Proposed Biofuels 2050

By Dr. Robert C. Ruhl

March 2024

robertruhl.com

Table of Contents

1. Summary

U.S. energy consumption in 2022 was responsible for fossil CO_2 emissions of 4.9 billion tonnes. Liquid biofuels (ethanol from corn or biodiesel from vegetable oils) supplied about 2% of this energy.

This document proposes a plan to manufacture by 2050 large quantities of four affordable new biofuels. The plan would produce a net annual reduction of 1.5 billion tonnes of fossil CO_2 emissions. The plan is expected to achieve attractive economics without government subsidies.

The new biofuels would be bio-natural gas, biopropane, biogasoline, and bio-kerosene. They would replace their fossil counterparts in all applications where CO_2 capture is impractical. Bio-kerosene would replace jet fuel and also utilized in many applications now using diesel fuel or heating oil.

The new biofuels would be made from rapidly-growing farm crops and mixed wastes. Crop-derived feeds would be hay from grasses and wood chips from trees. The wastes would be mostly biomass wastes (from farms, yards and gardens, food wastes, trash, etc.) plus any type of plastic waste not being recycled.

Novel, highly efficient, non-polluting converters would gasify the feeds and use chemical reactors and other equipment to produce the fuels, with part of their carbon captured as liquid CO_2 for permanent underground sequestration. Feed-to-biofuels conversion would occur in minutes. The grid-interactive converters would also enhance the economics of wind and solar power by providing virtual grid electricity storage.

The plan would phase out the production of ethanol, existing biodiesel fuels, and fuel gas from digesters or landfills. Incineration of carbon-containing wastes would be also phased out. Landfill additions would be far smaller.

2. Introduction

This document briefly summarizes a proposed plan to produce large annual quantities of new biofuels for the United States by 2050. The author's website, robertruhl.com, also contains previous essays on advanced energy recommendations. Another essay is planned for later in 2024 to show how the proposed biofuel technologies might be combined with other innovations, resulting in major economic and environmental benefits for the U.S. The author's recommendations combine concepts from open literature with his own ideas. All numerical values for future years are preliminary and approximate.

In this document, present and future verb tenses are used interchangeably for subsequent years. Section 8 contains abbreviations, definitions, and conversion factors of energy units. Metric units are primarily used in this paper (converted from the archaic units used by the DOE). References are in Section 9.

2.1 DOE Energy Data and Forecasts

Reference 1 is the most recent energy outlook from DOE, including actual quantities for 2022 and their forecasts to 2050. Fuel energy contents are higher heating values. Financial figures in this document use constant 2022 dollars.

U.S population is forecast to grow from 333 million in 2022 to 372 million in 2050. GDP is forecast to grow from $25.1 trillion in 2022 to $42.4 trillion in 2050.

In 2022, delivered U.S. energy consumption was 65.0 EJ of fuels plus 14.0 EJ of purchased grid electricity for a total of 79.0 EJ. Fuels used to generate grid electricity are not included in these values.

2022 user energy expenditures totaled $1.75 trillion (7.0% of GDP).

2022 energy-related fossil CO_2 emissions were 3.4 billion tonnes from fuels plus 1.5 billion tonnes from electricity generation for a total of 4.9 billion tonnes per year. Fossil CO_2 emissions have been proven to be a major contributor to global warming.

2.2 Present-Day Biofuels

The above 2022 fuels total includes 1.2 EJ of ethanol and 0.4 EJ of biodiesel.

Ethanol is made from corn, now using a third of the U.S. annual corn harvest. It is blended into gasoline at usual levels up to 10%. Ethanol production has a fossil carbon impact near zero when all the fossil energy used in its production is counted. It has about two-thirds of the energy content of gasoline per gallon. Its greater production cost versus gasoline is funded by massive federal subsidies.

Biodiesel is commonly an ester mix produced from vegetable oils and methanol (made from fossil natural gas). It is blended into petroleum diesel at levels of 10-20%. It is considerably more expensive than petroleum diesel.

The disadvantages of these fuels include high production costs, adverse impact on food prices, minimal global warming advantages, and unsuitability for an order-of-magnitude production increase by 2050.

2.3 Functional Objectives

The new plan should produce desired quantities of four types of premium biofuel (natural gas, propane, gasoline, and kerosene) with negative CO_2 emissions (net removal from the atmosphere). Biofuel distribution should use existing infrastructure. Pollution from biofuel production should be negligible.

The biofuels should be manufactured from hay, wood chips, solid biomass wastes, and any type of plastic wastes. The production of existing liquid biofuels should be phased out before 2050.

Virtual-battery operation should be included: boosting biofuels yields when low-cost grid power is available and exporting electricity to the grid when prices are high.

2.4 Economic Objectives

The biofuels should be affordable to users and enhance farm incomes without government subsidies.

Attractive returns on investment should be obtained from all biofuels-related equipment.

Fuel users should have financial incentives for conservation and desirable fuels selection.

Food prices should be little affected by biofuels production.

Technology development costs and risks should be moderate.

Exports of should be significantly increased.

User prices should fairly reflect delivered costs and environmental factors.

3. Feeds

The proposed converters would be continuously fed with prepared solid mixtures containing crops and/or wastes. Overall U.S. averages might be roughly two-thirds biomass crops with the balance being wastes. Plastic wastes might comprise about 5% of total feeds. Individual converters will usually be fed only one of the following categories.

3.1 Crops

Farms growing biomass crops would usually also grow conventional crops on part of their farmed land.

Biomass crops will preferably include both herbaceous crops (usually grasses) harvested during warmer months and woody crops (usually trees) harvested during colder months. Biodiversity within each type will benefit wildlife and reduce vulnerabilities to pests and diseases.

Preferred biomass crops are deep-rooted perennials well-adapted to local climate and its variability. Rapid growth is desirable, which is a characteristic of plants using C4 photosynthesis. Future plant breeding research is expected to develop new varieties with faster growth and other improvements. Preferred fertilizers include types made from biofuel converter ash as described herein. Well-engineered rainwater management systems can store surplus water on site (including pumping underground when appropriate) and minimize fertilizer runoff. Sustainable irrigation will reduce flammability and enhance growth rates.

No-till farming practices are preferred to limit costs and the release of methane (much worse than CO_2 for global warming) from buried biomass. Most weeds can be harvested along with the crops and included. Trees will be limited in height and planted to maximize sunlight capture. Coppice techniques (new growth sprouting from stumps after cutting) with trees such as poplar, willow, alder, and paulownia have the potential for large sustained yields.

Operators of advanced, semi-automated harvest machinery will sit in climate-controlled cabs, with negligible risk of injury. Tree-harvest equipment will include vision and artificial intelligence to maximize annual yields. Fallen leaves will be collected in season using new vacuum collectors.

3.2 Biomass Wastes

Suitable feeds will be obtained from farms, food processing plants, forest-product processing plants, residential and commercial yards and gardens, and similar sources. Some will be available seasonally and others throughout the year. Farm wastes will include manures.

3.3 Mixed Wastes

Suitable mixed wastes include sorted municipal solid wastes (from residential, commercial, and industrial sources) and sewage-treatment solids. They will consist primarily of biomass (“biogenic”) components such as assorted paper and food wastes, but will also contain any type of plastic not being recycled. The fossil carbon contained in the plastics will comprise only a small percentage of the carbon being permanently sequestered from the converters. This ability to divert plastic wastes from landfills into economically useful products is a significant added benefit of the proposed process.

3.4 Preparation, Transport, and Storage

Well-designed automated equipment will prepare each type of biomass for converter use, transport, and temporary storage. Preparation will include (as needed) drying, size reduction, and the automated removal of unsuitable objects. Most preparation equipment will be installed close to the feed sources. Grasses will be chopped into short lengths. Harvested wood will be reduced to small chips (sawdust and leaves may be included).

Trash (municipal solid wastes) will be sorted by advanced automated equipment equipped with vision, other sensors, and artificial intelligence. Numerous categories of recyclable items will be removed separately. Also removed will be any items not suitable as converter feeds. Some of these items will be subsequently be disassembled into usable components.

Feed transport will use pollution-free trucks designed for the specific type of biomass, enclosed to prevent losses during travel and contain odors. Silos and barns will be used for protected storage and designed to minimize odor emissions.

3.5 Feed Costs

The cost of different types of prepared feeds delivered to converter sites will vary considerably. Crops will usually be the most expensive, but available in larger quantities and affordable. Many types of waste will have a negative cost in their initial state, but their delivered cost will increase after required processing, transport, etc.

4. Products

The proposed converters operate alternately in three different modes based on their grid power flow: Zero, Import, or Export. Zero and Import modes will produce the four biofuels described below, with an example product mix of 15% bio-natural gas, 5% biopropane, 30% biogasoline, and 50% biokerosene (higher heating value basis). These ratios can be varied to satisfy contractual obligations and market demands.

4.1 Bio-Natural Gas

This fuel (abbreviated BNG) is very similar to fossil natural gas. It has the same heating value per standard cubic foot and contains a few parts per million of the same odorant for safety purposes (tetrahydrothiophene, THT, C_4H_8S). It will be co-mingled with fossil natural gas in conventional pipelines. BNG consists primarily of methane, with a small percentage of ethane and a very low percentage of propane.

It will be used in a wide variety of residential, commercial, and industrial applications where CO_2 capture from fossil natural gas is impractical or uneconomical. Such applications include a great variety of fired heating equipment (such as ranges, water heaters, and furnaces) and some engines. BNG will sell at higher prices than fossil gas, which will only be sold to users who perform complete carbon capture for sequestration.

4.2 Bio-Propane

This fuel is virtually identical with conventional (fossil) propane in composition (over 95% propane, balance butane) and properties. It has the same heating value and contains a few parts per million of the same odorant for safety purposes (ethyl mercaptan, ethanethiol, C_2H_6S). It is sold as pressurized liquid, transported in the customary large tank trucks.

The fuel will be used in place of fossil propane where CO_2 capture is impractical. Common applications will include outdoor grilles, portable torches, ranges, and many other types of heating equipment. Some will be used in advanced fuel-cell systems. It will rarely be used for forklift trucks, which will be replaced by plug-in models. By 2050, it is expected that fossil propane will no longer be sold for applications other than the manufacture of certain chemicals.

4.3 Bio-Gasoline

This will be a drop-in replacement for conventional premium (fossil) gasoline, with multiple advantages. Its octane rating is 98 and is free from the carcinogens present in conventional gasolines (benzene and other aromatics). Its Reid Vapor Pressure (RVP) is seasonally adjusted for ease of engine starting, matching existing gasolines. The product is comprised chiefly of isooctane (2,2,4-trimethylpentane, C_8H_{18}) with isobutylene (2-methylpropane, C_4H_{10}) added to regulate RVP. Due to its superior composition, it will produce lower engine emissions (CO, particulates, unburned hydrocarbons, odors, etc.). Its heating value per gallon is about 4% lower than conventional gasoline. It is transported in conventional tank trucks.

Most bio-gasoline will be used in hybrid vehicles which operate primarily on plug-in electricity and use gasoline engines for extended range. Other applications will include small portable tools, generators, outboard motors, and small aircraft. By 2050, it is expected that (fossil) gasoline made from petroleum will no longer be produced.

4.4 Bio-Kerosene

This distillate liquid fuel will be a drop-in replacement for conventional fossil jet fuel, diesel fuel, heating oil, and JP-8 military fuel. It is free from the carcinogens present in the fossil versions and has an excellent Cetane rating. It has good lubricity and is formulated for equivalent cold-temperature flowability. It is blend of normal alkane hydrocarbons only. It is transported in conventional tank trucks.

The majority of bio-kerosene production will be used in commercial jet aircraft. Significant quantities will also be used in other applications where CO_2 capture is impractical, including diesel engines, military purposes, and fired heating equipment where lower cost piped gas is not available. Ongoing sales of fossil diesel and heating oil (at lower prices than biokerosene) will by made only to customers who capture all their carbon for sequestration (usually employing advanced fuel cell systems).

4.5 Export Electricity

When grid prices are unusually high, converters are operated in Export mode, generating maximum electricity for sale to the utility grid and producing no biofuel.

4.6 Liquid CO_2

Pure liquid CO_2 is a byproduct in Zero and Export modes. It is temporarily stored in on-site tanks at about 15°C and 55 bar. Large dedicated trucks transport this liquid to sites performing permanent underground sequestration. With the expected average product mix and operating mode distribution, nearly half the biomass carbon will be sold as CO_2 for sequestration, with the balance incorporated in the biofuels. The sequestered CO_2 makes the proposed process significantly carbon-negative: photosynthesis captures CO_2 from the atmosphere to make biomass and nearly half its carbon is then permanently sequestered underground (see Section 6.2).

4.7 Water

Surplus pure water is captured during Zero and Export modes. It is temporarily stored in tanks to supply Import mode needs. With expected operating mode shares, net surplus of water is recovered, which can be used locally, with any excess used to assist equipment cooling.

4.8 Fertilizer

The converters will continuously produce in all operating modes a granular solid organic fertilizer containing all of the minerals present in the biomass (including phosphorus, potassium, and trace elements). The weight of this fertilizer is expected to average roughly 3.7% of dry biomass weight. Possible subsequent upgrading of this fertilizer is discussed in Section 6.4.

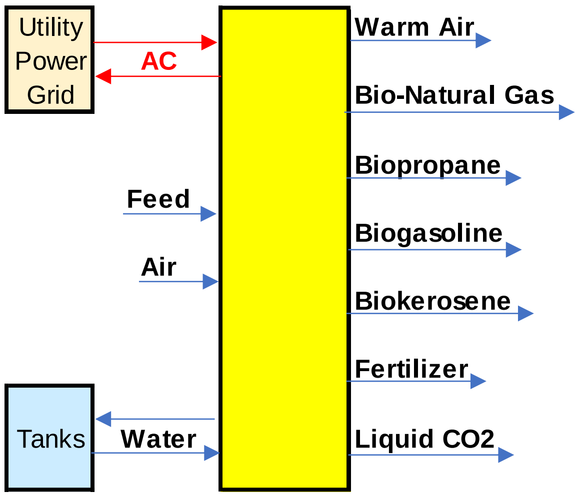
4.9 Usable Heat

All operating modes will also yield potentially usable byproduct heat as clean hot air. This heat might be used to dry wet feeds, in greenhouses, or for other purposes. This (filtered) air will have oxygen contents negligibly below ambient, since the great majority is used only for process cooling. Well-engineered greenhouses with no heating costs could produce valuable and desirable fresh local produce such as tomatoes and lettuces.

5. Converters

Below is an overall schematic of the proposed biofuel converters. This chapter gives an overview of their design and operation, with further details provided in Section 7.

Figure 1



The converters will alternately operate in three different modes: grid zero, grid import, or grid export. Most will operate the majority of the time in grid zero mode, with no utility power import or export. At other times they will either import power to maximize biofuels production or export maximum power with no biofuel production. Feed input and fertilizer output will remain constant in each mode. Mode operating fractions can be varied to meet contractual obligations and to take advantage of favorable grid pricing (typically changing frequently). Most of the air is used for process cooling, with the warm air output having potentially usable heat. The CO_2 byproduct is sold for permanent underground sequestration.

5.1 Grid Zero Mode

The four biofuels are produced in proportions which can be varied in response to market demands and contract obligations: Section 4.10 lists example averages. Over 80% of feed lower heating value (LHV) is present in the biofuels. They contain slightly over 50% of the feed carbon, with the balance captured as CO_2.

5.2 Grid Import Mode

When available, low-cost AC grid power is imported to enable the conversion of all feed carbon into biofuels (with no CO_2 produced). Water is input from storage. The required import power is slightly greater than feed LHV. Biofuels LHV totals about 1.57 times feed LHV, giving a converter energy efficiency over 75%.

5.3 Grid Export Mode
When grid prices are unusually high, the converters can generate export AC power at about 70% LHV efficiency (with no biofuels production). All carbon in the biomass is converted to liquid CO_2 and all feed hydrogen to stored water.

5.4 Capacities
The majority of the converters might have rated outputs of 1000 kW (1 MW) biofuels LHV in grid zero mode, 1900 kW biofuels LHV in import mode, and 850 kW power output in export mode. Biomass feed rate would be 565 pounds/hour (dry weight basis) and fertilizer production 21 pounds/hour.

At example operating mode shares of about 25% grid import and 20% grid export and with an average annual capacity factor of 93%, each such converter produces about 30.2 TJ/year biofuels LHV, 5.0 TJ/year (1400 MWh/year) grid export, and uses 9.3 TJ/year (2600 MWh/year) grid import. Approximate annual totals are 2300 tons dry feed, fertilizer 85 tons, and liquid CO_2 1700 tonnes.

Converters could be manufactured in a least two sizes, for example 1 MW and 3 MW. Most installations will use multiple converters.

A small percentage of the converters will use a modified designs for sites lacking grid connections and/or natural gas pipeline connections (needed for export of bio-natural gas). Converters without grid connections will always operate in zero-grid mode. Converters without pipeline connections will produce altered biofuels shares.

5.5 Installation
Converter sites will include multiple converters installed outdoors on concrete pads, conveyors for feeds and fertilizer, storage assemblies for feeds and products, grid-interface equipment, and interconnections. Each will also include a building containing maintenance and employee facilities plus a control room.

Since the converters will be designed for rapid installation, most complete installations by experienced contractors will require less than one year. Most converters will be installed near their sources of feeds.

Production downtime is minimized by using many independent converters at each installation, facilitating maintenance.

5.6 Manufacture
Perhaps ten highly automated factories distributed throughout the United States will manufacture complete converters, each factory tested before shipment. A converter will consist of two or more subassemblies suitable for road transport on conventional flatbed trucks.

The moderate capacity of each converter has a number of advantages. Transport and installation costs are minimized. Manufacturing costs are minimized by quantity production in factories using considerable automation.

Using cross-licensing, several independent companies will manufacture the equipment in competition with one another. Ongoing improvements will enhance reliability and reduce costs over time.

5.7 Technology Development

Although based on many proven technologies and technical calculations, considerable development work is needed to fully develop detailed converter designs and their manufacturing technology. The first full-sized demonstration converters could be operating by the early 2030s. A subsequent essay by the author planned for later in 2024 will discuss technology development recommendations for this and other advanced energy technologies.

6. Discussion

In this chapter, feed and fuel energies are given in higher heating values and financial estimates use constant 2022 dollars.

6.1 Proposed 2050 Energy Consumption

Major improvements in energy usage efficiencies are possible by 2050 and will be described in the report planned by the author later in 2024. A preliminary forecast for 2050 U.S. energy consumption is 60% of the 2022 total (see Section 2.1) or 47.4 EJ (HHV). This total might consist of 21.0 EJ of delivered electricity and 26.4 EJ delivered fuels. Fossil fuels used to generate some of the delivered electricity and are not included in the 26.4 EJ.

Production of the four proposed biofuels might have an HHV of 12.0 EJ (45% of delivered fuels). Additional solid biofuels (firewood and hardwood charcoal) would be 0.5 EJ. Delivered fossil fuels (used almost exclusively with complete CO_2 capture and sequestration) would consist of 10.0 EJ of natural gas, 2.5 EJ of diesel fuel, and 1.4 EJ of petroleum and natural gas liquids (used to produce materials and chemicals).

6.2 Biofuel Quantities

Production of the biofuels will require feeds having a heating value of 14.2 EJ. Their estimated dry weight is 850 million tons. Co-products will consist of 32 million tons of dry organic fertilizer, 620 million tonnes of liquid CO_2 for sequestration, and a large quantity of potentially usable heat. Avoided fossil CO_2 emissions by using these biofuels instead of their fossil equivalents is 890 million tonnes, for a combined reduction of 1510 million tonnes per year. Reference 2 summarizes DOE studies concluding that very numerous sites exist throughout the U.S. with the capacity to permanently store massive quantities of liquid CO_2. At many of these sites, the CO_2 will chemically combine with mineral deposits to form completely stable solid carbonates within a few years.

If two-thirds of the feed tonnage is biomass crops, this would require 75 million acres yielding an average of 7.6 annual tons per acre. U.S. farms in 2022 totaled about 900 million acres. Land now used to grow corn for ethanol production could be used to grow some of the biomass. Considerable biomass could also be grown on formerly farmed land not presently being used. Reference 3 is a significant DOE study which estimates that well over one billion tons per year of biomass for energy production could be produced in the U.S. without adverse impacts on food production.

Example operation of the converters in their virtual battery (grid import and export) modes will produce about 1.9 EJ of annual grid electricity exports and consume 3.5 EJ of imports.

The required converter capacity (biofuels LHV basis) for the example production is 370,000 MW (370 GW). Individual sites might have capacities ranging from 2 to 100 MW. If average site capacity were 30 MW, the total needed U.S. sites would be about 12,300.

6.3 Economics

The average installed capital costs of the proposed converters with their accessory equipment is forecast to average \$2.0 million per megawatt of nominal capacity. The total investment cost for the cited quantity of 370 GW is thus $740 billion. Over the 20-year period when installations are expected, average annual investment cost would be about $37 billion per year. Due to the good returns on investment expected, much of this sum could come from existing large energy companies.

If total user energy costs in 2050 were the same as 2022 actual costs ($1.75 trillion), their share of GDP spent on energy would fall from 7.0% to 4.1% of GDP. With the assumed 2050 delivered net energy consumption falling to 60% of the 2022 total, average user unit cost would be 167% of 2022 costs, which would help justify user investments to improve their energy usage efficiencies. The higher unit cost is also reasonable given a shift in product mix to more grid electricity and kerosene and less (low-cost) natural gas.

Appropriate 2050 energy wholesale and retail prices will have very little effect on food prices, enhance net farm incomes, provide good returns on investment for both biofuel producers and users, and pay for large-scale CO_2 capture and sequestration. The planned subsequent document will discuss direct air capture systems, which will remove and sequester considerably more CO_2 from the atmosphere than will the proposed biofuels converters.

Future retail prices should include a tax on all types of energy to fund a new National Carbon Administration, which would pay for safe and economical CO_2 capture, transport, and sequestration. Prices should also include ample funding for road system maintenance from vehicles using electricity and/or fuel energy. Relative prices for energy to different classes of customers should fairly reflect actual costs. Subsidies to the poor should also encourage them to improve efficiencies.

Production and prices of most fossil fuels are expected to decline, thereby extending the life of reserves and supporting fewer costly and dangerous offshore wells. The fossil fuel industries should be preserved, since they provide many valuable chemicals and materials feedstocks. The great majority of the carbon in fossil fuels will be captured and sequestered. The share of their carbon which cannot be practically captured will be far smaller than the expected net CO_2 removed from the atmosphere.

New processes can produce high-tonnage products including Portland cement, iron and steel, and ammonia from fossil fuels with zero CO_2 emissions. Since most plastics (made from fossil fuels) cannot economically be recycled, they can be used as feed components into the biofuel converters (without sorting).

Although new converter systems are possible which would produce chemicals (including polymers) and materials from biomass, it is recommended that such products instead be made from fossil fuels with CO_2 capture thus reserving this biomass for manufacturing biofuel exports.

6.4 Fertilizers

The fertilizers cited in Section 4.8 contain the phosphorus, potassium, and trace minerals from both biomass crops and feeds, but no nitrogen (which is needed by all plants). Anhydrous ammonia (the most common nitrogen fertilizer) could be produced in separate facilities from fossil natural gas. All carbon can be captured and sequestered as liquid CO_2, thereby making such ammonia production carbon neutral. Ammonia can be combined with the converter fertilizer in one of several ways, forming solid ammonium compounds such as ammonium phosphate. The resulting complete fertilizers might be further processed to make time-release pellets.

6.5 Landfills

The proposed plan will eliminate the vast majority of materials being added to landfills. Ongoing additions will consist mainly of earth and rock from excavations, etc. Existing landfills will cease producing fuel gases within a few years after organic wastes are no longer added. It will become economical for some existing landfills to then be mined to recover their usable components and free their sites for new uses.

6.6 Exports

This document cites only U.S. quantities. Major opportunities exist for large exports of technology licensing, consulting, converter systems, fossil fuels (to customers capable of sequestering CO_2), and biofuels. The United States has the potential to sustainably produce far more biofuels than needed for domestic uses with minimal food price impacts (see Reference 2).

6.7 Conclusions

The timeline to reach the example biofuel production of 12 EJ by 2050 is admittedly aggressive and optimistic, but believed possible. Governmental agencies need to pass enabling legislation, but their subsidies are not needed or even desirable.

The proposed plan is expected to achieve all the objectives listed in Sections 2.3 and 2.4.

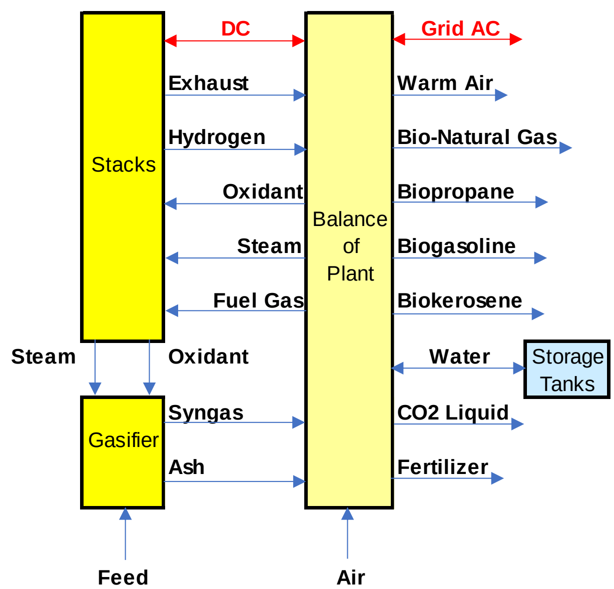
6.8 Additional Proposals

The author plans to add another essay on his website in late 2024 summarizing additional recommendations for the United States before 2050. These will include proposals to reduce total user energy consumption to about 60% of 2022 levels by implementing various major innovations in energy usage and conversion efficiencies. Net fossil CO_2 emissions will be drastically lowered to a negative 5 billion tonnes per year (a reduction of nearly 10 billion tonnes from 2022). Key strategies for additional CO_2 reductions will include efficiency improvements, increased use of renewable power generation aided by virtual-battery systems, capture and sequestration of nearly all CO_2 from the continued uses of fossil fuels, and direct air capture of CO_2 from the atmosphere (in addition to the biofuels plan described herein). The proposals will also include recommendations to greatly enhance user energy supplies during long grid outages.

7. Converter Details

Each converter is a complete automated assembly producing the Chapter 4 products from the Chapter 3 feeds. It consists of three major sections, each well insulated. The sections operate at 10 bar internal pressure. Figure 2 is a simplified schematic of the converter, which alternates between the three operating modes described in Chapter 5. The descriptions below are simplified.

Figure 2. Biofuels Converter



7.1 Gasifier Section

This adiabatic section fully reacts feed with steam and oxidant, producing synthesis gas ("syngas") and solid ash. It operates continuously in all three modes at input and output constant rates.

An airlock assembly continuously delivers prepared mixed feed (at near-ambient temperature) as described in Chapter 4. Oxidant and steam are fed at 900°C. The oxidant is 90% O_2 and 10% N_2 except during grid import mode when it is pure O_2. The gasifier contains internals to transport solids and produce near-equilibrium exit streams at 700°C. Solids residence time depends on feed details, but is only a few minutes. The syngas is comprised of H_2, H_2O, CO, CO_2, CH_4, and N_2 with insignificant levels of other gases.

The solid ash is typically 3.7% of dry feed weight. It contains all of the minerals present in the feed and less than 1% of its carbon. Gasifier exit streams are heat exchanged and cooled ash passes through an airlock (not shown).

7.2 Stacks Section

This section operates adiabatically at 900°C internal temperature. It contains numerous cylindrical solid-oxide electrochemical stacks, stack mounting assemblies, manifolds, heat exchange, DC power connections, reforming catalyst, and startup heaters.

The five streams to and from the balance of plant use multiple lines to enable differing flows when operating modes are switched. Oxidant composition is 90% O_2 and 10% N_2. The fuel gas contains all components present in the syngas cited above. When biofuels are being produced (Grid Zero and Import modes), the fuel gas also contains additional hydrocarbons having more than one carbon. Spent-fuel exhaust contains only H_2O vapor, CO_2, and N_2. Depleted-oxidant exhaust contains only 30% O_2 and 70% N_2. Electrolysis exhaust (Grid Import mode only) is pure O_2.

In Grid Zero mode, the fuel gas is fully oxidized to spent fuel by O_2 from both the oxidant (producing the small amount of power needed by the balance of plant) and steam (producing the hydrogen).

In Grid Import mode, a large DC input supplies energy needed to heat feed streams and electrolyze steam into hydrogen (needed for maximized biofuel production) and oxygen (for the gasifier, with the excess vented).

In Grid Export mode, stacks operate in fuel cell mode to generate maximum DC power with no hydrogen produced and the steam input also contains saturated liquid water for additional stack cooling.

7.3 Balance of Plant

The balance of plant (BOP) contains three major sub-sections: gasoline synthesis, main synthesis, and other. The synthesis sections are bypassed in Grid Export mode.

7.3.1 Gasoline Synthesis

A condenser is fed by cooled syngas (with cooled spent fuel also added in Import mode) to remove most of the water vapor. Multiple catalytic reactors are used, with operating temperatures between 200°C and 400°C. The dried syngas mixture is reacted (at moderate yield) to produce methanol vapor:

$$CO + 2\ H_2 \rightarrow CH_3OH$$

The methanol is separated by condensation and then converted (in one or more steps) to isobutylene and water vapor:

$$4\ CH_3OH \rightarrow C_4H_8 + 4\ H_2O$$

Most of the isobutylene is then dimerized into isooctene isomers:

$$2\ C_4H_8 \rightarrow C_8H_{16}$$

Hydrogenation of the isobutylene to isobutane and the isooctenes to isooctane (2-,2-,4- trimethyl pentane) is then performed:

$$C_4H_8 + H_2 \rightarrow C_4H_{10}$$
$$C_8H_{16} + H_2 \rightarrow C_8H_{18}$$

The desired biogasoline Reid Vapor Pressure is achieved by adding a small amount of isobutane to the isooctane. The gasoline section includes several heat exchangers and liquid water separation. As noted in Section 4.10, example biogasoline is 15% of the biofuels total.

7.3.2 Main Biofuels Synthesis

Syngas exiting the gasoline section is blended with more hydrogen and used to produce the other three biofuels. This section includes a distillation column, other heat exchange, liquid water separation, and catalytic reactors operating between 200°C and 500°C.

A Fischer-Tropsch reactor reacts CO and CO_2 with H_2 to produce an alkane hydrocarbon mixture (with one to over twenty carbons) plus water vapor. The CH_4 and N_2 components are inert. For example, decane is made by the following reactions:

$$10\ CO + 21\ H_2 \rightarrow C_{10}H_{22} + 10\ H_2O$$
$$10\ CO_2 + 31\ H_2 \rightarrow C_{10}H_{22} + 20\ H_2O$$

The column assembly removes liquid water, the desired biofuel products, and streams needing further processing. Heavy alkanes with more than about fourteen carbons are fed to one hydrocracker, which splits them (with added H_2) into smaller alkanes fed back to the column. An example reaction is:

$$C_{20}H_{42} + H_2 \rightarrow C_8H_{18} + C_{12}H_{26}$$

A light fraction containing two to seven carbons is fed to a hotter hydrocracker (with added H_2) to produce bio-natural gas. An example reaction is:

$$C_4H_{10} + 3\ H_2 \rightarrow 4\ CH_4$$

The balance of the gas mix not producing a biofuel product becomes the fuel gas, to which water vapor is added to prevent solid carbon formation in the stacks section. In Grid Zero mode, the fuel gas composition and flow are controlled to maintain the stacks at the desired constant temperature. In Grid Export mode, the fuel gas is the entire syngas stream at lower temperature. In Grid Import mode, the fuel gas contains (non-condensable) unreacted syngas components plus surplus alkanes with fewer than eight carbons.

7.3.3 Other BOP Equipment

Included are the control system, power conditioning circuits, fluid piping, manifolds, valves, heat exchange, solids handling to process ash into fertilizer, compressors, pumps, and miscellaneous other items. Some equipment is used only in one or two of the operating modes.

Oxidant is produced from air using a pressure-swing adsorption (PSA) subsystem. Liquid CO_2 byproduct is produced from spent fuel exhaust using condensation, purification, compression, and refrigeration. A turbine-generator is used in Grid Export mode, generating more power by expending exhaust from 10 bar to about 1.1 bar.

8. Glossary and Conversions

bar	Metric unit of pressure. 1 bar = 14.51 psi
BNG	Bio-natural gas. Methane plus small amounts of ethane and propane
BTU	British thermal Unit. 1 BTU = 1054.4 J
C4	A photosynthesis pathway with a four-carbon intermediate compound
DOE	U.S. Department of Energy
EJ	Exajoule. 1 EJ = 10^{18} J
GDP	U.S. Gross Domestic Product
GJ	Gigajoule. 1 GJ = 10^9 J
GW	Gigawatt. 1 GW = 10^9 W
HHV	Higher Heating Value. Heat of combustion with water as liquid
J	Joule. Basic metric unit of energy
kg	Kilogram. SI standard metric unit of mass
kW	Kilowatt. 1 KW = 1000 W
LHV	Lower Heating Value. Heat of combustion with water as vapor
MW	Megawatt. 1 MW = 10^6 W
MWh	Megawatt-hour. 1 MWh = 3.6 GJ
psi	Pounds force per square inch
Quad	Quadrillion BTU. 1 Quad = 10^{15} BTU = 1.0544 EJ
TJ	Terajoule. 1 TJ = 10^{12} J
te	Metric ton (tonne). 1 te = 1000 kg
W	Watt. Basic metric unit of power. 1 W = 1 J per second

9. References

1. Annual Energy Outlook 2023, eia.doe.gov

2. Carbon Sequestration Atlas Fifth Edition, National Energy Technology Laboratory, 2015

3. Billion-Ton Report 2016, Oak Ridge National Laboratory, ORNL/TM-2016/160