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Building energy modeling and analysis show that zero net energy all-electric retrofits are cost effective, energy efficient, and far lower in greenhouse gas emissions.

Additional submitted attachment is included below.

Energy and Solar PV Analysis for a Model Seven-Bedroom, All-Electric Retrofit in San Leandro, California

September 21st, 2017

By

Jeff Harkness

And

Jenna Bader

Redwood Energy

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Acknowledgements

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The Redwood Energy team would also like to give a special thanks to Dan Johnson at Beyond Efficiency for generously providing hourly CAISO data on his website, which we included in our greenhouse gas emissions analysis.

Acronym Legend

AB 920 – California Assembly Bill 920

AFUE – Average Fuel Utilization Efficiency

CAISO – California Independent System Operator

CARE – California Alternative Rates for Energy

CEC – California Energy Commission

CF – Capacity Factor

CO_2e - Carbon Dioxide Equivalent

COP – Coefficient of Performance

CSE – California Simulation Engine

DC – Direct Current

DHW – Domestic Hot Water

EER – Energy Efficiency Ratio

EF – Energy Factor

EPA – Environmental Protection Agency

GHG – Greenhouse Gas

GWP – Global Warming Potential

HP – Heat Pump

HPWH – Heat Pump Water Heater

HVAC – Heating, Ventilation and Air Conditioning

kW – Kilowatt

kWh – Kilowatt Hour

LCOE – Levelized Cost of Energy

LiDAR – Light Detection and Ranging

NBP – Non-Bypassable Charges

NEEA – Northwest Energy Efficiency Alliance

NEM 2.0 – Net Metering Agreement 2.0

NREL – National Renewable Energy Laboratory

NSC – Net Surplus Compensation

PG & E – Pacific Gas and Electric

PTAC – Package Terminal Air Conditioner

PTHP – Package Terminal Heat Pump

PV – Photovoltaic

SAM – System Advisor Model

SEER – Seasonal Energy Efficiency Ratio

TOU – Time of Use

ZNE – Zero Net Energy

Abstract

This report analyzes an all-electric residential retrofit modeled at 1480 159th Avenue in San Leandro, California. The report considers comparative annual energy costs, energy use, greenhouse gas emissions, and optimal residential solar PV sizing for the model home.

The report sizes a solar PV system for the modeled project and identifies an all-electric zero net energy nameplate capacity of roughly 8-10.1 kW DC, depending on the scenario. Under the analytical assumptions, the all-electric scenarios are found to have a lower undiscounted lifecycle cost of energy, ranging from $20,900-$26,600 over a twenty-year analysis period. This represents an undiscounted cost savings of $500-$5,200 over the corresponding hybrid models over the 20 year life cycle.

The report finds that the all-electric model with a high-performance mechanical system and added insulation has roughly equal annual energy costs to a gas hybrid model with water and space heating efficiencies close to 0.6 (EF and AFUE). The all-electric models use far less energy and emit far less annual greenhouse gases, saving 2,400-4,200 pounds of CO_2 equivalent emissions annually under the analytical assumptions.

As a consequence, the ZNE all-electric models are more compliant with California's greenhouse gas emissions laws, including AB 32 and AB 375

Introduction

As California seeks to adopt zero net energy for residential buildings to achieve its climate goals, the techno-economic feasibility of zero net energy design assumes increasing importance.

On-site greenhouse gas combustion in California's buildings is a major source of the state's greenhouse gas emissions (Sierra Club et. al., 2013). One promising strategy lies in fuel switching to all-electric retrofits.

The Redwood Energy Team created four scenarios for a zero net energy retrofit in San Leandro, California called the REFUGE (Figure 1). The REFUGE is a seven-bedroom, 3,100 $ft.^2$ home which serves as transitional housing for formerly houseless men. The floorplan for the REFUGE is shown below in figure 2.

The San Leandro area is characterized by a temperate coastal climate and lies in Pacific Gas and Electric baseline territory X. By conducting comparative energy analyses, Redwood Energy shows that ZNE all-electric retrofits using a solar PV array are cheaper than gas hybrid models.

Methods

Scenarios

The Redwood Energy team created four scenarios to compare the energy costs, environmental impacts, and energy use of all electric and hybrid models for the REFUGE.

Figure 1:The REFUGE in San Leandro, California.

Each scenario compares an all-electric model with a hybrid. The model specifications of each scenario are enumerated in Table 1 below.

Scenario one compares low-performance all-electric and hybrid models. The all-electric model uses a Mitsubishi mini-split heat pump for two floor zones, seven Amana package terminal air conditioners (PTAC) for seven bedrooms, an electric range, and an 80-gallon electric resistance water heater. The hybrid model uses a gravity wall furnace, 14 SEER PTAC, a gas range, and a conventional gas water heater with an energy factor (EF) of 0.63.

The second scenario compares mid-performance specifications, and the third scenario compares high performance models. In order to understand the economic and energy use effects of added insulation, the team created scenario version 3.2, which uses the same mechanical specifications as scenario 3.1.

The all-electric model for scenario two most closely mirrors the specifications being installed on-site, with minor modifications for software modeling purposes. The model uses the Stiebel Eltron in place of the Sanden Sanco₂ water heating system installed on-site, which has a higher energy factor of 3.84.

Figure 2: Floorplan for the REFUGE in San Leandro, California.

Table 1: Model Specifications

Analysis Scenarios								
	Scenario 1 - Federal Minimum		Scenario 2 - Mid Performance		Scenario 3.1 - High Performance		Scenario 3.2 - High Performance With Added Insulation	
Category	**All Electric**	**Hybrid**	**Mid-Performance All Electric**	**Mid-Performance Hybrid**	**High Performance Electric**	**High-Performance Hybrid**	**High Performance Electric with Added Insulation**	**High-Performance Hybrid with Added Insulation**
HVAC Heating	Mitsubishi Mini-Split Heat pump	Gravity Wall Furnace, 0.60 AFUE	Mitsubishi Mini-Split Heat pump	Furnace, AFUE .90	Ductless Mini-Split Heat Pump, HSPF 13	Gas Room Furnace, 0.96 AFUE	Ductless Mini-Split Heat Pump, HSPF 13	Gas Room Furnace, 0.96 AFUE
HVAC Cooling	Amana PTAC, COP 3.413, EER 11.4	14 SEER	Amana PTAC, COP 3.413, EER 11.4	Amana PTAC, COP 3.413, EER 11.5	33 SEER	33 SEER,	33 SEER	33 SEER,
Cooking	Electric Range	Gas Range	Electric Range	Gas Range	Electric	Gas Range	Electric	Gas Range
Water Heater	Electric Resistance, 80-Gallon	Lochinvar, EF 0.63	Steibel Eltron, A.O. Smith 80-gallon PTHP, EF 3.3	A.O. Smith Tankless, .91 EF	GE 80-Gallon, NEEA-Rated 2.9 EF	0.96 Energy Factor	GE 80-Gallon, NEEA-Rated 2.9 EF	0.96 Energy Factor
Building Envelope	R-15 Wall 2x4, R-0 Floor Crawlspace, R-38 Ceiling RAD Barrier	R-15 Wall 2x4, R-0 Floor Crawlspace, R-38 Ceiling RAD Barrier	R-15 Wall 2x4, R-0 Floor Crawlspace, R-38 Ceiling RAD Barrier	R-15 Wall 2x4, R-0 Floor Crawlspace, R-38 Ceiling RAD Barrier	R-15 Wall 2x4, R-0 Floor Crawlspace, R-38 Ceiling RAD Barrier	R-15 Wall 2x4, R-0 Floor Crawlspace, R-38 Ceiling RAD Barrier	R-15 Wall 2x4 + R-5 Extension, R-38 Ceiling RAD Barrier, Raised Floor +R-4	R-15 Wall 2x4 + R-5 Extension, R-38 Ceiling RAD Barrier, Raised Floor +R-5
Compliance Margin	-14.26	-13.02	1.02	-0.52	2.49	0.51	5.76	2.85

Energy Use, Solar PV Sizing and Cost Analysis

The cost analysis uses current PG & E CARE program rates for gas and electricity. A sensitivity analysis was conducted on the gas rate forecast to account for analytical uncertainty.

In order to size a cost-efficient residential solar PV system, PG & E electricity rates were combined with territory-specific baseline quantities to conduct an energy use and cost analysis. Hourly energy use results from EnergyPro 7.1, the Redwood Energy team's modeling software, were used to analyze annual energy costs.

The calculation did not include taxes or extraneous charges. It assumes that non-energy-use charges will be comparable within an acceptable margin of error between the all-electric and the hybrid models and that no energy efficiency or zero net energy incentives are used.

The resulting energy use and cost estimates were then compared with results from the National Renewable Energy Laboratory's System Advisor Model (SAM) and PG & E's solar calculator, which uses LiDAR data and current NEM 2.0 billing rate structures to size an approximate a near 100 % ZNE system specific to annual energy use and site characteristics.

Solar PV systems were then sized using insolation data from NREL for each scenario. The annual electricity use for each scenario and 100% ZNE sizing amounts are given in the results section.

Under the CEC's NEM 2.0 rules, hybrid and all-electric models with a solar PV system sized for all-electric ZNE will result in the all-electric model being cheaper. This is because for the annual "true-up" period whereby excess credits are disbursed at wholesale rates close to $.03/kWh, the wholesale rate compensation will not be sufficient to cover gas rate charges (for this to be possible in energetic terms, gas would have to be priced below $.90/therm, whereas current PG & E gas rates are closer to $1.20/therm). Importantly, this conclusion assumes that a hybrid gas customer could not use their credits at retail rates against their gas charges. A lifecycle cost analysis was conducted in order to determine an estimated levelized cost of energy for solar production.

Greenhouse Gas Emissions Analysis

Annual emissions for each model were estimated through the use of hourly emissions factors derived from CAISO electricity production data for 2016. A descriptive data analysis of CAISO data across years was used to understand the trajectory of hourly CAISO emissions factors and infer the likely trajectory of the emissions intensity of electricity over time.

As California's solar capacity continues to grow, the middle of the day will have an increasing energy surplus to support low-carbon electrification of ZNE retrofits, especially through the strategic use of demand response and energy storage.

Results

Energy Use

Results for all three scenarios show consistently that the all-electric models use less energy. Figure 2 shows that after conversion from therms to kWh hour equivalents, the all-electric models use far less energy than the hybrid models. This is especially true in the winter months.

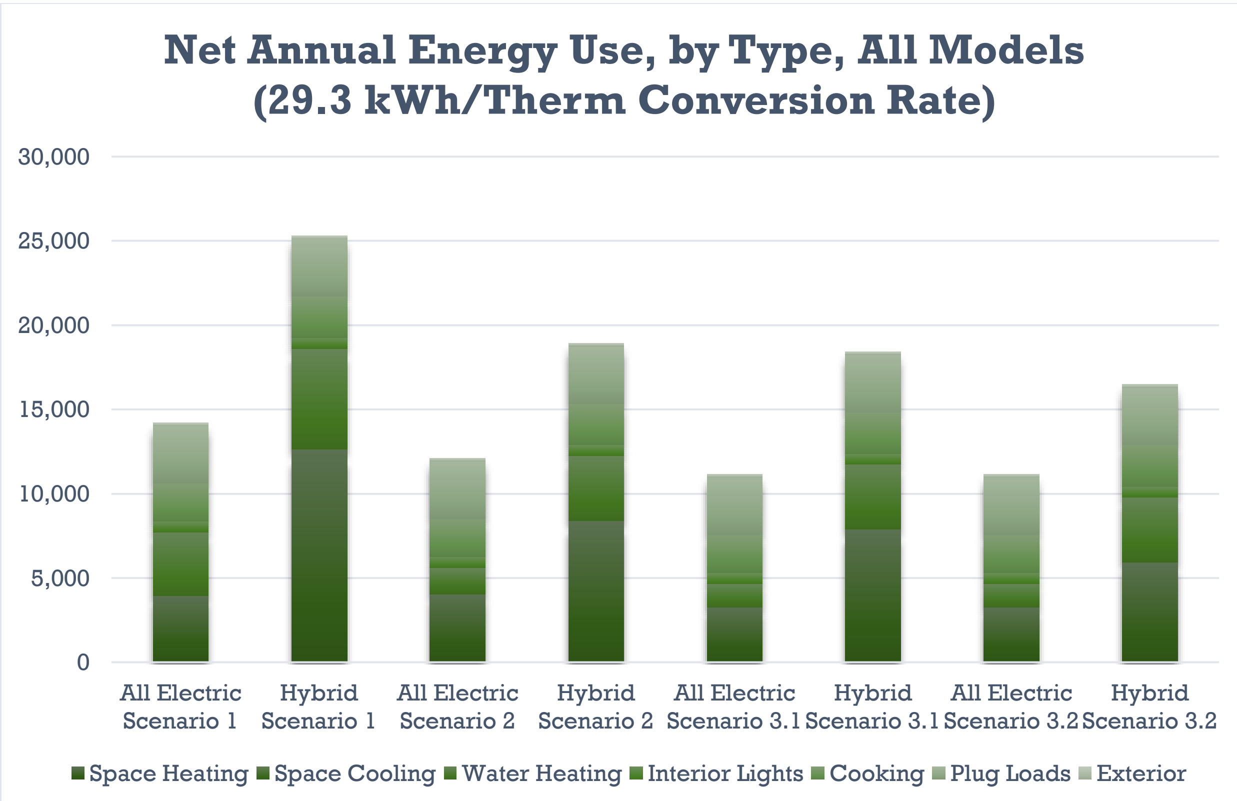


Figure 3: Comparative Net Annual Energy use.

Consequently, the overall efficiency of grid-sourced electricity, including efficiency losses from generation sources, transmission, and distribution, would have to be 67 percent for the two models to approximate each other if utility-sourced overall efficiency is included. This excludes energy losses from natural gas production, fugitive emissions and gas leaks, which lower the efficiency equilibrium point further.

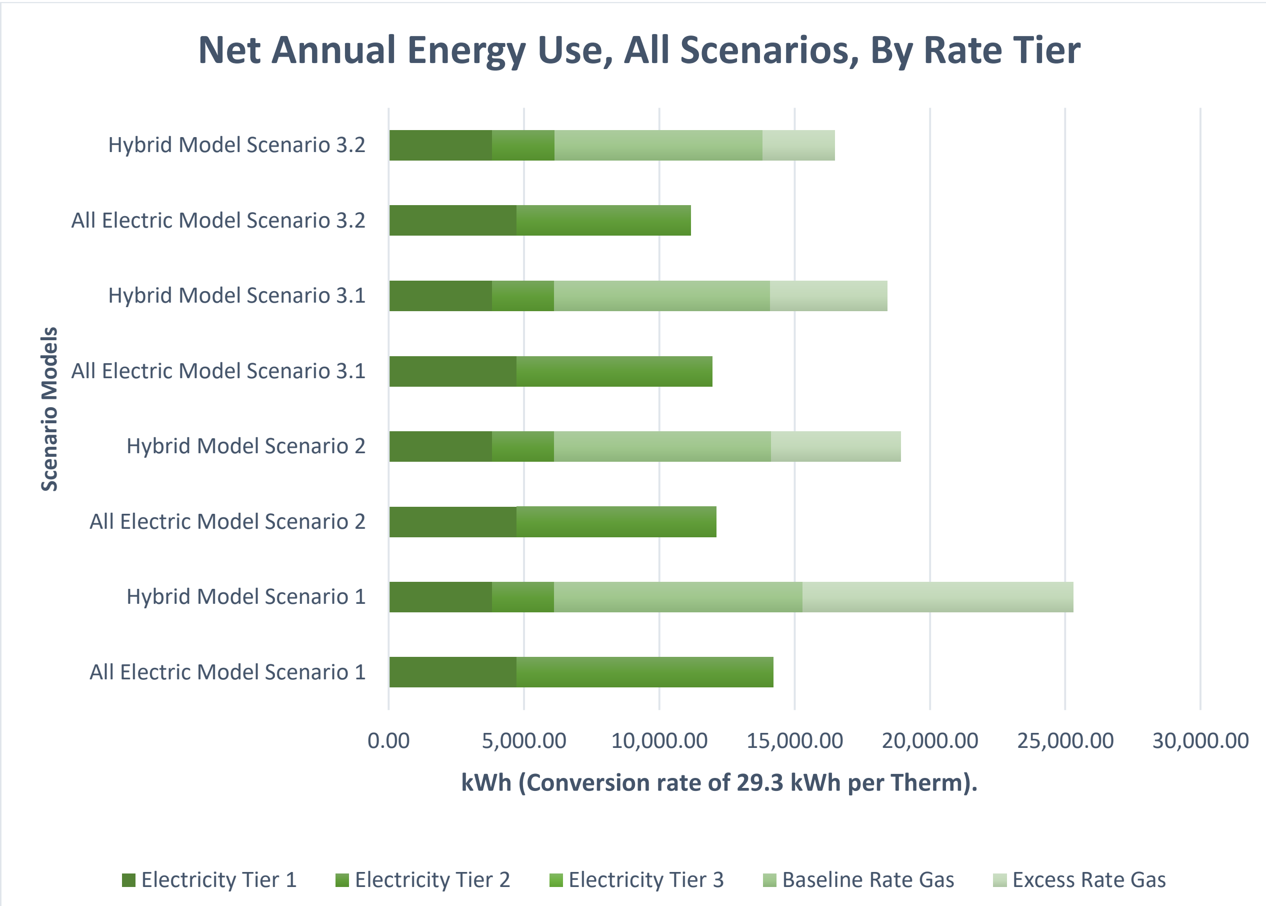


Figure 4: Annual energy use for Each scenario model, by type, using a conversion rate of 29.3 kWh per therm.

Figure 4 shows the average annual energy use for all-electric scenario 2 by use type. Space heating uses the most annual energy at 4046 kWh per year, following by plug loads (3408 kWh), cooking and appliances (2263 kWh), and water heating (1566 kWh). Interestingly, these results contradict conventional wisdom that water heating is a primary energy expense.

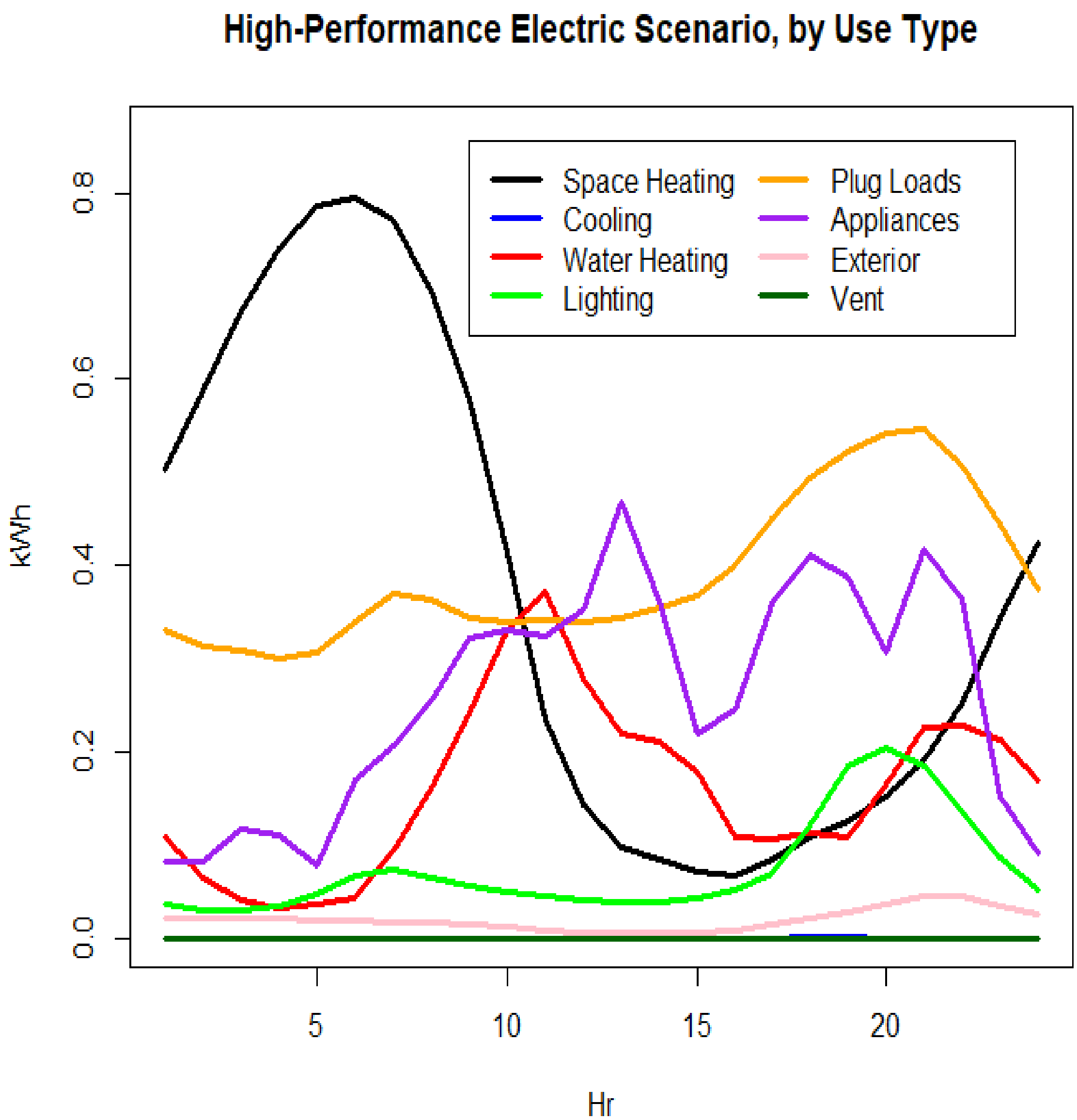


Figure 5: Scenario 3.2 all-electric average energy use, by hour of the day, by type. Contrary to conventional wisdom, higher-efficiency electric water heaters consume a lower proportion of the annual energy than other energy types.

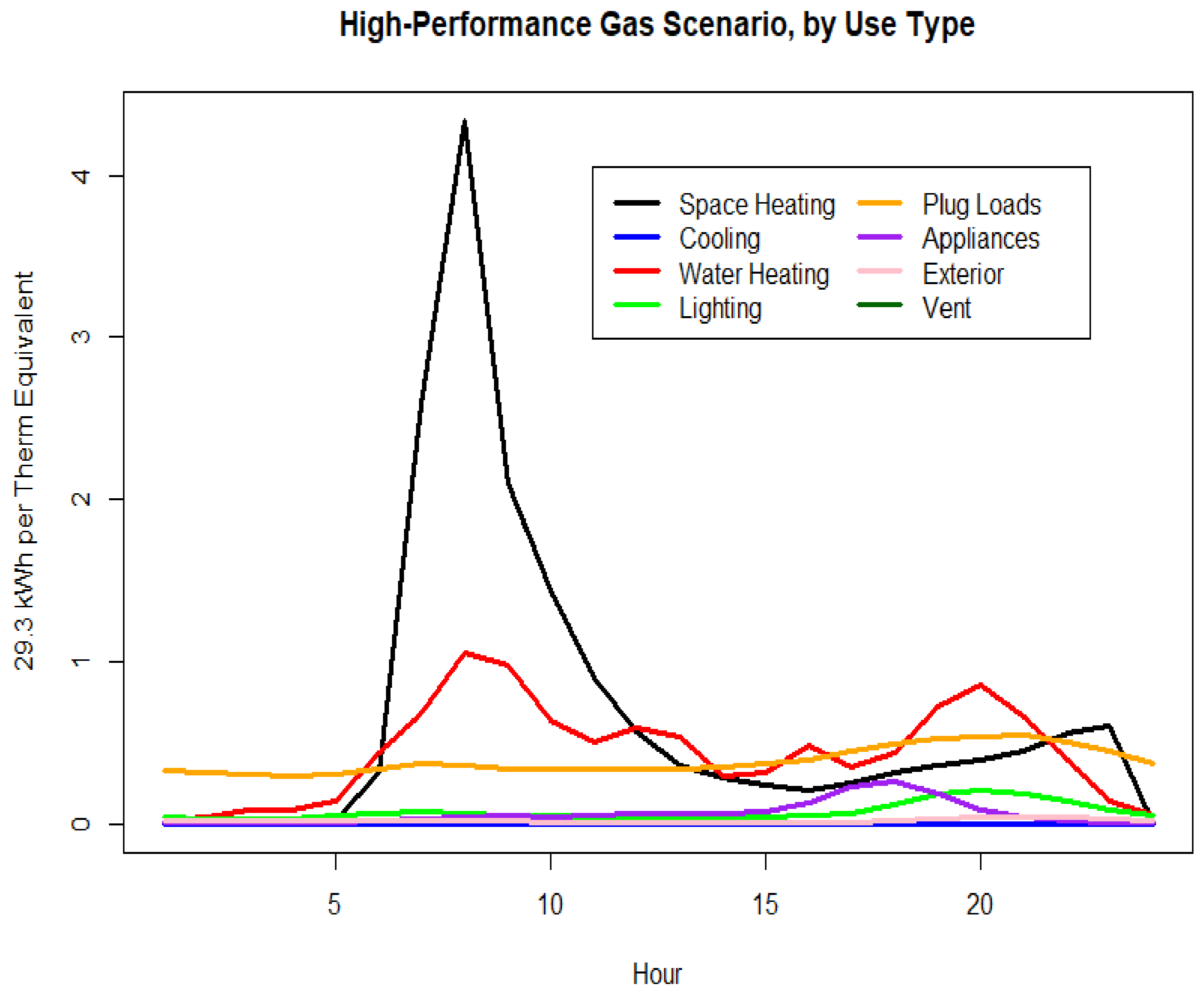


Figure 6: Scenario 3.2 gas hybrid average energy use, by hour of the day, by type (kWh).

Cost Analysis

The rate tier structure for electricity creates cost differences within the retrofit scenarios, but illustrates where annual energy cost equilibrium lies between scenarios. Figure 7 shows annual energy costs for each model, by gas and electrical rate tier.

The consistent results across scenarios illustrates that the electricity rate tier breakdown accounts for cost differences between the two models rather than comparative on-site energy use. Nearly one-third of the annual energy use occurs in tier 2, with most of this electricity used during the winter months. Every all-electric scenario exhibits a similar pattern.

As solar PV costs continue to fall, solar PV could increasingly be used to defray the costs of higher-tier electricity through demand response (DR) and planning mechanisms that arrange energy use to intersect with solar PV production. This report finds that depending on the underlying assumptions, the levelized cost of solar electricity is cheaper than current standard grid-sourced electricity rates.

Figure 6 below shows annual energy costs for each scenario. All-electric scenario 3.2 achieves energy cost parity with gas hybrid model 1 with DHW and space heating efficiencies of .63 EF and .6 AFUE, respectively. The annual energy costs of all-electric models decrease substantially as efficiency increases.

Analysis of monthly energy costs illustrates that the more efficient all-electric models closely resemble the hybrid models during the summer months, with the majority of the annual cost difference occurring in the winter. Consequently, higher efficiency of energy use in the winter months will offer the best strategy for insuring that zero net energy design is cheaper than, or cost-competitive with, a traditional gas hybrid.

	All Electric Scenario 1	Hybrid Scenario 1	All Electric Scenario 2	Hybrid Scenario 2	All Electric Scenario 3.1	Hybrid Scenario 3.1	All Electric Scenario 3.2	Hybrid Scenario 3.2
Total	2233	1719	1872	1413	1843	1387	1708	1292
Gas Excess	0	512	0	247	0	222	0	136
Gas Baseline	0	326	0	286	0	284	0	274
Electricity Tier 2	1635	396	1273	396	1245	396	1109	397
Electricity Tier 1	599	484	599	484	599	484	599	484

Model

Electricity Tier 1 Electricity Tier 2 Gas Baseline Gas Excess Total

Figure 7: Comparative annual energy costs using current PG & E residential CARE rates.

It should be noted that in real terms, the undiscounted lifecycle cost of energy for all-electric model scenarios with 100 percent solar-sourced electricity is cheaper than gas hybrid models. The figure below compares the undiscounted lifecycle cost, by scenario. However, higher cost of gas at the end of the analysis period allows for the opposite conclusion if a discount rate of three percent is used. This analysis does not include the cost of gas infrastructure, because the San Leandro house is a retrofit and it is assumed that gas infrastructure is already in place.

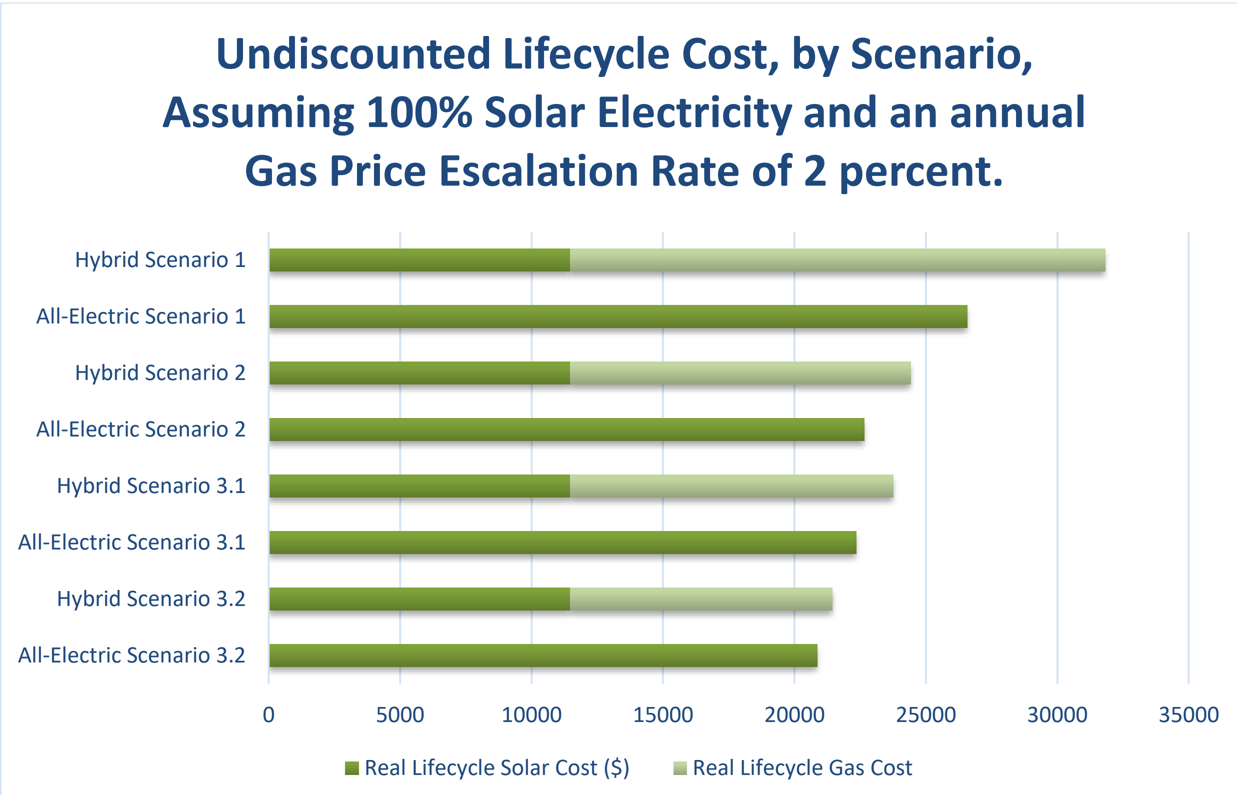


Figure 8: Undiscounted Lifecycle Cost, by Scenario, in dollars.

Solar PV Sizing Analysis

This report finds that a solar PV system of approximately 8-10.13 kilowatts DC would be required to achieve zero net energy design for the REFUGE under the assumptions and energy use the all-electric scenarios, with this capacity varying by the annual energy use of the specific scenario, solar PV system efficiency, and weather patterns. The hybrid scenarios would require a PV system of approximately 4.4 kW DC.

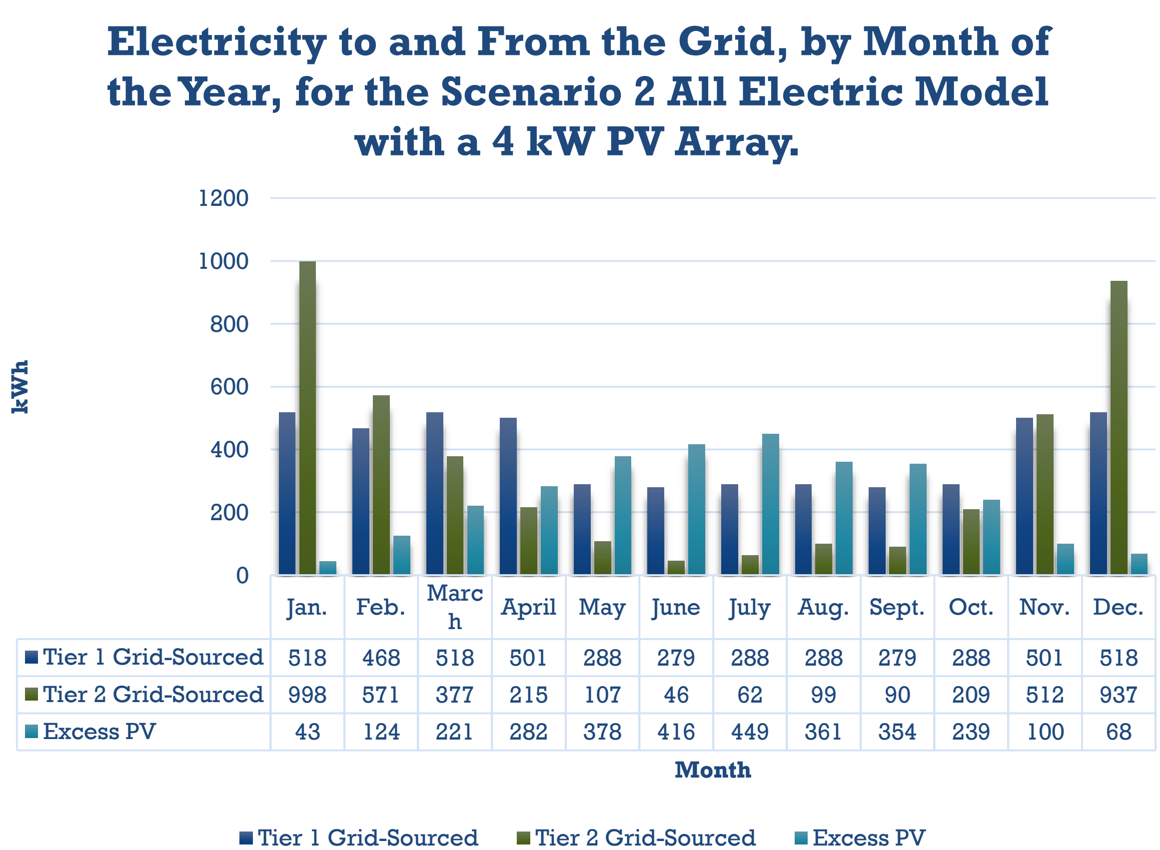
The analysis assumes an inverter efficiency of .97 and general system derate factor of 0.86.

Using a discount rate of 3 percent and average data from NREL, the LCOE for the solar PV systems was calculated to be near $.13/kWh, assuming the use of a 30 percent federal ITC and installed cost of $3.04/kW. It should be noted that solar PV prices continue to fall and installed costs per watt vary considerably across California, and so this should only be interpreted as a rough estimate to understand the cost of renewable energy in the context of all-electric ZNE fuel switching.

Table 2: Zero Net Energy All-Electric and Net-Zero Electricity PV Arrays, by Scenario

Scenario	Annual Electricity (kWh)	Average daily Consumption (kWh)	PV Array Size (kW DC)	PG & E Solar Calculator Size for near ZNE (kW DC)*
All-Electric Scenario 3.2	11159	30.57	7.96	7.7
Hybrid Scenario 3.2	6126	16.78	4.37	4.1
All-Electric Scenario 3.1	11946	32.73	8.52	8
Hybrid Scenario 3.1	6126	16.78	4.37	4.1
All-Electric Scenario 2	12110	33.18	8.64	8
Hybrid Scenario 2	6126	16.78	4.37	4.1
All-Electric Scenario 1	14206	38.92	10.13	9.1
Hybrid Scenario 1	6126	16.78	4.37	4.1

**PG & E results are not 100 percent ZNE, and are included for comparison purposes only*.



	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Tier 1 Grid-Sourced	518	468	518	501	288	279	288	288	279	288	501	518
Tier 2 Grid-Sourced	998	571	377	215	107	46	62	99	90	209	512	937
Excess PV	43	124	221	282	378	416	449	361	354	239	100	68

Figure 9: Electricity to and from the Grid, by Month, Scenario 2 (kWh).

Comparative Annual Greenhouse Gas Emissions

Using CAISO 2016 hourly emissions data as well as model results, the all-electric model for scenario 2 emitted approximately 5,150 pounds of carbon dioxide equivalent emissions, over 2,500 pounds less than the hybrid model, which emits over 7,700 pounds annually[1]. Figure 10 below shows annual totals for all scenarios.

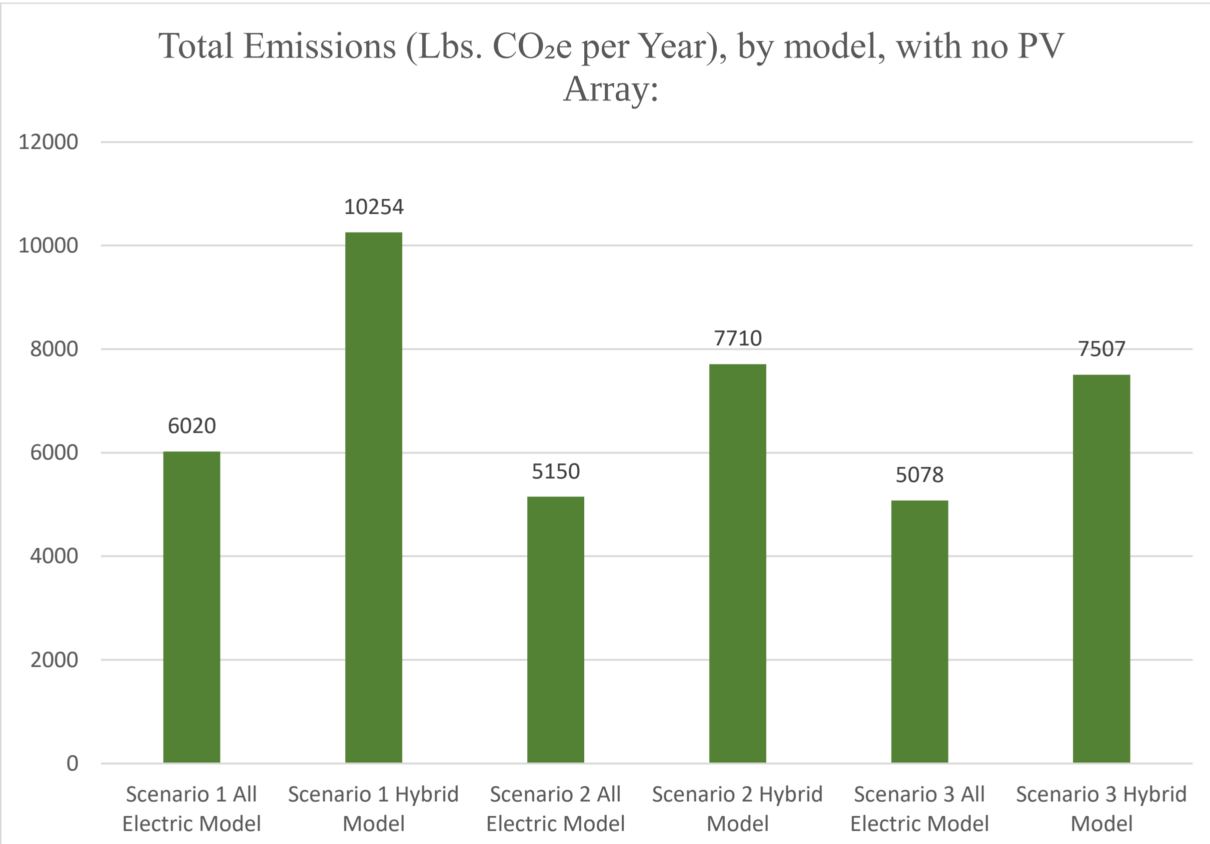


Figure 10: Annual greenhouse gas emissions.

These results reinforce consistent findings that eliminating natural gas use in residential buildings will lower carbon emissions and aid California in attaining the state's climate goals.

Figure 11 below graphs the average greenhouse gas emissions for each model, by hour of the day. The area under each curve represents the average daily greenhouse gas emissions for each model. The hybrid models all emit far higher greenhouse gas emissions, particularly in the morning hours.

[1] The Redwood Energy team would like to give a special thanks to Dan Johnson at Beyond Efficiency for sharing carefully gathered CAISO data on hourly emissions factors for California electricity.

The low-performance models have a greater difference than scenarios 2 and 3. Due to the use of an understated natural gas emissions factor and global warming potential, the conclusion of lower greenhouse gas emissions for all-electric models is robust to departures from the underlying assumptions in all 3 scenarios.

Because this report does not estimate leakage rates from natural gas leaks, the greenhouse gas emissions findings are a conservative underestimate. The likely greenhouse gas emissions savings from ZNE all-electric retrofits are substantially larger.

PG & E's emissions factor of 11.7 pounds per therm is virtually identical to the EPA's emissions factor, which uses a global warming potential of less than thirty. Given the likelihood that the global warming potential of natural gas might be as high as 80, the difference in greenhouse gas emissions could, in reality, be orders of magnitude higher than the model results. Additionally, these results are not adjusted for methane leakage rates.

The analysis uses 2016 hourly CAISO production data. A linear trend analysis was conducted on multi-year CAISO data, which were found to have a statistically significant multi-year downward trend which reflects the increasing percentage of renewable energy in CAISO's production mix. Consequently, the all-electric models can be expected to have a lower greenhouse gas emissions intensity in subsequent years.

Sensitivity Analysis and Discussion

<u>Model Assumptions</u>

Energy use and the corresponding cost analysis conclusions are dependent on a number of model assumptions and geographic characteristics. For instance, the modeling software can only accept certain parameters for the mechanical system. For this reason, the Stiebel Eltron was substituted for the Sanden water heater system in all-electric model 2. Additionally, the software assumes a specific level of use, that the specifications match real equipment performance, and other common simplifying assumptions.

<u>Solar PV Analysis</u>

The sensitivity of the solar PV sizing results to the model assumptions is notable. An all-electric energy total of over 12,000 kWh annually averages over 33 kWh per day. This represents more electricity than running a 1,000 Watt blender nonstop throughout the year, which may or may not reflect the actual energy use of a low-income household. In reality, the economics appear more forgiving than the model assumptions.

The underlying assumptions of the solar PV sizing analysis was tested using multiple calculators and SAM output. The analytical results between methods were all comparable.

The undiscounted lifecycle cost conclusions for 100 percent solar PV-sourced electricity are sensitive to the assumed escalation rate. At a one percent escalation rate, the hybrid model 3.2

has a lower undiscounted lifecycle cost by $281 over the 20-year analysis period, or approximately $24 annually.

Additionally, the calculation assumes that the annual electricity use follows the degradation rate perfectly and the residents use one percent less electricity annually, either through efficiency measures or reduced use. However, this could be addressed by sizing a slightly larger solar PV system.

Energy, Cost and Greenhouse Gas Emissions Analysis

The conclusions with regard to energy cost, use and emissions were tested through the analysis of multiple models with different input parameters.

Energy use assumptions are robust to departures from the analytical assumptions, because one therm contains close to the equivalent of 29.3 kilowatt hours of energy. Consequently, hybrid models consistently use more energy than all-electric models.

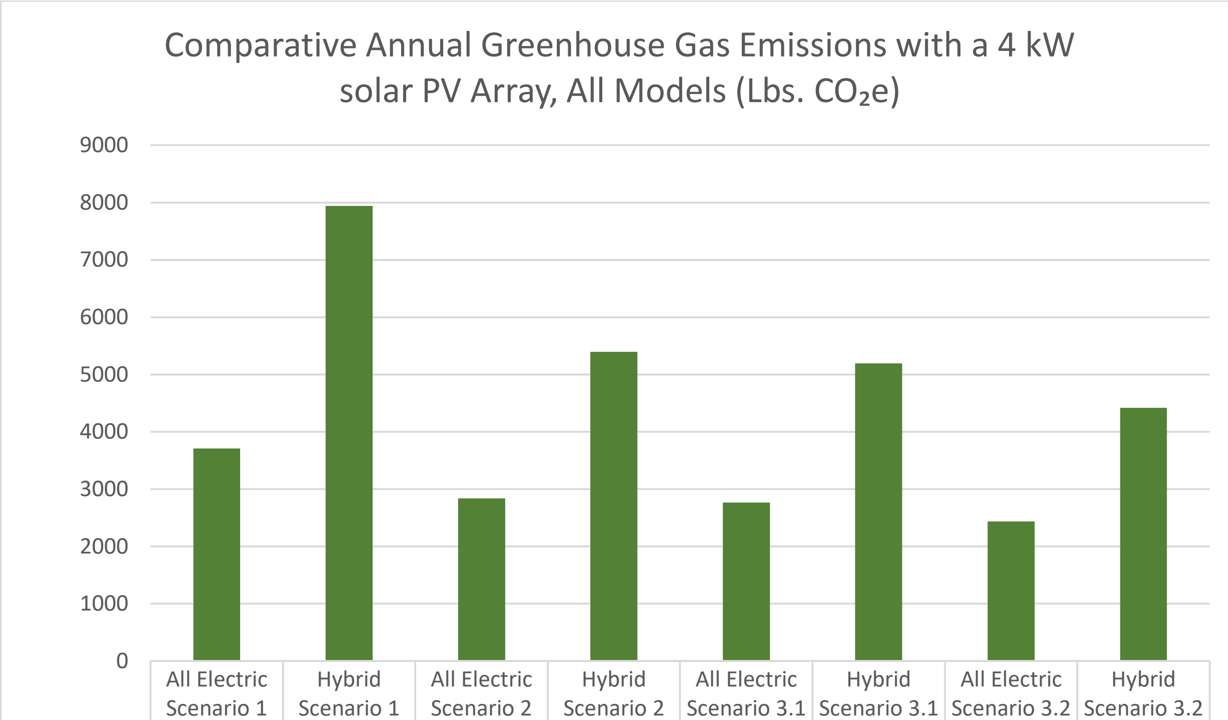
Greenhouse gas emissions assumptions, too, are robust from numerical assumptions concerning emissions factors and usage. If anything, the emissions factor of 11.7 pounds of carbon dioxide equivalent per therm is a conservative estimate of the real environmental impacts of natural gas use due to under-reported leakage rates and a very conservative global warming potential (GWP) of 23-25. A more interesting question would ask to what extent these numbers are understating the environmental benefits of fuel switching beyond the necessity of intellectual parsimony.

Energy costs are affected by the assumed electricity rates and the limitations of the modeling software. As noted previously, a different water heater with a lower energy factor was used for scenario 2, and other specifications could not be input into the software exactly. These create differences in the utility cost results. These efficiency differences could have substantial effects on the results.

On the other hand, fluctuations in the electricity rates tend to have a marginal effect on the results. Earlier models were tested using CARE and non-CARE energy rates and achieved similar annual energy cost difference results. The sensitivity analysis of the gas rate forecast shows that a decrease in gas rates of $.10/therm has no substantial effect on the annual energy cost difference.

As discussed previously, the modeling software limits the model parameters. In the case of the water heater and other inputs, the all-electric model for scenario 2 is less efficient than the real installed retrofit, which biases the means that there are likely smaller differences between annual energy costs than the model results in comparisons without solar PV. As Redwood Energy’s California Simulation Engine (CSE) team works to alter the modeling software input parameters, we hope to demonstrate that the annual energy cost differences are substantially less than the compliance software results due to the built-in derating of DHW energy factors.

Figure 14 below shows annual greenhouse gas emissions for models with a 4 kW solar PV array. The all-electric models emit substantially less greenhouse gases annually.



	All Electric Scenario 1	Hybrid Scenario 1	All Electric Scenario 2	Hybrid Scenario 2	All Electric Scenario 3.1	Hybrid Scenario 3.1	All Electric Scenario 3.2	Hybrid Scenario 3.2
Series1	3707	7941	2838	5397	2765	5195	2433	4418

Figure 11: Greenhouse gas emissions with a 4 kilowatt solar PV system

Recommendations and Conclusion

Comparison of the two models for the San Leandro home show that the all-electric model outperforms the hybrid model with respect to energy use and annual greenhouse gas emissions, and that these results appear to be robust to sensitivities and model assumptions.

It should be noted that the results are sensitive to energy calculation methods and assumptions and that a broader scope of inference should be achieved using a statistical analysis for the sake of scientific parsimony. Furthermore, the amount of energy used in the all-electric model above the seasonal baseline amounts suggest that economic results can be sensitive to climate zones, baseline territories, and other factors that could yield different results under different simulation models and assumptions.

Nonetheless, as California seeks to achieve its climate goals, the results of this analysis strongly support the economic feasibility of ZNE fuel-switching under specific efficiency assumptions, a conclusion that would only be strengthened by the inclusion of the environmental and social cost of carbon, increased use of solar, and higher mechanical and envelope efficiency.

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