Gas vs Electric: Heating System Fuel Source Implications on Low-Energy Single-Family Dwelling Sustainability Performance[1],[2]

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Abstract

With an increasing interest in sustainable infrastructure, focus has been placed on cost-effective low-energy residential buildings. However, limited research has been completed on the impact of heating fuel selection on sustainability performance when evaluating low-energy building design goals. Heating fuel type is an important factor because space and water heating accounts for a significant fraction of home energy consumption. Using data from the new BIRDS v4.0 Incremental Energy Efficiency for Residential Buildings Database, this case study observes the impacts of fuel source type on a building's sustainability performance based on comparisons of low-energy and net-zero energy residential building designs in Maryland. Results suggest that low natural gas prices provide incentives to install natural-gas fired equipment when minimizing life-cycle costs is the primary goal. Meanwhile, electric heating equipment is likely to perform better economically in reaching net-zero energy performance, but with higher environmental impacts.

Keywords: Space heating; domestic water heating; low-energy; net-zero energy: life-cycle assessment; life-cycle costing;

Published in the Journal of Building Engineering (JOBE), September 2019.

Citation: Eric O'Rear, David Webb, Joshua Kneifel, and Cheyney O'Fallon (2019), Gas vs Electric: Heating System Fuel Source Implications on Low-Energy Single-Family Dwelling Sustainability Performance, Journal of Building Engineering, DOI: https://doi.org/10.1016/j.jobe.2019.100779

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[1] Certain trade names and company products are mentioned throughout the text. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is the best available for the purpose.

1. Introduction

Increasing interest in sustainable infrastructure encourages the design of cost-effective low-energy residential buildings, and efforts to reach net-zero (ready) energy performance. The chosen definition of net-zero (e.g., site energy versus source energy) and location of the building being constructed (e.g., climate) impact the feasibility of net zero building design. However, there is limited research on the impact of heating fuel type selection on sustainability performance when evaluating low-energy buildings. Space and water heating accounts for a significant fraction of home energy consumption, and consumers often have an option between natural gas and electric heating systems. The residential sector accounts for ~21% of total U.S. energy consumption, with residential space and water heating contributing to ~40% of sector energy use (EIA 2017a).

The most important factors determining heating equipment selection include: (1) cost by fuel type and equipment, (2) climate/region, and (3) home age. Other factors, such as maintenance costs, safety issues, and personal preference, may also impact heating equipment choice. Natural gas is the most widely used fuel type and class of heating technology in the U.S. (EIA 2017b), with projections of significant increases in natural gas for heating relative to electricity (EIA 2017a). However, regional differences exist, with the Hot-Humid and Mixed-Humid climate regions being predominantly electric and equal shares electric and natural gas respectively (DOE 2015).

There are tradeoffs in using natural gas for heating. Currently, the cost of natural gas is lower than that of electricity per unit of energy and tends to have lower source emissions rates. However, natural gas systems require connecting to the local distribution system, have lower site efficiency than electric heating systems, and increase exposure risks to leaking gas and exhaust. Gas heating has been recommended for colder climates with more extreme heating loads, while electric heating is recommended in warmer climates.

Although many homeowners have the option between electric and gas-fired heating systems, there has yet to be a significant amount of research investigating some of the underlying tradeoffs of such a decision. For example, use of natural gas presently leads to fewer GHG emissions (given current electricity fuel mixes) – however, it could lead to increases in other environmental inputs. There also has been minimal research exploring how the interactions between a building's gas heating systems and its other systems differ from interactions between all-electric systems. Researchers at the National Institute of Standards and Technology (NIST) have developed a database available in an online software tool capable of addressing some of these gaps in research. The Building Industry Reporting and Design for Sustainability (BIRDS) tool evaluates the performance of U.S. buildings using whole-building sustainability metrics for energy use, life-cycle costs, and life-cycle environmental performance.

Numerous sustainability studies (Kneifel et al. 2018, Kneifel, O'Rear, and Webb 2016a, Kneifel and O'Rear 2015) have already been completed based on residential building data compiled in previous versions of BIRDS assuming electric heating equipment. Recent BIRDS updates have included natural gas heating options, allowing for much broader analyses. Using data from the BIRDS v4.0 Incremental Energy Efficiency for Residential Buildings Database in conjunction with whole-building sustainability metrics, this study evaluates alternative options for space and water heating, observing differences in the impacts alternative energy sources for heating can have on a building's overall sustainability. Although there has been some work comparing electric-driven and gas-driven heating equipment (Brenn, Soltic, and Bach 2010, Sanaye, Meybodi, and Chahartaghi 2010), there has been minimal work done making such comparisons within the context of a validated whole-building energy model of a single-family dwelling, none of which for the United States. Additionally, there is an absence of work investigating the full interaction of other building energy efficiency measures (EEMs) with changes in the heating equipment type and energy source. The findings of this paper will help to fill some of these gaps in the literature.

2. Literature Review

Three types of space and water heating equipment are considered in this study: gas furnace, electric resistance furnace, and electric heat pump for space heating, and gas fired water heater, electric resistance water heater, and heat pump water heater for water heating. The literature related to space and water heating in residential buildings will be discussed in each subsection below. Any of the heating methods considered in this study can be supplemented with a solar thermal heating element. It is rare for a water heater to rely solely on solar heating in the U.S. due to the need for faster heating during peak demand times and the impact of cloudy days on the ability to collect thermal energy (U.S. Department of Energy 2017). A discussion on why solar thermal was removed from the current analysis is presented as well.

2.1. Gas vs. electric space heating comparisons

The literature on direct comparisons of the economic and environmental efficiency of gas and electric heating is limited in part because fuel price per unit of energy is highly dependent on fuel mix and the time of consumption, efficiency of the heating system, and the climate region (EIA 2017c). Fuel mix for electricity generation varies across the U.S. and has a significant impact on environmental performance. These differences mean that studies are not necessarily transferrable, as cost and fuel efficiency will inevitably vary across geographical regions. If the electricity in a comparison is generated at a coal plant, the results may be very different environmentally and economically than if production is from a mixture of renewable energy sources and traditional fossil fuels. As such, all results relating to electricity that follow are implicitly based on the fuel mix of the region in each study.

Belsie (2012) found that, when comparing costs of heating fuel types in the EIA's Northeast region, natural gas was the cheapest, 28% lower than electricity. A similar analysis finds that the U.S. average winter expenditure (per household) for natural gas used for heating ($578) is $352 less than for electricity ($930) (EIA 2015). This is supported by Jeong, Kim, and Lee (2011) which found that natural gas has a higher utility (function of equipment price, energy price, and energy consumption given a budget constraint) when compared with electricity generation in South Korea. Gustavsson and Karlsson (2002) found that electrical heating systems could be either the most energy-efficient option or the least, depending on whether a high efficiency heat pump or an electric boiler with a resistance heater were used. Several studies focused on the U.K. and the European Union have generally found that air-source heat pumps are better than gas heating in terms of direct greenhouse gas emissions (Cabrol and Rowley 2012, Kelly and Cockroft 2011, Dorer and Weber 2009), but more costly to operate than gas heating (Kelly and Cockroft 2011). Dorer and Weber (2009) focused on micro-cogeneration, which is different than the focus of this paper, while Kelly and Cockroft (2011) and Cabrol and Rowley (2012) looked at gas condensing boilers, which are typically more efficient than forced air (non-condensing) furnaces. This result is also found by Yang, Zmeureanu, and Rivard (2008) in comparing electric and gas fired hot water systems and forced air furnaces for space heating in Quebec.

The situation in the U.S. is more complicated due to differences in fuel mix for generating electricity. Shah, Debella, and Ries (2008) found that heat pumps have higher environmental impacts in places where there is a high percentage of fuel generation from fossil fuels. From 15% to 40% of fossil fuel generation would need to be converted to renewable sources to minimize the heat pump's impact. Brenn, Soltic, and Bach (2010) performed a comparison of electric and natural gas driven heat pumps that found, in general, natural gas heat pumps were roughly equivalent to electric heat pumps powered from highly efficient natural gas combined power plants. Alternatively, if the electrical grid utilized low-CO_2 fuel sources, an electric heat pump is a better choice. Pitt et al. (2012) looked at retrofits for air-source heat pumps and gas furnaces in Blackburn, VA and found that gas heating had less CO_2 emissions. This difference in findings is due to Europe using far more nuclear (25%) and renewables (30%) than the U.S. (18% nuclear and 21% renewables), with the U.S. relying substantially more on coal in 2016 (IEA 2017). Europe sees similar variation in optimal technology by country (Martinopoulos, Papakostas, and Papadopoulos 2018) and within country (Martinopoulos, Papakostas, and Papadopoulos 2016, Abusoglu and Sedeeq 2013).

2.2. Water heating comparison

There is little direct comparison of water heating technology in the literature for the U.S., however there have been multiple studies on energy and environmental performance done in Europe. Tsilingiridis, Martinopoulos, and Kyriakis (2004) compared the lifetime environmental impact of a gas, electric, passive solar, and two types of hybrid passive solar water heaters (one using electricity and one using natural gas). Using life-cycle assessment (LCA) and a variety of system sizes, the authors found that there is a net gain in environmental performance for the hybrid system using electricity over a purely electric water heater, and a smaller net gain (reduction by a factor of 4) when natural gas is used in the hybrid system compared to an electric water heater. Tsilingiridis, Martinopoulos, and Kyriakis (2004) also found that the purely natural gas water heater outperformed the hybrid system using electricity, though only due to the electrical portion of the hybrid system being less efficient. Hong and Howarth (2016) found that natural gas had a larger negative impact on direct greenhouse gas emissions than high efficiency electric heat pumps when used for domestic water heating across both coal and natural gas produced electricity. Their findings suggest that natural gas technologies can result in higher emissions than using coal.

A study of environmental impacts beyond emissions focused on solar thermal water heating versus heat pumps and gas boilers found tradeoffs across environmental impacts. The results from Greening and Azapagic (2014) indicated that solar thermal systems are not necessarily the “cleanest” option in terms of overall environmental impact. While solar thermal outperformed electric resistance water heaters in eight of the eleven environmental categories considered, they underperformed the gas boiler in six out of the eleven. Solar water heating outperformed electric heat pump water heaters in seven of the eleven categories. Greening and Azapagic (2014) estimated that for 5 million installations of solar thermal water heating systems in the U.K., there would be a 9% reduction in global warming potential and fossil fuel usage from water heating. When looking only at direct emissions, the decrease in greenhouse gas emissions is only 1% for the domestic sector and 0.28% of all U.K. emissions while increasing the depletion of abiotic elements and toxicity-related impacts due to the manufacturing of the solar thermal collectors by 25%.

Economic comparisons between technologies are also lacking in the literature, however trade groups have done their own comparisons. Gas water heaters tend to cost less to operate and last slightly longer on average than an electric water heater and are generally less efficient on a site energy basis due to energy loss through venting of flue gases.

Although solar thermal water heaters can help reduce greenhouse gas emissions as noted previously, the bulk of literature suggests that it is not economical for the United States. A report by Clark (2012) found that solar thermal had a payback period for installation costs of roughly 30 years. This analysis is backed by findings from Croxford and Scott (2006) that suggest a short carbon payback time (no longer than 20 % of system lifetime), but a simple payback time of 100's of years for solar thermal, and 30 years for a building-integrated photovoltaic roof system if grants are included. National Renewable Energy Laboratory (NREL) found that break-even costs were not unobtainable based on available solar resources and electricity prices in some locations, however are precluded in areas with low electricity and natural gas prices (Cassard, Denholm, and Ong 2011). Solar thermal was also found to be more likely to replace some conventional electric systems as opposed to natural gas systems. This is further supported by a separate NREL report for the GSA that suggests proper siting and careful consideration can make solar thermal economically efficient in certain locations in the United States (Rockenbaugh et al. 2016). If conventional heating sources are used to supplement solar thermal, then a hybrid system can outperform traditional water heaters even in suboptimal climates (Hang, Qu, and Zhao 2012).

While solar thermal is not cost effective for most of the United States, studies in the European Union have shown that in the appropriate climate and with sufficient solar resources solar thermal can be cost competitive and provide enhanced environmental performance (Martinopoulos 2014, Martinopoulos and Tsalikis 2014, Martinopoulos 2018). An LCA by Simons and Firth (2011) found that 100% solar thermal for apartment buildings in Europe had superior performance to all other heating sources in terms of primary energy purchased and reductions in emissions, however the manufacturing processes involved can be as high as 38 times that for natural gas. Other potential environmental impacts were marginally worse for heat pumps and fossil fuel systems as a result. Solar thermal systems were found to be better overall for human health than fossil fuel systems and similar to heat pump systems. A study on performance, economic and environmental life cycle by Kalogirou (2009) found that a solar thermal system coupled with a gas or electric backup proved viable in terms of reducing greenhouse gas emissions and a realistic payback period while achieving desired performance. A cost-benefit analysis of solar thermal water heating in Greece concluded that, given Greece's solar radiation levels, solar water heating had a benefit-cost ratio (BCR) greater than one when compared to electric water heaters, however natural gas was superior in terms of BCR over solar water heating (Diakoulaki et al. 2001). Subsequent work by Martinopoulos, Papakostas, and Papadopoulos (2018) has shown that advancements in solar thermal have led it to be more cost-effective in Greece.

The data used in this paper, further discussed in Section 3, uses a fuel mix and technologies (appropriate for the selected location) that lead to inclusion of a solar thermal system being non-optimal in all cases based on the energy and economic efficiency metrics being used, and is therefore, excluded from the discussion of the current analysis. Changes in fuel mix of electricity in Maryland since the data have been generated or future developments in the installed costs of solar thermal systems may change its relative applicability.

3. Measuring Building Sustainability using BIRDS

BIRDS was developed to assist in evaluating the performance of U.S. buildings using whole-building sustainability metrics to assess the performance of the materials and energy used by a building spanning its construction, operation, and disposal. These metrics are based on applications of: (1) whole-building energy simulation modeling, (2) life-cycle costing, and (3) life-cycle impact assessment (LCIA) methods. Life-cycle costing – which serves as a metric of economic performance – is integrated with 12 environmental performance metrics to produce science-based measures of the business case for investment options in high-performance green buildings (Lippiatt et al. 2013). BIRDS metrics for whole-building environmental performance are based on a hybridized LCA approach which considers an inventory of inputs and outputs covering all phases of a building's service life. Also captured is the energy use associated with the operation of the building and any energy produced on site via renewable energy generation systems (Lippiatt et al. 2013). Environmental LCIA quantifies the potential contribution of these LCA inventory items to a range of environmental impacts categories, which are based on EPA's TRACI 2 impact categories (Bare 2011) plus two additional impact categories for land and water use.

The latest version of BIRDS, v4.0, is scheduled to be released in 2018 and includes several updates. The commercial and residential databases are condensed into a single database called "Building Energy Standards/Codes Database," while the existing low-energy residential database – now called the "Incremental Energy Efficiency for Residential Buildings Database" – has been expanded to include additional equipment/fuel type system options for household space and domestic water heating, as well as a larger PV array option (12.1 kW). The analysis conducted in this study is based on data contained in the new Incremental Energy Efficiency for Residential Buildings Database (referred to as the BIRDS Database hereafter), which allows for detailed analyses of incremental EEMs for Gaithersburg, MD.

Users have an opportunity to consider the impacts of alternative underlying assumptions: (1) study period length, (2) discount rate, (3) construction quality, (4) financing type, (5) exterior wall finish, and (6) heating fuel type. Users can select a study period length ranging from 1 year to 30 years. Two options are available for both the discount rate (3%

and 8%) and the construction quality (average and luxury). BIRDS users can factor quality into their LCC estimates by choosing either of the two options for construction quality: average and luxury. Two options are available for financing type: (1) an upfront, full cash purchase, and (2) a mortgage financing loan which assumes a 20% down payment with the remainder of the initial investment financed at 4.375%. Two options are available for exterior wall finish: brick veneer and wood siding. Like construction quality, exterior wall finish type has minimal to no impact on the changes in LCC. The final options for heating (electricity vs. natural gas) will be discussed later in this section.

Table A1 through Table A3 in the Appendix list alternative EEM options available for building envelope (i.e., wall, roof/ceiling, foundation, windows, doors) constructions. The exterior wall, basement wall and floor, and roof/ceiling constructions (Table A1) are listed in order of increasing thermal efficiency. The five window construction options (Table A2) are also increasing in energy efficiency and vary according to U-Factor and Solar Heat Gain Coefficient (SHGC). The air leakage rates (Table A3) are based on requirements of 2009 International Energy Conservation Code (IECC),[3] while Option 2 and Option 3 are based on 2015 IECC and the measured air leakage of the NZERTF, respectively.[4] Rates are expressed in terms of air changes per hour at 50 Pa (ACH_{50}) using a blower door test.

Listed in Table A-4 through Table A-7 are the updated EEM options for building systems. Lighting wattage options (Table A-4) are expressed as a fraction of total fixed lighting fixtures that use high-efficiency bulbs. These fractions are based on a "typical/baseline" lighting mix from Hendron and Engebrecht (2010), requirements defined in editions of IECC, and the NZERTF.[5] The four heating and cooling equipment options (Table A-5) cover both electric- and gas-powered space heating options as constrained by the heating fuel type selection in the analysis assumptions. Option 1 reflects a "standard efficiency" system that satisfies minimum federal efficiency and IECC requirements. There is mechanical dedicated outdoor air (OA) ventilation that meets ventilation requirements defined by ASHRAE 62.2-2010 (ASHRAE 2010a). The second option is a higher efficiency air-to-air heat pump system. Mechanical ventilation is provided using a separate, dedicated OA system with a heat recovery ventilator (HRV) to meet ASHRAE 62.2-2010. Both options include an electric heating element (0.98 efficiency) to supplement the heat pump when the primary system cannot meet the thermal loads. Option 3 is a standard efficiency split system that uses electric-based

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[3] The 2003 and 2006 IECC set no maximum limit on air leakage. The 2009 IECC limit is assumed for those editions in this study.

[4] Required conversion from air changes per hour to effective leakage area (ELA) done using formula in Chapter 16 of ASHRAE (2012). The ELA is split between the two conditioned floors based on fractional volume.

[5] Additional details on all EEM alternatives can be found in Kneifel, Lavappa et al. (2016).

cooling and natural gas for heating. Like Option 1, it provides mechanical dedicated OA ventilation. Option 4 is the higher efficiency gas-electric split system that uses a separate HRV system.

Eight DHW system options are available (Table A-6). Option 1 is an installed “standard” efficiency (Energy Factor (EF) = 0.95) electric water heater (50 gal) serving as the primary system. Option 2 is an air-to-water heat pump water heater (HPWH) with a Coefficient of Performance (COP) of 2.36 serving as the primary system. Option 3 and Option 4 are like Option 1 and Option 2, respectively, except that they both include an auxiliary two-panel, 4.6 m^2 (50 ft^2) solar thermal system. Option 5 and Option 6 swap out the electric water heaters for 50-gallon gas water heaters at EFs of 0.78 and 0.90, respectively. Option 7 and Option 8 add the auxiliary solar thermal systems to the primary gas systems in Option 5 and Option 6. The six roof-mounted solar photovoltaic (PV) system options (Table A-7) are based on the NIST NZERTF roof-mounted system (Option 5). The first four options depict the incremental removal of one-quarter capacity of the 10.2 kW system, while Option 6 depicts the addition of one-quarter capacity to 12.7 kW.

4. Research Methodology

This study explores tradeoffs in sustainability performance between residential building designs that use electric equipment to satisfy its space and domestic water heating demands, and those that rely on natural gas-powered systems. Three aspects of sustainability performance – energy, environmental, and economic performance are evaluated under a set of analysis assumptions.

4.1 Energy performance

Operating energy is based on an estimate of total net source energy use by a building’s occupants during the operational phase. The JEPlus parametric simulation tool is used to run the EnergyPlus (E+) v8.3 whole-building simulation model to compute annual household site energy use and solar PV production (DOE 2015a, Zhang and Korolija 2015).[6,7] Total net site energy use is then calculated by taking the difference, capturing any offsetting of household energy use by on-site renewable energy production. Total net source energy use is derived using a conversion multiplier to scale net site operating energy use.[8]

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[6] Site energy refers to the amount of energy shown on a utility bill. It is the final form of energy consumed by the homeowner.

[7] The weather file used for the simulations is the Typical Meteorological Year 3 (TMY3) for Gaithersburg, MD (KGAI weather station) obtained from Weather Analytics (Weather Analytics 2014).

[8] Source energy refers to the total amount of raw fuel used to power a building and maintain its daily operations. It considers all energy use, including production, transmission, and delivery losses.

Annual operating energy use is assumed constant from year-to-year with proper maintenance to simplify the analysis. This assumption does not hold true in the case of on-site solar PV production as previous research studies have observed consistent degradation of solar panels. It is assumed that there is an annual production degradation of 0.5% over the lifetime of the solar PV system (Kneifel, Webb, and O'Rear 2016). The estimates for net operating energy use over a selected study period are also used to derive net operating CO_2 emissions over the same study period.

4.2 Environmental performance

The evaluation of whole-building environmental performance in BIRDS uses LCA inventory data in conjunction with life-cycle impact assessment (LCIA) methods to quantify and link environmental impact contributions to twelve impact categories.[9] To address the complexities of a whole building, BIRDS takes a multi-layered approach to inventory analysis using a hybrid LCIA framework developed by Suh and Lippiatt (2012) that integrates top-down (Input-Output-based) and bottom-up (process-based) data in the inventory analysis LCA step (Bagley and Crawford 2015, Crawford et al. 2016, Stephan and Crawford 2016, Stephan, Jensen, and Crawford 2017, Crawford and Stephan 2013). For additional details on the LCA inventory data included in BIRDS, refer to Lippiatt et al. (2013). The environmental flows associated with a building's life-cycle stages fit into two categories: embodied (those associated with initial construction, maintenance, repair, and replacement (MRR), and disposal of building components and systems) and operating flows (those resulting from any energy consumed and produced during the building's use phase). See Kneifel et al. (2018) for descriptions on the approaches used to calculate embodied and operating environmental flows.[10,11]

Forming overall conclusions about the environmental performance of an individual building design based on LCIAs can be difficult because each of the LCIAs are measured in different units. BIRDS addresses this through a metric that combines the performance of all twelve categories into a single numeric environmental impact score (EIS) (Lippiatt et al. 2013). EISs are calculated using fixed scale normalization references based on annual contributions of U.S. economic activity to the LCIA categories (Table A8). For more information on EISs, refer to Lippiatt et al. (2013).

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[9] The twelve categories can be found in Table A8. More information on the impact categories, refer to Lippiatt et al. (2013).

[10] Building operation includes the energy consumed by the building and associated environmental flows over the study period. The energy use emissions are derived using LCA data based on the emissions rates for electricity and natural gas generation in Maryland, which treats all consumption and production (electricity only) the same temporally.

[11] Natural gas environmental flows are calculated by multiplying the source flow per unit of natural gas by the total net number of units of natural gas consumed each year in the study period and summing across all years. The sum of the flows for electricity and natural gas gives the total operational energy-related flows.

4.3 Economic performance

BIRDS uses a life-cycle cost (LCC) methodology to evaluate the cost-effectiveness of buildings (Fuller and Petersen 1996, ASTM 2012b). Life-cycle costing accounts for the discounted present value of all costs related to the construction, operating, maintenance, repairs, replacements, and disposing or resale (i.e. residual value) of a building for a given study period. In the case of comparing a baseline building design to a series of alternative designs, such as in BIRDS, the design alternative with the lowest LCC is the most cost-effective (Kneifel et al. 2018). The difference in LCCs (i.e., Net Savings) between a specified baseline design and an alternative that may install different building technologies (e.g., alternative heating system) reveals the additional costs (or savings) incurred by the homeowner. A positive net savings (NS) implies that the design alternative is more cost-effective than the baseline for the given study period. The general formula for calculating the LCCs of a building is:

$$LCC = C + O + MRR - RV$$

The LCC estimates use data from a combination of sources. Initial construction costs (C) include all costs of constructing the building, which is estimated using RS Means (2017) to estimate the typical construction costs for a simple family dwelling of the building plus the additional incremental costs of upgrading the design with each implemented EEM from Faithful and Gould (2012), Kneifel and O'Rear (2016b), and local contractor quotes (depending on the EEM). Maintenance, repair, and replacement rates and costs (MRR) are obtained from Census (2011), Faithful and Gould (2012), National Association of Home Builders (NAHB) Research Center (2007), and ENERGY STAR (2011). Maintenance, repair, and replacement costs and associated residual values (RV) are calculated separately for each building component that is replaced at different rates than the building structure (e.g. windows and equipment). Operational costs (O) include the energy costs and are the estimated combination of electricity and natural gas costs over the assumed study period. Operational energy costs are based on the standard residential rate schedule for electricity in Montgomery County, MD (PEPCO 2018) and annual average residential cost data for Maryland (EIA 2017d). Energy price escalation rates are based on Lavappa, Kneifel, and O'Rear (2017). All residual values are calculated using a linear depreciation method as defined in ASTM (2012a). More information on the above cost data and life-cycle cost approach can be found in Kneifel, O'Rear et al. (2018).

4.4 Building Component Options and Analysis Assumptions

This analysis compares the performance of a designated baseline building design constructed according to 2015 IECC (Maryland code-compliant or MCC design), to alternative building design options included in the BIRDS Database.

Each alternative has its own EEM combination, which may be more (or less) efficient than the baseline. Table 4-1 lists the building envelope and system specifications (excluding HVAC and DHW systems) for the baseline design.

Table 4-1 Maryland Code-Compliant Home Design Specifications

Category	Specifications	MCC
Windows	U-Factor and SHGC	1.99 W/m^2-K and 0.40
Framing and Insulation	Framing Exterior Wall (*finish: wood siding*) Basement Wall and Floor Roof/Ceiling Assembly	5.1 cm x 10.2 cm – 40.6 cm OC R_{SI}-3.5 or R_{SI}-2.3+0.9† R_{SI}-1.8† and R_{SI}-0† Ceiling: R_{SI}-8.6
Air Change Rate	Air Change Rate – Blower Door Test Effective Leakage Area (1st Floor; 2nd Floor)	3.00 ACH$_{50}$ 403.6 cm^2; 368.1 cm^2
Lighting	Efficient Lighting (%)	75% efficient built-in fixtures

† Interior Wall Cavity + Exterior Continuous Insulation

Given that the BIRDS Database includes designs that have either electric- or natural-gas powered space heating and DHW heating systems, two types of baseline MCC designs are considered: (1) all-electric MCC design (**MCC-E**) and (2) MCC design with natural gas-powered space heating and DHW systems (**MCC-NG**). Table 4-2 lists HVAC and DHW specifications for **MCC-E** and **MCC-NG**.

Table 4-2 HVAC and DHW Specifications for Alternative Baseline Designs

Category	Specifications	MCC-E	MCC-NG
HVAC	Heating/Cooling*	Air-to-air heat pump (SEER 13.0/HSPF 7.7)	Gas-electric split A/C system (SEER 13.0/80% AFUE)
DHW	Water Heater	189 L electric (EF = 0.95)	189 L gas (EF = 0.78)

* Minimum outdoor air requirements are based on ASHRAE 62.2-2010 (0.04 m3/s)
SEER = seasonal energy efficiency ratio; HSPF = heating seasonal performance factor; AFUE = annual fuel utilization efficiency

The alternative low and net-zero energy designs for comparison are selected based on their relative energy and economic performance under the assumptions of a 3% discount rate, 80% mortgage loan financing (20% down payment), average construction quality, 30-year study period, and wood siding exterior wall finish. Currently, the BIRDS Database does not account for financial incentives, but for this analysis the Federal Solar Investment Tax Credit (Congress 2015) is included because it's a significant factor in the economics of solar PV systems.

5. Results/Discussion

This study compares two Maryland code-compliant designs – electric-heated and gas-heated – using the sustainability performance metrics (energy, economic, and environmental performance) mentioned earlier. Analysis is extended to consider additional designs, many of which are low-energy or net-zero energy, to evaluate impacts of increasing energy efficiency in residential building codes in Maryland or other locations in the Mixed-Humid Climate Zone.

5.1 Electric vs. Natural Gas Heating

Sustainability performance results for the MCC-E and MCC-NG building designs are compared to identify co-benefits and tradeoffs in energy, economic, and environmental performance between fuel types. The results in Table 5-1 indicate that electric space and DHW equipment leads to higher construction costs (+$1,200), energy costs (+$7,940), and total LCC (+$9,715). Differences in construction costs are driven by the inclusion of a higher cost air-to-air heat pump, while the higher energy costs are driven by the comparatively higher cost per unit of energy for electricity. The MCC-NG design results in higher net site energy consumption (1,555,028 kWh) as the use of natural gas more than offsets reduced electricity consumption relative to the MCC-E design. Even with greater site energy use, the cost difference of natural gas versus electricity ($0.115/kWh-eq) leads to LCC savings for MCC-NG relative to MCC-E.[12]

Table 5-1 Sustainability Performance Results for the MCC-E and MCC-NG Building Designs

	Units	MCC-E	MCC-NG
Construction Costs	U.S.$ (2017)	364,292	363,092
Energy Costs	U.S.$ (2017)	80,570	72,630
Total LCC	U.S.$ (2017)	358,806	349,091
Total Electricity Consumption	kWh	706,646	301,226
Total Natural Gas Consumption	kWh	0	1,253,802
EIS (BEES and EPA Advisory Board)	n/a	15.30 and 13.86	9.92 and 9.19

To assess differences in how the two systems meet thermal comfort requirements, this analysis utilizes a thermal comfort metric based on ASHRAE Standard 55 that estimates the number of hours for which indoor conditions do not meet thermal comfort requirements of a building's occupants (ASHRAE 2010b), labeled "total hours uncomfortable."[13] For additional information on thermal comfort in BIRDS, refer to Kneifel et al. (2017). With 622 total hours uncomfortable annually, and roughly four times greater than that of the MCC-NG design (152 hours annually), the MCC-E design is "less comfortable," which is driven by the sizing of the heating equipment. E+ sizes an HVAC system by calculating capacities to meet the load for each HVAC system's heating and cooling components. The heating equipment in the MCC-E design is sized to 9933 W with a 5000 W electric resistance back-up element while the split AC system in the MCC-NG design includes a 29 667 W gas furnace. As the capacity of the gas furnace is about twice the size of the combination of the heat pump and electric back-up element, the MCC-NG can stabilize indoor temperatures more consistently than the all-electric alternative, leading to fewer total hours uncomfortable.

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[12] Assumed electricity price is ~$0.154/kWh. Assumed natural gas cost is ~$0.41/$m^3$ or $0.04/kWh (conversion factor of 10 350 kWh/m^3).

[13] Total hours uncomfortable computed by the E+ Building Energy Simulation Software refers to the total number of hours in a year that indoor building temperatures are outside pre-defined setpoint temperature levels

The BEES and SAB EISs suggest that the MCC-NG is more environmentally-friendly than the MCC-E design with EIS values of 9.92 and 9.19 versus 15.3 and 13.9, respectively. Figure 5-1 compares the MCC-NG design results for each of the environmental impact categories relative to the MCC-E design as a baseline (normalize each impact category value to 1.0). Using natural gas-fired heating systems reduces all but three impact categories (i.e., land use, water consumption, and ozone depletion). Despite greater energy use over the 30 years, improvements in the environmental performance by the MCC-NG design – in particular, in the categories of Primary Energy Use, Global Climate Change Potential, and Smog Formation – are largely driven by differences in: (1) site energy consumption and (2) emissions rates for the two fuels. Although total on-site energy consumption is ~2.2 times greater for the MCC-NG design, the assumed source CO_2 eq./kWh emissions rate for electricity in Maryland (0.65 kg CO_2 eq./kWh) is ~2.7 times higher than that of the assumed source emissions rate for natural gas (~0.24 kg CO_2 eq./kWh). This result is driven by the significant share of coal used for electricity generation in Maryland (> 50 %) in combination with transmission/distribution losses.[14] Lower overall source energy flows for the MCC-NG design, combined with the considerable difference in emissions rates for electricity and natural gas, bring about improvements in the environmental impact categories.[15]

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[14] U.S. Environmental Protection Agency (2008)

[15] The 2016 release of eGRID shows a shift away from coal towards more natural gas and nuclear generation in Maryland, which would lead to a reduction in source emissions rates for electricity in the analysis. Future research should evaluate how the shift impacts the results of this study.

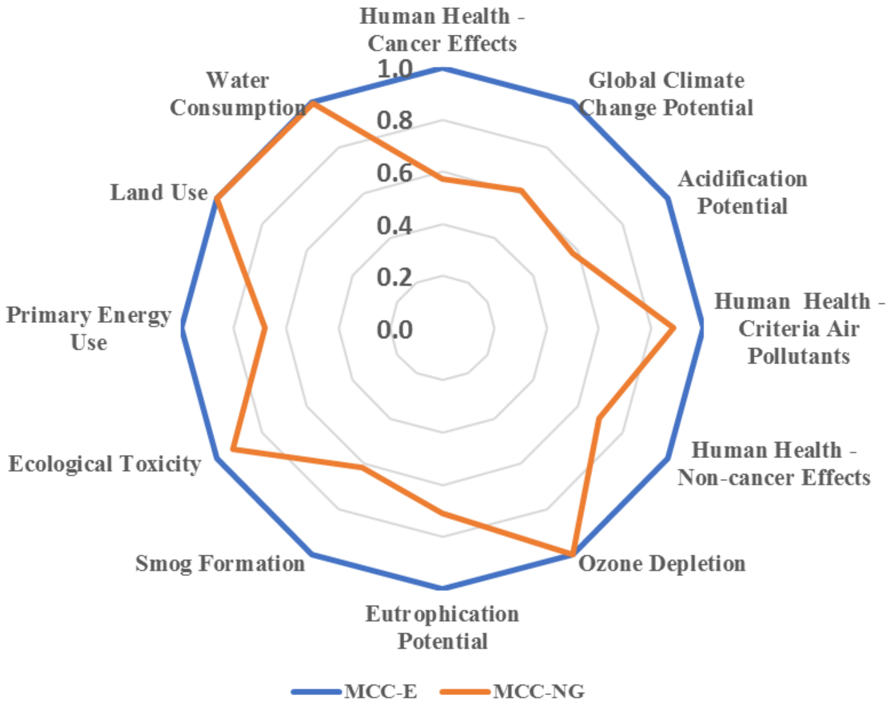

Figure 5-1 MCC-E vs. MCC-NG Designs (fractional performance relative to MCC-E)

5.2 All-electric designs in the BIRDS Database

The results discussed in this section are based on an analysis of all the building designs in the BIRDS Database adopting fully-electric space and water heating equipment (including the **MCC-E** design). Figure 5-2 displays energy and economic results based on the assumptions in Section 4.4 for 240 000 designs, each with a unique combination of EEMs with an assumed location of Gaithersburg, MD and identical usage patterns. Each data point includes either Option 1 or Option 2 for space heating (Table A5), as well as one of the first four options for domestic water heating (Table A6). The horizontal axis is the fractional reduction in total energy use relative to the code-compliant design (MCC-E), while the vertical axis is the change in LCC relative to the MCC-E design. All data points located on or to the right of the NZ-boundary line (blue) are building designs that perform at net-zero (site production equals or exceeds site consumption) or better over the 30-year study period.

Two main points can be drawn from the results: (1) fractional reductions in net energy consumption and changes in LCC are negatively correlated up to net-zero energy performance and (2) fractional reductions in net energy consumption and changes in LCC are positively correlated for designs that are net producers of electricity. The pivot at net-zero performance is driven by a discontinuity within the net metering structure in Maryland. Homeowners are reimbursed the retail price of electricity including all charges, fees, and taxes (15.4¢/kWh) for any electricity generation that offsets their consumption while excess generation is reimbursed only the generation charge (6.7¢/kWh). Consequently, additional reductions in net electricity consumption are uneconomical. We identify a group of designs that satisfy optimality conditions that will be elaborated on later: (1) electric-heated code-compliant design (**MCC-E**), (2) lowest cost design (**LCC-E**), and (3) design performing at net-zero or better at least cost (**NZLCC-E**).

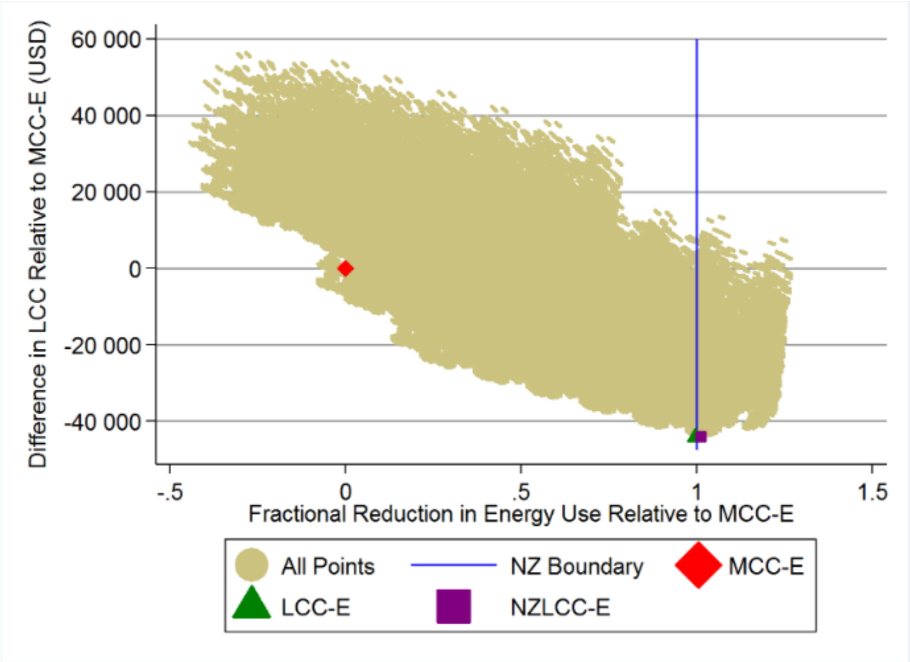

Figure 5-2 All-Electric Designs

Figure 5-3 illustrates the LCC optimization curves for each level of net site energy reduction for alternative configurations of the household HVAC and DHW systems. Figure 5-3(a) is based on six different configurations for the HVAC system, ventilation method, and air leakage rates. The first three configurations (Setup 1 through Setup 3) include a standard efficiency (SEER 13/HSPF 7.7) air-to-air heat pump, while the remaining three configurations (Setup 4 through Setup 6) include a high efficiency (SEER 15.8/HSPF 9.05) heat pump with separate HRV system. Findings suggest that designs performing at net-zero or better at least cost must be constructed for minimal air leakage (0.63 ACH). Although heat pump efficiency contributes to net energy use reductions, lower air leakage rates prove to be a bigger driver behind the declines in energy use.

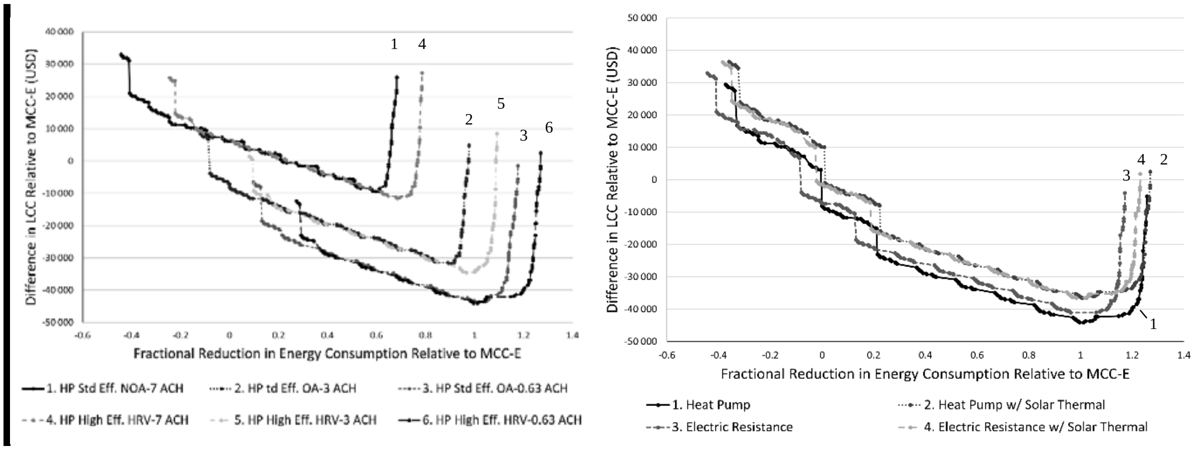

Figure 5-3 Optimization Curves for All-Electric Designs based on (a) HVAC System and (b) DHW System

Net-zero energy performance is achievable with all DHW system configurations (Figure 5-3(b)). The least costly reductions in energy use are achieved with the use of a HPWH (Setup 1), while designs pairing the HPWH with an auxiliary two-panel solar thermal system (Setup 2) achieve similar cutbacks in energy use but at a much greater cost to the homeowner given the additional cost of the solar thermal system. A similar dynamic is observed with designs using a typical electric resistance water heater with and without the additional solar thermal system.

Figure 5-4 displays the variation in solar PV system capacities across all building designs. Two major inferences can be drawn: (1) rooftop solar PV is a necessary EEM for low-energy or net-zero (or better) energy performance, and (2) system capacities must be at least 10.2 kW to reach net-zero. For medium to large capacities, the rooftop PV system will be the most expensive EEM in upfront costs for any given combination of EEMs. However, significant offsets in annual energy costs lead to declining LCCs, with the change in LCCs falling as the system capacities increase.

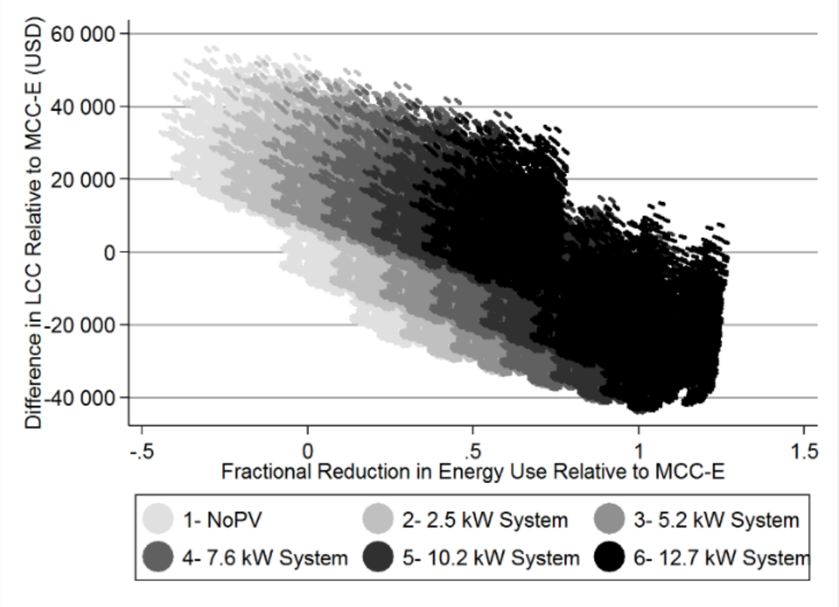

Figure 5-4 All-Electric Designs based on Solar PV System Capacities

5.3 Natural gas designs in the BIRDS Database

The results discussed in this section are based on an analysis of building designs using gas-fired HVAC and DHW equipment. Four key building designs are identified and will be discussed later: (1) gas-heated, code-compliant design (**MCC-NG**), (2) lowest cost design (**LCC-NG**), (3) net-zero energy design at least cost (**NZLCC-NG**) and (4) net-zero site electricity design at least cost (**LNZE-NG**).

Figure 5-5(a) displays the relative performance of each building design with the fractional reduction in total source energy use relative to the MCC-NG the horizontal axis and the difference in LCC relative to the MCC-NG design on the vertical axis. Both the LCC-NG and LNZE-NG designs are the same. When compared to Figure 5-2, the distribution is similar, but with the cost-optimal design occurring at ~77% reduction in site energy consumption instead of ~101% with fewer net-zero building designs. In fact, only the NZLCC-NG design is located beyond the NZ-Boundary (blue). This is a result of three factors: (1) higher initial total site energy use by the MCC-NG design, (2) smaller potential savings from heating equipment, and (3) net metering structure. Fewer designs can reach net-zero energy performance because greater reductions in energy use are required while the efficiency improvements in heating equipment are smaller for natural-gas fired equipment relative to electric equipment. For example, the EF of the gas water heater increases from 0.78 to 0.90 versus the increase in efficiency/COP from 0.95 for the electric water heater to 2.33 for the HPWH. Figure 5-5(b) shows the change in LCC relative to net electricity consumption. The LCC-optimal design (LCC-NG) is located just beyond net-zero electricity consumption.

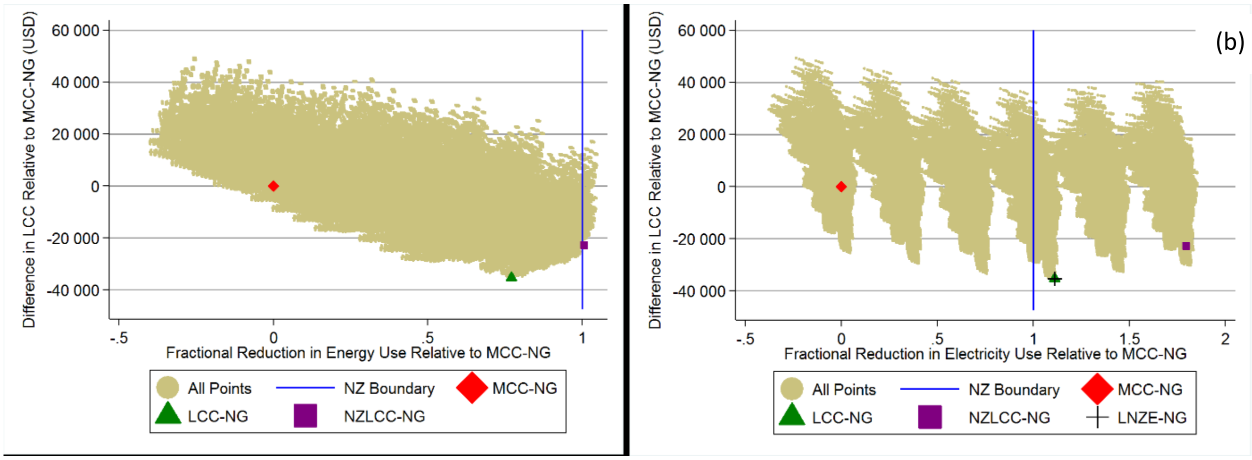

Figure 5-5 Gas-heated Designs based on Fractional Reduction in (a) Total Energy Use and (b) Electricity Use

Figure 5-6(a) illustrates the LCC optimization curves for each level of net site energy reduction for six alternative configurations for the HVAC system, varying based on the efficiency of the split ac system, method of outdoor ventilation, and air leakage rate. The first three setups include the standard efficiency gas-electric split AC system (SEER 13/80% AFUE), while the remaining three include the higher efficiency split system (SEER 16/96% AFUE). Like the analysis of the design cases, low air leakage rates (0.63 ACH) when paired with a high-efficiency split AC and HRV system (Setup 6), are the primary drivers behind the reductions in net energy use for all designs performing at net-zero energy or better. Large reductions in net energy use are attainable with a high efficiency split system (Setup 4 and Setup 5) – however, similar, less costly reductions can be attained when the standard efficiency system is paired with a leakage rate of 0.63 ACH (Setup 3). Figure 5-6(b) shows that only two of the four possible configurations for the DHW system lead to this design being a net-zero energy building: Setup 3 and Setup 4. Both configurations include a high efficiency gas-fired water heater. The addition of the solar thermal system produces marginally greater reductions in net energy use at a greater cost to the homeowner due to additional equipment costs.

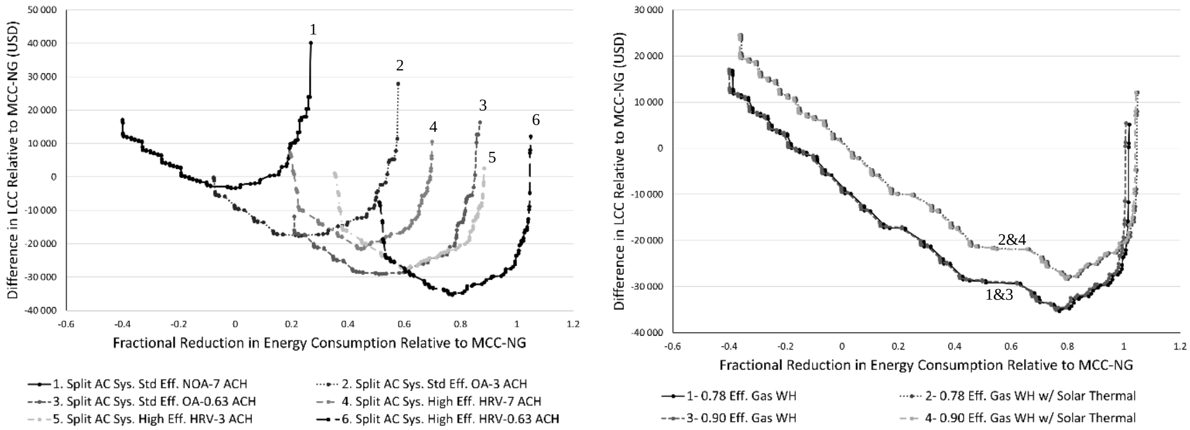

Figure 5-6 Optimization Curves for Gas-heated Designs based on (a) HVAC System and (b) DHW System

Inclusion of rooftop solar PV (not pictured) is also a necessary feature to reach net-zero energy performance when gas-fired heating equipment is installed. Only building designs with a 12.7 kW rooftop PV system can achieve net-zero energy performance because of the higher initial energy consumption of the MCC-NG design.

5.4 Cross-comparisons of selected building designs

This section discusses differences between key electric and heating system options based on combinations of EEMs, energy, and economic performance. Again, all key designs were chosen under assumptions of a 3 % discount rate, average construction quality, financed mortgage, and 30-year study period.

Table A-9 describes the design characteristics of the four key building designs. The energy and economic performance of these designs are shown in total values and relative to two baselines (MCC-E and MCC-NG). Note that it was previously reported that the MCC-E design has lower total site energy consumption but higher LCC relative to the MCC-NG design. To allow for comparability purposes to previous results, the analysis will focus on results relative to the MCC-E design regardless of heating fuel source. There are some consistent EEM selections regardless of heating fuel source. Energy savings realized by all four designs suggest use of higher efficiency lighting and HVAC and DHW equipment and lower building envelope air leakage can lower annual energy use. Across these designs, the solar PV system is sized to meet electricity consumption regardless of the heating fuel source selected.

Relative to results found in Kneifel, O'Rear et al. (2018), the optimal all-electric building designs implement different EEMs. Both LCC-optimal design (LCC-E) and lowest cost net-zero design (NZLCC-E) use less efficient windows and lower R-value wall assemblies while installing a more efficient HVAC system. These differences have been driven by the use of newer construction cost data, showing how the optimal design options can change over time as location-specific costs change. Additionally, there are likely building designs implementing different EEMs that are near optimal that would be reasonable design options.

The LCC-E design realizes greater energy savings (99.7% versus 50%), but less LCC savings ($44,103 versus $45,040) relative to the LCC-NG design. These results are driven by two factors. First, the value of a larger solar PV system is driven by the marginal value of electricity. Gas-fired heating equipment decreases electricity consumption, leading to a smaller installed solar PV system (7.6 kW) needed to reach net-zero electricity consumption but offsetting minimal amounts of energy use from natural gas consumption. Since LCC-E uses only electricity, the marginal value of reducing energy remains the same up to the point of reaching net-zero energy performance, resulting in a larger (10.2 kW) system selection. Second, the LCC-NG design leads to lower costs than the LCC-E design because the marginal cost of a unit of energy from natural gas consumption is lower than a unit of energy from electricity. The combination of lower energy costs with lower costs of construction (smaller solar PV system) lead to lower LCC for the homeowner. Given these results, there is a financial incentive to use natural gas for heating instead of electricity while natural gas prices will remain significantly cheaper than electricity on a per unit of energy basis in Maryland.

From the perspective of reaching net-zero site energy performance, electric heating equipment is preferable to natural gas heating equipment. The NZLCC-E design is the same as the LCC-E design, which nearly reaches net-zero at 99.6% energy reductions, except for the selection of a higher thermal performance roof assembly to exceed net-zero (~101%). As a result, the LCC savings are nearly identical. The NZLCC-NG design is more expensive to construct and has higher LCC by $11,489. To reach net-zero using gas-fired heating equipment requires additional EEMs, including higher thermal performance windows and wall assemblies. Even with the improved thermal performance of the building envelope, the NZLCC-NG design consumes an additional 104,575 kWh-eq. than the NZLCC-E design. Therefore, a larger solar PV system (12.7 kWh) is required to reach total net site energy consumption comparable to that of the NZLCC-E design.

The difference in total hours uncomfortable across the two LCC designs is negligible, suggesting that the LCC-E design is equally as comfortable as the LCC-NG design. Total hours uncomfortable measures for the NZLCC-E and NZLCC-NG designs are consistent with estimates for the MCC-E and MCC-NG designs, where the gas-heated building design proves to be the more comfortable of the two (difference of 117 hours/year). This difference is driven by additional insulation installed in the exterior wall cavity, lower U-factor windows, and larger sized space heating unit of the NZLCC-NG design.

With BEES- and SAB-weighted EISs of 6.19 and 5.96, respectively, the LCC-NG design appears to have lower environmental impacts than the LCC-E design, which has a BEES-weighted EIS of 7.14 and a SAB-weighted EIS of 6.84. A more in-depth comparison across the 12 impact categories reveals that the LCC-NG designs lower the environmental impact in 9 impact categories and equal impacts in 3 categories (Land, Water, and Ozone Depletion) relative to the LCC-E design. Reduced impacts are largely driven by the difference in energy use between the two designs, as well as differences in the types and/or capacities of the building equipment. For example, use of a smaller 7.6 kW PV system in the LCC-NG design has less of an environmental impact than the 10.2 kW system adopted by the LCC-E design. Similarly, the NZLCC-NG design is the more environmentally-friendly of the two net-zero designs with BEES- and SAB-weighted scores of 7.00 and 6.72, respectively – outperforming the NZLCC-E design in 7 out of 12 impact categories (i.e., Cancer Effects, Global Climate Change Potential, Acidification Potential, Criteria Air Pollutants, Non-cancer Effects, Smog Formation, and Primary Energy Use).[16] Again, these differences are largely driven by the differences in the types and/or capacities of the building equipment (e.g. solar PV system).

6. Conclusion, Implications, and Future Research

This paper uses data from the BIRDS Database with whole-building sustainability metrics to conduct a case study examining the impacts of alternative electric and gas-fired heating systems on the sustainability performance of a single-family dwelling located in Maryland under an assumed usage by a four-person family. Results suggest that low natural gas prices provide incentives to install natural-gas fired equipment when minimizing life-cycle costs is the primary goal. Meanwhile, electric heating equipment is likely to perform better economically in reaching net-zero energy performance, but with higher environmental impacts due to (currently) higher source emissions rates of electricity relative to natural gas.

In comparing two Maryland state code-compliant homes (2015 IECC), one all-electric and one with gas-fired space and water heating equipment, the natural gas-heated (MCC-NG) design is more economical (lower LCC) and environmentally-friendly (lower environmental impacts across numerous impact categories). Due to larger system capacities and faster heating responses, gas-fired equipment enjoys advantages with respect to indoor comfort.

Regardless of the optimization goal (energy and/or costs) relative to current state building codes, there are some consistent EEM selections across heating fuel source options: (1) higher efficiency lighting, (2) higher efficiency HVAC and DHW equipment, (3) lower building envelope air leakage, and (4) solar PV system sized to meet total

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[16] The NZLCC-E design has a BEES-weighted score of 4.66 and a SAB-weighted score of 4.62.

electricity load. EEMs precluded from the optimal building designs on cost-effectiveness grounds are additional rigid insulation in the roof assembly and the solar thermal system. Relative to results found in a previous study of the NZERTF, the optimal all-electric building designs implement different EEMs, using less efficient windows and lower R-value wall assemblies while installing a more efficient HVAC system, driven by the newer construction cost data used for the analysis. These results show how the variability in construction costs should be considered when interpreting the results of this study. Additionally, there are building designs implementing different EEMs that are near optimal that would be reasonable design choices.

The relative cost of electricity and natural gas combined with the marginal value of electricity discontinuity at net-zero electricity consumption (first unit of excess electricity production) created by the net metering structure in Maryland leads to varying optimal selections of heating equipment. The cost-optimal design uses natural-gas heating equipment (LCC-NG design), saving an additional $937 in LCC over the study period. Although the LCC-NG design saves half the site energy that the lowest cost all-electric (LCC-E) design does, it leads to lower overall environmental impacts because of the (currently) lower emissions rate for natural gas relative to electricity in Maryland.

The electricity value discontinuity is also the reason the lowest cost net-zero energy design uses electric heating equipment (NZLCC-E design), which increases LCC by $956 relative to the cost-optimal (LCC-NG) design. The lowest cost design that reaches net-zero energy performance using gas-fired electricity (NZLCC-NG) increases LCC by additional $11,489 relative to the NZLCC-E design due to additional construction costs and the lower marginal value of excess generation. These results could change if the relative cost of natural gas and electricity were to change or the net metering regulation were altered. The relative environmental performance remains (marginally) in favor of natural gas-fired heating equipment due to the assumed fuel mix of electricity.

Impacts of alternative HVAC and DHW systems on total hours uncomfortable appear to decrease as energy efficiency increases. There is a difference in maintaining indoor conditions for state code-compliant designs, with the natural gas-fired HVAC system having 152 “uncomfortable hours” relative to the comparable all-electric design at 622 “hours uncomfortable,” which is driven primarily by the difference in heating equipment capacity. However, differences in occupant comfort between electric and gas-fired heating equipment decrease with greater energy efficiency. Hours uncomfortable are nearly identical for the two cost-optimal designs (307 for LCC-E and 309 for LCC-NG) and both net-zero designs perform better than the cost-optimal designs (262 for NZLCC-E and 145 for NZLCC-NG). Regardless of heating fuel, these net-zero building designs perform as well or better than code-compliant designs.

This study focused on the use of electric- versus natural gas-fired systems for household space heating and domestic water heating requirements for new, average-sized, single-family home constructed in Gaithersburg, MD. However, the study is limited in scope in terms of equipment, occupant loads, and location considered. The research could be expanded in the future to include alternative equipment such as ground source heat exchangers, multi-split, mini-split, and small-duct high velocity HVAC systems and be expanded to other locations to account for differences in climate and costs. Also, the sensitivity of the results to alternative occupant loads should be considered because building operation varies widely from occupant to occupant. Additionally, several underlying assumptions in the current analysis change over time, potentially leading to changes in the relative sustainability performance of alternative building designs. Building construction costs and materials environmental impacts, energy costs and fuel mixes, and the cost and efficiency of solar PV all are changing. Future research must account for theses dynamics to remain current and accurate over time.

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8. Appendix

Wall Constructions[17]		Option 1	Option 2	Option 3	Option 4	Option 5•
Exterior Wall	Framing	Typical†	Typical	Advanced††	Advanced	Advanced
	Insulation	R_{SI}-2.3	R_{SI}-2.3+0.9*	R_{SI}-3.5	R_{SI}-3.5+2.1*	R_{SI}-3.5+4.2*

Foundation Constructions		Option 1	Option 2	Option 3	Option 4•
Basement	Wall; Slab	R_{SI}-1.41; R_{SI}-0	R_{SI}-1.76; R_{SI}-0	R_{SI}-3.9; R_{SI}-0	R_{SI}-3.9; R_{SI}-1.8

Roof/Ceiling Constructions		Option 1	Option 2	Option 3	Option 4	Option 5•
Roof/Ceiling	Roof**	R_{SI}-0	R_{SI}-0	R_{SI}-7.92+0.7	R_{SI}-7.92+2.64	R_{SI}-7.92+5.28
	Ceiling***	R_{SI}-6.69	R_{SI}-8.63	R_{SI}-0	R_{SI}-0	R_{SI}-0

† 5.1 cm x 10.2 cm – 40.6 cm OC; †† 5.1 cm x 15.2 cm – 61.0 cm OC; *Interior Wall Cavity + Exterior; **Insulation in Rafters + Exterior Roof; *** Insulation blown into ceiling joists; • NZERTF Design

Table A1 Constructions – Roof, Ceiling, Wall and Foundation

Parameter[18]	Units	Option 1	Option 2	Option 3	Option 4	Option 5
U-Factor; SHGC	W/m^2-K; Fraction	2.57; 0.60	2.28; 0.60	2.00; 0.60	2.00; 0.40	1.14; 0.25

Table A2 Window Design Options

Design Option		Assumed Effective Leakage Area (cm^2)	
	ACH_{50} [19]	1st Floor	2nd Floor
Option 1 (2003 & 2006 / 2009 IECC)	No Maximum / 7.00	1473.3	1343.3
Option 2 (2012/2015 IECC)	3.00	403.6	368.1
Option 3 (NZERTF)	0.63	132.6	120.9

Table A3 Design Options for Alternative Air Leakage Rates

	Option 1 (2003/2006)	Option 2 (2009)	Option 3 (2012/2015)	Option 4 (NZERTF)
Fraction	34 %	50 %	75 %	100 %

Table A4 Fraction of High Efficiency Fixtures by Requirement

Design Option	System Components[20]
Option 1	Air-to-air heat pump (SEER 13/HSPF 7.7); Min. Outdoor Air (0.04 m^3/s)
Option 2 (NZERTF)	Air-to-air heat pump (SEER 15.8/HSPF 9.05); Separate HRV system (0.04 m^3/s)
Option 3	Gas-electric split A/C system (SEER 13/80 % AFUE); Min. Outdoor Air (0.04 m^3/s)
Option 4	Gas-electric split A/C system (SEER 16/96 % AFUE); Separate HRV system (0.04 m^3/s)

Table A5 Heating and Cooling Equipment Design Options

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[17] The R-values (R) in Table A1 refers to the capacity of an insulating material to resist heat flow. A higher R-value implies a greater insulating power. The R_{SI} values are the derived SI units.

[18] *U-factor* refers to the heat loss of a window assembly. A lower U-factor implies a greater resistance by the window to heat flow. The solar heat gain coefficient (*SHGC*), a fractional number between 0 and 1, refers to the fractional amount of incident solar radiation admitted through a window.

[19] ACH_{50} – Air Changes per Hour at 50 Pascals

[20] SEER is the rated cooling efficiency. HSPF is a measure of heating efficiency for air-source heat pumps. Annual fuel utilization efficiency (AFUE) factor indicates how efficiently a furnace utilizes it fuel.

Design Option	System Components[21]
Option 1	189 L electric water heater (EF = 0.95); No Auxiliary
Option 2	189 L HPWH (COP 2.36); No Auxiliary
Option 3	189 L electric water heater (EF = 0.95); 2 panel, 302.8 L solar thermal storage tank
Option 4 (NZERTF)	189 L HPWH (COP 2.36); 2 panel, 302.8 L solar thermal storage tank
Option 5	189 L gas water heater (EF = 0.78); No Auxiliary
Option 6	189 L gas water heater (EF = 0.90); No Auxiliary
Option 7	189 L gas water heater (EF = 0.78); 2 panel, 302.8 L solar thermal storage tank
Option 8	189 L gas water heater (EF = 0.90); 2 panel, 302.8 L solar thermal storage tank

Table A6 Domestic Hot Water System Design Options

Design Option	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
System Size (kW)	0.0	2.5	5.1	7.6	10.2	12.7

Table A7 Solar PV System Options

Impact Category	Normalization reference	Units	EPA Science Advisory Board	BEES Stakeholder Panel
Global Warming	7.16E+12	kg CO_2 eq.	18	29.9
Primary Energy Consumption	3.52E+13	kWh	7	10.3
HH – Criteria Air	2.24E+10	kg PM10 eq.	7	9.3
HH – Cancer (Carcinogenic)	1.05E+04	CTUh	8	8.2
Water Consumption	1.69E+14	L	3	8.2
Ecological Toxicity	3.82E+13	CTUe	12	7.2
Eutrophication	1.01E+10	kg N eq.	5	6.2
Land Use	7.32E+08	hectare	18	6.2
HH – Non-cancer (Non-Carcinogenic)	5.03E+05	CTUh	5	5.2
Smog Formation	4.64E+11	kg O_3 eq.	7	4.1
Acidification	1.66E+12	mol H+ eq.	5	3.1
Ozone Depletion	5.10E+07	kg CFC-11-eq.	5	2.1

Table A8 Normalization References (Annual U.S. Contributions) and EIS Weights

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[21] Energy efficiency of a water heater is indicated by EF based on the amount of hot water produced per unit of fuel consumed over a typical day. COP is the ratio of useful heating/cooling to work required, characterizing heat pump/AC unit performance.

Design Category	**LCC-E**	**LCC-NG**	**NZLCC-E**	**NZLCC-NG**
Windows (U; SHGC)	2.56 W/m^2-K; 0.60	2.56 W/m^2-K; 0.60	2.56 W/m^2-K; 0.60	1.99 W/m^2-K; 0.60
Heating & Cooling	SEER 16.5/ HSPF 9.1	SEER 16.0/ AFUE 96%	SEER 16.5/ HSPF 9.1	SEER 16.0/ AFUE 96%
Ventilation	Separate HRV	Separate HRV	Separate HRV	Separate HRV
Air Leakage	0.63 ACH_{50}	0.63 ACH_{50}	0.63 ACH_{50}	0.63 ACH_{50}
Lighting	100% efficient fixtures	100% efficient fixtures	100% efficient fixtures	100% efficient fixtures
Solar PV	10.2 kW	7.6 kW	10.2 kW	12.7 kW
DHW	Heat Pump	Gas – 90%	Heat Pump	Gas – 90%
Roof	Ceiling: R_{SI}-6.7	Roof: R_{SI}-7.92 + 0.9	Roof: R_{SI}-7.92 + 0.9	Roof: R_{SI}-7.92 + 0.9
Wall	Typical Frame R_{SI}-2.3	Typical Frame R_{SI}-2.3	Typical Frame R_{SI}-2.3	Advanced Frame R_{SI}-3.5+4.2
Found. Wall	R_{SI}-1.41	R_{SI}-1.41	R_{SI}-1.41	R_{SI}-1.41
Found. Floor	R_{SI}-0	R_{SI}-0	R_{SI}-0	R_{SI}-0
Site Energy (kWh)	~2,435	~355,880	~-7,908	~-9,628
Total LCC	$324,760	$321,259	$324,779	$338,733
Energy Savings vs MCC-NG*	-	~77%	-	~101%
Δ LCC vs MCC-NG*	-	-$35,325	-	-$22,880
Energy Savings vs MCC-E	99.7%	50%	~101%	~101%
Δ LCC vs MCC-E*	-$44,103	-$45,040	-$44,084	-$32,595
Hrs Uncomfort./Yr	~307	~309	~262	~145
*30-yr study period				

Table A9 Design Features for All-Electric and Gas-heated EE and LCC Building Designs