1 Example 2060 Prices

|                    | EJ    | Price GJ | Price billions | Other Units Unit | Other Units Price |
|--------------------|-------|----------|----------------|------|---------|
| Fossil Natural Gas | 3.80  | $7.71    | $29            | mcf    | $8.38   |
| Petroleum          | 3.70  | $19.44   | $72            | bbl    | $119    |
| Natural Gas        | 2.50  | $32.00   | $80            | mcf    | $34.78  |
| Propane            | 1.00  | $32.00   | $32            | gallon | $2.99   |
| Gasoline           | 0.50  | $32.00   | $16            | gallon | $3.91   |
| Jet Fuel           | 4.35  | $26.00   | $113           | gallon | $3.50   |
| Kerosene           | 1.65  | $31.00   | $51            | gallon | $4.17   |
| Kerosene CCS Net   | 5.50  | $28.00   | $154           | gallon | $3.77   |
| Electricity        | 28.80 | $29.93   | $862           | kWh    | $0.108  |
| Total              | 51.80 | $27.22   | $1,410         |        |         |

These prices include other taxes and are averaged over time of use (where applicable) and user categories. Electricity average prices will be highest for residential users and lowest for industrial users. The fossil fuels in Table 11.1 (Petroleum and Natural Gas) will be sold only to licensed industrial plants who practice CO$_2$ capture and/or manufacture materials and chemicals.

The pricing shown will encourage energy users to favor electricity, which will also enable higher efficiencies in many cases. Transportation users unable to use electricity will have cost incentives to use bio-kerosene with CO$_2$ capture. The average price of $29.22 per GJ is 150% of the extrapolated 2060 DOE projections (which assume much more low-cost natural gas), but total user energy expenditures are only 90% of DOE extrapolation (due to the large increases in energy usage efficiencies).

The prices shown for fossil natural gas, petroleum, and electricity equal those from the extrapolated DOE forecasts. The Table 11.1 example prices will create incentives for users to choose electricity instead of fuel for most purposes. For example, expected high-efficiency electric heat pumps can perform space and water heating at far greater energy efficiency than fuel-fired furnaces and water heaters. Electric energy can be used in transportation at notably

higher efficiency than fuels (even with advanced fuel cell systems). The difference in net cost for large transportation equipment to capture CO$_2$ for sequestration will yield attractive returns on investment for such add-on systems where annual fuel use is high.

## 11.3 Primary Energy Costs

Table 11.2 shows example prices and acquisition costs for the primary fuel quantities shown in Table 1.2 (the Natural Gas here is fossil natural gas). The average prices for natural gas and petroleum are the same as used in Table 11.1. The coal price is the DOE extrapolated price for steam coal (Ref. 1). The assumed average biomass price was partly based on the factors discussed in Chapter 3. Although sales of byproducts from biomass and coal conversion (i.e., organic fertilizer, sulfur, and coal ash for cement manufacture) will reduce net input costs by perhaps 3%, such sales are not subtracted (since price uncertainties are above 3%).

### Table 11.2 Example 2060 Primary Energy Costs

|             | HHV   | Price   | Cost     | Quantity |              | Converted Price |      |
|-------------|-------|---------|----------|----------|--------------|-----------------|------|
|             | EJ    | GJ      | billions | Value    | units        | Price           | unit |
| Biomass     | 27.95 | $6.50   | $182     | 1654     | million tons | $110            | ton  |
| Natural Gas | 20.07 | $7.71   | $155     | 18.46    | billion mcf  | $8.38           | mcf  |
| Coal        | 17.34 | $2.38   | $41      | 864      | million tons | $48             | ton  |
| Petroleum   | 3.70  | $19.44  | $72      | 605      | million bbl  | $119            | bbl  |
| Sum         | 69.06 | $6.51   | $450     |          |              |                 |      |

Total primary energy costs (including energy used for CO$_2$ capture) of $450 billion are 32% of the $1410 user prices: an attractive ratio.

## 11.4 CO$_2$-Related Costs

The proposed combination of technologies is expected to achieve the cited net CO$_2$ removal from the atmosphere of 5151 million tonnes per year in 2060, for a total reduction of about 10.6 billion tons per year below the extrapolated DOE forecast.

The associated costs of this reduction include the costs of emissions avoidance, capture, CO$_2$ transport, and sequestration costs. Cost elements include added energy, maintenance, personnel, and capital charges. Total CO$_2$ related costs in 2060 are calculated to be approximately $100 billion per year, for an average of $9.40 per tonne reduced or $12.80 per tonne sequestered (7.8 billion tonnes sequestered). The total is 7% of user energy expenditures, from which the costs will be funded. The largest single component of the $100 million is $41 billion for coal.

## 11.5 Biomass Converter Capital Costs

Installed costs of the biomass converters described in Section 4.6 will be higher in early years and then expected to drop to mature values near $1000 per kW of electric power output or its equivalent in biofuel HHV. The combined total of converter outputs is 15.5 EJ/yr biofuels plus 4.1 EJ/yr of net electricity (Tables 14.1 and 14.2) or 19.6 EJ per year. If average converter size were 1 MW, about 620,000 converters are needed for the entire country. Their installed cost would total $620 billion (an average of $21 billion/year for 30 years).

### 11.6 Natural Gas Power Plants
The 12.39 EJ of electric power from natural gas power plants at an average capacity factor of 70% would require 560 GW of capacity. At a mature average installed cost of $800 per kW (residential systems will cost more, large systems less), capex would total about $450 billion.

### 11.7 Transportation and Manufacturing Equipment
Advanced fuel cell systems are assumed to be employed in many of the trucks, buses, locomotives, and ships as described in Chapter 7. Their higher capital costs will be recovered by expected fuel cost savings in most cases. The average cost of these systems in mature years is expected to average approximately $500 per rated kW. Mature capacity in the U.S. might total roughly 700 GW, costing a total of $350 billion. The manufacturing systems described in Chapter 7 might have additional installed capex of $100 billion.

### 11.8 Greenhouses
Each 1 MW biomass converter could provide surplus heat for about a hectare (2.47 acres) of well-designed greenhouses in winter (Section 3.4). Greenhouses might be associated with 70% of converters. If they averaged ten employees per hectare, the total of 620 GW of converter capacity would create 4.3 million greenhouse jobs.

### 11.9 Job Creation
The proposed program will create equipment-related jobs in manufacturing, sales, service, and support functions. Many new employees will be needed for jobs related to producing biomass. Many highly skilled personnel will be needed to consult for other countries and to manage domestic and international trade and licensing. Including the greenhouse jobs cited above, the net total of new jobs is expected to approach ten million full time equivalents.

# 12. Alternatives

In 2060, many alternatives to the above technologies, quantities, and fuels are possible, some of which are briefly cited below.

## 12.1 Annual Quantities
Actual U.S. material and energy flows in 2060 are likely to differ (in either direction, perhaps significantly) from the example values in this report. The example values were calculated to be compatible among themselves and to differ from extrapolated DOE values (Ref. 1) for specific reasons. Public and governmental attitudes and priorities will have major impacts.

## 12.2 Prices
Energy retail and wholesale prices might be higher than example values (but probably not lower). The example relative prices should help steer energy users to environmentally preferred choices. CO$_2$ fees embedded in all prices are intended to fully cover the extra costs for CCS.

However, the projected total energy expenditures are a smaller share of GDP in 2060, limiting financial incentives for users to eliminate energy waste and seek higher efficiencies. Higher prices could also enhance energy-producer profitability and/or governmental revenues.

## 12.3 Conventional Fossil-Fuel Power Plants
As shown in Table 4.1, 57% of 2060 electricity is forecast by DOE to be generated from conventional natural gas and coal power plants. This proposal would retire all such plants, eliminating their large fossil CO$_2$ emissions (together with other air pollutants).

## 12.4 Nuclear Power Plants
Table 4.1 shows nuclear electricity at 10% of the 2060 DOE total. This paper proposes to use no nuclear power for multiple reasons. They have higher expected costs (even with new designs) than the proposed alternatives. They produce extremely long-lived radioactive wastes, for which there is no satisfactory solution. They are potentially vulnerable to terrorism. At best they are zero carbon, rather than the negative carbon proposed in Section 4.6.

## 12.5 Other Possible Types of Power Plants
It is now recognized that sizeable hydroelectric plants create serious harm to most ecosystems. Many old small dams and their hydro plants are being removed to restore free flow of rivers. The U.S. does not have suitable sites for significant addition of added hydroelectric capacity.

Geothermal power plants produce a small amount of power today (included in the cited totals for hydro power). Few suitable sites exist for added capacity.

Systems to generate power from the ocean, using currents, temperature differences, or tidal height variations are presently under study. They would be zero carbon, rather than negative. They are considered unlikely to match the predicted costs of the proposed Chapter 4 alternatives.

## 12.6 Alternative Fuels

The proposed 2060 fuels for electricity generation, buildings, and transportation will exclude the alternatives listed in this section.

Oxygenated fuels, including ethanol and biodiesel esters, will be phased out due to their higher expected cost versus the proposed bio-hydrocarbons. Ethanol also has lower energy density (Table 14.3). Biodiesel ester production often is associated with tropical rain forest destruction.

Although hydrogen could be produced with negative $CO_2$ emissions from biomass or with zero emissions using other processes, it is less convenient than the preferred bio-kerosene and has higher total costs.

Biomass-derived ammonia, BNG, or bio-propane could be used as vehicle fuels, but are less convenient and are projected to offer no cost advantage over bio-kerosene.

## 12.7 Ammonia-Air Batteries for Transportation

The transportation energy systems described in Chapter 7 use lithium-ion batteries, fuel cell systems, and/or engines. Another possible option for plug-in long-haul trucks and buses would be the use of ammonia-air-water rechargeable batteries (incorporating reversible solid-oxide fuel cell stacks). Although their round-trip energy storage efficiency would be lower than lithium-ion batteries, they would exhibit lower cost, lighter weight, and smaller volume. They could also be fully recharged in only minutes using fluid exchange (stored water exchanged for liquid ammonia).

## 12.8 Fossil Natural Gas for Transportation

Fossil compressed natural gas (CNG) might be used instead of bio-kerosene in some of the trucks and buses described in Section 7.2 with $CO_2$ capture. Although calculated total costs per mile would be lower, these vehicles would be zero-$CO_2$ rather than the negative result of biocarbon sequestration. Additional capital expenditures would be needed for filling station equipment and high-pressure tanks on vehicles. Typical vehicle driving ranges would be lower.

## 12.9 Alternative CO$_2$ Capture Schemes

Processes using fuel combustion with air produce exhaust streams with high nitrogen and low $CO_2$ percentages, making liquid $CO_2$ recovery quite costly. Processes using cryogenic air-separation plants to make pure oxygen for combustion are also considerably more expensive than the proposed technologies (which operate at considerably higher overall energy efficiencies).

## 12.10 Nuclear Fusion

Economical fusion power without radioactive-waste production is expected to eventually become available after 2060. Its expansion will gradually allow the proposed use of fossil fuels (with carbon capture) to be phased out. Fusion-produced electricity can eventually become the energy source for direct capture of $CO_2$ from the atmosphere, making it possible to remove even greater annual quantities than proposed herein.

# 13. Discussion and Conclusions

## 13.1 Technology Development
Although all of the new processes and equipment proposed in this paper are based upon known science and technology, they will require considerable engineering development prior to commercialization. The development of each type of equipment should employ a phased program, limiting the time and cost to reach proof-of-concept demonstrations.

All early demonstrations can be performed at small laboratory scale (3 to 10 kW). The use of small early systems will speed progress, allow alternative details to be economically explored, and reduce technical and financial risks. Systems with commercial sizes of 100 kW and larger might use multiple smaller demonstration sizes.

Proof-of-concept demonstrations will be followed by beta-test installed systems, in small quantities. A strategy of continuous product improvement should be pursued for all types of equipment. Improvements sought will be better reliability, reduced maintenance costs, higher efficiency, and lower installed costs. Technology development should never cease.

In order to minimize up-front costs, development should begin on only a few of the proposed types of equipment initially. Once these have entered profitable manufacturing, developments can begin on other processes and equipment. The time to reach proof-of-concept for each type of equipment will vary with funding level, but several years is considered a minimum for each major new program.

## 13.2 Manufacturing
Manufacturing of each product line will begin at very small scale to produce equipment for beta field testing. As annual quantities increase, progressively more automation should be phased in, enabling continual cost reductions and quality improvements while employing a well-paid domestic workforce. Individual manufacturing plants are best limited to no more than a few hundred employees, after which additional facilities should be built.

## 13.3 Deployment
Multiple well-organized companies should perform marketing, sales, training, installations, and field service. Established firms serving the transportation industry can acquire new skills and equipment for the new technologies being phased in. Farming can expand significantly to grow, harvest, and process the large quantities of biomass. Greenhouses can be progressively added.

## 13.4 Governmental Roles
The federal government would supervise the National Carbon Administration (described in Section 4.6), which would purchase liquid $CO_2$ (from both biomass and fossil sources), transport it, and permanently sequester it underground (with suitable monitoring).

The federal government would gradually increase fees on fossil $CO_2$ emissions until they become prohibitive. They would also license CCS users of fossil fuels and monitor their annual quantities.

Other federal roles would include the enactment and enforcement of environmental and safety regulations. Subsidies for energy companies should be discontinued well before 2060.

State and local governments should collect road usage fees from all users based upon their weight and travel. Such fees would no longer be added to fuel prices, since so much travel would use electricity. Road use revenues should be used for first-class maintenance of travel infrastructure and to subsidize public transportation (which eases road congestion and saves energy).

### 13.5 International
This paper has attempted to quantify energy and carbon parameters only for the United States. Nearly all countries intend to reduce their $CO_2$ emissions and improve their energy economics. Most of the technologies described in this report can be implemented in other countries, aided by appropriate imports and exports. It appears possible that the entire planet could reach negative total annual $CO_2$ emissions shortly after the proposed U.S. achievement.

### 13.6 Other Greenhouse Gases
Although increased $CO_2$ is the principal cause of global warming, human-caused emissions of methane ($CH_4$), nitrogen oxides ($NO_x$), and ozone ($O_3$) also contribute. The proposed new processes and equipment will have negligible emissions of these gases.

### 13.7 Conclusions
The proposed strategy uses solar power (directly or indirectly) for 64% of domestic delivered energy and for part of the proposed $CO_2$ capture from the atmosphere. Solar power drives photosynthesis, which yields both biomass and removes $CO_2$ from the air. It also produces wind, is responsible for moving water, and enables solar photovoltaic and other solar-electric technologies. The proposed non-solar energy sources are geothermal (renewable, but very minor) and the fossil fuels coal, petroleum, and natural gas (used with complete carbon capture).

Solid-oxide fuel cell and reversible electrochemical systems will be employed very extensively for both energy supply and utilization, due to their expected cost-effectiveness and environmental advantages. In addition to the cited economic benefits and $CO_2$ emissions reduction, the proposed new technologies would yield very large reductions in pollution, especially air pollution.

The 2060 energy scenario described in this report is intended to be one self-consistent example of possible technologies, quantities, and economics. Although it is very likely that actual 2060 results will differ in many ways, the report describes a desirable and achievable possibility.

The combined annual economic benefits from the proposed strategy will exceed one trillion 2018 dollars. U.S. fossil $CO_2$ emissions will exhibit accelerating decline after 2020 (Fig. 1), reach zero by 2045, and become highly negative by 2060.

# 14. Appendix

## 14.1 Material and Energy Balance

The simplified flowsheet below shows proposed 2060 material and energy streams, with their values in Tables 14.1 and 14.2. Not shown are organic fertilizer byproducts from the converters (61 million tons/yr) or the various industrial products made from inputs 4 and 5 (Chapter 8).
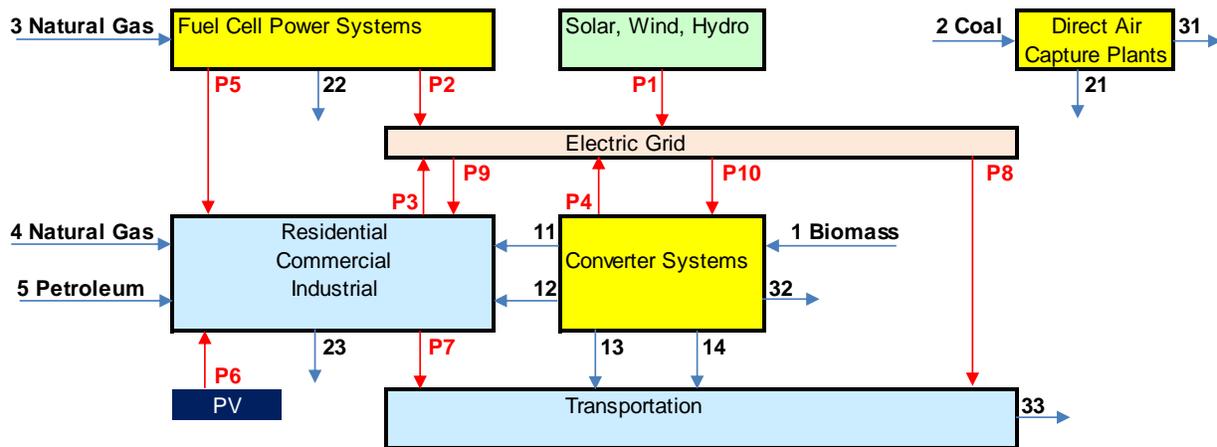
### Figure 2. Flowsheet 2060



### Table 14.1 Material Flows 2060

| Stream | Name | EJ | Other Units Value | Units |
|---|---|---|---|---|
| 1 | Biomass | 27.95 | 1654 | million tons |
| 2 | Coal | 17.34 | 864 | million tons |
| 3 | Natural Gas | 16.27 | 14.97 | trillion scf |
| 4 | Natural Gas | 3.80 | 3.50 | trillion scf |
| 5 | Petroleum | 3.70 | 605 | million bbl |
| 11 | Bio-Natural Gas | 2.50 | 2.30 | trillion scf |
| 12 | Propane | 1.00 | 10.3 | billion gal |
| 13 | Bio-Gasoline | 0.50 | 4.1 | billion gal |
| 14 | Bio-Kerosene | 11.50 | 85.4 | billion gal |
| 21 | Sequestered Fossil CO2 | | 1573 | million tonnes |
| 22 | Sequestered Fossil CO2 | | 821 | million tonnes |
| 23 | Sequestered Fossil CO2 | | 250 | million tonnes |
| 31 | Sequestered CO2 from Air | | 3174 | million tonnes |
| 32 | Sequestered CO2 from Air | | 1618 | million tonnes |
| 33 | Sequestered CO2 from Air | | 359 | million tonnes |
| | | | | |
| | Organic Fertilizer | | 61 | million tons |

**Table 14.2 Electricity 2060**

| Stream | Name | EJ | billion kWh |
|---|---|---|---|
| P1 | Solar, Wind, Hydro to Grid | **10.00** | **2778** |
| P2 | Natural Gas Fuel Cells to Grid | **5.39** | **1497** |
| P3 | User Facilities to Grid | **1.00** | **278** |
| P4 | Biomass Converters to Grid | **7.08** | **1967** |
| P5 | Natural Gas Fuel Cells to Users | **7.00** | **1944** |
| P6 | On-Site Solar | **3.50** | **972** |
| P7 | User Facilities to Transportation | **1.50** | **417** |
| P8 | Grid to Transportation | **1.90** | **528** |
| P9 | Grid to User Facilities | **17.40** | **4833** |
| P10 | Grid to Biomass Converters | **3.00** | **833** |
|  | Grid Losses | **1.17** | **325** |

## 14.2 Heating Values

Typical higher heating values of most of the fuels cited in this paper are listed below. Divide by 3.6 to obtain HHV in kWh.

**Table 14.3 Higher Heating Values**

|  | Higher Heating Value | |
|---|---|---|
|  | MJ | units |
| Hydrogen | **341** | mcf |
| Natural Gas | **1087** | mcf |
| Methanol | **68.3** | gallon |
| Ethanol | **89.2** | gallon |
| Propane | **93.4** | gallon |
| Bio-Gasoline | **122.1** | gallon |
| Gasoline | **127.0** | gallon |
| Bio-Kerosene | **134.6** | gallon |
| Jet Fuel | **142.3** | gallon |
| Diesel | **145.1** | gallon |
| Petroleum | **6120** | barrel |
| Dry Biomass | **16898** | ton |
| Steam Coal | **20076** | ton |

### 14.3 Carbon Dioxide Properties

Carbon dioxide is a solid (known as dry ice) below -57ºC, but this form will not be produced or used in the proposed strategy. At 0ºC, it is a gas at pressures below 35 bar (490 psig) and liquid above this pressure. Its critical point is 31ºC and 74 bar (1057 psig), above which it is a supercritical fluid (separate liquid phases do not exist above this temperature). At a refrigeration temperature of -23ºC (-9ºF), its vapor pressure is 18 bar (244 psig). At 0ºC, its liquid density is 93 percent of water.

The processes which isolate pure liquid CO$_2$ described in Chapters 4 and 6 use a combination of compression and refrigeration to condense the liquid from gas mixtures which have been previously been dried of water vapor. Storage and transport of CO$_2$ are described in Section 5.4.

# 15. Acknowledgements

# 16. Glossary, Abbreviations, and Conversions

| | |
|---|---|
| AC | Alternating current (60 Hertz in U.S.) |
| BNG | Bio-natural gas |
| BTU | British thermal unit (3414 BTU = 1 kWh) |
| capex | Capital expenditure (installed cost) |
| CCS | Carbon capture and sequestration |
| 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 Quads |
| 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 |
| 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) |
| LHV | Lower heating value, water vapor not condensed |
| LNG | Liquefied natural gas |
| mcf | Thousand standard cubic feet (scf) |
| MJ | Megajoule = $10^6$ Joules |
| MMBTU | Million BTU higher heating value |
| MW | Megawatt = 1000 kW |
| NCA | National Carbon Administration (proposed) |
| NGL | Natural gas liquids (chiefly ethane, propane, and butanes) |
| oxygenate | Compound of carbon, hydrogen, and oxygen (e.g., alcohols, esters) |
| PJ | Petajoule = $10^{15}$ Joules |
| PV | Photovoltaic (solar) |
| psig | pounds per square inch gage (above atmospheric) |
| Quad | Quadrillion BTU = $10^{15}$ BTU = 1.0544 EJ |
| Ref. | Reference |
| ROI | Return on Investment (annual) |
| scf | Standard cubic feet (cubic feet of gas at 1 atmosphere and 60ºF) |
| sequester | To permanently store underground |
| 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 |
| yr | Year |

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