Final Report: Natural Gas Community of the Future

Xin Jin,[1] Jeff Maguire,[1] Michael Blonsky,[1]
Prateek Munankarmi,[1] and Phil Markham[2]

1 National Renewable Energy Laboratory
2 Southern Company Services

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Strategic Partnership Project Report
NREL/TP-5500-80254
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List of Acronyms

CARE	Carbon-neutral, Affordable, Resilient, and Equitable Community
DER	Distributed Energy Resource
HRV	Heat Recovery Ventilator
NREL	National Renewable Energy Laboratory
RNG	Renewable Natural Gas
RTP	Real-Time Pricing
SOC	State of Charge

Executive Summary

There are many challenges in designing future residential communities. New construction homes are becoming less affordable in many regions because of the growing demand and shortage of affordable housing. Low-income families may be disproportionally affected by the high energy bills during cold winters and hot summers. Climate change has the potential to increase the frequency and severity of natural disasters, which is likely to cause extended power outages and threaten the critical loads in many homes. While the power grid is incorporating more and more clean energy resources into its generation mix to achieve the decarbonization goal, we need to provide efficient, equitable, affordable, and resilient communities during the transition that enable all to benefit, particularly historically disadvantaged communities.

Nicor Gas, a subsidiary of Southern Company Gas and its parent company Southern Company, is developing the concept of the Carbon-neutral, Affordable, Resilient, and Equitable Community **("CARE Community")** to address the challenges of accessibility and affordability of grid-interactive efficient buildings in historically disadvantaged communities. The CARE Community is proposed to be a new construction net-zero energy and carbon neutral residential neighborhood consisting of 50 homes with electricity and natural gas services in South Suburban Chicago, built as low-income affordable housing. The National Renewable Energy Laboratory (NREL) is assisting Southern Company to explore how energy efficiency, renewable technologies, and natural gas can be combined and optimized in an islandable energy system as part of a broader effort to understand the role natural gas may play in communities integrated with renewable energy and improved energy efficiency.

The CARE Community will demonstrate how energy efficiency, distributed energy resources (DERs), and advanced controls can be combined with existing natural gas infrastructure to serve historically disadvantaged communities in a cold climate with low energy cost for affordable housing programs and enhanced resilience to withstand extreme weather. Homes will be a part of an islandable energy system, integrating multiple DER technologies such as solar panels, natural gas fuel cells, reciprocating natural gas engines, and battery storage. The CARE Community will provide a replicable template that affordable housing developers and energy companies can adopt throughout the United States.

In this report, we present the design and modeling of the community and potential approaches for integrating DERs. We analyze and discuss annual simulations under normal operating conditions and week-long simulations under electric power grid outage conditions. Simulation results show that homes in South Suburban Chicago with natural gas services can achieve carbon neutrality when integrated with energy efficiency measures and solar photovoltaic (PV), and are more affordable under current utility rates[1] and more resilient than all-electric homes. Note the future energy price and carbon intensities of the power grid and natural gas supply are uncertain, and may significantly affect the cost savings and carbon emission reduction potential of our design. While it is difficult to predict future energy price, we use the available forecast of electricity and natural gas carbon intensities to analyze the CARE community's future carbon emissions through 2050.

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[1] The electricity and natural gas utility rates were taken in June 2020.

The best energy efficiency package that was analyzed can provide 33% source energy savings and save homeowners 28% of the energy charges on their utility bills without advanced controls. Oversized rooftop PV systems can offset carbon emissions from natural gas and nonrenewable power sources and make the homes carbon neutral, but the local electric utility may have constraints on how much PV can be interconnected and the overproduced PV may not be compensated under the net metering policy. Integration of other DERs (such as natural gas generator and battery) and making them responsive to the local electric utility's real-time pricing (RTP) plan provides moderate utility bill savings (up to $49 annual savings) and is not cost-effective when accounting for these bill savings alone after considering the equipment cost, but these integrations greatly improve the resilience of the community. Also note that RTP strategies vary significantly across the country and impact cost-effectiveness. As more renewable systems are added to the electric grid, it is anticipated that RTP will evolve such that responsive DERs will increase in cost effectiveness. Natural gas technology also provides enhanced resilience during extreme weather events. A natural gas generator is the most effective resilience solution during a polar vortex with the least amount of thermal discomfort despite its relatively low efficiency. Our study shows that, when integrated with natural gas generators, the homes can operate as an islanded nanogrid and provide services without shortage of thermal comfort in the event of a 5-day power grid outage due to a polar vortex. The solar plus battery solution was also effective with slightly higher thermal discomfort. The addition of a natural gas-powered fuel cell improves the resilience but is less cost effective because of its high equipment cost.

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1 Introduction

There are many challenges in designing future residential communities. New construction homes are becoming less affordable in many regions because of the growing demand and shortage of affordable housing. Low-income families may be disproportionally affected by the high energy bills during cold winters and hot summers. Climate change has the potential to increase the frequency and severity of natural disasters, which is likely to cause extended power outages and threaten the critical loads in many homes. While the power grid is incorporating more and more clean energy resources into its generation mix to achieve the decarbonization goal, we need to provide efficient, equitable, affordable, and resilient communities during the transition that enable all to benefit, particularly historically disadvantaged communities.

Nicor Gas, a subsidiary of Southern Company Gas and its parent company Southern Company, is undertaking a range of initiatives exploring how natural gas can support an equitable path to a clean energy future. As a part of these initiatives, Nicor Gas is looking to build on the success and learnings of Southern Company's Smart Neighborhood initiatives to understand the role natural gas plays in future communities integrated with renewable energy and improved energy efficiency. The Carbon-neutral, Affordable, Resilient, and Equitable Community ("CARE Community") will be a new construction net-zero energy and carbon neutral residential neighborhood consisting of 50 homes with electricity and natural gas services in South Suburban Chicago, built as low-income affordable housing. NREL is assisting Southern Company to explore how energy efficiency, renewable technologies, and the reliability and resilience of natural gas can be combined and optimized in an islandable energy system. The objective of the CARE Community is to demonstrate a synergy between renewable technology and affordable energy supported by natural gas.

Natural gas has the potential to provide affordable and resilient energy solutions for customers, especially in a cold climate. The objective of the CARE Community is to demonstrate how energy efficiency, distributed energy resources (DERs), and advanced controls can be combined with existing natural gas infrastructure to serve historically disadvantaged communities in a cold climate with low energy cost for affordable housing programs and enhanced resilience to withstand extreme weather. Homes will be a part of an islandable energy system, integrating multiple DER technologies such as solar panels, natural gas fuel cells, reciprocating natural gas engines, and battery storage. Each home, when integrated with natural gas generators, can operate as an islanded nanogrid and ensure thermal comfort in the event of an extended power grid outage due to a polar vortex. The CARE Community will be designed to achieve carbon neutral status through a combination of energy efficiency (23% carbon reduction) and rooftop solar photovoltaics (PV) (77% carbon reduction). This will be achieved by properly sizing the rooftop solar PV such that the exported solar PV energy offsets the emissions from natural gas and imported electricity. The CARE Community will provide a template that affordable housing developers and energy companies can replicate throughout the United States.

This report is organized into five sections. Section 2 describes the design and modeling approach of the community and the optimal energy efficiency package and rooftop PV sizes. Section 3 introduces the simulation framework for evaluating the integration of DERs in the community. Section 4 discusses the simulation results under normal operation scenarios, resilience scenarios, and future emission scenarios. Section 5 concludes the findings of the study. The appendix presents the details of the building efficiency measure optimization results.

2 Design and Modeling of the CARE Community

The National Renewable Energy Laboratory (NREL) modeled the community and performed simulations to optimize the efficiency of homes within the community with support from Nicor Gas and the local Habitat for Humanity partner. Habitat for Humanity provided a floor plan (Figure 1) that will be built as part of this community as well as the rendered concept of community layout (Figure 2). Approximations were used because only one floor plan was available at the current stage of the community design, and some details of the home design such as the exact window area were unknown. A baseline model of this building was generated in BEopt™ [1] with the code-minimum efficiency, as shown in Table 1. The baseline building simulated includes gas appliances for space heating, water heating, and cooking. All-electric buildings were also simulated for comparison purposes.

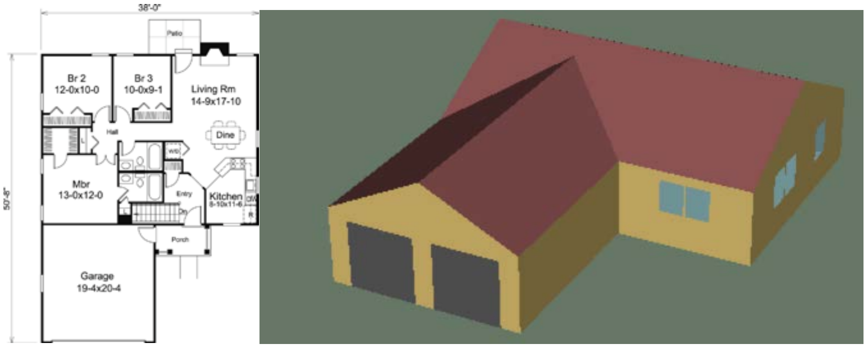

Figure 1. Building floor plan and the corresponding building energy model

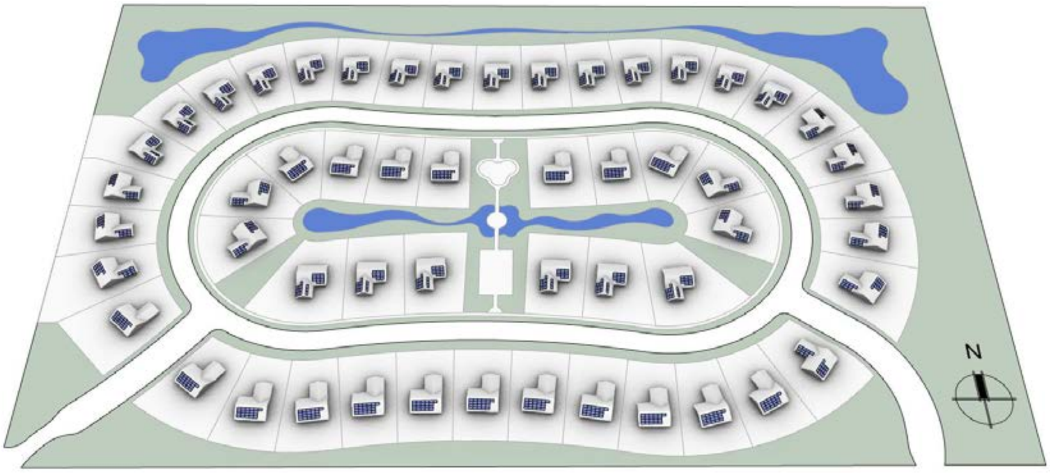

Figure 2. Rendered concept of the community layout

Table 1. Code-Minimum Efficiency Features

Category	Baseline Efficiency Level
Walls	R13+5
Slab	R10, 2 ft
Ceiling	R49
Windows	U=0.3
Infiltration	4 ACH_{50}
HVAC	90% AFUE Gas Furnace / SEER 13 AC
Ducts	Supply R8, Return R6, 4 cfm per 100 ft^2
Lighting	100% CFL
Appliances	Federal Minimum
Water Heating	Gas Tank, Federal Minimum Efficiency

2.1 Parametric Optimization of Efficiency Measures for the Homes

The code-minimum model served as the baseline for a cost optimization that examined different efficiency measures as well as PV. Categories to consider for efficiency measures were selected based on our ongoing discussions with Nicor Gas and what could practically be achieved by the builder in the final community. These measures included upgrades to the wall insulation, attic insulation, air sealing, windows, HVAC, water heating, lighting, and most major appliances (clothes washer, clothes dryer, dishwasher, and refrigerator). A full list of the options considered as part of the parameter space for this optimization is given in the list on the next page. Each option has an installed cost and lifetime, taken directly from the National Residential Efficiency Measures Database [2], which contains national average new construction and retrofit costs for each efficiency measure. This optimization focused on a cost optimization from the homeowner's perspective. At different efficiency levels, the 30-year life cycle cost of the building was calculated and annualized as a financial metric. This cost includes the initial installation cost, any equipment replacement costs, and the utility bills over the entire period. The time value of money was considered, with a discount rate of 2.4% and an inflation rate of 3%. However, changes to the utility rate over this period are not considered.

For this project, two separate optimizations were run for each case. The first case includes all these efficiency options as well as PV (south facing, at the roof pitch). PV sizes range from 1–12 kW in increments of 1 kW. However, some of the larger sizes may end up not being practical to install, for either roof area or utility constraints. The utility allows PV sizes up to 110% of the prior year's electricity consumption [3]. This case captures what would be the most cost-effective way to invest in both efficiency and renewable technologies. The second case included only efficiency measures. This case is designed to examine the cost-effectiveness of just efficiency measures and to see how much energy could be saved through energy efficiency alone. All optimizations were run using a typical meteorological year (TMY) [4] weather file for Chicago, IL to capture performance in a typical year.

For the optimization, the following categories and efficiency options were considered:

- **Wall Insulation:** R13; R19; R21

- **Wall Sheathing Insulation (wrap insulation):** R5; R10
- **Attic Insulation:** R49; R60
- **Windows:** Double-pane (U=0.3, SHGC=0.46); Triple-pane air filled (U=0.21, SHGC=0.4); Triple-pane argon filled (U=0.19, SHGC=0.4)
- **Air Leakage:** 3 ACH_{50}; 2 ACH_{50}; 1 ACH_{50}
- **Mechanical Ventilation:** Exhaust; Exhaust with Heat Recovery Ventilator (HRV) (70% Efficient)
- **Furnace:** 90% AFUE; 92.5% AFUE; 95% AFUE; 96% AFUE; 98% AFUE
- **Air Conditioner:** SEER 13; SEER 15; SEER 16; SEER 17; SEER 18; SEER 21; SEER 24.5
- **Air Source Heat Pump (all electric homes only):** SEER 13/8.2 HSPF, SEER 14/8.2 HSPF, SEER 15/8.5 HSPF, SEER 16/8.6 HSPF, SEER 17/8.7 HSPF, SEER 18/9.3 HSPF, SEER 22/ 10 HSPF.
- **Ducts:** 4 cfm_{25}/100 ft^2 with R8 insulation; in conditioned space
- **Water Heater:** Gas Tank (EF=0.59); Gas Tankless (EF=0.82); Condensing Tankless (EF=0.96)
- **Lighting:**100% CFL; 60% LED; 100% LED
- **Refrigerator:** Standard (EF=17.6); ENERGY STAR® (EF=20.4); ENERGY STAR (EF=21.9)
- **Dishwasher:** Standard; ENERGY STAR
- **Clothes Washer:** Standard; ENERGY STAR
- **Clothes Dryer:** Standard; ENERGY STAR.

In conducting the optimization, several measures that affect energy consumption were held constant. These include the slab insulation (set to 2ft of R10 exterior insulation), heating and cooling setpoints (71°F and 76°F, respectively), the hot water distribution system (by default an uninsulated copper trunk and branch), the cooking range, and miscellaneous electric loads. These parameters were either considered unlikely to be upgraded, based on conversations with our partners, or occupancy driven. Foundation insulation improvements were not considered as part of this analysis because Habitat for Humanity has not finalized whether homes in this community will have a slab foundation or a basement.

For some of the community scale scenarios, all electric homes were simulated as well as different natural gas designs. For these homes, optimizations were performed with an air source heat pump with varying SEER and HSPF. Homes with an air source heat pump also have backup electric resistance elements, which may turn on during the coldest hours of the year if the heat pump is unable to keep up with the large load. These heat pumps were sized in accordance with ACCA Manual J (add ref) for the heating load, but there are still times of the year where backup heat is required. Based on the optimization results (see Appendix A), for the design home a SEER 16/8.6 HSPF heat was selected, while code minimum homes get the federal minimum allowable efficiency of SEER 13/ HSPF 8.2.

A utility rate needed to be selected to perform the cost optimization. The local electric utility offers several different electricity rates. The standard rate plan includes summer (June–September) and winter rates, but no time-of-use variation. For homes with gas heating, the summer electricity rate is $0.1016/kWh, and the winter electricity rate is $0.1076/kWh. For homes with electric heating, the summer electricity rate is \$0.0829/kWh, and the winter electricity rate is \$0.0889/kWh. Electricity rates were taken directly from the OpenEI Utility Rate Database [5] and correspond to 2019 rate structures. The local electric utility also offers several other rate plans, including a time-of-use pilot and a novel residential real-time-price (RTP) rate. The RTP rate is currently available as a pilot program that can be opted into by homeowners. Simulations were performed under the standard rate and a dynamic rate using the 2019 historical RTP (as shown in Figure 3) to examine the sensitivity of the results to the utility rate. Although the RTP is highly variable and has some very high peaks, the hourly average is only \$0.025/kWh. The charges under the dynamic rate for the local electric utility's residential customers include [6]:

- RTP charge
- Additional charges for transmission charge, distribution charge, taxes, and miscellaneous charges (\$0.045/kWh)
- Capacity charge, i.e., demand charge (\$6/kW/month) multiplied by prior year's peak demand
- Monthly fixed charges (\$15/month)

We included the RTP and additional charges when calculating the energy cost in Section 4. Capacity charge and monthly fixed charges were not included. Capacity charge depends on peak demand from prior years and can be affected the DER operation, therefore it is challenging to compare the capacity charges across scenarios with different DER combinations. The gas design homes have lower capacity charge due to the lower peak demand, but the savings is offset by the gas service charge that all-electric homes do not need to pay. Note that for simulations under the RTP, occupancy responses to the RTP (shifting loads out of high price periods) were not simulated due to the complexity of including this behavior in an optimization. Future simulations could include a home energy management system that is aware of the RTP to capture ideal occupant responses to the price signal for an optimal home but cannot easily be included in the optimization process. For cases with PV, net metering was used to calculate the value of the excess electricity generated; the electric utility pays for the exported electricity at the RTP rate.

Nicor Gas has a gas supply cost that shifts monthly depending on the commodity price, as well as a monthly service charge of about \$18 and a distribution cost of \$0.0838/therm. During the past year, the supply cost varied from \$0.29/therm to \$0.24/therm. BEopt requires a flat rate per therm for optimizations, so an average value of \$0.26/therm plus the distribution cost was used for optimizations. The monthly service charge is also included in all utility bill calculations.

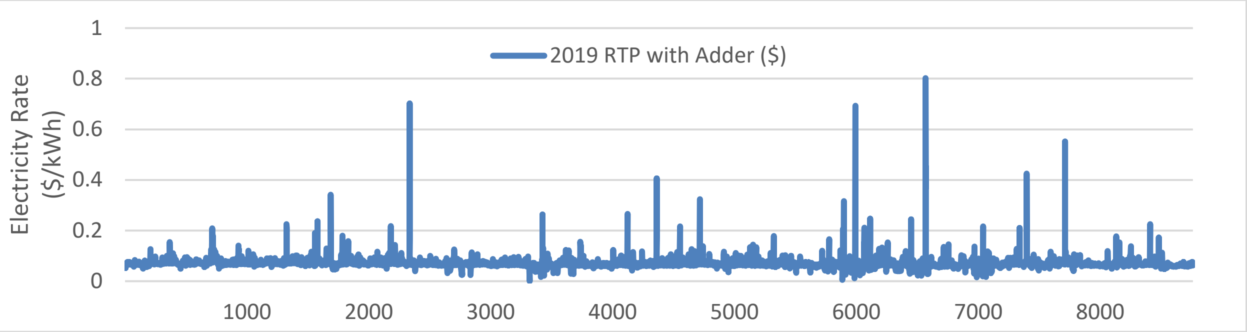

Figure 3. 2019 RTP from the local electric utility

2.2 Building Efficiency Measures

Based on the results of these optimizations, the optional RTP offered by the local electric utility is likely to provide savings to the homeowner over the standard rate structure for both homes with and without natural gas service as costs are relatively similar before considering any load shifting, which can provide substantial additional savings. A smart thermostat controlling the air conditioner to avoid peak periods could provide the homeowners with substantial additional bill savings while avoiding any comfort issues by preconditioning the space, and homeowners may shift other tasks like clothes washing or dishwashing out of the peak periods as well. It is recommended that all future analysis assume homeowners opt into the RTP, and future simulations will capture some level of occupant response to the price signals based on the historical RTP.

A variety of efficiency measures were simulated as part of this effort, and some were much more cost-effective than others. LED lighting, moving the ducts to conditioned space, and some level of additional air sealing was always part of the optimal efficiency package. While there are a variety of cases and optimal curves for each, including a wide variety of efficiency measures, our results show that it is optimal to include an efficiency package that is close to cost neutral while providing a substantial efficiency benefit. While all-electric cases were simulated for comparison purposes, the community will be built with natural gas service. Homes with natural gas have a lower annualized energy related cost at the cost neutral point than all-electric homes due to lower utility bills, so building the community with natural gas will provide direct economic benefit to the homeowners. This package can achieve 33% source energy savings and goes beyond the Nicor Gas energy efficiency program standard offerings. It is also able to save homeowners 28% of the energy charges on their utility bills. The increased thermal insulation of the envelope, including air sealing, will reduce the energy required for any resilience use cases to be examined as part of this study. Optimal efficiency measures to be included in this community are shown in Table 2, and this point relative to the other points of interest is shown in Figure 4.

Table 2. Optimal Building Efficiency Measures for the Community

Italic values indicate above code improvements to the building

Efficiency Measure Category	Optimal Option
Wall Insulation	***R21***
Wall Sheathing	***R10***
Attic Insulation	***R60***
Windows	Double Pane
Air Leakage	***1 ACH_{50}***
Mechanical Ventilation	***HRV***
Furnace	***98% AFUE***
Air Conditioner	***SEER 16***
Ducts	***In Conditioned Space***
Water Heating	***Condensing Tankless***
Lighting	***100% LED***
Refrigerator	***ENERGY STAR (EF=21.4)***
Dishwasher	***ENERGY STAR***
Clothes Washer	***ENERGY STAR***
Clothes Dryer	***ENERGY STAR***

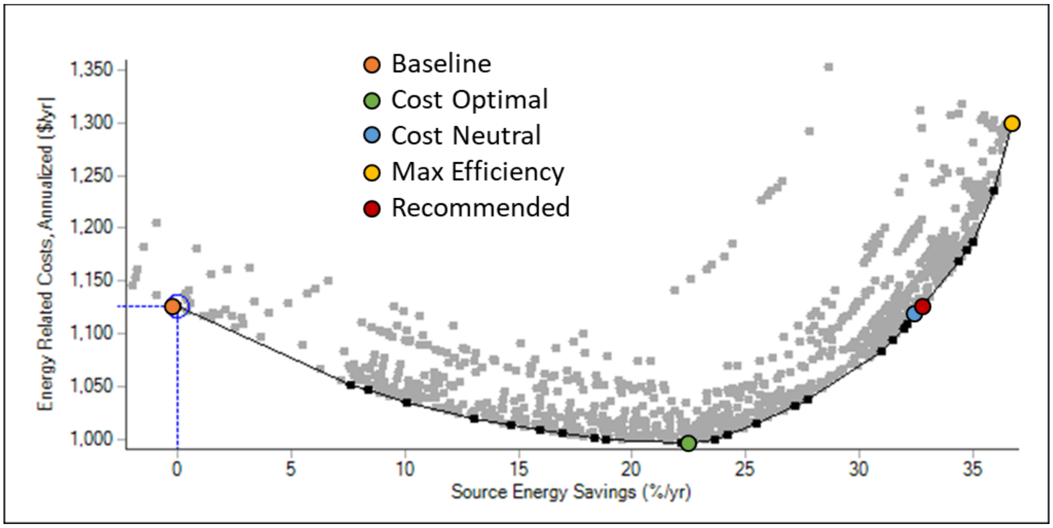

Figure 4. Cost optimization results for homes with natural gas service under RTP, including the optimal efficiency package

There is one efficiency feature included in this package that is just slightly off the optimal. Two different refrigerator efficiency levels (EF=20.4 and EF=21.4) were considered: the cost-optimal point includes the less efficient option, but the most efficient refrigerator option included here provides a slightly higher energy savings at a cost increase of $8 in the annualized energy related costs due to the higher first cost. Due to the limited impact on annualized costs, the remainder of this analysis uses the most efficient refrigerator option because it slightly increases the overall efficiency of the building.

This efficiency package has been discussed with Habitat for Humanity to ensure that it would be feasible to build. They did not raise any concerns about any of the efficiency measures included here, so it is likely that all the efficiency measures simulated will be included in the community. When a decision about the foundation type has been finalized, additional foundation insulation above what code requires may be explored to potentially increase the efficiency of this building even further. To make these homes net zero energy, PV could easily be added to these homes to offset energy use of the buildings. A south-facing 6-kW PV array should be able to offset all the home's source energy use on a typical year. Section 2.3 performs an analysis on the optimal roof pitch to maximize annual PV production for these homes. For homes facing due south, a 10:12 pitch (about 40°) is optimal. Additional details and results for different orientations are provided in that section.

Homes with natural gas provide some utility bill savings compared to all-electric homes due to the lower energy costs. Having natural gas be available on-site also provides a resiliency benefit for these homes. This project will explore incorporating natural gas electricity generation into these homes that can power the buildings through an outage. The natural gas generator can also be run during any peak price events under the RTP, leading to even more benefit to the homeowners beyond resiliency. Installing enough battery storage to provide the same resiliency benefit as the gas generator would make the all-electric case substantially more costly to provide the same resiliency, another benefit natural gas service could provide. Natural gas service can also meet the heating loads indefinitely regardless of the weather (provided the natural gas generator is able to power the much smaller electrical loads associated with running the furnace) should an electricity outage occur during an extreme weather event such as a polar vortex.

2.3 Roof Tilt Angle for Maximizing PV Production

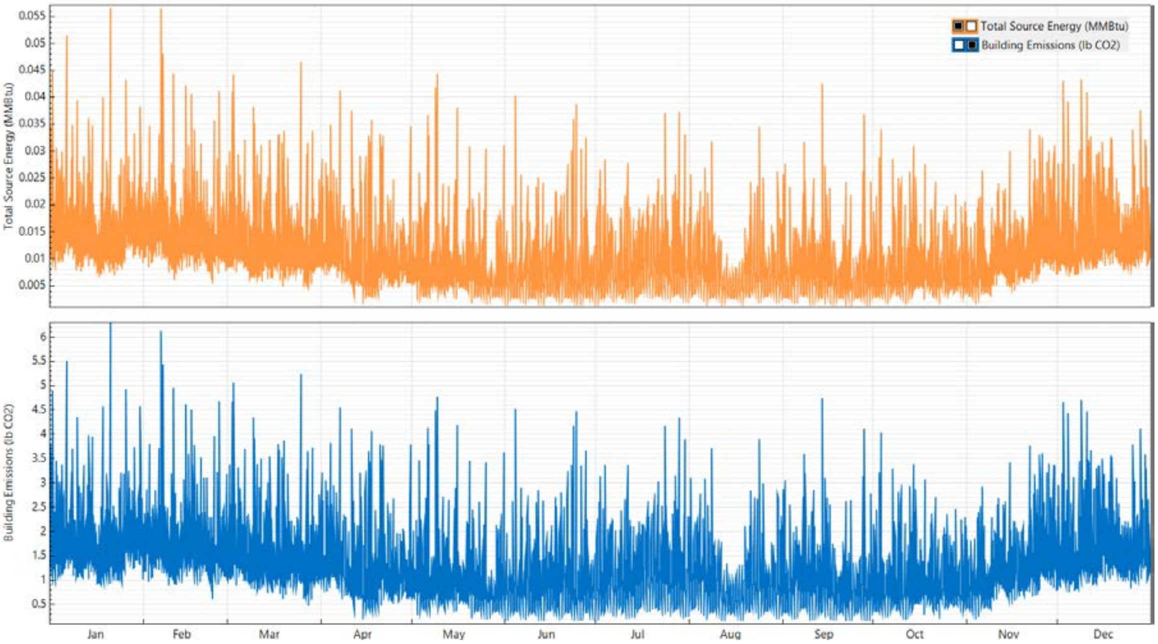

Figure 5. Hourly profile of source energy consumption and CO_2 emissions of the community

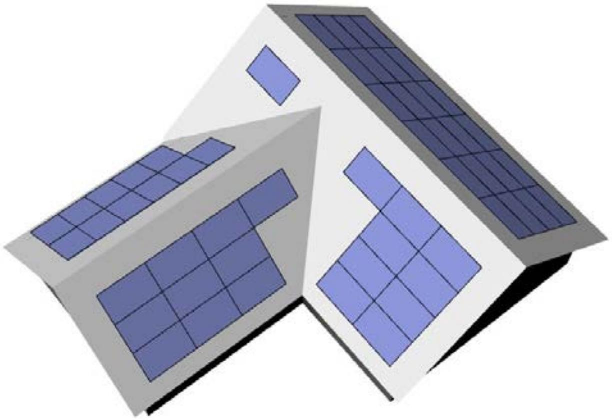

Figure 6. Maximum potential PV that can be installed in homes in the CARE Community

The PV sizes were determined based on the hourly load profiles for each building in the community. The panels were sized to not just make the community net zero energy but net zero carbon, which requires slightly more PV panels. The carbon-neutral status of the community was achieved through a combination of energy efficiency (23% carbon reduction) and rooftop solar PV (77% carbon reduction). Based on data from WattTime [7], hourly emissions intensity factors for electricity consumption were determined for this region and combined with an average emission rate for natural gas to determine the carbon impact of these buildings under normal operation without any PV or generator run time. The emission rate for natural gas only includes emissions generated from onsite combustion and does not account for the upstream emissions. Figure 5 shows the hourly profile of source energy consumption (top) and the CO_2 emissions of the community (bottom). For each of the cardinal directions, appropriate PV sizes were calculated for making the community net zero carbon, with south-facing panels being prioritized and then east- or west-facing panels added as necessary to reach the net zero goal. The PV size for each orientation is listed in Table 3.

Table 3. PV Sizes to Achieve Net Zero Carbon in the CARE Community

Building Orientation	South-Facing PV Size	West-Facing PV Size	East-Facing PV Size	Total Size
North	6.72 kW (21 Panels)	0	0	6.72 kW (21 Panels)
South	3.20 kW (10 Panels)	3.52 kW (11 Panels)	0.64 kW (2 Panels)	7.36 kW (23 Panels)
East	3.52 kW (11 Panels)	3.84 kW (12 Panels)	0	7.36 kW (23 Panels)
West	3.20 kW (10 Panels)	0	4.16 kW (13 Panels)	7.36 kW (23 Panels)

While sizing was done to achieve net zero emissions, the local electric utility does impose their own restrictions on the allowable size of PV that can be installed on a home. The utility requires that the PV size for each home not be larger than 110% of the prior year's electric load [3]. For new construction homes, they typically use a "class average" amount from similar customers. For the purposes of this project where the class average value is not known, we used the modeled electricity consumption of the optimal efficiency package for homes with natural gas service to calculate the PV sizes that would be allowable under those utility-imposed limits. Sizing results for this case are shown in Table 4.

Table 4. PV Sizes Within 110% of Electric Load in the CARE Community

Building Orientation	South-Facing PV Size	West-Facing PV Size	East-Facing PV Size	Total Size
North	4.48 kW (14 Panels)	0	0	4.48 kW (14 Panels)
South	3.20 kW (10 Panels)	1.28 kW (4 Panels)	0	4.48 kW (14 Panels)
East	3.52 kW (11 Panels)	0.96 kW (3 Panels)	0	4.48 kW (14 Panels)
West	3.20 kW (10 Panels)	0	1.28 kW (4 Panels)	4.48 kW (14 Panels)

Past smart community projects have shown that the building energy consumption is relatively insensitive to the building orientation, but PV production is highly sensitive to it [8]. When the building orientation changes, the solar gains at different times of day may shift due to differing window areas facing each direction, but this has had an impact of less than 5% on annual building energy consumption. In this section we explore the effect of roof pitch on PV production. A standard roof pitch of 6:12 (26.6°) was used for the building energy optimizations, but both Southern Company and Habitat for Humanity are open to revising the roof pitch if there is an alternative that will maximize PV production. To explore these impacts, a separate parametric analysis was performed of the annual PV production at different roof tilt angles and orientations. A 6-kW PV array was used for the purposes of this analysis, but because the results scale linearly with PV size, the analysis is applicable to any size array. South-, east-, and west-facing orientations were simulated, along with tilt angles between 0° (facing vertically upward) to 90°. An additional point of tilt angle equal to latitude, a common rule of thumb for orienting PV arrays, was included as well. All simulations were performed using BEopt, which models a typical PV array and inverter. When a specific PV array and inverter are selected, additional simulations may be performed with the System Advisor Model (SAM) [9] of the equipment to be installed to better estimate the performance of this equipment. Energy production of each orientation are shown in Figure 7, and the utility bill credit under RTP is shown in Figure 8.

For the south-facing homes, the optimal tilt angle is around 40°, slightly off from latitude. This is close to a 10:12 pitch angle (39.81°), steeper than was originally planned. Although east- and west-facing arrays are not optimal, some of the buildings in the community will not have roof area facing south. For these homes, a shallow pitch provides the highest PV production. However, assigning a shallower pitch angle to some roofs is more challenging for Habitat for Humanity because they would have to build multiple roof pitches for the same community, and this could also lead to potential snow loading issues. If a single pitch angle is to be used for the entire community, a 10:12 angle would maximize the community PV production as well as the benefit to the homeowners. Changing a south-facing roof to be flat would lead to a reduction in electricity produced of 1,120 kWh/year, while changing a west-facing roof to a 40° pitch angle only reduces the production by 600 kWh/year. For this community layout where there are many more buildings oriented north/south rather than east/west, choosing the optimal pitch angle for south-facing roofs increases the overall production of the community. When given the choice between east facing and west facing, there is slightly larger production from east-facing roofs than west-facing, likely due to the timing of cloud cover in the TMY weather file, but the utility bill credit is larger for west-facing roofs due to higher RTP values in the afternoon. A west-facing roof also better synchronizes maximum PV production with grid needs.

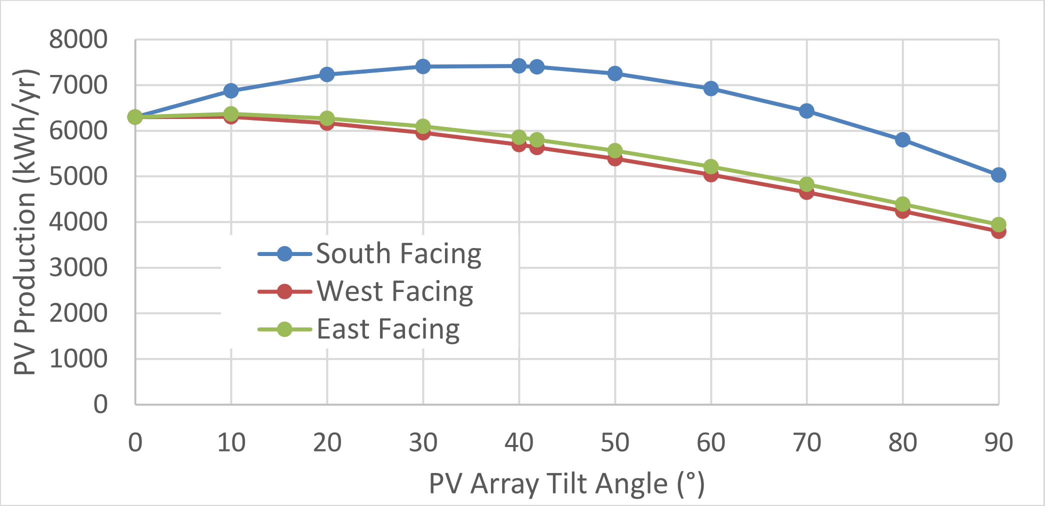

Figure 7. The relationship between PV production and tilt angle for a 6-kW PV array

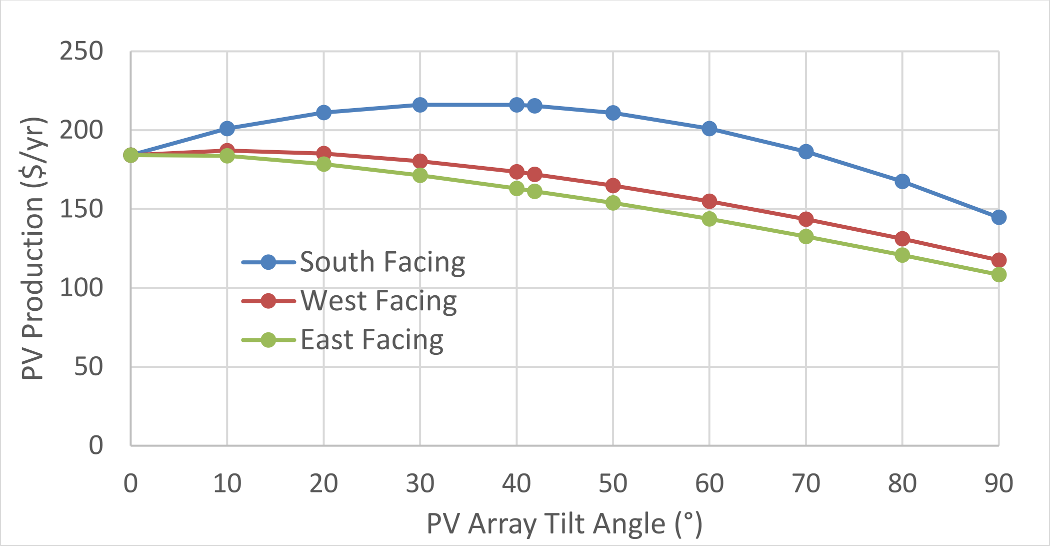

Figure 8. The utility bill credit for each tilt angle of a 6-kW PV array under RTP and net metering

3 Simulation Methodology

We simulated the community with the optimal efficiency package and multiple sets of DERs. Both normal operation and resilient operation were performed to evaluate the DERs. Normal operations were simulated for one full year to determine the impact of DERs on the energy consumption, costs, and emissions. Resilience simulations were run for one week to determine the impact of DERs and efficiency packages on outage duration and occupant comfort during a multiday outage caused by a polar vortex.

We used NREL's OCHRE model [10] to simulate the homes in the CARE Community. The Object-oriented Controllable High-resolution Residential Energy (OCHRE) is a residential building model that simulates a variety of behind-the-meter equipment. It simulates energy consumption (electricity and gas) at a high resolution (one-minute interval), and is designed to integrate in co-simulation with controllers, distribution systems, and other agents. Most equipment is controllable through an external controller to simulate the impact of device controllers, home energy management systems, demand response, or other control strategies.

3.1 Modeling of DERs

The DERs considered in this project include rooftop PV, natural gas generators (referred to as gas generators hereafter), natural gas-powered solid oxide fuel cells (referred to as gas fuel cells hereafter), and batteries. The gas generator and gas fuel cell models are based on product specifications that were chosen by the team. The gas generator uses specifications from residential backup generators from Generac [11], and the gas fuel cell uses specifications from Special Power Sources fuel cells [12]. Both models include a maximum capacity limit and a maximum ramp rate limit, which increases the time for the model to achieve a new electrical power setpoint. Figure 9 shows the relative efficiency of the models as a function of the capacity ratio (i.e., the part-load ratio). Both models have maximum efficiency at full load. The generator's maximum efficiency is much lower than the fuel cell's and has a lower efficiency at part load.

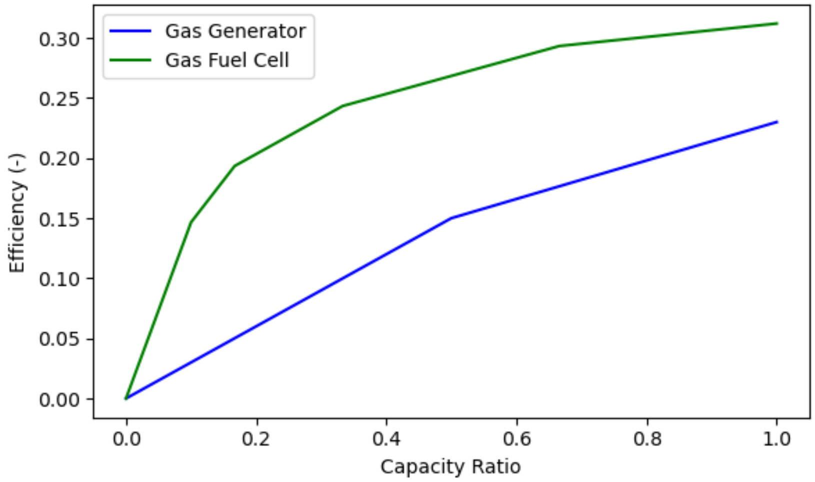

Figure 9. Efficiency of the gas generator and gas fuel cell models, as a function of capacity ratio

The battery, gas generator, and gas fuel cell model parameters are shown in Table 5. The gas generator and battery do not have a ramp rate limitation, which allows them to perfectly match the house load when in self-consumption mode. The gas fuel cell ramp rate is derived from product specification sheets.

Table 5. Parameters of the DER Equipment for Each Home

Equipment Type	Capacity	Max Efficiency	Ramp Rate
Gas Generator	10 kW	23%	Immediate
Gas Fuel Cell	1.5 kW	31.2%	25 W/min
Battery	8.6 kWh / 4.3 kW	93% (round-trip)	Immediate

The rooftop PV sizes vary by house orientation as described in Table 3 and Table 4 in the previous section. All scenarios with PV were implemented twice with two levels of PV sizes: net-zero carbon sizing (see Table 3) and 110% of load sizing (see Table 4).

3.2 Control of DERs

3.2.1 Normal Operation Scenario

Annual simulations were performed in normal operation scenarios with the objective of minimizing energy costs for the residents. DERs were controlled according to the local electric utility's 2019 real time price (RTP) [13]. A retail rate with net metering was assumed for all scenarios as described in Section 2.1. The threshold prices shown in Table 6 were chosen to operate the DERs for 50–100 hours per year and to maximize energy arbitrage while keeping DER degradation low. The carbon intensity for electricity was taken from WattTime [7] and we used the historical data from 2019 with 5-minute resolution. Gas prices vary by month, whereas the gas carbon intensity is constant throughout the year at 117 lb CO_2/ MMBtu [14]. All DERs were controlled based on the RTP, not based on the carbon intensity of imported electricity.

Table 6 shows the detailed control strategies for annual simulations. The battery and gas fuel cell operated in a grid-connected mode in all annual scenarios. The gas generator operated in islanded mode, which requires the home's rooftop PV to turn off and make the generator output follow the load. As shown in Figure 9, running the generator at part-load can have a significant impact on its efficiency. We also ran a separate scenario (GH2-b) in which the gas generator operates in grid-connected mode (using the same control strategy as the gas fuel cell) to measure the impact of these limitations on the community.

3.2.2 Resilience Scenario

Resilience simulations were run for one week in the winter that includes very cold weather conditions from a polar vortex. Five of the seven simulation days were run with the community disconnected from the electric grid. During the outage days, the battery and gas generator operated in self-consumption mode to eliminate all electricity flow to and from the grid. If the DER could not meet the house load, all loads and DERs were shut off. The PV and gas fuel cell controls were also modified to ensure that the battery remained sufficiently charged and to ensure no export of electricity to the grid. Table 6 shows the detailed control strategies for resilience simulations.

There are two situations in which an outage may occur. If the battery state of charge falls to 0%, it cannot meet the house load and an outage will occur. In addition, an outage will occur if the net house load (the load minus PV and/or fuel cell) exceeds the power capacity of the battery or generator. For example, a clothes dryer load may draw more power than the battery can handle, leading to an outage. We assume that occupants do not adjust their behavior and that all house loads are still operable, which may lead to more, longer outages than expected with real occupant behavior.

Table 6. DER Control Strategies for Annual and Resilience Simulations

DER Type	Normal Operation	Resilient Operation
Gas Generator	Turn on at RTP > $0.10/kWh and net power > 1 kW, PV forced off when generator on	Self-consumption mode, PV forced off when generator on
Gas Fuel Cell	Turn on at RTP > $0.08/kWh	Always off—cannot balance load due to ramp rate limitations
Battery	Discharge at RTP > $0.10/kWh, Charge at RTP < $0.03/kWh	Self-consumption mode, PV curtails when battery state-of-charge (SOC) is high
Battery + Gas Fuel Cell	DERs act independently, same controls as above	Battery in self-consumption mode, Fuel cell turns on at battery SOC < 10%, Fuel cell turns off at battery SOC > 50%, PV curtails when battery SOC is high

3.3 Stochastic Occupancy Schedule

Building occupancy plays an important role in building energy modeling and control. Many building energy modeling tools use “smooth” occupancy profile that represent the average consumption of an appliance (such as a dishwasher) based on data from a large number of homes. These smooth schedule-based occupancy approaches work well when annual energy consumption is the primary concern; however, they may not capture all the realistic behavior of actual equipment cycles and the effect they may on peak demand. To address this issue, we have developed a framework to integrate a stochastic occupancy model into our residential buildings to model the major end-use behavior of individual household members. The model first employs a clustering technique (i.e., K-means) to identify the distinct patterns of occupant behavior and then uses a homogenous Markov chain to realistically simulating occupant behavior [15].

All simulations use stochastic occupancy schedules to model load diversity within the community. While each home is assumed to have the same efficiency package, these stochastic schedules enable a more realistic profile of energy consumption of the community. Each of the 50 homes was assigned a different schedule that includes hot water draws, appliance and lighting usage, and occupancy status. Each house was also assigned a different set of heating and cooling setpoints using NREL’s ResStock™ tool for homes in the Chicago area to create a more realistic distribution of HVAC loads. A sample occupancy schedule for a week is shown in Figure 10.

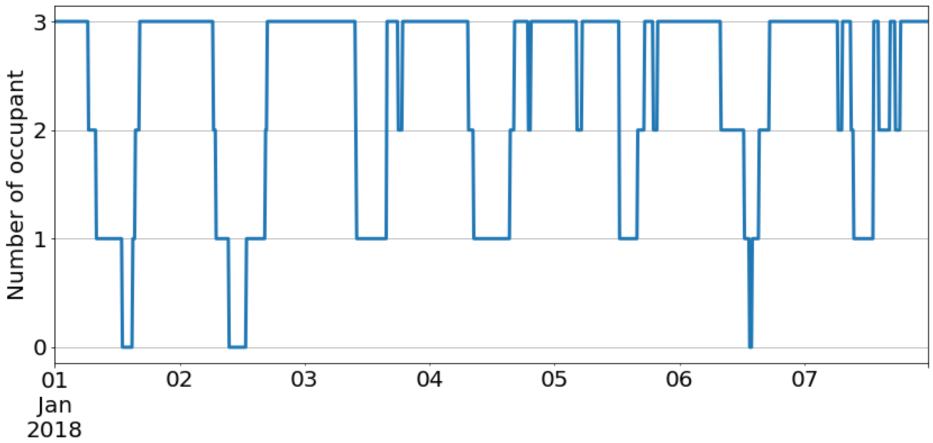

Figure 10. Example occupancy schedule from the stochastic occupancy model

3.4 Limitations and Assumptions

The methodology used in this study has some limitations, including:

- **Lack of diversity in building models**: Because we are at the early stage of the development process, the design of the CARE community was not finalized yet when we developed the building models. Different floor plans will diversify the building load profiles, but the impact is relatively small.
- **Snow-covering effects on PV panels were not considered:** When sizing the PV panels, we did not consider the snow-covering effect on PV panels because of lack of data; instead, we added one more panel to mitigate the effect. Evident by the results in Table 9, the increased PV generation capacity was able to cover the loss due to the snow-covering effects and the homes in the CARE community achieved the carbon neutral goal.

However, this approach might not be effective for communities in colder climate with more snow accumulation and lower temperature during the winter.

- **Cost savings are based on current utility rates:** The analysis in the report was based on the utility rates in 2019. The cost savings may not be the same in the future when the utility rates change. For example, the increase in natural gas price in 2021 is likely to reduce the amount of cost savings in homes with gas furnaces and water heaters, and it will be less cost effective to operate gas fuel cell or gas generator to power the homes when the RTP is high.
- **Carbon neutral status might change over time**: The energy consumption and carbon intensity data from 2019 were used to size PV and make the CARE community carbon neutral. However, the community might or might be carbon neutral in future years when the carbon intensities change. On one hand, as the power grid gets cleaner every year, the value of the oversized PV in terms of emission reductio becomes lower. On the other hand, natural gas utilities are also reducing the carbon intensity on the gas fuel by blending renewable natural gas (RNG) in the natural gas supply.
- **Capital and maintenance cost was not considered:** We focused on the energy cost in the analysis and did not consider the capital and maintenance cost of DERs such as gas generator, gas fuel cell, and battery. The equipment size used in the analysis was based on available product on the market and not optimized for individual homes. The gas generator was oversized and resulted in low efficiencies at low part load. From the resilience perspective, a neighborhood system or community microgrid that could be staged to meet the demand might be more economically and energy efficient.

4 Simulation Study

We simulated the community with different efficiency levels and different sets of DERs. An overview of the simulated scenarios is shown in Table 7. Resilience scenarios were simulated for one week, with 5 days of grid outage. The building efficiency and equipment type packages are described in Section 2. DER sizes and control strategies are described in Section 3. Scenarios with PV were implemented twice with different PV sizes as described in Table 3 and Table 4.

Table 7. List of Scenarios for the CARE Community

Scenario Name	Season	Building Efficiency	Equipment Type	PV	Battery	Gas Generator	Gas Fuel Cell
B1	Annual	Code Minimum	Gas				
B2	Annual	Design	Gas				
B3	Annual	Code Minimum	All-Electric				
B4	Annual	Design	All-Electric				
G0	Annual	Design	Gas	X			
GH1	Annual	Design	Gas	X	X		
GH2	Annual	Design	Gas	X		X	
GH2-b	Annual	Design	Gas	X		X	
GH3	Annual	Design	Gas	X			X

Scenario Name	Season	Building Efficiency	Equipment Type	PV	Battery	Gas Generator	Gas Fuel Cell
GH4	Annual	Design	Gas	X	X		X
E0	Annual	Design	All-Electric	X			
EH1	Annual	Design	All-Electric	X	X		
G0-r	1 week in winter	Design	Gas	X			
GH1-r	1 week in winter	Design	Gas	X	X		
GH2-r	1 week in winter	Design	Gas	X		X	
GH3-r	1 week in winter	Design	Gas	X			X
GH4-r	1 week in winter	Design	Gas	X	X		X

We present the results of these scenarios in batches. We first present the baseline results (B1-B4) in Section 4.1 under the 2019 carbon intensities of electricity and gas, followed by the baseline results under future emission scenarios in Section 4.2, then all annual gas scenarios (G0-EH1) in Section 4.3, and finally all resilience scenarios (G0-r-GH4-r) in Section 4.4.

4.1 Baseline Scenario Results

Table 8 compares the results from all baseline scenarios on a per-home basis. These scenarios do not include PV or any other DERs. The design cases include the energy efficiency packages discussed above. These packages reduce the electricity and gas consumption of the homes, which in turn reduce energy costs and emissions. The gas homes have lower energy costs than the all-electric homes, and the gas design case has the lowest cost and emissions of all baseline cases. We note that historical data from 2019 were used for the carbon intensity of electricity and gas, and the results may be different if another year's RTP data are used. The carbon intensities are expected to decrease due to the growth of renewable generation sources [16] and RNG [17].

Table 8. Annual Simulation Results on Per-Home Basis for Baseline Scenarios Without DERs

Metric	B1 (Gas Code Minimum)	B2 (Gas Design)	B3 (All-Electric Code Minimum)	B4 (All-Electric Design)
Energy				
Household Electric Energy (kWh)	6,883	6,529	13,454	9,481
Household Gas Energy (therms)	471	240	0	0
Cost				
Total Electricity Cost ($)	499	469	977	686
Total Gas Cost ($)	158	81	0	0
Total Cost ($)	657	550	977	686
Emissions				
Total Electricity Emissions (tons)	4.85	4.61	9.57	6.74
Total Gas Emissions (tons)	2.76	1.40	0	0
Total Emissions (tons)	7.61	6.01	9.57	6.74

Note the costs shown in Table 8 and Figure 11 represent only commodity costs and exclude annual utility customer charges for the gas and electric bills.

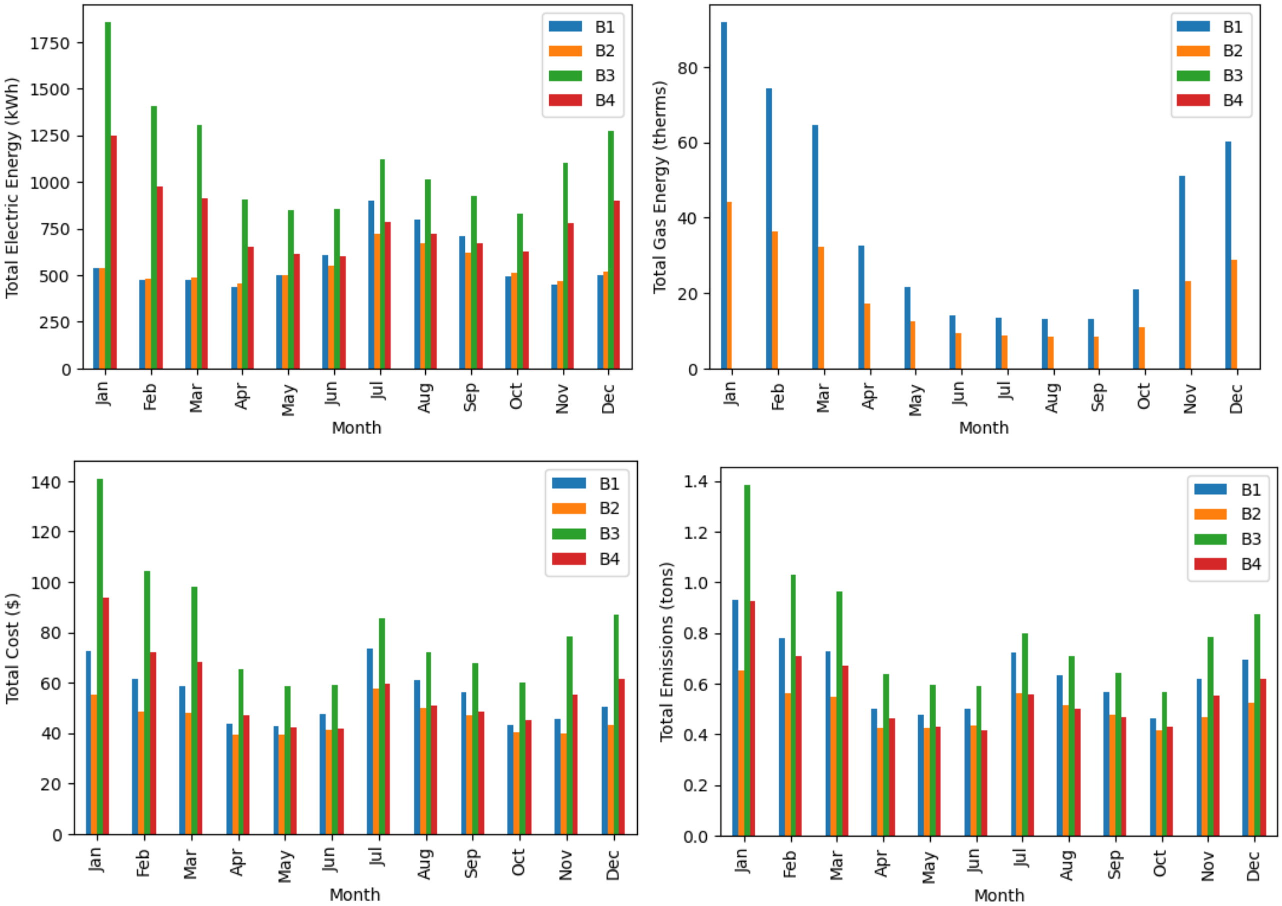

Figure 11. Comparison of monthly community energy, costs, and emissions for the baseline scenarios

Figure 11 shows the monthly community energy usage, costs, and emissions for the baseline scenarios. Energy usage, costs, and emissions are largest in the winter and summer months due to larger HVAC loads. The code-minimum cases (B1 and B3) have the largest costs and emissions for most months. Costs and emissions are very closely correlated because both depend on energy consumption, and the energy prices and carbon intensities do not fluctuate very much.

4.2 Future Emission Scenarios

As discussed in Section 3.4, the initial analysis on carbon emissions was based on the 2019 WattTime data whereas the carbon intensity of the power grid evolves with time. With President Biden’s goal of making the U.S. power sector carbon free by 2035, it is expected the grid carbon intensity is going to decrease quickly between now and 2035. On the other hand, natural gas utilities are exploring the possibility of blending the natural gas supply with RNG, which will also significantly reduce the emissions from natural gas.

4.2.1 Forecast of Carbon Intensities

To evaluate the trend of carbon emissions of the CARE community in the future, we performed additional analysis based on the energy data from the simulation. On the power grid side, we used NREL's Cambium data sets [18] as the source of future emission rates of electricity from the power grid. Cambium data sets contain hourly emission, cost, and operational data for modeled futures of the U.S. power sector with metrics designed to be useful for long-term decision-making through 2050 [18]. The long-run marginal emission rate was used in our analysis. Three levels of power grid decarbonization were considered:

- **Low RE:** No new carbon policies beyond those in place as of June 2021 (Mid-case**,** least aggressive)
- **Mid RE:** National power sector carbon emissions decrease linearly to 95% below levels by 2050 (Mid-case 95 by 2050)
- **High RE**: National power sector carbon emissions decline to 95% below 2005 levels by 2035 and are eliminated on a net basis by 2050 (Mid-case 95 by 2035, most aggressive)

On the natural gas side, the forecast of Nicor Gas's potential natural gas carbon intensities [20] was used in our analysis. Table 9 shows the forecast through 2050 under different RNG penetration rates. Natural gas carbon intensities were calculated based on the baseline emission intensities less the emissions removed by the RNG, including emission reduction by power to gas and offsets.

Table 9. Forecast of potential natural gas carbon emission intensities (lbs/therm)

RNG Penetration Rates	2020	2025	2030	2040	2050
Low RNG	11.69	11.60	11.10	10.52	9.96
High RNG	11.69	11.43	9.80	5.17	2.70

Figure 12 visualizes the average grid electricity and natural gas carbon intensities. Cambium provided grid electricity carbon emission forecast every two years whereas the ICF report [20] provided natural gas carbon emission forecast every five or ten years. Emission data from both sources were interpolated and plotted annually in Figure 12.

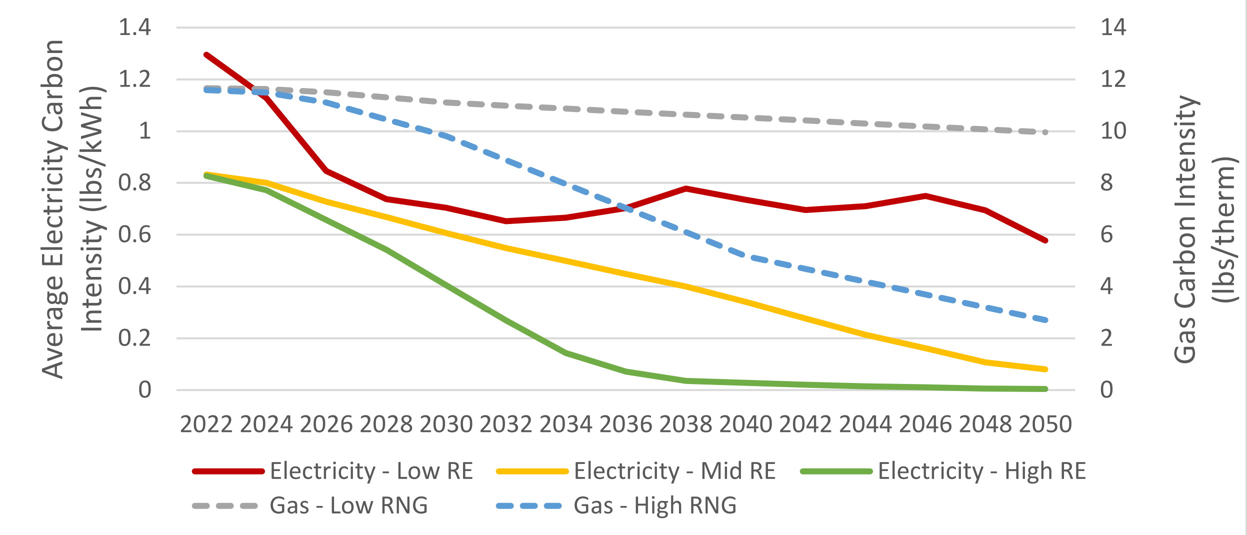

Figure 12. Average grid electricity and natural gas carbon intensities

Overall, the electricity and gas carbon intensities decrease with time in all scenarios. Note there are minor fluctuations in the carbon intensity in the Low RE case beyond 2032, probably because the ability of the power grid to absorb more renewable energy before 2032. In addition, in the Low RE case, the new generation is a mix of fossil energy (mostly gas) and renewable energy. In the Mid RE and High RE scenarios, because there is a future requirement for reduced emissions in 2035 or 2050, new generation in 2022 is more likely to be renewable energy. That is why the starting points for electric grid carbon intensity are different: Low RE starts around 1.30 lbs/kWh whereas Mid/High RE starts at 0.83 lbs/kWh.

4.2.2 Scenarios and Results

Table 10 enumerates the future emissions scenarios considered in this study. The scenarios are categorized by power grid renewable penetration levels. Annual energy simulations were performed with various community models as described in Table 7, including B1: gas code minimum homes, B2: gas efficient homes, B3: all-electric code minimum homes, and B4: all-electric efficient homes. The code minimum homes are also referred to as baseline homes hereinafter. Comparison of future annual carbon emissions of the CARE community is shown in Figure 13 (carbon scenarios with low RE: C1a and C1b), Figure 14 (carbon scenarios with mid RE: C2a and C2b), and Figure 15 (carbon scenarios with high RE: C3a and C3b). The cumulative carbon emissions of those scenarios are shown in Figure 16 through Figure 18.

Table 10. Summary of future emission scenarios

Carbon Scenario #	Power Grid Renewable Penetration	RNG Penetration
C1a	Low RE (Mid-case)	Low RNG
C1b	Low RE (Mid-case)	High RNG
C2a	Mid RE (Mid-case 95 by 2050)	Low RNG
C2b	Mid RE (Mid-case 95 by 2050)	High RNG
C3a	High RE (Mid-case 95 by 2035)	Low RNG
C3b	High RE (Mid-case 95 by 2035)	High RNG

Note: The future natural gas carbon emission intensities are estimated utilizing Southern Company Gas illustrative pathways for RNG based on the changing fuel mix and the lower carbon intensity of delivered fuel to 2050 as detailed in the Southern Company Gas ICF report [20].

In Figure 13, with low RE and low RNG, gas baseline homes have lower carbon emissions than all-electric baseline homes during 2022–2028 and 2038–2050. The carbon emissions in all-electric baseline homes fluctuate after the initial drop, following the trend in the power grid carbon intensities in the Low RE scenario. The cumulative carbon emissions, as shown in Figure 16, are almost the same in efficient homes, whereas gas baseline homes always have lower cumulative carbon emissions than all-electric homes. For cases with low RE and high RNG, gas homes always have lower or similar levels of carbons emissions compared to all-electric homes regardless of the home efficiency levels. For the mid RE cases shown in Figure 14, gas baseline homes have lower carbon emissions than all-electric homes before 2026 in both Low RNG and High RNG scenarios. For efficient homes, gas homes always have higher carbon emissions than all-electric homes regardless of the RNG penetration levels. The cumulative carbon emissions, as shown in Figure 17, are almost the same in baseline homes across all scenarios until 2032. Similar trend also exists in efficient homes.

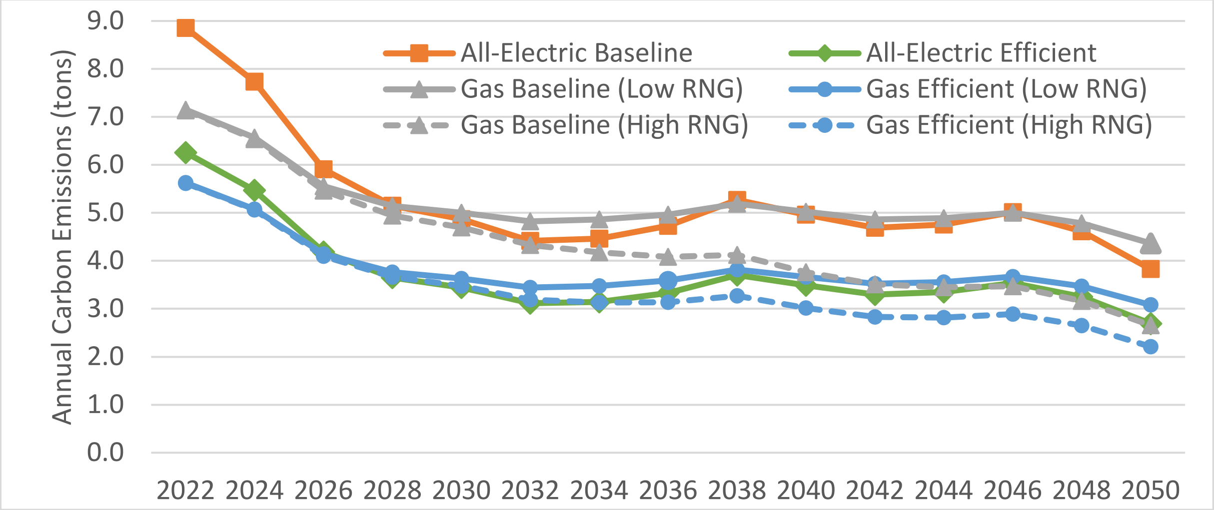

Figure 13. Annual carbon emissions per home of the CARE community (Low RE)

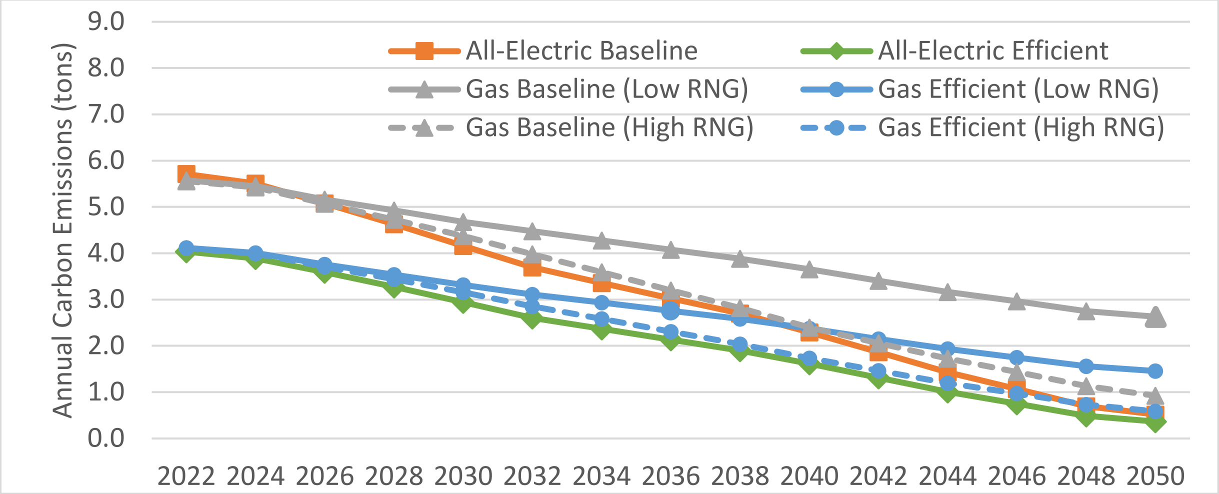

Figure 14. Annual carbon emissions per home of the CARE community (Mid RE)

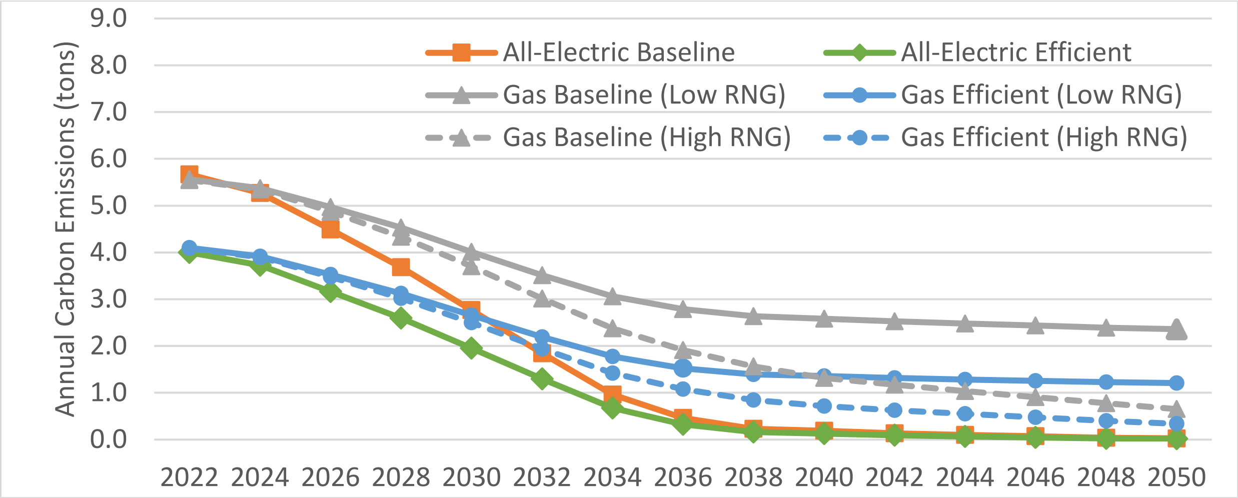

Figure 15. Annual carbon emissions per home of the CARE community (High RE)

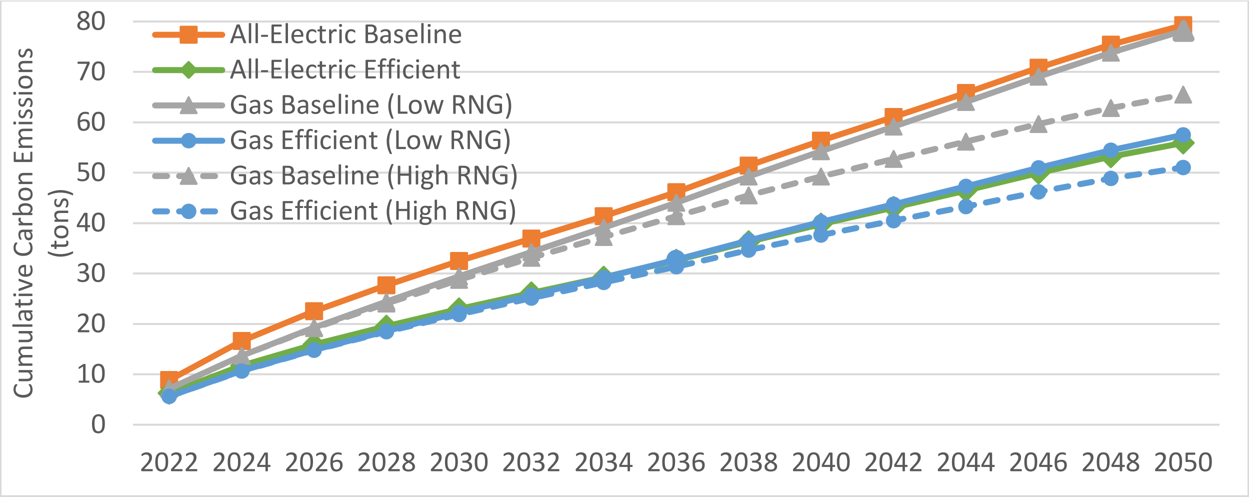

Figure 16. Cumulative carbon emissions per home of the CARE community (Low RE)

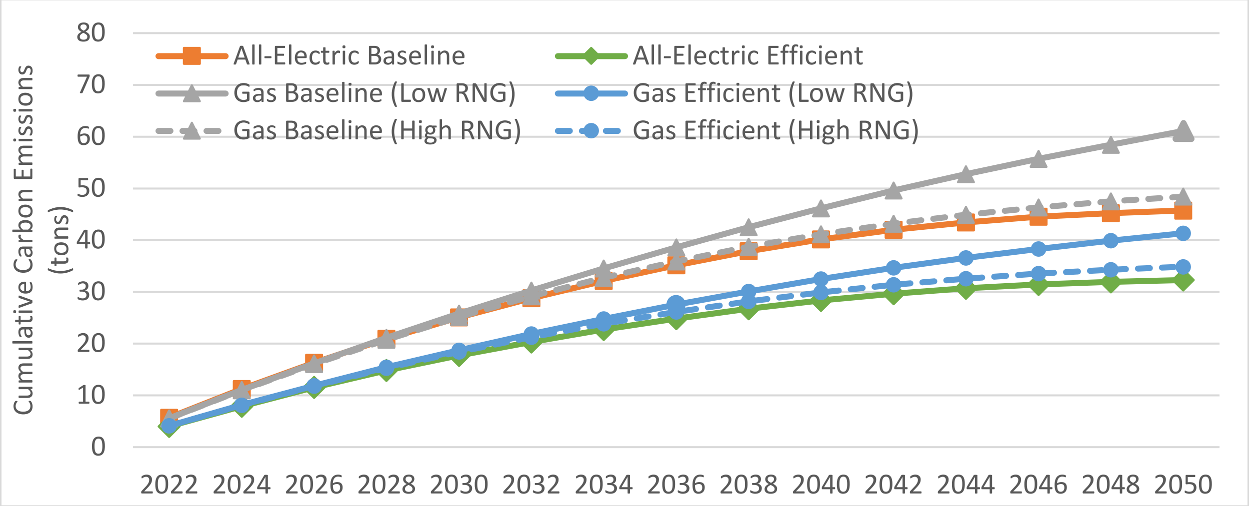

Figure 17. Cumulative carbon emissions per home of the CARE community (Mid RE)

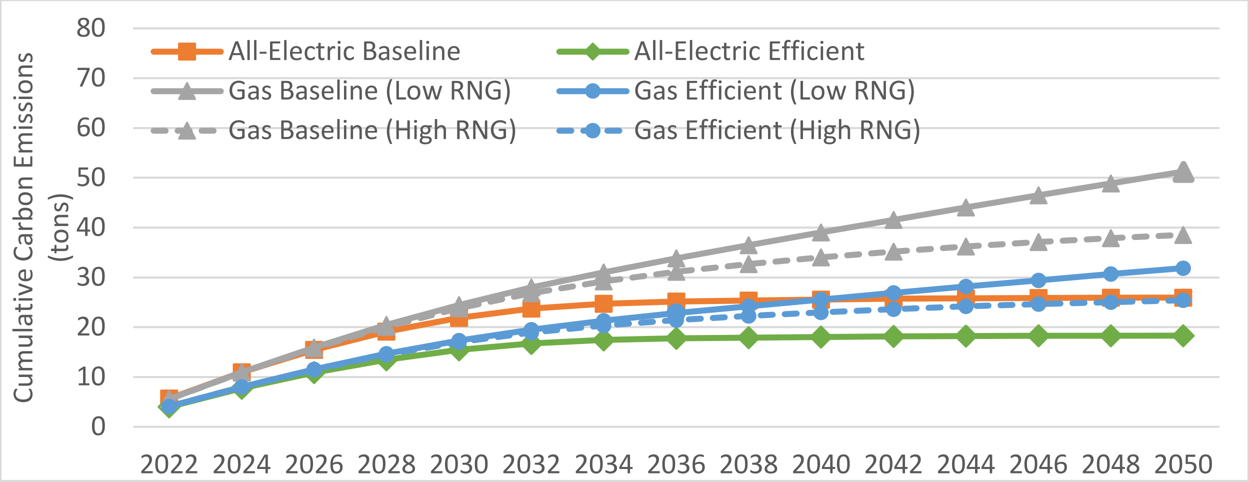

Figure 18. Cumulative carbon emissions per home of the CARE community (High RE)

The high RE in Figure 15 makes all-electric baseline homes emit less carbon emissions than gas homes right after 2023 for both low RNG and high RNG scenarios. For efficient homes, all-electric homes always have lower carbon emissions than gas homes regardless of the RNG penetration levels. The cumulative carbon emissions shown in Figure 18 are almost the same in baseline homes across all scenarios until 2028. Similar trend exists in efficient homes. The differences in cumulative emissions between gas homes and all-electric homes in 2050 in the high RE scenarios are much larger than those in the mid RE scenarios.

Key takeaways from the future emission scenario analysis are:

- Decarbonization in both the power and natural gas sectors have significant contribution to reducing the homes' carbon footprint.
- As the adoption of renewable energy into the electric grid continues to increase, homes with natural gas combined with renewable energy and energy efficiency can be a "complimentary strategy" to minimize cumulative carbon emissions during the transition.
- Home efficiency level affects how soon the carbon emission in gas homes exceeds that in all-electric homes. For homes under low RE and low RNG scenario, the transition occurs in 2028 for baseline homes and in 2026 for efficient homes. With mid RE and low RNG, the transition becomes sooner (2026) for baseline homes and as soon as 2022 for efficient homes. With high ER and low RNG, the transition occurs even earlier.
- The RNG penetration rates have little impact on the transition time because the difference in carbon intensity between the low RNG and high RNG scenarios is small before 2028, whereas the transitions in all scenarios occur on or before 2028. The carbon intensities of natural gas drop much more quickly after 2028 because of the increase in RNG penetration and reduction of the overall natural gas consumption.

4.3 Normal Operation Scenarios with DERs

Table 11 and Table 12 compare the results of the annual scenarios with DERs, including energy consumed, energy costs, and energy emissions on a per-home basis. Scenarios use either the gas design or all-electric design homes. Note the 2019 energy price and carbon intensity data were used in this analysis. Table 11 shows scenarios with PV sized for carbon neutral, and Table 12 shows scenarios with PV sized at 110% of electric load. In most net zero carbon scenarios, the PV generation leads to net negative electricity (i.e., net production), and net negative total energy costs and emissions. The annual energy consumption, gas consumption, energy cost and carbon emissions with PV sized for carbon neutral are shown in Figure 19 through Figure 22, and the ones with PV sized at 110% of electric load are shown in Figure 23 through Figure 26.

In general, scenarios with other DERs besides PV have lower costs and slightly higher carbon emissions. The battery is most effective at reducing costs, followed by the gas fuel cell. The gas fuel cell is the only non-PV DER to reduce carbon emissions. The energy usage of non-PV DERs is relatively small compared to the house consumption and PV production. All DERs run for less than 100 hours in a year.

We find that the main factors in determining the costs and benefits of a given DER strategy include the DER efficiency and DER runtime. The battery model has a round-trip efficiency of 93%, which leads to a small but significant increase in electricity consumption and emissions. The battery runtime (which is indirectly set by the control strategy) impacts the magnitude of the cost savings as well as the increase in consumption and emissions. The gas generator model has a significantly lower efficiency than the gas fuel cell model, which leads to higher costs and emissions. The low efficiency is primarily due to the large size of the generator and the requirement to be run during islanded operation, which causes the generator to run at very low part-load conditions.

It is noted the cost savings in the cases of PV sized for carbon neutral may be lower than what has been shown in Table 11 and Figure 21, because the net metering policy of the electric utility [3] sets the energy credit from oversized PV to expire at the end of a year and does not allow the energy credit to offset other service charges. Therefore, operating DERs following the RTP may not generate cost savings due to PV overproduction, and the total electricity cost in scenarios G0, GH1, GH2, GH2-b, GH3, and GH4 will be higher than the current values unless there is a special agreement between the CARE community and the electric utility on the overproduced PV energy. The cases of PV sized at 110% of electric load do not have this issue because the PV size is smaller, and the net electric energy is positive in all scenarios.

Although the real-world cost savings may be lower, the carbon reduction benefit was not affected. As shown in Figure 22, the community with PV sized for carbon neutral did achieve the carbon neutral goal in all gas scenarios (G0–GH4) and exceeded the net zero energy goal on an annual basis. On average, each home in the community has about -0.15 tons annual carbon emissions in the gas scenarios and about 0.6 tons annual carbon emissions in the all-electric scenarios. Note that fugitive gas emissions were not accounted for in the carbon emission calculation. However, when a smaller PV size is deployed following the guideline from the local electric utility, the community is no longer carbon neutral or net zero energy, as shown in Figure 30. Each home has 0.2 tons annual carbon emissions in the gas scenarios and 2.7 tons annual carbon emissions in the all-electric scenarios.

Table 11. Annual Simulation Results of the CARE Community with Different DERs and PV Sized for Carbon Neutral

Metric	G0	GH1	GH2	GH2-b	GH3	GH4	E0	EH1
Equipment Type	Gas	Gas	Gas	Gas	Gas	Gas	All-Electric	All-Electric
DERs Included (besides PV)	None	Battery	Generator (Islanded)	Generator (Grid Connected)	Fuel Cell	Battery + Fuel Cell	None	Battery
Electricity Usage								
House Electric Energy (kWh)	6,529	6,529	6,529	6,529	6,529	6,529	9,481	9,481
PV Electric Energy (kWh)	-8,829	-8,829	-8,827	-8,829	-8,829	-8,829	-8,829	-8,829
DER Electric Energy (kWh)	0	20	-11	-730	-69	-49	0	23
Net Electric Energy (kWh)	-2,300	-2,280	-2,309	-3,030	-2,369	-2,349	653	676
Gas Usage								
House Gas Energy (therms)	240	240	240	240	240	240	0	0
DER Gas Energy (therms)	0	0	5	110	8	8	0	0
Total Gas Energy (therms)	240	240	245	350	248	248	0	0
Costs								
Total Electricity Cost ($)[2]	-183	-218	-185	-346	-199	-234	34	-1
Total Gas Cost ($)	81	81	82	117	83	83	0	0
Total Cost ($)	-102	-137	-103	-229	-116	-151	34	-1
Emissions								
Total Electricity Emissions (tons)	-1.56	-1.54	-1.57	-2.08	-1.61	-1.59	0.57	0.59
Total Gas Emissions (tons)	1.40	1.40	1.44	2.05	1.45	1.45	0	0
Total Emissions (tons)	-0.16	-0.14	-0.13	-0.03	-0.16	-0.14	0.57	0.59
DER Metrics								
DER Runtime (hours)		93	36	75	75	124		94
DER Efficiency		89%	7%	23%	29%			89%

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[2] The overproduced PV may not receive full energy credit under the electric utility's net metering policy and the real-world electricity cost may be higher. The energy credit is set to expire at the end of a year and cannot be used to offset other service charges according to the net metering policy.

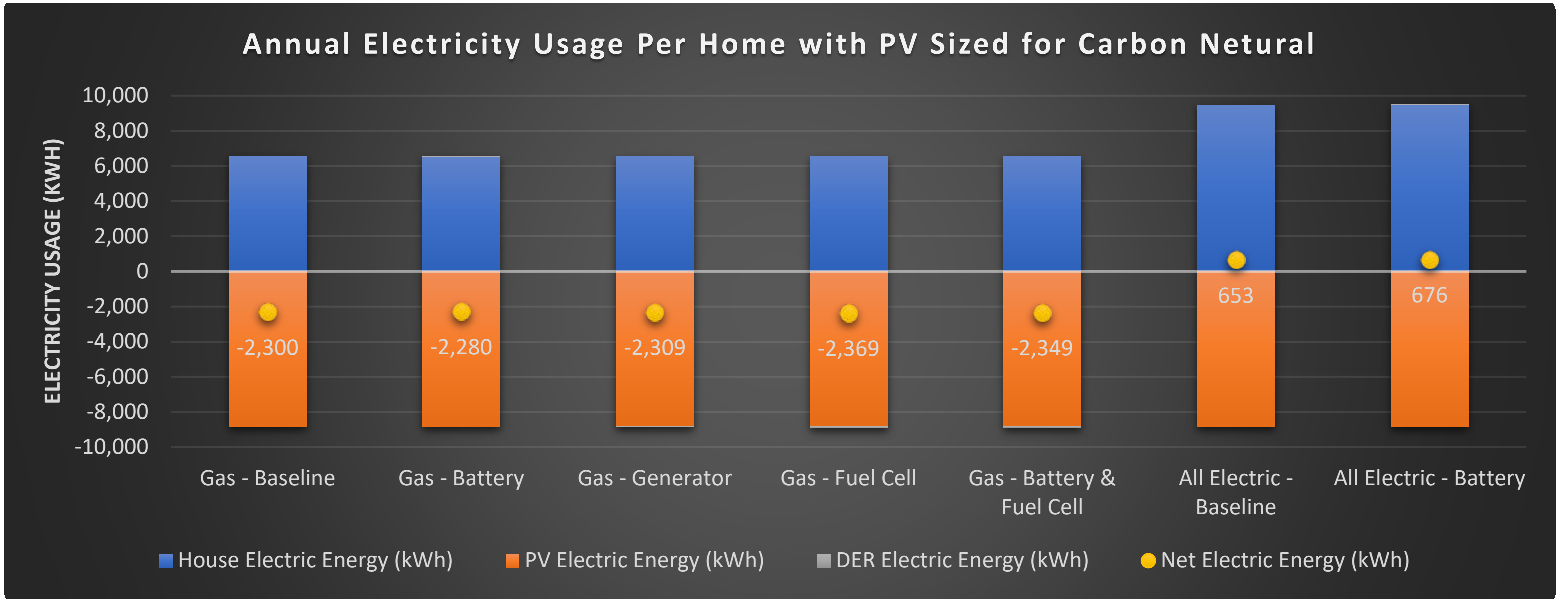

Figure 19. Annual electricity usage per home with PV sized for carbon neutral in various gas and all-electric scenarios

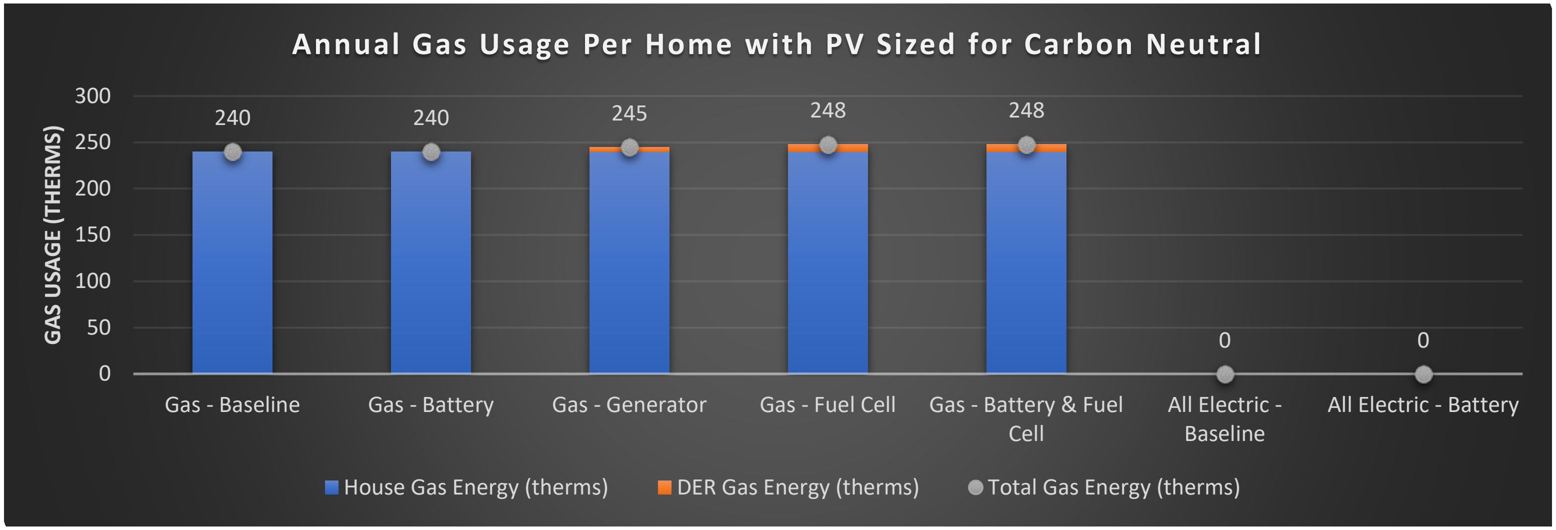

Figure 20. Annual gas usage per home with PV sized for carbon neutral in various gas and all-electric scenarios

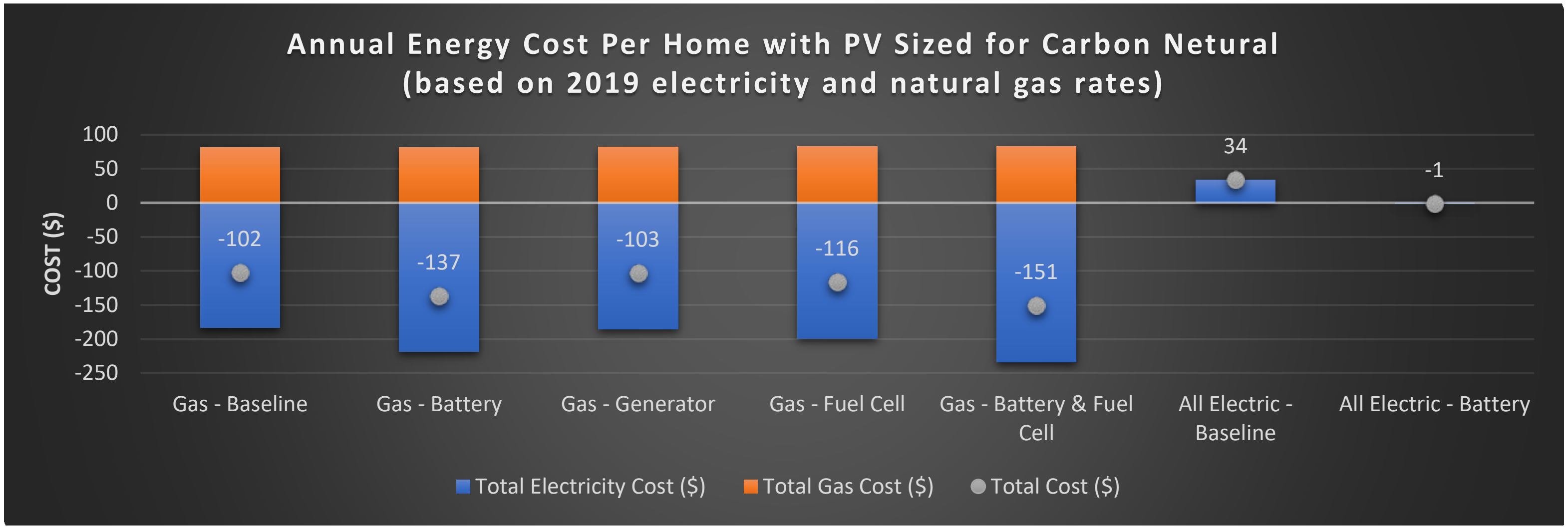

Figure 21. Annual energy cost per home with PV sized for carbon neutral in various gas and all-electric scenarios (based on 2019 electricity and natural gas rates). Real-world energy cost may be higher because the energy credit from overproduced PV expires at the end of a year and cannot be used to offset other service charges under the electric utility's net metering policy.

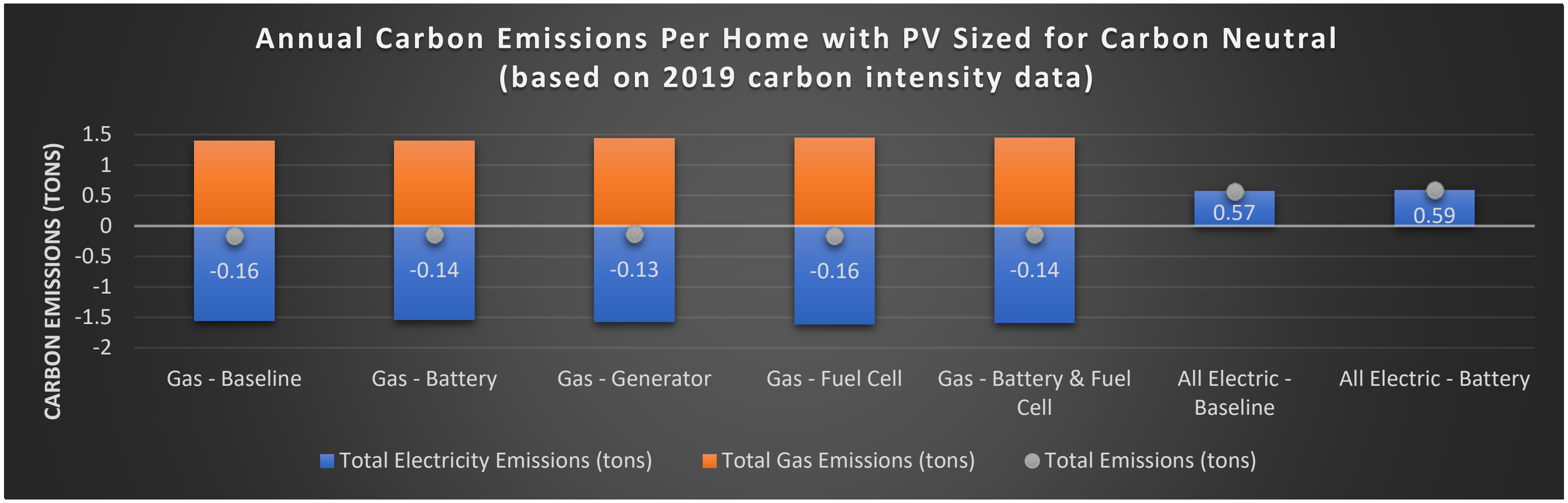

Figure 22. Annual carbon emissions per home with PV sized for carbon neutral in various gas and all-electric scenarios (based on 2019 carbon intensity data)

Table 12. Annual Simulation Results of the CARE Community with Different DERs and PV Sized at 110% of Electric Load

Metric	G0	GH1	GH2	GH3	GH4	E0	EH1
Equipment Type	Gas	Gas	Gas	Gas	Gas	All-Electric	All-Electric
DERs Included	None	Battery	Generator (Islanded)	Fuel Cell	Battery + Fuel Cell	None	Battery
Electricity Usage							
House Electric Energy (kWh)	6,529	6,529	6,529	6,529	6,529	9,481	9,481
PV Electric Energy (kWh)	-5,758	-5,758	-5,756	-5,758	-5,758	-5,758	-5,758
DER Electric Energy (kWh)	0	23	-12	-69	-46	0	23
Net Electric Energy (kWh)	771	794	760	702	725	3,723	3,746
Gas Usage							
House Gas Energy (therms)	240	240	240	240	240	0	0
DER Gas Energy (therms)	0	0	6	8	8	0	0
Total Gas Energy (therms)	240	240	246	248	248	0	0
Costs							
Total Electricity Cost ($)	44	9	41	28	-7	261	226
Total Gas Cost ($)	81	81	83	83	83	0	0
Total Cost ($)	125	90	124	111	76	261	226
Emissions							
Total Electricity Emissions (tons)	0.58	0.60	0.57	0.53	0.55	2.71	2.73
Total Gas Emissions (tons)	1.40	1.40	1.44	1.45	1.45	0	0
Total Emissions (tons)	1.99	2.01	2.01	1.98	2.01	2.71	2.73
DER Metrics							
DER Runtime (hours)		94	38	75	124		94
DER Efficiency		89%	7%	29%			89%

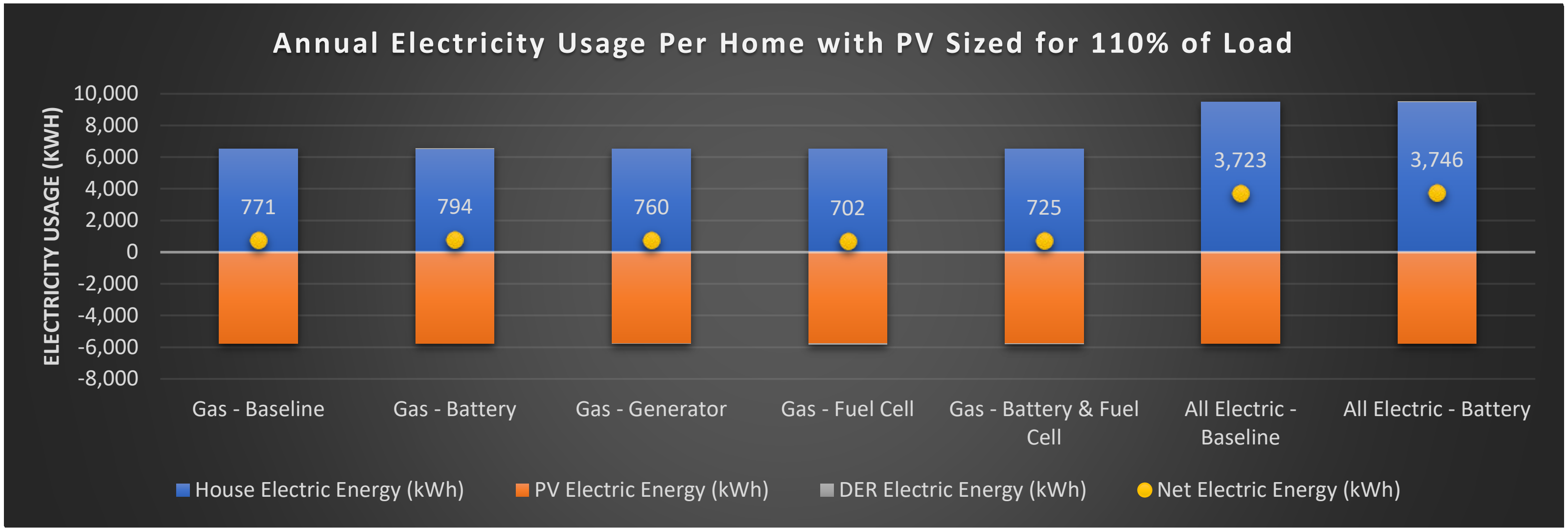

Figure 23. Annual electricity usage per home with PV sized at 110% of electric load in various gas and all-electric scenarios

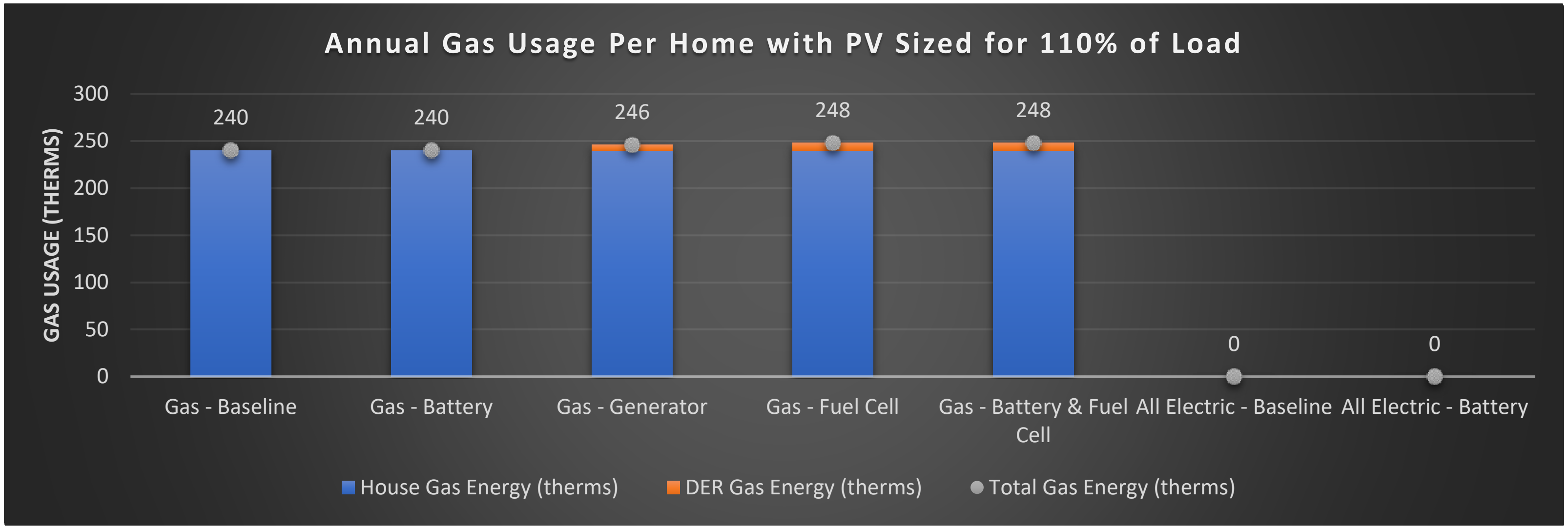

Figure 24. Annual gas usage per home with PV sized at 110% of electric load in various gas and all-electric scenarios

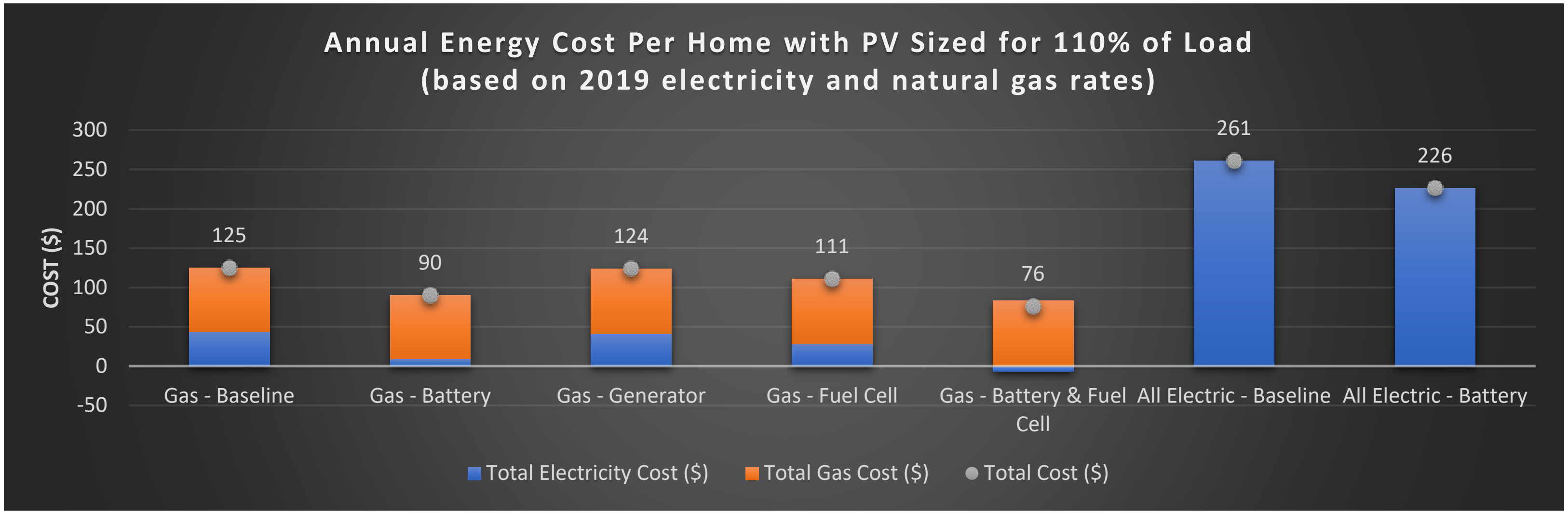

Figure 25. Annual energy cost per home with PV sized at 110% of electric load in various gas and all-electric scenarios (based on 2019 electricity and natural gas rates)

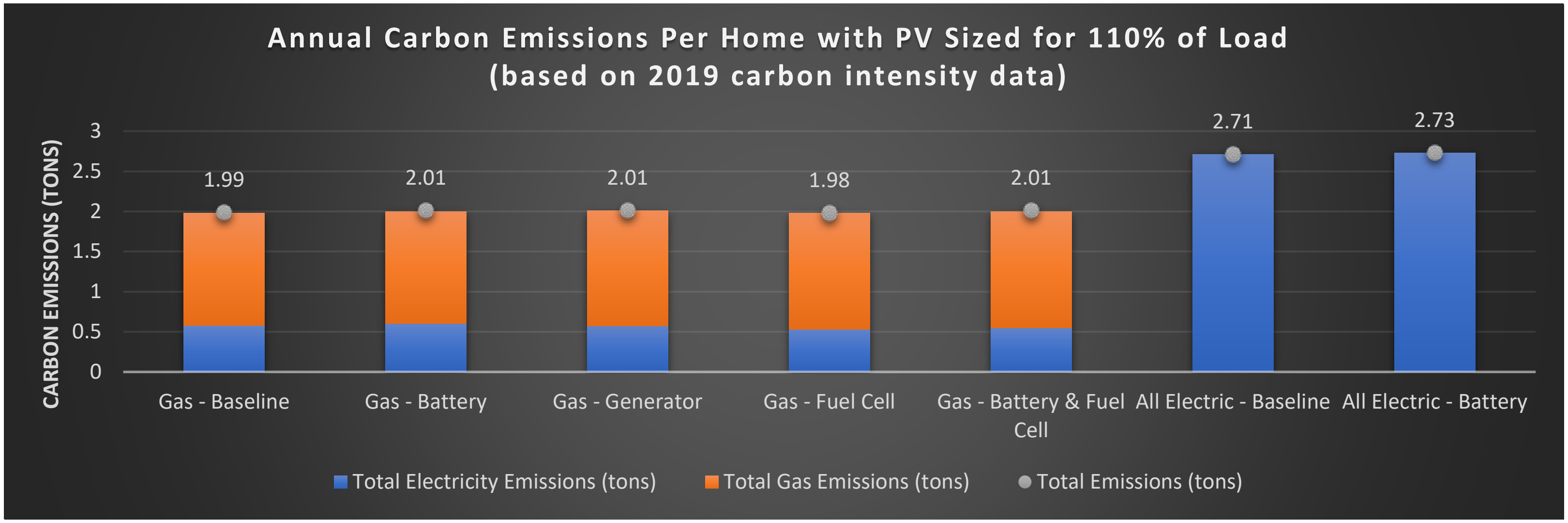

Figure 26. Annual carbon emissions per home with PV sized at 110% of electric load in various gas and all-electric scenarios (based on 2019 carbon intensity data)

4.4 Resilience During a Polar Vortex

The remaining part of this section focuses on the gas home simulation results for 5 winter days (January 28–February 1, 2019) during a polar vortex that brought record to near-record cold in Northern Illinois. The coldest temperature in Chicago in 34 years (-23°F) was recorded on the morning of January 30, 2019, during several days of bitter cold. The polar vortex caused widespread electrical grid outages in the region. We simulated the community under both normal operation and resilient operation. In the normal operation scenario, both the electrical grid and the natural gas infrastructure functioned normally during the 5-day period without any service disruption. In the resilient operation scenario, we assumed a 5-day electric grid outage and the gas infrastructure functioned normally during those days. Outdoor air temperature and solar irradiance during the outage period are shown in Figure 27. Figure 28 shows the assumed price and carbon intensity of gas and electricity for 5 days of the simulation. The electricity price includes the RTP and an additional $0.045/kWh for utility services.

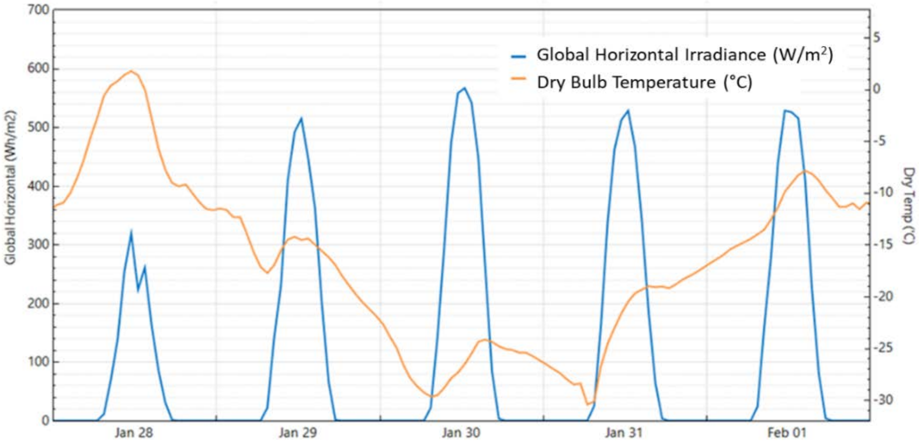

Figure 27. Weather conditions during the polar vortex

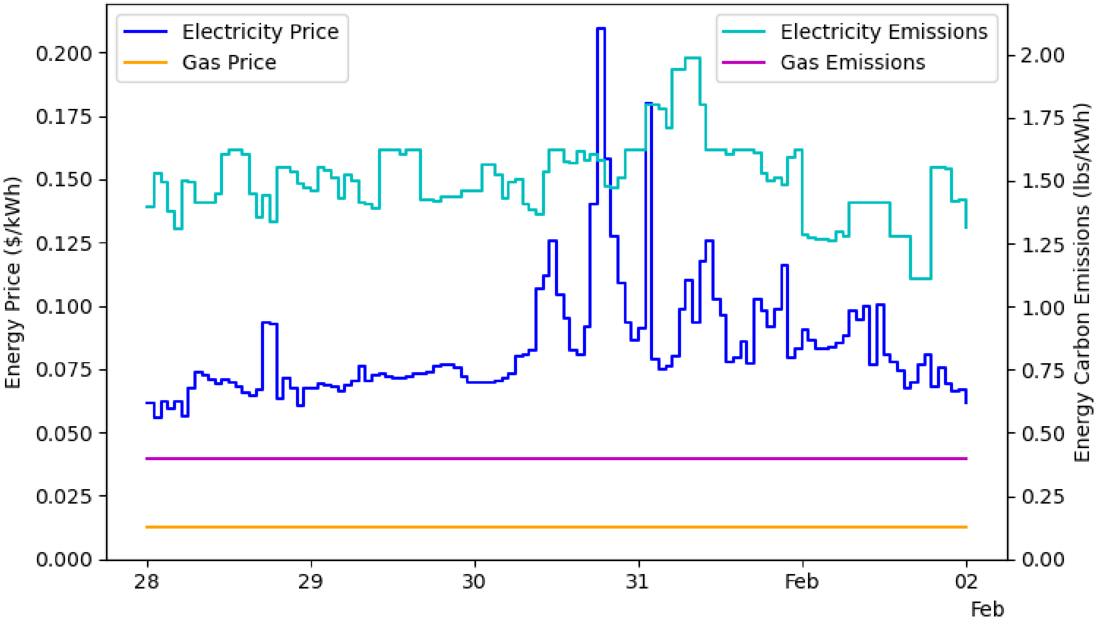

Figure 28. Energy prices and carbon intensities for gas and electricity during the polar vortex

4.4.1 Normal Operation

Figure 29 shows the total community power for the GH3 scenario with gas fuel cell for the 5-day period. The co-simulation platform models electricity and gas consumption for each device in each home of the community, and then aggregates the consumption to the community level. The gas fuel cell turns on for a few hours on January 30 and 31 when the RTP exceeds $0.08/kWh, consuming gas and producing electricity.

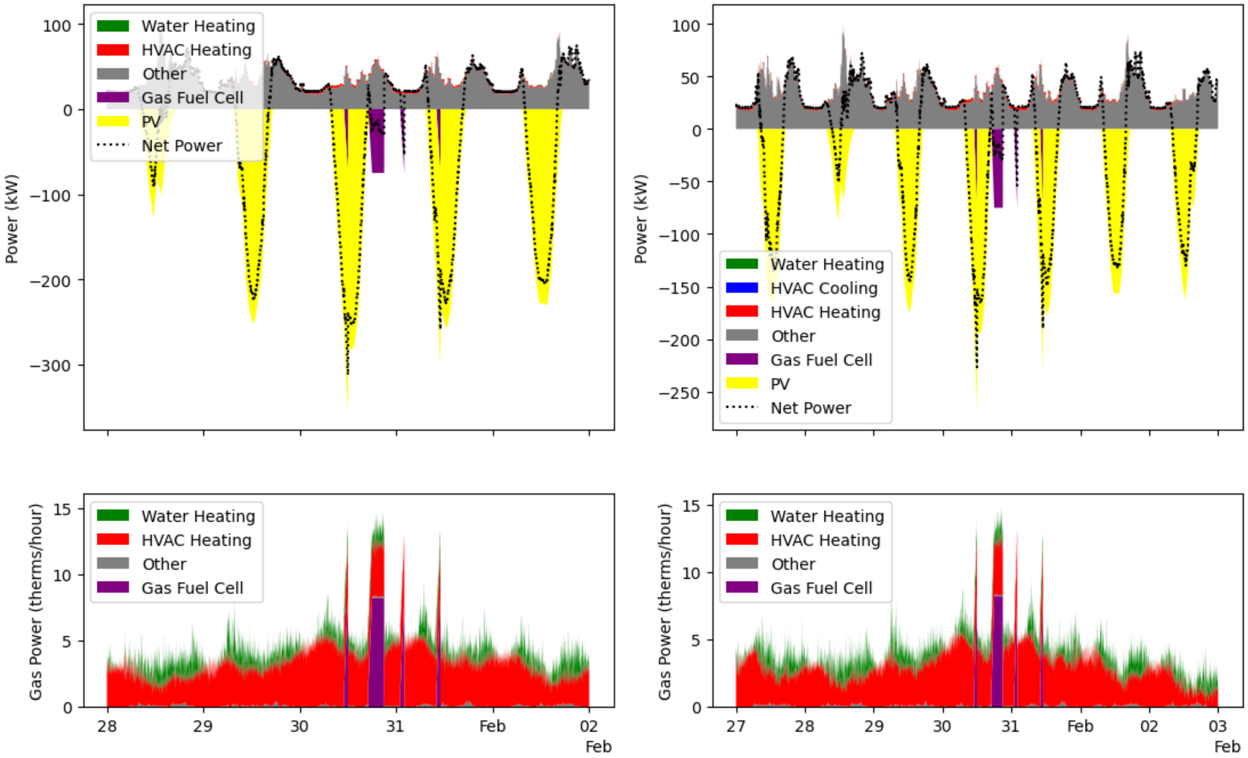

Figure 29. Total community power during a polar vortex for scenarios with a gas fuel cell and PV sized for net zero carbon (left) and 110% of electric load (right)

A comparison of total community power, energy cost, and emissions for scenarios with PV sized for net zero carbon is shown in Figure 30. For most hours, all scenarios have the same energy consumption. There are a few hours when the RTP is very high or very low when the DERs turn on. For example, all DERs turn on in the evening of January 30 causing electric power to decrease and gas power to increase (for the gas DERs). Early on January 31, the battery recharges. During the event on January 30, the batteries and fuel cells reduce the total community energy costs and emissions, while the gas generator increases the costs and emissions. During battery recharging, community costs increase at a lower magnitude, showing that the energy arbitrage is working.

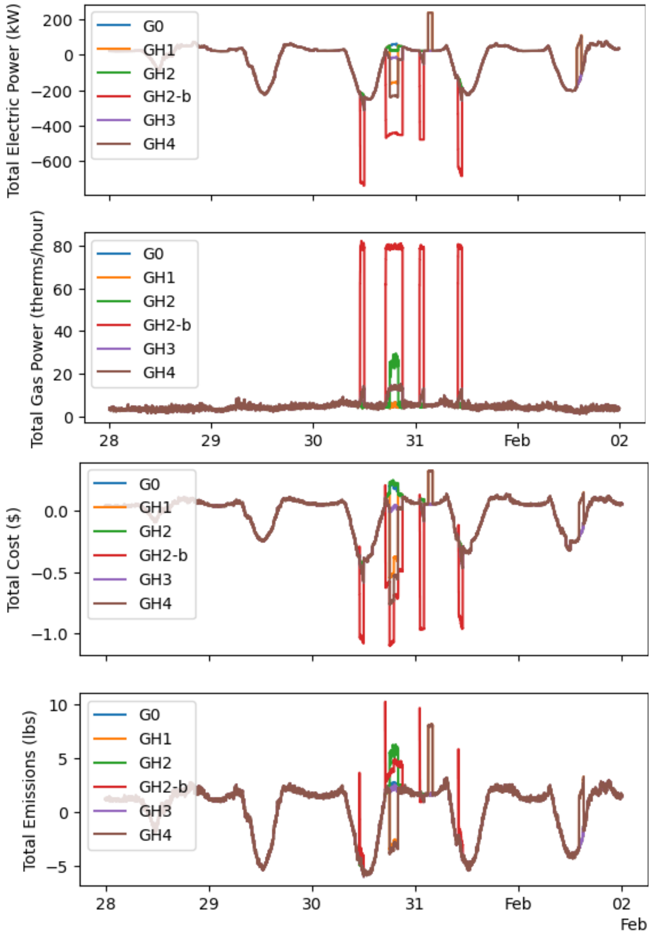

Figure 30. Comparison of total community power, energy costs, and emissions on an hourly basis during a polar vortex for scenarios with PV sized for net zero carbon

4.4.2 Resilient Operation

Table 13 shows the results of the resiliency scenarios on a per-house basis. All scenarios shown were run with the gas design efficiency package and with PV sized for net zero carbon. Results are aggregated for all 50 homes and include the 5-day outage as well as one day before and after the outage. The scenarios with no DER and with a gas fuel cell were unable to island at any point during the outage. In GH2-r, the gas generator was able to maintain power throughout the outage. The scenarios with a battery (GH1-r and GH4-r) maintained power for most of the outage, but lost power during some time periods due to low battery SOC or house load that exceeded the battery power capacity. The PV production in GH1-r and GH4-r was also higher than other scenarios because excess PV had to be curtailed if no energy storage was available.

The unmet heating load describes occupant discomfort due to cold house temperatures. 1°C-hour corresponds to a temperature 1° Celsius below the heating deadband for one hour, for one home. There is a small unmet heating load in the gas generator case, corresponding to about 2°C-hours of discomfort per house per day, which occurs because the HVAC capacity, sized based on Manual J [21], is too low to handle very cold ambient temperatures. Other scenarios have larger unmet loads, which are caused by the electric grid outage. We note that the gas furnace is unable to turn on during the outage because it requires electricity to run the HVAC fan.

Figure 31 shows the load profile for a single house during the 5-day outage. The left plot shows the battery maintains power for most of the outage by charging from solar during the day (snow covering not modeled), but it runs out of charge twice during the outage. The battery operates in self-consumption mode, leading to zero import or export of electricity during the outage. The right plot shows the gas generator maintains power for the whole outage. The generator uses a significant amount of gas because its efficiency is very low at low part load ratios.

Table 13. Resilience Simulation Results (on a Per-House Basis) With Different DERs with PV Sized for Net Zero Carbon

Metric	G0-r	GH1-r	GH2-r	GH3-r	GH4-r
DERs Included	No DER	Battery	Gas Generator	Gas Fuel Cell	Battery + Gas Fuel Cell
DER Metrics					
PV Electric Energy (kWh)	-55	-120	-55	-55	-109
DER Electric Energy (kWh)	0	8	-71	0	-16
DER Gas Energy (therms)	0	0	134	0	2
DER Runtime (hours)	0	123	120	0	123
DER Efficiency	NA	89%	2%	NA	30% (fuel cell)
Outage Metrics					
Unmet Heating Load (°C-hours)	1,585	70	10	1,585	20

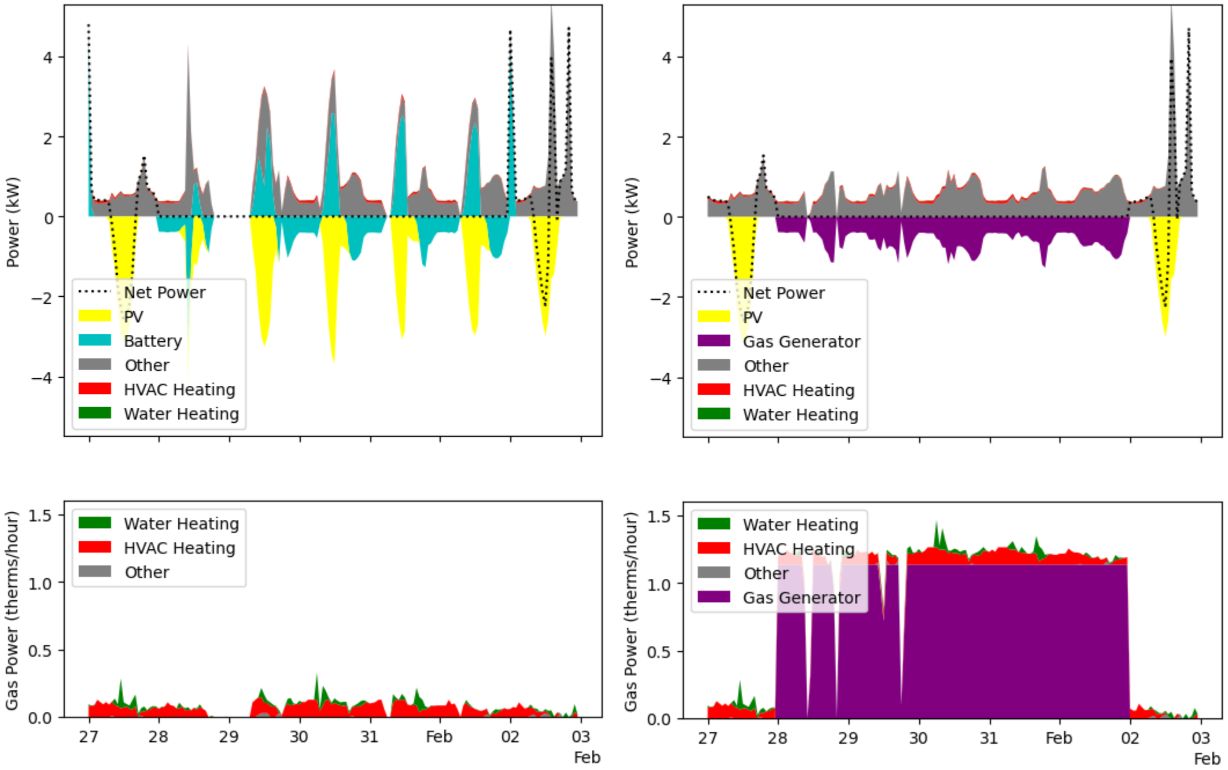

Figure 31. Electricity and gas power for a single house with a battery (left) and a gas generator (right) during a 5-day outage

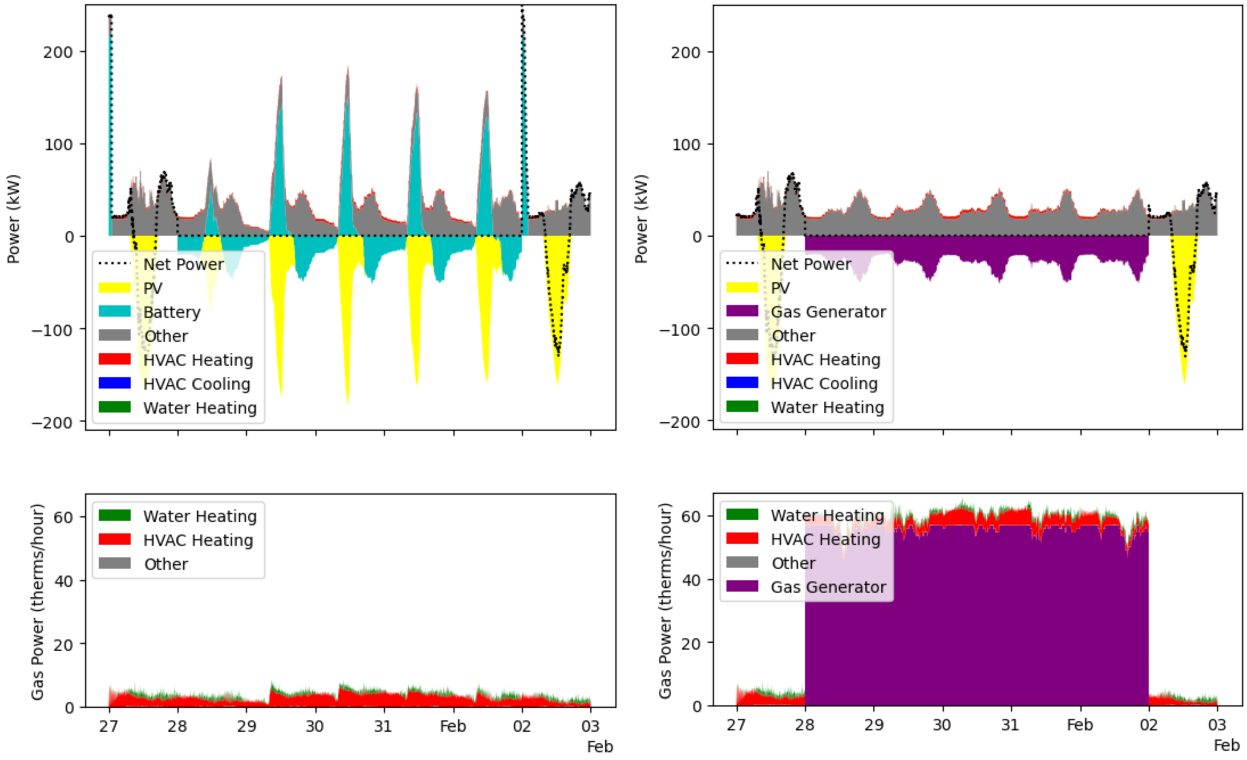

Figure 32. Electricity and gas power for the community with a battery (left) and a gas generator (right) during a 5-day outage

Figure 32 shows the community-scale load profile. With battery, some homes were able to maintain power throughout the night. The community electric power decreases later at night, indicating that some homes lost power at night. The gas generator-maintained power for all homes during the entire outage at the cost of a significant amount of gas to provide that power.

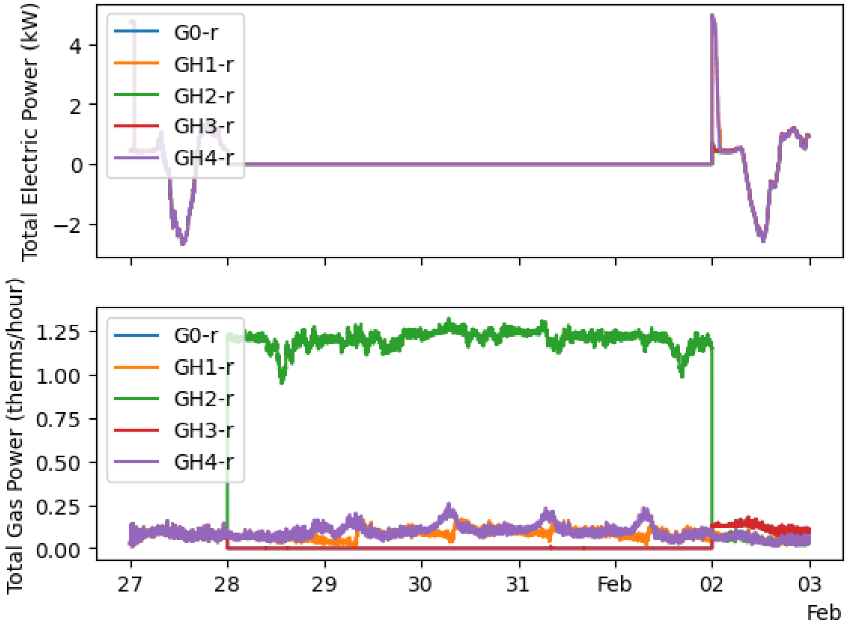

Figure 33. Community electricity and gas power for all resilience scenarios during a 5-day outage

Figure 33 compares the community power for all resilience scenarios on a per-home basis. The net electric power remains 0 for the duration of the outage. Gas consumption is much larger for the scenario with gas generators, which leads to larger costs and emissions.

5 Conclusions

In this study, we developed energy models of the CARE Community with 50 homes in South Suburban Chicago. The optimal energy efficiency package alone can achieve 33% source energy savings and save homeowners 28% of the energy charges on their utility bills without advanced controls. The CARE community's carbon emissions depend on the carbon intensities of the power grid and natural gas supply. With the deployment of rooftop PV, the CARE Community can achieve carbon neutrality by a combination of energy efficiency (23% carbon reduction) and rooftop solar PV (77% carbon reduction). However, the overproduced PV energy may not be compensated under the electric utility's net metering policy. When the electric utility's constraint on the PV size is applied (i.e., no larger than 110% of the prior year's electric load), the community is no longer carbon neutral and each home produces about 2 tons of carbon emissions per year. Decarbonization in both the power and natural gas sectors will further reduce the community's carbon footprint in the near future. When integrated with DERs and responding to the local electric utility's RTP, the homes in the CARE Community have an additional $49 annual utility bill savings, but it is not sufficient to recover the equipment cost over its lifespan. However, we note that RTP strategies vary significantly across the country and impact cost-effectiveness. Despite the moderate utility bill savings from DERs, the integrated strategy can greatly enhance the resilience of the community when the homes operate in islanded mode during extreme weather events. In a simulated 5-day outage during the 2019 polar vortex, homes with gas generator or a combination of battery and gas fuel cell can both survive the bitter cold with negligible thermal discomfort. Homes with battery can also support resilient operation but with higher thermal discomfort because the battery capacity used in the study (8.6 kWh/4.3 kW) cannot support large, simultaneous electric loads—the results will significantly improve if the homeowners change their behavior and avoid turning on large loads simultaneously. The 10-kW gas generator was able to handle those electric loads, but the large size also caused low load fraction, which significantly decreased its efficiency and increased fuel consumption and carbon emissions. Proper sizing of the gas generator and homeowners' behavior change during the outage will help resolve those issues. We find as the adoption of renewable energy into the electric grid continues to increase, homes with natural gas combined with renewable energy and energy efficiency can be part of a transition strategy to minimize cumulative carbon emissions while providing enhanced resiliency during extreme weather events.

References

[1] NREL, "BEopt: Building Energy Optimization Tool," [Online]. Available: https://www.nrel.gov/buildings/beopt.html.

[2] NREL, "National Residential Efficiency Measures Database," [Online]. Available: https://remdb.nrel.gov/measures.php?gId=12&ctId=216&scId=2374&acId=2378 .

[3] ComEd, [Online]. Available: https://www.comed.com/SmartEnergy/MyGreenPowerConnection/Pages/NetMetering.aspx.

[4] NREL, "Typical Meterological Year (TMY): Learn about the TMY data type used in the NSRDB," [Online]. Available: https://nsrdb.nrel.gov/about/tmy.html.

[5] "OpenEI Utility Rate Database," [Online]. Available: https://openei.org/wiki/Utility_Rate_Database .

[6] ComEd, "Current Rates and Tariffs (see rate BESH).," [Online]. Available: https://www.comed.com/MyAccount/MyBillUsage/Pages/CurrentRatesTariffs.aspx.

[7] WattTime, [Online]. Available: https://www.watttime.org/ .

[8] R. El Kontar and X. JIn, "A Framework for Optimal Placement of Rooftop Photovoltaic: Maximizing Solar Production and Operational Cost Savings in Residential Communities," *Journal of Engineering for Sustainable Buildings and Cities,* vol. 1, no. 4, p. 041006, 2020.

[9] NREL, "System Advisor Model," [Online]. Available: https://sam.nrel.gov/.

[10] M. Blonsky, J. Maguire, K. McKenna, D. Cutler, S. P. Balamurugan and X. Jin, "OCHRE: The Object-oriented, Controllable, High-resolution Residential Energy Model for Dynamic Integration Studies," *Applied Energy,* vol. 290, p. 116732, 2021.

[11] Generac, [Online]. Available: https://www.generac.com/all-products/generators/home-backup-generators/guardian-series/10kw-7171-wifi-enabled .

[12] Special Power Source, [Online]. Available: From https://spsources.com/products/#arp1000 and associated Technical Datasheet.

[13] ComEd, [Online]. Available: https://hourlypricing.comed.com/hp-api/ .

[14] EIA, [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=73&t=11 .

[15] NREL, "ResStock," [Online]. Available: https://www.nrel.gov/buildings/resstock.html .

[16] NREL, "Cambium," [Online]. Available: https://www.nrel.gov/analysis/cambium.html .

[17] Southern Company Gas, [Online]. Available: https://southerncompanygas.com/resources/renewable/.

[18] "Cambium," National Renewable Energy Laboratory, [Online]. Available: https://www.nrel.gov/analysis/cambium.html .

[19] P. Gagnon, W. Frazier, W. Cole and E. Hale, "Cambium Documentation: Version 2021," National Renewable Energy Laboratory, Golden, CO, 2021.

[20] ICF, "Decarbonization Pathways for Nicor Gas," 2021.

[21] H. Rutkowski, Residential Load Calculation, Arlington, VA: ACCA, 2011.

Appendix A. Building Efficiency Measure Results

Optimizations were performed for homes with natural gas or all electric, with and without PV, and under both the standard rate and the RTP for electricity costs. The community is planned to include natural gas, but all-electric homes were simulated for comparison purposes. The broader community-scale modeling, including DERs, will also include all-electric cases. Including PV in cases leads to results where PV becomes more cost-effective than certain efficiency measures, so cases without PV were simulated to give a better idea of the impact of all the efficiency measures considered. Simulations under different rate structures were performed to determine which rate would be most beneficial to the homeowner. While the cost-effectiveness of results does not change substantially between cases using the RTP and the standard rate, this is without considering occupants shifting loads based on the RTP, which will provide additional savings beyond what is simulated in the base case here.

The optimizations include hundreds of different building simulations covering the full range of combinations of different efficiency options. Results are plotted with the x-axis representing source energy savings and the y-axis representing the annualized energy related costs. The points along the line represent the lowest cost design for each source energy savings level. Rather than covering all the points on the optimal curve, this paper focuses on several key points:

- **Net Zero Energy**: The point where the home's net consumption will match its net production. Only exists for cases with PV.
- **Cost Optimal Point**: The point with the lowest annualized energy related costs. This is the lowest cost point when considering capital costs, utility bills, and any replacement costs.
- **Cost Neutral Point**: The point with the same annualized energy related costs as the baseline, but a higher level of source energy savings. This point represents a cost neutral design with substantial source energy savings.
- **Maximum Efficiency**: Highest level of source energy savings that can be achieved through efficiency measures alone.

Not all these points exist in every case simulated here and will be excluded from plots they do not apply to. For reference, the baseline point will also be highlighted for each case.

A.1 Gas Homes Without PV and Under Standard Rate

Results for this case are shown in Figure 34. Cost optimization results for homes with natural gas service and no PV under the standard rate structure. More than 15% source energy savings is achievable in a cost-effective way through efficiency alone by incorporating increased wall batt insulation, air sealing to 2 ACH_{50}, moving the ducts to conditioned space, using a tankless water heater, and installing LED lighting. A cost neutral package is able to achieve more than 25% source energy savings with additional efficiency measures, including increased wall sheathing insulation, increased ceiling insulation, air sealing to 1 ACH_{50}, installing an HRV, a condensing tankless water heater, and ENERGY STAR appliances. The maximum efficiency package includes increases in the furnace and air-conditioner efficiency and triple-pane windows. Of the efficiency measures included only in the cost optimal, increasing the furnace efficiency is the closest to cost-effective, with a 98% AFUE furnace leading to an additional annualize energy related cost of $10/year, while increasing the cooling efficiency and installing triple-pane windows are substantially less cost-effective.

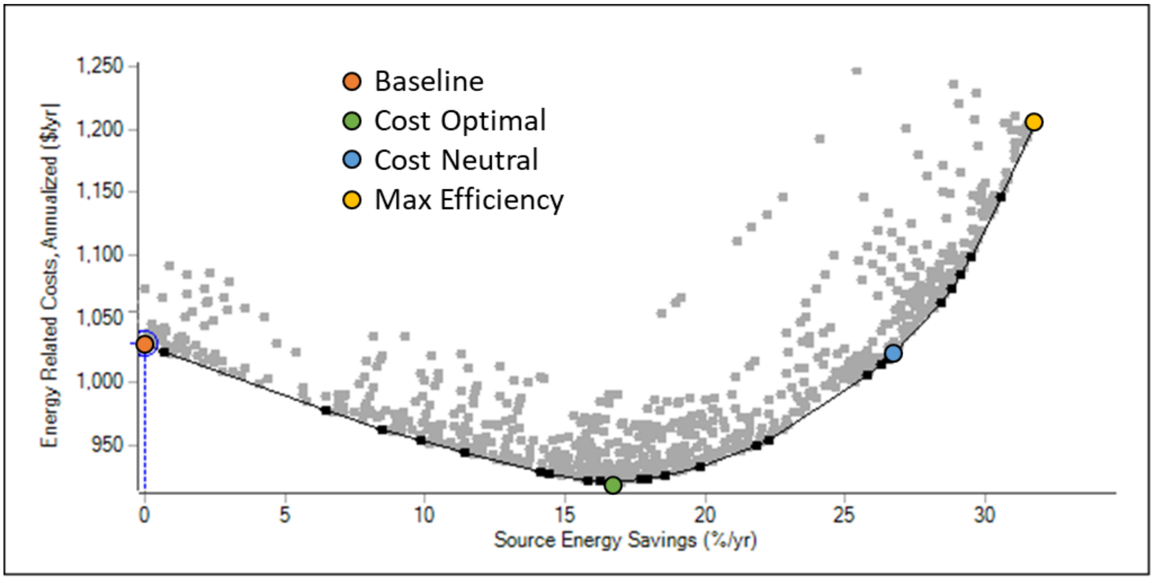

Figure 34. Cost optimization results for homes with natural gas service and no PV under the standard rate structure

A.2 Gas Homes Without PV and Under RTP

Results for this case are shown in Figure 35. In this case, efficiency can reduce the energy related costs up to 23% source energy savings. Measures included in the cost-minimal package include increased wall batt insulation, air sealing to 2 ACH_{50}, moving the ducts to conditioned space, a tankless water heater, LED lighting, and an ENERGY STAR clothes washer. Source energy savings can be achieved in a cost-neutral way, with the utility bill savings offsetting the first cost, up to a source energy savings of 33% by including additional wall sheathing insulation, additional ceiling insulation, air sealing, an HRV, a SEER 16 AC and a 98% AFUE furnace, a condensing tankless water heater, and ENERGY STAR appliances. Additional efficiency measures, including a more efficient air conditioner and triple-pane windows provide additional savings up to 37%. The triple-pane windows and a higher-efficiency air conditioner are substantially less cost-effective than the options included in the cost-neutral case. Efficiency measures included in the homes under the RTP are largely similar to those under the standard rate structure with some minor differences.

These simulations did not include any sort of occupant response to the price signals, which could provide substantial utility bill savings. Without this load shift, annualized energy related costs are slightly higher under the RTP, but it is expected that some amount of load shifting would be able to offset this additional cost without an impact on the occupant comfort. As a result, this analysis assumes that the homeowners opt in to the RTP when this community is built to take advantage of this savings opportunity. Given the benefit the RTP provides to the homeowners, analysis of other scenarios was done using this rate structure.

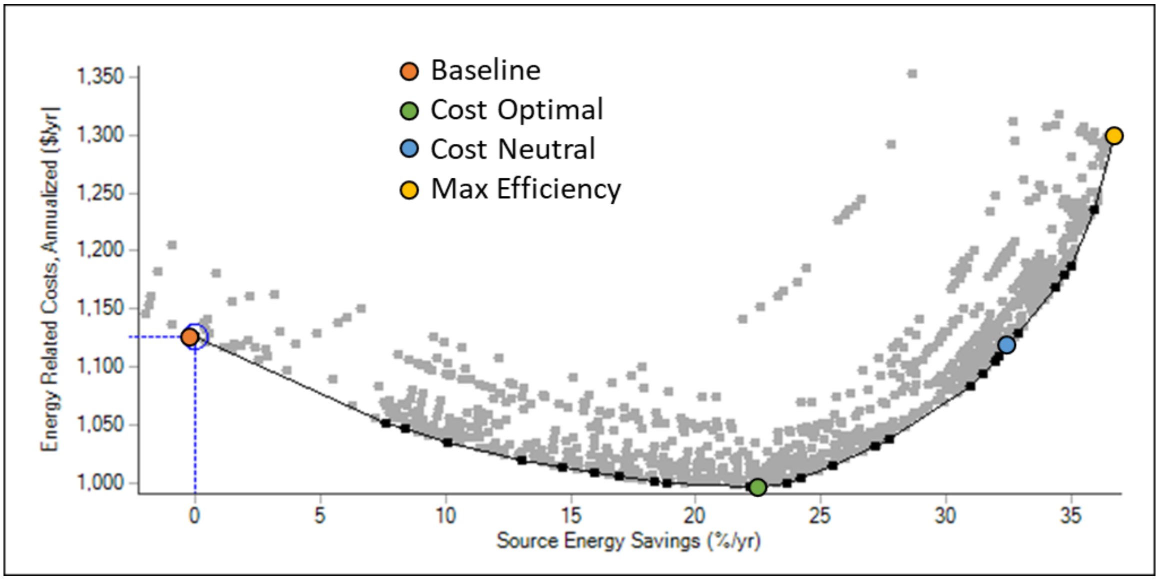

Figure 35. Cost optimization results for homes with natural gas service and no PV under RTP

A.3 Gas Homes with PV Under RTP

Results for homes with natural gas and PV under the RTP are shown in Figure 36. In this case, the cost-optimal point is made up of efficiency measures that provide about 15% source energy savings over the baseline of a code-minimum home. Efficiency measures included in this package include additional wall insulation (R21 batts in 2×6 construction, but no additional sheathing insulation), air sealing to 2 ACH_{50}, moving the ducts to conditioned space, installing a tankless water heater, and LED lighting. Efficiency alone is part of the optimal curve up to a little less than 20% source energy savings. After this point, PV starts providing additional source energy savings, with each cost-optimal points consisting of a larger PV system. Based on the RTP with net metering, PV is not fully able to pay for itself in this case, leading to the rise in cost at higher levels of source energy savings. However, the PV costs used here include economies of scale, which make the PV cheaper per watt installed as the system's size increases. This leads to the annualized energy related costs eventually decreasing at large enough system sizes as the cost per kilowatt of installed PV decreases. While the lowest cost option includes the largest PV system modeled, this system is larger than would be allowed under the local electric utility's PV sizing rules (and also would be constrained by the roof area).

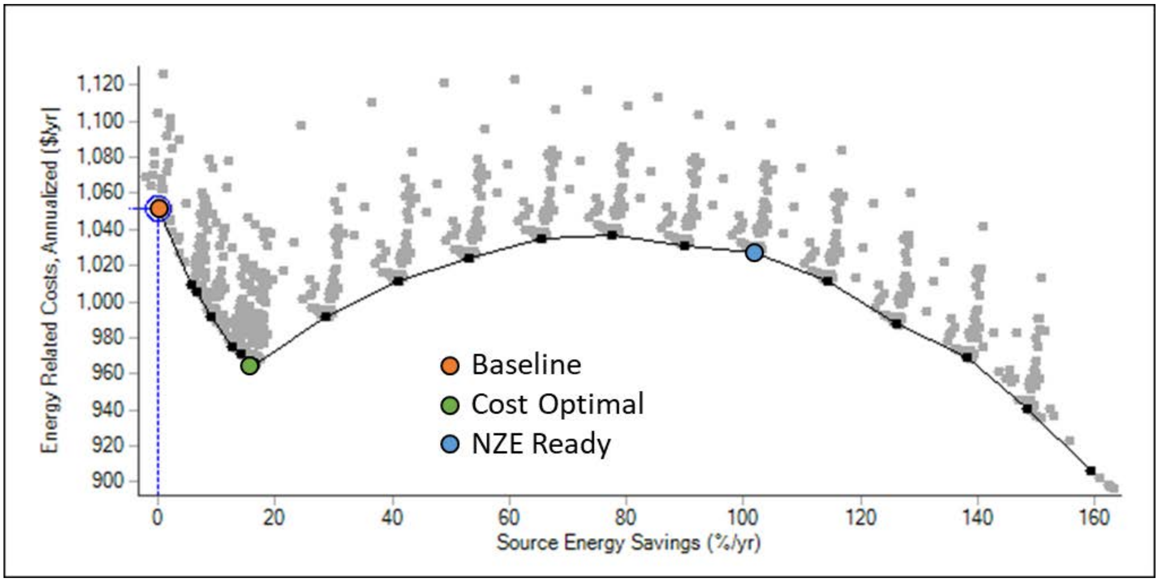

Figure 36. Cost optimization results for homes with natural gas service and PV under RTP

A.4 All-Electric Homes Without PV Under RTP

Results for all-electric homes without PV under the RTP are shown in Figure 37. Efficiency is able to achieve source energy savings cost-effectively up until about 15%. Efficiency measures included in this package include additional wall insulation (up to R21 plus sheathing insulation to R10), air sealing to 1 ACH_{50}, moving the ducts into the conditioned space, and installing LEDs and an ENERGY STAR clothes washer, clothes dryer, and dishwasher. Incorporating all the efficiency measures included as part of this optimization leads to up to 26% source energy savings, but at a fairly substantial cost. The optimal point closest to cost neutral achieves a very similar level of savings source energy savings and includes several additional efficiency measures over the cost-optimal point, including additional attic insulation, a highly efficient ASHP, triple-pane windows, and an ENERGY STAR refrigerator. The main difference between the cost neutral point and the max efficiency point is the inclusion of an induction range, which can achieve some additional energy savings but at a substantial cost.

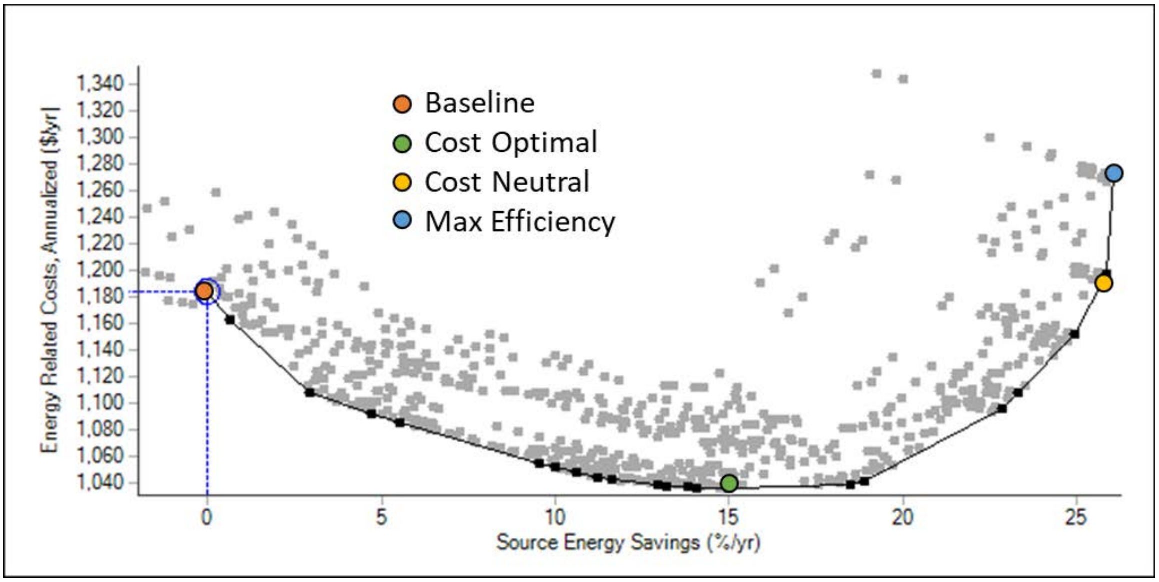

Figure 37. Cost optimization results for homes without natural gas service under RTP

A.5 All-Electric Homes With PV Under RTP

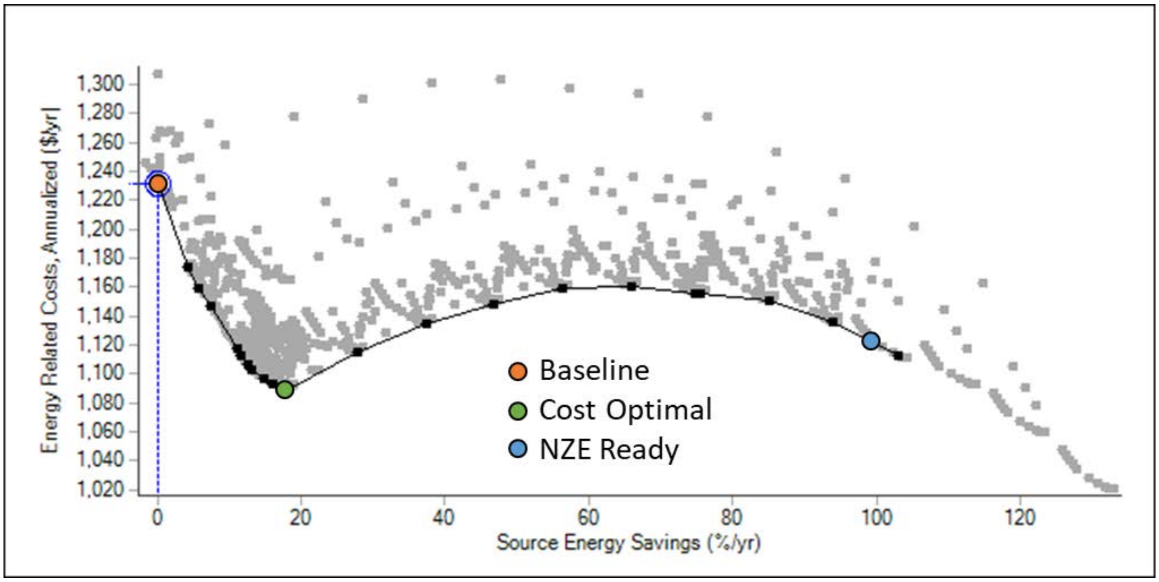

Figure 38. Cost optimization results for homes without natural gas service with PV under RTP

Results for all-electric homes with PV under the RTP are shown in Figure 38. In this case, the efficiency alone can achieve cost-effective source energy savings up to 19%. After this point, PV becomes more cost-effective than additional efficiency measures. Increasingly larger PV arrays are then installed until net zero energy is achieved. The results show a similar curve to homes with gas service and PV, where economies of scale make PV more cost-effective as the PV system gets larger, with an inflection point in the annualized energy related costs around 60% source energy savings and a PV system size of 4–5 kW.