# <u>United States Energy 2050</u>

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Fuel Cell Systems
Global Warming
Greenhouse Gases

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# Chapter One: Summary

This volume outlines recommendations for major transformations to energy production and use in the United States by 2050. The U.S. can affordably become energy independent and reach complete carbon neutrality.

Chapters following this provide many details and further explanations. The outstanding benefits described will result from the development and deployment of some cost-effective new technologies, which are firmly based upon known scientific and engineering principles. Although the Federal Government must play an essential role enabling zero net fossil $CO_2$ emissions, governmental energy subsidies will be eliminated.

## 1.1 Overview

Table 1.1 compares proposed key values with DOE figures (taken from Reference 1 as discussed in Chapter 2). All economic quantities in this report are nominal dollars (including expected inflation: 2050 prices are 1.78 times 2013 prices). Values are annual unless noted. Cells with zero values are shaded. Annual energy quantities are shown in exajoules (EJ) throughout this report (1 EJ =$10^{18}$ Joules = 1.054 Quads or quadrillion BTU). Prices per gigajoule (GJ) are given (1 GJ = 1.054 million BTU).

**Table 1.1 U.S. Energy Comparisons**

| | | DOE | | Proposed | Proposed |
|---|---|---|---|---|---|
| | | 2013 | Forecast 2050 | 2050 | Ratio |
| Purchased Energy | EJ | 75.04 | 82.64 | 41.32 | 50% |
| Average User Price | GJ | $18.18 | $45.38 | $68.08 | 150% |
| Energy Expenditures | billions | $1,364 | $3,750 | $2,813 | 75% |
| Energy/GDP | | 8.1% | 5.0% | 3.7% | 75% |
| Fossil CO2 Emissions | million tonnes | 5405 | 5584 | 0 | 0% |
| Net Imports | billions | $312 | $902 | $0 | 0% |
| Net Exports | billions | $0 | $0 | $1,170 | 0% |

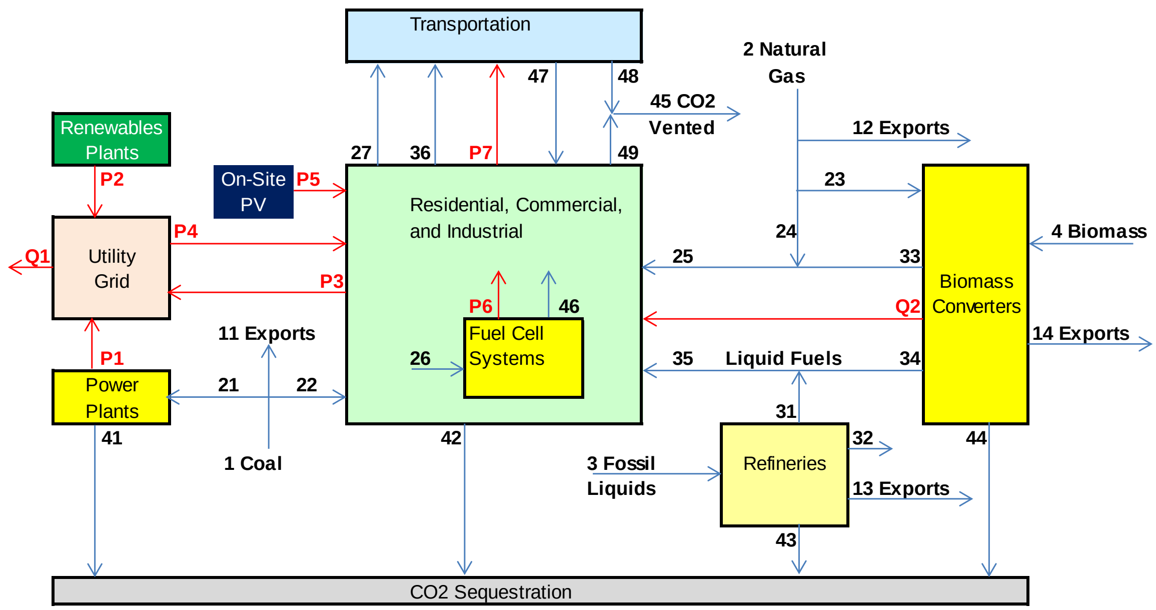
The DOE forecasts 2050 domestic energy use and fossil $CO_2$ emissions to rise due to population and economic growth. Energy expenditures as a share of GDP are expected to decrease due to efficiency improvements and to the GDP becoming less energy intensive. Energy imports are forecast to triple.

The proposed 2050 scenario (explained in this report) halves domestic energy consumption. Fossil $CO_2$ emissions are completely eliminated. Although user prices rise, energy expenditures are only three-fourths DOE forecast.

Annual economic benefits are outstanding. User energy cost savings total $937 billion. Trade balance improves $2072 billion. Forecast growth of permanent good jobs is 10 million.

Figure 1.1 is a simplified schematic of the proposed U.S. 2050 energy system, with annual energy quantities listed in Tables 1.2 and 1.3. Streams 41-49 are $CO_2$ streams discussed in Chapter 11, with annual quantities listed in Table 11.2.

## Figure 1.1 Proposed 2050 U.S. Energy Overview




## Table 1.2 Proposed 2050 Material Streams

| Material Stream | EJ | Quantity | Units |
|---|---|---|---|
| 1 Coal | 22.79 | 1125 | million tons |
| 2 Natural Gas | 25.84 | 23.86 | trillion scf |
| 3 Petroleum and NGL | 14.46 | 2384 | million bbl |
| 4 Biomass | 15.48 | 979 | million tons |
| 11 Coal Exports | 6.00 | 296 | million tons |
| 12 Natural Gas Exports | 7.00 | 6.46 | trillion scf |
| 13 Fossil Liquid Exports | 4.00 | 713 | million bbl |
| 14 Liquid Biofuel Exports | 8.00 | 1477 | million bbl |
| 21 Power Plant Coal | 16.25 | 802 | million tons |
| 22 Industrial Coal | 0.54 | 27 | million tons |
| 23 Converter Natural Gas | 9.50 | 8.77 | trillion scf |
| 24 User Fossil Natural Gas | 9.35 | 8.63 | trillion scf |
| 25 Comingled Natural Gas | 12.52 | 11.56 | trillion scf |
| 26 Fuel Cell Natural Gas | 8.88 | 8.20 | trillion scf |
| 27 Transportation Natural Gas | 2.66 | 2.46 | trillion scf |
| 31 Liquid Fossil Fuels | 6.67 | 1189 | million bbl |
| 32 Chemicals and Materials | 0.90 | | |
| 33 Bio-Natural Gas | 3.17 | 2.93 | trillion scf |
| 34 Bio-Liquid Fuels | 6.67 | 1230 | million bbl |
| 35 Comingled Liquid Fuels | 13.33 | 2418 | million bbl |
| 36 Transportation Liquid Fuels | 12.93 | 2346 | million bbl |

Stream 33 is bio-natural gas (BNG). Liquid biofuels 34 are premium quality hydrocarbons for transportation: gasoline, jet fuel, and diesel fuel. Fossil fuels 13 and 31 (from petroleum and natural gas liquids) are also liquid hydrocarbons (the same three plus propane). Stream 32 consists of asphalt and petrochemicals. Exports 14 include fuels, chemicals, and asphalt. Subsequent chapters discuss all processes and streams.

**Table 1.3 Proposed 2050 Energy Streams**

| | EJ | billion kWh | Ratio |
|---|---|---|---|
| P1 Power from Coal | 10.40 | 2889 | 50.0% |
| P2 Grid Renewables | 4.59 | 1275 | 22.1% |
| P3 Exports to Grid | 1.40 | 389 | 6.7% |
| Q1 Losses | 0.96 | 266 | 4.6% |
| P4 Grid Delivered | 15.43 | 4287 | 74.3% |
| P4-P3 Net from Grid | 14.03 | 3898 | 67.5% |
| P5 On-Site PV | 1.10 | 306 | 5.3% |
| DG Direct Use | 5.65 | 1569 | 27.2% |
| Usable Electricity | 20.78 | 5773 | 100.0% |
| P6 Fuel Cell Generation | 5.95 | 1653 | 28.6% |
| P7 Transportation Use | 1.04 | 289 | 5.0% |
| Q2 Converter Heat | 7.49 | 2081 | 36.0% |

## 1.2 Primary Energy

Table 1.4 gives a simplified summary of primary energy sources. NGL is natural gas liquids (mostly propane) condensed from natural gas wells. The difference between the last two columns is due to exports.

**Table 1.4 Primary Sources**

| EJ | DOE | | Proposed 2050 | |
|---|---|---|---|---|
| | 2013 | Forecast 2050 | Domestic | Total |
| Coal | 18.98 | 19.82 | 16.79 | 22.79 |
| Natural Gas | 28.36 | 33.95 | 14.53 | 25.84 |
| Petroleum and NGL | 37.85 | 37.85 | 9.46 | 14.46 |
| Renewables | 8.54 | 14.21 | 14.53 | 21.17 |
| Nuclear | 8.75 | 9.38 | 0 | 0 |
| Primary Sum | 102.48 | 115.21 | 55.30 | 84.26 |

Nuclear power has been retired by 2050. Total coal is 15% above DOE forecast, total natural gas is 76% of forecast, and petroleum plus NGL is 38% of forecast. Total renewables are 49% higher than DOE forecast (and 2.48 times 2013). Domestic primary fossil fuel use is 44% of DOE forecast.

**1.3 Delivered Domestic Energy**
Table 1.5 shows delivered energy by market sector and Table 1.6 details its product mix.

**Table 1.5 Energy Purchases by Market Sector**

| EJ | DOE | | Proposed | Proposed |
|---|---|---|---|---|
| | 2013 | Forecast 2050 | 2050 | DOE |
| Residential | 11.89 | 11.09 | 4.94 | 45% |
| Commercial | 9.13 | 11.39 | 4.94 | 43% |
| Industrial | 25.71 | 32.04 | 14.81 | 46% |
| Transportation | 28.32 | 28.12 | 16.63 | 59% |
| Total | 75.05 | 82.64 | 41.32 | 50% |

Expected percentage energy savings in transportation is slightly smaller than for the stationary sectors.

**Table 1.6 Delivered Energy Products**

| EJ | DOE | | Proposed | Proposed |
|---|---|---|---|---|
| | 2013 | Forecast 2050 | 2050 | DOE |
| Propane | 3.31 | 4.33 | 0.40 | 9% |
| Gasoline | 17.25 | 12.86 | 6.64 | 52% |
| Jet Fuel | 3.13 | 4.33 | 3.72 | 86% |
| Diesel | 8.54 | 9.71 | 2.57 | 26% |
| Other Petroleum | 5.36 | 6.46 | 0.90 | 14% |
| Natural Gas | 19.51 | 23.15 | 12.52 | 54% |
| Coal | 1.60 | 1.53 | 0.54 | 35% |
| Purchased Renewables | 3.06 | 3.22 | | |
| Grid Net | 13.29 | 17.03 | 14.03 | 82% |
| Total | 75.05 | 82.64 | 41.32 | 50% |

Delivered energy is also called purchased energy. On-site photovoltaic power P5 is excluded from Table 1.6. Propane and Other Petroleum are of fossil origin, while the other liquid fuels are about 52% biofuel and 48% fossil fuel. Purchased renewables have become zero since biomass has been redirected into stream 4 (Table 1.2) for conversion into biofuels. More details about the Table 1.6 proposed numbers are contained in chapters below.

**1.4 Proposed Energy Technologies**
In addition to many evolutionary improvements in energy efficiency, the following four new interrelated technologies are expected to play major roles in the proposed 2050 energy scenario.

**1.4.1 Biofuels**
The production of existing biofuels (chiefly ethanol and biodiesel esters) will be phased out, and replaced by considerably less expensive proposed new biofuels and processes. New types of converters will convert a wide variety of biomass wastes and perennial crops (including switchgrass and poplar trees) into bio-natural gas and liquid hydrocarbon biofuels: gasoline, jet fuel, and diesel fuel. The moderately-sized converters will be suitable for installation near biomass sources. Some will be co-fed with natural gas to boost biofuel yields. Each will capture all of their excess carbon as liquid $CO_2$ for permanent underground sequestration (see 1.4.4). The

converters and the use of their products will produce no fossil carbon emissions and in fact will sequester some of the carbon in their biomass feed, thereby offsetting emissions from fossil fuels. All the biofuels will be of premium quality (for example, the gasoline will be 99 octane and free from aromatics and sulfur). The biofuels will cost the same or less than their fossil counterparts. By 2050, these biofuels are projected to comprise half of domestic liquid fuels and about one fifth of natural gas delivered to users. Chapter 4 describes the proposed biofuels and their production.

### 1.4.2 Fuel Cell Systems

Advanced solid-oxide fuel cell systems will be extensively used for electric power generation and in many types of transportation. Unlike many present-day fuel cell systems, these will operate from carbonaceous fuels (including natural gas, gasoline, diesel fuel, and syngas from coal) rather than more expensive and less convenient hydrogen. Each fuel cell system will capture all carbon as liquid $CO_2$ for sequestration. The systems will be economical, highly efficient, non-polluting, and quiet. Chapter 5 describes fuel cell systems.

### 1.4.3 Electric Power Generation

In 2050, electric power will comprise a greater fraction of user energy consumption than at present. By 2050, nuclear power plants will have been phased out due to their higher costs and concerns about radioactive wastes and vulnerabilities. Renewable power (primarily solar, wind, hydro, and geothermal) will increase more than DOE forecasts. A large quantity of new generation capacity using advanced fuel cell systems with no $CO_2$ emissions will be installed. Some of this capacity will use coal, with the remainder being distributed cogeneration fueled by natural gas. Chapter 6 discusses the 2050 electric power proposals.

### 1.4.4 Carbon Dioxide Systems

Pure $CO_2$ will be affordably captured from biofuel converters and fuel cell systems (including those used in the new coal power plants and in transportation). It will be recovered as pressurized liquid for permanent underground sequestration. By 2050, net fossil $CO_2$ emissions in the U.S. are proposed to reach zero, bringing the U.S to carbon neutrality. Chapter 11 discusses carbon dioxide further.

## 1.5 Compelling Benefits

The proposed plan would create the following compelling benefits in 2050 over the base case forecast by DOE:

- User annual energy costs are reduced by $937 billion
- Zero net fossil $CO_2$ emissions are achieved
- Ten million net permanent jobs are created
- $900 billion in annual energy imports will be replaced by $1150 billion in exports
- Annual net profits will be increased by over $500 billion

## 1.6 Other Significant Benefits

The plan would also produce other significant benefits in 2050 (most are further discussed in later chapters):

- User convenience and performance would be enhanced. For example, stationary fuel cell systems will provide uninterruptible power to the entire facility. Transportation fuel cell systems will reduce fuel consumption and boost range.

- Cost-effective new greenhouses would grow fresher food for local sale.

- Air pollution (including $NO_x$, $SO_2$, mercury, particulates, CO, and organics) will be drastically reduced.

- Nuclear power plants would be shut down.

- Significant improvements on infrastructure would occur, including road networks, electric power grids, and pipeline networks.

- Government finances would be improved by eliminating energy subsidies. Higher profits and employment would enhance tax collections.

- Energy consumption is halved, slowing depletion of fossil fuel reserves.

# Chapter Two: Introduction

The recommendations presented in this document are based upon the present beliefs of the author, but are not necessarily claimed to originate from him. Extensive calculations were performed to obtain many of the numerical values listed. These calculations included detailed material and energy balances, thermodynamic, electrochemical, cost, and other types. Both novel and known equipment design concepts were assumed.

The following chapters summarize recommended major innovations to achieve the results cited in Chapter 1. The proposed 2050 case has been simplified for clarity. The forecast numbers are examples of what is believed possible and will undoubtedly differ (in many cases considerably) from actual results. The number of significant figures in forecast quantities was selected to facilitate comparisons with the Reference 1 values and to minimize rounding errors.

Section 14.3 discusses possibilities for the rest of the world. Section 14.4 discusses expectations after 2050. Appendix A3 is a glossary with conversions and abbreviations.

## 2.1 DOE Data and Forecasts

The Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) publishes an Annual Energy Outlook (AEO) with compiled U.S. energy data for recent years and forecasts for the future. The 2015 Outlook (Reference 1) includes their projections until 2040, with financial figures given in both constant 2013 dollars and nominal (with forecast inflation) dollars. The report cites annual energy quantities in Quads (one Quad is a quadrillion or $10^{15}$ BTU).

This document will use nominal dollars only and report national energy quantities in exajoules (EJ = $10^{18}$ Joules). One Quad is 1.054 exajoules. All energy quantities use higher heating value (see Glossary for its definition). $CO_2$ is customarily reported in tonnes (1 tonne = 1 metric ton = 1000 kg or 2204.5 pounds), while solid fuels and other pollutants are reported in the U.S in short tons.

The AEO includes a base line forecast (their Tables A1 through A21) which gives projections based upon existing laws and trends. Linear extrapolations of 2030 and 2040 values were used to obtain the DOE 2050 forecast values in this report.

Table 2.1 shows 2013 and forecast 2050 emissions. Fossil $CO_2$ emissions are from all energy-related sources, whereas the other values are from electric power generation only.

**Table 2.1 DOE U.S. Emissions**

| | | 2013 | 2050 |
|---|---|---|---|
| Fossil CO2 | million tonnes | 5405 | 5584 |
| SO2 | million tons | 3.27 | 1.62 |
| NOx | million tons | 1.69 | 1.58 |
| Mercury | tons | 27.94 | 6.39 |

Fossil $CO_2$ emissions contribute to global warming and are discussed in Chapter 11. $SO_2$ and $NO_x$ are primary causes of acid rain, smog, and some respiratory problems. Mercury in the air is extremely toxic. The vast majorities of the $SO_2$, $NO_x$, and mercury from electric power generation are emitted from conventional coal plants. All the Table 2.1 emissions are far higher than desirable.

## 2.2 Evolutionary Improvements

Between now and 2050 many evolutionary improvements in U.S. energy production, distribution, and utilization are expected. Some of these are implicit in the DOE forecasts, but significant additional improvements are also expected as summarized in this document. Additional evolutionary improvements which are not described are also expected.

### 2.2.1 Energy Utilization Efficiencies

It should be noted that energy efficiency is quite different from conservation. Efficiency means doing a job using less energy. Conservation means not using energy. For example, LED lighting is efficient, while turning off lights when no one is home is conservation.

Listed below are some of the emerging technologies which will gradually evolve and be implemented to yield major aggregate improvements in energy utilization efficiencies.

The largest energy use in residential and commercial buildings is for space heating and cooling (HVAC). Ongoing upgrades to insulation, windows, and doors will boost efficiencies in existing buildings. New construction will place increased emphasis upon thermal efficiency. Superior heat pump systems will replace much existing HVAC equipment.

Light-emitting diode (LED) lighting will gradually replace most lighting due to its superior efficiency and increasing cost-effectiveness. Additional savings will occur from more efficient timing and focusing of light sources.

Electricity use by refrigerators, clothes driers, entertainment systems, and ranges will decline as superior known technologies become more cost effective. A secondary benefit will be reduced HVAC cooling duty in warm weather.

Energy use in all types of transportation will be reduced by evolutionary improvements of many kinds, including weight reduction, improved aerodynamics, and the greatly increased use of hybrid drives with regenerative energy recovery (used today on the Toyota Prius and many other vehicles). Electric and plug-in hybrid vehicles will gain market share as their costs decline and plug-in options multiply.

### 2.2.2 Infrastructure

Major improvements to U.S. infrastructure are expected to be implemented by 2050, yielding multiple benefits and facilitating the other innovations described herein. Improvements will occur to roads, bridges, electricity transmission and distribution, and natural gas pipelines. Infrastructure improvements will enhance reliability and efficiencies. They will increase capacity where needed and serve new sources and customers. Improvements to the electrical grid are described in section 6.2.

# Chapter Three: Fossil Fuels

As shown in Figure 1.1 and Table 1.2, the proposed 2050 plan uses large quantities of fossil fuels for domestic applications and exports, all domestically sourced. Their continued use provides welcome sales revenues and profits for traditional energy enterprises. As shown in Table 1.4, total coal production increases, while natural gas and petroleum production both decrease. The proposed use of fossil fuels takes advantage of their affordable costs and large proven reserves. The new technologies described herein eliminate their key disadvantages of global warming and pollution. Fossil fuel use is expected to steadily decline after 2050 (see section 15.5). Fossil natural gas and fossil liquid fuels will be co-mingled with their biofuel counterparts in pipelines and distribution channels (except for propane, which will remain 100% fossil in 2050).

## 3.1 Coal

All coal mined in the U.S. in 2050 should be obtained in a responsible manner, with the environmental impacts of its mining held to an absolute minimum. Likewise, the processing, handling, and transport of this coal should also be performed responsibly. As described herein, all coal consumed in the U.S. should have 100% of its carbon captured and sequestered.

As Table 1.2 shows, 1125 million tons of coal in 2050 will be divided 296 million tons for export (stream 11), 802 for coal power plants (stream 21), and 27 for industrial uses (stream 22). Proposed 2050 domestic coal use is 85% of DOE forecast (Table 1.4).

While most of the coal will be mined in the West, the complete sulfur recovery by the new processes will also permit significant quantities of midwestern and Appalachian coals to be used.

Coal is proposed for use in advanced power plants (stream 21, Section 6.7) and new industrial processes (stream 22, Sections 9.4 and 9.5). None of these new systems will emit any pollution or $CO_2$ emissions.

## 3.2 Natural Gas

All natural gas wells in the U.S. in 2050 should be created and operated in a responsible manner, with minimized environmental impacts. Well gas is processed to remove sulfur (for sale) and to separate natural gas liquids (NGL) for sale at higher prices. In Figure 1.1, stream 25 consists of fossil natural gas comingled with bio-natural gas (stream 33). Natural gas pipelines will transport export gas 12, converter input 23, and user input gas 24. The export gas will be liquefied (to LNG, liquefied natural gas) at very cold temperature before shipment. Pipelines will use natural gas fuel cell systems (section 5.3) with $CO_2$ capture to power their compressors.

In Table 1.2 natural gas liquids are part of stream 3. The proposed 2050 total natural gas of 23.68 trillion scf will be divided 6.46 for export (stream 12), 8.77 for converters (stream 23), and 8.63 for users (stream 24). Proposed domestic natural gas use in 2050 is 43% of DOE forecast (Table 1.4).

**3.3 Petroleum and Refineries**

Petroleum (also called crude oil) and natural gas liquids will be fed to refineries (stream 3) to produce Chemicals and Materials (stream 31) and liquid fossil fuels (stream 32). Additional products (along with some petroleum) are exported (stream 13). All carbon consumed in the refineries will be captured for sequestration (stream 43). Table 1.2 gives stream quantities. Domestic petroleum and NGL use is 25% of 2050 DOE forecast (Table 1.4).

Refineries will produce four liquid fossil fuels (stream 31): propane, gasoline, jet fuel, and diesel. They will also produce (stream 32) materials (chiefly asphalt) and petrochemicals, plus liquid $CO_2$ (stream 43). All products except $CO_2$ will be sold both as exports (stream 13) and domestically. The great majority of petrochemical tonnage will consist of monomers for polymer manufacturing (ethylene, propylene, styrene, and many others).

Since total refinery output in 2050 will be lower than now, many refineries will be retired. The remainder will be extensively modified for carbon capture (all carbon oxidized for process energy will be captured as liquid $CO_2$: stream 43 in Figure 1.1 and Table 11.2) and will operate with essentially zero emissions of any kind. Propane will be produced from natural gas liquids. Crude will be processed similar to existing practice for gasoline, jet fuel, diesel, and heavy materials including asphalt, tars, and petroleum coke for graphite manufacturers. The liquid fuels will be much cleaner with much lower sulfur and carcinogens such as benzene.

New gasification systems will recycle heavy liquids and surplus lighter cuts to produce additional quantities of the target fuels. Clean synthesis gas (syngas) from these feeds will be catalytically reacted to produce the target hydrocarbon fuels, using the same types of reactors cited in section 4.2.2. Gasifier ash could be blended with asphalt. All sulfur contained in gasifier feeds will be captured and converted for sale into either sulfuric acid or pure liquid sulfur.

# Chapter Four: Biofuels

New types of converters are proposed which will convert domestic biomass to bio-natural gas (BNG) and bio-liquid paraffins (BLP). The BNG will be very similar in composition to conventional pipeline natural gas. The BLP will consist of premium-quality gasoline, jet fuel, and diesel: superior in nearly every way to their fossil counterparts. They will have cold weather properties to match requirements (some seasonal). Bio-gasoline will be 99 octane (chiefly isoparaffins), suitable for all engines. The bio-jet fuel and diesel will be blends of linear alkanes.

The proposed plan will discontinue the use of biomass to produce oxygenated fuels (such as ethanol or biodiesel esters) which are considerably more expensive to produce and have inferior properties. Most other low-value energy uses of biomass (e.g., combustion to heat steam boilers) will also be phased out in favor of producing high-value premium fuels. A small fraction of biomass wastes will continue to be directly recycled on farms to enhance soil physical structure and microorganism populations.

## 4.1 Biomass

The biofuel converters described in Section 4.2 could utilize any type of solid biomass feed (wastes and crops, herbaceous and woody). Feeds would be dried on site before conversion, using surplus heat from the converters.

Reference 2 describes in detail how the United States could sustainably and economically produce in 2030 a total of 1.37-1.63 billion tons (dry weight) per year of solid biomass without harming food production. If their cited increase APR is used for extrapolation to 2050, dry biomass production would be 2.06-2.77 billion tons.

A sizeable minority of this biomass is various wastes: municipal solids, agricultural, yard and garden, forest, sewage plant solids, food processing, animal manures, and other. Biomass wastes often have negative costs at their point of origin (i.e., waste generators will pay for proper disposal). A valuable new market for biomass wastes will have many other benefits. Odors from manures and other wastes can be greatly reduced. Additions of waste to landfills can be greatly reduced, while existing landfills can be responsibly mined for their buried biomass. The methane (which is over 20 times more potent for global warming than $CO_2$) released from buried biomass can be significantly reduced by burying much less biomass (see also section 4.3 on recycling nutrients).

A very large potential supply of solid biomass could be harvested from sustainable farms growing crops such as grasses and trees. The United States has the largest area of under-utilized potential farm land in the world with favorable climate (without the negative aspects of tropical rain forests). Many fast-growing perennial crops such as switchgrass and poplar trees are deep rooted and can thrive on natural rainfall. Application of organic fertilizers (section 4.3) from the converters described below can help sustain high yields. No-till farming is preferred to minimize burial of biomass (where it will emit more $CO_2$). If irrigation is desirable, buried drip systems can maximize water utilization by the plantings.

If biodiversity is practiced on farms growing energy crops, vulnerability to pests and diseases can be reduced while augmenting bird and animal habitats. Farms growing energy crops could practice desirable 12-month harvesting if hay were cut in warmer months and wood in the winter. Continuous harvesting would minimize biomass storage requirements and provide full-time employment.

The annual quantity of biomass assumed in the example herein (for both domestic and export biofuels production) is 960 million tons per year: well below the potential supply.

## 4.2 Biomass Converters

New types of converters are proposed which will convert solid biomass to BNG or BLP. Biomass will be gasified at elevated pressure (e.g., 10 bar) and temperature (e.g., 900ºC) to produce clean synthesis gas (syngas), which will immediately be catalytically converted at intermediate temperatures in multiple steps to the desired biofuel product. Biomass-to Gas (BTG) converters will produce BNG, and two converter types will produce BLP, namely BTL (biomass to liquids) and BNTL (biomass and natural gas to liquids). Each converter will be transportable by standard truck and (usually) installed at a site where biomass is produced. Examples of the three types are summarized in Table 4.1.

**Table 4.1 Proposed Biomass Converters**

| Type | | BTG | BTL | BNTL |
|---|---|---|---|---|
| Product HHV | kW | 1000 | 1000 | 1000 |
| Bio-natural gas | mcf/24 hr | 79.8 | | |
| Bio-jet fuel | gallons/24 hr | | 657 | 657 |
| Liquid CO2 | tonnes/24 hr | 6.24 | 6.07 | 2.96 |
| Organic Fertilizer | lbs/24 hr | 493 | 546 | 262 |
| Thermal Output | kW | 326 | 469 | 381 |
| Dry Biomass Feed | tons/24 hr | 6.68 | 7.40 | 3.55 |
| Natural Gas Feed | mcf/24 hr | | | 54.1 |
| Energy Efficiency | HHV | 76.5% | 69.1% | 72.9% |
| Installed Cost | million | $1.10 | $2.60 | $2.30 |

All will produce saleable liquid $CO_2$ (stream 44) and organic fertilizer co-products. The $CO_2$ from the BTG and BTL converters will contain 100% bio-carbon, whereas the BNTL converter will output liquid $CO_2$ with all fossil carbon. The converters also produce considerable heat usable for greenhouse heating (section 4.4) and other uses. These converters will require no water or electric power input and generate no wastes and little noise. Each site might have a single or multiple converters (of the same of different types). Small farms might jointly own and/or operate a converter. Chapter 12 discusses $CO_2$ storage and transport. Table 4.1 uses jet fuel as the example liquid.

The listed energy efficiencies include drying of feeds with typical moisture contents. Automated operation will permit 24/7 production with labor needed only on the day shift (for solids handling, maintenance, and product quality monitoring). Expected operating margins will provide attractive returns on installed cost.

Deluxe-model converters could also generate additional electric power from biomass (at lower cost than alternatives) for farm uses and sale. Such power is not included in the cited example case.

### 4.2.1 Biomass-to-Gas (BTG) Converters

These converters will convert biomass waste into compressed bio-natural gas (BNG), consisting primarily of methane, with small percentages of ethane, nitrogen, and bio-$CO_2$. The product will be virtually identical to fossil pipeline natural gas, with a few parts per million odorant added for safety. The converters will be directly connected to a gas pipeline network, where their BNG product will be co-mingled with fossil natural gas.

Most of these converters will be installed at sites where biomass wastes are produced or collected, including farms, food processing plants, sewage treatment plants, and forest product plants. Their continuous operation will minimize odors and other negatives. Total feed costs to the converters will often be close to zero (or even negative). The utilization of most farm wastes for biofuels production will reduce methane (a very potent greenhouse gas) emissions from burying wastes below soil.

BTG converters will convert about 42% of feed carbon into BNG, with virtually all remaining carbon converted into liquid bio-$CO_2$ for sequestration.

BTG converters will have a lower installed cost and lower feed cost versus the liquid converters below. They are expected to be commercialized sooner than converters producing liquids, due to their greater simplicity. On the minus side, BNG will sell for lower prices than liquid biofuels.

### 4.2.2 Biomass-to-Liquid (BTL) Converters

BTL converters will use dried biomass (usually crops, but available wastes may be blended in the feed) to produce a selected liquid biofuel (BLP): gasoline, or jet fuel/diesel. All products will consist entirely of paraffin hydrocarbons (alkanes), with no aromatics, olefins, or sulfur. All will exhibit zero gum formation and superior storage properties. Their sole disadvantage will be a slightly lower density per gallon versus fossil equivalents. For domestic use, they will usually be co-mingled with fossil fuels.

The proposed biogasoline will be super-premium, 99-octane, consisting chiefly of isooctane (2,2,4-trimethyl pentane) with sufficient isobutylene added to produce the desired seasonal volatility for engine starting (Reid Vapor Pressure, RVP).

The other liquid converter type will produce mixed linear alkanes, with average molecular weights controlled to produce either jet fuel (lighter) or diesel (heavier). The desired product could be changed whenever desired via keyboard input.

A BTL output with higher heating value of 1000 kW will yield 708 gallons of bio-gasoline, 657 gallons of jet fuel, or 642 gallons of diesel per 24 hours. Each converter will be dedicated to produce either bio-gasoline or the heavier fuels (jet fuel or diesel could be selected each day via keyboard input).

BTL converters will convert about 48% of feed carbon into BLP, with virtually all remaining carbon converted into liquid bio-$CO_2$ for sequestration.

This type of BLP converter will be required where no suitable natural gas pipeline service is available. It will produce less profit per ton of biomass, but at greater margin.

### 4.2.3 Biomass and Natural Gas to Liquid (BNTL) Converters

These converters are fed both biomass and natural gas to maximize biofuel production. All carbon in the biomass is converted to liquid biofuel while all the carbon in the natural gas is captured for sale and sequestration. As with BTL converters, two models will be available to produce either biogasoline or jet fuel/diesel.

This converter will have higher feed costs and sales revenues than a BTL converter.

## 4.3 Organic Solid Fertilizers

A valuable byproduct from biomass converters is a dry solid organic fertilizer, which contains all the phosphorus, potassium, sulfur, and trace elements present in the biomass feed. This fertilizer is expected to be essentially odorless (unlike most other organic fertilizers). A typical dry feed will yield about 3.7 weight percent fertilizer. All the valuable nutrients in the fertilizer can be recycled to fields and woodlots where biomass crops are grown.

Some converter operators may choose to operate their units at less than 100% biomass carbon gasification, resulting in the fertilizer also containing bio-char. Such chars have very high surface area and have been reported to persistently improve soil properties.

The sole major nutrient not present in the fertilizer is nitrogen, which is converted into harmless (and useless) $N_2$ gas and vented by the converters. Section 9.6 describes a proposed process for making organic liquid ammonia from biomass, with capture of all carbon in the biomass for sale and sequestration. This ammonia could be applied to farms separately, reacted with the solid fertilizer to form solid nitrogen compounds including ammonium phosphate, or converted into a slow-release nitrogen solid fertilizer.

Organic fertilizers have been gaining in market desirability. The types proposed here are more convenient and concentrated than existing alternatives, making their storage and handling more attractive. They will be less susceptible to runoff during rain events compared with chemical fertilizers and will not produce methane when buried. Most will also be nearly odorless.

## 4.4 Greenhouses

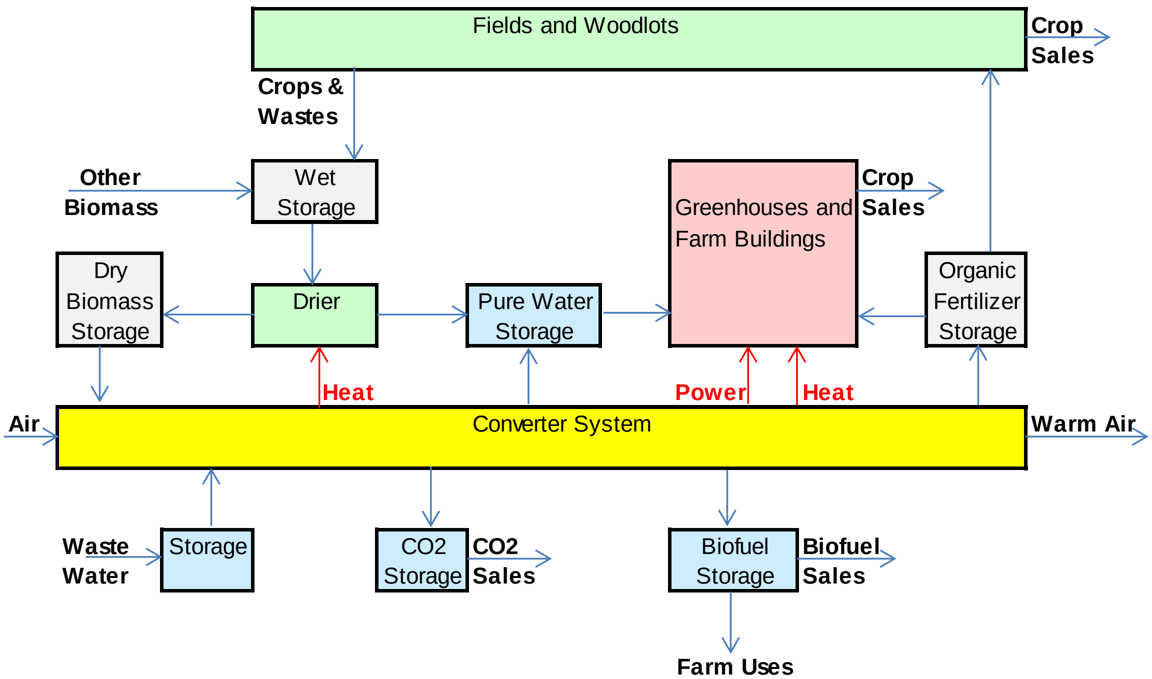
The large usable surplus heat from each converter can be used to heat adjacent greenhouses producing fresh local produce and flowers up to 12 months per year. The above organic fertilizers could be applied in many cases. The converters could supply still more heat in very cold weather while producing slightly less biofuel. In warmer weather, additional biofuel would be made to achieve the annual average of 1000 kW biofuel HHV. Each acre of well-designed greenhouse might have a 2050 capex of $800,000, employ four people, and utilize 220 kW of the Table 4.1 thermal output at design cold-weather conditions. The majority of the installed converters are expected to add greenhouses and hence many additional jobs as listed in section 13.4.

Potential future greenhouse enhancements (not assumed in calculations) might include bio-$CO_2$ addition from BNG or BLP converters and/or the use of blue and red LED supplemental lighting.

## 4.5 Example Farm in 2050

Figure 4.1 shows the principal material and energy flows on a 2050 farm with one or more biomass converters.

**Figure 4.1 Example Farm**




## 4.6 Exports

The United States is highly advantaged over most countries in its potential biomass supply without harming food production (Reference 2). Large exports of biofuels forecast will create many additional domestic jobs, major economic benefits, and environmental improvements for the entire planet. Biofuel exports are expected to increase further after 2050.

## 4.7 Quantities in 2050

Table 1.2 lists quantities of biofuels converter feeds and products (a barrel is 42 gallons). U.S liquid biofuels consumption is proposed to consist of 28.1 billion gallons bio-gasoline, 14.6 billion gallons bio-jet fuel, and 9.8 billion gallons bio-hydrocarbon diesel (not to be confused with present-day biodiesel esters).

Based upon the converter sizes in Table 4.1, the number of installed converters will total about 565,000 (100,000 BNG, 22,000 BLP, and 443,000 BNLP). Associated greenhouses will total about 660,000 acres (about 1030 square miles).

The 979 million tons of biomass shown in Table 1.2 would contain about 7.2 million tons of nitrogen (using an assumed average biomass composition), equivalent to 8.8 million tons ammonia. The example ammonia production in section 9.6 is 20 million tons per year, which would approximate that needed for biomass crops, food production, and other uses.

The assumed biomass used for biofuels (including exports) and bio-ammonia production in 2050 (979 million tons) is less than half the possible supply cited in section 4.1.

**4.8 Comparison with Alternatives**

The proposed gasifier-based converters will convert biomass feed to biofuel product in minutes, with carbon recovery very close to 100% (including bio-char if this co-product is desired) and excellent energy efficiencies. Biological fermentation processes need days and anaerobic digesters need weeks to produce inferior biofuels at lower yields and efficiencies and higher costs. Intermediate-temperature pyrolysis routes also are slower, more costly, and yield less-desirable products.

Landfill gas (rich in methane) can be used as an interim biofuel before 2050. However, most landfills should become virtually free of biomass by 2050 as new biomass is redirected as described above and old biomass is either mined or ceases to emit gas.

The hydrocarbon molecules in the biofuel products will be fully saturated and thus stable in long-term storage. The liquid fuels will contain no oxygenates and thus have excellent energy per unit volume and weight (ethanol has about two-thirds the energy per gallon as gasoline). The fuels will be non-corrosive (unlike alcohols).

# Chapter Five: Fuel Cell Systems

## 5.1 Introduction

A fuel cell is a device which produces DC electric power by an electrochemical reaction between a fuel and an oxidizer (usually air). Since an individual cell produces less than one volt, cells are stacked to obtain desired much higher voltages. Fuel cells are silent and the systems incorporating them are usually substantially quieter than combustion engines with mufflers. Fuel cell systems have the potential for fuel-to-power conversion efficiencies considerably higher than engine systems. They also have the potential to offer superior cost effectiveness for a wide variety of applications. Capacities can range from Watts to multiple megawatts. Stack DC power can be efficiently inverted (using solid-state electronic circuits) to produce AC with any desired specifications.

Although fuel cells can directly use hydrogen as a fuel, carbonaceous fuels are considerably more practical and less expensive. The fuels recommended for the proposed future fuel cell systems are the following (all contain carbon):

1. Natural Gas
2. Propane
3. Gasoline
4. Jet Fuel
5. Diesel Fuel
6. Clean Gasifier Syngas

The first five fuels, all hydrocarbons, are reformed into clean syngas using a reformer.

The recommended fuel cells are solid oxide type. These cells utilize ceramic solid electrolytes and operate at high temperatures (typically near 900ºC). They have the potential for excellent efficiency and reliability combined with long life and low maintenance costs. Their high-grade surplus heat facilitates cogeneration systems with very high energy efficiencies (see 5.2). They can operate directly on clean syngas from a reformer or gasifier, with no need for carbon monoxide shifting or removal. Solid-oxide fuel cell systems are herein envisioned with power outputs from one kilowatt to three megawatts. Multiple systems could be connected in parallel for any desired larger capacity.

All of the proposed fuel cell systems described below will include $CO_2$ capture for sequestration (CCS) except the military and standby systems (sections 5.5 and 5.6).

## 5.2 Natural Gas Cogeneration Systems

Natural gas fuel cell cogeneration systems with capacities from one to 100 kW will be installed at many residential and smaller commercial and industrial sites. They will supply all or most of the AC power needs of the site, with any surplus power sold to the utility grid whenever pricing is favorable. They will provide uninterruptible power during grid outages of any duration. They will be capable of idling when grid selling prices are lower than generation variable costs. The systems will include an interface for connecting optional photovoltaic arrays to reduce fuel consumption.

These fuel cell systems will perform cogeneration (also called combined heat and power or CHP), with high-grade surplus heat available for absorption heat pumps (for space cooling and heating, section 7.3) and additional usable heat for water and space heating. Their expected energy efficiencies (higher heating value basis) are as follows:

AC Power: 58%
Absorption Heat Pump Input: 23%
Total Usable Heat: 41%
Total Usable Energy: 99%

They will produce salable liquid $CO_2$ byproduct for sequestration at the rate of 309 g/kWh AC output. Planned system modules will have rated power outputs of 1, 3, 10, 30, and 100 kW. Any combination of modules may be connected together (ganged) for higher capacity and redundancy. Available 60 Hertz AC voltages will include 120/240, 208Y/120, and 480Y/277. Built-in battery subsystems will provide surge power during grid outages. These systems will require no input water for cooling or other uses. They produce a pure water byproduct at 245 g/kWh AC output.

## 5.3 Turbocharged Stationary Systems

Natural gas turbocharged fuel cell systems for larger commercial and industrial sites will be offered with capacities from 100 to 3000 kW. They will exhibit AC efficiencies of 72-75% (higher at larger capacities), with less available cogeneration heat (maximum energy efficiency will also be 99%). Planned module sizes are 100, 300, 1000, and 3000 kW. Multiple modules may be ganged to deliver larger outputs. These systems also require no input or cooling water. Their typical byproduct rates are 249 g $CO_2$ and 197 g water per AC kWh.

## 5.4 Transportation Systems

Fuel cell systems for transportation will be offered in capacities from 10 to 3000 kW, with a greater variety of capacities than the above systems. Most systems of 100 kW and larger will be turbocharged. Suitable fuels will include compressed natural gas (CNG), gasoline, jet fuel, and diesel. They will be hybridized with battery systems to provide significant surge power for attractive durations. They will capture all their $CO_2$ as liquid for sale at filling stations (except for systems installed in aircraft).

Applications will include light-duty vehicles (cars, SUVs, minivans, pickup trucks), two-wheeled vehicles, commercial trucks of all sizes, buses, rail, ships, and auxiliary power units (APUs) for aircraft. Most locomotives and ships will employ multiple 3000 kW modules. Projected fuel economy for light duty vehicles (without plug-in battery charging) is 100 miles/gallon gasoline. Projected average fuel economy for freight trucks is 29 miles/gallon diesel. Both of these ratios are far higher than DOE forecasts (see also Section 13.5). Chapter 10 further describes the proposed transportation fuel cell systems.

## 5.5 Military Generators

Small transportable fuel cell systems will operate on military liquid hydrocarbon fuel (JP-8, a modified jet fuel). Capacities will range from 1 kW to 100 kW. Most will not capture $CO_2$ (their collective fuel usage is small). Average AC efficiency is projected to be 58%: far above existing engine generators. They will be extremely quiet and odorless. These generators will also be capable of operating with vegetable oil as fuel: an advantage in some locales.

**5.6 Fuel Cell Standby Generator Systems**

Many residences and businesses without natural gas service will wish to install standby fuel cell systems for uninterruptible power. These systems will use their integral battery systems to power loads until the fuel cell system can warm up (about 30 minutes from cold). Standby generators will be capable of operation on propane, heating oil (diesel), or other clean liquids. They will be available in sizes from 1 to 100 kW and could be ganged for larger capacities.

**5.7 Coal Power Plants**

The advanced coal power plants described in section 6.7 will use fuel cell subsystems producing 3000 kW each and operating at 30 bar pressure. Their fuel will be clean syngas from the associated gasifier system. Downstream equipment will capture all their $CO_2$ for sequestration.

**5.8 Related Systems**

Petroleum refineries and biofuels converters will generate site power needs from integrated fuel cell systems operating on syngas or recycled hydrocarbon streams.

If extra 100% hydrogen is needed, solid-oxide stacks similar to fuel cell stacks can be fed syngas on the fuel side and steam on the oxidizer side to convert the steam into hydrogen. Some DC power input (from adjacent fuel cells) will be required.

Sealed reversible high-pressure hydrogen-oxygen electrochemical systems called "water batteries" could be used for electrical energy storage (see Section 12.5).

Solid-oxide electrolyzers would use electric power (from the grid or distributed generation) to perform electrolysis at temperatures near 900ºC and elevated pressures. Possible uses for solid oxide electrolyzers include the following:

- $H_2$ and $O_2$ from steam
- Syngas (for subsequent hydrocarbon synthesis) from $CO_2$ and steam
- Pure sulfur and $O_2$ from $SO_2$

Solid-oxide electrolyzers could have energy efficiencies up to 98% HHV.

**5.9 Quantities in 2050**

Proposed total installed fuel cell capacity is 3360 GW, comprised of 61.4 million individual installations (average capacity 55 kW each). Fuel cell systems and subsystems will be utilized in transportation (72% of the 3360 GW), coal power plants (14%), and in numerous other stationary applications. Fuel cell vehicles are expected to travel 20% of the annual miles of light-duty vehicles, 65% of light truck miles, and 75% of freight truck miles. The light-duty vehicles will use gasoline in their fuel cells, while the trucks will use diesel. Fuel-cell APUs in aircraft will use jet fuel.

# Chapter Six: Electric Power

Table 6.1 summarizes key numbers for electric power. DG is distributed generation (from all sources), NG is natural gas, and T&D means transmission and distribution (electric power grid). CF is average capacity factor. The DOE numbers are from Ref. 1, with extrapolations to 2050. 1.0 exajoule (EJ) = 278 billion kWh. 1 gigawatt (GW) = one million kW or 1000 megawatts. Streams with labels P1 through P5 refer to Figure 1.1.

**Table 6.1 U.S. Electric Power**

| | DOE | | Proposed | Proposed | |
|---|---|---|---|---|---|
| **Energy EJ/yr** | **2013** | **Forecast 2050** | **2050** | **Ratio** | |
| Power from Coal P1 | 5.66 | 6.04 | 10.40 | 1.72 | |
| Renewables on Grid P2 | 1.67 | 3.82 | 4.59 | 1.20 | |
| DG Sales to Grid P3 | 0.14 | 0.24 | 1.40 | 5.83 | |
| Natural Gas | 3.67 | 5.24 | | | |
| Nuclear | 2.77 | 3.09 | | | |
| Other | 0.41 | (0.29) | | | |
| Grid Inputs | 14.32 | 18.14 | 16.39 | 90% | |
| T&D Losses | 1.03 | 1.11 | 0.96 | 86% | |
| Grid Delivered P4 | 13.29 | 17.03 | 15.43 | 91% | |
| Net Delivered P4-P3 | 13.15 | 16.79 | 14.03 | 84% | |
| Non-Marketed PV P5 | 0.09 | 0.83 | 1.10 | 1.33 | |
| DG Direct Use | 0.48 | 1.44 | 5.65 | 3.92 | |
| Total Use | 13.86 | 19.30 | 22.18 | 1.15 | |
| Losses/Delivered | 7.8% | 6.5% | 6.2% | 95% | |
| **Capacity GW** | | | | | **CF** |
| Coal Plants | 305 | 257 | 471 | 1.83 | 70% |
| NG Combined Cycle | 214 | 354 | | | |
| NG Gas Turbine | 160 | 224 | | | |
| NG Steam | 96 | 64 | | | |
| Renewables on Grid | 155 | 264 | 455 | 1.72 | 32% |
| Nuclear | 99 | 108 | | | |
| Total | 1029 | 1271 | 790 | 62% | |

The proposed case differs considerably from the DOE forecast. Total electrical energy use is 15% higher due primarily to advanced heat pump systems (Chapter 7). Power delivered from the grid is 9% lower due to much greater on-site distributed generation and non-marketed PV installations P5.

All electric power in the proposed case emits no $CO_2$, since complete carbon capture is used with all fueled generation systems (coal and natural gas distributed generation systems). Harmful pollutants (Table 2.1), sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), and mercury (Hg) from power generation are completely eliminated.

Coal power capacity is increased 83% using new technology described in 6.7. Renewable capacity is increased 72%, from added solar and wind (section 6.3). Existing natural gas utility generation is retired, due to its higher costs (versus the new coal technology) and its inability to economically capture carbon. Nuclear plants are retired due to higher costs and concerns about radioactive wastes and multiple vulnerabilities. An increased share of grid power is obtained from distributed generation (section 6.4).

The proposed 2050 inputs to the grid consist of about 63% from coal, 28% from renewables, and 9% from distributed generation sales. The assumed average capacity factor for coal plants declines from 74.5% (DOE case) to 70% due to the elimination of utility natural gas units.

Sections 13.1 and 13.6 discuss proposed 2050 grid power prices and costs.

## 6.1 Electric Power Use 2050

The 19.30 EJ total electric power use in the DOE 2050 column is 23% of the corresponding purchased energy (82.64 EJ) in Table 1.1. The proposed total power use of 22.18 EJ is 54% of purchased energy (41.32 EJ). The increased use of electric power in the proposed case is primarily due to the substitution of highly efficient electric heat pumps for most furnaces, boilers, and water heaters. Other factors include greater use of plug-in vehicles, large improvements in transportation fuel efficiency, and significant changes in industrial energy use. Chapters 7 through 10 describe some of the expected new equipment and changes.

## 6.2 Electric Power Grid

By 2050, the grid which performs electric power transmission and distribution will have been significantly upgraded and modernized. Reliability will be greater due to replacement of outdated equipment and greater use of buried lines (facilitated by more cost effective advanced tunneling machines). Smart meters for nearly all users will enable time-of-use (TOU) pricing, user sales to the grid, and micro-grid implementation to reduce the number of users affected during some outages.

However, in spite of reliability improvements, grid power will remain vulnerable to outages. Grid availability to individual customers is expected to average between 99.0% and 99.9% (over a multi-year period) and thus many users without natural gas fuel cell systems will install fuel cell standby systems as described in section 5.6.

Grid power pricing will continue to be lower for larger users, but will have differences from today. Each user will pay fixed monthly charges based primarily upon peak use. Variable pricing will be lower for user sales to the grid than for purchases (to properly reflect avoided costs). Power prices will vary hourly based upon supply and demand, allowing users with distributed generation to choose to buy, sell, or load-follow their site requirement.

### 6.3 Renewable Power

Table 6.2 compares DOE totals with the proposed plan.

**Table 6.2 Renewable Grid Power**

| | | DOE | | Proposed | Proposed |
|---|---|---|---|---|---|
| | | 2013 | Forecast 2050 | 2050 | Ratio |
| Wind | EJ | 0.60 | 1.42 | 2.13 | 1.50 |
| Solar | EJ | 0.07 | 0.54 | 1.07 | 2.00 |
| Hydro | EJ | 0.96 | 1.08 | 1.08 | 1.00 |
| Biomass | EJ | 0.21 | 0.48 | | |
| Geothermal | EJ | 0.06 | 0.31 | 0.31 | 1.00 |
| Total | EJ | 1.91 | 3.82 | 4.59 | 1.20 |
| Wind | CF | 32% | 34% | 34% | |
| Solar | CF | 17% | 21% | 21% | |
| Hydro | CF | 39% | 42% | 42% | |
| Biomass | CF | 55% | 87% | | |
| Geothermal | CF | 72% | 88% | 88% | |
| Total | CF | 36% | 37% | 32% | |
| Wind | GW | 61 | 132 | 198 | |
| Solar | GW | 13 | 82 | 164 | |
| Hydro | GW | 79 | 81 | 81 | |
| Biomass | GW | 12 | 17 | | |
| Geothermal | GW | 3 | 11 | 11 | |
| Total | GW | 167 | 324 | 455 | |

Total renewable power to the grid (P2 in Figure 1.1 and Table 1.2) is forecast to increase 20% above the DOE forecast due to considerably greater use of wind and solar power. The increases will result from more favorable economics (resulting from higher production and advances not assumed the DOE forecasts) in spite of the expected ending of governmental subsidies. Further increases will be constrained by the attractive cost of new coal power (see section 13.6). No grid power will be generated from biomass, since it will all be used for biofuel converters (chapter 4). The Hydro category includes power from emerging technologies which generate power from waves, tides, or water temperature differences.

On-site renewable solar photovoltaic power P5 of 1.10 EJ is not included in P2 and Table 6.2, but is included in Table 6.1.

### 6.4 Distibuted Generation

As Table 6.1 shows, distributed generation yields 5.65 EJ of electric power for direct use and sells another 1.40 EJ to the grid. This DG power is generated by the natural gas fuel cell systems at residential, commercial, and industrial sites.

### 6.5 Coal Power Plants

Section 6.7 describes the proposed new coal power plants. Advanced, zero-emission power plants using coal are forecast to generate about 63% of grid electric power in 2050, due to their having the lowest total cost of electricity under most conditions.

The United States contains huge reserves of accessible coal: sufficient to sustain the projected 2050 rates of domestic consumption and exports for more than 200 years. The proposed new power plants could use any type of coal or lignite (high or low sulfur) from mines anywhere in the U.S. For calculation purposes, the Reference 1 average higher heating value of 19.21 million BTU per ton for steam coal was used for the new plants. Enforcement of existing (and enactment of new) mining laws can minimize environmental damage from mining operations.

## 6.6 Coal Plants Today

As Table 6.1 shows, coal plants generated about 40% of U.S. grid power in 2013: more than from any other source. Existing coal plants range from very old to new (average age about 50 years). None yet have $CO_2$ capture and all emit copious air pollution. $CO_2$ emissions from coal power plants in 2013 were 1.58 billion tonnes and are forecast to reach 1.65 billion tonnes in 2050 (Ref. 1). Nearly all the $SO_2$, $NO_x$, and mercury emissions listed in Table 2.1 are from coal plants. There is no affordable way to modify existing coal plants to produce very low pollution or to capture $CO_2$.

Although the energy efficiency of existing coal plants is rather low (about 30-38% higher heating value, with the world's best about 44%), their total cost of electricity is usually lower than all current alternatives due to their very low fuel cost (and in many cases also because their capital cost has been paid off). Existing plants consume significant quantities of water, which has led to operating difficulties at some plants during droughts.

Due to the combination of future regulatory uncertainty, rising coal plant capital costs, and low natural gas prices, no new conventional coal plants are being initiated today in the U.S. Coal plant capacity was 305 GW in 2013 and is forecast by DOE to fall to 257 GW by 2050. Assumed improvements in average capacity factors lead to the higher 2050 forecast DOE annual energy output P1 of 6.04 EJ shown in Table 6.1. Although most of today's major coal plants have capacities of 500 MW and larger, roughly 1500 plants were thought to be in service in 2013, making their average size about 200 MW.

## 6.7 Proposed Coal Power Plants

The proposed new coal plants would each consist of hundreds of 3 MW complete modules operating in parallel. Each module would include an oxygen system, gasifier system, fuel cell system (section 5.3), $CO_2$ system (chapter 11), turbines, compressors, heat exchangers, power conditioning, controls, and auxiliary subsystems. The modules will be manufactured and tested in factories and transported to the site on standard trucks.

The proposed 2050 energy scenario assumes retirement of all existing coal generation equipment while substituting the described new technology. The new plants would have a combined capacity of 471 GW (1.83 times the 257 GW shown in Table 6.1) and would output 72% more electric energy than the DOE forecast, but consume only 86% as much coal due to their doubled net efficiency. The plants will have zero emissions of $SO_2$, $NO_x$, and mercury, with 99.9% of their $CO_2$ captured and sequestered.

Preferred sites for the new plants will allow cost-effective $CO_2$ pipelines to be installed to sequestration sites (some sites may require rail transport of $CO_2$). In many cases, existing coal plant sites can be converted to the new technology. New sites will require no water supply, which will widen location possibilities (more mine-mouth sites may be practical).

New plant capacities are expected to range from 300 to over 1000 MW each. If their average capacity were 1000 MW, 471 new plants would be needed to total 471 GW. They would employ a large quantity of identical complete 3 MW modules, enabling extremely high plant availability, ease of load following, and convenient capacity growth. Projected installed capital cost in 2050 (nominal dollars) is $2300 per kW or $6.9 million per 3 MW module. The required total production of 157,000 modules would lead to excellent economies of factory mass production (unlike existing coal plants which are generally of unique designs and require extensive on-site construction work). Expected coal to AC power efficiency is 64% higher heating value: approximately double today's dirty coal plants. All of the sulfur in the coal will be converted to sulfuric acid or pure sulfur for sale. All of the ash in the coal will be processed for sale to the construction industry. The plant will generate no liquid or solid wastes.

The total cost of electricity from the new coal plants, including fuel, capital, $CO_2$ transport and sequestration, and maintenance is projected to be lower than competing sources (section 13.6). The modules could also be designed to use lignite instead of coal, with very similar expected efficiency.

## 6.8 Coal Power Alternatives

Reference 3 provides a detailed analysis of five selected coal plant alternatives, with and without carbon capture and sequestration (CCS). Key values from Ref. 3 and calculations from these values are shown below, together the technology proposed above.

**Table 6.3 Future Coal Plant Alternatives**

| | | Supercritical PC | | Oxy-PC | IGCC | | Proposed |
|---|---|---|---|---|---|---|---|
| | | no CCS | CCS | CCS | no CCS | CCS | |
| CO2 Capture | | | 90% | 90% | | 90% | 100% |
| CO2 Produced | g/kWh | 828 | 1088 | 1042 | 830 | 1022 | 498 |
| CO2 Emissions | g/kWh | 828 | 109 | 104 | 830 | 102 | 0.50 |
| Emissions Ratio | | 1662 | 218 | 209 | 1667 | 205 | 1.0 |
| Capex 2007 | $/kW | 1330 | 2140 | 1900 | 1430 | 1890 | 980 |
| Capex 2035 | $/kW | 2316 | 3726 | 3308 | 2490 | 3291 | 1706 |
| Capex 2050 | $/kW | 3116 | 5014 | 4452 | 3351 | 4429 | 2296 |
| Capex Ratio | | 1.36 | 2.18 | 1.94 | 1.46 | 1.93 | 1.00 |
| Efficiency | HHV | 38.5% | 29.3% | 30.6% | 38.4% | 31.2% | 64.0% |
| Fuel Use Ratio | | 1.66 | 2.18 | 2.09 | 1.67 | 2.05 | 1.00 |

Supercritical pulverized coal (PC) plants use steam pressures above 3400 psi. Oxy-PC and IGCC plants use oxygen from an air liquefaction plant. IGCC stands for integrated gasification combined cycle with both a gas and steam turbine. The Proposed column refers to plants summarized in section 6.7 above. An assumed inflation rate of 2.0% per year was used to adjust installed capital costs (capex). The example fuel is Illinois No. 6 bituminous coal. The capex estimates in Table 6.3 assume each technology has matured and is being replicated in quantity. The five alternatives in Ref. 3 are based upon proven technology and are now being built or seriously considered. Worldwide spending on coal CCS plants is currently several billion dollars per year. However, the proposed new technology will have compelling advantages in capex, efficiency, and $CO_2$ emissions. They will also have negligible $SO_2$ and $NO_x$ emissions.

**6.9 Other Power Generation Technologies**

Large turbocharged natural gas fuel cell systems of the type summarized in 5.3 could be operated in a stand-alone mode, connected to the grid. However, their economics will be improved by installing them at commercial and industrial sites where their surplus heat can be at least partially utilized and where they can provide uninterruptible power (as shown in figure 1.1 and table 1.3).

Numerous development programs are underway with the ultimate goal of generating cost-effective electric power using thermonuclear reactions (nuclear fusion). All face extremely large engineering challenges. No contribution from this technology is forecast by 2050 in this document. However, it may begin to contribute after 2050.

Although thermoelectric systems are used in small specialized applications today, they are not expected to become cost effective for large-scale generation by 2050.

Still other technologies for electric power generation are being explored today and additional ideas will emerge in the coming years. It is considered quite unlikely that any of these will have a major impact by 2050.

# Chapter Seven: Residential Systems

The majority of residential energy use is for thermal purposes. These include space heating, space cooling, humidity control, water heating, clothes driers, hair driers, and cooking appliances. Other energy uses (where electricity is required) include lighting, electronics, plug-in vehicle charging, motorized tools and appliances (e.g., refrigerators, vacuum cleaners, power tools, kitchen mixers), and miscellaneous. Improved insulation, windows, and doors can reduce HVAC requirements. Expected improvements in the efficiency of lighting, electronics, and appliances will reduce their electric power needs. Conventional water heaters normally use natural gas when available (and usually electricity otherwise). Conventional clothes driers use either natural gas or electricity. By 2050, many more homes will have installed charging stations for one or more plug-in vehicles (pure electric or hybrid: see Chapter 10).

The majority of today's residences in the U.S. employ ducted heating and cooling (HVAC) systems with a furnace and central air conditioning unit (although a large minority use many other configurations). Such systems can dehumidify and many also can humidify. Where natural gas is available, it is the furnace fuel of choice. Higher cost fuels (propane or heating oil) are used when necessary. These conventional HVAC systems have efficiencies much lower than the options discussed below. Their ducts tend to have issues with allergens such as molds, pollen, and other airborne particles.

## 7.1 Ductless Heat Pump Systems

Ductless heat pump systems with higher heating and cooling efficiencies are now beginning to penetrate the U.S. market. Instead of ducts, they use small sealed tubes carrying liquid and vapor "refrigerant" to rooms, where space heating and cooling is accomplished as desired. They use electric power to move heat to or from the outdoors to the rooms. While their energy costs for space heating (U.S. averages) are presently comparable to natural gas furnaces, their space cooling efficiencies are about double a typical central air conditioner. Individual thermostats can provide zone control in each room served. Heat-exchange ventilator units can be added to bring fresh air into the home while exhausting stale air (some can also adjust humidity of the fresh air). Installed costs of ductless systems are declining with time as their numbers increase.

By 2050, ductless systems are expected to have further advances in performance and installed cost. Natural gas is expected to become more expensive relative to grid power. Ductless heat pump systems will have been installed in many residences, complete with ventilation and humidity controls. Improvements will further reduce possibilities for mold and dust. Homes without natural gas will operate the systems from grid power (many of these will own standby power systems per section 5.6). A significant fraction of homes with natural gas will integrate their heat pumps with fuel cell systems as described below. Some advanced heat pump systems will include a burner system for use in extremely cold weather (thereby reducing installed cost somewhat).

## 7.2 Natural Gas Fuel Cell Cogeneration Systems

Residences with natural gas fuel cell cogeneration systems (Section 5.2) can integrate these with advanced ductless heat pump systems to obtain combined electrical-thermal systems with superior efficiencies, reduced costs, and uninterruptible performance. Surplus heat from the fuel cell system can perform all water heating and assist with space heating. Water condensate from fuel cell operation can supply all the needed pure water for humidification. In cool to cold weather, the combined electrical plus thermal energy efficiency of a fuel cell cogeneration system can exceed 100% higher heating value. The proposed fuel cell systems will capture all their $CO_2$ emissions for sale and sequestration, unlike furnaces which cannot capture $CO_2$. Utilization of cogeneration heat reduces the variable cost of surplus power sold to the grid.

Residential systems with the proposed fuel cell cogeneration systems and ductless heat pumps provide all of the following benefits:

- uninterruptible whole-house power throughout grid outages of any duration
- large annual energy cost savings
- superior performance, comfort, and convenience
- near-zero greenhouse gas emissions

Although the great majority of the proposed fuel cell cogeneration systems will capture all their input carbon for sequestration, other site uses of natural gas will vent $CO_2$. Such uses might include a gas range, outdoor grille, and/or fireplace. Although fairly small, they can be minimized by using electric alternatives (e.g., electric ovens, induction cooktops, electric fireplaces). Clothes driers should be of the high-efficiency electric type. Water heating will be integrated with the fuel cell system.

## 7.3 Absorption Heat Pumps

Absorption heat pumps use thermal energy to power their refrigerant compression rather than the electric power used for conventional heat pumps (ductless or ducted). They employ a sealed refrigerant loop (typically containing ammonia and water). The required thermal input is preferably low pressure (e.g., 2 atmospheres absolute) saturated steam, which can be furnished from a fuel cell cogeneration system. Like electric heat pumps, they can perform both heating and cooling. The expected advanced versions in 2050 will include design features to achieve excellent coefficients of performance (much higher than today's designs). When properly integrated with a fuel cell and electric ductless heat pump HVAC system, the combination can achieve higher total energy efficiency for both heating and cooling than all comparable alternatives. However, absorption add-on systems will provide only modest incremental cost savings in most well-insulated homes and have extended payback times. They are expected to enjoy limited market share.

## 7.4 Standby Fuel Cell Systems

Residences without natural gas service will typically operate on grid power over 99% of the time. These residences can be equipped with a standby fuel cell system (section 5.6) with a residential-size propane tank. The standby system can provide uninterruptible whole house power during grid outages lasting up to many days (unlimited times with refills). The propane can also be used for a kitchen range and outdoor grille. Fossil $CO_2$ emissions from propane use will be offset by the sequestration of bio-carbon (chapter 11).

## 7.5 Zero Annual Energy Cost

Some homes with natural gas fuel cell systems (especially those which include solar photovoltaic arrays and/or absorption heat pumps) will be able to generate annual revenues from surplus power sales to the grid which can offset their total annual natural gas costs. Some could even reach zero cost with their annual vehicle fuel energy included (chapter 10 discusses transportation and section 13.5 has cost examples).

## 7.6 Autonomous Energy Residences

An autonomous energy residence is here defined as one operating independently of the utility power grid and using zero fossil energy for both the home and its vehicles. Using less than one half acre of land, selected plants (fast-growing grasses and shrubs) are grown, harvested, chopped, dried, and stored on site. Solar photovoltaic panels are roof mounted. A small gasifier system (fed household wastes in addition to the biomass grown) is integrated with a fuel cell cogeneration system, an advanced heat pump, and a converter (a very small version of the type in section 4.2) producing liquid biofuels (propane for the home and diesel or gasoline for the vehicles). Small annual sales of surplus bio-gasoline and bio-$CO_2$ will offset energy used on vacation trips. Surplus solar energy will produce extra liquid biofuels. The included battery bank is used sparingly. Supplemental wood chips or other biomass can be purchased if needed during the first year or two. Although it would have considerably higher installed costs than the other systems described, it would provide deep satisfaction to some homeowners. Installed cost of autonomous systems will depend upon market demand. Annual energy cost savings would accumulate over time. The home would qualify for various awards.

## 7.7 Other Residential Innovations

Future (electric powered) laundry equipment could be designed to perform both washing and drying in the same machine with superior energy efficiency and considerably faster total times.

Robotic units with high-capacity rechargeable batteries could perform automated lawn mowing and snow removal.

The home could become independent of municipal water and sanitary sewer systems if multiple advanced systems were installed. A large water tank could store rain water. A purifier system could produce safe drinking and household water. Concentrated wastes could be used as gasifier feed. An outdoor pond could store water for the garden and most of the excess rain water.

# Chapter Eight: Commercial Systems

The commercial sector encompasses a very wide range of facility sizes, from small retail stores the size of residences to very large buildings and multiple buildings. Examples of the latter include universities, medical complexes, and government campuses. Their maximum electric power requirements range from a few kilowatts to many megawatts. An increasing minority of commercial facilities own emergency backup generators, which can power at least part of their loads during power outages. Such generators have typical startup times of 10 to 60 seconds. Most commercial facilities have electric energy needs much larger than their thermal needs. In hot weather, space cooling needs can significantly increase electric power use in many cases.

## 8.1 Small Facilities

Most small sites have larger thermal/electric usage ratios than larger sites. Commercial facilities having natural gas and maximum power use up to 100 kW can use the same types of fuel cell cogeneration systems and heat pump systems described in residential Chapter 7. Such systems can readily be engineered for a variety of capacities from 3 to 100 kW electrical as desired. They can supply all site electrical and thermal needs with zero carbon emissions and at significant annual cost savings versus conventional alternatives. Surplus electric power can be profitably sold to the grid when prices are favorable. Liquid $CO_2$ can be profitably sold, with truck pickups every month or two.

Commercial sites without natural gas can use grid power and advanced ductless heat pumps. They can install the standby fuel cell systems described in Section 5.6 to provide uninterruptible power from propane or heating oil.

## 8.2 Medium and Large Facilities

Larger commercial facilities with natural gas service can install one or more turbocharged fuel cell systems of the type described in section 5.3. These systems will be available with individual capacities from 100 to 3000 kW and may be connected in parallel for any desired larger capacities. Turbocharged systems offer outstanding electrical efficiency (72 to 75% higher heating value, depending upon capacity) and can also be equipped with optional heat recovery for thermal uses. They can continue to power the entire site (in an uninterruptible manner) during grid outages of any duration. They will have zero carbon emissions and provide large energy cost savings. Liquid $CO_2$ pickup can occur every day or two by tank trucks. Some very large facilities might have a rail connection for $CO_2$ transport.

Appropriate distributed ductless heat pump systems can be installed in any size facility.

Large commercial sites without natural gas service would use the same approach as smaller ones described above.

# Chapter Nine: Industrial Systems

Table 9.1 summarizes the advanced new technologies discussed in the following sections. All are expected to be in extensive use by 2050.

**Table 9.1 Proposed New Processes**

| Section | System Type | Fuel | Module kW | CO2 Capture | Efficiency HHV |
|---|---|---|---|---|---|
| 9.1 | Fuel Cell Cogeneration | Natural Gas | 3-1000 | Yes | 58-101% |
| 9.2 | Turbocharged Fuel Cell | Natural Gas | 100-3000 | Yes | 72-75% |
| 9.3 | High-Temperature Furnace | Natural Gas | 10-3000 | Yes | 81% |
| 9.4 | Cement | Coal | 3000 | Yes | 70% |
| 9.5 | Iron | Coal | 3000 | Yes | 83% |
| 9.6 | Ammonia | Biomass | 3000 | Yes | 61% |
| 9.7 | Standby Fuel Cell | Propane | 3-1000 | | 45% |

## 9.1 Fuel Cell Cogeneration Systems

Advanced fuel cell cogeneration systems (Section 5.2) will be installed at many industrial sites. They will operate with natural gas fuel and capture all of their $CO_2$ for sale. They will average 58% electrical efficiency (AC output/natural gas higher heating value) and also produce usable heat at two different temperatures. Saturated steam at 120ºC will be suitable for absorption heat pumps (section 7.3) with available energy of 23% HHV. Hot air at 55ºC will also be produced to heat water and assist with space heating. Combined energy efficiency will be up to more than 100% HHV in cold weather when all cogeneration heat can be utilized. The cited efficiencies are net after supplying system internal power needs. The latent heat release of $CO_2$ condensation to liquid enables over 100% efficiency.

These systems will provide uninterruptible power (to the entire site, if sized appropriately) for unlimited durations during grid outages. Integrated battery subsystems will supply surge power during such outages. Uninterruptible whole-site power can avoid large costs often associated with grid outages. Whenever grid purchase prices exceed variable operating costs, surplus power can be sold to the grid. These variable costs will be reduced by the use of available cogeneration heat. The fuel cell systems may be hot idled when grid selling prices are below variable cost. They can load follow during grid outages or when grid-neutral operation is most cost effective.

The cogeneration systems will be sold with module sizes from 3 kW up to 1000 kW. Multiple modules may be connected in parallel for higher capacities, expansions, and added redundancy. Larger modules will cost less per kW of capacity.

## 9.2 Turbocharged Fuel Cell Systems

Commercial and industrial sites whose electric power needs are considerably larger than the thermal needs suitable for the above cogeneration systems would benefit from proposed turbocharged natural gas fuel cell systems (Section 5.3). These systems would be available with modules sizes from 100 to 3000 kW each. They would offer outstanding 72-75% higher heating value efficiency (larger systems having higher efficiencies), but less available cogeneration heat than the above systems. All $CO_2$ would be captured for sale. Turbocharged systems would operate at elevated pressure, which improves fuel cell efficiency and also allows their turbine to generate additional net power after driving its air compressor. Although their cost per kW of capacity will be similar to the cogeneration systems, they will have less turndown flexibility and will be louder. Compared with available existing (gas turbine + steam turbine) combined-cycle systems, they will be available in far smaller sizes, will be considerably more efficient, and need no cooling water.

### 9.3 High-Temperature Furnaces

New types of natural gas furnaces with complete $CO_2$ capture are proposed. They could operate at desired hot zone temperatures from 500ºC up to more than 1400ºC, with expected HHV efficiencies of 81%. These furnaces would incorporate oxygen enrichment (via molecular sieves) and small fuel cell subsystems. They would perform natural gas reforming and use high-temperature heat exchange (metallic or ceramic as appropriate). Thermal capacities would range from 10 to 3000 kW per module, with multiple modules ganged for larger needs. These furnaces will be more efficient than nearly all conventional gas furnaces and less costly to operate than electric furnaces.

### 9.4 Cement Manufacturing

The major chemical reaction in cement manufacturing is the liberation of $CO_2$ from limestone ($CaCO_3$) to form calcium oxide (CaO). Existing kilns are heated by natural gas and have only medium energy efficiencies. The combined $CO_2$ emissions from fuel burning and calcining make cement manufacture the largest existing industrial emitter of $CO_2$.

The proposed completely new process would use less costly coal as the fuel, capture all of the $CO_2$ from both fuel and limestone, and usefully incorporate coal impurities into the product cement to enhance its properties. Typical cement contains 62% CaO. If U.S. cement production were 80 million tons per year, coal use (at 13,000 BTU/lb) would be 8 million tons, with HHV of 0.22 EJ. Sequestered $CO_2$ would total 54 million tonnes per year. The new process would also use oxygen enrichment via molecular sieve. Its overall energy efficiency is projected to be 70% HHV. The process could use any quantity of identical 3000 kW (HHV input) modules in parallel to obtain desired plant capacities.

### 9.5 Iron Production

Iron production from ores in the U.S. is currently performed (almost entirely) using blast furnaces, which are fueled by coke made from premium grades of coal in coke ovens. Virtually all the carbon in the coal is eventually emitted as $CO_2$, along with considerable air pollution. Energy efficiency is only moderate.

A proposed new process would use inexpensive coal and ore as direct inputs. Oxygen would also be added and all $CO_2$ captured for sequestration. Sulfur would be also captured for sale, with no air pollution released. Coal impurities would be incorporated in the slag containing ore impurities. The projected energy efficiency of 83% is excellent. If 40 million tons per year of iron were made from ore, coal use would be about 12 million tons, with HHV of 0.32 EJ. Sequestered $CO_2$ would be 28 million tonnes per year. Sulfur for sale would be 230,000 tons per year.

## 9.6 Ammonia Production

Ammonia today is manufactured from natural gas, with all its carbon emitted as fossil $CO_2$. A much more desirable process is proposed, which would produce organic bio-ammonia from renewable biomass, with all the $CO_2$ captured for sale and sequestration. Projected HHV efficiency is 61%. The modular process could be installed near large sources of biomass. The pure anhydrous ammonia product could be used on farms directly or chemically reacted with other fertilizers. The new process would also yield an organic fertilizer byproduct, rich in phosphorus and potassium, and containing sulfur and trace minerals.

An example 20 million tons per year of ammonia would require 33 million tons of dry biomass with a higher heating value of 0.52 EJ. Sequestered bio-$CO_2$ would be 51 million tonnes per year. These quantities are included in the example case.

Ammonia could also be produced from natural gas with total carbon capture and sequestration, using elements of the new technology. Bio-ammonia and/or ammonia from natural gas with CCS could also be exported (ammonia exports are not assumed in the example 2050 case).

## 9.7 Standby Fuel Cell Systems

Industrial sites without natural gas service could install standby fuel cell systems (Section 5.6) for operation on propane or heating oil. These systems would include battery banks and could provide uninterruptible power during grid outages lasting up to weeks. Since they would operate very rarely (their expensive fuel invariably makes grid power cheaper), they would have no carbon capture or cogeneration features.

# Chapter Ten: Transportation Energy Systems

Tables 10.1 and 10.2 compare DOE 2013 U.S. actual, 2050 extrapolated forecast, and proposed 2050 values (in EJ per year). The proposed total is 40% of total domestic delivered energy.

**Table 10.1 Transportation by Mode**

| | DOE | | Proposed | Proposed |
|---|---|---|---|---|
| | 2013 | Forecast 2050 | 2050 | Ratio |
| Light-Duty Vehicles | 15.95 | 12.03 | 7.40 | 62% |
| Freight Trucks | 5.82 | 8.03 | 3.24 | 40% |
| Air | 2.43 | 3.43 | 3.08 | 90% |
| Pipeline Fuel | 0.93 | 1.03 | 0.52 | 50% |
| Military | 0.71 | 0.91 | 0.63 | 69% |
| Shipping | 0.76 | 0.74 | 0.55 | 74% |
| Commercial Light Trucks | 0.57 | 0.60 | 0.39 | 65% |
| Rail | 0.59 | 0.56 | 0.34 | 61% |
| Boats and Lubricants | 0.39 | 0.47 | 0.38 | 81% |
| Buses | 0.27 | 0.35 | 0.10 | 29% |
| Total | 28.42 | 28.15 | 16.63 | 59% |

**Table 10.2 Transportation by Energy Type**

| | DOE | | Proposed | Proposed |
|---|---|---|---|---|
| | 2013 | Forecast 2050 | 2050 | Ratio |
| Gasoline | 16.81 | 12.44 | 6.64 | 53% |
| Diesel | 6.85 | 8.62 | 2.57 | 30% |
| Jet Fuel | 2.95 | 4.09 | 3.72 | 91% |
| Natural Gas | 0.98 | 2.35 | 2.66 | 113% |
| Residual Oil | 0.81 | 0.57 | | |
| Electricity | 0.02 | 0.08 | 1.04 | 1300% |
| Total | 28.42 | 28.15 | 16.63 | 59% |

Light-duty vehicles include cars, SUVs, minivans, and pickup trucks. The DOE forecast shows total energy consumption declining by 1% from 2013 to 2050 in spite of significantly more transportation performed, due to efficiency improvements. Residual Oil includes a small amount of propane in the DOE columns.

The proposed 2050 case will use 13 times the electricity due to higher prices for fuels versus grid power and expected significant improvement in the cost effectiveness of plug-in transportation. Most of the proposed 2050 total energy savings, however, will result from the widespread replacement of engines by advanced fuel cell systems (section 5.4).

**10.1 Transportation Fuels**

Liquid hydrocarbon fuels are preferred for most transportation due to their excellent energy content per unit weight and volume and their desirable required tanks (light weight and inexpensive). Transportation fuels will usually be comingled biofuels/fossil fuels. The three expected 2050 transportation liquid fuels are gasoline, jet fuel, and diesel. All the cited fuels can be used in fuel cells, but each type of engine requires a specific type. For fuel cell use, diesel will often be the preferred liquid due to its superior safety (higher flash point) and higher energy content per gallon.

A fourth transportation fuel, compressed natural gas (CNG), will also be used for some commercial truck and bus fleets. The lower cost of this fuel compared with liquids will justify the greater costs for high pressure (up to 6000 psi) tanks and compressor stations. For comparisons, one mcf (thousand standard cubic feet) of CNG has the same energy content as 7.2 gallons of diesel fuel. The efficiency (electric power/fuel higher heating value) of the fuel cell systems will be essentially the same for any of the four fuel types.

Hydrogen has a much lower energy density versus CNG and is considerably more expensive (per unit of HHV) to produce and deliver. Although it could be made with zero fossil $CO_2$ emissions (from natural gas or biomass), its present-day appeal is due chiefly to its suitability for use in PEM fuel cell systems. Before 2050, solid-oxide fuel cells are expected to displace PEM fuel cells and thus render hydrogen quite unattractive.

**10.2 Transportation Fuel Cell Systems**

By 2050, advanced fuel cell systems (section 5.4) are expected to replace (or used together with) engines in a large share of transportation vehicles and equipment. These fuel cell systems will offer important advantages over engines:

- Far lower fuel consumption
- Capture of virtually all $CO_2$ for sale
- Zero emissions of $NO_x$ and other pollutants
- Lower maintenance costs
- Quieter
- Continuous, economical power and heat during rest periods

Compact, high-efficiency solid-oxide fuel cell systems with integrated $CO_2$ capture are proposed (except systems for military and aircraft applications, which would vent their $CO_2$). Their continuous power output ratings could range from 10 kW to many megawatts. Most would be hybridized with batteries for peak combined power (to assist acceleration and hill climbing) of 200% to 400% of their continuous power rating. The batteries would also store regeneration energy from deceleration and hill descents (as with most hybrids).

The fuel cell systems could interchangeably operate from gasoline, jet fuel, diesel, or natural gas. Where diesel was available at competitive cost, it would be the preferred liquid fuel for land and sea due to its better safety and energy density versus the other liquids. CNG will be the lowest cost fuel where available. The added weight, volume, and cost of its tanks for a given driving range will have a small impact on a vehicle equipped for on-board $CO_2$ accumulation.

The fuel cell systems would be used in light duty vehicles, commercial and freight trucks of all sizes, buses, locomotives, ships, and airliners (as auxiliary power units). They would achieve from two to four times the miles per gallon (in non-flight applications) as the same size vehicles with engines. Section 13.5 shows cost and energy usage comparisons for selected vehicle types. Conventional freight trucks in 2050, for example, are forecast to average 9.1 miles per gallon of diesel. Projected freight truck average with fuel cell power is 28.9 mpg (3.2 times higher). Light-duty vehicles in 2050 are forecast to average 50 miles per gallon of gasoline. Fuel cell LDVs are expected to average 100 miles per gallon of gasoline (double).

Liquid $CO_2$ would be recovered by fuel cell systems and stored in on-board tanks. All filling stations would be equipped to offload liquid $CO_2$ during refueling, using convenient combination nozzle-connectors. $CO_2$ sales value would automatically be subtracted from fuel cost at the pump.

The hybridization of fuel cells with batteries will enable ample peak power to be available using fuel cell systems of moderate size. For example, a compact LDV seating five passengers might have maximum power of 100 kW (134 hp) but use a fuel cell system rated 30 kW. Small vehicles for urban use might have fuel cell systems as small as 10 kW. Many freight trucks could use 100 kW fuel cell systems, with higher power installed in some cases. Most transportation fuel cell systems of 100 kW and larger will include turbocharging, which will increase fuel efficiency by up to 25%.

Very large turbocharged fuel cell systems (capacities in megawatts) will be used in locomotives and ships. Fuel cell commuter rail cars will typically use 100 kW each.

Fuel cell and hybrid drive systems use electric traction motors, which provide excellent torque at zero and low speeds, allowing good vehicle performance with lower horsepower than engine systems.

### 10.3 $CO_2$ Emissions and Sequestration

The proposed transportation fuels (excluding electricity) in Table 10.2 would contain carbon, which in turn would have varying destinations. The three liquid fuels would contain (in the example) half fossil and half bio-carbon. The natural gas would have 75% fossil carbon. Plug-in electricity would have zero associated carbon emissions.

The various types of transportation equipment would capture for sale and sequestration a significant fraction of the carbon in their fuels. Since some of the sequestered carbon is bio-carbon and some of the emitted carbon is fossil carbon, net fossil $CO_2$ emissions from the transportation sector can be relatively small.

# Chapter Eleven: Carbon Dioxide

Carbon dioxide ($CO_2$) released into the atmosphere from fossil carbon sources (chiefly coal, petroleum, and natural gas) increases $CO_2$ concentration in the atmosphere, which is known to be the principal greenhouse gas causing global warming. The $CO_2$ from biomass and biofuel oxidation merely recycles carbon back into the atmosphere and thus causes no net increase. This report described how the U.S. can affordably achieve complete carbon neutrality by 2050.

Table 11.1 lists all the carbon dioxide flows in Figure 1.1. Streams 41 and 43 are entirely fossil $CO_2$, while the others all contain both bio- and fossil-$CO_2$.

**Table 11.1 Carbon Dioxide Flows in Figure 1.1**

| | million tonnes |
|---|---|
| 41 Coal Plants | 1419 |
| 42 User Sequestered | 702 |
| 43 Refineries | 217 |
| 44 Converters | 810 |
| 45 Total Vented | 863 |
| 46 Fuel Cell Sequestered | 448 |
| 47 Transportation Seq | 202 |
| 48 Transportation Vented | 787 |
| 49 RCI Vented | 76 |

$CO_2$ is fungible: the molecules are the same regardless of their source. This document proposes to reach zero net U.S. fossil carbon emissions by sequestering a quantity of biomass $CO_2$ which equals total fossil $CO_2$ vented to the atmosphere as summarized in Table 11.2.

**Table 11.2 Zero Net Fossil Carbon Emissions**

| | million tonnes CO2 | | | Proposed |
|---|---|---|---|---|
| | 2013 | 2050 DOE | Proposed | Ratio |
| Fossil Generation | 5405 | 5584 | 2865 | 51% |
| Fossil Sequestration | 0 | 0 | 2375 | |
| Fossil Emissions | 5405 | 5584 | 490 | 9% |
| Bio-Sequestration | 0 | 0 | 490 | |
| Net Fossil Emissions | 5405 | 5584 | 0 | 0% |

## 11.1 Carbon Dioxide Capture

Nearly all existing equipment utilizing carbonaceous fuels uses air combustion, which produces exhaust mixtures with high nitrogen and low (typically 4 to 8%) $CO_2$ content. Moreover, the exhaust gas is invariably at near-atmospheric pressure. Examples of such equipment are conventional coal and natural gas power plants, engine-powered transportation, and furnaces (which collectively consume the great majority of fossil fuels today). The recovery of $CO_2$ from such exhaust mixtures requires considerable energy and expensive bulky equipment. Since costs and energy use rise rapidly with recovery percentage, most demonstration $CO_2$ recovery systems recover 90% or less of contained $CO_2$. Carbon dioxide recovery from air combustion systems thus appears to be an unattractive option for the future (see also section 6.8).

Alternative combustion processes have been proposed which use oxygen from air liquefaction plants instead of air. Such schemes also add considerable capital and energy cost and would be practical only at very large stationary facilities such as power plants. Since cost studies on this approach show little advantage over the above systems, this approach also has minimal appeal (see also section 6.8).

The proposed new processes employ fuel-cell, gasifier, and other emerging technologies to produce pressurized exit gas with high (over 90%) $CO_2$ content (other gases present are nitrogen, oxygen, and $H_2O$ vapor). The exit gas can be processed in compact inexpensive equipment using affordable amounts of energy (about 100 kWh per tonne $CO_2$) to isolate pure pressurized liquid $CO_2$, with the $N_2$, $O_2$, and $H_2O$ vapor vented. The recovery system includes compression, heat exchange, refrigeration, and a molecular sieve. Practical $CO_2$ recovery for sequestration can exceed 99%.

## 11.2 Handling and Storage

Pure carbon dioxide can be most economically handled and stored as pressurized liquid, as has been practiced commercially for many decades. $CO_2$ liquid only exists below its critical temperature of 31ºC (above this temperature it becomes a supercritical fluid). The use of insulated storage tanks and refrigeration can be used to minimize required storage volumes and pressures. Expected 2050 tanks will have either spherical or cylindrical (with rounded ends) shapes. Most will be made of fiber-reinforced composites.

Mobile $CO_2$ tanks will be mounted on tank trucks, rail tank cars, and zero-emission fuel-cell vehicles (described in Chapter 10). $CO_2$ would be offloaded from vehicles at filling stations during refueling. Some $CO_2$ transport (from many coal power and some large industrial plants) will use dedicated pipelines, with insulation and periodic pumping/refrigeration stations. Buffer storage will be installed at collection depots and sequestration sites.

Storage tanks will be installed at user buildings and stationary facilities which capture $CO_2$. Most will be outdoors, with some buried or indoors (the latter requiring extra protective features). $CO_2$ will be collected from stationary sites at suitable intervals, based upon its production rate. Such intervals might range from every few days to every few months for optimum transport economy, convenience, and minimized storage investment.

## 11.3 Permanent Underground Sequestration

Permanent underground sequestration of $CO_2$ will use numerous sites around the country with suitable geology. The fact that enormous quantities of natural gas (which is lighter than $CO_2$) have remained underground for many tens of millions of years proves that permanent storage is possible. Of course, the sites chosen will require monitoring. Many sites around the world are already being used for $CO_2$ injection, most for enhanced oil recovery. Reference 3 includes an extensive discussion of potential U.S. sequestration sites and concludes that safe sequestration may be assumed. The Ref. 3 estimated U.S. $CO_2$ storage capacity of 8613 billion tonnes would require over 2700 years to fill at the proposed 2050 sequestration rate. The expected emergence of affordable fusion power within 100 years would allow ongoing bio-carbon sequestration to gradually lower atmospheric $CO_2$ to pre-industrial levels (see also 15.5).

Required injection pressures for permanent underground sequestration will vary with the site, but are typically 200 to 300 bar. Such pressures can be obtained at much lower capital and energy cost by using cold-liquid pumping from typical storage pressures of 35 bar (rather than by compression of gas). The $CO_2$ will become a supercritical fluid upon warming to underground storage temperatures (typically above 60ºC).

The sequestered quantity of 2.9 billion tonnes per year of $CO_2$ has a volume of 1.5 cubic miles at example (supercritical) storage conditions of 100ºC and 200 bar pressure. If this volume were stored under 1% of the area of the 48 states in formations averaging 25% porosity, the sites will be filled at the rate of one foot per year. For comparison, 2.9 billion tonnes $CO_2$ equals 55 trillion standard cubic feet, which is 2.3 times U.S. natural gas production in 2013.

Under the warm high-pressure underground conditions at many sequestration sites, $CO_2$ will slowly react chemically with oxide minerals to form stable carbonate minerals, yielding further increases in site storage capacity.

## 11.4 National Carbon Administration

Congress should establish the National Carbon Administration, which will collect fees from fossil carbon users (which will be added to prices). The fees will be used to purchase $CO_2$ from all users who capture it and to pay contractors for its transport and sequestration. Some of the captured $CO_2$ will contain renewable carbon from comingled biofuels. The fees should vary with transport cost for different types of users. The agency should operate on a cash-breakeven basis, with fees and purchase prices gradually rising until net U.S. fossil emissions reach (or pass) zero by 2050 or sooner. It should be required to minimize its operating costs by using competitive bidding where appropriate. The Federal government must assume permanent responsibility for safe $CO_2$ sequestration, with indemnification of contractors who comply with its regulations. It should also assume any associated liabilities, including payment of any proven damages.

Users capturing and selling $CO_2$ will thus enjoy lower net fuel cost versus other users. Example fees and costs for $CO_2$ are given in Chapter 13. The National Carbon Administration should monitor safety and fugitive-emissions performance of equipment, companies, and sequestration sites. Early efforts should thoroughly study and test underground sequestration to ensure its viability, safety, and costs. Fossil fuel exports would probably not pay fees to the NCA, but rather to corresponding bodies in the country of use.

## 11.5 Carbon Dioxide Properties

Carbon dioxide can exist as a solid, liquid, or gas depending upon temperature and pressure. Its triple point (where all three phases may coexist) is 5.18 bar and -56.6ºC. The solid form, called dry ice, is of little interest here since $CO_2$ will only be handled at higher temperatures and pressures in the processes and equipment described herein. Its critical point is 73.8 bar and 31.1ºC (88ºF). Above this temperature, $CO_2$ is a supercritical fluid which undergoes no liquid-gas phase transition. Carbon dioxide gas is colorless, odorless, and non-toxic. Its normal concentration in the air is about 0.04% by volume. If present in air at concentrations more than ten times normal, it alters human breathing and affects the body. At still higher concentrations, it can cause asphyxiation.

### 11.6 Tanks for Storage and Transport

Advanced pressure vessels for $CO_2$ storage and transport should be developed, with ongoing reductions in their cost of mass production. The vessels must have appropriate pressure safety factors and be equipped with pressure-relief valves and/or rupture discs. Most will have a layer of excellent but inexpensive thermal insulation outside. Cost studies will be needed to determine the most cost-effective temperatures for liquid $CO_2$ storage and transport (optimum temperatures are expected to vary over time for each type of application).

Spherical tanks require the least material for a given pressure and internal volume and would thus be preferred in some cases. However, many vessels would be cylindrical with hemispherical or dished ends for higher storage capacity with a given diameter. Cylindrical tanks require twice the wall thickness as spheres of the same diameter and allowable stress. The ratio between vessel weight and capacity is independent of diameter (for a given pressure and allowable stress): larger vessels require proportionally thicker walls.

The most cost-effective material for vessels will probably become advanced fiber-reinforced-polymer composites, which will also be lighter in weight than metallic-alloy alternatives. The low oxygen content of the liquid will also allow alloy steels to be used in some cases.

An example spherical advanced composite tank operating at 0ºC, costing \$10/lb, with composite wall density of 0.100 lb/in$^3$ and an allowable working stress of 100,000 psi would cost \$0.50 per kg of liquid $CO_2$ capacity. A 36-inch (914 mm) ID tank has a capacity of 371 kg $CO_2$, a wall thickness of 0.045 inches (1.14 mm) and an empty weight of 18.1 lb (8.2 kg). Values from Table 4.2 may be used to compute values for other temperatures. Alternative values for cost per pound, composite wall density, and allowable stress will give linear changes per kg of $CO_2$ stored. Cylindrical tanks would cost \$1.00 per kg of $CO_2$ capacity with the same assumptions.

### 11.7 Carbon Dioxide from Exports

The proposed energy exports add no fossil emissions to the United States. Suitable sites for permanent $CO_2$ sequestration are believed to lie under most sizeable countries in the world. Tanker ships could be used to transport liquid $CO_2$ from one country to another (including to the U.S.) for sequestration where necessary.

### 11.8 Fraud and Leakage

It is expected that a small fraction of the $CO_2$ captured and sold for sequestration will be vented to the atmosphere due to fraud and leakage. Since complete monitoring of sequestration sites is impossible, some sites are expected to cheat to lower operating costs. Unintentional leakages will also occur, mostly from the underground reservoirs. The 490 million tons of vented fossil $CO_2$ shown in Table 11.2 includes estimated fraud and leakage. Additional bio-$CO_2$ could be sequestered to compensate for higher fossil venting.

# Chapter Twelve: Grid Balancing and Energy Storage

This chapter summarizes some of the alternatives for grid balancing and energy storage expected in 2050. Most are used today at least to some extent.

## 12.1 Grid Balancing

The total quantity of electric power (megawatts) fed to each local utility electric grid must continually balance total user loads, since power flows are instantaneous (slight imbalances are handled by allowing grid voltage to vary slightly). The expected connection of considerably more renewable and distributed generation (DG) capacity to the grid will increase possible variations in supplies to the grid (e.g., wind speeds and cloudiness vary). On the user side, the expected increase in electric-powered heat pump usage could increase variations in demand (especially in very cold weather).

Time-of-use (TOU) grid pricing is expected to become much more significant, giving financial incentives to users to reschedule loads to less expensive times. TOU pricing will also encourage maximized DG when prices are high.

As discussed in Chapter 6, existing (inflexible) nuclear power plants and conventional coal plants will be retired. Their capacity will be replaced by modular fuel-cell based systems, which will be capable of economical and very rapid load following to help balance grid supply with demand.

## 12.2 Energy Storage

Numerous types of energy storage will be employed. Storage will be used of necessity, to enhance performance, and/or to reduce costs.

The most widely used and lowest cost type of energy storage is of fuels (gaseous, liquid, and solid).

Small batteries are essential for a wide range of portable devices. They include primary types (such as alkaline) and secondary or rechargeable types (such as lithium-ion and nickel-metal hydride).

A special type of medium-sized rechargeable battery is the SLI (starting, lighting, ignition) battery. These lead-acid types are nearly universal in cars and other vehicles. They can deliver high power for short times but are not intended for frequent deep cycling.

Most of the fuel cell systems discussed in Chapter 5 will include secondary deep-cycle batteries for peak power and to enhance delivered power quality. These batteries will be designed for numerous deep cycles.

The sections below discuss other selected storage options.

**12.3 Vehicles**
The great majority of terrestrial vehicles are expected to include deep-cycle secondary batteries (probably advanced lithium-ion type) to power electric motors and store energy recovered during deceleration and descents. Most of these vehicles will be hybrids with engines or fuel-cell systems. Some will require or allow plug-in charging. These vehicles will range in size from scooters to locomotives.

**12.4 Water Batteries**
A possible future electrical energy storage system is a water battery, which is a type of flow battery. It would use a high-pressure sealed enclosure containing hydrogen and oxygen and a reversible solid-oxide fuel cell/electrolyzer. Water batteries could achieve specific energy storage much higher than alternatives: up to over 1000 Watt-hours per kilogram. Round-trip storage efficiencies would depend upon cycle times, and could range from about 72% to 90%. Water batteries could be recharged slowly by plug-in power or in a minute or two by exchanging fluids at a filling station. The filling station could use electrolysis (section 5.8) to produce the hydrogen and oxygen.

Although water batteries would be ideal for some aerospace applications, they are expected to be more costly than alternative systems in the vast majority of domestic uses before 2050. However, they could be useful in other countries with limited biofuels before 2050 and more widely worldwide after 2050 if low-cost fusion power becomes available (see sections 15.4 and 15.5).

**12.5 Supercapacitors**
These store DC electric energy electrostatically in sealed devices with very high specific surface area (usually containing some type of carbon). They offer very fast response time, excellent life, high power, and good energy efficiency. Since they have low volumetric energy density and high unit cost, they are best suited for applications needing high power delivery lasting only seconds. Supercapacitors could be used to enhance load following in fuel cell systems which have no batteries. Practical supercapacitors use many cells internally connected in series (for higher working voltage) with built-in circuitry to limit maximum cell voltages during charging. Their high self-discharge rate will not be a problem in load-following applications.

**12.6 Other Electrical Energy Storage Methods**
Other methods include flow batteries differing from 12.4, flywheels, pumped hydroelectric, superconducting magnetic energy storage (SMES), and compressed air storage systems. None are expected to play significant roles in 2050.

**12.7 Virtual Batteries**
Various types of systems can absorb electric power at some times and deliver power at other times (thus acting in some respects like battery systems), but perform this function without using storage batteries. Unlike actual batteries, virtual batteries may have output energy considerably different from input energy. The timing of their energy flows is also not subject to the constraints of batteries.

Users with distributed generation systems may act as virtual batteries, buying grid power when prices are low, becoming grid zero at intermediate prices, and selling to the grid when prices are high. Some biofuels plants might boost biofuel yield using low-cost grid power and then export power instead of making biofuel when prices are high.

## 12.8 Thermal Storage

The use of thermal storage can lower operating costs for HVAC. Passive storage uses the large sensible heat of buildings for thermal inertia. Many buildings will also use insulated tanks for hot water storage (especially when heated by cogeneration).

Active thermal storage can use phase-change systems with electric-powered heat pumps to take advantage of lower TOU pricing and/or more favorable outdoor temperatures. Example phase-change systems use ice (for space cooling) and/or paraffin wax (for space heating).

# Chapter Thirteen: Financial Summary

This chapter summarizes preliminary and approximate financial estimates for the proposed 2050 U.S. energy plan (in nominal 2050 dollars).

## 13.1 Energy Prices and Savings

The example 2050 prices detailed below are higher than those extrapolated from the DOE forecast for multiple reasons (listed in no particular order):

- Encourage energy conservation and more efficient use
- Encourage energy users to capture and sell $CO_2$
- Pay all costs of $CO_2$ purchase, transport, and sequestration
- Increase renewables use
- Eliminate pollution from power generation
- Eliminate government subsidies for energy
- Boost profits of most energy companies
- Enhance infrastructure maintenance and upgrading

The new pricing structure would also more accurately reflect the true costs of the various forms of energy by incorporating the following. Natural gas and grid electricity prices would be split into fixed (to pay all infrastructure-related costs) and variable (to pay all delivered energy costs), with rates differing appropriately for different types of customers. Electric utilities would purchase excess power generated by customers at prices lower than their selling prices, based upon their true avoided cost. Electricity variable time-of-use (TOU) pricing will be used, but variations will be reduced somewhat by expected changes in power-use patterns.

Several types of energy will have no user $CO_2$ price adder for the following reasons. All electric power will be fossil carbon free, as described in Chapter 6. Propane and jet fuel will be used in equipment with no $CO_2$ capture options and thus no $CO_2$ sales. Chemicals and materials are assumed to not emit fossil $CO_2$ during use. Natural gas, coal, and the liquid fuels will have associated $CO_2$ selling prices, with examples listed. The proposed prices could include excise and sales taxes. Table 13.1 shows example weighted-average prices.

**Table 13.1 Example 2050 Prices**

| Type | Prices per GJ HHV | | | | | CO2 | Mean Price/Unit | |
|---|---|---|---|---|---|---|---|---|
| | AEO | Net | CO2 | Gross | Mean | tonne | Mean | Units |
| Natural Gas | $21.81 | $23.09 | $9.89 | $32.98 | $30.00 | $196 | $32.49 | mcf |
| Propane | $48.84 | | | $74.20 | $74.20 | | $6.64 | gallon |
| Gasoline | $65.91 | $61.94 | $15.48 | $77.42 | $74.20 | $234 | $9.50 | gallon |
| Jet Fuel | $59.75 | | | $74.20 | $74.20 | | $10.56 | gallon |
| Diesel | $70.94 | $64.52 | $16.13 | $80.65 | $74.20 | $244 | $10.73 | gallon |
| Coal | $5.50 | $9.00 | $9.00 | $18.00 | $9.00 | $103 | $182 | ton |
| Electricity | $65.44 | $60.00 | | | $60.00 | | $0.216 | kWh |
| Mean | $45.38 | | | | $68.08 | | | |

The above $CO_2$ prices are 20% of the gross price for the liquids, 30% for natural gas, and 50% for coal. The total costs of buying, transport, temporary storage, and permanent sequestration should equal the total revenue from the carbon adders on all fossil fuels. $CO_2$ fees (not shown, but included in gross prices) and purchase prices can be slowly adjusted to achieve zero net fossil $CO_2$ emissions by 2050 at minimum cost to users. The example $CO_2$ prices are believed large enough to compensate many users for the increased capital and operating costs to purchase and operate equipment with $CO_2$ capture (especially when such equipment also is more efficient).

Table 13.2 uses the above pricing with the proposed 2050 user energy purchases from Table 1.6 (delivered energy). The totals match those shown in Table 1.1: user costs are reduced by $937 billion per year (25%), while weighted-average prices are 150% of extrapolated DOE forecast.

**Table 13.2 Proposed 2050 User Costs**

| | Proposed EJ | User Cost billions |
|---|---|---|
| Natural Gas | 12.52 | $376 |
| Propane | 0.40 | $30 |
| Gasoline | 6.64 | $493 |
| Jet Fuel | 3.72 | $276 |
| Diesel | 2.57 | $191 |
| Chemicals & Materials | 0.90 | $67 |
| Coal | 0.54 | $5 |
| Electricity Net Purchases | 14.03 | $842 |
| Road User Fees | | $535 |
| **Total** | **41.32** | **$2,813** |

The large annual user savings would be expected to increase in subsequent years. As noted previously, 2050 average prices include an inflation factor of 1.78 from 2013.

Proposed fuel prices in 2050 will include no road use taxes as are presently charged. The greatly changed mix of vehicle energy sources (including electricity and natural gas) and their energy efficiency variations will make an alternative fee structure desirable. The proposed road user fees would be based on vehicle ton-miles, using a sliding scale (i.e., doubling weight would increase fees less than double). The proposed total is a larger proportion of vehicle energy cost than presently to fund much better maintenance and improvements. Light-duty vehicles in the example would pay fees averaging 8 cents per mile while freight trucks would pay an average of 48 cents per mile.

Biofuels are expected to have wholesale prices higher than their fossil counterparts, with the cost differential declining as 2050 is approached. The example prices in Table 13.1 are average user prices. In some cases, users might be offered the choice of buying biofuel, blended fuel, or fossil fuel at differing prices, even though the fuels are comingled.

## 13.2 Capital Expenditures

The advanced energy systems described in the foregoing chapters will have estimated installed capital costs shown in Table 13.3. Totals are estimates through 2050 and annual costs are averages over 25 years. Transportation expenditures are incremental costs for adding the advanced fuel cell systems. Capex costs are expected to decline faster than inflation (averages are used). The different categories shown will vary considerably with time. After 2050, little additional coal power or $CO_2$ systems capacity will be needed. Biofuels capacity growth will be reduced. However, significant ongoing capex will occur for transportation, distributed generation, and standby systems.

**Table 13.3 Capital Costs**

| | billions | |
|---|---|---|
| | Total | Mean Annual |
| Coal Plants | $1,083 | $43 |
| Biofuels Converters | $1,187 | $47 |
| Greenhouses | $531 | $21 |
| Distributed Generation | $503 | $20 |
| Transportation | $1,271 | $51 |
| Standby Power Systems | $103 | $4 |
| Other Industrial Systems | $118 | $5 |
| CO2 Systems | $281 | $11 |
| Total | $5,078 | $203 |

Excluded from Table 13.3 are capital expenditures for heat pump systems and the many evolutionary improvements cited. Also excluded are capital expenditures for the factories which will manufacture the new equipment and its components (very roughly estimated to be only about $200 billion total, due to the nature of the required equipment).

The first five lines in Table 13.3 will have quite attractive returns on investment and payback times. As a result, many financing options will be available to owners. Standby power systems provide other benefits and limited financial returns. $CO_2$ systems will have adequate returns on investment to their owner-operators, paid out of the fees collected.

## 13.3 Example Exports

Table 13.4 gives example energy exports, using quantities from Table 1.2 and example average export prices. The fossil liquids total also includes chemicals and materials. The LNG price includes $7.00 per GJ for natural gas liquefaction.

**Table 13.4 Example Energy Exports 2050**

| Item | Quantity EJ | Export Price per GJ | Value billions |
|---|---|---|---|
| 11 Coal | 6.00 | $10.00 | $60 |
| 12 Liquefied Natural Gas | 7.00 | $30.00 | $210 |
| 13 Fossil Liquids | 4.00 | $65.00 | $260 |
| 14 Liquid Biofuels | 8.00 | $80.00 | $640 |
| Total | 25.00 | | $1,170 |

In addition to the above exports, exports of the types of equipment in Table 13.3 will occur as well as licensing fees for this equipment manufactured in other countries. Equipment-related exports are not included in the financial or jobs estimates.

Since the extrapolated 2050 DOE imports forecast is $902 billion (Table 1.1), the predicted trade balance improves by $2072 billion per year.

**13.4 Job Creation**

In 2050, good full-time jobs might average $40.00 per hour plus 25% fringes. With improved average paid vacation of 15 days and 10 paid holidays, work time is 236 days or 1888 hours at 8 hours per day. Total pay thus totals $75,520 per year ($94,400 with fringes). The 2013 equivalent of $40.00 per hour is $22.47 per hour (before fringes). The cost (pay plus fringes) of 10 million such jobs in 2050 is $944 billion.

As shown in Table 1.1, $902 billion annual imports in 2013 are forecast to be replaced by $1152 billion exports in 2050: an improvement of $2054 billion per year. Since $944 is 46% of $2054, it appears reasonable that the improved trade balance could support 10 million good permanent new jobs, as estimated in Table 13.5.

**Table 13.5 New Jobs 2050**

| | |
|---|---|
| New Equipment Capex | 1,130,000 |
| New Equipment Maintenance | 600,000 |
| Biomass and Biofuels Production | 1,700,000 |
| Greenhouse Operations | 2,670,000 |
| Added Road Work | 1,840,000 |
| Other | 2,060,000 |
| Total | 10,000,000 |

The new equipment lines are net additions. The Other category includes many jobs at suppliers and support services, less jobs lost from reduced production of fossil fuels. It also includes jobs in categories not tabulated, such as $CO_2$ related activities, international consulting, infrastructure upgrades other than road work, and others.

**13.5 Transportation Cost Comparisons**

Table 13.6 compares light-duty vehicles of the types expected in 2050, with their estimated travel shares. All will use gasoline and the first three are hybrids containing batteries. The example 15,000 annual miles is higher than the 12,000 miles expected average of all LDVs.

**Table 13.6 Light-Duty Vehicles 2050**

| | | 2015 | per mile | | | Gasoline | 15,000 | Range | Miles |
|---|---|---|---|---|---|---|---|---|---|
| | | Example | Energy | Ratio | CO2, g | mpge | miles | miles | share |
| 1 | Engine Hybrid | Prius | $0.198 | 3.00 | 169 | 50.0 | $2,974 | 600 | 52% |
| 2 | Plug-In Hybrid | Volt | $0.096 | 1.45 | 34 | 99.2 | $1,440 | 600 | 20% |
| 3 | Fuel Cell | | $0.079 | 1.20 | | 100.0 | $1,190 | 1200 | 20% |
| 4 | Electric | Leaf | $0.066 | 1.00 | | 142.3 | $990 | 100 | 8% |

In this table, $CO_2$ is given in grams per mile and mileage in miles per gallon of gasoline equivalent (mpge). Although electric vehicles emit no $CO_2$ and have the lowest energy cost, their use will be limited by their short range and charging constraints. Fuel cell vehicles will emit no $CO_2$ since they capture it for sale at filling stations. Their use will be constrained by higher initial cost.

Plug-in hybrids (with engines) will cost more than the first type and will also be limited by charging access and convenience. Most legacy older vehicles will be the first type.

Table 13.7 compares freight trucks. CNG is compressed natural gas. All have electric motors and batteries.

**Table 13.7 Freight Trucks 2050**

| | | per mile | | | 120,000 | Diesel | Range | Miles |
|---|---|---|---|---|---|---|---|---|
| | | Energy | Ratio | CO2, g | miles | mpge | miles | share |
| 1 | Engine Diesel | $1.28 | 7.94 | 1052 | $154,046 | 9.1 | 1600 | 10% |
| 2 | Engine CNG | $0.83 | 5.11 | 901 | $99,096 | 8.1 | 1600 | 10% |
| 3 | Fuel Cell Diesel | $0.33 | 2.02 | | $39,258 | 28.5 | 1600 | 25% |
| 4 | Plug-In Electric | $0.28 | 1.71 | | $33,259 | 32.1 | 100 | 5% |
| 5 | Fuel Cell CNG | $0.16 | 1.00 | | $19,394 | 28.9 | 1600 | 50% |

The example annual mileage is for intercity service: trucks operating locally will accrue many fewer annual miles. Plug-in trucks will usually travel far less than shown, but their hypothetical cost is given for comparison. Compressed natural gas for transportation is expected to be less universally available than diesel in 2050. Trucks using diesel will also have somewhat lower initial costs than CNG vehicles. Fuel-cell trucks will capture and sell their $CO_2$ at truck stops. By 2050, fuel-cell trucks will dominate the high-mileage fleet.

## 13.6 Electric Power Costs

Table 13.1 shows weighted-average 2050 user cost of grid power of $60.00/GJ or $0.216 per kWh. Residential users will pay more than this average, while most commercial and industrial users will pay less.

Power from coal (P1 in Table 1.3) is calculated to have a 2050 total average generation cost (including return on investment) of $0.131 per kWh, using assumptions given in section 6.7. Variable generation cost in 2050 is projected to be $0.071 per kWh. Coal power plants will load follow as needed to continuously balance supply and demand. Utility-scale wind and solar farms installed at favorable sites (P2 in Table 1.3) will have total generation costs per kWh similar to coal power (and variable costs far lower).

The mean user price (for P4 in Table 1.3) shown in Table 13.1 includes transmission and distribution costs (with return on investment) as well as paying for energy losses (Q1) from generation to users.

On-site photovoltaic generation (P5 in Table 1.3) will have a total cost (with return on investment) per kWh slightly higher than grid price at sites with good sun. Its variable cost will be very low. The total cost of distributed generation (P3 and DG direct use) by natural gas fuel cell cogeneration systems (section 5.2) will usually be lower than grid purchase rates. Its net cost will depend upon outdoor temperature and hence system thermal capacity factor (share of available surplus heat which can be utilized). Time-of-use grid pricing will sometimes make grid power lower in cost than on-site generation and/or make the sale of surplus power to the grid unprofitable. Sales to the grid will also be limited by the amount of surplus capacity installed.

## 13.7 Biofuels Value

User expenditures for domestic and export biofuels are shown below.

**Table 13.8 Biofuels Summary 2050**

| Quantities | | Domestic | Exports | Total |
|---|---|---|---|---|
| BNG | EJ | 3.17 | | 3.17 |
| BLP | EJ | 6.67 | 8.00 | 14.67 |
| Biofuels | EJ | 9.84 | 8.00 | 17.84 |
| **Mean User Prices** | | | | |
| BNG | GJ | $30.00 | | $30.00 |
| BLP | GJ | $74.20 | $80.00 | $77.36 |
| Biofuels | GJ | $59.96 | $80.00 | $68.95 |
| **Annual Values** | | | | |
| BNG | billions | $95 | | $95 |
| BLP | billions | $495 | $640 | $1,135 |
| Biofuels | billions | $590 | $640 | $1,230 |

Biofuel exports comprise about 55% of total energy exports shown in Table 13.4.

## 13.8 Costs of $CO_2$ Capture and Sequestration

The costs of carbon dioxide capture and sequestration to achieve zero net fossil $CO_2$ emissions are included in the Table 13.2 user energy cost total in 2050 of $2813 billion. The estimated total costs for carbon capture and sequestration (CCS) in 2050 for domestic energy are $127 billion (4.5% of $2813; $46 per tonne $CO_2$). These CCS costs are less than 14% of the $937 energy cost savings shown in Table 1.1. CCS costs are the sum of personnel, energy, capital amortization, and miscellaneous costs. Without any CCS, user costs would total $2686 billion (95.5% of $2813 billion). The small CCS cost percentage seems well worth paying, given the benefits to the planet. The small size of the CCS costs is due to the highly innovative equipment designs proposed. $CO_2$ purchase costs for domestic energy total $169 billion (6.0% of $2813). However, purchase costs are funds transferred from fossil energy users to carbon dioxide sellers: it is therefore not a net cost to the U.S. economy.

## 13.9 Profits

Net profits are expected to increase significantly by 2050. Inevitable declines in profits from fossil fuel production, petroleum refining, and reduced energy usage will be more than offset by the large increases in biofuels production, capital spending, and infrastructure spending. The very large improvement in energy trade balance (over $2000 billion) will indirectly also enhance profits. A conservative estimate of the improvement in net profits is $500 billion per year.

# Chapter Fourteen: Technology Development

The outstanding benefits expected from the proposed program are dependent upon the successful development of key cost-effective new technologies. Although these technologies are firmly based upon known scientific and engineering principles, their development will be a very large challenge.

The required early development work might be accomplished by a single company or a few companies, assisted by subcontracts with a small number outside firms and consultants. Later, when the profitable expansion stage is reached, licensing the technology to multiple independent manufacturers (including international firms) will be logical. Numerous patents can be obtained on details of the new equipment. Major technology efforts are needed in the following four areas, which are interrelated (and thus development synergies will exist).

## 14.1 Fuel Cell Systems

Chapter 5 describes production models of proposed fuel cell systems. The 2050 proposal uses fuel cell systems very extensively for utility coal power generation, distributed generation, and in transportation. Individual fuel cell systems will have capacities ranging from 1 to 3000 kW, with some applications using multiple systems connected in parallel. The assumed 2050 total rated capacity of fuel cell systems is about 3400 GW, which is much larger than the existing U.S. grid generation capacity of 1030 GW. Some 61 million fuel cell systems are proposed, with nearly three-fourths of their capacity used in transportation.

The fuel cell systems will operate from a variety of carbonaceous fuels, including coal syngas, natural gas, propane, gasoline, jet fuel, and diesel fuel. They will use solid oxide technology and offer excellent efficiency, low maintenance cost, affordable installed cost, compact size, and low sound levels. The great majority of these fuel cell systems (except aircraft APUs, standby systems, and most military systems) will capture virtually all input carbon for sale as liquid $CO_2$ to be sequestered. Extensive further development of this technology from the 2016 state of the art is needed to meet all targets.

The early commercialization of small fuel cell systems for residential cogeneration will be an important element in this development, since it will provide valuable information on both design and manufacturing. This commercialization can also yield a rapidly growing revenue stream to help finance many of the other required development programs.

## 14.2 Gasifier Systems

Novel gasifier systems are needed for both the biofuels converters (Section 4.2) and advanced coal power plants (Section 6.7). They will produce clean syngas and salable byproducts from their solid feeds. The two types will have many features in common, although the coal models will be larger. Each will be co-fed pressurized steam and oxygen-enriched air from an associated subsystem and include sulfur and particulate capture. Their syngas will be free from tars and other contaminants and be suitable for fuel cell power generation (from coal) or hydrocarbon fuel synthesis (from biomass).

The total number of gasifiers assumed is about 720,000, with a total downstream product capacity of about 1100 GW (individual size from 1000 to 3000 kW each). The gasifiers will be autothermal (thermally neutral), highly efficient, compact, and have moderate cost. Many of them (those used in BNTL systems) will be co-fed natural gas in addition to biomass in order to produce syngas using less biomass feed.

## 14.3 Hydrocarbon Synthesis Systems

These systems are employed in the proposed biofuels converters (Section 4.2). Three types of synthesis systems will convert clean bio-syngas into hydrocarbon biofuels. Each will employ highly selective catalysts, heat exchange, phase separation, and other auxiliary subsystems. Each will produce liquid water and pure liquid $CO_2$ as byproducts.

The total number of converters needed for exports and domestic use is 570,000 (see Section 4.6), each with a biofuel HHV capacity of 1000 kW.

## 14.4 Carbon Dioxide Sequestration

The above fuel cell and hydrocarbon synthesis systems will include subsystems for $CO_2$ capture, purification, liquefaction, and temporary storage.

A significant additional program is required under U.S. governmental supervision (and funded by early small $CO_2$ fees on fossil fuels). This program will study likely sites for permanent underground sequestration, develop injection and monitoring techniques and equipment, and perform pilot injection trials. Most of the required $CO_2$ development work will use private contractors with close government supervision. Concurrent programs in other countries can be monitored, with information exchanged. The projected 2050 total $CO_2$ sequestered is 2.9 billion tonnes (see Table 11.2) with the total number of $CO_2$ capture systems being 62 million.

## 14.5 Subsystems

Subsystems development is also needed and should use working partnerships between subcontractors, consultants, and the parent firm(s). Work should include three areas, as follows.

### 14.5.1 Mechanical Systems

The various systems cited above will use large to very large quantities of active mechanical components, including compressors, blowers, fans, pumps, valves, and turbines. The desired specifications of many of these devices differ from items currently in mass production. Known technology can be used to design the suitable new components. Automated manufacturing will be appropriate for the large quantities needed. Ongoing opportunities will exist for improvements in efficiency, durability, reliability, and cost.

### 14.5.2 Electrical Systems

The required electrical subsystems include power conditioning (for main power output, battery interfacing, and auxiliary power needs), control systems, safety protection, and contactors. New designs using available mass-produced components (together with custom software) will usually be needed to meet specifications. Ongoing opportunities will exist for improvements to efficiency, durability, reliability, and cost.

**14.5.3 Materials**
Opportunities will exist for significant and ongoing performance and cost improvements to several categories of materials used in the above equipment. The categories will include catalysts, molecular-sieve materials, absorbents, structural materials (including some for elevated-temperature service), and fuel cell components. The use of very expensive or rare materials (e.g., precious metals) should be avoided or highly restricted.

**14.6 Manufacturing Technology Development**
The proposed program requires the mass-production of new products and components for these products. Custom manufacturing technology must be developed which maintains very high product quality while minimizing costs, especially personnel costs. Smaller fuel cell systems will enter mass production first, followed by larger fuel cell systems, and then biofuels and coal power systems. By 2050, over 60 million systems of the various types will have been manufactured for the U.S. alone. The primary company (or companies) must (in many cases) work with major component vendors to assist their manufacturing technology developments.

The ongoing challenges for manufacturing technology include having good flexibility to allow continual product improvements and modifications for new market segments. The use of inherently expensive manufacturing processes must be avoided. Other challenges include minimizing manufacturing capital costs and lead times to facilitate rapid expansion. Continual improvement in manufacturing costs will enhance competitive advantages, grow sales, and create desired additional jobs. The very large projected quantities and annual sales rates will enable progressively higher degrees of automation, which can also optimize quality.

Manufacturing technology should evolve with sales volume, avoiding the excessive addition of equipment investment too early.

**14.7 Contributions from Universities Etc.**
Institutions of higher learning can play a very important role by educating the required new engineers, scientists, managers, technicians, and other skilled personnel needed. They and governmental laboratories can perform research into many areas of supporting technology. Relevant topics will include catalysts, materials, small compressor designs, agricultural science, advanced manufacturing techniques, electronic components and circuits, and many others.

**14.8 Techical Strategies**
This section refers to sections 14.1 through 14.3 (work on $CO_2$ sequestration will not be discussed further in this chapter).

The required technology development program requires no scientific breakthroughs or discoveries. It will require, however, thorough understanding of engineering principles and techniques and a willingness to develop innovative designs wherever available designs do not meet requirements or are projected to be too expensive in mass production.

A relatively small team of highly capable engineers and technicians is needed, supported by a few scientists, administrative personnel, and managers. The technical team should mainly have multi-disciplinary skills, although a few narrow specialists could also be valuable. Ample funding and fast-track procurement processes are essential. A “skunk works” atmosphere should prevail in the early years. Time schedules and target dates should be flexible to avoid the adoption of technology destined to probable failure (of performance or cost).

Early development work should be performed at bench scale, with fast design-build-test-improve schedules. Parallel paths are desirable in many cases. Each design concept should have a conceptual path to later low-cost mass production. The goal of early development work is to demonstrate proof of concept, including extended and unattended run times with good interim efficiency and output quality.

After bench-scale success is achieved, pilot-scale designs and demonstrations can occur. Concurrently with pilot work, additional bench-scale efforts can continue to explore promising alternatives.

Preliminary work on manufacturing engineering for fuel cell components and stacks can begin as soon as designs are chosen for field-test fuel cell systems.

The United States is uniquely qualified to pioneer all these technologies. However, if the required technology is not developed in the United States, it is thought inevitable that other countries will eventually develop and commercialize the described equipment, relegating the U.S. to be importers, with many more jobs sited abroad.

Preliminary proof-of-concept demonstrations of all key new equipment are believed possible at a total development cost under $250 million over 5 years. Reaching overall profitability for a single company making all equipment types should be possible with a cumulative total investment under $1 billion and total time of 8 years (small fuel cell cogeneration systems should reach profitability much sooner and require much lower investment). These numbers are far lower than many recent advanced-energy alternatives.

# Chapter Fifteen: Discussion

## 15.1 Timing

This document describes an example scenario with the United States having zero net fossil carbon emissions in 2050 (with negative net emissions in subsequent years). The actual year when zero carbon is achieved will probably differ. However, the very large magnitude of the required efforts make it unlikely that zero can be reached much earlier. On the other hand, there are many reasons why zero might be reached later than 2050.

## 15.2 Technical Philosophy

The proposed 2050 energy plan includes a number of major innovations with a key attribute in common: they depend upon relatively small modular integrated equipment which is mass-produced in very large quantities. Small in this case is defined as a complete system no larger than can be carried on a standard flatbed truck. The most expensive individual module (currently thought to be a 3 MW coal power module) is expected to have an installed cost of $6.9 million in 2050, whereas recent coal plants have cost billions and use only a single huge piece of many equipment items.

Small equipment has multiple advantages. It can be developed and demonstrated faster and at lower cost than large systems. It makes exploration of alternatives affordable. It allows continual evolutionary improvements with short cycle times, which benefit customers and slow late-entry competitors. Factory mass production can utilize considerable automation and use manufacturing labor more productively. Product quality can be enhanced by factory pre-testing of each system and by using state-of-the art manufacturing quality procedures.

An analogy may be seen between the multi-million-dollar computer mainframes of the early 1960s and later mass-produced inexpensive personal computers, laptops, and smart phones. Existing coal power plants and oil refineries are analogous to the old mainframes, while the proposed mass-produced modules are analogous to personal computers.

The use of small modular systems allows users to expand incrementally when needed and also to gradually upgrade their systems as improved models become available. Very rapid coal power plant construction schedules are possible compared with conventional systems. The use of expensive services from large engineering firms can be minimized.

## 15.3 Roles of Government

Although governmental funding and subsidies are not required to develop and commercialize the new technologies, the Federal government must play an essential role for carbon dioxide, establishing the National Carbon Administration (section 11.4). Federal, state, and local governments should also play a role in establishing, collecting, and spending new road-use fees which replace fuel taxes.

Governments must also play important roles in education. The public must be educated to support and participate in the transition to clean and more efficient energy. The millions of new workers needed must be educated with the required skills.

More stringent air pollution regulations must be adopted, which will ensure the phase out of existing coal power plants and other highly polluting sources before 2050.

**15.4 International**

The rest of the world also seeks to eliminate or drastically lower its $CO_2$ emissions and reduce energy costs. The United States can export large quantities of biofuels and fossil fuels as shown in Table 13.4, with significant possible growth after 2050. We can also sell the advanced equipment described herein, partnering with local companies for its manufacture in many cases. The equipment can greatly improve energy efficiencies and user costs, while making CCS practical and affordable. Since very few countries have potential responsibly-exploitable biomass resources of a size approaching the United States, we will have a sustainable advantage for ongoing large biofuels exports. By 2050, many countries could join the U.S. in having zero net fossil carbon emissions. However, it will undoubtedly take longer for the entire world to reach zero (see below).

**15.5 Future Years**

After 2050, a number of trends are expected. Energy efficiencies, biofuels production, use of electric power for transportation, renewable power production, and CCS will all increase further, leading to growing net removal of $CO_2$ from the atmosphere by the United States. As cited in 4.1, potential U.S. production of biomass for conversion to biofuels (BNG and BLP) could exceed two billion annual dry tons by 2050, with continued growth.

Fusion (thermonuclear) power might gradually emerge after 2050, enabling a slow phase-out of coal power plants throughout the world. Inexpensive electric power can gradually replace fossil natural gas for many uses. The use of petroleum for fuels production can be phased out. Captured carbon from bio-fueled transportation can be recycled into bio-hydrocarbon liquid fuels using electrolysis (section 5.8) and hydrocarbon synthesis (section 4.2).

The entire planet possibly could reach zero net fossil $CO_2$ emissions sometime after 2050, and then begin a net removal of $CO_2$ from the atmosphere. All fossil fuel use as energy sources can probably be nearly eliminated before 2100. With growing sequestration of bio-carbon after 2050, the $CO_2$ concentration of the atmosphere could eventually be reduced to pre-industrial levels, possibly before 2150.

**15.6 Alternatives**

Numerous energy production and utilization alternatives (existing or possible) are not included in the proposed plan. This section will mention some of these and the reason for their exclusion. The actual 2050 case will probably include small amounts of many.

(1) Natural gas turbines and combined-cycle plants. These existing systems have no affordable path to $CO_2$ capture and will have generation costs considerably higher than the proposed new coal plants.

(2) Natural gas to liquids (GTL) plants. These could produce liquid fossil fuels with capture of excess carbon. Their products could have lower cost than liquids from petroleum, but higher cost than liquid biofuels, which would be preferred for their absence of any fossil carbon in the fuel.

(3) Natural gas for cement or iron making. New processes for producing cement and iron using coal are described in sections 9.4 and 9.5. If natural gas were used instead of coal, capital costs would be lower but operating costs higher. It is believed that coal alternatives will have more attractive combined cost.

(4) Coal to liquids (CTL) plants. These would have higher capital cost than biomass to liquids plants and much more difficult material handling. Their feed costs would be similar or higher than biomass plants (section 4.2.2), which would thus be preferred.

(5) Biomass to power. The proposed biofuels converters will include fuel cell subsystems to produce electric power for their own needs and could be designed to produce extra power for the associated facility. However, liquid biofuels are expected to sell for higher prices than wholesale electric power and thus would usually be a preferred product from biomass (with very large export potential). After 2050, some biofuels converters might be configured to produce only power when prices are high and biofuels when grid prices are lower. If grid power prices reach very low levels sometimes, liquid biofuels could be produced using electrolysis (see 5.8) of water and previously captured bio-$CO_2$. The electrolysis could be performed by power-generation fuel cell subsystems operating in reverse.

(6) Nuclear fission power. As noted in section 7.9, fission power has issues with radioactive wastes, safety, vulnerability, and cost which make its phase out probable (as is occurring in some European countries already).

(7) Energy storage. Chapter 13 discusses energy storage options, which are important for vehicles and short-term stationary systems. Most storage systems with high capacities are believed to be more costly than alternatives.

(8) Hydrogen. Relatively small quantities of hydrogen will be made from syngas for use in petroleum refining, liquid biofuels production, and ammonia production as discussed in the respective sections above. Section 10.1 explains why hydrogen is expected to be phased out as a vehicle fuel. Although hydrogen fuel for fuel uses could be made in the future from coal or natural gas with CCS (or from biomass with or without CCS), it would be more expensive, less efficient, and less convenient than the alternative fuels discussed.

(9) Petroleum. The proposed 2050 vision uses petroleum to produce fossil liquid fuels. Although it would be possible to replace these with biofuels taken from exports (bio-propane could also be made if desired), the continued limited production of fossil liquid fuels would reduce the costs of producing chemicals and materials and soften the impact of the downsizing of refineries.

(10) Alternative biofuels. Small quantities of biofuels and processes in use today might remain in use: used or new vegetable oils, ethanol via fermentation, biodiesel esters (which could be made entirely from biomass), and biogas from digesters. Most of these will be replaced by the superior alternatives described herein.

Vegetable oils could also be converted (using hydrogen) completely to alkanes to produce jet fuel, diesel, and propane. Although supplies would be limited, this method could be used in the interim before the proposed gasifier processes were available.

(11) Interim fuel cell systems The 2050 fuel cell systems described in Chapter 5 include $CO_2$ capture (except for a small percentage for standby, military, and flight use). Such systems are expected to succeed much smaller quantities of precursor designs. Fuel cell systems in use today and expected for the next few years will vent all $CO_2$ to the atmosphere. These will be followed by "capture ready" designs, which could subsequently be easily field-upgraded for CCS.

(12) Reduced energy usage Greater implementation of the most efficient user systems described could reduce consumption from the example totals.

(13) Increased use of renewables The 2050 totals of renewable power generation and biofuel production might be higher than the example.

(14) Altered biofuels product mix The ratio of BNG to BLP could differ from assumed totals.

(15) Liquefied natural gas (LNG) This form of natural gas (or BNG) could be used instead of compressed natural gas (CNG) to an increased extent, in spite of its higher costs for most domestic uses.

## 15.7 Outlook

Many arguments can be made why the proposed program will not succeed. Several of the proposed technical elements have been under development for decades and have consumed huge amounts of money without profitable results thus far. However, prior work has yielded both useful technical knowledge and cost information which are relevant to the proposed program.

The success of the proposed program requires the combination of four essential factors:

(1) Vision
(2) Technical Talent
(3) Management Talent
(4) Funding

With the proper quantity and quality of all four factors, the author believes a very high probability of success is likely.

# Appendix

## A1. Acknowledgements

Technology Management Inc. (TMI) has employed the author from November 1993 to the present, for which he is very grateful. Special thanks to Benson Lee, Michael Petrik, Dr. Chris Milliken, and Janet Gladstone. Helpful suggestions were also received from Drs. Philip Taylor and David Farrell and from my wife Katharine.

## A2. Author

Dr. Ruhl received BSE degrees in Chemical and Metallurgical Engineering in 1963 from the University of Michigan (Ann Arbor), with a minor in Electrical Engineering. This was followed by a PhD in Metallurgical Engineering in 1967 from the Massachusetts Institute of Technology (Cambridge), with a minor in Physics. His academic years included technical publications, extracurricular activities, and various honors.

From 1967 to 1982 he worked at Chase Brass and Copper Co. (subsidiary of Kennecott Copper) in Cleveland, Ohio. Chase manufactured and sold brass and copper mill products: sheet, strip, tubing, and rod. Job titles included Director of Engineering, Vice President of Engineering, and corporate director. He managed numerous manufacturing capital equipment projects, some highly innovative, with costs up to more than $5 million each. He acquired considerable experience with electrical, mechanical, and control engineering. He also was responsible for financial analyses, budgets, and technical management.

From 1969 to 1992 he worked part-time for Carbon Technology Inc. in Slocum, Rhode Island. CTI manufactures and sells mechanical carbon parts (including rotating seals and bearings) to many manufacturers. He served as a director and consultant to CTI and finally managed the profitable sale of the company.

From 1982 to 1993 he worked for BP (British Petroleum) research in Cleveland, Ohio. He worked on and managed a considerable variety of development and engineering projects, most of which involved high temperatures (ranging from about 900 to 2300 ºC). Some projects were concerned with ceramics manufacturing, some with syngas production, some with high-temperature chemical reactors, and some with hydrocarbons. One of his projects was the invention of a novel solid-oxide fuel cell in 1985 which led to the formation of a company dedicated to its development: Technology Management Inc. (TMI).

From 1993 to the present, Dr. Ruhl has been Vice President – Technology for TMI. Using his skills in mechanical, chemical, electrical, and materials engineering, he has played key roles in the design and development of successive laboratory and demonstration complete fuel cell systems. He has also performed extensive calculations and conceptual designs for many other fuel cell and advanced energy systems, and completed many cost, financial, and manufacturing projections.

## A3. Glossary, Abbreviations, and Conversions

| | |
|---|---|
| AEO | Annual Energy Outlook, published by the EIA (see Reference 1) |
| Alkane | Compound of carbon and hydrogen with no double or triple bonds |
| APR | Annual percentage rate |
| bbl | Petroleum or liquid fuel barrel. 1 bbl = 42 gallons |
| BLP | Bio-liquid paraffins (saturated-hydrocarbon biofuels): gasoline, jet fuel, and diesel |
| BNG | Bio-natural gas |
| BNTL | Biomass and natural gas to BLP |
| BTG | Biomass to BNG |
| BTL | Biomass to BLP |
| BTU | British Thermal Unit. 1 BTU = 1054.4 Joules |
| Capex | Installed capital expenditure |
| CCS | Carbon capture and sequestration |
| CF | Capacity factor. Percentage of theoretical maximum energy output per year |
| CHP | Combined heat and power (also called cogeneration) |
| CNG | Compressed natural gas |
| Cogeneration | Co-production of electric power and usable heat |
| $CO_2$ | Carbon dioxide |
| ºC | Degrees Celsius ºC = (ºF – 32)/1.8 |
| DG | Distributed generation |
| DOD | Battery depth of discharge |
| DOE | U.S. Department of Energy |
| EIA | Energy Information Association (a unit of DOE) |

| | |
|---|---|
| EJ | Exajoule 1 EJ = $10^{18}$ J = 1.0544 Quads |
| g | Gram |
| GDP | Gross Domestic Product of the U.S. |
| GJ | Gigajoule 1 GJ = $10^9$ J = 1.0544 million BTU = 277.8 kWh |
| GW | Gigawatt 1 GW = $10^9$ Watts = 1.0544 BTU/hr |
| HHV | Higher heating value. Enthalpy of combustion with water as liquid |
| HVAC | Heating, ventilation, and air conditioning |
| IGCC | Integrated gasification combined cycle |
| J | Joule. Metric energy unit. 1 J = 1 Watt-second |
| kg | Kilogram 1 kg = 2.2046 pounds |
| kW | Kilowatt 1 kW = 1000 Watts |
| kWh | Kilowatt-hour 1 kWh = 3.6 x $10^6$ J |
| $\Delta H_v$ | Latent heat of vaporization |
| LED | Light-emitting diode |
| LNG | Liquefied natural gas |
| LHV | Lower heating value. Enthalpy of combustion with water as vapor |
| mcf | Thousand standard cubic feet (scf) |
| mpge | Miles per gallon equivalent (based on energy content of gasoline or diesel) |
| MW | Megawatt 1 MW = $10^6$ Watts |
| NCA | National Carbon Administration (proposed Federal agency) |
| NG | Natural gas |
| NGL | Natural gas liquids (mostly propane and butane) |
| $NO_x$ | Nitrogen oxides (NO, $N_2O$, $NO_2$, and others) |

| | |
|---|---|
| PEM | Polymer electrolyte membrane (a type of fuel cell) |
| PV | Photovoltaic (usually for solar conversion) |
| Quad | Quadrillion BTU. 1 Quad = $10^{15}$ BTU = 1.0544 EJ |
| RCI | Residential, commercial, and industrial |
| RVP | Reid vapor pressure. The standard measurement of gasoline volatility |
| scf | Standard cubic feet. Used for natural gas. 1 scf has typical HHV = 1027 BTU |
| Syngas | Synthesis gas (mix of $H_2$, $H_2O$, CO, $CO_2$, $CH_4$, and $N_2$) |
| T & D | Electricity transmission and distribution |
| te | Tonne (metric ton) 1 te = 2204.6 pounds |
| TOU | Time-of-use grid power pricing |
| W | Watt, metric unit of power. 1 W = one Volt times one Ampere |

## A4. References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