

Virtual Battery Systems

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Summary

New technologies are described which can help achieve major net fossil CO₂ removal from the atmosphere while reducing the share of GDP spent on energy. Also recommended are efficiency and infrastructure improvements which increase the advantages of the proposed systems.

Virtual battery (VB) systems will perform the equivalent function of very large-scale storage of electricity from wind and solar. VB systems are considerably more cost effective and have far superior timing flexibility than chemical storage batteries.

Virtual batteries use surplus wind and solar power (transported by the power grid) to immediately perform a valuable function. At any other time (when user needs exceed renewable supplies), they generate power for the grid. Four types of virtual-battery systems are recommended, all with zero or negative fossil carbon emissions (using permanent underground sequestration of CO₂):

1. Distributed generation systems produce on-site power at residential, commercial, and industrial sites.
2. Biomass converters produce superior biofuels from biomass crops and wastes.
3. Modified petroleum refineries utilize VB systems to improve profitability and reduce emissions.
4. Direct air capture systems remove CO₂ from the atmosphere.

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Chapter 2. Introduction

This report briefly summarizes studies undertaken during the past several years by the author.

2.1 Virtual Battery Definition

Virtual batteries are defined in this document as stationary systems which can economically "store" extremely large quantities of electricity for later to much later use.

Conventional rechargeable (secondary) batteries can deliver roughly 85% of input electricity at a later time. Their total storage cost per kWh of delivered output is reasonable only when they are cycled very frequently (typically daily). Existing secondary batteries are commonly lead-acid or lithium-ion. Many other systems are under development, including flow batteries.

In contrast, virtual battery systems use grid input power for an immediate valuable purpose. At another desired time, they generate grid output power. The quantity of output energy (kWh) may be considerably higher or lower than input energy. Also, the timing of inputs and outputs is completely flexible: the virtual-storage function is economical for periods of hours, days, weeks, months, or seasons. The proposed systems enhance their economics by also operating profitably using no grid input or output when appropriate. Extensive use of virtual battery systems can assist a massive expansion of solar and wind systems, since their generation timing often poorly matches user-consumption timing.

The terms "virtual battery" and "virtual battery system" are used interchangeably herein.

2.2 Objectives

Future U.S. energy systems should have three major objectives.

Environmental

Fossil CO₂ emissions should be completely eliminated and replaced by net CO₂ removal from the atmosphere. Anthropogenic emissions of methane and other potent greenhouse gases as well as air pollution of other types (especially NO_x, SO_x, and particulates) should be drastically reduced. Energy-related pollution of water and land should also be virtually eliminated.

Effectiveness

The reliability of electricity for users should improve. The performance, comfort, and convenience of energy systems should be enhanced.

Economics

The above benefits should be achieved using a smaller share of GDP for user energy expenditures than at present.

2.3 Remarks

Although this report focuses on the United States, the proposed approaches are desirable worldwide. Section 13.3 cites international considerations.

Present and future verb tenses are used interchangeably for later years.

Fuels not labeled biofuels are fossil fuels (e.g., natural gas, propane, gasoline, diesel).

Chapter 14 contains lists abbreviations and references.

PART ONE: SHARED TECHNOLOGIES

Chapters 3 through 7 summarize considerations and technologies relevant to all the virtual battery systems described in Part Two.

Chapter 3. Timing

Electric utilities cope with continual challenges in matching the timing of power generation with varying user demands. These demands vary considerably with time of day, day of the week, weather, and other factors. Nearly all existing power grids have negligible electricity storage and thus require real-time balancing of supply with demand.

A variety of methods are presently used to continuously maintain balance. Delivered voltage is varied somewhat, slightly affecting consumption. Power is exported to or imported from adjacent grids. Most types of connected generation equipment are capable of at least some intentional variation in power output ("load following"). Many customers are charged rates which vary with supply-demand balance (seasonally, daily, or even hourly), providing incentives to adjust their consumption timing.

Extra power needs are often met using natural-gas peaking turbo-generators, which can be started and stopped quickly. However, their total cost per kWh is expensive due to moderate fuel efficiencies and low average capacity factors (capacity factor is the ratio of actual generation kWh to possible generation if operated full time). In addition to higher cost, peaking turbo-generators emit more CO₂ and pollution per kWh.

Unwanted surplus power can be avoided by curtailment. Fueled generators can be shut down. Solar arrays can be taken off-line. Wind turbines can have their blades furled to halt generation. All types of curtailment increase the average cost per kWh delivered from that equipment, since capital costs are spread over reduced output.

The desired large future increases in solar and wind power systems will greatly increase timing challenges. Their instantaneous power output varies from zero to maximum values which are over five times their annual average. Ideally, wind and solar power timing complement each other. However, this is often not the case (for example, during "silent nights").

Wind turbines produce zero power at wind speeds below a threshold value (roughly 7 miles per hour). They must be halted to avoid equipment damage at very high wind speeds.

Solar arrays produce zero power at night and very low power under thick daytime clouds. Some variations are predictable by time, date, and site. Others depend on weather.

The proposed virtual battery systems have excellent synergy with increased solar and wind power, delivering excellent timing flexibility as well as environmental and economic benefits.

Chapter 4. Efficiencies

Known and emerging technologies can more than double average U.S. energy usage efficiency by 2050, halving delivered consumption in spite of expected population and GDP growth. While some energy uses will improve by only moderate percentages, others can more than double their efficiencies. Expected future energy price increases will improve returns on investment for efficiency improvements. Total annual user energy costs as a share of GDP can remain about the same if efficiency improvements offset higher prices.

The virtual battery systems described in this report will have a greater benefit if energy usage efficiencies significantly improve, since their practical maximum installed capacity will be constrained by factors such as biomass production and their ROIs will be greater.

4.1 Electrification

Expected large-scale electrification of transportation will include pure-electric as well as plug-in hybrids (having engines also). All are expected to use advanced lithium-ion battery systems. Light-duty vehicles (cars, SUVs, pickup trucks, minivans, etc.) under 5000 pounds will comprise the majority. Other applications will include most short-haul commercial trucks and buses and a growing number of short-haul aircraft. Electric vehicles often achieve more than triple the energy efficiency of conventional engine vehicles.

Highly-efficient, air-source electric ductless heat pumps will replace conventional furnaces, fired heaters, and traditional central air conditioners. These systems can more than double HVAC efficiencies for most residential and commercial buildings. Advanced designs of ductless heat pump systems will be powered by both electrical and thermal inputs, enabling even higher energy efficiencies and superior flexibility of operation.

Many industrial processes now heated by burning fuels can be made more efficient using electric heating systems.

4.2 Building Envelopes

Major efficiency improvements are possible in residential, commercial, and industrial buildings by substituting high-efficiency windows and doors and greatly enhancing roof, door, and underfloor insulation. Other features can reduce unwanted solar gains and/or enhance desired solar heating.

4.3 Advanced Fuel-Cell Systems

Large long-distance transportation equipment such as freight trucks, ships, and locomotives can be built or converted to use highly-efficient advanced fuel cell systems for both primary and auxiliary power. These would be fueled by clean diesel fuel (Chapter 10) with 100% carbon capture and sequestration (zero carbon emissions). Energy efficiencies would be roughly double conventional engine-based systems.

The stationary distributed-generation systems in Chapter 8 also use advanced fuel cell systems.

4.4 Other

Efficiency improvements will result from infrastructure improvements (Chapter 5).

Chapter 5. Infrastructure

Infrastructure enhancements are needed for many of the proposed virtual battery systems. They can also improve efficiencies and effectiveness.

5.1 Utility Electric Grid

The existing grid includes both transmission and distribution (T&D) subsystems. Today's grid requires major efforts to remedy deferred maintenance and correct deficiencies. With the aid of future automated equipment, some of the existing grid could be replaced by more reliable underground lines.

Major additions of solar and wind capacity will require considerable expansions. The proposed expansion of user electricity use and addition of virtual battery systems will also require additions. Power reliability can be enhanced using many types of improvements. Small microgrid features can be added to allow distributed generation to power neighbors during outages.

During the interim period before all grid power becomes zero carbon, the grid will carry comingled zero and non-zero power, which can be billed at different rates.

Grid billing will undergo major changes from existing practices. Most users will pay fixed monthly charges (possibly waived for some virtual battery systems) based upon their maximum instantaneous power. Electricity prices will vary hourly (over a considerable range) based on grid supply versus demand. In many cases, net metering will apply (user variable sell price equals buy price).

5.2 Natural Gas Pipeline Network

The existing pipeline network will be significantly improved to greatly reduce methane leakages. It will also be expanded to serve new virtual battery systems where needed.

The network will transport co-mingled fossil natural gas and bio-natural gas (BNG), which have nearly identical properties. The two fuels will be billed at different rates. Users will pay both fixed and variable charges. The variable rates are expected to vary monthly and by only modest ratios compared with grid variable rates.

5.3 Road Network

The public network of roads and bridges requires major work to remedy deferred maintenance and correct deficiencies. Expansions and improvements will be required to serve some of the larger virtual battery systems. Enhancements to traffic control systems can speed travel, improving efficiency and convenience.

New funding methods for road maintenance and needed construction will replace existing taxes on liquid fuels. All road vehicles will be charged for ton-miles traveled, regardless of their energy source.

5.4 Air Travel

Efficiency improvements in air travel will result from improved air traffic control systems which reduce travel distances and flight times. Other improvements will result from adoption of improved turbofan engines and airframe designs. Advanced large aircraft fueled by liquid hydrogen (Section 10.3) will be even more efficient. Battery-powered planes will begin to fly shorter commercial routes, with the highest energy efficiency

Chapter 6. Carbon Sequestration

The term carbon sequestration is used in this report for the permanent storage of carbon dioxide (CO₂) deep underground. Carbon capture and sequestration (CCS) refers to the capture of gaseous CO₂ followed by its purification, liquefaction, and sequestration.

Pressurized carbon dioxide is a liquid at room temperature (at atmospheric pressure it is a gas at all temperatures above -57°C, below which it is solid "dry ice"). The liquid is commonly transported today in specialized trucks and rail cars for making carbonated beverages and many other uses.

The virtual battery systems described below perform CO₂ capture, liquefaction, and temporary on-site outdoor storage in dedicated tanks. Any surplus which is not later recycled by the virtual battery system is periodically pumped onto trucks which will transport it to nearby collection tankage. Specialized rail cars (or trucks) will then move the liquid to carefully chosen facilities which will pump the liquid deep underground for permanent sequestration into suitable formations.

Reference (1) summarizes extensive studies which have identified hundreds of sites throughout the United States with an estimated capacity to permanently store hundreds of years' worth of all fuel-related CO₂. Huge quantities of natural gas (lighter and more stable than CO₂) have remained underground for over one hundred million years. In many types of underground rock formations, CO₂ is expected to react (within decades) with the minerals present, forming stable solid carbonates.

The proposed virtual battery systems will perform CCS on all their surplus fossil CO₂. Proposed future transportation and other systems using fossil fuels will also capture all their CO₂. The systems described in Chapters 9 and 11 will include CCS on CO₂ removed from the atmosphere. Straightforward accounting can quantify CO₂ sequestered from mixed sources.

By capturing and sequestering nearly all fossil CO₂ emissions plus large quantities removed from the atmosphere by biomass and direct capture, a large net annual removal of CO₂ can be achieved before 2050 (negative carbon emissions).

Chapter 7. Electrochemical Systems

All of the virtual battery systems described in Chapters 8 through 11 incorporate similar advanced electrochemical subsystems. This chapter briefly summarizes features of their preferred design and operation.

The proposed subsystems have important attributes in common. They operate at excellent energy efficiencies, have useful lives in continuous operation measured in years, are compact, and are projected to be moderate in cost when mass-produced on automated machinery. They operate inside sealed, well-insulated enclosures with hot-zone temperatures near 900°C. Multiple stacks of identical electrochemical cells are used. Unlike many other types of electrochemical systems, no precious metals are employed. Annual maintenance costs are modest.

7.1 Reversible Cells

Each cell is a circular disc with a diameter near 65 millimeters and a total thickness (including separator) under one millimeter. A pattern of small internal holes inside each cell is used for internal gas manifolds. Each cell is assembled from five types of elements, as follows.

Its solid-oxide ceramic **electrolyte** is an impervious thin flat disc. It is made from yttria-stabilized zirconia (YSZ), which readily conducts oxygen ions but not electrons.

Its impervious **separator** has the same shape as the electrolyte. It is made of a different oxide ceramic which readily conducts electrons but not oxygen ions. A separator is used between each pair of cells.

Two porous **electrodes** on either side of the electrolyte distribute incoming gas mixtures over the electrolyte surfaces, where charge-transfer reactions occur between oxygen ions and electrons. Gases in each electrode flow from a feed manifold to an exit manifold. When an electrode delivers oxygen ions to the electrolyte, it is operating as a **cathode**. If it is receiving oxygen ions from the electrolyte, it is acting as an **anode**. Most of the cells employed are reversible: each electrode is sometimes used as a cathode and other times as an anode. Proprietary materials and fabrication methods ensure high performance and long life under such conditions.

A number of impervious **seals** are used to isolate the gas flows in each electrode. In most cases, one electrode in each pair has a 360-degree rim seal while the other one has an open rim with no seal. The chamber surrounding the cells serves as one manifold.

Many cells comprise each stack and multiple stacks are used in even the smallest 1 kW systems.

7.2 Hot Subassembly

Stacks are installed inside a hot subassembly, which is designed for reversible operation. In small systems, about 300 cells form each stack (inherently connected in series electrically), with a height under 12 inches. Larger systems employ taller stacks.

A well-insulated vessel (designed for the planned maximum pressure) also includes heat exchange to maintain the desired nearly-uniform stack temperature distribution, fuel-mixture hot catalytic reactor (when needed), gas manifolding, power connections, ceramic-spring stack clamping assemblies, and sensors. Valving outside the hot section alters gas flow paths when operating modes are switched.

7.3 Operation

In the proposed virtual-battery systems, the reversible stacks are operated in two modes, as follows. Temperature is controlled to a target level (typically 900°C). Depending upon the application, stack operating pressure (all stacks, both electrodes) is maintained at about 1.1 to 30 bar.

7.3.1 Fuel-Cell Mode

Electric power is electrochemically generated by operating stacks with an oxidizing gas mixture (air or enriched air with up to 90% O₂) fed to their cathodes and a carbonaceous fuel mixture (containing H₂, H₂O vapor, CO, CO₂, CH₄, and often N₂) fed to their anodes. Depending upon the application, the fuel mixture is produced by a gasifier, as synthesis-reactor tail gas, or by a hot catalytic fuel processor.

DC power is produced by the stacks (typically 0.7 to 0.8 Volts per cell) along with considerable surplus heat, which is heat-exchanged to supply the fuel-processing endotherm (if present) and partially preheat incoming reactants.

7.3.2 Steam-Electrolysis Mode

Hydrogen gas is produced from steam by its electrolysis to H₂ and O₂. The stacks employed are fuel cell stacks operated in reverse or dedicated to this mode (depending upon application). A steam mixture with about 2% H₂ is fed to the cathode, which yields the desired exit hydrogen-steam mixture with up to 98% H₂. The oxygen removed at the anode either reacts with fuel gas (present when appropriate) or collected for an alternative purpose. Chapters 8 through 11 cite the numerous hydrogen uses.

PART TWO: VIRTUAL BATTERY SYSTEMS

The four types of virtual battery systems listed in Table One and described in Chapters 8 through 11 can be developed, improved, and installed very extensively before 2050. **All will operate with zero or negative fossil carbon emissions.**

When grid prices are low, virtual battery systems will import (purchase) grid power for immediate profitable use (in the VB system and site loads). When grid prices are high, VB systems will profitably export (sell) surplus power to the grid. At medium prices, the systems will also operate for profit maximization: either exporting to the grid or supplying only site loads ("load following" with neither import nor export), depending upon prevailing fuel versus electricity prices.

Table One. Virtual Battery Systems

Type	Distributed Generation	Biomass Converters	Refineries	Direct Air Capture
Fuel Input	Natural Gas or Propane	Biomass	Petroleum plus NGL	Coal
Power vs Grid Price				
Low	Import	Import	Import	Import
Medium				
High	Export	Export	Export	Export
Outputs vs Grid Price				
Low	Natural Gas or Propane	100% Biofuel	100% Products	
Medium	Variable Power	50% Biofuel	85% Products	
High	Max Power	Max Power	70% Products and Max Power	Max Power
Atmospheric CO2 Removed vs Grid Price				
Low				Maximum
Medium		50%		67%
High		Maximum		33%

Available models of each type of system will have differing ratios of maximum import to maximum export power (often but not always greater than 1.0).

Future grid electricity pricing will differ from today. Fixed monthly charges to each customer will fund grid maintenance and returns on transmission and distribution (T&D) capital, based on true costs. Variable pricing per kWh will vary considerably with time based on supply and demand, strongly influenced by larger, highly-variable solar and wind supplies. Variable prices for different categories of users (residential, commercial, and industrial) will differ less than presently. Export variable prices will equal or be only slightly below import prices ("net metering" or near net metering).

By 2050, all conventional fossil-fueled power plants (including peaking gas turbines) should have been retired. Zero-carbon dedicated power plant types will include hydroelectric, geothermal, solar, wind, and possibly nuclear. Virtual-battery installations will supply all remaining electric power needs. They will eliminate the need for curtailment from the dedicated power plants.

Some distributed generation systems will use heating oil instead of propane fuel (not shown in Table One).

Chapter 8. Distributed Generation

Distributed-generation (DG) virtual battery systems will be installed at many millions of sites: residential, commercial, and industrial. Each will reduce net user energy cost and supply the entire facility with true uninterruptible power during grid outages of any duration (eliminating the need for backup generators). The systems will be non-polluting, have zero carbon emissions, and operate with minimal noise. Available sizes will range from 1 kW to 3000 kW (3 MW), with larger needs using multiple 3 MW systems. Pipeline (fossil) natural gas fuel will be used for most systems due to its cost advantage. Models using propane and heating oil fuel will also be sold. All carbon from the fuel will be captured as pressurized liquid CO₂, stored outdoors in insulated tanks for periodic removal.

The new DG systems will employ the solid-oxide electrochemical technology outlined in Chapter 7. They will operate with outstanding energy efficiencies (figures below are based on fuel lower heating value (LHV)). Net AC electric output efficiency averages 60%. An additional 34% of high-grade heat is available to operate absorption heat pumps for space heating or cooling. Up to 18% of lower-temperature heat can assist space heating (the sum can reach 112% due to heat released by water and CO₂ condensation). No known alternative DG system type can even approach such efficiencies.

Each DG system will be sized to at least supply maximum site demand, allowing surplus power to be sold whenever profitable. Sites having absorption heat pumps can further increase export sales (by turning off their electric heat pumps) when prices are very high.

At low grid prices, the novel VB systems will import considerable grid power for fuel synthesis. This low-priced import power will also power all site loads (the fuel cell system generates no power in synthesis mode). By operating the electrochemical stacks in reverse, steam (from input water) is converted into hydrogen (plus oxygen, which is used or vented). Liquid CO₂ from the on-site storage tank is vaporized and catalytically reacted with the hydrogen to efficiently produce synthetic natural gas (SNG), which immediately flows into the connected pipeline (reducing net fuel purchases). Systems fueled by propane or heating oil fuel will synthesize them instead.

At intermediate grid prices, the system can either load follow (supplying only site loads) or operate at maximum power and sell the surplus, based prevailing prices. At high grid prices, maximum-power DG operation will be advantageous.

All DG systems are designed for the optional addition (at their installation or subsequently) of solar photovoltaic (PV) systems. They will also include a moderate-size battery bank to enhance load following and increase maximum available surge power during grid outages. Connected PV systems will enjoy reduced cost versus conventional stand-alone installations due to shared subsystems.

These VB systems thus operate continuously, with economic benefits at all grid prices. The grid supplies site peak power needs, minimizing use the battery bank (except during outages). The VB location at a user site provides the added benefits of surplus heat availability and uninterruptible power. DG systems will reduce grid energy losses, since their export power will travel very short distances to nearby users. In many cases, they can be used by the utility to power local "microgrids" to deliver power during outages to neighbors lacking their own DG systems.

Chapter 9. Biofuels

By about 2040, very large annual quantities of biofuels are produced and sold in the United States. They consist of bio-natural gas (BNG) and the liquids bio-kerosene, bio-propane, and bio-gasoline. Since by that time fossil fuels are sold only for applications which capture for sequestration all their CO₂, all other fueled equipment uses biofuels.

Today's processes for obtaining useful energy from biomass will have been phased out by 2040, including the production of ethanol and biodiesel-ester fuels and its combustion for steam generation and space heating (except in some domestic fireplaces). All these processes have very poor energy efficiency and most emit harmful pollution. Superior new VB biomass energy conversion systems ("converters") are described in this chapter.

The converters are usually installed close to sources of their principal feeds. Their virtual battery function requires connection to a suitable utility grid. BNG converters are also connected to a natural gas pipeline. A fraction of their biomass feed carbon is sequestered as Bio-CO₂, making the converters carbon negative (net CO₂ removed from the air).

The converters operate in three modes, depending upon prevailing grid prices (which the utility may vary hourly based on their supply versus demand). At low grid prices, maximum biofuel is produced with the assistance of grid imports. At intermediate prices, grid power is zero (neither import nor export) and biofuel is produced solely from biomass. At high grid prices, biofuel production is paused and maximum power exported to the grid. Such operation provides true virtual battery function.

Converters operate throughout the year, with occasional brief maintenance shutdowns. They produce considerable surplus heat, which can be utilized to heat adjacent greenhouses and for other purposes. The availability of such heat may often enable cost-effective year-round growing of fresh produce for local sale (with improved overall energy efficiency).

Biomass converters are manufactured in several sizes, with maximum electric outputs from 300 to 3000 kW. Each is transported on standard trucks to the installation site as factory-built subassemblies. Multiple converters are used for larger capacities.

9.1 Biomass Feeds

Each converter is continuously fed with biomass at constant rate. Suitable storage of biomass enables 12-month operation in any U.S. climate. Most converters will use blended feeds containing both crops and wastes.

Dedicated biomass energy crops are expected to comprise the majority of converter feeds. It is desirable that they are: well-suited to the local climate, deep-rooted perennials, fast growing (C4 plants preferred), of multiple species (biodiverse), and include both herbaceous and woody types. Examples include switchgrass, miscanthus, and paulownia (a C4 tree which repeatedly re-sprouts from its stump). Any weeds can be harvested with the crop and also utilized. Good rain water management design can usually eliminate pumped irrigation needs. No-till farming can minimize methane emissions and reduce costs. Sustainable farming practices can apply the organic fertilizers described below and minimize the need to apply (organic) pesticides or fungicides.

Staggered harvesting (e.g., grasses in warmer months, woody plants in colder months) can minimize required storage and provide year-round employment. New designs of automated harvesters for woody plants can improve worker safety and productivity.

Reference (2) details extensive studies by the federal government which show that up to 1.5 billion tons per year of dry biomass (including wastes) for energy can be sustainably produced in the United States without harming food supplies. This total can exceed 2.0 billion tons annually by 2050 if numerous possible improvements are implemented.

Many types of biomass wastes are suitable, including those from food processing, forest-products processing, yard and garden collections, manures, and sewage treatment solids. New types of driers (sited near generation points) can very efficiently dry manures and sewage solids in an odorless manner. Many wastes have minimal-to-negative selling prices.

Biomass wastes can be co-fed with plastic wastes, municipal solid wastes, and various other wastes (after automated pre-processing to remove items which can be profitably recycled and any large inorganic pieces). The sequestration of part of the feed carbon will exceed the fossil carbon included.

The great majority of plastic wastes (nearly all made from fossil fuels) are not being recycled today. It is expected to remain uneconomical to significantly increase their recycling in the future. These wastes decompose extremely slowly in landfills and are a serious source of land and ocean pollution. The proposed converters can profitably utilize their energy while capturing all their carbon as CO₂ for sequestration. Plastic wastes usually have negative selling prices. Municipal solid wastes have components of both biomass and fossil origin. Their usual landfill disposal is somewhat costly and causes pollution (even when control attempts are in place). Mixed biomass liquids and slurries could also be pumped (in limited quantities) into converters designed for their co-feeding with the usual solids. Examples are dirty solvents and contaminated food syrups.

9.2 Bio-Natural Gas (BNG) Converters

Virtual-battery BNG converters produce either BNG or export electric power from the above feeds. Their superior-quality BNG product is 98 to 99% methane (CH₄), with the balance being CO₂ and N₂ plus several parts per million of the usual odorant. The BNG is fed into the natural gas pipeline, where it co-mingles with the flowing fossil natural gas.

Byproducts from the converter are pressurized liquid CO₂ (mostly of biomass origin, usually also with a little of fossil origin) at about 15°C, solid organic fertilizer (containing all minerals in the feed, including phosphorus, potassium, and sulfur), and useful heat. The fertilizer can be enriched with bio-ammonia (see Section 9.3) and used in biomass crop farming.

Converters are fully automated and sealed to prevent odors and pollution emissions. They operate at minimal noise levels (no engines or turbines are used). Their subsystems include material handling, heat exchange, feed gasification, reversible electrochemical (Chapter 7), and a catalytic methanation reactor. Their balance of plant includes compressors, pumps, valves, molecular-sieve (PSA) oxygen enrichment, refrigeration for CO₂ liquefaction, power conditioning, control, miscellaneous equipment, framing, and enclosures. Their hot section operates at temperatures up to 900°C and pressures up to 30 bar. Hydrogen made from steam in the hot electrochemical section reacts with CO and CO₂ from biomass gasification to produce CH₄ in the methanation reactor (operating near 250°C).

Forecast lower-heating value (LHV) converter efficiencies are about 85% in grid-input mode, 83% in zero-grid mode, and 65% in grid-export mode. Surplus heat utilization will enhance combined energy efficiencies.

9.3 Bio-Liquid Converters

Biomass converters with many similarities to BNG converters will produce three hydrocarbon bio-liquids (in proportions which can be varied during operation according to market demands). Bio-propane is extremely similar to fossil propane: over 95% propane plus butanes and the same odorant. Bio-gasoline is greatly superior to conventional premium fuel: 99 octane, with no aromatics. It will have the same seasonally-adjusted Reid vapor pressure (RVP). Bio-kerosene consists entirely of mixed alkanes and is suitable for use as jet fuel, diesel, heating oil, and military fuel (JP-8 equivalent). These biofuels will be mandated by law for equipment not able to capture CO₂.

The reactor section (considerably more complex than used in BNG converters) will incorporate multiple catalytic reactors plus more heat exchange and separations. Gasifier exit gas and hydrogen from the electrochemical section will be reacted to the desired products, with process tail gases used as electrochemical fuel. LHV efficiencies of these converters are 7 to 8% lower than BNG converters in their fuel-production modes (the same 65% in grid-export mode). However, their higher capital and operating costs will be justified by the higher selling prices of their products.

Another type of bioliquid converter can make anhydrous bio-ammonia fertilizer from biomass (with optional virtual-battery capabilities). This may be sold directly or reacted with gasifier byproduct solid fertilizer to form a complete organic fertilizer (the gasifier solid output is nitrogen free).

Chapter 10. Refineries

Virtual-battery refineries will succeed all current petroleum refineries. Most will result from extensive modifications to existing facilities. They will be completely pollution free., emitting no odors, NO_x, SO_x, particulates, CO, or organics. All input carbon not transferred to their products will be captured as pure liquid CO₂ for sequestration.

The new refineries will employ very large electrochemical systems, fueled by carbonaceous gas mixtures made from refinery inputs. The systems will continually produce both electric power and hydrogen from steam. They will include reversible sections which sometimes use low-cost import power to produce additional product and at other times generate export power for sale when grid prices are high.

Sections 10.2 through 10.7 describe the refinery output streams. Although their contained carbon is fossil in origin, very little will reach the atmosphere.

10.1 Feeds

The refineries are fed by five streams as follows.

Petroleum (crude oil), domestically produced from on-shore wells operated with superior environmental practices. Suitable inputs may have any density and sulfur content. Off-shore wells are no longer used due to their higher costs and multiple environmental risks.

Natural gas liquids (NGL) are separated from well natural gas at improved, distributed, pollution-free gas processing systems (which remove sulfur for sale and excess CO₂ for sequestration). Processed natural gas (with an odorant added) is fed into the pipeline system. NGL consists of hydrocarbons with two to six carbons: propane is the largest component.

Liquid carbonaceous wastes include used lubricants, dirty organic solvents, and various organic mixtures needing pollution-free disposal with zero-CO₂ emissions. Their carbon content is nearly all of fossil origin.

Treated makeup water is sustainably obtained from nearby rivers, lakes, and/or groundwater.

Low-cost grid power (when available) from a transmission line designed for ample bidirectional flow.

10.2 Diesel Fuel

Diesel fuel will comprise perhaps half of the refinery output fuels. It will be similar to today's best in composition and properties, with only a few parts per million sulfur.

Diesel is sold only for applications which capture all its carbon as liquid CO₂ for sequestration. Suitable equipment will chiefly use advanced fuel cell technology. The majority of applications will be in transportation: freight trucks, commercial trucks, locomotives, and ships. Some stationary systems without natural gas service will prefer diesel (then called heating oil) to propane as their fuel.

The refineries will manufacture diesel by two different methods: conventional and new.

The conventional method (used today) distills petroleum in complex column assemblies. Some fractions are used in the product directly. Additional product is obtained by cracking heavier distillates.

The new refineries will gasify most of the residual oil from distillation in equipment of improved design. The resulting synthesis gas can be combined with additional hydrogen (from the electrochemical section) to produce kerosene by a method similar to that used for bio-kerosene (Section 9.3). This kerosene is completely suitable for addition to the diesel mixture (and has similar properties).

10.3 Other Fuels

Three other fuels will be produced by the new refineries: propane, natural gas, and hydrogen.

The propane will be identical to today's product: it will consist of about 95% propane plus butanes and traces of other hydrocarbons. It will contain a few parts per million of ethyl mercaptan odorant. The great majority will be separated from NGL feed, augmented by a small amount from petroleum processing. Nearly all this (fossil) propane will be used in DG systems (Chapter 8) which capture all carbon for sequestration.

Synthetic natural gas (SNG) is produced as a byproduct of conventional petroleum processing. Additional SNG can be made as needed from gasifier synthesis gas and hydrogen as described in Section 9.2. SNG is fed to pipeline systems, where it co-mingles with BNG and natural gas separated from well gas.

Pure hydrogen fuel is produced electrochemically from steam, as is the considerable hydrogen used internally in the refinery. It is liquefied using ultra-low temperature cryogenic equipment and is stored and transported in highly insulated tanks (internal pressures are moderate). The major expected market for liquid hydrogen fuel is in aircraft of completely new designs (for passengers and freight) using ultra-efficient, low-NO_x turbofan engines. Liquid hydrogen offers zero carbon, unexcelled energy per unit weight, but low energy per unit volume. New aircraft will look much different, with large fuel tanks inside their triangular bodies.

10.4 Materials, Chemicals, and Feedstocks

The new refineries will produce many of the same carbonaceous non-fuel products as presently. The largest tonnage is asphalt (bitumen), used mainly for paving and also for roofing products. Many will also produce ethylene and propylene, used primarily as monomers but also as chemical-plant feedstocks. Other hydrocarbon products include paraffins (for lubricants, candles, etc.) and various chemical plant feedstocks (including olefins, aromatics, and paraffins). Solid high-carbon petroleum coke is sold for graphite manufacture, etc.

10.5 Export Power

When grid prices are high, the reversible electrochemical sections can produce extra electric power for profitable export sale by producing less hydrogen and hence less of some products.

10.6 Carbon Dioxide

Virtually all of the feed carbon which is not contained in the products is captured as liquid CO₂. Large on-site storage tanks are well insulated to prevent evaporation in all weather conditions. Typical storage conditions are 15°C and 51 bar (725 psi). Removal for sequestration usually employs specialized rail cars. In some cases, pipeline or waterborne transport is practical.

10.7 Byproducts

The refinery byproducts are ash, sulfur, and heat.

Ash is produced in the gasifiers from petroleum, water treatment waste, and other waste feeds. It is fused into a slag for sale: suitable for use as aggregate in many asphalts and concretes.

Sulfur is separated from petroleum during its gasification. Depending upon market demands and prices, it is converted into either concentrated sulfuric acid or pure liquid sulfur. Both are sold for transport in specialized rail cars. The largest market for sulfuric acid is manufacture of phosphate fertilizers. Pure sulfur can be used to enhance the properties of road asphalt or to manufacture sulfuric acid.

Surplus heat has various potential uses, including the very economical desalination of seawater using advanced equipment designs.

10.8 Operation

The refinery gasifiers will operate at a constant rate. Their feed will be primarily residual oil from petroleum distillation plus a small percentage of the wastes cited. As Table 1 indicates, product output rates will vary with grid prices. Expected time to change operation to the adjacent category is under an hour.

At low grid prices, considerable grid power will be imported and used to power the site and also to make extra hydrogen, enabling maximum product production.

At intermediate grid prices, no grid power is imported or exported. The refinery produces all its electricity needs and an intermediate amount of hydrogen and products.

At high grid prices, maximum power is produced allowing considerable export. Hydrogen production is minimized resulting in lowest levels of product manufacture.

Chapter 11. Direct Air Capture

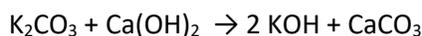
Numerous new virtual-battery Direct Air Capture facilities will remove CO₂ from the atmosphere for permanent underground sequestration. Collectively, domestic direct air capture (DAC) systems will affordably remove billions of tonnes (metric tons) of CO₂ per year (totals approaching today's annual U.S. emissions) by 2050. They will use coal as their primary energy source in novel systems which totally prevent pollution. Their VB feature will utilize surplus low-cost grid power to augment CO₂ capture rates and export power to the grid when prices are high. Many of these new facilities will be located at former coal power-plant sites, which already have grid transmission-line connections, rail service, coal handling and storage, and a source of makeup water. Each facility will consist of the following subsystems.

11.1 Absorption

Multiple large assemblies use large fans to create intimate contact between ambient air (having perhaps 450 ppm CO₂ by mid-century) and water saturated with potassium hydroxide (KOH). A significant fraction of the incoming CO₂ reacts with the dissolved KOH to form aqueous potassium carbonate (K₂CO₃). Air exiting the assembly contains about 150 ppm CO₂ (two-thirds removal). Although the absorption reaction is exothermic, some of the water from the solution evaporates, increasing exit air humidity and slightly lowering its temperature. The equipment is designed to minimize loss of solution as entrained aerosols (Section 11.7 further discusses these). The high solute concentration in the absorber solution prevents freezing in all but the coldest weather (operation is briefly paused when necessary).

11.2 Solution Processing

Solid calcium oxide (CaO) from calcining (Section 11.5) is dissolved in water to form a saturated solution of calcium hydroxide (Ca(OH)₂). It is reacted with absorption exit solution as follows.



Since calcium carbonate (CaCO₃) is virtually insoluble, it precipitates from solution and the reaction proceeds nearly to completion. The calcium carbonate is efficiently dried before being fed to calcining (Section 11.5). The absorption solution is slightly heated by these exothermic reactions. Treated makeup water replaces absorption evaporation losses.

11.3 Coal Gasification

Coal with average particle size 1-2 cm is fed through airlocks into novel pressurized adiabatic gasifiers. Co-fed hot steam and enriched air or oxygen gasify the coal, producing raw synthesis gas ("syngas") fuel. All sulfur in the coal is converted into H₂S which is removed by a ZnO bed during syngas cooldown (sulfur recovery is discussed in Section 11.7). Cooled coal ash exits through airlocks. The gasifiers operate continuously at constant flows. The gasifier and electrochemical sections typically operate at 30 bar. Gasifier hot zone temperature is near 700°C.

11.4 Electrochemical

The well-insulated electrochemical subsystem contains solid-oxide electrochemical stacks, heat exchange, gas valves and manifolds, and electrical connections. The stacks operate reversibly based on variable grid power pricing. At low prices, power flows into this section, electrolyzing input steam into hydrogen (added to calciner fuel) and oxygen (fed to the gasifier along with more steam) and providing necessary heat. At medium or high prices, part of the clean fuel gas from the gasifier is fed to this

section along with steam and enriched air. Outputs are electric power, superheated steam and enriched air for the gasifier, and exhaust containing mainly steam and CO₂ plus small percentages of N₂ and O₂. Typical stack temperature is 900°C.

11.5 Calcining

The calcining section uses high-temperature heat input to decompose solid CaCO₃ into solid CaO and CO₂ gas. Included are a pressurized calcining assembly, solids handling, gas manifolding, airlocks, heat exchange, and burner assemblies. Feeds are dried CaCO₃, fuel gas, and enriched air. Exit streams are CaO and an exhaust mixture with approximately 60% CO₂, plus steam and a little nitrogen. Typical pressure is 10 bar and hot zone temperature near 1025°C.

11.6 CO₂ Recovery

All the CO₂ from both the coal and the CaCO₃ are separated as pure liquid CO₂ for permanent sequestration. Calcining exhaust is compressed to at least 25 bar and both exhausts are cooled to 2°C, thereby condensing nearly all their contained H₂O. The resulting high-CO₂ mixtures are processed using refrigeration, pressure-swing absorption (PSA), and heat exchange to yield pure liquid CO₂ (typical delivery temperature 15°C and saturation pressure 51 bar) with nitrogen and water vapor vented. The sequestered liquid CO₂ is a mixture of fossil and atmospheric CO₂, with their ratio depending upon grid power import or export. Example calculations show about 2.8 tonnes air CO₂ per tonne coal CO₂ with grid import, 1.9 ratio with zero grid power, and 0.9 with export to grid.

11.7 Balance of Plant

The balance of plant (BOP) subsystems employed includes air enrichment, sulfur processing, ash processing, power conditioning, water purification, solids handling, storage, grid interface, and others.

Pressure-swing absorption (PSA) subsystems include compressors and molecular-sieve beds to enrich ambient air to about 90% O₂. Sulfur processing converts ZnS from the gasifier section into ZnO for reuse and produces either pure liquid sulfur or concentrated sulfuric acid for sale. Coal ash is fused to produce a dust-free slag salable as a construction aggregate. Power conditioning converts stack power (typically about 400 Volts DC) to or from high-voltage transmission-line AC. It also provides suitable power to all BOP equipment.

An extremely small fraction of the absorption solution will be lost as entrained aerosols in air discharged from the absorption units. This solution contains dissolved K₂CO₃ and KOH. Potassium is an essential plant nutrient, present in all complete fertilizers. Its required makeup to the facility will be moderate in cost and will provide slight benefits to surrounding farms or woodlands.

Example calculated LHV efficiencies of the DAC systems (based on CaCO₃ calcining enthalpy change at 0°C) are 77% in grid-import mode, 73% in grid-zero mode, and 69% in grid-export mode. CO₂ air capture rates (relative to grid-zero rate) used in these examples are 150% in import mode and 50% in export mode.

11.8 Economics

DAC plants will be paid a fair ROI for each tonne of CO₂ captured from the atmosphere, funded by the general energy tax (Section 12.1). Their total coal use by 2050 is expected to approach the high levels consumed the late 1990s.

PART THREE: CONCLUSIONS

Chapter 12. Implementation

Rapid development of the proposed highly innovative new technologies can preferably occur in the private sector. The very large long-term profit (and breakthrough environmental) opportunities should attract ample patient investment. Small teams of skilled technical personnel with highly capable management should vigorously pursue development programs leading to small-sized demonstration equipment, parallel technological paths, rapid timelines, and iteration. Concurrent with the product development efforts, preliminary planning for economical mass production should occur. All development programs should begin by thoroughly surveying existing technologies, with licenses obtained where desirable.

For distributed-generation applications, one program should develop the proposed new advanced thermal systems (including highly efficient absorption heat pump subsystems). Larger programs should pursue the proposed reversible fuel cell and fuel-synthesis subsystems. Satisfactory first-generation complete prototype systems of 3 to 10 kW size should be ready for demonstrations in under five years.

The biofuels systems require a similar program. Early demonstration systems should be far smaller than proposed commercial size to speed progress and to enable parallelism and iterations. The electrochemical subsystems for biofuels can use similar technology to the residential systems. Bench-scale reactor and catalyst studies for liquid biofuels should precede prototype development of those systems.

Development of virtual-battery systems for refinery applications can begin after distributed-generation and biofuel system successes. Coal systems development should partner with an existing company already demonstrating absorption subsystems.

12.1 Governmental Roles

Government subsidies of energy from general tax revenues should be phased out before about 2040. With major biomass farming, farm subsidies can be reduced. A tax on fossil CO₂ emissions should be enacted and steadily increased until (when ample biofuels are available) such emissions are prohibitively expensive.

A new National Carbon Administration should be created to supervise and fund companies who transport and safely and permanently sequester billions of tonnes per year of liquid CO₂. Sequestration would be funded by a moderate tax (possibly called by another name) on all fuel users. Funds from this tax would also purchase liquid CO₂ removed from the atmosphere by biofuels converters and direct air capture systems, providing a fair ROI to them.

A different small tax on all forms of energy can be used to assist low-income consumers with energy-saving improvements (and sometimes with energy purchases).

Utility rate regulations should be significantly modified to improve fairness and encourage desired electricity consumption patterns. Electricity exports from coal-fueled DAC systems should be limited to preserve their major purpose of atmospheric CO₂ removal.

Chapter 13. Discussion

The author plans another report in early 2022 presenting a new numerical example proposed energy summary for the United States in 2050.

13.1 Calculations

The virtual battery systems and some of the other advanced energy technologies cited were studied using extensive technical calculations. Types included material and energy balances, thermodynamic equilibrium, electrochemical, heat transfer, rotating equipment, and electrical. Many financial calculations were also performed to compare new alternatives to conventional systems and to one another. The planned 2022 report will include summaries of key calculations.

13.2 Alternatives

Many alternatives to the specific technologies described have been examined.

If a DG system were operated (part or full time) on more-costly biofuel rather than the assumed fossil fuel, the resulting bio-CO₂ sequestration from its operation would increase total removal from the atmosphere. However, increased biofuel consumption might strain available production capacity.

Alternative DG systems without CO₂ capture nor fuel synthesis would also be sold (at lower installed cost) to users lacking suitable outdoor sites for liquid CO₂ tanks. They would use more costly biofuel and their VB import power would only supply site needs.

Biomass converters could produce more biofuel from the same biomass feed if fossil natural gas were co-fed (and its carbon sequestered). However, such systems would reduce net CO₂ removal from the atmosphere (reduced bio-CO₂ sequestration).

Biomass converters with a different gasifier design could produce solid biochar from a fraction of the feed carbon. This biochar would incorporate the organic fertilizer components discussed in Chapter 9 and would be an excellent additive to farming soils, which would permanently sequester this carbon. However, biochar production would reduce biofuel production, possibly leading to difficulty meeting market demands. Biofuels are also likely to yield higher sales revenues than biochar.

Some of the largest virtual-battery systems could achieve higher energy efficiency in grid export mode if a turbine-generator were included. However, their addition would increase sound levels, reduce operating flexibility, and increase both capital and maintenance costs.

In applications where low grid prices do not justify the added capital cost of using import power in VB systems, alternative models could hot idle at these prices, using grid import only for other site loads.

13.3 Exports

Although this document discusses only the United States, its recommendations are applicable to the rest of the world (with certain modifications). The U.S. can export many elements of the new technologies using licensing, joint manufacturing ventures, equipment sales, and consulting. It can also export limited quantities of biofuels, liquefied natural gas (LNG), petroleum, and coal.

The challenge of limiting global warming must involve the entire world, which can also greatly benefit from the proposed financial and other benefits discussed.

13.4 Longer Term

The installed capital cost of all types of VB systems is expected to decline gradually after high-volume manufacturing is reached. Their modular nature will allow capacity expansions to improve profits and/or meet greater site needs.

After 2050, nuclear fusion power may become cost effective and practical. If so, it can gradually reduce and eventually eliminate the need for any fossil fuels. Continued net removal of CO₂ from the atmosphere will probably be desirable until its concentration returns to the pre-1900 level.

13.5 Author

The author earned degrees in chemical and metallurgical engineering in 1963 from the University of Michigan and a PhD in materials engineering from MIT in 1967. He subsequently acquired extensive experience in electrical, mechanical, and manufacturing engineering. His career in the private sector, with experience in technology development and capital projects management. He has worked in the field of advanced energy since 1985, joining Technology Management Inc. (a fuel cell developer, succeeded by Anywherenergy) in 1993 after years at BP. He is now a part-time consultant and author.

His website, robertruhl.com, contains eight previous reports on advanced energy topics plus this one. Another report is planned for 2022, as mentioned above.

13.6 Conclusions

The proposed energy system changes can achieve all of the major objectives listed in Section 2.2 by 2050. U.S. fossil CO₂ emissions (nearly 5 billion tonnes per year in recent years) are replaced by a net removal of a similar magnitude. Other air pollutants will also be greatly reduced. Electricity supply reliability will significantly improve, as will comfort and convenience. Total annual energy expenditures as a share of GDP will be lower than today.

All of the proposed types of VB systems produce significant potentially-usable surplus heat. DG systems will perform water and space heating and power combination heat pumps (with both electrical and thermal inputs). Biofuel systems could heat and cool large greenhouses. Refinery systems could provide thermal and electrical energy to large seawater desalination equipment. DAC systems would utilize their heat for humidification of their CO₂-depleted exit air.

Unlike most other comprehensive plans for combatting global warming, this proposal preserves the continued major production and use of fossil fuels (without CO₂ emissions and in a less-polluting manner), preserving jobs and profits. The expected reduced petroleum and natural gas consumption will extend life of reserves and enable increased exports. The desirable increase in coal use (returning to historic maximum rates) is sustainable for over a hundred years due to very large known reserves.

The proposed repurposing of many types of problem wastes as supplemental energy sources for the new gasifiers is a valuable additional result. Problem wastes include plastics not recyclable economically, mixed wastes headed for landfills, unwanted manures, and dirty solvents.

The financial benefits of the proposed program will partly result from a near doubling of average energy efficiency, which more than offsets considerably higher unit prices. Significant additional benefits will result from building upgrades, equipment sales and service, and exports. A net increase of well-paying full-time jobs with benefits is expected. The added costs for the huge fossil CO₂ emissions reduction and other environmental benefits are included in the net financial totals.

Chapter 14. Abbreviations and References

AC	Alternating current
BNG	Bio-natural gas
BOP	Balance of plant
°C	degrees Celsius
C4	Photosynthesis path with four-carbon intermediate
CCS	CO ₂ capture and sequestration
CH ₄	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
DAC	Direct air capture of CO ₂
DC	Direct current
DG	Distributed generation
GDP	Gross domestic product
H ₂	Hydrogen
H ₂ O	Water liquid or vapor
HVAC	Heating, ventilation, and air conditioning
kW	Kilowatt (a unit of power)
kWh	Kilowatt-hour (a unit of energy)
LHV	Lower heating value (H ₂ O as vapor)
MW	Megawatt (1000 kW)
N ₂	Nitrogen
NGL	Natural-gas liquids
NO _x	Oxides of nitrogen
O ₂	Oxygen
PSA	Pressure-swing adsorption
PV	Photovoltaic
ROI	Return on investment
SNG	Synthetic natural gas
SO _x	Oxides of sulfur
T & D	Transmission and distribution
VB	Virtual battery
YSZ	Yttria-stabilized zirconia

References

1. Carbon Storage Atlas Fifth Edition, National Energy Technology Laboratory, 2015
2. Billion-Ton Report 2016, Oak Ridge National Laboratory, ONRL/TM-2016/160