Advanced Natural Gas Energy Systems

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1. Summary

This document summarizes recommendations for improved residential energy systems, which will greatly reduce user costs and fossil CO_2 emissions, while virtually eliminating electricity interruptions. When bio-natural gas becomes available, it will replace some fossil natural gas.

An example 3000-square-foot home with personal vehicles near St. Louis, Missouri was considered. The table shows annual results, using example 2035 prices. CO_2 emissions are in metric tons ("tonnes").

Table 1. Example Residence

Case	Energy Costs	Fossil CO2 tonnes
Base	**$12,400**	**22**
Enhanced	**$5,900**	**7**
Fuel Cell	**$2,800**	**5**
Zero Carbon	**$2,900**	**0**
Negative Carbon	**$3,100**	**(16)**

The Base case has conventional characteristics. The Enhanced case includes recommended existing technologies:

- Superior insulation, windows, and doors
- Higher-efficiency appliances and lighting
- Plug-in hybrid and all-electric vehicles
- Advanced heat pump system
- Solar photovoltaic system

The Fuel Cell case adds an advanced natural gas fuel cell system, which profitably sells electricity to the utility grid. Its surplus heat furnishes all hot water and assists with space heating. This system will also supply whole-house uninterruptible power throughout grid outages of any duration.

The Zero Carbon case uses bio-natural gas (co-mingled in the same pipelines) instead of fossil natural gas. The Negative Carbon case uses bio-natural gas manufactured with capture and sequestration of part of the biomass feed carbon. The Negative case achieves considerable net annual removal of CO_2 from the atmosphere at minimal cost above the Fuel Cell case.

Probable benefits of the proposed new technologies for non-residential users are also cited.

2. Introduction

This paper focuses on advanced domestic energy systems using natural gas or bio-natural gas (BNG) fuel. The United States has very large reserves of fossil natural gas, resulting in forecast affordable prices for at least the next two decades. The U.S. also has the future potential to manufacture large quantities of affordable BNG, with zero or negative fossil carbon emissions. Chapter 5 summarizes recommended new BNG manufacturing processes.

Recommended usage enhancements and new technologies are described which have three primary objectives:

- Much lower user energy costs
- Much lower fossil CO_2 emissions
- Full-load uninterruptible power for unlimited durations

Unless indicated, energy quantities are given in kilowatt-hours (kWh). 3414 BTU equals one kWh. Fuel energy contents use higher heating values (HHV), which include enthalpy of condensation for exhaust water vapor. DOE forecasts (e.g., Ref. 1) use HHV. Carbon dioxide (CO_2) quantities are quoted in metric tons ("tonnes"). One tonne is 1000 kilograms (2205 pounds).

Actual 2035 costs, efficiencies, and quantities will undoubtedly differ from the examples, which are intended to be plausible and illustrative. The conclusions of this paper are expected to remain valid with the actual values. The author's website (Reference 4) contains seven previous papers on advanced energy topics.

2.1 Natural Gas

Conventional natural gas is the preferred fossil fuel for many uses since it is lower in cost and fossil CO_2 emissions than all other fossil fuels. It is obtained from natural gas wells. Wellhead gas is treated to remove all its sulfur (mostly as H_2S) and to reduce its CO_2, ethane, and higher alkanes to low (non-condensable) percentages. The resulting gas sold has varying compositions, with typically about 90% methane, plus nitrogen, CO_2, ethane, propane, butanes, and traces of higher alkanes. A few ppm of sulfur-bearing odorant (usually tetrahydrothiophene, THT) is added to make leaks more obvious. Typical gas has 1020 BTU/scf HHV.

Synthetic natural gas (SNG) can be made from coal or other fossil fuels. It can also be made entirely from biomass, yielding bio-natural gas (BNG). These products typically contain over 96% methane, with the balance being N_2 and CO_2 (plus the same odorant). Typical HHV is about 3% lower due to their absence of higher hydrocarbons. Chapter 5 will discuss BNG manufacture.

Either conventional or synthetic natural gas may be compressed to high pressures (over 300 bar) for storage, transport, and/or use as a transportation fuel. Such compressed natural gas (CNG) is increasingly being used today by buses and some trucks.

If pressurized natural gas is cooled below -85ºC, it can be liquefied. Long-distance natural gas transport via ship employs LNG.

2.2 Energy Costs

All dollar values in this paper are 2035 nominal (inflated) dollars. DOE forecasts (Ref. 1) for residential natural gas and electricity and for transportation gasoline were used as starting points for assumed price estimates. Table 3 in Chapter 10 summarizes the example variable prices used herein.

2.2.1 Infrastructure Charges

It is assumed that energy users by 2035 will pay separately for infrastructure use and energy consumed. These charges will pay for capital amortization, maintenance, and overhead.

Piped natural gas and grid electricity fixed charges will vary with neighborhood particulars (location, average home size, etc.). This document assumes fixed charges of $55/month for piped gas and $60/month for grid electricity.

Road use will be charged by annual travel and vehicle weight (instead of being included in energy prices). For light-duty vehicles, the assumed average rate is $0.040/mile.

Using an assumed annual vehicle travel (by 2 or 3 vehicles) of 24,000 miles total, the sum of the three infrastructure charges is $2340/year (same for all cases considered). This total is believed to be somewhat higher than is included in DOE forecasts (which imply under-funding of infrastructure costs).

2.2.2 Fossil Carbon Charges

Fossil fuel use to generate grid power and consumed as natural gas and gasoline creates fossil CO_2 greenhouse-gas emissions. New charges for fossil carbon are expected to begin at a low rate by 2025 and steadily increase in succeeding years. In 2035, the example rate of $150 per tonne CO_2 is used herein. DOE estimates (Ref. 1) 337 grams average CO_2/grid kWh in 2035 (grid power is generated using coal, natural gas, nuclear, and renewables). Natural gas yields 182 g/kWh and gasoline 266 g/kWh of CO_2. The resulting carbon charges (one possible euphemism for carbon taxes) are included in the assumed prices (unless otherwise noted).

It is expected that some of the revenues from fossil carbon charges will be used to assist low-income energy users. Most of the revenues are expected to subsidize programs to capture and permanently sequester CO_2, including processes which store carbon removed from the atmosphere. Section 8.6 further discusses this topic.

2.2.3 Fossil Energy Prices

The average variable costs used herein were derived by removing estimated infrastructure charges and adding carbon charges to the Reference 1 forecasts for 2035. The resulting assumed variable prices are $0.072/kWh for (fossil) natural gas, $0.182 (average) for purchased ("imported") grid power, and $0.132 for gasoline. Additional price assumptions are explained in the following chapters. Table 3 summarizes all assumed variable prices.

2.3 Common Assumptions
All of the example residential cases in this paper share the following assumptions.

A 3000-square-foot detached single-family home is located near St. Louis, Missouri. This site was chosen to approximate the U.S. averages for heating, cooling, and solar power potential. The home could be either new or previously built. It is connected to an electric utility grid supplying 120/240 Volts AC at 100 Amps (24 kVA) maximum. It is also served by piped natural gas.

It averages 3627 degree-days heating and 1881 degree-days cooling per year (using 65ºF reference temperature). Hot water use averages 450 Watts net. Natural gas consumption for its range, clothes drier, and outdoor grille averages 450 Watts HHV. Its (two or more) light-duty vehicles (cars, SUVs, etc.) total 24,000 miles travel annually. A garage is desirable.

A natural gas range and drier are used, enabling the proposed fuel cell system (now or later) to furnish whole-house uninterruptible power. A natural gas grille is more convenient than propane and uses less expensive/less polluting fuel.

2.4 Base Case
This case has typical characteristics for a home which has not yet adopted energy-saving approaches. Its heat-transfer coefficient (thermal power for space heating or cooling plus humidification or dehumidification) is 800 Watts/ºC. Annual-average general electricity use (excluding air conditioning) is 600 Watts. Furnace mean energy efficiency is 85% HHV. Central air-conditioning mean coefficient of performance (COP) is 2.8. Gas water heater average efficiency is 58% HHV. Conventional gasoline vehicles average 30 miles per gallon.

Annual variable energy costs (at section 2.1 prices) are natural gas at $4092, gasoline at $3720, and electricity at $2264. When infrastructure charges of $2340 are added, the total annual energy cost is $12,416.

Total associated fossil CO_2 emissions are 22.1 tonnes per year. No electricity is available during grid outages (no backup generator is assumed).

3. Enhancements

This chapter describes various enhancements to the base case residence (Section 2.4) which lower annual energy costs and fossil CO_2 emissions. All of these enhancements are commercially available in quantity today, but are expected to evolve in the coming years for improved cost-effectiveness. Each type of enhancement may be implemented independently. Section 3.5 summarizes energy cost and CO_2 impact of each.

3.1 Higher Efficiencies

The assumptions listed in Section 2.4 are improved as follows. Heat transfer coefficient is lowered to 600 W/ºC by use of improved insulation, windows, and doors. General electricity use is reduced to 500 mean Watts. Average furnace efficiency is increased to 92% HHV using a condensing type. Central air conditioner mean COP is improved to 3.8. Water heater efficiency improves to 62% HHV. Mean gasoline mileage rises to 33.3 miles/gallon (equaling Ref.1 forecast for 2035 average). The applicable assumptions given here also apply to all cases below and in succeeding chapters.

3.2 Plug-In Vehicles

The household vehicles (driving the same 24,000 combined miles per year) are replaced by two plug-in types (PIVs). One is a hybrid with gasoline engine and the other is a pure electric vehicle (EV). A typical 2035 hybrid may have an all-electric range of 50 miles per charge and a combined range of 500 miles using gasoline also. A typical EV may have a range of 200 miles per charge. Assumed plug-in travel totals 20,000 miles, with 4000 miles using gasoline. Average assumed efficiency is 3.6 miles/plug-in kWh and 1.4 miles/gasoline kWh (49 mpg). Gasoline CO_2 emissions decline from 6.8 te/yr (for the Section 3.1 case) to 0.8 te/yr.

Smart charging systems in the vehicles and stationary charging unit will allow the user to minimize charging power costs (see Section 4.1) and limit charging rates during grid outages.

3.3 Heat Pump System

An advanced high-efficiency heat pump system replaces the furnace, central air conditioner, and its associated humidity-control features. It includes an energy-recovery ventilation (ERV) subsystem. For the average St. Louis year, its assumed mean heating COP is 4.4 and mean cooling COP 5.4. Maximum electrical input is 3.5 kW. The system includes a natural-gas oxidizer subsystem for supplemental heat when outdoor 24-hour average temperature is less than -4ºC (25ºF). Oxidizer efficiency is 98% HHV. The heat pump system is designed to utilize surplus heat from a fuel cell system if present (Chapter 4).

3.4 Photovoltaic System

A multipurpose residential grid interface and DC-to-AC inverter is installed, which can be connected to both a solar photovoltaic (PV) array and a fuel cell system (Chapter 4). Section 4.2.2 describes the interface and inverter.

The example PV array is rated 5 kW, roof-mounted facing south. The complete PV system will generate an average of 3500 AC kWh/year during 5000 space heating hours plus 3800 kWh during 3766 cooling hours. About 1500 kWh of this energy is exported (sold) to the grid, with the balance offsetting grid purchases (assuming prior additions 3.2 and 3.3). An example 10% premium is obtained for zero-carbon exports. Table 3 in Chapter 10 summarizes all variable energy prices. The ratio between AC generation to panel nominal capacity is 1460 kWh/array kW-year (16.7% mean annual capacity factor).

The example PV system will supply no power during grid outages unless a fuel cell system is also present (Chapter 4).

3.5 Results

The table below lists (rounded) 2035 results for enhancements made in the stated order. With other sequences, the bottom line will remain unchanged, but intermediate lines will differ slightly.

Table 2. Costs and CO_2 Emissions

Addition	Energy Costs	Fossil CO2 tonnes
Base Case	**$12,400**	**22**
Higher Efficiencies	**$10,200**	**17**
Plug-In Vehicles	**$8,300**	**13**
Heat Pumps	**$7,200**	**10**
Photovoltaic System	**$5,900**	**7**
Enhanced Case Total	**$5,900**	**7**

The top and bottom lines equal the Table 1 values (and include both variable and fixed annual costs). The Enhanced Case has annual energy costs 48% of the base case and one-third its CO_2 emissions. Section 8.7 discusses investment costs.

4. Residential Fuel Cell Systems

An advanced fuel cell system can be installed with or without the enhancements described in Chapter 3. However, since these enhancements produce synergies with the fuel cell systems, they are assumed to also be present in the example results. Fuel cell systems for single-family homes will be available with continuous electrical capacities from 1 kW upwards. The use of deliberately oversized systems will be financially advantageous in many cases. The example uses a 6 kW fuel cell system, which is large enough to provide whole-house power in any weather during grid outages of any duration. Since the fuel cell systems furnish both electricity and useful heat, they are cogeneration systems.

4.1 Grid Pricing

By 2035, time-of-use (TOU) grid pricing is expected to become standard, using new types of electric meters. User prices will vary hourly based upon utility system supplies and demands: higher when system demands are tending to exceed supplies (thus requiring the use of more expensive peaking generators and/or purchases from other sources) and lower when supplies are tending to exceed demands. With the expected large increases in solar photovoltaic and wind generation (both of which are highly variable in nature) average utility cost of electricity (COE) will vary more than presently. TOU pricing will give users incentives to adjust their power usage timing to save money (while also influencing generation sources).

This document assumes that residential TOU pricing will vary relative to its average of $0.182/kWh (for purchases from the grid or "imports"). Example import prices will vary from 25% to 175% of average. For calculation examples, five mean price brackets are assumed, each in effect for one-fifth of the kWh transferred. The mean bracket multipliers are 40%, 70%, 100%, 130%, and 160% of the average price. Exports (sales to the grid) are priced $0.030 lower than the corresponding import price. Using the above assumptions, the lowest-price import bracket is $0.073/kWh and the highest-price import bracket is $0.291/kWh. The corresponding export brackets are $0.043 to $0.261/kwh. Zero-carbon exports from PV arrays receive 10% premiums. Table 3 in Chapter 10 summarizes all variable prices used in this paper, with ranges of bracket multipliers grouped.

4.2 Design

The fuel cell system uses natural gas to generate electricity and useful heat. The example system is rated 6 kW maximum continuous AC inverter output. Installed indoors (or in an attached garage), the system operates continuously, safely, reliably, and with a noise level similar to a quality refrigerator. It includes fuel cell, electrical, and thermal subsystems, briefly summarized as follows.

4.2.1 Fuel Cell Subsystem

DC power is electrochemically generated from a fuel gas mixture and air by solid-oxide fuel cell stacks operating near 900ºC inside a well-insulated enclosure. The fuel gas mixture is made by catalytically reacting natural gas with steam (generated from internally-recycled water). The fuel cell subsystem also includes heat exchange, blower, fans, pumps, and controls. It can rapidly load follow between hot idle (no electrical output) and any desired power output up to maximum. The system delivers DC power to the electrical subsystem and useful heat (as hot water and warm air) to the thermal subsystem. Its ultraclean, cooled exhaust (containing CO_2) is vented outdoors through a wall vent similar to those used by clothes driers.

4.2.2 Electrical Subsystem

Included are a grid interface, power conditioning, battery pack, and control system.

The grid interface connects the home to the utility AC grid (nominal 120/240 Volts, 60 Hertz), in compliance with all applicable codes. It includes a bidirectional meter (owned by the utility) which continually communicates power to the utility. A high-speed contactor disconnects the grid within milliseconds of an outage (or large disturbance). When a stable grid returns, the contactor recloses. Typical interface continuous rating is 100 amps at 240 volts (24 kVA). The interface includes sensors connected to the control system.

The power conditioning circuits receive input power from the fuel cell and PV systems (both operating at the same voltage near ±200 VDC) and occasionally also from the battery pack (typical discharge near 50 VDC). An inverter produces main output AC power whose voltage and phasing are synchronized with the grid. In the example case, maximum continuous AC output is 10 kW (fuel cell plus PV) and maximum short-time output (with battery assistance) 20 kW. Other DC outputs power all fuel cell system auxiliary items and recharge the battery pack.

A moderate-sized lithium-ion battery pack is used only during grid outages for surge power and load-following assistance. Typical ratings are 20 kW peak discharge power and 5 kWh usable energy storage for the example fuel cell system size.

System operation is fully automated. The control system includes data logging and options for communication to the user. A fuel-cell service company can be automatically notified of any required field service. Annual service visits for system inspection and filter cleaning are assumed. Fuel cell electrochemical stacks will be replaced when their performance has declined to a predetermined level.

The fuel cell system will provide whole-house uninterruptible power for unlimited duration during grid outages. During these outages, the oxidizer system will supply a larger share of any required space heating and the smart vehicle charging systems will limit maximum power used.

4.2.3 Thermal Subsystem

The fuel cell system outputs usable thermal energy as hot water (typically 70ºC) and warm air (typically 40ºC). The hot water is used to supply all hot tap water needs using an attached system (replacing a conventional water heater) with a 100-gallon storage tank. Surplus hot water is routed to the Section 3.3 heat pump system when space heating assistance is desired. Warm air is directly discharged indoors when appropriate. All unneeded heat is discharged outdoors as warm air.

4.3 Operation

The fuel cell system will operate in three different modes: idle, load following, and maximum. Example maintenance cost is $0.015/kWh of electrical output (included in annual energy costs). Assumed AC/fuel HHV efficiency is 54% and maximum energy (AC + useful heat) efficiency is

98%. With natural gas at $0.072/kWh, the cost of electricity from the fuel cell system ranges from $0.148 to $0.088/kWh, depending upon usefulness of surplus heat at that time.

4.3.1 Idle Mode
Idle mode is used when grid import prices are in the lowest bracket ($0.073/kWh) since it costs more to generate power than to buy it. In the example, idle mode is used an average of 1753 hours/year (20%).

In this mode, the fuel cell system outputs zero power. It is fed 480 Watts (HHV) of natural gas and produces 480 Watts of potentially useful heat (used for water and/or space heating as needed). Idle mode operation maintains the hot zone at hot standby temperature, allowing power generation to resume in a few seconds.

4.3.2 Load-Follow Mode
In this mode, fuel cell generation matches consumption minus PV generation (if any). This mode is used during grid outages and whenever mean TOU prices are near 70% of average and outdoor temperatures are above -6ºC (resulting in generation costs lower than import prices but higher than export prices). Example hours per year are 1666 (16.6%).

4.3.3 Maximum Mode
At TOU prices of 100% of average and higher (and below -6ºC at 70%), the fuel cell system operates at 6 kW maximum generation, with surplus power profitably exported (sold) to the grid. Example hours per year total 5347.

4.3.4 Virtual Battery Function
A residence with the above enhancements will act as a virtual battery: importing surplus grid power (especially surplus power from PV and wind generation) and exporting power when grid demand exceeds economical supplies. Section 8.3 further discusses virtual batteries.

4.4 Results
As seen in Table 1, annual energy costs with a fuel cell system are $3100 lower than the Enhanced case, with annual fossil CO_2 emissions two tonnes lower. Both energy costs and fossil CO_2 emissions are only 23% of the Base case. The utilization of much of the surplus heat from the fuel cell systems yields average annual natural gas energy-utilization efficiencies superior to the best conventional (very large) natural gas power plants. Since fuel cell export power can be consumed by neighbors, grid transmission and distribution losses are also reduced.

Another valuable benefit is the ability of the fuel cell system (with included battery pack) to furnish whole-house uninterruptible power for unlimited times during power outages. Such outages are caused by both weather events and utility equipment problems and are becoming more common. Standby engine-generator systems (some available models use natural gas) do not provide uninterruptible power, since they require up to a minute for automatic startup. Systems large enough to power the example home have typical total installed costs over $10,000.

5. Biomass Converters

Photosynthesis is the natural process which converts sunlight, CO_2 from the air, and water into stored energy (as carbohydrates). Although its energy efficiency is an order of magnitude lower than photovoltaic (PV) panels, it has three important advantages over PV systems: storage, CO_2 absorption from the air, and much lower total cost.

Innovative converters are proposed to convert biomass crops and wastes into bio-natural gas (BNG). They would be designed to operate as virtual battery systems: importing grid power when grid prices are low to maximize BNG production, and exporting power to the grid instead of producing BNG when grid prices are high. With optional add-on subsystems, the converters could capture all surplus carbon as pure liquid bio-CO_2 for sequestration (Section 5.3).

The product BNG has the composition given in Section 2.1. It would be co-mingled with the fossil gas flowing in natural gas pipeline networks. The converters would also produce an organic-fertilizer byproduct (typically 3.7% of dry feed weight), containing all the phosphorus, potassium, and trace minerals present in the biomass feeds.

5.1 Biomass Feeds

Primary feeds will be fast-growing crops grown specifically for the converters. They will include grasses (e.g., switchgrass, miscanthus, and many others suited to the local climate) and wood chips from trees (e.g., poplar, willow, pine, paulownia, and many others). Staggered harvesting and ample storage can enable the converters to operate continuously throughout the year. Surplus heat from the converters would be employed to dry feeds, minimizing weight and storage issues. Crop diversity would minimize threats from pests and diseases.

The converters could also utilize biomass-waste feeds, co-fed with crops. Examples include animal manures, farming and food-processing wastes, municipal yard and garden wastes, non-recyclable plastics and paper, and other types. Reference 2 summarizes large government studies which conclude the United States could sustainably produce well over one billion tons of biomass annually without harming food production.

5.2 Design and Operation

This section describes converters which operate at zero fossil carbon emissions (from both converter operation and BNG use): all their carbon is taken from the atmosphere and later returned. Section 5.3 describes the negative-carbon option.

The automated converter uses internal pressures near 30 bar and maximum internal temperatures near 900ºC. A multi-purpose solid-oxide electrochemical section is integrated with a biomass gasifier, methanation reactor, compressors, heat exchangers, molecular-sieve beds, and auxiliary equipment. A complete factory-tested converter is transported by a standard flat-bed truck to the installation site. An example converter size is fed 1000 dry tons biomass/year (HHV 499 kW) at a constant rate and produces 37 tons/year dry organic fertilizer. Large sites would employ multiple converters.

As grid prices vary, the converter operates as a virtual battery by alternating between the following three modes. The modes would be selected for highest profitability based on prevailing prices for BNG sales and grid power. Mode timing is fully flexible: durations of import and export modes are independent and may vary by season, weather, day of the week, etc. Annual total grid input energy (MWh) is independent of export energy. The time required for switching operating modes is less than one hour.

5.2.1 Maximum Grid Import

558 kW of (zero-carbon) grid power is fed to the converter, converting all feed carbon to BNG with HHV of 939 kW HHV. Energy efficiency is 89% HHV. This mode is used when grid prices are low.

5.2.2 Zero Grid

No grid power flows in either direction. BNG production has HHV of 401 kW giving energy efficiency of 80% HHV. This mode is used at intermediate grid prices.

5.2.3 Maximum Export to Grid

No BNG is produced. The converter exports 269 kW of (zero-fossil-carbon) AC power to the grid. HHV efficiency is 54%. This mode is employed when grid prices are high.

5.3 Negative Carbon

An optional-add on subsystem captures bio-CO_2 (for subsequent sequestration) and has an estimated capital cost about 5% of the converter capital cost. It will capture all surplus feed carbon (not contained in its BNG product) as pure pressurized liquid CO_2 for temporary storage and truck transport, followed by permanent underground sequestration. Converters equipped with negative-carbon equipment will yield the following calculated results.

During Maximum Import mode the CO_2 capture subsystem will not operate since all feed carbon is transferred to BNG (production rate and efficiency remains the same as Section 5.2.1). It is assumed that purchased grid power is zero carbon (e.g. from surplus renewable or nuclear power).

In Zero Grid mode, 243 grams bio-CO_2 would be captured for sequestration per kWh of BNG HHV and energy efficiency would decline to 79% HHV. BNG production HHV is 397 kW.

In Maximum Export mode 633 grams bio-CO_2 would be captured per kWh of AC exports and energy efficiency would drop to 53%. Export power is 265 kW.

5.4 Other BNG Possibilities

Some filling stations and fleet-vehicle depots will compress BNG to high pressures (e.g., 300-400 bar) for use as vehicle fuel instead of (fossil) gasoline or diesel. Such vehicles require design or modifications for this fuel, which would be less expensive than the liquids and enable zero or negative fossil-carbon vehicle emissions. BNG has an octane rating above 110. The residential vehicles in the zero and negative carbon cases are assumed to use BNG instead of gasoline.

Homes (and filling stations) not connected to natural gas pipelines could install storage-tank systems, occasionally refilled with BNG (or fossil gas) delivered by high-pressure tank trucks. Such fuels would sell for somewhat more than piped gas (but considerably less than propane once these systems were used in quantity). The fixed annual charges for pipeline natural gas service (described in Section 2.2.1) might be similar to those funding these systems.

5.5 Pricing and Results

5.5.1 Example User Prices

Zero-carbon BNG (produced without CO_2 capture) would sell for a 15% premium over fossil natural gas or \$0.083/kWh HHV. The same fuel for vehicles (Section 5.5) would sell for a premium of \$0.020/kWh over piped residential BNG or \$0.103/kWh (versus gasoline at \$0.132/kWh). Negative-carbon BNG would sell for a premium of 25% over fossil natural gas and thus for \$0.090/kWh residential and \$0.110 for vehicles. As noted earlier, zero-carbon export electricity (made by PV arrays or fuel cell systems using zero-carbon BNG would sell for a 10% premium over exports made using fossil natural gas. The assumed premium for exports to the grid made using negative-carbon BNG is 15%. All energy price assumptions used in this report are summarized in Table 3 in Chapter 10.

5.5.2 Results

The Zero-Carbon row in Table 1 was calculated using zero-carbon BNG as both the residential fuel (instead of fossil natural gas) and vehicle fuel (instead of gasoline), with the same annual energy quantities. For only about \$100 per year additional, fossil CO_2 emissions drop to zero.

The Negative-Carbon row in Table 1 uses example negative-carbon BNG and grid export pricing. An additional annual energy cost of about \$200 funds net annual removal of fossil CO_2 from the atmosphere of 16 tonnes (a savings of 38 tonnes per year from the Base Case).

5.6 Liquid Biofuels

The above converters produce BNG as their sole biofuel product. They use a simple process with well-known catalysts. Large-scale BNG production could begin before 2035.

Following development work, more complex processes could produce alternative hydrocarbon biofuels: propane, gasoline, and/or jet fuel. These fuels would be superior to their conventional counterparts. The biogasoline would be 100 octane. Their residual carbon could be converted into CO_2 (vented or liquid for sequestration) or into biochar (see Section 7.1). Bio-jet fuel (kerosene) would be a highly desirable zero- or negative-carbon fuel for jet aircraft. The other liquid biofuels could displace their fossil counterparts. Liquid-hydrocarbon biofuels made by the proposed new processes will probably not become available in quantity until after 2035.

The liquid biofuels now being manufactured are oxygenates (not hydrocarbons): primarily ethanol (via fermentation of carbohydrates) and biodiesel (via transesterification of vegetable oils with methanol). These biofuels have major environmental and cost disadvantages versus the proposed alternatives.

6. Other Fuel Cell Applications

This chapter briefly summarizes larger new applications for natural gas systems using solid-oxide fuel cell technology.

6.1 Larger Cogeneration Systems

The fuel-cell cogeneration systems described in Chapter 4 are suitable for a single residence. Larger systems using the same technology are expected to become available with continuous electrical output capacities up to 1000 kW. Their expected electrical efficiency is the same, as is their maximum possible energy efficiency (when all available heat is being used). Their installed cost per kW of capacity will decline somewhat with increased size.

Larger cogeneration systems will be suitable for many types of applications, including multi-unit residential, commercial facilities, and industrial plants. Although some applications will use a lower fraction of the available surplus heat than the Chapter 4 example, attractive economic and environmental results should be possible in most cases. The potential synergy with solar PV systems will also apply to the larger systems.

6.2 Power Plants

Utilities and independent power producers (IPPs) presently operate natural gas electricity generation systems ranging from peaking turbine-generators (commonly 5 to 50 MW, with HHV efficiencies near 30%) to very large combined-cycle plants (up to over 500 MW, with HHV efficiencies up to about 55%). These combined-cycle plants use both steam and gas turbines and consume considerable water. Typical grid transmission and distribution (T&D) losses from generation to users are 5 to 10%.

Compared with existing natural gas generation technologies, fuel-cell power plants could reduce generation costs and CO_2 emissions and operate as virtual battery systems.

6.2.1 Medium-Size Systems

These systems would each consist of one or more parallel-connected modules. Example module sizes are 100, 300, and 1000 kW. Common AC (grid-connected) voltage options will be 120/240 single phase, 120/208 three phase, and 277/480 three phase. They could be installed at many types of sites (indoors or outdoors), including large multi-unit residential, commercial, industrial, or utility substation. Their expected electrical efficiencies (AC power/natural gas HHV) are 63% (higher than conventional combined-cycle systems). Due to their locations at or very near points of use, T&D losses would be minimal. The systems could operate as virtual batteries, as described in Section 4.3.4. Systems installed at buildings could also furnish usable heat, boosting energy efficiencies.

6.2.2 Larger Systems

Larger fuel-cell systems are proposed which would integrate turbo-generators with fuel cell systems for outstanding electrical efficiency (72-73% HHV). Each module (capable of paralleling for larger capacities) would output three-phase 3 or 10 MW power at the desired voltage. Systems could be installed at utility substations and large commercial or industrial sites. During grid outages, they could power microgrids of connected buildings. These systems would be designed for the later addition of economical CO_2 capture subsystems (see below). Each module could be cycled between hot standby and full power in one minute, but could not load follow like the medium-sized systems. Modules would be factory tested and delivered by standard trucks.

6.2.3 Carbon Dioxide Capture

Add-on subsystems for total CO_2 capture would be available for the systems described above. They would include a two-stage compressor, refrigeration, heat exchangers, molecular sieves, and pumps. They would be fed exit gas from the spent-fuel turbine and deliver liquid water, pressurized pure liquid CO_2, and vent tail gas ($N_2 + O_2$). Their incremental installed capital cost would be under 10% of the fuel cell systems. Resulting combined electrical efficiency would decline to 70-71% HHV. The liquid CO_2 can be transported by specialized trucks or rail cars to suitable sites for permanent underground sequestration (see section 8.6).

Power made from fossil natural gas in equipment capturing all resulting CO_2 would yield zero-carbon power saleable at premium prices. If the same equipment used BNG fuel, they would generate power with negative emissions. It is assumed herein that negative-carbon power from these systems would be used to offset fossil grid carbon emissions and not directly offered for sale to users.

6.3 Transportation

Compact versions of the fuel cell systems described in Section 6.2 could be combined with electric motors to replace engines in many types of trucks, buses, locomotives, and ships. Most would use hybrid drive systems with lithium-ion battery banks (some with optional plug-in recharge). Expected fuel efficiencies are at least double those of engines. The fuel cell systems could be designed to operate on compressed natural gas (CNG), diesel, or kerosene. Operation using biofuel could reduce their fossil carbon emissions to zero or negative.

7. Alternatives

A variety of alternatives to the technologies described in preceding chapters have been considered and explored via calculations. Some of these are summarized below.

7.1 Biochar

The biomass converter concepts in Chapter 5 maximize conversion of biomass carbon into BNG (or export electricity), with all residual carbon either vented (in the zero fossil carbon case) or captured as liquid bio-CO_2 for underground sequestration (in the negative fossil carbon case). All biomass carbon is gasified into synthesis gas, which includes the carbonaceous gases CO, CO_2, and CH_4. Part of this synthesis gas is used as fuel (converting all fuel carbon to CO_2), while the balance is catalytically reacted with hydrogen to form BNG and water vapor (which is then removed).

Alternative gasifier designs (also fed dried biomass, steam, and oxygen) would gasify only a fraction of the feed carbon (for example, half to two-thirds) into synthesis gas and convert the balance into solid biochar. Such biochar would consist mostly of porous stable amorphous carbon, intermingled with the solid organic fertilizer described Chapter 5. All converters producing biochar co-product would deliver negative-carbon BNG (or electricity).

Biochar is an excellent farm soil amendment. It has been shown to be capable of sequestering bio-carbon for many thousands of years. It acts as a substrate for beneficial soil microbes and permanently enhances soil physical structure. Processes producing biochar instead of vented or liquid CO_2 are expected to yield lower annual profits than the Chapter 5 cases, but could be employed where liquid CO_2 sequestration was unavailable.

7.2 Industrial Processes

Three types of industrial processes emit large quantities of fossil CO_2: cement manufacture, iron making, and ammonia manufacture. Innovative processes using natural gas in combination with elements of some of the above technologies could completely eliminate fossil carbon emissions from these processes. All carbon present would be captured as liquid CO_2 and sequestered (CCS).

A new cement manufacturing process would include electrochemical oxidation of natural gas with CCS of all the CO_2 from both limestone calcining and fuel oxidation.

A new ironmaking process would use natural gas instead of coke as the iron-ore reducing agent, electrochemical fuel oxidation, and CCS.

A new ammonia process would include electrochemical oxidation of natural gas, electrochemical reduction of steam, and CCS.

On-site fuel cell systems of the types described in Chapter 6 could also help reduce industrial fossil carbon emissions, even if not equipped for CCS.

8. Discussion

This chapter supplements topics from previous chapters and adds other topics.

8.1 Efficiencies

Large improvements in energy usage efficiencies are possible by 2035, enabling major cost and fossil CO_2 emissions savings. Examples of these improvements are given in Chapter 3..

HVAC energy consumption in residential, commercial, and industrial buildings can be significantly lowered by using advanced, high-efficiency (air-source) heat pumps together with superior insulation, windows, and doors. On-site fuel cell systems can further improve efficiencies by more efficient electricity generation while reducing space- and water-heating energy consumption (via utilization of their surplus heat). Section 3.3 and Chapter 4 give examples.

Transportation energy consumption may be significantly reduced by shifting to hybrid drive systems, which combine engines, batteries, and electric motors. Plug-in vehicles (with or without engines) are even more energy efficient. Although not suitable for aircraft, major savings are possible in most other types of transportation.

Large natural gas fuel cell systems have electricity generation efficiencies higher than today's best combined-cycle systems, with the further advantages of much smaller practical sizes and no cooling water requirement.

8.2 Electric Grid

The utility electric grid will continue to be connected to over 99% of residences, commercial sites, and industrial facilities. The majority of input electricity will continue to be generated by existing types of sources: natural gas combined cycles, natural gas turbogenerators, coal plants, nuclear plants, and renewable sources (wind, hydroelectric, solar, and geothermal). By 2035, however, their shares are expected to change. For example, coal is expected to decline in importance while wind and solar both increase.

Significant new inputs to the grid will be from emerging types of distributed generation as described in the preceding chapters. Most of the new electricity will be generated by fuel cell systems using natural gas, bio-natural gas, or biomass fuel.

The power timing of each type of grid input varies markedly. All sources experience outages for planned or unplanned maintenance (and sometimes for other reasons). Most of the largest plants (coal, nuclear, and combined cycle) are best operated continuously at full power: they are slow to load follow, have limited turndown ratio, and have higher costs per kWh at part load. The output of large hydroelectric plants depends on flow: it can be varied at will by gate operation, but capacity may vary seasonally. Wind and solar vary with weather and time of day from zero to maximum, often with considerable unpredictability.

The required second-by-second balancing of grid inputs with combined user demand is presently accomplished using multiple methods. Grid voltage is varied over a range of about ±10%, which slightly alters consumption. Natural gas turbogenerators are switched on and off and their output varied. The larger sources are varied to limited degree. In some regions today, solar and wind inputs must be curtailed (solar by opening contactors, wind by furling blades).

With the expected large increases in solar and wind capacity in future years, grid balancing will become more challenging. The proposed virtual batteries can provide major assistance.

8.3 Virtual Batteries

8.3.1 Conventional Battery Systems

Conventional batteries store chemicals which are reacted electrochemically to generate electricity on demand. Primary batteries (such as AA alkaline cells) are single use and not rechargeable. Secondary (storage) batteries can be repeatedly recharged. The most common secondary battery is the lead-acid SLI (starting-lighting-ignition) battery used in vehicles for engine starting and many other purposes. These types are not suitable for repeated deep discharge cycles, which cause extremely short life.

Deep-cycle secondary batteries are used for many purposes, including portable electronics, tools, hybrid vehicles, and plug-in vehicles. The principal types in use today are lead-acid, lithium-ion, and nickel/metal hydride. Many other types are also in use or under development, including flow battery systems (which separate chemicals storage from their electrochemical reaction subsystems). Energy storage efficiencies (including charging and discharging losses) are typically 70% to 85%. Their useful life depends upon temperature, depth-of-discharge, and other factors. Measured lives are typically 400 to 3000 charge/discharge cycles. Although lithium-ion manufacturing costs have been declining as their production increases, they remain quite expensive per kWh of useful discharge capacity.

Various types of secondary battery systems have been connected to the grid for storage demonstrations. Even when operated on daily cycles, their forecast energy-storage cost (if manufactured in very large quantities), are quite high. Such systems would be far too expensive for long-term (e.g., seasonal) storage. They are always constrained by their output/input energy ratios (70% to 85%).

8.3.2 Virtual Battery Systems

The expected nearly universal use of time-of-use (TOU) grid pricing (Section 4.1) for all classes of customers by 2035 will encourage one type of virtual battery function by giving users an incentive to shift grid consumption from higher-cost to lower-cost times.

More powerful and flexible virtual battery functions can be provided by residential fuel cell systems (Chapter 4), biomass converters (Chapter 5), and larger fuel cell systems (Chapter 6). Each of these systems (with its attached equipment) will purchase surplus (low-cost) grid electricity and sell considerable (higher cost) electricity to the grid when desired. Unlike conventional secondary batteries, their grid input and output energies (kWh) are completely independent and the timing of inputs and outputs is completely flexible. As one example, virtual batteries can import surplus summer solar energy and export energy in winter when solar generation is low.

The economics of virtual battery operation will assist in holding down average grid user prices, make greater solar and wind capacities cost-effective (by eliminating or reducing curtailments), and help prolong the useful life of zero-carbon nuclear plants.

8.3.3 Other Storage Technologies

Two other types of systems are in use today which can deliver power from previously stored energy. They supply a very small share of total energy used and have little potential for expansion. Hydroelectric systems use turbines driven by stored or pumped water from reservoirs. Compressed-air systems combine underground storage caverns with natural-gas turbines.

8.4 Electrochemical Systems

The systems summarized in Chapters 4 through 6 all utilize advanced high-temperature solid-oxide electrochemical technology. Tall stacks of electrochemical cells are used to perform a variety of chemical reactions which either generate of consume electricity (and are either exothermic or endothermic). Each cell is about 60 mm diameter and under 1 mm thick. Its solid electrolyte is made from yttria-stabilized zirconia (YSZ) and conducts oxygen ions ($O^{=}$) but not electrons (e^-). The remainder of each cell consists of an impervious electron-conducting separator, porous anode and cathode layers, and impervious high-temperature seals.

Depending on the desired reaction, each cathode is fed either air, O_2-enriched air, or steam. The cell removes pure oxygen from the cathode gas and delivers it via the solid electrolyte to the anode layer. The gas exiting the cathodes is either O_2-depleted air or a hydrogen-rich steam mixture.

The anode layer is usually fed a fuel gas mixture (usually a mix of H_2, steam, CO, CO_2, CH_4, and N_2), which reacts with arriving oxygen to form a spent fuel mixture, consisting of CO_2, steam, N_2 and a very small percentage of excess O_2. For biomass gasifier input, some of the anodes are fed steam and deliver steam-O_2 mixtures.

When biomass converters are operated as virtual batteries, the same stacks perform different reactions when converter operating modes change.

8.5 Bioenergy

As described in Chapter 5, advanced biomass converters could produce BNG biofuel and/or electricity from biomass crops and/or bio-wastes. Since biomass growth consumes atmospheric CO_2, use of BNG or biomass-derived electricity is at worst carbon neutral (zero fossil CO_2 emissions). If part of or all the biomass carbon is sequestered, net carbon removal from the atmosphere occurs (Section 8.6).

Today a small amount of electricity is generated by burning biomass. Although such power is zero-carbon, nearly all existing equipment used for this purpose is very inefficient and often emits harmful air pollutants.

Production of existing biofuels should be considerably reduced by 2035. Ethanol production from carbohydrates is inefficient, costly, and yields little net fossil CO_2 reduction. Biodiesel ester production (mostly in other countries) has led to harmful tropical deforestation and is also quite expensive.

8.6 Carbon Sequestration

The permanent underground sequestration of pure liquid CO_2 is an option cited in Sections 5.3 and 6.2. If used to sequester fossil CO_2 from large natural gas fuel cell systems, it makes their electricity production zero carbon. If used with biomass converters (or with fuel cell systems using BNG fuel), the resulting bio-CO_2 sequestration is carbon negative (net carbon removal from the atmosphere).

Reference 3 lists identified sites in the U.S. for permanent underground storage of CO_2 with extremely large total estimated capacity.

Section 7.1 describes an alternative means of carbon sequestration using biochar, which might be used with biomass converters. Although this possibility would have certain advantages over liquid CO_2 sequestration, it results in lower yields of bioenergy products.

8.7 Investment Costs

All of the enhancements and new equipment described in Chapters 3 through 7 have significant investment costs. The enhancements using mature technologies (such as improved building insulation, doors, and windows) will likely have costs which track inflation. Existing technologies which are rapidly growing in importance today (including plug-in vehicles, photovoltaic arrays, and heat pumps) should see costs rising slower than inflation due to ongoing manufacturing and design improvements. New technologies not yet in volume production (fuel cell systems and biomass converters) are expected to have high early costs which will decline rapidly with time.

In the case of new-home construction, additional vehicle purchase, etc. the effective investment cost is only the increment over the conventional alternative. In other cases, an existing system (such as an HVAC system) needs replacement or is inadequate and thus an incremental calculation is appropriate. The energy cost savings over the first five to seven years will often justify the added investment in either case.

Biomass converters and large fuel cell systems are expected to earn satisfactory returns on investment once they are manufactured in quantity.

Governmental incentives (see Section 8.10) are expected to help offset investment costs for some early adopters.

8.8 Fossil Fuels

By 2035, expected other trends plus the widespread adoption of the proposed technologies will alter the likely domestic production of the major fossil fuels: natural gas, petroleum, and coal.

Natural gas production will increase somewhat over government forecasts (Ref. 1) due to its increased consumption in the systems described herein. The very large known and probable domestic reserves will restrain its prices. The increased efficiency of natural gas uses and the partial sequestration of some of its carbon by large fuel cell power plants will reduce average fossil CO_2 emissions from natural gas.

Petroleum production is expected to decline due to reduced sales of gasoline and diesel fuel. Coal production will decline due to gradual closing of coal power plants and replacement of coke by natural gas in iron making (Section 7.2). Section 8.12 discusses possible new longer-term applications for petroleum and coal.

8.9 Exports and Imports

This section refers to international trade, rather than power to and from the grid discussed elsewhere in this document.

Compared with the DOE forecast (Ref. 1, Table A1), 2035 coal exports are expected to be higher and crude oil imports much lower. Significant technology exports of fuel cell systems and biomass converters are expected to be on the increase by 2035. The new exports will include equipment sales and revenues from licensing.

8.10 Technology Development

Considerable efforts will be needed to develop the proposed new fuel cell and biomass converter systems. Prototypes must be designed, built, installed, demonstrated, and improved. Small-scale equipment manufacturing will be followed by progressively larger plants. Development work can be phased to minimize risks. The private sector can supply most of the funding, but early government assistance (8.11.1) is also desirable.

Additional development work (of a completely different nature) is needed on CO_2 underground sequestration systems.

8.11 Government Roles

Important roles assisting the implementation of the proposed improvements should be played by both Federal and state governments. All of the proposed new and increased government expenditures and costs can be funded by energy user charges and subsidy reductions rather than from general revenues.

8.11.1 Fossil Carbon Charges

The Federal government will collect charges (Section 2.2.2) on each tonne of fossil CO_2 emissions. Such charges (which might also be called user fees or emission taxes) are expected to begin in the 2020s. Their rate (assumed to be $150/tonne in the 2035 example) is expected to increase annually from a low starting value. The considerable revenue collected can fund permanent underground sequestration facilities, purchase liquid CO_2 for sequestration, aid low-income energy users, assist technology development, and provide financial assistance to early adopters of new technologies such as proposed herein.

8.11.2 Road Use Charges

Road use charges will be based upon vehicle travel and average weight, rather than the present practice of taxing fuels (thus fairly including all types of vehicles). The example average 2035 charge rate might be $0.020 per ton-mile. Travel charges could be paid quarterly or annually, with revenues properly distributed to Federal and state budgets for road and bridge maintenance, replacements, and additions.

8.11.3 Fuel Production Subsidies

Existing Federal subsidies for ethanol and petroleum fuels would gradually be reduced. Farmers will earn more by growing the proposed biomass than by growing corn for ethanol. Early biofuel production from the new converter types might be subsidized somewhat.

8.11.4 Energy Rate Regulation

Existing state electricity and gas rate schedules would be replaced with rational new systems of fixed charges plus variable rates. Charges and rates would fairly reflect actual costs. Grid variable rates would vary with time of use (TOU). Differentials would exist between electricity buy and sell prices, zero- and negative-carbon energy, and for filling-station natural gas. Table 3 summarizes example 2035 prices used herein.

8.12 Longer Term

After 2035, further increases in photovoltaic and wind generation capacity are expected. Building enhancements will expand. Large increases in fuel cell power plants with 100% carbon sequestration are likely. BNG manufacture is expected to grow significantly. Biokerosene jet fuel (Section 5.6) should gradually replace fossil jet fuels. A large fraction of biofuels will be made using sequestration of part of the feed carbon (negative net fossil carbon emissions).

Fuel cell systems will gradually replace engines in many types of transportation (Section 6.3), providing higher efficiency and reduced fossil CO_2 emissions. Some transportation fuel cell systems will capture liquid CO_2 from their exhaust for sale and sequestration. Such CCS systems can help limit expected declines in petroleum demand.

New direct air capture (DAC) systems powered by coal will affordably remove large quantities of CO_2 from the atmosphere, sequestering all resulting CO_2 (including that from the coal). Reference 4 includes papers describing such systems and giving example U.S. fossil carbon balances for 2050 (showing large net annual removal of fossil CO_2 from the atmosphere and increased coal production).

The rest of the world can also implement most of the approaches described in this paper, thus enjoying their financial benefits and helping to combat global warming.

9. Conclusions

This paper summarizes recommendations for future advanced energy systems using natural gas of either fossil or biomass origin. Four groups of technologies are outlined and their 2035 benefits for residences and light-duty vehicles estimated (details in Table 4). An example residence has estimated base-case annual energy expenditures (including gasoline for two vehicles) of $12,416 and associated fossil CO_2 emissions of 22.1 tonnes/year.

9.1 Evolutionary Improvements

Existing technologies (with expected future improvements) are substituted or added to the same home. Higher-efficiency insulation, doors, windows, and appliances and installed. Vehicles are replaced by plug-in types (one pure electric and one engine hybrid). Advanced heat pumps perform all space heating and cooling instead of furnaces and conventional central air conditioning systems. A rooftop solar photovoltaic system is added.

The combined result of these improvements reduces annual energy costs to $5,908 (48% of base case) and fossil CO_2 emissions to 7.3 tonnes/year (33% of base).

9.2 Fuel Cell Systems

An advanced fuel-cell cogeneration system is installed, which profitably sells power to the utility at favorable times, provides uninterruptible whole-house power throughout grid outages of any duration, supplies all hot tap water, and reduces heating costs.

Its addition further reduces net annual energy costs to $2,845 (22.9% of base case) and fossil CO_2 to 5.0 tonnes/year (22% of base).

9.3 Bio-Natural Gas

Bio-natural gas (BNG), made using a new carbon-neutral process, is substituted for fossil natural gas in the home and for gasoline in a vehicle (which is modified or replaced). Net annual energy costs slightly increase to $2,887 (23.3% of base) while fossil CO_2 emissions drop to zero.

9.4 Carbon Sequestration

More expensive BNG (made using CO_2 sequestration) is substituted for carbon-neutral BNG. Net annual energy costs rise to $3,083 (24.8% of base). A total of 16.4 tonnes/year of CO_2 are *removed* from the atmosphere (a ratio of -74% to the base case). Comparing this case to the Section 9.2 case, fossil CO_2 emissions are reduced by 21.4 tonnes/year at an added user cost of only $238/year (about $11/tonne).

10. Appendix

10.1 Price Summary

Table 3 summarizes the example variable 2035 residential and vehicle filling station prices (per kWh HHV) used to calculate Tables 1, 2, and 4. Annual charges which are independent of these prices total $2340 per year (Section 2.2.1).

Table 3. Example 2035 Prices

	Purchases (Imports)			Sales (Exports)		
	Fossil	Zero C	Negative C	Fossil	Zero C	Negative C
Natural Gas or BNG	$0.072	$0.083	$0.090			
Vehicle BNG		$0.103	$0.110			
Gasoline	$0.132					
Grid Multiplier						
40%	$0.073	$0.080		$0.043	$0.050	$0.054
70%	$0.128	$0.140		$0.098	$0.110	$0.117
100%	$0.182	$0.200				
130%	$0.237	$0.261		$0.207	$0.231	$0.242

The grid multiplier examples are explained in Section 4.1. The 40% row is the mean of low prices, 70% the mean of medium prices, and 130% the mean of high prices. The weighted overall mean is the 100% row. Prices not used in this report are left blank.

10.2 Tables 1 and 2 Details

The table below lists 2035 values used to compute the totals in Tables 1 and 2 (case numbers were not previously cited). Vehicle fuel is gasoline through case 6, followed by BNG (zero and negative carbon).

Table 4. Details of Tables 1 and 2

Case	1	2	3	4	5	6	7	8
Addition	**Base**	**High Eff**	**PIV**	**Heat Pump**	**PV**	**Fuel Cell**	**Zero C**	**Negative C**
Net Grid Purchases	$2,264	$1,520	$2,532	$3,517	$2,205	($5,299)	($5,910)	($6,226)
Piped Natural Gas or BNG	$4,092	$3,036	$3,036	$987	$987	$4,914	$5,651	$6,143
Vehicle Fuel	$3,721	$3,352	$377	$377	$377	$377	$293	$314
Fuel Cell Maintenance						$513	$513	$513
Fixed Costs	$2,340	$2,340	$2,340	$2,340	$2,340	$2,340	$2,340	$2,340
Energy Costs	$12,416	$10,248	$8,285	$7,221	$5,908	$2,845	$2,887	$3,083
Ratio to Case 1	100%	83%	67%	58%	48%	22.9%	23.3%	24.8%
Fossil CO2 Emissions								
Tonnes	22.1	17.3	13.1	9.8	7.3	5.0		(16.4)
Ratio to Case 1	100%	78%	60%	44%	33%	22%		-74%
Mean Prices per kwh								
Grid Imports	$0.182	$0.182	$0.182	$0.182	$0.182	$0.073	$0.080	$0.080
Grid Exports					$0.170	$0.202	$0.225	$0.237
Piped Natural Gas or BNG	$0.072	$0.072	$0.072	$0.072	$0.072	$0.072	$0.083	$0.090
Vehicle Fuel	$0.132	$0.132	$0.132	$0.132	$0.132	$0.132	$0.103	$0.110

10.3 References

1. Annual Energy Outlook 2020, Energy Information Administration, DOE, Jan. 2020

2. 2016 Billion-Ton Report, Oak Ridge National Laboratory, ONRL/TM-2016/160

3. Carbon Storage Atlas Fifth Edition, National Energy Technology Laboratory, 2015

4. Website with papers by the author: robertruhl.com