Residential Energy 2040

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Chapter 1. Summary

This essay describes proposed improvements to an example home which would provide major benefits to the homeowner, the environment, and electric utilities. Table 1 summarizes expected results. Table 2 (page 12) shows their components.

Table 1. Comparisons for 2040

Case	1 Traditional	2 Enhanced	3 Fuel Cell
Energy Costs	**$12,500**	**$4,600**	**$1,500**
CO2 Ratio	**100%**	**18%**	**2%**
Outage Protection		**Partial**	**Full**
Return on Investment		**20%**	**21%**

An example 3000 square foot home near the center of the United States is evaluated using (inflated) 2040 dollars. It is supplied with piped natural gas. Energy costs (rounded) are estimated net expenditures for the home and its associated vehicles.

The Traditional case uses technologies typical of those used in 2023. The Enhanced case has significantly improved energy efficiencies, replaces vehicles with plug-in pure electric types, and adds a rooftop solar array. The Fuel Cell case provides even better economic, environmental, and grid-outage advantages.

The Enhanced case uses existing technologies with evolutionary improvements. The Fuel Cell case uses new technology based upon well-known precedents. Cases 2 and 3 also promise major profit opportunities for many commercial and industrial companies. Reducing energy-related CO_2 emissions from the residential sector will help combat global warming.

Chapter 2. Introduction

This document is a condensed summary of recommended energy technologies which could be widely deployed by United States residences before 2040. Most of these technologies already exist, while others remain to be developed. The discussion is limited to detached residences, but most of the technologies could also be deployed to advantage in other applications. Selected 2040 forecast values were obtained from the 2022 Annual Energy Outlook (eia.doe.gov).

2.1 Objectives

The major objectives of the recommended energy strategies are to provide the homeowner with large annual reductions in energy costs and CO_2 emissions and reduce or eliminate the adverse impacts of grid power outages.

Additional objectives are earning an attractive return on the required investments, improving comfort and convenience, and assisting the expanded use of zero-carbon electricity.

Table 1 shows predicted results which satisfy these objectives.

2.2 CO_2 Emissions

Carbon dioxide emissions from the use of fossil fuels (natural gas, petroleum, and coal) significantly contribute to global warming. Most U.S. homes today consume natural gas in addition to electricity from the grid (partly made from fossil fuels). Their vehicles use gasoline made from petroleum. The Traditional Case in Table 1 has 21 metric tons ("tonnes") of fossil CO_2 emissions in 2040.

The DOE forecasts U.S. 2040 grid electricity to average about 280 grams of fossil CO_2 emissions per delivered kilowatt-hour (kWh). Part of the power will be produced with zero emissions (using solar, wind, biomass, and nuclear. A considerably larger contribution from solar and wind generation is expected by 2040. Most of the remainder will be generated by conventional power plants burning natural gas or coal. Actual CO_2 emissions will vary considerably with time based upon the fluctuating fraction of zero-carbon power being used to supply varying user demands.

2.3 Prices

DOE 2040 price forecasts for residential natural gas, electricity, and (transportation) gasoline in nominal (inflated) dollars from the 2022 Annual Energy Outlook were used as the starting point for calculating assumed prices used here. An assumed 2040 tax (or user fee) of $160 per tonne of associated CO_2 was added to each price.

Electricity and natural gas prices were divided into fixed and variable components. Fixed charges will pay for infrastructure maintenance and capital. Variable charges will pay for the actual quantities used.

Future residential grid electricity variable prices will continually vary with time, based on supply-demand balance. The larger use of solar and wind generation will increase balancing challenges. This essay divides electricity pricing into three brackets (low, medium, and high), with one-third of annual time in each bracket (time-of-use pricing"). Case 1 (chapter 3) assumes all grid power purchased at average price. Cases 2 and 3 assume the low, medium, and high brackets to average 50%, 100%, and 150% of average price respectively. The predicted average variable grid price is $0.172 per kWh. Grid prices are equal for imports and exports ("net metering"), since exports from residences benefit the grid in several ways.

Assumed variable costs are $0.092/kWh for natural gas and $0.189/kWh ($6.38/gallon) for the gasoline used in Case 1.

Added maintenance costs for the new Case 2 and 3 systems are included in cost totals.

2.4 Example Cases

The next three chapters describe assumptions and 2040 results for the example residences summarized in Table 1. They assume a 3000 square foot stand-alone single-family home located near St. Louis, Missouri (a location selected for its climate and sunlight being near U.S. averages). The home was built sometime before 2025. Cases 2 and 3 assume upgrades to the same dwelling.

It has an attached two-car garage. Roughly half its pitched roof faces south, with no shading from nearby trees or buildings. It is equipped with natural gas and grid electric service.

The residence is assumed to have two light-duty vehicles (typically SUVs or cars) driving a combined total of 20,000 miles per year. They are assumed to pay a total road-use fee of 6.0 cents per mile in 2040, for a total of $1200 (not included in cited energy costs). This fee (calculated on annual ton-miles of travel) will replace gasoline taxes and charge vehicles powered by electricity and/or liquid fuels more fairly.

Grid power outages are becoming more common and often of longer duration (sometimes even weeks), due in part to aging equipment, more extreme weather events, and older trees. Short outages cause inconvenience, while longer ones can produce major difficulties. Space heating systems in nearly all traditional homes require electricity to operate, sometimes causing the additional risk of frozen pipes. The following chapters discuss effects of power outages on each case.

Dollar figures in this document use nominal (inflated) 2040 dollars. Energy quantities have been converted to kilowatt-hours (kWh), with lower heating values (LHV) used for fuels.

Chapter 3. Traditional Case 1

This case resembles most 2023 homes. Its thermal insulation, windows, and doors are typical of such homes, as are most of its appliances, lighting, and entertainment systems (with minor improvements in their energy efficiencies).

HVAC (heating, ventilation, and air conditioning) uses a natural gas furnace, central air conditioning attachment, and a minimal ventilation system with automatic humidifier and air filters. HVAC energy efficiencies are typical of 2023 (since the equipment is either old or had been selected for its low installed cost). Hot water is supplied by a conventional natural gas water heater. The electric range and clothes drier are both typical of 2023 types.

Two conventional gasoline-engine vehicles are over eight years old and drive a combined 20,000 miles per year. They average 29.7 miles per gallon (predicted value for 2040 from the 2022 Annual Energy Outlook).

The example Case 1 home has no backup electricity, heating, or cooling (its furnace needs grid power for its blower) and risks frozen pipes during any long winter outages. Its total 2040 energy costs (in 2040 dollars) are $12,500 per year. Its associated energy-related fossil CO_2 emissions are 21 tonnes (metric tons) per year. Table 2 (page 12) shows details.

Chapter 4. Enhanced Case 2

Case 2 adds multiple energy-related improvements to reduce consumption and use the sun to generate part of home energy needs. All the enhancements recommended in this chapter employ products readily available today, with expected evolutionary improvements made over the next decade. In addition to the efficiency improvements summarized below, energy conservation practices can also reduce costs and CO_2 emissions.

With the expected time-of-use electricity pricing, significant cost savings are possible by shifting the timing of larger electrical uses (the Case 2 and 3 examples assume some such shifting).

4.1 Thermal Efficiency

Most homes consume more energy for heating, ventilation, and air conditioning (HVAC) than any other purpose. Significant improvements are possible in most 2023 structures.

Thermal efficiency can be increased by using highly effective insulation in walls, beneath roofs, and under the lowest floors. Windows can be replaced with advanced designs (often using triple glazing, coatings on inside surfaces, and lower-conductivity gas between their sealed panes). Advanced exterior doors can have similar features in any windows present and often add storm doors. Windows are available with virtually zero air leakage and door systems with very low leakage.

Overhangs and/or awnings can minimize solar gains in hot months. Winter thermal performance can sometimes be improved by south-facing windows collecting passive solar heating assistance.

Energy needs for HVAC can also be reduced by minimizing the opening of windows and doors. The ventilation systems described in section 4.5 provide cleaner incoming air and superior energy efficiency in most types of weather.

4.2 Electrical Efficiency

General electricity is here defined to include consumption for uses other than HVAC and vehicle charging. Its consumption can be minimized by using highly-efficient lighting (such as LEDs), appliances, and entertainment systems. The kitchen range will use an induction cooktop and convection oven.

Affordable new models of electric driers are expected before 2040 which will incorporate a condenser and compressor in a sealed loop, providing much of the needed drying heat by condensing water vapor. Such driers will use less than half the electricity input of conventional types.

Section 4.5 discusses heat pump systems which have superior electrical efficiencies and consume considerably less total energy than systems using furnaces. Inexpensive space heating equipment using electric resistance heating should be used very sparingly, if at all.

4.3 Electric Vehicles

Cases 2 and 3 assume plug-in pure electric vehicles with an overall average of 3.2 miles per kWh, for an annual total of 6250 kWh used in 20,000 miles. All charging is assumed to be performed at home (the small amount of charging done elsewhere on long trips will have minimal extra cost and CO_2 emissions).

Annual travel will average about 27 miles per day per vehicle. The smaller one will have a minimum cold-weather range of perhaps 150 miles on a full charge, with the other vehicle having a larger battery giving at least twice this range. High-power recharging stations will become very widely available for use on long trips, restoring considerable range in under a half hour.

The home will have a two-port intelligent charging station in the garage. Unless manually over-ridden, charging will be performed at lower grid prices when convenient. During grid outages, charging power and timing will be modified as appropriate to limit maximum demand.

4.4 Solar Photovoltaic (PV) Generation

The enhanced homes have a rooftop photovoltaic array and associated indoor electrical equipment. These systems intermittently generate zero-carbon electricity (at varying power) which reduces purchases from the grid. Surplus generation is profitably sold to the grid. The array is assumed to have negligible shading from nearby trees or buildings. The installed system will comply with all applicable safety codes.

4.4.1 Photovoltaic Array

The examples assume a nominal rated photovoltaic panel capacity of 10 kilowatts, which will yield an annual average of about 14,600 kWh of net AC electricity at a site near St. Louis (facing south on an angled roof surface). This array will average 1666 Watts over the entire year (24 hours a day basis), with varying solar-energy timing, intensity, angle of striking the array, and system electrical losses.

By 2040, typical panel capacities are expected to be near 15 watts per square foot and so the example array will occupy about 660 square feet (for example, 20 feet tall by 33 feet wide).

A visiting professional maintenance crew is assumed to thoroughly clean the array at intervals which maximize net economic benefit (cleaner panels generate more power).

A wiring harness will use series/parallel connections to deliver array power to indoor equipment at preferred DC voltages. Lightning protection will be included.

4.4.2 Power Conditioning System

A highly efficient power conditioning system will convert input DC power to conventional AC output at 120/240 Volts, 60 Hertz. It will continuously synchronize its voltage and phasing with the grid (except during outages, when it will self-regulate). This system will operate with excellent electrical efficiency, with its small heat release augmenting space heating in cold weather.

In addition to input from the solar array, it will interface with the battery subsystem cited below and also accept DC input from a fuel cell system added subsequently or concurrently (chapter 5). A versatile control, data-logging, and communications system is included, which provides wireless two-way communication with the electric utility and the user.

4.4.3 Battery Subsystem

A lithium-ion battery subsystem is included in the power conditioning system (example battery capacity 8 kWh) and used only during grid outages. It provides electricity during outages to priority loads (which are wired to a dedicated breaker panel). The solar system can recharge the battery during extended outages, significantly increasing available energy. In combination with the heat pump system described below, continuous heating of the entire home can be maintained throughout long grid outages. The battery system also helps provide surge and peaking power.

4.4.4 Grid Interface

The grid interface includes bidirectional metering, sensors, overcurrent and overvoltage protection, and a fast-acting contactor to automatically disconnect the home from the grid during outages or major grid disturbances. When stable grid power returns, it will reconnect. The current sensors assist the user in adjusting usage timing to benefit from lower rates.

4.5 Heat Pump System

An advanced, highly efficient, ductless heat pump system is used in Cases 2 and 3 to provide space heating, space cooling, and humidity control. Its main components are an indoor refrigerant compressor/heat exchanger subassembly, an outdoor heat exchanger with fan, and multiple room units with fans and heat exchangers. Each of its room zones has a wall-mounted programmable thermostat for optimized comfort and energy efficiency. Its compressor and fans all operate at variable speeds to maximize efficiency and minimize noise levels.

The Case 1 furnace and central air conditioning system are removed, since the heat pump system provides far superior energy efficiency and is designed to provide ample capacity over the full range of outdoor temperatures.

An attached oxidizer subsystem is used in the coldest weather to augment heating capacity. It uses catalytic oxidation of natural gas to vaporize additional liquid refrigerant for the room circuits. This amply-sized subsystem also provides whole-house heating during grid outages, with the battery system (4.4.3) powering room fans and controls.

A versatile ventilation system is attached to the heat pump system. Small fans continually exhaust stale air from the home and supply makeup fresh air with adjusted temperature and humidity. This system is called an energy-recovery ventilator (ERV), since it can exchange thermal energy between the incoming and exit air flows. Required heating or cooling is obtained from the heat pump system. The ventilation system includes highly-effective cleaning of incoming air (using a filter plus an electrostatic grid). The pure water needed for humidification is obtained by a miniature reverse-osmosis water purifier subsystem in Case 2 and from fuel cell system condensate in Case 3. Water condensed during dehumidification is evaporated by the outdoor fan flow to assist heat rejection.

Small tubes carry refrigerant liquid and vapor to and from each room unit (wall or ceiling mounted). The entire system is very well sealed, with sensors to detect unlikely refrigerant leakage. The refrigerant of choice today is R410A (compounds of hydrogen, fluorine, and carbon), which might be superseded by 2040.

4.6 Results

As shown in Table 1, energy costs for Case 2 are reduced by almost $8000 per year from the traditional case. Associated CO_2 emissions are cut by over 80%. An example Case 2 investment of $40,000 earns a return on investment near 20%. Table 2 (page 12) provides details of these totals.

During grid outages of any duration, the home continues to be fully heated. Uninterruptible power continues to be supplied to priority loads (e.g., refrigerator, security system, backup heating system, portable-device charging outlets, and key lighting). Depending upon sunlight received during long outages, other loads can also receive power (e.g., cooking equipment, vehicle charging, space cooling).

The Case 2 home thus has compelling advantages over a traditional home. Indoor comfort is significantly improved, with very good indoor air quality (cleanliness and humidity) and zoned room temperature control with minimized drafts and noise. Full heating and partial electricity are provided during grid outages of any duration. Major cost and CO_2 savings are achieved. Case 2 homes have key provisions to assist the desirable addition of Case 3 systems concurrently or subsequently.

Chapter 5. Fuel Cell Case 3

The energy performance of a Case 2 home can be significantly improved by the addition of a proposed new fuel cell system, which could become available in quantity by about 2030.

5.1 Description

A fuel cell cogeneration system will be added. It will use natural gas and indoor air to generate electric power, useful heat, and pure water. Its power output will (normally) be 5000 Watts at 120/240 Volts AC nominal, synchronized to the utility grid. When grid prices are below net generation cost, the system will operate in hot-idle mode (and continue to provide hot water).

During grid outages, fuel cell generation will automatically follow site load demands in excess of solar generation to provide uninterruptible whole-house power until grid power is restored. The battery system cited in section 4.4.3 will assist load following and provide peak power during outages.

Heat produced during fuel cell system operation will be used for water heating and to assist space heating. Excess heat will be added to the continuous stale-air outdoor-vent flow.

Since the combined site electric loads will usually be lower than the sum of fuel cell plus solar generation, some of the power will be profitably exported (sold) to the grid. When residential demand occasionally exceeds total generation, some grid power will be imported.

The compact fuel cell system will operate continuously, reliably, and safely, with sound levels resembling a quality refrigerator. It will be installed adjacent to the HVAC equipment to facilitate utilization of its surplus heat.

The system will operate with outstanding energy efficiencies. At full power it will convert about 70% of fuel energy content (lower heating value) to AC power. Its available useful heat will be 40% additional, for a sum up to 110% (values above 100% are due to water condensation from the exhaust: natural gas molecules are rich in hydrogen).

Fuel cell systems generate electricity using electrochemical reactions rather than noisy high-maintenance heat engines. The proposed systems operate at high internal temperatures inside well-insulated enclosures. They will produce no air pollutants, such as the particulates, CO, and NO_x produced by some other types of natural gas equipment. Since their energy efficiencies will exceed existing types of natural-gas-fueled generation equipment, they will produce significantly less CO_2 per electrical kWh.

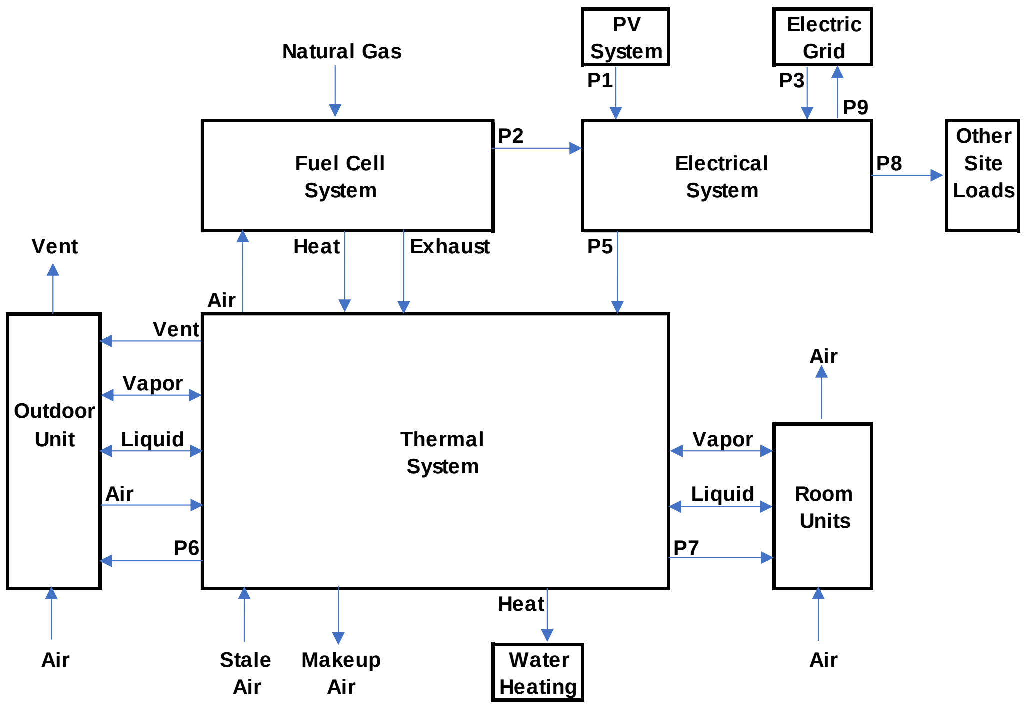
5.2 Results

As Table 1 shows, the Case 3 system has annual cost savings over $3000 from Case 2, giving cumulative ROI of 21% on an estimated cumulative investment of 52,000. CO_2 emissions are further lowered to 2% of Case 1. Table 2 (page 12) provides details.

A Case 3 home has full uninterruptible power for unlimited duration during grid outages, including full HVAC in all weather and vehicle charging (with adjustments in the timing of charging automatically made when necessary). It also helps the grid to accommodate more solar and wind capacity by exporting an average of over 4500 Watts when grid prices are high (often due to low renewable inputs).

Figure 1 shows the interconnections in a Case 3 system.

Figure 1. Interconnections



Streams P1 through P9 are electric power. P6 and P7 drive variable-speed fans. When outdoor temperatures are low, the Outdoor Unit evaporates low-pressure liquid refrigerant and the Room Units condense high-pressure refrigerant vapor. When outdoor temperatures are high, The Room Units evaporate low-pressure liquid refrigerant and the Outdoor Unit condenses high-pressure vapor. The Thermal System includes a refrigerant compressor, heat exchangers, pumps, valves, and controls. Grid power is input (P3) when prices are below fuel cell operating cost and export (P9) at higher prices. Surge power needs are also supplied by P3. In the simplified diagram, some features (such as automatic outdoor defrosting in winter) are not shown. The Vent stream from the thermal system contains stale air, CO_2 from natural gas consumed, and any unneeded surplus heat.

Chapter 6. Discussion and Conclusions

Table 2 shows details of the Table 1 totals. Natural gas and grid electricity costs include both fixed and variable components. Maintenance costs are for the solar array and fuel cell systems. Negative values are net reductions.

Table 2. 2040 Details

Case	1 Traditional	2 Enhanced	3 Fuel Cell
Natural Gas	$5,000	$1,900	$5,300
Grid Electricity	$3,200	$2,400	($4,600)
Gasoline	$4,300		
Maintenance		$300	$800
Annual Energy	$12,500	$4,600	$1,500
Natural Gas	10.7	2.0	11.5
Grid Electricity	2.8	1.7	(11.1)
Gasoline	7.5		
CO2 tonnes/year	21.0	3.7	0.4
Incremental Investment		$40,000	$12,000

More extensive treatment of some of the topics in this document is included in prior essays at robertruhl.com (which exists solely to present energy ideas).

The proposed residential energy improvements in Case 2 will be available as improved versions of products already in mass production today. Expected competition among existing and new providers will enhance their future cost effectiveness.

The advanced fuel cell systems proposed in Case 3 require a sizeable technology development program.

6.1 Case 3 Implementation

Implementation of Case 3 will be most likely to succeed if early technology development is performed by an appropriate startup company. The ideal new firm will be amply funded by a patient and wealthy "angel" investor with a strong desire to reduce global warming. The company will have a small management team which is highly capable, energetic, technically knowledgeable, and focused. Total employment of the new company should remain under a hundred and total expenditures below about $50 million until key milestones have been reached, which should be possible before 2030.

Fuel cells were invented in 1838 and billions of dollars have since been spent worldwide on their development and manufacturing. However, the solid-oxide systems proposed here differ from existing systems, promising higher performance and lower costs once in mass production.

Early in the development program detailed equipment designs should be prepared for both early trials and initial production models. Early systems should begin shop testing within two years, with continuing improvements made. The moderate cost of each system will permit rapid progress, parallel paths, and collection of reliability data on multiple copies.

Since a 5-kW fuel cell system will use over a thousand cells made to close tolerances, it is essential that automated equipment to manufacture and stack these cells be developed from the start. While prototype complete systems can be assembled by hand, automated welding of subassemblies should also be developed early.

Government subsidies are not recommended for multiple reasons. It will be desirable, however, for governmental organizations to revise various regulations on utility pricing and building codes. Taxes or fees on fossil carbon emissions would enhance the advantages of advanced technologies. Governments should also assist publicizing the benefits of improved energy options.

Once prototype systems have been demonstrated in field tests to be satisfactory, it should be easy to obtain investment capital for profitable large-scale production. Additional manufacturing companies can be licensed. By 2040, the number of homes with Case 3 capabilities should approach a million and profits from their sale and installation are expected to be in the billions of dollars. Since the United States has over 100 million residences, the potential markets are very attractive.

6.2 Other Possibilities

Actual 2040 prices are likely to differ from these used in the above examples and by location within the country. However, the major benefits are still expected to be very attractive. Most homes will use annual energy quantities differing from the example. Production models of the equipment described will be manufactured in both smaller and larger sizes than the cited examples. Fuel cell systems operating from propane or heating oil (instead of natural gas) will also become available.

Many homeowners will drive at least one plug-in hybrid vehicle which uses a gasoline engine in addition to electricity. Although such vehicles emit far less CO_2 than traditional types, the expected future availability of bio-gasoline will enable these to operate with zero (or even negative) fossil carbon emissions when using liquid fuel.

The heat pump systems described in section 4.5 could be enhanced by the addition of an absorption (heat-driven) compressor subsystem. This compressor would use an ammonia-water solution inside a compact sealed circuit. Increased energy efficiencies and cost savings for both heating and cooling would result, with part of the heat from fuel cell and oxidizer operation driving the added compressor.

Reduced energy usage, larger capacity on-site electricity generation, and/or more favorable pricing could further reduce annual energy costs for the example (possibly to less than zero). Such variations might also reduce CO_2 emissions below net zero (avoided grid emissions from exports exceeding natural gas emissions).

Multifamily residential and small commercial buildings can be served by larger systems with more complex thermal systems attached.

Expected future natural gas kitchen ranges will produce negligible air pollution and be an alternative to the electric types assumed.

Natural-gas-fueled backup engine-generator systems are presently available in many sizes for use during outages. Unlike the proposed Case 3 fuel cell systems, they would not reduce costs or CO_2 emissions. Their installed costs can be comparable to the recommended alternatives.

Larger lithium-ion battery systems are also now available to supply additional backup power. They are quite expensive and do not remotely approach the grid-outage capabilities of the proposed Case 3 systems.

6.3 Interim Years

All the recommended Case 2 technologies are already in mass production. Although their assumed 2040 performance, cost effectiveness, and power-outage capabilities are better than today's models, most of the Case 2 benefits (adjusted for inflation) can be obtained sooner. The Case 3 fuel cell systems are expected to become available (at higher installed cost than the 2040 forecast) in limited quantities by the early 2030s.

6.4 Subsequent Years

The proposed new technologies are expected to be installed in far more homes after 2040, multiplying the advantages. U.S. residences and their associated vehicles presently account for over one billion tonnes of annual fossil CO_2 emissions: over 20% of the U.S. total.

The expected gradual decarbonization of the utility grid will reduce the CO_2 reductions from export power (but not the likely cost savings). Bio-natural gas is expected to become available by 2040 (co-mingled in existing pipes) and would enable net CO_2 removal from the atmosphere.

Large-scale implementation of affordable CO_2 capture and sequestration (CCS) is expected. This technology will reduce the average carbon footprint of grid power. It will also enable biofuels to be manufactured with negative CO_2 emissions (net carbon removal from the atmosphere).

Future virtual-battery systems are expected which would economically "store" large quantities of lower-cost grid power for delivery much later (even in other seasons). Such systems might be advantageous to homes lacking natural gas service.

6.5 Conclusions

Residential energy upgrades are proposed which can improve indoor comfort, remove grid-outage concerns, and drastically reduce annual energy expenditures and CO_2 emissions. Two examples of upgrades are given. The Case 2 example enhancements provide major benefits and can be installed starting now. Subsequent Case 3 addition of an advanced fuel cell system produces the full benefits described.