NIST Technical Note 2120

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This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2120

National Institute of
Standards and Technology
U.S. Department of Commerce

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September 2020

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

National Institute of Standards and Technology Technical Note 2120
Natl. Inst. Stand. Technol. Tech. Note 2120, 40 pages (September 2020)
CODEN: NTNOEF

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2120

Preface

This manuscript builds on analysis completed in an article by O'Rear, Webb, Kneifel and O'Fallon (1) that focuses on a case study evaluating the sustainability performance of single-family homes in Maryland. Since most of the background, literature, methodology, and analysis remain the same, numerous sections are abbreviated versions of sections in the article For additional details on these sections refer to the prior study.

Abstract

Updates to the underlying cost and environmental data have recently been implemented in the BIRDS database. This study evaluates the updated results for validation, as well as determines the potential changes in the results relative to those found in O'Rear, Webb, Kneifel and O'Fallon (1). The updates are found to have a minor impact on the total LCC and the LCA results, but there is a shift in some energy efficiency measures (EEMs) in optimal designs. The continued reduction in solar photovoltaic (PV) installation costs leads to larger system sizes being utilized in life-cycle cost (LCC) designs, while including few additional EEMs. Reducing the efficiency of some building components is possible and still reaching net-zero energy performance. As in the previous study, net-zero energy performance is reached at the lowest LCC using an all-electric design. The incremental increase in initial construction costs relative to the code-compliant design in Maryland is $28 222, which has continued a trend in decreasing premium for net-zero energy performance. Over the 30-year study period, NZLCC-E saves the homeowner $34 063. Although the homeowner could save more designing to meet the lowest LCC design using natural gas heating (LCC-NG), the additional savings is only $527 while still consuming about 50 % of the baseline building design's total energy.

The concept of low-energy buildings must be reconsidered to determine whether new targets should be set, such as a combination of total consumption and net consumption or net-zero goals that include embodied energy. These results are limited in their generalization because they are based on a case study using validated simulation models of the NIST Net-Zero Energy Residential Test Facility (NZERTF). The findings should not be extrapolated to buildings with different climates, energy costs, building codes, or occupancies. The assumptions on the economic analysis are also important factors to consider when using the results and implications in this study for decision making. The baseline building designs in this study are based on 2015 IECC. Maryland has since adopted 2018 IECC, which would influence the relative differences between the optimal designs and the baseline.

Key words

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

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1. Introduction

A focus on sustainable infrastructure in the U.S. has given rise to interest in cost-effective low-energy residential buildings, even goals of reaching net-zero (or net-zero ready) energy performance. The feasibility of reaching net zero energy performance and the optimal building design is impacted by the selected definition of net-zero (e.g., site energy versus source energy) as well as the climate of the building being constructed. 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 (≈40 %), and consumers often have an option between natural gas and electric heating systems.

Although fuel and equipment costs, climate/region, and home age are the primary influencers in the selection process, other factors such as maintenance costs, safety concerns, and personal preferences may also impact heating equipment choice. Natural gas is currently cheaper than electricity per unit of energy and typically has lower source emissions rates relative to electricity from the power grid. However, natural gas equipment requires a local distribution system connection, have lower efficiencies, and result in some risk to exposure of leaked gas and exhaust.

Gas heating has been recommended for colder climates with more extreme heating loads, while electric heating is recommended in warmer climates where fuel cost savings are minimal due to the low heating loads. Natural gas is the most widely used fuel type and class of heating technology in the U.S. followed by electricity [2]. The majority heating source varies by region, with the warmest climate (Hot-Humid) being primarily electricity. The fraction of electric heating decreases and the fraction of natural gas heating increases as the climate gets colder with approximately equal shares in the Mixed-Humid climate zone and all other climate zones being dominated by natural gas. [3, 4].

Previous work in O'Rear, Webb, Kneifel and O'Fallon (1) compared a set of gas heating systems against electric heating systems in the context of low and net-zero homes using the Building Industry Reporting and Design for Sustainability (BIRDS) database. Since the prior study, the data underlying BIRDS has been updated to include new cost and environmental data[1]. Dollar values have been inflated from 2015 to 2018 dollars while construction costs have been updated with more recent consumer price indices and industry construction costs, specifically for solar photovoltaic systems. The environmental data for operational energy consumption has also been updated to incorporate electricity and natural gas life cycle assessment (LCA) data published since the analysis in the previous study. The purpose of this report is to implement the exact same methodology to reanalyze the same whole building sustainability metrics for the gas versus electric comparisons with the more recent underlying data to understand what, if any, results and associated interpretations from the previous work have changed.

[1] Update occurred in September 2020

2. Literature Review

As in the previous study, 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 on space and water heating in residential buildings is discussed below. Solar thermal as a supplemental heat source for domestic hot water is included in the BIRDS database but is excluded from the analysis. The reason for which is presented below.

2.1. Gas vs. Electric Space Heating Components

The literature on direct comparisons of the economic and environmental efficiency of gas and electric heating is limited. Additionally, studies are often limited in generalization because of the significant economic and environmental differences in underlying conditions across locations, including the cost, fuel mix, and efficiency of electricity generation. For example, the sustainability performance of a building consuming electricity from a coal-fired generating facility will be different than that same building consuming electricity from a mixture of utility-scale solar PV, wind farms, and natural gas-fired generation. As such, all operational energy-related analysis is implicitly based on the fuel mix of the region in each study. The remainder of Section 2.1 and all of Section 2.2 are abbreviated versions of the literature review in O'Rear, Webb, Kneifel and O'Fallon (1).

Several studies have found natural gas to be cost-effective relative to electricity for heating in the United States. Belsie (5) found that natural gas was 28 % cheaper than electricity for heating in the Northeast region. EIA (6) reports that the U.S. average winter expenditure per household for natural gas used for heating ($578) is 38 % less than for electricity ($930).

Most studies comparing electric and gas heating equipment were completed for non-U.S. locations. Jeong, Kim and Lee (7) found natural gas has a higher utility (defined as a function of equipment cost, energy costs, and energy consumption given a budget constraint) when compared with electricity generation in South Korea. Gustavsson and Karlsson (8) found that electrical heating systems could be either the most energy-efficient option or the least, depending on the selected system. Several studies from the U.K. and European Union have generally found that air-source heat pumps are better than gas heating in terms of direct greenhouse gas emissions [9-11], but more costly to operate than gas heating [10]. Dorer and Weber (11) focused on micro-cogeneration, which is different than the focus of this paper, while Kelly and Cockroft (10) and Cabrol and Rowley (9) looked at gas condensing boilers, which are typically more efficient than forced air (non-condensing) furnaces but uncommon in U.S. single-family homes. Yang, Zmeureanu and Rivard (12) found similar results in comparing electric and gas fired hot water systems and forced air furnaces for space heating in Quebec.

Evaluating gas and electric heating equipment in the U.S. is more complicated due to variation in generation fuel mix across the country. Shah, Debella and Ries (13) found that heat pumps have higher environmental impacts in places where there is a high percentage of fuel generation from fossil fuels, with a transition of 15% to 40% of fossil fuel generation to renewable sources required to offset these impacts. Brenn, Soltic and Bach (14) performed a comparison of electric and natural gas driven heat pumps in Central Europe that found, in general, natural gas heat pumps were roughly equivalent to electric heat pumps using electricity from natural gas combined cycle generators. Alternatively, if the electrical grid utilized low-CO_2 fuel sources, an electric heat pump is preferred. Pitt, Randolph, Jean and Chang (15) found that heating with a gas furnace had lower CO_2 emissions than using air-source heat pumps in Blackburn, VA. The 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 [16]. Europe sees similar variation in optimal technology both across countries [17] and within countries [18, 19].

2.2. Water Heating Comparison

There is little direct comparison of water heating technologies in the literature for the U.S. However, there have been multiple studies on energy and environmental performance conducted in Europe. Tsilingiridis, Martinopoulos and Kyriakis (20) 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). A net gain in environmental performance was found for the hybrid systems compared to an electric water heater, with the hybrid-electric system outperforming the hybrid-gas system. Tsilingiridis, Martinopoulos and Kyriakis (20) also found that the natural gas water heater performed the best, outperforming the hybrid-electric system due to the lower efficiency of the electrical component of the hybrid system. Hong and Howarth (21) found that natural gas water heaters led to higher direct greenhouse gas emissions than high efficiency electric heat pump water heaters for both coal and natural gas produced electricity. Their findings suggest that natural gas technologies can result in higher emissions than using coal-fired electricity generation if efficiency gains in coal burning can more than offset the higher per unit of energy emissions rates for coal relative to natural gas.

A study of multiple environmental impacts that focused on solar thermal water heating versus heat pumps and gas boilers found tradeoffs for each technology type. Greening and Azapagic (22) found that solar thermal systems are not necessarily the "cleanest" option in terms of overall environmental impact. Solar thermal outperformed electric resistance water heaters and electric heat pump water heaters but underperformed gas boilers in a majority of environmental categories.

Economic comparisons between technologies in the literature are also limited, with most studies being completed by trade groups. Gas water heaters tend to cost less to operate on average than electric water heaters and are generally less efficient on a site energy basis. Although solar thermal water heaters can help reduce greenhouse gas emissions, the bulk of literature suggests that they are not economical for the United States. A report by Clark (23) found that solar thermal had a payback period for installation costs of roughly 30 years. Croxford and Scott (24) suggests a short carbon payback time (no longer than 20 % of system lifetime), but a simple payback of 100s of years for solar thermal if grants or rebates are included. The National Renewable Energy Laboratory (NREL) found that break-even costs were obtainable for solar thermal water heating systems using electric back-up based high solar resource availability, low electricity prices and high natural gas prices [25]. Solar thermal was also found to be more likely to replace some conventional electric systems as opposed to natural gas systems. Rockenbaugh*, et al.* (26) had similar findings where proper siting and careful consideration can make solar thermal economically efficient in certain locations in the United States. If conventional heating sources are used to supplement solar thermal, then a hybrid system can outperform traditional water heaters even in suboptimal climates [27].

Studies in the European Union have found that solar thermal can be economically and environmentally competitive in the appropriate climate and with sufficient solar resources [28-30]. Simons and Firth (31) found that solar thermal in apartment buildings in Europe outperformed other heating sources on primary energy purchased and reductions in emissions, however, these benefits are a trade-off for more substantial negative environmental impacts due to the embodied emissions from the equipment manufacturing process. Solar thermal systems were found to be better overall for human health than fossil fuel systems and similar to heat pump systems. Kalogirou (32) found that a solar thermal system coupled with a gas or electric backup proved viable in reducing greenhouse gas emissions with a realistic payback period. A cost-benefit analysis of solar thermal water heating in Greece concluded that solar water heating was cost-effective relative to electric water heaters, but was not cost-effective relative to natural gas [33]. Subsequent work by Martinopoulos, Papakostas and Papadopoulos (17) has shown that advancements in solar thermal have led it to now be more cost-effective than natural gas water heating 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 a solar thermal system being non-optimal in all cases based on the chosen energy and economic efficiency metrics, and is therefore excluded from the discussion within the current analysis.

2.3. Recent Literature

Literature has been published comparing gas and electric heating since O'Rear, Webb, Kneifel and O'Fallon (1). Eguiarte, Garrido-Marijuán, de Agustín-Camacho, del Portillo and Romero-Amorrortu (34) found that heat pumps become more cost-effective as total energy consumption increases, but natural gas water heating remains the most efficient equipment option. Zhao*, et al.* (35) examined the impacts on emissions in moving from coal-fired to other energy sources in China and found that pollution decreased significantly in switching to natural gas or other non-coal based electricity sources. Another study in China found that natural gas was insufficient to fully decarbonize the heating sector, requiring heat pumps to reach that goal [36].

3. Measuring Building Sustainability Using BIRDS

BIRDS provides whole-building sustainability metrics developed using whole-building energy simulation modeling, life-cycle costing, and life-cycle impact assessment (LCIA) methods to produce science-based measures for evaluating high-performance green buildings [37]. BIRDS environmental performance metrics are based on a hybridized LCA approach, which considers an inventory of inputs and outputs covering all phases of a building's service life. Operational energy consumption in the building includes any on-site renewable energy generation [37]. Environmental LCIA quantifies the potential contribution of these LCA inventories to a range of environmental impact categories based on EPA's TRACI 2 impact categories [38] plus two additional impact categories for land and water use. The remainder of this chapter is an abbreviated version of the same section in O'Rear, Webb, Kneifel and O'Fallon (1).

The latest version of BIRDS (v4.1) is scheduled to be released in 2020 and includes an update to one of the three databases in BIRDS, the "Incremental Energy Efficiency for Residential Buildings Database" that includes updates to the underlying cost data and operational energy LCA data. The analysis conducted in this study is based on this updated database (referred to as the BIRDS Database hereafter), which allows for detailed analyses of incremental EEMs for Gaithersburg, MD based on NIST's Net Zero Energy Residential Test Facility (NZERTF). BIRDS users can evaluate impacts of alternative underlying assumptions, including study period (1 to 30 years), discount rate (3% or 8%), construction quality (average or luxury), financing type (20 % down loan or paid in full upfront), exterior wall finish (brick veneer or wood siding), and heating fuel type (electricity or natural gas).

Appendix A provides the EEM options available in the BIRDS Database. **Table A-1** and **Table A-3** in the Appendix list alternative EEM options for building envelope constructions (i.e., wall, roof/ceiling, foundation, windows, doors, air leakage rates), which are based on requirements in different editions of IECC for Residential Buildings and components installed in the NZERTF[2][3]. Listed in **Table A-4** through **Table A-7** are the EEM options for building systems (lighting, space conditioning, water heating, solar photovoltaics (PV)). Lighting wattage options (**Table A-4**) are on a "typical/baseline" lighting mix from Hendron and Engebrecht [39], requirements in different editions of IECC, and the NZERTF.[4]

Heating and cooling equipment options (**Table A-5**) include both electric and gas space heating system. For each fuel type there are two equipment options: a "standard efficiency" system that satisfies minimum federal efficiency and IECC requirements and a "high" efficiency system based on what was deemed a cost-effective high-end system based on the NZERTF design. Mechanical dedicated outdoor air (OA) ventilation requirements defined in ASHRAE 62.2-2010 [40] are met for all systems. The high efficiency systems include a heat recovery ventilator (HRV).

Eight DHW system options are available (**Table A-6**), which are different combinations of a "standard" efficiency electric water heater, an air-to-water heat pump water heater (HPWH), a standard efficiency gas water heater, or a high efficiency gas water heater with and without an auxiliary two-panel solar thermal system.

The six roof-mounted solar photovoltaic (PV) system options (**Table A-7**) are incremental sizes ranging from 25 % to 125 % of the NIST NZERTF roof-mounted system (Option 5).

4. Research Methodology

This study explores tradeoffs in sustainability (energy, environmental, and economic) performance between residential building designs that use electric space and water heating equipment and natural gas-fired equipment. This chapter provides the methodology applied in this study and is an abbreviated version of the Research Methodology in O'Rear, Webb, Kneifel and O'Fallon (1).

[2] The 2003 and 2006 IECC set no maximum limit on air leakage. The 2009 IECC limit is assumed for those editions in this study.
[3] 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.
[4] Additional details on all EEM alternatives can be found in Kneifel, Lavappa et al. (2016).

4.1. Energy Performance

Operating energy is based on an estimate of total net source energy use by a building's occupants during the building's service life from parametric simulation runs of EnergyPlus (E+) [41, 42].[5,6] Total net site energy use is the difference between total consumption and on-site renewable energy production. Total net source energy use is derived using a conversion multiplier to scale net site operating energy use.[7]

Annual operating energy use is assumed constant from year-to-year with proper maintenance. On-site solar PV production, based on previous research studies, is assumed to have an annual production degradation rate of 0.5% per year over the lifetime of the solar PV system [44]. 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

Environmental performance uses LCA inventory data and life-cycle impact assessment (LCIA) methods to quantify and link environmental impact contributions to twelve impact categories.[8] BIRDS uses a hybrid LCIA framework developed by Suh and Lippiatt (45) that integrates top-down (Input-Output-based) and bottom-up (process-based) methods [46-50]. For additional details on the LCA inventory data see Lippiatt, Kneifel, Lavappa, Suh and Greig (37). The environmental flows associated with a building's life-cycle stages can be grouped in embodied flows [initial construction, maintenance, repair, and replacement (MRR), and disposal] and operating flows (energy consumed and produced during building operation). See Kneifel, O'Rear, Webb and O'Fallon (51) for approaches implemented to calculate the embodied and operating environmental flows.[9,10]

The underlying LCIA data is identical to that used in Kneifel, O'Rear, Webb and O'Fallon (51) except for operational electricity and natural gas. Since its publication, new LCA data has been published for each by federal agencies that provides improved methodologies, approaches, and LCI flows as well as more recent underlying source data. These LCI data, summarized below, are publicly available and well documented.

The Federal LCA Commons created a publicly available Electricity Baseline LCA Model (collaborative effort between EPA, USDA, and DOE national laboratories) that can calculate the LCA data (generation-based or consumption-based) for any region (national average,

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

[6] The weather file used for the simulations is the Typical Meteorological Year 3 (TMY3) for Gaithersburg, MD (KGAI weather station) obtained from Weather Analytics [43] Weather Analytics (2014) TMY Meteorological Year 3 (TMY) Formatted Weather Data File. ed Database A-GW (Athenium Analytics (formerly Weather Analytics), https://www.athenium.com/).

[7] 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.

[8] The twelve categories can be found in **Table A-8**. More information on the impact categories, refer to [37] Lippiatt B, Kneifel J, Lavappa P, Suh S, Greig A (2013) Building Industry Reporting and Design for Sustainability (BIRDS) Technical Manual and User Guide. *NIST Technical Note* 1814.

[9] 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.

[10] 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.

FERC market region, balancing authority) in the country. The electricity baseline was accessed in the Grid Mix Explorer tool to calculate the LCIA for electricity consumed in the PJM balancing authority (shown in the red dashed box of **Figure 1**) [52].

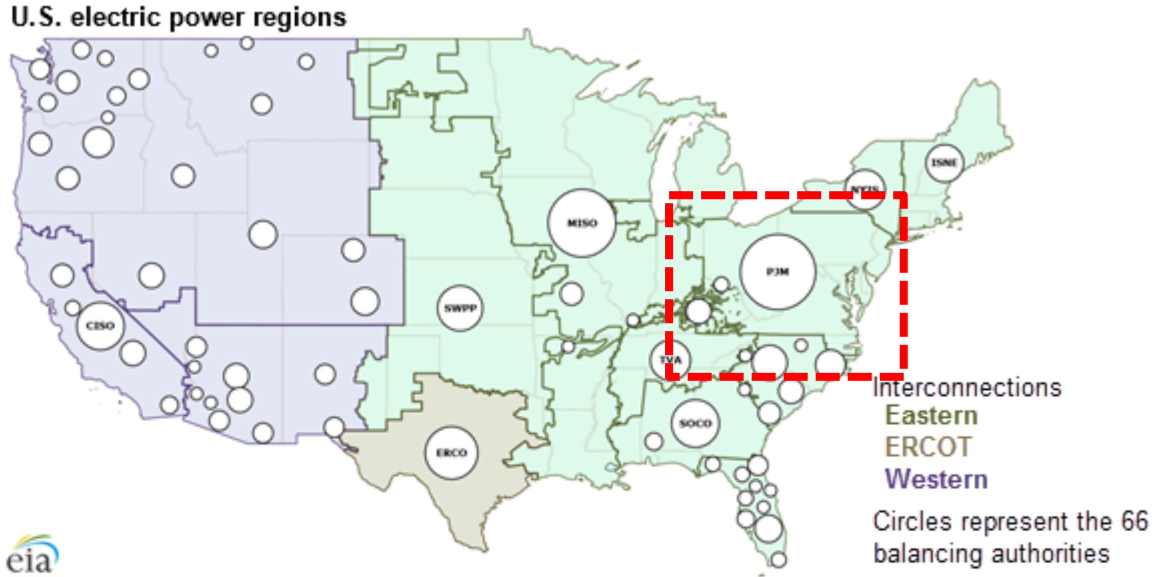


Figure 1. NERC Regions and Balancing Authorities[11]

The electricity baseline was developed using emissions reported to the EPA via three main programs: Air Markets Programs Data, the National Emissions Inventory (NEI), and the Toxics Release Inventory (TRI). The inventory is divided by the annual generation reported to the Energy Information Administration (EIA) (Form 923) for each power plant in the United States. The remainder of the life cycle is completed using data from NETL coal, natural gas, and petroleum baseline models to represent the supply chain emissions associated with extracting and transporting the fuels [53]. These models primarily rely on the same EPA inventories used for power plant stack emissions. Other non-fossil technologies (e.g., wind, solar, nuclear, geothermal, hydro) are largely based on existing models modified in consultation with other DOE experts.

NETL published a Natural Gas Baseline LCA Model that provides both national average as well as basin specific LCA data for the delivery of direct use natural gas (excluding on-site combustion). The two baseline databases published in 2019 (2016 data) were used to generate consumption-based LCIA results for the PJM balancing authority (where Maryland is located) and LCIA results for average delivered (direct use) natural gas produced in the Appalachian Shale basin using it's respective extraction technologies (100 % shale), which can be identified as the eastern-most natural gas basin in the U.S. (see red dashed box in **Figure 2**).

[11] Source: https://www.eia.gov/todayinenergy/detail.php?id=27152

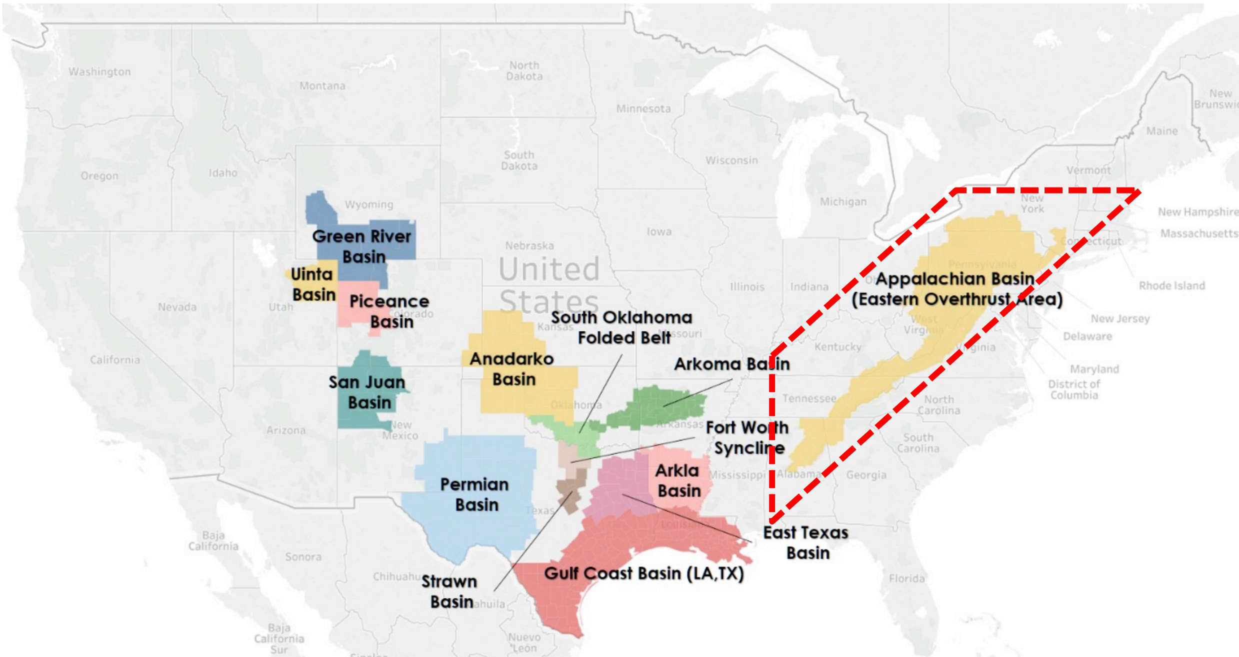


Figure 2. Basins that Account for Majority of U.S. Natural Gas Production [54]

NETL has also published LCA data for the unit process for natural gas combustion [55]. The LCA data is used to generate the LCIA results for each of the TRACI impact categories. By combining the LCIA results for natural gas delivered and its combustion, total LCIA results for the on-site use of natural gas can be calculated.

The LCI data from these "baseline" models are used to develop LCIA results consistent with the BIRDS impact category units for GWP, acidification, particulates, eutrophication, ozone depletion, and smog. Due to a lack of available data, the original data for the other impact categories is used. The resulting LCIA data is shown in **Table 1**.

Table 1. Operational Energy LCIA Data

2016 Data		Flow Per kWh	
Impact Category	**Unit**	**Electricity**	**Direct Use Nat Gas**
Global warming	kg CO2 eq	6.06E-01	2.51E-01
Acidification	mol H+ eq	7.86E-02	2.47E-02
Respiratory effects	kg PM10 eq	3.06E-04	5.18E-05
Eutrophication	kg N eq	6.38E-05	3.28E-05
Ozone depletion	kg CFC-11-Eq	6.80E-09	2.95E-11
Smog	kg O3 eq	2.72E-02	1.48E-02
Energy	Per unit of energy	3.64E+00	2.93E+00

Data uses the BIRDS impact category units.
The electricity baseline for PJM from the LCA Commons is used for electricity.
The supply chain data for the App. Basin from NETL is used for delivered natural gas.
The updated US LCI data provided by Four Elements for combustion of natural gas.

The updated data shows similar trends to the prior data used in BIRDS with electricity resulting in higher environmental impacts per unit of energy consumed on-site, but with lower environmental impact "premiums", with premium reductions ranging from 11 % to 62 % (**Table 2**). One of the key factors for the relative reduction is because the electricity fuel mix for PJM in 2016 included 29 % coal, which is significantly lower than for the prior data. The use of a cleaner fuel mix lowers emissions and the resulting environmental impacts.

Table 2. Operational Energy Impact Ratios by Data Source

Relative Emissions Rate	**Electricity to Gas Ratio**		
Impact Category	**BIRDS 4.0**	**BIRDS 4.1**	**"Premium" Change**
Global Warming	271%	241%	-11%
Eutrophication	317%	195%	-39%
Smog Potential	478%	184%	-62%
Energy	169%	124%	-26%
Ozone Depletion is excluded because the values are so small that a small change in a single LCI flow can lead to massive changes.			

It is important to note that even though the data was released in 2019, the source data for these estimates are based on 2016 data (most recent data available at the time of development). Any changes in the electricity fuel mix or natural gas extraction and distribution would influence these estimates. For example, the PJM fuel mix for 2019 decreased to 24 % coal[12]. The analysis should be completed again when more recent data becomes available.

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) [37]. EISs are calculated using fixed scale normalization references based on annual contributions of U.S. economic activity to the LCIA categories (**Table A-8**). For more information on EISs, refer to Lippiatt, Kneifel, Lavappa, Suh and Greig (37).

4.3. Economic Performance

BIRDS uses a life-cycle cost (LCC) methodology to evaluate the cost-effectiveness of buildings [56, 57]. Life-cycle costing includes the discounted present value of all costs related to the construction, operation, maintenance, repairs, replacements, and residual value of a building for a given study period. When evaluating a series of alternative designs relative to a baseline building, the design alternative with the lowest LCC is the most cost-effective [51]. The difference in LCCs (i.e., Net Savings) between a baseline and alternative reveals the additional costs (or savings) incurred by the homeowner. A positive net savings (NS) implies that alternative is more cost-effective than the baseline. The generalized formula for calculating LCCs of a building is:

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

The LCC estimates in this study use data from a number of sources. Initial construction costs (C) include costs of constructing the building as estimated using RS Means (58) for the typical construction cost for a single family dwelling of the particular type of building, plus

[12] Source: https://gats.pjm-eis.com/GATS2/PublicReports/PJMSystemMix

the additional incremental costs of upgrading the design with each implemented EEM (Faithful and Gould (59), Kneifel and O'Rear (60), and local contractor quotes). Operational costs (O) are those associated with normal functioning of the house, while maintenance, repair, and replacement costs (MRR) are related to upkeep of the structure. Residual Value (RV) is the value left in the structure and its components at the end of the study period.

Most of the construction cost data was assumed unchanged except for an adjustment for general inflation to get all costs to 2018 dollars. The only cost data that changed significantly was the installed cost of the solar PV systems. The linear cost estimate of $3.29/W was replaced with a more accurate cost function based on 2018 EnergySage data that includes a fixed cost ($1611) and a proportional cost ($2.67/W) [61]. As in the previous study, the federal tax credit is included in the LCC analysis, which decreased from 30 % to 26 % of total installed cost in 2020.

Maintenance, repair, and replacement rates and costs (MRR) are obtained from Census (62), Faithful and Gould (59), National Association of Home Builders (NAHB) Research Center (63), and ENERGY STAR (64). MRR costs and associated residual values (RV) are calculated for each building component with different rates of replacement than the building structure. Operational costs (O) include estimated electricity and natural gas costs. Operational energy costs are based on the standard residential rate schedule from PEPCO (65), annual average residential natural gas cost data for Maryland [66], and energy price escalation rates in Lavappa, Kneifel and O'Rear (67). Residual values are based on the linear depreciation method defined in ASTM (68).

For more information on the cost data and life-cycle cost approach, see Kneifel, O'Rear et al. (2018).

4.4. Building Component Options and Analysis Assumptions

This analysis compares the performance of a 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 design. **Table 3** lists the building envelope and system specifications (excluding HVAC and DHW systems) for the baseline design.

Table 3. 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** lists HVAC and DHW specifications for MCC-E and MCC-NG.

Table 4. 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 optimal alternative designs are selected based on their relative energy and economic performance under the same assumptions as applied in the prior study: 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 [69] is included because it's a significant factor in the economics of solar PV systems. The value of the tax credit decreased from 30 % (used in the previous study) to 26 % for 2020 and will further drop to 22 % for 2021.

5. Results and Discussion

This report focuses on a comparison of the changes in the results relative to O'Rear, Webb, Kneifel and O'Fallon (1) using the same methodology and the updated data. For a full discussion of the results using the original data see O'Rear, Webb, Kneifel and O'Fallon (1).

5.1. Comparison of Maryland Code Compliant Designs

Table 5 presents the results for the Maryland Code Compliant (MCC) designs in BIRDS for both the All Electric heating systems (E) and the Natural Gas heating systems (NG) from the prior study. The natural gas system has slightly lower construction costs while having approximately 10% lower energy costs. This leads to a lower LCC for the design with natural gas heating. In terms of environmental performance, natural gas has a lower EIS due to the fuel mix that makes up the location's electricity generation.

Table 5. Results for Maryland Code Compliant designs from [1]

	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

The results using the updated data are found in **Table 6**. Construction costs increase due to price inflation while the energy costs decrease, driven by lower projected energy escalation rates. Overall, the LCC for both MCC designs is cheaper than the results from O'Rear, Webb, Kneifel and O'Fallon (1) due to the lower energy costs overwhelming the higher construction costs. Natural gas still maintains an edge over the all-electric design on LCC, although the difference is reduced by approximately 50 %. Energy consumption is unchanged from the prior study because the same simulation runs are used, showing MCC-NG consumes over twice the energy than MCC-E, driven by the relative lower efficiency of the natural gas-fired equipment. Even with the additional consumption, the relative lower cost of natural gas leads to lower overall energy costs to the homeowner. Both designs show improvement in environmental performance as measured by the EIS, with the all-electric design having the larger decrease in magnitude. These results are driven by the decrease in the environmental impacts from the new energy LCA data, with electricity realizing a greater relative decrease from the prior study. The nature of the EIS score calculations makes comparing magnitude difference infeasible, however it is meaningful that the gap between the all-electric and natural gas designs is reduced.

Table 6. Results for Maryland Code Compliant Designs using Updated Data

	Units	MCC-E	MCC-NG
Construction Costs	U.S. $ (2019)	368 278	367 049
Energy Costs	U.S. $ (2019)	68 990	66 304
Total LCC	U.S. $ (2019)	350 546	346 042
Total Electricity Consumption	kWh	706 620	301 226
Total Natural Gas Consumption	kWh	0	1 253 802
EIS (BEES and EPA Advisory Board)	n/a	13.44, 11.49	9.08, 8.10

As in the previous study, this analysis utilizes a thermal comfort metric based on ASHRAE Standard 55: number of hours for which indoor conditions do not meet thermal comfort requirements of a building's occupants [70], referred to as "total hours uncomfortable" .[13] For additional information on thermal comfort in BIRDS, refer to Kneifel, Lavappa, O'Rear, Greig and Suh (71). The thermal comfort results remain identical to those from O'Rear, Webb, Kneifel and O'Fallon (1), which indicate that the MCC-E design is "less comfortable" with 622 hours where the temperature requirements were not met as compared to 152 hours for the MCC-NG design.

Figure 3 presents the radar plot from the previous study comparing the impact category results for MCC-E design to the MCC-NG design with the updated results overlayed. The MCC-NG design has the same or lower environmental impacts as the MCC-E design in every category.

[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

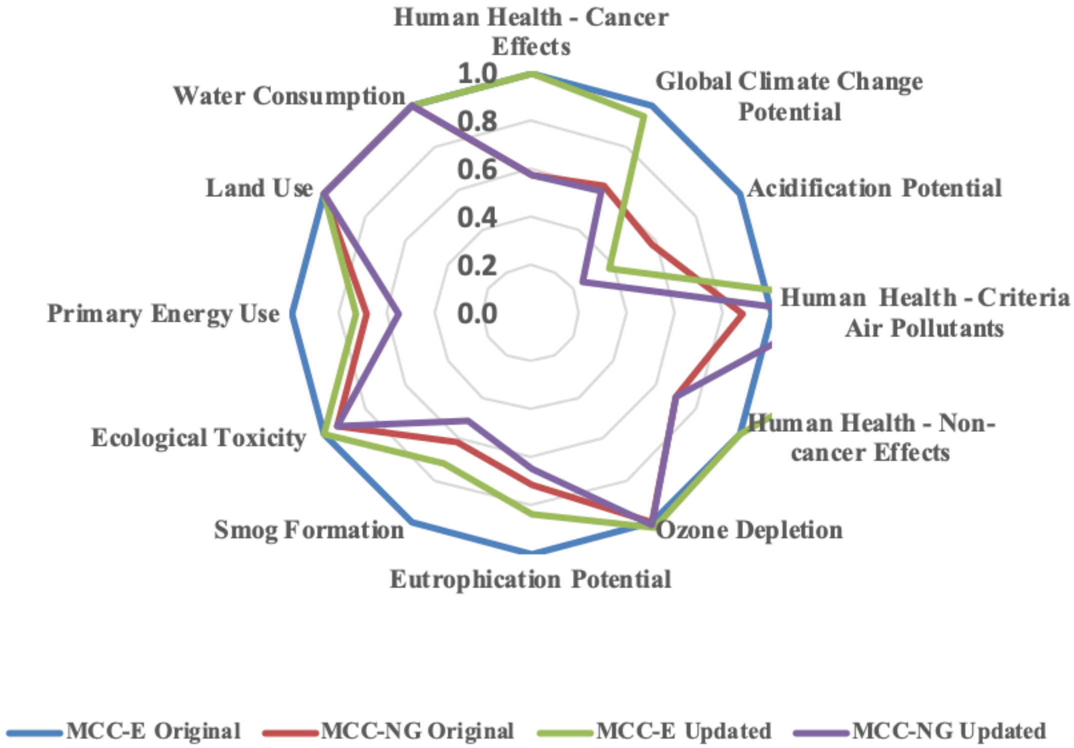


Figure 3. MCC-E vs. MCC-NG Designs (fractional performance relative to MCC-E Original) from [1]

Comparing the original results to the updated results show the same general trend of MCC-NG outperforming MCC-E. The only differences are the relative magnitude of the outperformance. The acidification potential is now closer to parity while the air pollutants flows are diverging with natural gas being less intensive. Apart from those changes most other flows are identical, or very similar, between the older results and those using the updated data.

5.2. All-Electric Design Results

This section analyzes all the building designs in the BIRDS Database using electric space and water heating equipment. **Figure 4** and **Figure 5** display 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 A-5**), as well as one of the first four options for domestic water heating (**Table A-6**). 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.

The plot of all results from the previous study is shown in **Figure 4**. A decrease in net energy use is correlated with a decrease in LCC until net-zero energy performance is achieved, at which point LCC begin to increase due to a discontinuity in the compensation between offset energy usage (retail electricity price) and compensation for excess generation (avoided cost to the utility). The updated data (**Figure 5**) shows the same trend with a slight flattening of the slope of the data. This flatter trend is a result of the increase in construction costs when combined with reductions in the energy cost savings over time. In all, the LCC for the cost-optimal designs for given energy reductions are higher for the updated data by approximately $5000. Note that some of this increase is a result of general inflation from 2016 to 2018 dollars.

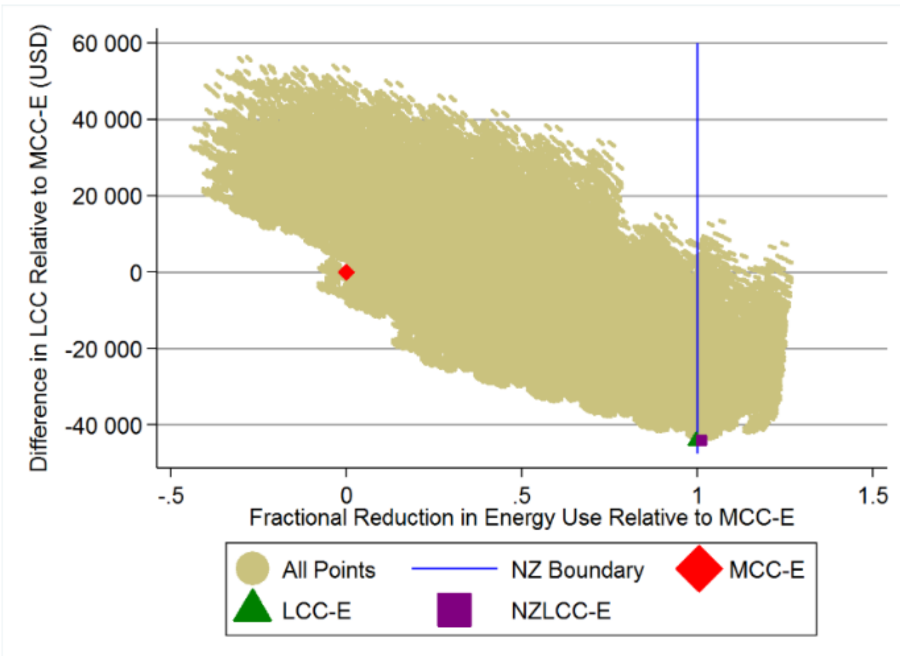


Figure 4. All-Electric Designs from [1]

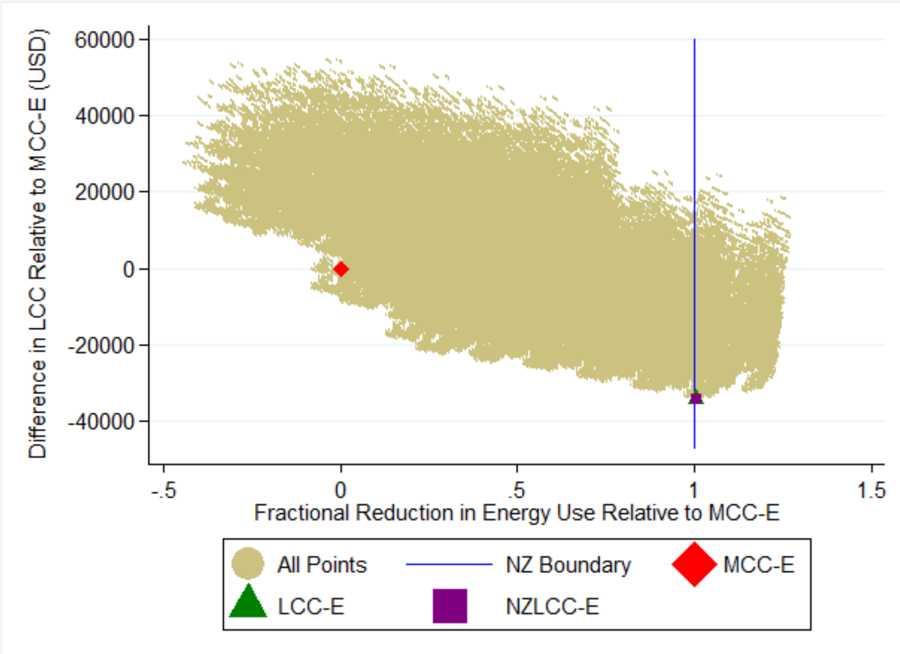


Figure 5. All-Electric Designs using Updated Data

The optimization curves from O'Rear, Webb, Kneifel and O'Fallon (1) are presented in **Figure 6**. The downward trend evident in **Figure 4** is also seen in the plot of both the HVAC system and DHW curves. The higher efficiency HVAC systems tend to be on par in terms of LCC than the low efficiency systems but achieve higher energy efficiencies along the curve, while being slightly more costly if all other EEMs are held constant. The performance of the DHW systems are less differentiated, but the solar thermal heating system leads to higher LCC while offering only slightly more efficient energy consumption. **Figure 7** shows the same curves for the updated data. The curves are flatter for the designs with the lowest LCC, mirroring the effect of **Figure 5** relative to **Figure 4**, while retaining the fast rise in diminished value after reaching net-zero. The general inferences of the previous paper remain intact, namely that air change rate is the largest driver for energy efficiency and LCC, while HVAC system provides a meaningful, but smaller, impact.

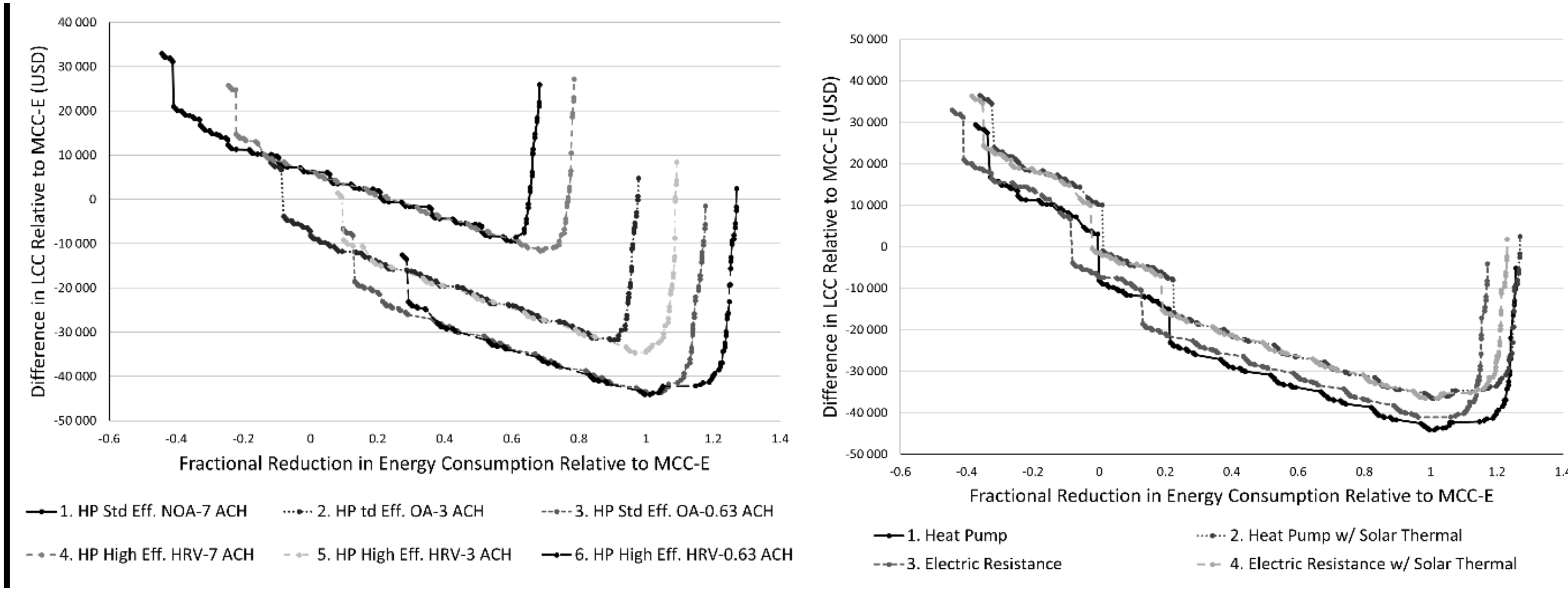


Figure 6. Optimization Curves for All-Electric Designs based on (a) HVAC System and (b) DHW System from [1]

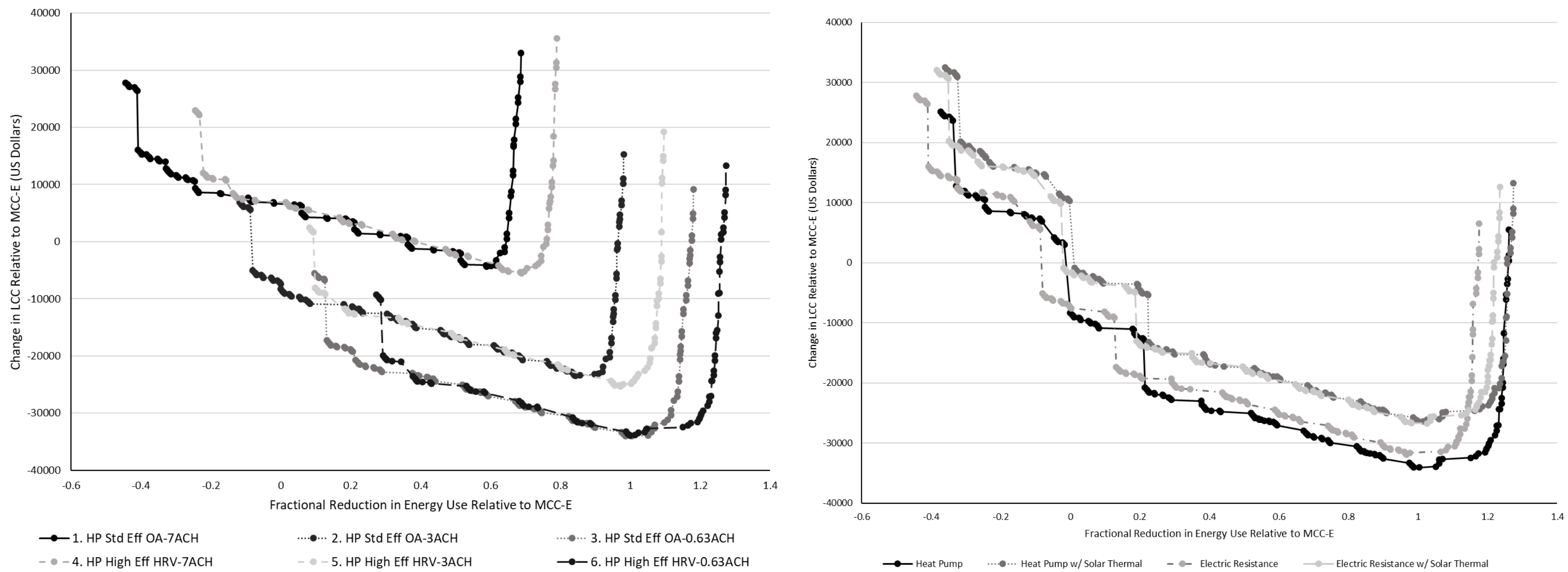


Figure 7. Optimization Curves for All-Electric Designs based on (a) HVAC System and (b) DHW System using Updated Data

Figure 8 and **Figure 9** contain the plot for all designs separated by PV system from O'Rear, Webb, Kneifel and O'Fallon (1) and using the updated data, respectively. Aside from the flattening of the slope on the lower LCC values which has already been mentioned, the general observations from O'Rear, Webb, Kneifel and O'Fallon (1) are unchanged. First, Solar PV is a necessary EEM to substantially lower net energy usage. Second, the solar PV system must be at least 10.2 kW (if limiting options to those discrete sizes that exist in the database) to achieve net-zero performance.

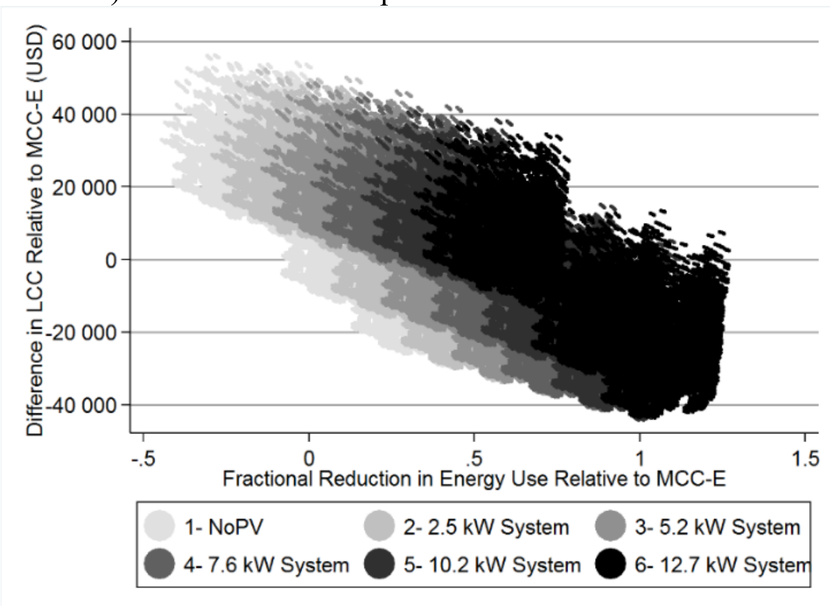


Figure 8. All-Electric Designs based on Solar PV System Capacities from [1]

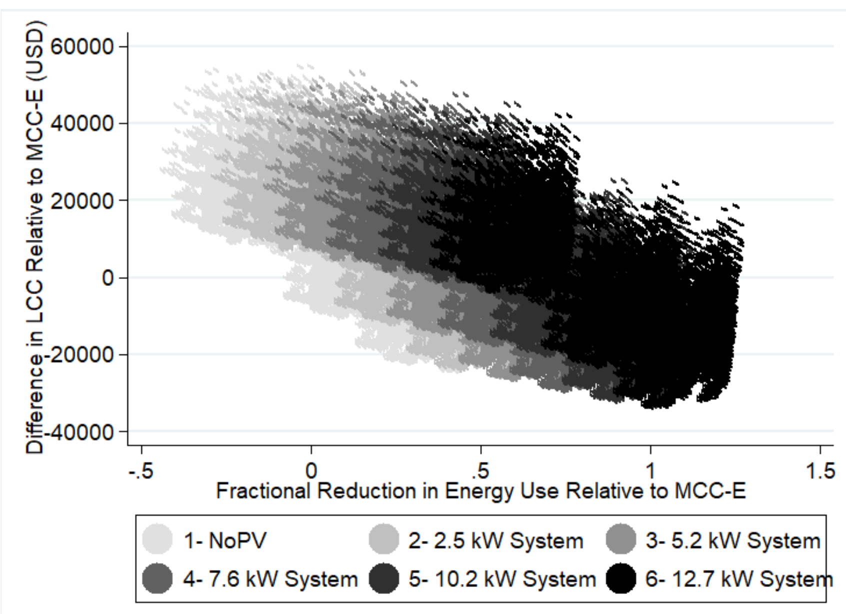


Figure 9. All-Electric Designs based on Solar PV System Capacities using Updated Data

5.3. Gas Design Results

This section analyzes the 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) gas-heated, lowest cost design (LCC-NG), (3) gas-heated, net-zero energy design at least cost (NZLCC-NG) and (4) gas-heated but with net-zero site electricity design at least cost (LNZE-NG).

Figure 10 presents the relative LCC performance of all designs using natural gas for heating from O'Rear, Webb, Kneifel and O'Fallon (1) relative to (a) reduction in total energy consumption and (b) reduction in electricity consumption. Both the LCC-NG and LNZE-NG designs are the same design. When compared to the all-electric designs in **Figure 4**, the distribution is similar, but with the cost-optimal design occurring at ≈77% reduction in site energy consumption instead of ≈101% and with far fewer designs meeting the net-zero threshold. 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) relative cost of natural gas to electricity in combination with the 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. Electricity production from solar PV is cost-effective in reducing net energy consumption to the point of offsetting all electricity consumption. However, as discussed earlier, the value of excess electricity production is lower than the value of reducing electricity consumption. Additionally, the relative cost of natural gas is much lower than electricity, leading to it being not cost-effective to reduce natural gas consumption using excess production. As a result, the LCC-optimal design (LCC-NG) is located just beyond net-zero electricity consumption.

Figure 11 provides the same comparison as **Figure 10**, but for the updated data. As with the all-electric results, the increase in construction costs causes the slope of the lower LCC designs to flatten slightly, although the difference is less pronounced for the natural gas systems. Otherwise, all the same general results hold.

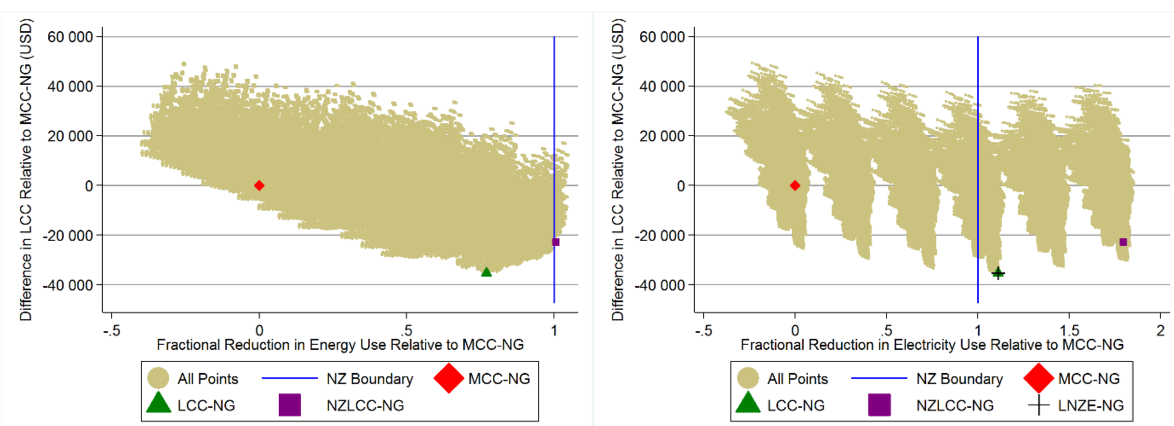


Figure 10. Gas-heated Designs based on Fractional Reduction in (a) Total Energy Use and (b) Electricity Use from [1]

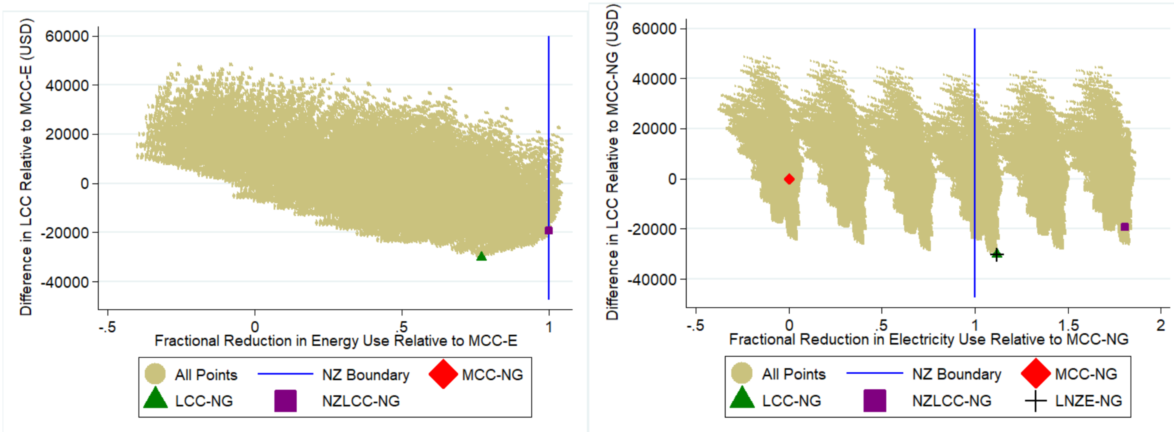


Figure 11. Gas-heated Designs based on Fractional Reduction in (a) Total Energy Use and (b) Electricity Use using Updated Data

Figure 12 illustrates the LCC optimization curves from the previous study for each level of net site energy reduction for six alternative configurations for the gas-fired HVAC system, varying based on efficiency, method and rate of ventilation, and air leakage rate. Like the analysis of the all-electric design cases, a building envelope having a low air leakage rate (0.63 ACH @ 50 Pa) AND 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 or beyond net-zero energy. Although large reductions in net energy use are attainable with a high efficiency split system (Setup 4 and Setup 5), similar, less costly reductions can be attained when the standard efficiency system is paired with a building envelope having a leakage rate of 0.63 ACH @ 50 Pa (Setup 3). In order to reach net zero energy performance, DHW system must include the high efficiency gas-fired water heater (Setup 3 or Setup 4). The inclusion of a solar thermal system produces additional but marginal reductions in net energy use, but at a greater LCC to the homeowner. Aside from the upward shift in the lower LCC values, the results using the updated data (**Figure 13**) show the same general trends.

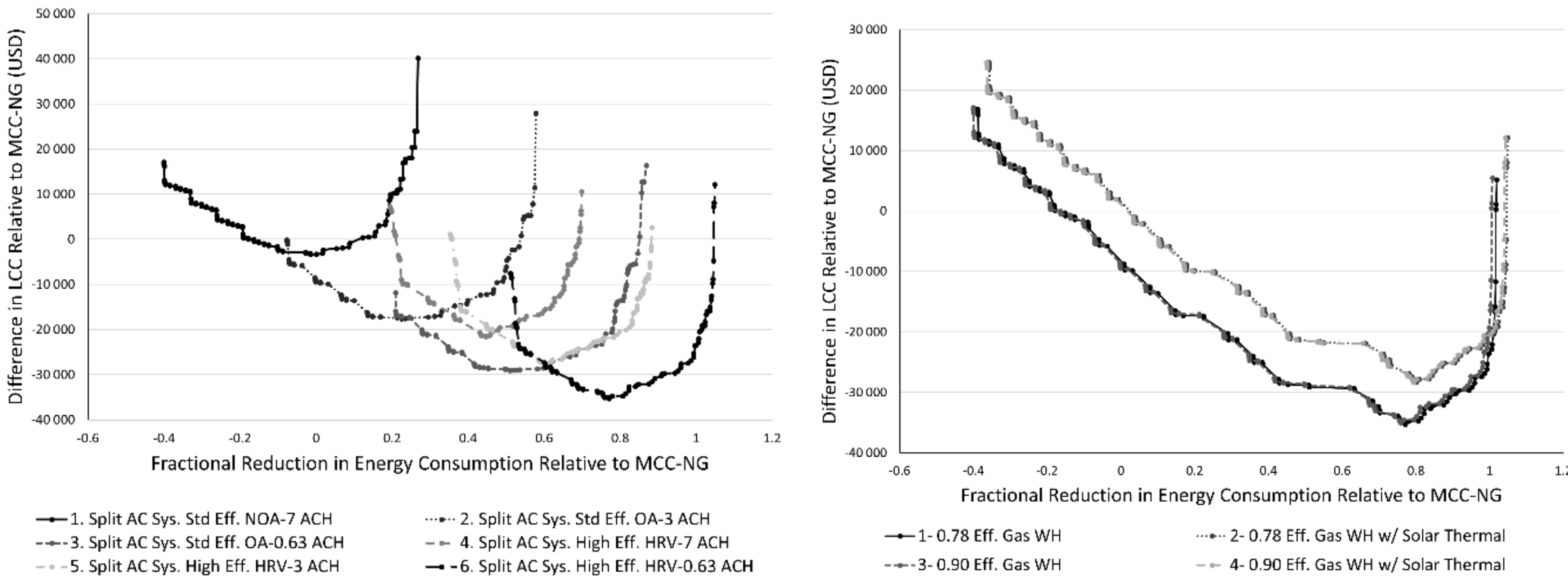
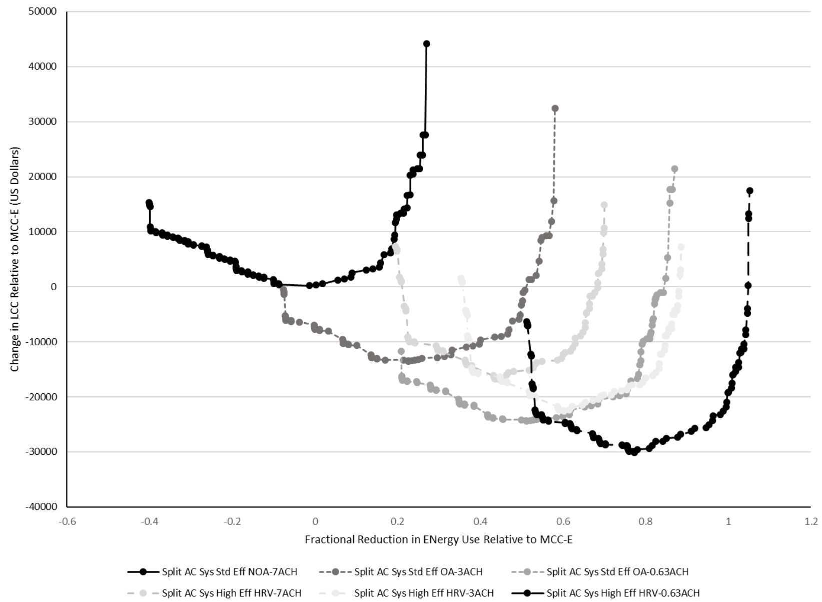


Figure 12. Optimization Curves for Gas-heated Designs based on (a) HVAC System and (b) DHW System from [1]



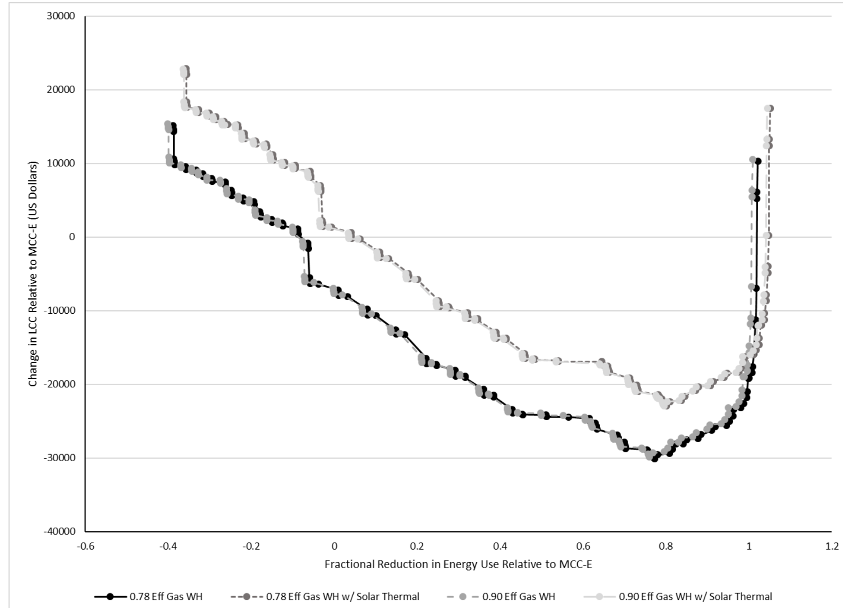


Figure 13. Optimization Curves for Gas-heated Designs based on (a) HVAC System and (b) DHW System using Updated Data

5.4. Cross-comparisons of selected building designs

This section discusses differences between key electric and gas heating system options based on combinations of EEMs, energy, and economic performance.

Table 7 describes the design characteristics of the four key building designs from O'Rear, Webb, Kneifel and O'Fallon (1), while **Table 8** does the same for the updated data. For all four key designs, air leakage performance, lighting, DHW, walls, foundation wall, and foundation floor are identical in the two studies. The windows are the same for LCC-E, LCC-NG, and NZLCC-E while NZLCC-NG installs a less efficient window. The roof assembly is the same for LCC-NG, NZLCC-E, NZLCC-E while LCC-E includes more insulation.

The most noticeable changes are for LCC-E and NZLCC-E, which are now identical. Considering how similar the designs were in the prior study, it is not unexpected that the minor changes in the cost data lead to a shift in the specific EEMs included in the updated results. Both designs increase the size of the installed solar PV system while using the less efficient available HVAC system. The decrease in the marginal cost of installing the additional 2.7 kW of solar PV now makes it more cost-effective than installing the more efficient HVAC system to reach net-zero performance. The LCC-NG result is consistent between the data sets and is the only design that does not include the largest solar PV system available. Even with the minor changes in the selected EEMs, energy consumption values are nearly identical for all four designs relative to the prior study (within 1 %).

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 with the exception of the NZLCC-NG design, which has roughly 150 less hours uncomfortable compared to the NZLCC building and an additional benefit of roughly 100 hours over the all-electric designs.

As in the previous study, net-zero energy performance is reached at the lowest LCC using an all-electric design (NZLCC-E). Reaching net zero using natural gas heating requires additional EEM installations because of higher on-site heating energy consumption. The incremental increase in initial construction costs relative to the code-compliant design in Maryland (MCC-E) is $28 222, which continues a decreasing trend in estimates using the BIRDS database. For example, the BIRDS 4.0 database estimates the same additional construction costs at $34 659. There are two reasons for this result: (1) solar PV has become so relatively cheap to install that the optimal solar PV installation leads to less efficient building envelope selections than is required by the prescriptive path in Maryland code. The 12.7 kW solar PV system, after subtracting the tax credit, costs $26 285. The other EEMs implemented to reach net-zero are replacing light bulbs with LEDs, installing a heat pump water heater, reducing the air leakage rate, and adding slightly more insulation in the roof assembly. Much of the additional costs of these additional EEMs is offset by lower costs by installing less efficient windows and wall assemblies. Over the 30-year study period, NZLCC-E saves the homeowner $34 063. Although the homeowner could save more by designing to meet the lowest LCC design using natural gas heating (LCC-NG), the additional savings is only $527 (over 30 years) while still consuming about 50 % of the site energy relative to that of the MCC-E.

Table 7. Design Features for All-Electric and Gas-heated EE and LCC Building Designs from [1]

Design Category	LCC-E	LCC-NG	NZLCC-E	NZLCC-NG
Windows (U; SHGC)	2.56 W/m²-K; 0.60	2.56 W/m²-K; 0.60	2.56 W/m²-K; 0.60	1.99 W/m²-K; 0.60
Heating & Cooling	SEER 13.0/ HSPF 7.7	SEER 16.0/ AFUE 96%	SEER 13.0/ HSPF 7.7	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 + 0.7	Roof: R_{SI}-7.92 + 0.7	Roof: R_{SI}-7.92 + 0.7
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 8. Design Features for All-Electric and Gas-heated EE and LCC Building Designs using Updated Data

Category	LCC-E	LCC-NG	NZLCC-E	NZLCC-NG
Windows (U; SHGC)	2.56 W/m²-K; 0.60	2.56 W/m²-K; 0.60	2.56 W/m²-K; 0.60	2.28 W/m²-K; 0.60
Heating & Cooling	SEER 13.0/ HSPF 7.7	SEER 16.0/ AFUE 96%	SEER 13.0/ HSPF 7.7	SEER 16.0/ AFUE 96%
Ventilation	Outdoor Air	Separate HRV	Outdoor Air	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	12.7 kW	7.6 kW	12.7 kW	12.7 kW
DHW	Heat Pump	Gas – 90%	Heat Pump	Gas – 90%
Roof	RSI-7.92+0.7	RSI-7.92+0.7	RSI-7.92+0.7	RSI-7.92+0.7
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	RSI-1.41	RSI-1.41	RSI-1.41	RSI-1.41
Found. Floor	RSI-0	RSI-0	RSI-0	RSI-0
Site Energy (kWh)	≈-2796	≈355 880	≈-2796	≈-$2230
Total LCC	$316 483	$315 956	$316 483	$326 876
Energy Savings vs MCC-NG*	-	≈77 %	-	≈100 %
Δ LCC vs MCC-NG*	-	-$31 839	-	-$22 008
Energy Savings vs MCC-E	≈100 %	≈50%	≈100 %	≈100 %
Δ LCC vs MCC-E*	-$34 063	-$34 590	-$34 063	-$23 670
Hrs Uncomfort./Yr	≈415	≈309	≈415	≈155
*30-yr study period				

As in the previous study, the overall environmental performance using the EIS shows that the natural gas designs lead to lower environmental impacts (**Table 9**). As discussed previously, the electricity fuel mix for the PJM Balancing Authority remains "dirtier" than natural gas, leading to higher environmental impacts even when comparing a net-zero energy all-electric design (NZLCC-E) to a natural-gas heated building designed for cost-optimization (LCC-NG). It is difficult to compare these EIS results to the previous study on a total magnitude basis.

Table 9. Environmental Impact Score (EIS) by Key Design and Weighting Approach

Weighting		LCC-E	LCC-NG	NZLCC-E	NZLCC-NG
Updated Database	**BEES**	7.40	6.26	7.40	4.94
	EPA	7.07	6.05	7.07	5.08
*30-yr study period					

6. Conclusion, Implications and Future Research

To maintain the relevance of BIRDS, regular updates to the baseline data are required. It's ability to produce results that are not just accurate, but also meaningful, to users is dependent on the underlying environmental and cost data as well as keeping up with emerging technologies. Recent updates to the underlying cost and environmental data have recently been implemented. As both a validation of these changes and an analysis of changes created in the data, the results of O'Rear, Webb, Kneifel and O'Fallon (1) have been reproduced using the new dataset.

The updated cost and environmental data have a minor impact on the total LCC and the LCA results. Cost changes shift the slope of the LCC against relative energy efficiency slightly upward. Natural gas effects are slightly less in magnitude compared to the all-electric LCC, while relative environmental effects are more pronounced in the all-electric data. Updating the data does shift a few EEMs in optimal designs. The reduction in solar PV installation costs leads to the largest system size (12.7 kW) being utilized in LCC designs, further increasing the ability to achieve energy reductions cost efficiently. However, the magnitude of these benefits is decreased due to the increased construction costs and lower federal solar tax credit.

As in the previous study, net-zero energy performance is reached at the lowest LCC using an all-electric design (NZLCC-E). Reaching net zero using natural gas heating requires additional EEM installations because of higher on-site heating energy consumption. The incremental increase in initial construction costs relative to the code-compliant design in Maryland (MCC-E) is $28 222, which has continued to decrease relative to previous estimates based on previous versions of the BIRDS database. For example, BIRDS 4.0 estimated the net-zero energy design to have an additional initial construction costs of $35 000 relative to 2015 IECC. Other studies of the NIST NZERTF, which relied on the as-constructed specifications of the NZERTF, estimated the additional construction costs as high as $130 000.

The reason for these decreasing additional costs is that solar PV has become so relatively cheap to install that the optimal solar PV installation leads to less efficient building envelope selections than is required by the prescriptive path in Maryland code. The 12.7 kW solar PV system, after subtracting the tax credit, accounts for 93 % of these additional costs ($26 285). The other EEMs implemented to reach net-zero are replacing light bulbs with LEDs, installing a heat pump water heater, reducing the air leakage rate, and adding slightly more insulation in the roof assembly. Much of the additional costs of these additional EEMs (all but $1937) is offset by lower costs from installing less efficient windows and wall assemblies.

Over the 30-year study period, NZLCC-E saves the homeowner $34 063. Although the homeowner could save more designing to meet the lowest LCC design using natural gas heating (LCC-NG), the additional savings is only $527 while still consuming about 50 % of the site energy of the MCC-E.

The implications of on-site generation from solar PV being cheaper than reducing on-site consumption is unexpected because conventional wisdom in reaching net-zero has been to decrease energy consumption as much as possible and then install solar PV to offset the consumption that could not be eliminated. The concept of low-energy buildings must be reconsidered to determine whether new targets should be set, such as a combination of total consumption and net consumption or net-zero goals that include embodied energy. For example, the goal could be set as a 50 % reduction in total annual consumption relative to code-compliance in combination with a net-zero on-site consumption goal. Alternatively, net-zero can be defined as the sum of operational energy and embodied energy. These results are limited in their generalization because they are based on a case study using validated simulation models based on in-situ performance of the NIST NZERTF located in Gaithersburg, MD. The implications should not be extrapolated to buildings with different climates, energy costs, building codes, or occupancies. The assumptions on the economic analysis are also important factors to consider when using the results and implications in this study for decision making. The baseline building designs in this study are based on 2015 IECC. Maryland has since adopted the 2018 IECC, which would influence the relative differences between the optimal designs and the baseline.

Construction costs and environmental impacts of building materials and energy consumption will inevitably change over time, requiring the BIRDS database to be maintained in an ongoing process to keep it up to date. BIRDS is currently limited by its available EEMs and the need to maintain construction cost and building LCA data. For example, the average installed cost of solar PV system has continued to decrease while the federal tax credit will drop from 26 % to 22 % in 2021. At the same time solar panels are becoming more efficient along with shifts in manufacturing locations and processes that will influence the embodied environmental impacts. Additionally, the electric grid fuel mix continues to shift from coal towards natural gas and, to a lesser extent, renewables. All these factors will influence the benefits and costs associated with solar PV installations.

Significant effort and funding are required to maintain BIRDS. In addition, it has been determined there should be a shift to providing sustainability performance (economic and environmental) through separate software tools moving forward. As a consequence, the software tool BIRDS NEST, a collaboration with the Athena Sustainable Materials Institute (ASMI) and Department of Energy (DOE) National Renewable Energy Laboratory (NREL) that allows users to generate custom whole residential building LCIA results, is under development. BIRDS NEST combines the capabilities of Impact Estimator for Buildings with a more expansive set of residential building system options, allowing for whole building LCIA results estimates for any E+ whole building energy simulation developed in OpenStudio. A second software tool that is under development, the Economic Evaluation Engine (E3), provides an API that can be used for back-end calculations of LCCA. The E3 API provides a standardized format using the same ASTM Building Economic Standards implemented in BIRDS. By focusing on the underlying standards-based source data development and back-end calculations engines, NIST will be able to focus its resources on the greatest value add to society. Any user interface will be able to leverage the capabilities of BIRDS NEST and/or E3 to assist and accelerate their own development and analysis.

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Appendix A

Table A-1. Constructions – Roof, Ceiling, Wall and Foundation

Wall Constructions[14]		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 A-2. Window Design Options

Parameter[15]	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

[14] The R-values (R) in **Table A-1** refer 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.
[15] *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.

Table A-3. Design Options for Alternative Air Leakage Rates

Design Option		Assumed Effective Leakage Area (cm^2)	
	ACH$_{50}$[16]	1[st] Floor	2[nd] 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 A-4. Fraction of High Efficiency Fixtures by Requirement

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

Table A-5. Heating and Cooling Equipment Design Options

Design Option	System Components[17]
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 A-6. Domestic Hot Water System Design Options

Design Option	System Components[18]
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 A-7. Solar PV System 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

[16] ACH$_{50}$ – Air Changes per Hour at 50 Pascals
[17] 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.
[18] 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.

Table A-8. Normalization References (Annual U.S. Contributions) and EIS Weights

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