Homes with Energy Storage

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1. Summary

Energy-system alternatives for an example existing or new home with no piped gas service have been forecast for the year 2040. The home is located near St. Louis, Missouri.

A traditional case uses an oil furnace, central air conditioning, and gasoline vehicles. The second case uses superior equipment widely available in 2026: a ductless heat pump system, all-electric vehicles, rooftop solar photovoltaic system, and battery bank. The third case adds a new technology: a reversible fuel cell system capable of economically storing very large quantities of usable energy.

Table One summarizes key results (costs include forecast inflation). "Backup Energy" is electricity and heating available to the home during extended grid outages. Example returns on investment for cases 2 and 3 exceed 25% (details in section 8).

Table One: 2040 Predictions

Case	1 Traditional	2 Now Available	3 Proposed
Energy Costs	**$10,900**	**$3,800**	**($600)**
Fossil CO2 tonnes	**19**	**4**	**(8)**
Backup Energy	**none**	**Fair**	**Excellent**

The traditional case has large annual energy costs and fossil CO_2 emissions. Case 2 has far lower energy costs and CO_2 emissions. Case 3 adds a proposed energy storage system, leading to negative net annual energy costs and CO_2 emissions as well as excellent backup energy.

The energy storage system could become commercially available before 2040. It would add economical electricity storage capacity 150 times that of a typical residential lithium-ion battery bank. The storage system would be changed with low-cost, carbon-free surplus electricity from the grid and the rooftop solar panels. This electricity would later be profitably sold to the grid when prices are high, displacing grid inputs from high-cost, high-carbon peaking generation equipment. Surplus summertime solar power from the grid could be practically stored for sale in winter using this system. The large storage capacity could also generate full residential backup power and HVAC for long durations.

The energy storage system would utilize a sealed reversible fuel cell system with compact tanks storing its captive liquid reactants: pure water, pressurized carbon dioxide, and kerosene. Its operation would also produce usable heat used to supply hot water and assist space heating. Section 6 contains more details.

2. Introduction

This essay summarizes relevant ideas and detailed calculations by the author for example U.S. detached single-family residences in 2040. It describes three alternative energy systems installations, with predicted investment costs, annual operating costs, fossil CO_2 emissions, and capabilities during prolonged grid outages. Case 1 uses traditional energy technologies, case 2 uses superior technologies readily available today, and case 3 adds an advanced new technology expected to become available before 2040. The example homes have no connection to piped natural gas (only about 60% of U.S. homes are so connected).

A companion essay entitled “Bio-Natural Gas Homes” has also been completed. Reference 1 includes both essays plus prior writings by the author.

Although the numerical results will differ, large cost and environmental improvements with the proposed technologies are also believed possible for most multifamily residential buildings and many commercial buildings.

Nominal 2040 dollars (including inflation) are used throughout this essay.

The heating oil and gasoline assumed are fossil fuels refined from petroleum. Grid power purchased at medium or high prices is partly made from fossil fuels with no carbon capture or sequestration. Low-priced grid power is assumed to have been produced with zero fossil carbon emissions (from solar, wind, hydroelectric, nuclear, or other zero-carbon generation systems).

3. Common Factors

This section summarizes assumptions used in all three cases discussed.

3.1 Example Homes

This residence exists in 2025 (however, a new home built before 2040 could have essentially the same characteristics). The home is located near St. Louis, Missouri (a site selected for its climate and sunlight being near U.S. averages).

The single-family detached home is 2500 to 3000 square feet. It could be either multi-story or single story, with or without a basement and attached garage. Before 2040, its insulation, windows, and doors have become excellent and its lighting, appliances, and electronics highly energy efficient. Systems are included to supply fresh air, exhaust stale air, and regulate indoor humidity. Two (or more) personal vehicles are included, with combined annual travel of 20,000 miles.

Its roof has a sizeable slope facing approximately south with no significant shade from nearby trees or buildings. The range and clothes drier are electric. An installed security system includes fire, cold, smoke, and CO detection as well as burglar alarms. A quality electric grid connection exists at 120/240 Volts AC. Energy used by an optional fireplace or outdoor grille is not included.

3.2 Enhancements

The enhancements included in case 2 could be installed at any time before 2040. The case 3 enhancement requires case 2 to be in place. The case 2 enhancements are expected to decline in price and improve in performance between now and 2040.

3.3 Example 2040 Energy Prices

The DOE 2025 Annual Energy Outlook (Reference 2) includes their estimates of U.S. 2040 prices in nominal (inflation included) dollars for residential and transportation sectors. Cost calculations for this document used example prices averaging 1.2 times the DOE values, allowing for included new energy fees to fund carbon sequestration programs, lower sales volumes of fossil fuels, and refinery upgrades.

By 2040, grid electricity pricing is expected to vary considerably every day (in response to utility costs which depend on their supplies and user demands). Such variable pricing is called “time of use” pricing. The expected large future increases in solar and wind generation fed to the grid are expected to increase price variations.

Prices paid to residents selling power to the grid (including those with case 2 or 3 enhancements) will be lower than for purchases from the grid at the same time. Bidirectional utility meters will track user consumption and sales in real time, with pricing and power data continuously available to users. Grid prices will be lowest when bright sunlight coincides with low to moderate user demand. They will be highest when high user demands occur with minimal wind and/or sunlight.

New road use fees (based on vehicle weights and miles traveled) are expected to become universal, since increased use of electric vehicles reduces fuel tax revenues funding infrastructure maintenance and enhhancements. These fees are excluded from this essay, since they are not an energy cost.

4. Traditional (Case 1)

The example traditional case energy systems resemble the majority of existing 2025 homes near St. Louis without piped gas. By 2040, most will have improved insulation and more efficient lighting and appliances.

The home uses an oil-fired furnace with a conventional central air-conditioning unit attached. Forced hot or cooled air is supplied to rooms via a duct network, which also includes return-air ducts. Additionally, this system performs automatic humidification and dehumidification when appropriate.

A large oil tank is installed, typically in a basement or buried next to the home. Heating oil fuel has several advantages over propane: it is safer, usually lower cost per unit heating value, and needs a less costly tank.

Hot water is provided by a conventional electric water heater, with a tank of ample size.

The personal vehicles use gasoline engines without hybrid-drive subsystems. In 2040, the DOE forecasts (Reference 2) average on-road mileage of 30.5 miles per gallon.

Many 2040 homes of this description are expected to persist in spite of the many advantages of the following cases, usually due to owner indifference or unwillingness to invest in upgrades.

Some traditional homes will have insulation, windows, doors, and/or appliances inferior to those assumed and hence energy costs and fossil CO_2 emissions higher than shown in Table One. Homes larger or smaller than the example will have energy costs higher or lower in all three cases.

The example traditional homes have no systems to supply electricity or heat during grid outages (other than a possible fireplace). Section 7 discusses outages.

5. Available Systems (Case 2)

This significantly enhanced case adds or substitutes a number of superior systems which are already commercially available in 2026. Between 2026 and 2040 all of these systems are expected to gradually improve in performance and features, with installed costs trending downwards as manufacturing volumes and techniques improve. Traditional systems no longer being used would either be left in place or removed.

5.1 Heat Pump System

The oil furnace with its attached central air conditioning and humidity adjustment systems would be replaced by a very high efficiency **ductless heat pump system**, powered by electricity. It would be capable of whole-house heating with outdoor temperatures down to -25°F and whole-house cooling with outdoor temperatures up to 105°F. This system would include an advanced heat-recovery ventilation (HRV) system to supply temperature- and humidity-controlled fresh air, heat exchanging fresh air with vented stale air. A resistance-heater subsystem would provide supplemental space heating (if the case 3 system is not present) at temperatures below 20°F.

5.2 Vehicles

The two (or more) gasoline-engine vehicles would be replaced by all-**electric plug-in vehicles**. A dual-port "smart" charging station would be installed in the garage or near the driveway. The user could select charger timing, using lower-cost power when convenient. The average AC energy efficiency for the vehicles is assumed to be 3.25 miles/AC kWh.

5.3 Multifunction Electrical System

This system includes four subsystems: grid interface, battery, power conditioning, and control.

The **grid interface** system is rated 120/240 Volts AC, 60 Hertz, 100 amps per leg (24 kVA maximum). It includes an electromechanical contactor to disconnect the home from the grid in milliseconds when a grid outage or major disturbance is detected, a bidirectional power meter, overvoltage and overcurrent protection, and a lockable manual switch.

The **power conditioning** system very efficiently converts AC to and from DC at the desired voltages. AC output is synchronized with the grid (whenever the grid is active). Terminals are provided for the grid, battery system, photovoltaic system (see below), and the case 3 reversible fuel cell system. Maximum AC power capacity is 24 kW.

The **battery** is a bank of lithium-ion batteries rated at 20 kWh maximum output (AC basis) with charging and discharging by the power conditioning system. In Case 2, the battery system is used only during grid outages (so that a full battery is always available whenever an outage begins), whereas in Case 3 it is extensively used to store low-cost grid and solar power for later sale at high prices. The round-trip electricity storage efficiency of the battery system is higher than the case 3 storage efficiency.

The **control** system includes sensors and controls the operation of the above equipment, performs data logging, and communicates with both the electric utility (receiving price information and transmitting energy flows) and the occupant (with built-in wireless).

5.4 Solar Photovoltaic Array

A 12 kW (peak panel rating) rooftop **solar photovoltaic array** would supply part of the energy to operate the home, with any surplus sold the grid, and/or fed to a future reversible fuel cell system (Chapter 6). In the St. Louis vicinity, this subsystem is expected to average about 17,500 kWh AC generation per year (about 2000 Watts averaged over 24 hours, 365 days).

5.5 Oxidizer System

A 20 kW (lower heating value) **heating-oil oxidizer system** would be used only during grid outages to provide whole-house space and water heating. It would perform moderate-temperature catalytic air oxidation and heat exchange with the heat pump system. A 60-gallon fuel tank would be added if a furnace tank were not present.

6. Proposed (Case 3)

The addition of an advanced **energy storage system** incorporating a reversible fuel cell system is proposed to significantly lower net operating costs and fossil CO_2 emissions, while greatly enhancing grid-outage capabilities. The proposed system is not yet available (as discussed in Chapter 9), but would combine a number of known technologies already demonstrated in other scenarios. The only electricity imported from the grid has low prices and zero fossil carbon, since it is certified by the utility to be surplus from zero-carbon sources.

This reversible fuel cell (RFC) system would be housed in an enclosure about the size of a small refrigerator, with its liquid reactants stored in external tanks (described below). The enclosure would contain a compact pressure vessel plus support components: medium-temperature catalytic reactors, compressors, pumps, valves, heat exchangers, tubing, wiring, electrical circuits, and a control system.

The well-insulated pressure vessel would have an internal pressure of 130 psi and maximum hot-zone temperature near 900°C (1650°F). It would contain solid-oxide electrochemical stacks, each consisting of hundreds of thin circular cells with multiple layers and seals (no precious metals are used). Other items contained include stack mounting assemblies, heat exchanger, catalyst, wiring, tubing, and thermocouples.

The RFC system employs sealed circuits containing three captive reactants: liquid hydrocarbon fuel (similar to kerosene), water, and both liquid and gaseous carbon dioxide (CO_2). External tanks (section 6.3) store the liquid reactants. The RFC enclosure receives room air and vents totally clean exhaust outdoors at about 120°F. It includes the sealed "cogeneration" system described below.

6.1 Cogeneration System

A sealed hot water loop removes surplus heat from the operating RFC system, using variable water flow. This heat heats all domestic hot water and assists space heating when appropriate, with any excess used to superheat stale air vented outdoors. When needed, an oxidizer system (section 6.3) supplies supplemental cogeneration heat.

6.2 RFC System Operation

The RFC energy storage system can also be called a 'flow battery." It alternately operates in two modes:

6.2.1 Generation Mode

In generation ("fuel cell") mode, captive liquid hydrocarbon fuel and air are converted into DC electric power, usable heat, liquid CO_2, exhaust, and surplus heat (removed by the cogeneration water loop). A subsystem uses pressure-swing absorption (PSA) to enrich air to a oxidant gas having 90% O_2. The liquid fuel is reformed with steam to produce a fuel gas mixture. The reversible stacks are fed fuel and oxidant gases to electochemically generate DC power and hot exhaust. The DC is fed to the shared power conditioning system to deliver any desired power from zero to 6000 Watts. The exhaust gas heat is used to generate steam for fuel reforming and cogeneration. All water is removed from the exhaust by condensation and a desiccant, leaving pure CO_2 gas, which is further compressed, liquefied by refrigeration, and then pumped to higher pressure for storage.

6.2.2 Synthesis Mode

In synthesis ("electrolysis") mode, DC power, liquid CO_2, and water are fed to the RFC system, which produces liquid hydrocarbon fuel, usable heat (removed by the cogeneration system), and exhaust warm air with increased oxygen. The stacks electrolyze steam into pure hydrogen and oxygen. The hydrogen is catalytically reacted with CO_2 to synthesize the desired hydrocarbon fuel (also employing additional reactions not described here). A distillation column separates main catalyst output into liquid fuel product (containing 6 to 16 carbons), a heavy bottom liquid (with 17+ carbons; hydrocracked to lighter components), and top gas (containing H_2, H_2O vapor, CO, CO_2, and hydrocarbons with one to five carbons) which is fully oxidized by some of the stacks into steam plus CO_2.

6.2.3 Reactant (Energy) Storage Tanks

These tanks are large enough to economically store surplus energy from summer for use in winter (unlike known battery systems). Additionally, they have the capacity to fully power the home throughout long grid outages (see Chapter 7). The example spherical CO_2 tank (buried outside the home) has an outside diameter of 56 inches. The example combined cylindrical fuel/water tank (installed in a garage or utility room) has an outside diameter of 28 inches and a height of 58 inches. Liquid CO_2 is stored near 60°F and 730 psi. Fuel and water are stored at 40° to 80°F and 15 psi (tank insulated if necessary). Energy storage capacity (AC output basis) is 3000 kWh (150 times the 20 kWh example lithium-ion battery capacity).

6.3 Oxidation System

Additional cogeneration heat is efficiently generated when needed (mostly at very cold outdoor temperatures) in a small oxidation subsystem operating at near-atmospheric pressure. Liquid hydrocarbon fuel and air are catalytically oxidized at moderate temperature with the resulting cooled exhaust refrigerated and compressed to yield liquid water, liquid CO_2, and depleted air (vented outdoors). The liquids share the same storage tanks as the RFC system.

7. Grid Outages

Grid Electricity is not 100% reliable. Interruptions of grid electricity are called outages and can last from under a second to multiple weeks in extreme cases.

7.1 Causes

Outages can be caused by either grid equipment failures or weather events, such as high winds, unusual precipitation, unusual cold events, etc. Grid outage frequencies and durations have been getting worse due to climate change, maintenance shortfalls, tree growth, and aged equipment. Recent histories of power outages show wide variations with location, but future grid behavior can deviate from the past.

7.2 Effects

Short outages are usually only a nuisance, turning off electronics and appliances. Longer outages cause many inconveniences, which worsen with their duration. Nearly all residential space heating systems cannot operate without electricity. Security systems have limited battery times. Refrigerators and freezers slowly warm. Charging of batteries in portable devices or plug-in vehicles is not possible. In very cold weather, pipes can freeze if the home is unoccupied.

7.3 Backup Energy Capabilities

Most 2026 homes, including the case 1 example, have no energy backup systems, which may become less appropriate in the future. Table Two on the next page summarizes outage energy available for cases 2 and 3. Example priority loads (connected to a separate circuit-breaker box) include refrigerator-freezers, heating system electricals (fans, blowers, and pumps), well pumps, security systems, garage-door openers, microwave ovens, emergency lights, outlets for charging portable devices, and wireless routers. Priority loads are expected to average under 200 Watts (total annual-average power consumption in the example Case 3 home is about 2000 Watts).

7.4 Backup Energy Alternatives

Engine-generator sets are available with capacities ranging from under 1 to above 15 kW and fueled by gasoline, diesel, or propane. All are quite loud when operating. Many exhibit safety hazards: fire, CO emissions, and/or electric shocks. Those with small fuel tanks require frequent refilling. Larger units with automatic switching can be quite expensive. None provides uninterruptible power nor generates a return on investment (as do the systems present in cases 2 and 3).

7.5 Grid Transients

In addition to power outages, grids can experience (usually very brief) voltage transients. Some transients are caused by lightning and others by falling trees, accidents, or equipment failures. Low-voltage transients are called sags and can cause some electronic equipment to automatically shut down. High-voltage transients are called surges and may damage to electronic equipment and/or appliances. The power conditioning systems described in section 3.2 minimize the risks of adverse consequences from transients.

8. Conclusions

Below are key parameters for the three cases in 2040. Annual energy costs are purchased fuels and electricity plus added maintenance costs for cases 2 and 3, less revenue from grid power sales.

Table 2. Example Results

Case	**1 Traditional**	**2 Now Available**	**3 Proposed**
Space Heating	Oil Furnace	Heat Pump	Heat Pump
Space Cooling	Central Air Cond	Heat Pump	Heat Pump
Water Heating	Electric	Electric	Cogeneration
Vehicles	Gasoline	Electric	Electric
Solar/Battery System		Yes	Yes
Reversible Fuel Cell System			Yes
Results			
Annual Energy Costs	**$10,900**	**$3,800**	**($600)**
Cumulative Capital Cost		**$26,000**	**$38,000**
Return on Investment vs Case 1		**27%**	**30%**
Fossil CO2 tonnes	**19**	**4**	**(8)**
Grid Preferred MWh	**(1)**	**(13)**	**62**
Outage Energy			
Priority Electricity Days		**Over 60**	**Over 60**
Heating Days		**5 to 10**	**Over 60**
General+Vehicles Electricity		**15% to 100%**	**100%**
Space Cooling		**0% to 40%**	**100%**

Most homeowners are expected to prefer the major cost, environmental, and backup advantages of Case 2 over Case 1. A variety of attractive financing options are expected to become available to fund most or all of the required Case 2 capital cost. Case 2 saves $7,100 per year in energy costs and reduces annual fossil carbon "footprint" by 80%.

Grid Preferred MWh is the annual net sum of high-priced exports and low-priced imports to and from the grid. Case 2 is the least attractive to the grid, while Case 3 is highly desirable.

Case 3 uses proposed new technology expected to become readily available by 2040. Additional energy cost savings of $4,400 per year result in net payments to the user averaging $50 per month. Residential carbon footprint becomes negative, due to considerable zero-carbon electricity sold to the grid which eliminates the need for fossil-fuel generation of that energy (by natural gas turbogenerators). Case 3 also has excellent backup energy capacities.

9 Discussion

All cost values in this document use 2040 (inflated) dollars.

9.1 Operating Costs

In addition to the assumed grid and fuel prices mentioned in section 3.3 , numerous other assumptions (not included in this essay) were used to calculated the estimated costs in Table 2. Since the resulting costs differ so greatly among the cases, considerable differences in these assumptions result in similar conclusions. While other sites within the 48 states have differing climate and sunlight averages, the energy system configurations here are expected to be appropriate for most locations. For example, sites requiring more winter heating usually require less summer cooling and vice versa.

9.2 Capital Costs

The example capital (investment) costs are lower than would result by using today's costs for similar equipment. The expected very large increases in production and sales of advanced heat pump systems, solar panel arrays, and electric vehicles are expected to result in many improvements in products and manufacturing methods. The proposed new case 3 systems should reach the example costs upon reaching high sales volumes. Intensive competition will drive both cost and reliability improvements. Streamlined regulatory approvals will lower installation costs. Of course, capital costs will depend upon factors such as size of the home and its solar array.

9.3 Homes without Solar Panels

Some homes are not suitable for rooftop solar panels due to unfavorable roof configuration and/or orientation. Others receive serious shading by nearby tall trees or buildings. Some homeowners will delay installation, while others will object to panel appearance. Therefore, two additional cases were calculated:

Case 2 with no solar generation

Capital cost is $7000 lower, annual operating cost $1600 higher, and CO_2 emissions 0.6 tonne higher than case 2. Such homes have minimal grid outage capabilities: priority electricity and heating for up to 4 days and no general, vehicle, or cooling electricity.

Case 3 with no solar generation

Capital cost is $7000 lower, annual operating cost $2000 higher, and CO_2 emissions 0.4 tonne higher. These homes have the case 3 grid-outage capabilities for up to 30 days.

9.4 Technology Development

The proposed high-efficiency reversible-fuel-cell energy storage systems could be developed by multiple U.S. companies and brought into quantity production in under fifteen years with no governmental funding. The riskier early development and demonstration phases could take under six years and require total spending under $300 million (all supplied by private investors) per company. Total employment during these phases should not exceed a few hundred and include skilled technical and financial management.

The compelling advantages of these products should lead to early installations in tens of thousands of homes (even at the expected higher introductory prices), followed by rapid profitable growth thereafter.

9.5 Homes with Piped Gas

A companion essay by the author entitled “Bio-Natural Gas Homes” is available in Reference 1. The three cases there described have cost, environmental, and other differences from those in this document.

9.6 Government Roles

Federal, state, and local governments should implement many changes to energy-related regulations and practices. Permitting practices should be simplified and made must faster. Energy subsidies and tax credits should be largely phased out, except for some assistance to low-income households. New energy fees can be collected to fund early investments on permanent underground CO_2 sequestration. The maintenance of road systems should by funded by user fees per ton-mile driven and no longer by fuel taxes per gallon (to make electric vehicles pay their fair share of costs).

References

1. Advanced Energy Concepts, robertruhl.com

2. Annual Energy Outlook 2025, eia.doe.gov