Residences with Zero Fossil Carbon Emissions

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1. Summary

This document compares a residence using traditional energy technologies with a proposed alternative using improvements which could be deployed extensively before 2050. The residences and their vehicles produce zero fossil CO_2 emissions.

An example 2800 ft^2 home with two personal vehicles is used, with possible 2050 energy pricing. It is connected to both an electricity grid and gas pipeline. The residence is well insulated and uses energy-efficient lighting, appliances, and electronics. Purchased energy includes zero-carbon grid power, bio-natural gas, and bio-gasoline.

The traditional case uses common technologies from the 2020s, including a gas furnace with central air conditioner and conventional gasoline-powered personal vehicles. It has no backup power system. Its 2050 energy costs are projected to total $18,700 per year.

The proposed residence includes multiple enhancements, with a combined investment cost of $72,000. Its total 2050 energy costs are only $500 per year, providing an annual ROI of 25%. The residence will maintain its full heating, cooling, and electricity throughout grid outages of any duration. In addition to the above types of purchased energy, it will use abundant, lower-cost fossil natural gas with complete capture of its CO_2 and permanent sequestration. The residence will act as a virtual-battery to assist economical use of additional solar and wind power.

2. Introduction

The example residence is located hear St. Louis, Missouri: a site with annual space heating, space cooling, and solar energy all close to U.S averages. Section 3 describes a traditional case and four enhanced cases, with financial results listed in Section 4. All grid power has zero fossil carbon emissions. Financial numbers are 2050 (inflated) dollars, with annual values rounded to the nearest $100.

A larger document by the author entitled "Combatting Climate Change" was concurrently posted on the website robertruhl.com. It includes descriptions of all the proposed major technology innovations cited herein: new biofuels, advanced heat pump systems, fuel cell systems, carbon capture and sequestration, and virtual battery systems. That document describes an affordable strategy to achieve large net fossil carbon removal from the atmosphere before 2050.

2.1 Fuels

The residence and its vehicles will consume two new biofuels: bio-natural gas (BNG) and bio-gasoline, both manufactured by new technologies from biomass crops and wastes with negative CO_2 emissions (part of the renewable biomass carbon is captured and permanently sequestered). The premium bio-gasoline will have 99 octane and contain no oxygen or sulfur.

The BNG will be co-mingled with fossil natural gas (having virtually identical properties) in conventional pipelines supplying homes and other users. Natural gas will be sold (at a lower price) only to users who capture all its carbon as liquid CO_2 (Case 5).

Case 5 will manufacture a superior grade of fossil kerosene (free of sulfur and aromatics) from low-priced grid power, stored pure water, and stored fossil CO_2 previously captured from natural gas. Trucks will occasionally remove kerosene and surplus liquid CO_2 from a divided outdoor tank. The kerosene will later be sold only to customers using equipment with complete CO_2 capture (usually fuel cell systems for transportation or stationary applications), thus maintaining zero fossil CO_2 emissions.

2.2 Cost and Price Assumptions

Before 2050, all energy prices are expected to be restructured and significantly increased. Users of piped gas and grid electricity will pay fixed annual charges to cover infrastructure maintenance and overhead costs. Maintenance costs of roads, bridges, and other travel infrastructure will be based on annual ton-miles rather than by fuel taxes. In the example used herein, the sum of these changes is $4,100 per year for all cases. Variable grid prices will vary considerably every day, based on total grid supplies, demands, and input costs. When supplies tend to exceed demands, prices will be lowered. When demands tend to exceed supplies, prices will be raised. Variable pricing will provide incentives to both users and generators to maximize their economics. The modeling used herein assumes mean low prices 50% of average for 1/3 of the time and mean high prices 125% of average for 2/3 of the time. Hourly prices will vary above and below the mean values.

Assumed 2050 Variable Prices

Bio-Natural Gas (BNG)	**$0.14**
Biogasoline	**$0.26**
Grid Average	**$0.28**
Grid Mean Low	**$0.14**
Grid Mean High	**$0.35**
Natural Gas	**$0.10**
Kerosene Sales	**$0.20**

Net metering (same prices for buying and selling power) is assumed for grid low and high prices, since exports to the grid need to travel very short distances to nearby customers and also aid the grid in other ways. Surplus liquid CO_2 is removed at no cost, since its price is net of associated external costs.

2.3 Virtual Battery Operation

Before 2050, the utility electrical system will rely on a considerably higher percentage on input power from solar and wind equipment, with less from fossil-fueled generation (then equipped with CO_2 capture for sequestration). The inherent and seasonal variability of greater renewable energy will make the essential continual balancing of grid input power with user consumption more challenging.

Methods in use today for short-term (usually up to 24 hours) electricity storage include battery banks, hydroelectric systems with reservoirs, and systems using compressed-air cavern storage. All of these are costly and unsuitable for storing massive quantities for weeks or months. The principal equipment used today for grid balancing are natural gas turbine-generators, which would be very expensive to equip with complete (or nearly complete) CO_2 capture.

Virtual battery systems could be highly suitable for grid balancing, with complete timing flexibility (hours to months). When grid supplies exceed demands (low grid prices), virtual batteries would use grid power to perform a valuable function. When user demands exceed supplies (high grid prices), virtual batteries would feed power to the grid. Cases 4 and 5 described below perform a virtual battery function, with Case 5 having a desirable much higher input power at low prices.

3. Cases

Five cases were evaluated. All assume a home with very good insulation, windows, and doors. Its appliances and lighting are assumed to be highly efficient. All HVAC systems include humification and dehumidification. Pure water condensed from fuel cell and oxidizer exhausts is used for humidification (with any excess having multiple use options). A kitchen range and outdoor grille use piped BNG. An advanced electric clothes drier has excellent efficiency. The results are applicable to either an existing or new home. Cases 2 through 5 assume all prior enhancements have been installed (subsequently or simultaneously). Combined vehicle travel is 24,000 miles per year.

Case 1: Traditional

Heating, ventilation, and air conditioning (HVAC) are provided by an efficient conventional ducted gas furnace with central air conditioner and air filtering (such HVAC systems are used only in Case 1). A conventional electric water heater is used. The vehicles are conventional gasoline-engine types, with fuel efficiencies using the DOE forecast 2050 average. No backup power system is present. Traditional homes are expected to be less numerous than the cases below, due to their high annual costs, vulnerability to power outages, and lower comfort.

Case 2: Enhanced

Enhancements in this case include an alternative HVAC system, backup power and heating systems, alternative vehicles, and maximizing use of low-cost grid power. A wireless communication system with the utility transmits varying rate information, including estimates for the succeeding 24 hours or more. A user interface logs grid power flow and cost data versus time and communicates with on-site user electronic equipment.

The HVAC system utilizes an advanced ductless (and very quiet) heat pump system with individual thermostats (and the ability to heat some zones and cool others simultaneously). An advanced ventilation system provides cleaned fresh air with regulated humidity and exhausts stale air.

During grid outages, a contactor disconnects the grid and a moderately-sized battery subsystem provides power to priority loads (security system, refrigerator, portable-electronics charging, hall lights, and backup heating system) for a minimum of 60 hours. A full-capacity BNG backup heating subsystem is attached to the heat pump system.

Two plug-in vehicles replace the Case 1 types. One is a pure battery model with no engine, while the other is an engine-battery hybrid with an average battery range of 80 miles on a full charge. A highly versatile dual-port charging station allows either or both vehicles to be plugged in, with manual or computer-selected timing. Gasoline travel is assumed to be 4000 miles per year.

Low-cost grid power is preferentially used for vehicle charging and water heating.

Case 3: Solar Photovoltaic System

This includes a rooftop solar photovoltaic (PV) array, power conditioning system, and control system. Its nominal AC capacity is 10 kW, providing an annual average of 14,600 kWh. The power conditioning system is designed to also operate with the Cases 4 and 5 additions.

While the majority of the PV power is generated at low mean grid price, it nevertheless provides major economic benefits. It also increases the minimum backup time of the Case 2 battery system to at least 100 hours (and much longer with significant sunlight).

Case 4: Fuel Cell System

A 5-kW fuel cell system uses BNG at very high efficiency to generate AC power and usable surplus heat whenever grid prices are in their upper range. At low grid prices, the fuel cell system is hot idled (no input fuel) with a small power input which also heats water.

An additional thermal system is added to the Case 3 heat pump system. It includes a thermally-driven (absorption) compressor which is used instead of the Case 3 electric compressor in cooler weather and together with it in warmer weather. It also includes a BNG oxidizer subsystem for supplemental heat in cooler weather and additional heat exchange for water and space heating.

The addition of the fuel cell system allows whole-house uninterruptible power, heating, and cooling for unlimited durations during grid outages (the fuel cell system will load-follow site power consumption when exports to the grid are not possible).

Case 5: Capture and Synthesis System

Two subsystems are added to the Case 4 configuration. One captures and stores pure (fossil) liquid CO_2 and water from fuel cell and oxidizer exhaust, allowing less-expensive fossil natural gas to be used (instead of BNG) for these systems while maintaining zero fossil carbon emissions. The other subsystem uses low-cost power to convert CO_2 and water into kerosene for profitable sale.

The capture subsystem is fed fuel cell and oxidizer exhausts. It employs heat exchange, a two-stage compressor, refrigeration, and other elements to deliver all contained (fossil) CO_2 and water vapor as pure liquids. Its clean vent gas contains nitrogen, oxygen, and argon.

An add-on subsystem uses 10 kW of low-cost grid power (when available) to convert liquid CO_2 and pure water into a superior grade of pure kerosene for profitable sale. The synthesis system operates the fuel cell stacks in reverse to electrolyze steam into pure hydrogen and oxygen. The hydrogen is catalytically reacted with CO_2 to produce kerosene, while the oxygen is vented. In the example case, 63% of the annual captured CO_2 is converted to kerosene, with the remainder removed for sequestration.

A special divided outdoor insulated tank is used to store the three liquids: CO_2, water, and kerosene. The tank is maintained at about 15°C internal temperature and the corresponding CO_2 saturation pressure of 725 psig. Moveable dividers automatically accommodate the varying volumes, with CO_2 vapor also present in its section. Surplus CO_2 and kerosene for sale are occasionally removed by special trucks. Surplus pure water may be used to assist system cooling or for other purposes.

4. Results

Summaries for the described example cases are shown (rounding appears to cause addition errors). All have zero fossil CO_2 emissions. Case 5 employs carbon capture and sequestration (CCS).

Calculations for 2050

Case	1 Traditional	2 Efficient	3 Solar	4 Fuel Cell	5 Synthesis
BNG	$3,800	$200	$200	$7,300	$200
Biogasoline	$7,500	$700	$700	$700	$700
Natural Gas					$5,100
Kerosene					($5,000)
Grid Power	$3,100	$5,400	$2,100	($10,500)	($6,700)
Maintenance			$400	$1,200	$1,800
Fixed	$4,200	$4,200	$4,200	$4,200	$4,200
2050 Costs	$18,700	$10,600	$7,700	$2,900	$500
Investment		$30,000	$42,000	$60,000	$72,000
ROI		27%	26%	26%	25%

The investment and ROI values are versus Case 1. All cases yield high returns on investment.

During grid outages, Case 1 has no power or heat. Case 2 typically has up to 60 hours of priority-load power and full heating, extended to at least 100 hours in Case 3. Cases 4 and 5 have complete whole-house power and HVAC for unlimited times.

Cases 4 and 5 act as valuable virtual battery systems throughout the year. Each averages over 5 kW of power exported to the grid when prices are high. Case 5 desirably imports an average of nearly 10 kW from the grid when prices are low (Case 4 low-price imports average about 0.5 kW).

Residents using any of the Cases 2 through 5 will also have the satisfaction of helping minimize total U.S. energy consumption, and assisting the transition to a carbon negative country (since the proposed biofuels are produced by carbon-negative technology). The use of (abundant) natural gas in Case 5 minimizes consumption of BNG (whose total domestic production will be limited).

5. Discussion

5.1 Sizes

The proposed technologies are applicable to single homes of nearly any size and to most small multifamily buildings. The fuel cell systems will be manufactured in a wide range of capacities from 1 kilowatt to over 100 kilowatts (the example home uses a 5-kW system). Systems using very similar technologies will also be installed in many commercial and small industrial buildings.

5.2 Photovoltaic Arrays

The above example includes a 10-kW PV array, which saves $2900 per year (Case 2 minus Case 3). Some sites are unsuitable for a PV array and for these the savings and incremental investment can be subtracted for Cases 3 through 5. Other sites may use smaller sizes due to site or funding limitations. Larger arrays (when suitable) will have similar investment costs and savings per kW and can lead to net annual profit instead of cost.

5.3 Alternative Fuels

Roughly 40% of the homes in the U.S. lack piped natural gas service. Fuel cell and associated thermal systems will be sold for operation with bio-kerosene (also available by 2050). Ranges and grilles can use bio-propane (similarly available). The Case 5 systems will use fossil kerosene fuel (with CO_2 capture), synthesizing part of their own needs when grid prices are low. Investment costs and energy efficiencies will be essentially same as those for BNG and natural gas. The higher expected 2050 prices for the alternative fuels will increase annual energy costs for Case 1 by roughly $2000 and for Cases 4 and 5 by about $4000, giving somewhat smaller (but still attractive) Case 4 and 5 ROIs.

5.4 Deployment

All U.S. residences are expected to have zero fossil carbon emissions before 2050, since their available energy sources will all be zero carbon. Many homes will avoid some or all of the proposed enhancements (for a variety of reasons) or install other types of energy systems. Others will delay upgrades until after 2050. The associated document "Combating Climate Change" being posted on robertruhl.com assumes limited (but significant) deployment of the proposed systems.