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An Exploration of the Relationship between Improvements in Energy Efficiency and Life-Cycle Energy and Carbon Emissions using the BIRDS Low-Energy Residential Database

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Abstract

To conduct a more complete analysis of low-energy and net-zero energy buildings that considers both the operating and embodied energy/emissions, members of the building community look to life-cycle assessment (LCA) methods. This paper examines differences in the relative impacts of cost-optimal energy efficiency measure combinations depicting residential buildings up to and beyond net-zero energy consumption on operating and embodied flows using data from the Building Industry Reporting and Design for Sustainability (BIRDS) Low-Energy Residential Database. Results indicate that net-zero performance leads to a large increase in embodied flows (over 40%) that offsets some of the reductions in operational flows, but overall life-cycle flows are still reduced by over 60% relative to the state energy code. Overall, building designs beyond net-zero performance can partially offset embodied flows with negative operational flows by replacing traditional electricity generation with solar production, but would require an additional 8.34 kW (18.54 kW in total) of due south facing solar PV to reach net-zero total life-cycle flows. Such a system would meet over 239% of operational consumption of the most energy efficient design considered in this study and over 116% of a state code-compliant building design in its initial year of operation.

Keywords

Embodied emissions; embodied energy; low-energy; net-zero energy; whole-building simulation; residential buildings; life-cycle assessment; life-cycle costing

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1. Introduction

In 2014, the Energy Information Administration (EIA) reported that U.S. residential buildings were responsible for roughly 22% of total domestic primary energy use (U.S. Department of Energy 2015b). As a result, members of the building community underscore the potential to reduce domestic energy use and associated greenhouse gas (GHG) emissions by introducing measures targeting the life-cycle energy and carbon emissions of U.S. residential buildings. Life-cycle energy/emissions, as it relates to buildings, refers to the total energy inputs/emissions released over its life cycle which includes initial construction, maintenance, repair, replacement, and disposal of building components and systems, and operating energy consumption and production (Ramesh, Prakash et al. 2010). Measuring life-cycle energy and carbon emission flows requires the summing of all embodied and operating flows incurred over a building's life-cycle phases. Embodied energy/emissions is the energy utilized/emissions released during the manufacture, installation, and maintenance, repair, and replacement (MRR), and disposal of a building, while the operating energy/emissions is the energy used/emissions released in order to power building systems and maintain daily indoor comfort levels during the operating phase (Dixit, Fernández-Solís et al. 2010, Ibn-Mohammed, Greenough et al. 2013). Currently, building energy codes are a widely-adopted series of measures by many U.S. states and municipal-level governments impacting total life-cycle energy and emissions. The International Energy Conservation Code (IECC), for example, targets the operating energy consumption of commercial and residential buildings. With the release of each new IECC edition, code requirements become more stringent – driving up the minimum efficiency of newly constructed buildings reducing operating energy and GHG emissions. Despite their success, energy codes and other similar standards worldwide only target operating flows, while ignoring embodied energy and carbon (Crawford and Stephan 2013).

Operations-based energy/emissions, as revealed by several studies, account for majority of life-cycle energy demands and carbon emissions for a conventional building (Adalberth, Almgren et al. 2001, Chen, Burnett et al. 2001, Thormark 2002, Blengini and Di Carlo 2010). Increased building efficiency reduces operating energy/emissions at the expense of increased embodied flows potentially offsetting, partially or completely, savings in operational flows (Winther and Hestnes 1999, Monahan and Powell 2011). In fact, it has been found that up to 60% of total life-cycle energy for a low-energy home can be attributed to production-based embodied energy (Thormark 2002, Gustavsson and Joelsson 2010, Praseeda, Reddy et al. 2016).² Given this trend, there has been growing interest within the building community for the use of life-cycle assessment methods to conduct a more complete analysis of buildings that considers both operating and embodied flows. Life-cycle assessment (LCA) is a cradle-to-grave systems approach for measuring environmental performance accounting for inputs and outputs across all stages of a product's life-cycle (Blanchard and Reppe 1998, Fouquet, Levasseur et al. 2015, Anand and Amor 2017). Ibn-Mohammed, Greenough et al. (2013) argue that the omission of embodied flows in building LCAs is increasingly important to rectify as operating efficiency is improved, which holds

²Production-based embodied energy refers to all of the required energy inputs during the production phase of a building, which covers the extraction of raw materials through the development of building materials and energy feedstocks.

true particularly in the case of low-energy and net-zero energy buildings. An area of increasing agreement in studies, at least in principle, if not practice, is the need to account for embodied energy and emissions to properly evaluate energy use and environmental impacts of energy-efficient buildings (Dixit, Fernández-Solís et al. 2012, Ibn-Mohammed, Greenough et al. 2013).

Numerous case studies of conventional and low-energy buildings have included analysis and discussion of operating and embodied energy, as well as tradeoffs between the two (Cole and Kernan 1996, Sartori and Hestnes 2007, Gustavsson and Joelsson 2010, Cellura, Guarino et al. 2014, Reddy, Leuzinger et al. 2014, Chastas, Theodosiou et al. 2016, Crawford, Bartak et al. 2016, Praseeda, Reddy et al. 2016). Upon conducting a study of office buildings in which initial embodied energy accounted for less than 10% of total life-cycle energy, Cole and Kernan (1996) concluded that embodied energy will begin playing more of a dominant role over operating energy as energy standards continue to improve building energy efficiency. Twenty years later, Crawford, Bartak et al. (2016) continues to support this point arguing that the diminishing returns to operating energy efficiency investments warrants the consideration of embodied energy in future building energy codes. In a 2007 study on building life-cycle energy use, Sartori and Hestnes (2007) surveyed literature covering 60 different cases to investigate the relative importance of operating and embodied energy for both conventional and low-energy building designs. From their survey, the authors discovered the existence of a significant “substitution effect” for low-energy buildings as large shares of operating energy associated with conventional buildings are largely offset by increased shares of embodied energy displaying signs of an apparent substitution effect. Gustavsson and Joelsson (2010) later explored tradeoffs between primary energy use during a building’s construction phase and operating energy, showing that production-based energy for conventional single-family homes and apartments can amount up to 40% of total life-cycle primary energy use, while production-based energy for low-energy residential buildings can amount up to 60%. Bagley and Crawford (2015) demonstrate the use of an input-output-based (I-O-based) hybrid LCA model to evaluate alternative building design strategies capable of significantly improving the environmental performance of a single-family dwelling. Relative to their baseline or “original” house design, they determined that life-cycle energy and environmental performance can largely be improved by: (1) reducing heating-related operating energy demands and GHG emissions by replacing the original split system with central heating convectors; and (2) switching out more energy-intensive materials found in the building substructure with materials that traditionally embody less energy. Their work shed light on the potential tradeoffs between operating and embodied flows given the specifications of alternative design strategies. More recently, a literature review conducted by Chastas, Theodosiou et al. (2016) revealed that embodied energy was becoming an increasing share of total life-cycle energy despite growing reductions in operating energy. Estimates from across the literature have embodied energy comprising between 26-57% and 74-100% in the case of low-energy and net-zero energy buildings, respectively.

Crawford, Bartak et al. (2016) utilize a case study house in two Australian cities (Brisbane and Melbourne) to examine total life-cycle energy impacts associated with increases in building thermal efficiency required by Australia’s building efficiency regulations for a 50-

year study period. Using dynamic building energy simulation software and an I-O-based hybrid LCA model to calculate operating and embodied energy measurements, respectively, Crawford, Bartak et al. (2016) find that reductions in operating energy spurred by thermal efficiency improvements have the potential to be offset by increases in embodied energy flows given the use of higher efficiency windows and increased levels of insulation within the building envelope. Similarly, Stephan and Crawford (2016) use I-O-based hybrid LCA methods and operating energy calculations to explore the connection between building size and total life-cycle energy demands. Results suggest a “sublinear” relationship between house size and life-cycle energy demands, as shares of embodied energy demands (relative to total life-cycle energy demands) gradually displace operating energy shares as house size increases. Both Crawford, Bartak et al. (2016) and Stephan and Crawford (2016) underline the importance of making future iterations of building energy efficiency regulations more comprehensive by incorporating embodied energy measurements. More recently, Stephan, Jensena et al. (2017) utilize hybrid LCA to evaluate 87 different façade design variations for an apartment building based on total life-cycle energy impacts. Findings reveal that façade options reducing the overall amount of glazing via reduced window-to-wall ratios and the installation of double-glazed low-emissivity windows have the greatest impacts on building life-cycle energy performance as they significantly drive down both operating and embodied energy flows.

Other studies (Huberman and Pearlmuter 2008, Yeo and Gabbai 2011, Basbagill, Flager et al. 2013, Huberman, Pearlmuter et al. 2015, Stephan and Stephan 2016, Stephan, Jensena et al. 2017) have looked beyond just the tradeoffs between operating and embodied flows for whole-buildings, investigating the impacts of building components on operating and embodied energy/emissions, and how component modifications can be helpful in minimizing these flows. Huberman and Pearlmuter (2008) find that embodied energy made up roughly 60% of the total life-cycle of their building which could be lowered by using alternative building material compositions – in their case, alternative wall infill material. In a later 2015 study, these same authors along with two others discover that the use of alternative structural roof forms can lower production-based embodied energy by as much as 48%, thereby reducing cumulative life-cycle energy flows. Basbagill, Flager et al. (2013) develop a framework applicable to the early building design stage to assist designers in choosing building materials and design components to minimize the building’s overall level of embodied energy. Their case study analysis adopting the framework identified the building’s substructure, shell, and interiors as the largest contributing building components to overall embodied energy. The use of less energy-intensive materials and building practices in these areas could potentially reduce embodied flows significantly. Stephan and Stephan (2016) evaluate the efficacy of 22 different energy reduction measures targeting operational, embodied, and transport-related energy based on their ability to cost-effectively lower total life-cycle energy use. Using a comprehensive I-O-based LCA model, they find that relative to their base conventional design, only minor reductions in embodied energy were achievable using measures reducing the amount of steel and concrete incorporated in the building’s structural system. Installation of a roof-mounted solar photovoltaic system proved to have the single-most impact on operating energy, reducing household energy use at the expense of substantially increasing embodied energy.

In a recent study, Kneifel, O'Rear et al. (2016) investigate the impacts of increased building energy efficiency on the individual components of sustainability performance (energy, economic, and environmental performance) using the BIRDS (Building Industry Reporting and Design contributions of various materials for Sustainability) v3.0 Low-Energy Residential Database. Measurements of sustainability performance for buildings considers building life-cycle costs, energy use, and environmental impacts. They conducted their analysis by comparing the performance of a 2015 IECC compliant single-family dwelling serving as the baseline to alternative residential building designs at varying degrees of efficiency. The new Low-Energy Residential Database included in this latest version of BIRDS is based on measured experimental data from the National Institute of Standards and Technology's Net-Zero Energy Residential Test Facility (NZERTF) and allows users to analyze numerous incremental energy efficiency measures (EEMs) based on 240,000 building component combinations at varying levels of energy-efficiency (Kneifel, Lavappa et al. 2016). Data on the energy and environmental performances of each design in BIRDS is measured using validated whole-building energy simulations and innovative hybrid life-cycle inventories for fuel and building materials, accounting for both the embodied and operating flows.

Kneifel, O'Rear et al. (2016) evaluated energy and environmental performance using measurements of total life-cycle energy and carbon emissions. They did not, however, investigate the implications of efficiency improvements on the individual components (operating and embodied flows) of each life-cycle measurement, or the possible tradeoffs that exist between operating and embodied flows stemming from increases in energy efficiency. This case study serves as an extension of their previous work (Kneifel, O'Rear et al. 2016). Using data from the BIRDS v3.0 Low-Energy Residential Database and a similar methodology, we disaggregate total life-cycle energy and emissions into its operating and embodied counterparts, and examine how these separate components are affected by increases in building energy efficiency. In other words, alternative combinations of EEMs will be evaluated based on their relative impacts on not just operating energy and emissions, but also on embodied energy and emissions. Doing this entails making comparisons between an IECC code-compliant design serving as the baseline, and a group of cost-effective, low-energy and net-zero energy building designs selected based on a series of pre-defined objectives. Our focus on cost-effective, low-energy and net-zero energy designs is driven by the likelihood that these types of homes will be constructed in the future. Since greater efficiency in homes is becoming more and more attainable at a lower cost to the developer and/or homeowner over a building's life-cycle, future building energy codes will continue calling for stricter energy efficiency requirements – thereby, increasing the significance of embodied energy relative to total life-cycle energy. Findings from this work will reveal: (1) the best possible combination of EEMs to minimize household operating energy use and emissions; (2) the best possible combination of EEMs to minimize embodied energy and emissions; and (3) tradeoffs between operating and embodied flows for different combinations of EEMs.

Unlike much of the previous work on embodied energy and emissions for whole-buildings – in, low-energy and net-zero energy buildings – an advantage of the approach taken in this study is that the tradeoffs entailed in incremental design changes can be evaluated within the

consistent context of a fully specified, validated whole-building energy model of a single-family dwelling. The impact of design choices on the energy and environmental outcomes are not additive functions of the EEMs chosen but interact in a nonlinear fashion. The marginal effect of changing any component is informed given the state of other critical design choices. As a result, the findings of this paper demonstrate the value of the BIRDS software tool and its databases as a decision support tool.

2. BIRDS Low-Energy Residential Database

The BIRDS Low-Energy Residential Database depicts homes at differing levels of energy-efficiency based on alternative combinations of EEMs characterizing aspects of the building's envelope and systems. These variations in efficiency coincide with variations in measured operating and embodied energy/carbon levels. The following sections provide background on the BIRDS software tool and the low-energy database, as well as describe each of the building envelope and system component options available within the database. Combinations of these building components will later be used in the paper to define alternative building design cases from which the estimated operating and embodied flows will be used to explore the relationship between energy efficiency and embodied and operating energy/carbon.

2.1 Background

Developed by researchers at the National Institute of Standards and Technology (NIST), the BIRDS software tool evaluates the sustainability performance of buildings by applying whole-building sustainability metrics based on the use of whole-building energy simulations, as well as life-cycle impact assessment (LCIA) and life-cycle costing approaches to entire buildings (Lippiatt, Kneifel et al. 2013). The measurement system assesses the sustainability performance of the materials and energy used by a building over a period of operation. It integrates 12 environmental performance metrics with economic performance metrics to yield science-based measures of the business case for investment choices in high-performance green buildings (Lippiatt, Kneifel et al. 2013).

BIRDS uses a hybridized LCA approach for measuring whole-building environmental performance by considering an inventory of inputs and outputs across all stages and associated activities of a building's service life: initial construction, maintenance, repair, replacement, and disposal of building components and systems, and operating energy consumption, and on-site production. 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 ten impact categories (Bare 2011)³ and includes two additional impact categories.⁴ For further details on the impact categories, see Kneifel, Lavappa, et al. (2016). Given the nature of the underlying LCA inventory data used in BIRDS, environmental impact measurements can be disaggregated into its embodied and

³The TRACI 2 impact categories: (1) Acidification Potential, (2) Global Climate Change Potential, (3) Ecological Toxicity, (4) Eutrophication Potential, (5) Human Health – Criteria Air Pollutants, (6) Human Health – Cancer Effects, (7) Human Health – Non-cancer Effects, (8) Ozone Depletion, (9) Primary Energy Consumption, and (10) Smog Formation.

⁴The other two impact categories are: Land Use and Water Use.

operating environmental flow components – providing a means by which one can examine measures of embodied and/or operating environmental flows for alternative building designs.

The latest version of BIRDS (v3.0) allows for the detailed analyses of incremental EEMs for a single location (Gaithersburg, MD) through its inclusion of the Low-Energy Residential Database, which includes data for 240,000 incremental whole-building (residential) energy simulations based on Kneifel (2012), Kneifel (2013), Kneifel, Payne et al. (2015), Kneifel, Lavappa et al. (2016), and Kneifel, O'Rear et al. (2016), which used architectural specifications and experimentally measured performance data from the demonstration phase of the NZERTF to validate the simulation results.⁵ The database covers requirements based on the five most recent editions of the IECC (ICC 2003, ICC 2006, ICC 2009, ICC 2012, ICC 2015), the NIST NZERTF as described by Petit, Gates et al. (2015), and incremental EEMs for study period lengths up to 40 years. The Low-Energy Residential Database was developed for evaluating the sustainability performance of homes at differing levels of energy-efficiency. Given the BIRDS methodology to evaluating a building's environmental performance, database results can be used to explore the dynamics between energy efficiency and operating and embodied flows – in, energy and carbon.

2.1.1 Building envelope, building systems, and analysis options—The current EEM construction options for each component of a buildings' envelope (wall, roof/ceiling, foundation, windows, air leakage rates) are listed in Table A1, Table A2, and Table A3 in the Appendix section. Options are listed in order of increasing energy efficiency. The five window options vary based on alternative specifications for the U-Factor, Solar Heat Gain Coefficient (SHGC), and Visible Transmittance (VT).⁶ Air leakage rates are expressed in terms of air changes per hour at 50 Pa (ACH₅₀) using a blower door test. The first leakage option is based on the requirements of the 2009 IECC,⁷ while Option 2 and Option 3 are based on the 2015 IECC and the measured air leakage of the NZERTF, respectively.⁸

Options for each of the primary building systems are listed in Table A-4, Table A-5, Table A-6, and Table A-7. Lighting wattage options (Table A-4) are defined in terms of the fraction of light fixtures that utilize high efficiency bulbs, and are based on a “typical/baseline” lighting mix from Hendron and Engebrecht (2010), requirements defined in editions of the IECC, and the NZERTF.⁹ Additional details on the interior lighting options can be found in Kneifel, Lavappa et al. (2016). Option 1 for the heating and cooling equipment (Table A-5) reflects a “standard efficiency” system that meets the minimum federal efficiency and IECC requirements. There is also mechanical dedicated outdoor air ventilation which meets the ventilation requirement defined by ASHRAE 62.2-2010

⁵Gaithersburg, MD is the assumed location for all simulations given that the NIST NZERTF is located on the NIST main campus in Gaithersburg, MD.

⁶Window parameter values are based on minimum requirements specified in editions of the IECC and Building Science Corporation (BSC) window specifications for the NZERTF (ICC 2003, ICC 2006, ICC 2009, ICC 2012, ICC 2015, Petit, Gates et al. 2015). Using these parameters assumes no difference in performance regardless of the window type (awning or double hung).

⁷Note that 2003 IECC and 2006 IECC set no maximum limit on air leakage and assumed to have the same requirement as 2009 IECC for the purpose of this study.

⁸Modeling air leakage in our simulations required that we convert the air changes per hour to a measure of effective leakage area (ELA). This was done using the conversion formula found in the Chapter 16 of ASHRAE (2012). The resulting ELA is then split between the two conditioned floors of the home based on the fractional volume of each floor.

⁹Additional details on the interior lighting options can be found in Kneifel, Lavappa et al. (2016).

(ASHRAE 2010). Option 2 is a higher efficiency, multispeed air-to-air heat pump. Mechanical ventilation is provided using a separate, dedicated outdoor air system with a Heat Recovery Ventilator (HRV) to meet ASHRAE 62.2-2010 outdoor air requirements. Both options include a supplementary electric heating element (0.98 efficiency) to supplement the heat pump when the primary system cannot meet the thermal loads of the building.¹⁰

The household domestic hot water (DHW) options (Table A-6) include: (1) an installed “standard” efficiency (0.95) electric water heater (50 gal) serving as the primary system; (2) an air-to-water heat pump water heater with a Coefficient of Performance (COP) of 2.36 serving as the primary system; (3) a standard efficiency electric water heater for the primary system with an auxiliary two-panel, 4.6 m² (50 ft²) solar thermal system; and (4) a heat pump water heater with auxiliary solar thermal system.¹¹ The five roof-mounted solar photovoltaic (PV) system options defined in Table A-7 are based on the NIST NZERTF roof-mounted system (Option 5). The other options depict the removal of roughly one-quarter capacity of the 10.2 kW system until there is no solar PV system at all. It is assumed that all panels degrade annually at a rate of 0.5%.¹²

BIRDS v3.0 offers alternative assumptions for four primary analysis parameters: study period length, discount rate, financing option, and construction quality. Each parameter directly affects calculations of building life-cycle costs. The database gives users the option to choose between: (1) study period lengths of 1 year to 40 years;¹³ (2) discount rates of 3% and 8%.¹⁴ (3) an upfront, full cash purchase and standard mortgage financing;¹⁵ and (4) average versus luxury construction quality.¹⁶ As will be discussed in greater detail in a later section, the economic analysis component of this study will be based on a distinct combination of these parameters.

3. Research Methodology

This case study compares the environmental performance of a baseline building design constructed according to the requirements of the 2015 IECC for the state of Maryland, to that of select group of low-energy and net-zero energy design alternatives available within the BIRDS Low-Energy Residential Database and more energy-efficient than the baseline. The following sections provide background on the specifications of our baseline building, an

¹⁰See Kneifel, Lavappa et al. (2016) for additional details on the components of each HVAC system option.

¹¹See Kneifel, Lavappa et al. (2016) for additional details on the domestic hot water heating systems.

¹²See Kneifel, Lavappa et al. (2016) for additional details on the alternative solar PV system setups.

¹³The wide-range of study period length options captures an array of different attitudes or preference held by investors. In an effort to remain consistent with the building life-cycle cost analysis structure outlined by the Energy Independence and Security Act of 2007, we allow for a maximum study period length of 40 years.

¹⁴The 3% discount rate is the accepted discount rate by the Department of Energy for use in the cost analysis of federal energy conservation projects. It is based on average 10-year Treasury note yields and reflects a more conservative, risk-averse investor. The 8% rate better represents the long-run real (inflation adjusted) rate of return from investments in equities and reflects an investor more accepting of risk.

¹⁵The loan option assumes a 20% down payment with the remainder of the initial investment financed at 4.375%, which was the prevailing U.S. national average rate for a 30-year mortgage during the creation of the BIRDS Low-Energy Database.

¹⁶Building investors/owners generally consider the role construction quality plays in overall building costs, as it affects initial investment/construction costs. Users of BIRDS v3.0 can factor quality into their life-cycle cost estimates by choosing between either average construction quality or luxury construction quality.

in-depth explanation on how the three individual aspects of sustainability are measured, and the use of Pareto frontiers to select the key building designs evaluated in this study.

3.1 Specifications of the Maryland Code-Compliant Design

To analyze alternative combinations of EEMs in this study, comparisons across 240,000 building designs must be made relative to a baseline building. The Low-Energy Residential Database is based on NIST's NZERTF constructed in Gaithersburg, MD; therefore, it was decided that the baseline building should reflect Maryland's building energy code, which is based on the 2015 IECC. The baseline building, also referred to as the Maryland Code-Compliant (MCC) design in this study, was developed based on the 2015 prescriptive path requirements (ICC 2015). Table A-8 lists the building envelope and building systems specifications for the MCC design.

3.2. Operating Energy Performance

The energy performance for each of the 240,000 building component combinations included in the BIRDS Low-Energy Residential Database is based on a measure of total net operating energy flows – difference between the total source energy used to operate a building and the amount of source energy offset by on-site solar PV production.¹⁷ 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 (Zhang and Korolija 2015, U.S. Department of Energy 2015a).¹⁸ The difference in the two simulation outputs is then scaled using a multiplier to derive total source energy. In comparing the net operating energy flows between the MCC design and other energy-efficient alternatives, the potential energy savings recouped by incrementally changing a component or components of a building envelope and/or system is revealed.

To simplify the analysis, it is assumed that buildings maintain their level of energy-efficiency over the study period and annual energy use remains constant from year to year. The reasoning for this assumption being that the costs and associated embodied energy/emissions of maintaining and/or replacing aspects of the building is reflected in the analysis. This, however, will not be the case for on-site renewable energy production, which is assumed to have annual production degradation of 0.5% over the lifetime of the solar PV system. The net operating energy flow estimate over the study period will be used as the basis for calculating the net operating energy-related emissions in Section 4.2.3.

3.3. Environmental Impact Performance

This study uses LCA inventory data and LCIA methods to quantify environmental impacts and link their potential contributions to a range of impact categories. Since the focus of this study is embodied and operating energy/carbon, only two impact categories are considered: Primary Energy Consumption and Global Climate Change Potential. Primary energy consumption (Btus) measures fossil fuel resource depletion, and includes both the operating

¹⁷Source energy, as it relates to buildings, refers to the total amount of raw fuel used to power a building and maintain its daily operations. It considers all energy use, including that which is lost during production, transmission, and delivery.

¹⁸Site energy refers to the amount of energy shown on a utility bill. It is the final form of energy consumed by the homeowner.

energy consumption and the embodied energy consumption in the building material's life-cycle. Global climate change potential measures the amount of greenhouse gas emissions in carbon dioxide-equivalent (CO₂e) released into the atmosphere, including carbon dioxide, methane, chlorofluorocarbons, and ozone, throughout a building material's life-cycle.

The BIRDS LCIA approach assesses a building design's environmental impact performance using the integrated I-O-based hybrid LCIA framework developed in (Suh and Lippiatt 2012) specifically designed to allow for whole-building LCA analysis. Process-based LCA systematically estimates detailed environmental inputs and outputs using all non-negligible process flows, which requires time consuming and costly data collection and leads to boundary conditions that truncate some fraction of associated flows. I-O LCA analysis quantifies proportional interrelationships among economic sectors, which eliminates the boundary conditions by accounting for the entire economy. However, I-O analysis can only be completed at the granularity of the economic sector data (Dixit 2017). A hybrid LCA approach attempts to combine the best characteristics of the two approaches to improve consistency in system boundary selections and minimize truncation that results from process-based LCA while accounting for differences between specific building technologies not differentiated in I-O LCA data tables (Guan, Zhang et al. 2016, Dixit and Singh 2017). In the case of a building, it is not feasible given time and budget constraints to develop a process-based LCA for every product installed in a building. At the same time, I-O analysis cannot identify the trade-offs between two building components. The integrated I-O-based hybrid LCIA framework is applied in BIRDS by combining "top-down" I-O environmental flow data used in estimating the total LCIA flows for a baseline building design, with "bottom-up," processed based data to account for environmental flows associated with changes in individual building components and component combinations, including embodied flows and operational energy flows (Kneifel, Lavappa et al. 2016). Compared to other LCA assessments methods, I-O-based hybrid LCA offers the most comprehensive approach to embodied energy assessments, combining the advantages of both a bottom-up and top-down approach. Many studies discussed in the introduction (Crawford and Stephan 2013, Bagley and Crawford 2015, Crawford, Bartak et al. 2016, Stephan and Crawford 2016, Stephan, Jensen et al. 2017) were conducted using I-O-based hybrid LCA models – an indication of the method's growing popularity amongst LCA practitioners.

The scope of the LCA analysis requires defining the study period, functional unit, and allocation method. In the BIRDS model, the functional unit is construction and use of a building prototype over a user-defined study period. A residential building lifetime is assumed to be 65 years, longer than the 30-year study period considered in this study. Therefore, 100% of each building is "recycled" at the end of the study period and there are no end-of-life waste flows allocated to the building at the end of the study period. Rather, end-of-life waste flows should be allocated to a different "product," representing use of the building from the end of the study period to the end of the building service life. Similarly, the environmental burdens from building construction are allocated only to its first use (equally distributed across each year of the selected study period). This effectively credits the use of existing buildings over new construction and ensures there will be no double counting if the framework is applied to existing building LCA analysis (Kneifel, Lavappa et al. 2016). The equal distribution of construction flows across each year of a building's

service life, or annualized flow approach, is a common practice (Hannon, Stein et al. 1978, Zimmermann, Althaus et al. 2005, Hernandez and Kenny 2008, Blengini and Di Carlo 2010, Hernandez and Kenny 2010) in building-related LCA evaluation. Annualization allows for relatively straightforward comparison of embodied and operating flows independent of the selected study period because the flows associated with the initial construction are allocated across its service life instead of now of finished construction. This allows for a long-term environmental impact perspective while allowing BIRDS users to select a shorter study period that aligns with their desired investment time horizon. Treating the construction flows as “sunk” at the beginning of the study period will lead to embodied flows accounting for much larger fractions of overall flows than is the case for longer study periods, which can skew interpretations of the energy and environmental trade-offs of greater energy efficiency. Building components that have a different service life than the building itself (e.g. HVAC systems) use the same annualized approach based on their specific service life.

Scoping also requires defining data requirements. The BIRDS inventory data are generally U.S. average data. An exception is made for the electricity production inventory data applied to a building’s use of electricity to convert site flows to source flows, which are customized to each U.S. state using 2008 eGRID data from NERC subregions (U.S. Environmental Protection Agency 2008), while data for specific fuel use/combustion in a utility originates from the U.S. LCI database. The *top-down* inventory data is based on the 2007 release of the 2002 BEA I-O data (newest available at the time of development) quantifying 6,204 environmental inputs and outputs occurring throughout production supply chains for the construction sector, which was disaggregated into building type-specific flows per dollar of expenditure for construction, maintenance, and repair (Lippiatt, Kneifel et al. 2013). For this study, LCA flows per dollar of expenditure for “residential new construction” and “residential maintenance and repair” were used in the analysis.

For the *bottom-up* inventory data on building energy technologies, the most representative technology for which data are available is evaluated using both primary and secondary data sources dependent on the level of disclosure preference by coordinating organizations and companies. The most temporally, technologically, and geographically representative data was selected for each building component based on four types of data sources in descending order of preference: (1) Primary data from a group of companies and/or an industry association, compiled into an industry average product; (2) primary data on a product provided by one company; (3) secondary data that represent an average or typical product; and (4) secondary data that represent one product in a category. Background data sources are primarily the U.S. LCI database and Ecoinvent v2.2 database (Kneifel, Lavappa et al. 2016). All building component process-based LCA data are in terms of flow per functional unit of the specific component.

The flows from a building’s life-cycle stages are grouped into two categories, embodied flows that include flows associated with the initial construction and the maintenance, repair, replacement, and disposal of building components and systems, and operating flows resulting from energy consumed and produced during the use of the building. The formulas described below are used in calculating the flows for both the embodied and operational flows for energy and embodied and operational flows for CO₂e.

The embodied energy flows and embodied CO₂e flows (non-energy-related flows) for the baseline design (i.e., **MCC**) are estimated using the I-O (top-down) environmental flow data described above, which are expressed as a flow per dollar. According to Equation (3-1), the embodied flows for the baseline design ($LCIA_{MCC}^{Embod}$) are calculated by adding the annualized embodied flows of constructing the building and the baseline MRR embodied flows over the study period (T), otherwise known as the investor time horizon. The annualized embodied construction flows are calculated by multiplying the baseline construction costs ($Const_{MCC}$) by the associated flows per dollar spent on construction ($Flow/\$_{Const}$) for “residential new construction” discussed above, and then multiplying by the ratio of the study period length to the building’s assumed service life (L_B). The embodied flows from baseline MRR are calculated by taking the sum of the baseline MRR costs (MRR_{MCC}) for each year over the study period by the associated flows per dollar ($Flow/\$_{MRR}$) for “residential maintenance and repair” discussed above.

$$LCIA_{MCC}^{Embod} = (Const_{MCC} * Flow/\$_{Const} ; *T/L_B ;) + \left(\sum_1^t MRR_{MCC,t} * Flow/\$_{MRR} ; \right) \quad (3-1)$$

Where	$LCIA_{MCC}^{Embod}$	= embodied flows for the baseline design
	$Const_{MCC}$	= baseline construction costs
	$Flow/\$_{Const}$	= flows/dollar spent on new construction
	$Flow/\$_{MRR}$	= flows/dollar spent on <i>MRR</i>
	$MRR_{MCC,t}$	= baseline <i>MRR</i> costs in year “ <i>t</i> ”
	L_B	= building’s assumed service life
	T	= study period

For a given building design, the baseline embodied energy and embodied CO₂e flow estimates are adjusted for building component differences (e.g. more insulation or higher efficiency HVAC equipment) relative to the baseline design (**MCC**) using “bottom-up,” process-based LCA data for building envelope assemblies and building systems described above. The unit for each of the building components (U_C) are expressed as flows per unit ($LCIA_{X,C}^{Const}$) for each building component “*C*”, for which units are in area for building envelope assemblies and per system for building equipment.

For building design “*X*,” the total embodied flows ($LCIA_X^{Embod}$) is sum of three values as shown in Equation (3-2): baseline design embodied flows, differences in embodied flows associated with each building component with relation to construction, and differences in embodied flows associated with each building component’s MRR. Construction related flows for a building component “*C*” are the difference in embodied construction flows per unit of “*C*” between building design “*X*” ($LCIA_{X,C}^{Const}$) and the baseline building design ($LCIA_{MCC,C}^{Const}$) multiplied by U_C multiplied by the ratio of the study period to the service life each building component “*C*” (L_C). The MRR-related flows are the difference in MRR

flows per unit of “C” for each year between building design “X” ($LCIA_{X,C,t}^{MRR}$) and the baseline building design ($LCIA_{MCC,C,t}^{MRR}$) multiplied by U_C summed over the study period.

$$\begin{aligned}
 LCIA_X^{Embod} &= LCIA_{MCC}^{Embod} \\
 &+ \sum_1^C \left[\left(LCIA_{X,C}^{Const} - LCIA_{MCC,C}^{Const} \right) * U_C * \frac{T}{L_C} \right] \\
 &+ \sum_1^T \sum_1^C \left[\left(LCIA_{X,C,t}^{MRR} - LCIA_{MCC,C,t}^{MRR} \right) * U_C \right] \quad (3-2)
 \end{aligned}$$

Where	$LCIA_X^{Embod}$	= embodied flows for building design “X”
	$LCIA_{MCC}^{Embod}$	= embodied flows for the baseline building design
	$LCIA_{X,C}^{Const}$	= embodied construction flows/unit of “C” for building design “X”
	$LCIA_{MCC,C}^{Const}$	= embodied construction flows/unit of “C” for baseline building design
	$LCIA_{X,C,t}^{MRR}$	= MRR flows per unit of “C” for year “t” for building design “X”
	$LCIA_{MCC,C,t}^{MRR}$	= MRR flows per unit of “C” year “t” for baseline building design
	U_C	= unit for building component “C”
	L_C	= component “C” assumed service life
	T	= study period

Equation (3-2) does not account for the energy consumption and CO₂e emissions associated with the operation of the building. Building operation includes the energy consumed by the building and associated CO₂e emissions over the study period. Energy-related CO₂e emissions are derived using bottom-up, process-based LCA data based on the average source CO₂e emissions rates for electricity generation in Maryland (Kneifel, Lavappa et al. 2016), which treats all units of consumption and production as equivalent regardless of date and time of consumption during the year.¹⁹ Because electricity is the sole energy source consumed by all building designs in the BIRDS Low-Energy Residential Database, all energy-related CO₂e emissions are from electricity consumption.

According to Equation (3-3), operation-related energy and CO₂e emissions for each building design ($LCIA_X^{Elec}$) are calculated by multiplying the source flow per unit of electricity ($Flow/U_{Elec}$) by the total net number of units of electricity consumed (consumption minus production) for each year in the study period ($U_{Elec,t}$) and summing over all years of the study period.

¹⁹This assumption does not account for differences in the source fuel mix of electricity, which varies both by day and by time of day. Future research should consider how the timing of on-site production from solar photovoltaics may offset generation that may have a different fuel mix than the average fuel mixes over the year.

$$; LCI A_X^{Elec} = \sum_1^t \left(U_{Elec,t} * Flow / U_{Elec} \right) \quad (3-3)$$

The sum of the embodied flows ($LCI A_X^{Embod}$) and operational flows ($LCI A_X^{Elec}$) is the total life-cycle flows for a given building design for the given study period.

3.4. Economic Performance – Life-Cycle Costing

To evaluate the economic performance of each building design, the life-cycle cost (LCC) methodology, as defined in Handbook 135 (Fuller and Petersen 1996), is used. The LCC for a building accounts for all costs of constructing, operating and disposing of a building for a given study period length. In calculating LCC, the sum of the costs (C_t) realized in each year (t) of the study period (N) is discounted using discount rate d into present value terms as shown in Equation (3-4). When comparing a baseline building design to some alternative, the design with the lower LCC is the more lower cost alternative.

$$LCC = \sum_{t=0}^N \frac{C_t}{(1+d)^t} \quad (3-4)$$

Use of the LCC methodology sheds light on the economic viability of building design options captured by the BIRDS Low-Energy Residential Database for given levels of energy efficiency. In comparing LCC estimates for the baseline design and more energy-efficient design alternatives, the additional costs to the homeowner of reducing their annual energy use are revealed. Conversely, cost comparisons also reveal the existence of building designs that are not only more energy-efficient than the MCC design, but also prove to be more economical over the selected study period.

3.5. Constructing the Pareto Frontier and Selecting Key Building Designs

The select group of cost-effective, low-energy and net-zero energy building designs evaluated in this study were chosen based on both an energy and economic analysis performed under the assumptions of a 3% discount rate, average construction quality, use of mortgage loan financing (20% down payment), and a study period of 30 years. Owners of energy-efficient homes are not likely to recoup the significant upfront costs required to construct these homes in the first few years of ownership. The lower discount rate option was chosen given that it best reflects a more patient investor/homeowner. The luxury construction quality option was ignored since the upgrading of amenities relative to an “average” design impacts investment costs equally across all building designs – thereby, having no impact on the relative economic performance of each building. The mortgage loan financing and a 30-year study period assumptions best reflect common home buying practices in the U.S. today, as most U.S. homeowners do not have the means to fully finance the construction of a new home themselves, and rely on home loan financing programs with a typical financing period of 30 years. The low-energy database currently does not account

for financial incentives, such as the Federal Solar Investment Tax Credit (ITC),²⁰ which can significantly decrease costs of a building over its lifetime.²¹ This economic analysis includes the recently extended ITC (U.S. Congress 2015).²²

The results of both the energy and economic analysis were used to construct a Pareto frontier, from which a select group of cost-effective designs were identified based on meeting one of the following criteria: (1) the most energy-efficient design at a level of LCC equal to that of the baseline (**EE-BaseLCC**), (2) the most energy-efficient design overall (**EE**), (3) the minimum LCC design (**Min-LCC**), and (4) the design achieving net-zero or better at least cost (**LCC-NZE**). A Pareto frontier, in this case, refers to the set of all building designs that are possible “best” choices based on a relationship between two or more performance variables. The relationship between energy savings and changes in LCC was used to construct the frontier. All the best or “optimal” design choices are located along the frontier. Those located above the frontier are not considered optimal as there will always be an option that performs just as well (as it relates to net energy savings), and is more cost-effective.

The first step in constructing the Pareto frontier is to plot all 240,000 data points (in blue) based on the results of our energy and economic analyses assuming a 3% discount rate, average construction quality, mortgage loan financing, and a 30-year study period (Figure 3-1). The horizontal axis (x-axis) is the percent reduction in net energy consumption relative to the baseline **MCC** design (x-axis), while the vertical axis (y-axis) is the difference in LCC between the plotted design and the **MCC** design. From the data plot, we then create the Pareto frontier (in orange) by connecting all the data points for building designs realizing the lowest LCC for a given level of net energy savings.

Only five building designs along the Pareto frontier were selected for this analysis to limit its scope. Again, the **MCC** design serves as the baseline. The performance of the other four designs (**EE-BaseLCC**, **EE**, **Min-LCC**, **LCC-NZE**) will be evaluated relative to the baseline. When compared to the **MCC** design, these four designs are all more energy-efficient but vary in relative cost-effectiveness.

4. Results and Discussion

Kneifel, O’Rear et al. (2016) analyzed the BIRDS Low-Energy Residential Database to estimate the effects of incremental changes in energy efficiency on a building’s overall life-cycle energy, economic, and environmental performance. The analysis excluded consideration of the impacts energy efficiency improvements have on the individual components of total life-cycle energy use and CO₂e emissions. Our study builds on their work and by disaggregating total life-cycle flows into operating and embodied flows,

²⁰The recently extended Federal Solar Investment Tax Credit (ITC) was initially established under the Energy Policy Act of 2005. It gives a 30% tax credit for solar systems on residential and commercial properties through 2019 – after which, the credit decreases before disappearing in 2023.

²¹The Solar ITC and other financial incentives were not included in BIRDS v3.0 because: 1) the federal mandate requires a ramping down of the tax credit over the next few years; and (2) a desire to maintain the flexibility of the BIRDS tool, so that its users are able to apply incentives that are specific to their own interest. Future versions of BIRDS will include an option for the ITC.

²²Inclusion of the ITC in our analysis is done using the raw dataset from the BIRDS v3.0 database. The credit is applied at year zero to offset the upfront investment costs of the solar PV system in all life-cycle cost calculations.

examining how the relative proportions of each changes given incremental improvements in building energy efficiency.

In the sections that follow, we first examine the effects incremental changes in individual EEMs have on operating and embodied flows relative to our **MCC** design, compare the **MCC** design to four optimal design alternatives, and reveal the potential tradeoffs between operating and embodied energy and CO₂e emissions for different combinations of EEMs.

4.1. Evaluating the Impacts of Incremental Building Design Options on Sustainability

The first comparison considers changes in flows associated with incremental changes in each EEM holding all other EEMs constant. To do this, the **MCC** design is modified for one building component at a time based on component options discussed in Section 2. Table 4-1 shows the calculated percentage changes in net operating energy (OENF), operating CO₂e or “carbon” emissions (OEMF), embodied energy flows (EENF), and embodied emission flows (EEMF). In the case operating energy and emissions, a single value is listed for each option since changes in operating carbon emissions are proportional to changes in operating energy. These results hold across all discount rates, financing, and construction quality assumptions because there is no cost-based EEM selection process. The EEMs that lead to the greatest reductions in operating energy and carbon are the installation of the solar PV systems (up to 60.60%), reduced air leakage (20.60%), more efficient HVAC equipment (15.20%), more efficient DHW equipment (up to 9.2%), and advanced framing coupled with additional rigid insulation in the wall assembly (up to 6.80%). Other EEMs lead to fewer savings in operating energy and carbon, including higher efficiency windows and increased ceiling/roof assembly insulation that generate savings of 3.00% or less.

Unlike operating flows, EENF and EEMF do not change proportionally. Table 4-1 reveals that EEMs leading to the greatest reductions in operating flows (i.e., solar PV, air leakage rates, HVAC, and DHW) also produce the greatest increases in embodied flows. Reducing the air leakage rate of the **MCC** to 0.63 ACH₅₀ increases EENF and EEMF by roughly 7.0% and 30.3%, respectively. Installation of a roof-mounted solar PV system can increase EENF by as much as 25.8% and EEMF by as much as 31.1%. The use of more efficient HVAC equipment increases EENF by 1.4% and EEMF by 4.5%, while the installation of more efficient DHW equipment can increase EENF and EEMF by as much as 4.0% and 5.2%, respectively. Similarly, measures triggering minor reductions in operating flows trigger minor increases in embodied flows.

The results from Table 4-1 highlight potential tradeoffs between operating and embodied flows for increasing energy efficiency performance, with incremental EEMs reducing operating energy and emissions while simultaneously increasing embodied energy and emissions. The ratio of reduced net operational energy use to increases in embodied energy – referred to as the “energy tradeoff ratio” for energy in this study – ranges approximately from 1:1 to 89:1 depending on the building component. The 1:1 ratio is based on the use of R_{SI}-3.9 insulation in the foundation walls, while the 89:1 ratio stems from the use of a high efficiency heat pump water by the DHW system. The “emissions tradeoff ratios” comparing reductions in operating emissions to increases in embodied emissions range approximately from 1:1 to 19:1, where the former ratio reflects the use of advanced framing and

R_{SI}-3.5+4.2 wall insulation, and the latter reflects the use of a heat pump water heater by the DHW system. Both the energy and emissions tradeoff ratios reveal two things: (1) the impacts of incremental increases in energy efficiency on net life-cycle energy and emissions; and (2) which measures can capture the greatest amount of operating energy and emissions savings given an incremental increase in embodied flows.

Although it is important to understand the impacts of incorporating individual EEMs into a building design, evaluating combinations of EEMs based on their impacts on operating flows is not as simple and straightforward as adding up operating flow changes across the individual EEMs due to the interactions between building components. For example, improving the thermal performance of the building envelope by increasing the level of insulation in the walls will decrease the thermal loads of the house. Smaller heating and cooling loads decrease the amount of energy consumed by the HVAC system and lead to less savings in operating energy and emissions realized by the installation and use of more efficient HVAC equipment. This case study explores these building component interactions, analyze how these interactions translate to disproportional changes in operating energy and emissions flows. Additionally, tradeoffs between operating and embodied energy and emissions flows for alternative combinations of EEMs are explored.

4.2. Case Study using BIRDS v3.0

The four key building designs evaluated in this case study were selected based on both their energy and economic performance under assumptions of a 3% discount rate, average construction quality, the use of loan financing, and a 30-year study period. This section discusses the different design feature combinations of each optimal design, as well as include results on the varying impacts these designs have on operating and embodied energy and emissions flows.

4.2.1 Summary of key building designs—Table 4-2 lists the primary building design feature combinations for each of the building designs selected for this study, which are the optimal designs to meet the four goals specified in Section 3.5. The operating energy savings and changes in total LCC for these four designs relative to the **MCC** design given a 30-year study period are also included. The four key designs are consistent across several of the EEMs, all having incorporated the most energy-efficient options for windows, air leakage rate, solar PV, and lighting. All four key designs achieve significant reductions in total operating energy, but with noticeable differences in LCCs. For example, the most efficient building design (**EE**) achieves roughly the same level of energy savings (112%) as the **EE-BaseLCC** design, but at an additional cost of more than \$5,000. These added costs are due to installing twice as much exterior continuous insulation in the roof assembly than the **EE** design, along with increased insulation in the foundation wall assembly. The **Min-LCC** and **LCC-NZE** designs achieve slightly lower energy savings (92% and 101%) than the others, while realizing LCC savings of \$24,206 and \$20,306, respectively, driven primarily by their use of a standard efficiency air-to-air heat pump, less insulation in both the roof and basement wall assemblies, and lack of an auxiliary solar thermal system for the household hot water heating system. Collectively, these results suggest that net-zero energy performance can be gained for negligible costs, or even cost savings, to the homeowner.

Additionally, considering the interactions of EEMs and their associated costs is important to selecting the most cost-effective combination of EEMs given a specific energy performance goal.

4.2.2. Energy performance—Figure 4-1 shows total net operating energy and embodied energy flows for the four optimal designs and the **MCC** design given a 30-year study period (expressed in kWh of primary energy). As expected, the least energy-efficient design (**MCC**) requires the most energy for household operating activities with net operating energy flows over 30 years at 1,226,875 kWh (40,896 kwh/year). Conversely, the two most energy-efficient designs, **EE-BaseLCC** and **EE**, both realize savings in net operating flows of −141,667 kWh (−4,722 kWh/year) and −146,536 kWh (−4,885 kWh/year), respectively. Although much less significant, the **LCC-NZE** design also realizes negative net operating flows of roughly −7,347 kWh (−245 kWh). The negative flow values reveal that the 10.2 kW solar PV system in combination with other EEMs more than offsets household electricity demands over the 30-year study period. In the case of the **Min-LCC** design where net operating energy flows are approximately 92,543 kWh (3,085 kWh/year), nearly the entire electricity demand is offset by the solar PV production.

The results in Figure 4-1 are largely consistent with relevant literature which states that embodied energy levels for a building either increases or remains constant for given increases in building energy efficiency. According to the figure, the least efficient design (**MCC**) is associated with smallest level of embodied energy totaling 467,129 kWh for a 30-year study period. The second least energy-efficient design (**Min-LCC**) realizes a 33% increase in embodied energy relative to the baseline, followed by the **LCC-NZE** design with an increase of 35%. Increases of 40% and 41% are realized by the **EE-BaseLCC** and **EE** designs, respectively. Note that the differences in embodied energy across designs (**EE** and **MCC**) is smaller (189,201 kWh) than the differences in operating energy (1,373,410 kWh).

Figure 4-2 shows total life-cycle energy flows (sum of net operating and embodied), as well as the the relative proportion of net operating and embodied energy flows, for the baseline design and the four alternative designs. The **MCC** design realizes the greatest life-cycle energy flows (1,694,004 kWh), followed by the **Min-LCC** (711,721 kWh) and **LCC-NZE** (625,177 kWh) designs. The smallest life-cycle energy flows are realized by the two most energy-efficient designs, **EE-BaseLCC** and **EE**, with total life-cycle energy flows of 511,564 kWh and 509,795 kWh, respectively. As shown in Figure 4-2(b), the driver behind total life-cycle energy flows for the **MCC** design is net operating energy (72% of total), while embodied energy is driving total flows for the remaining building designs due to the installation of solar PV in the **EE-BaseLCC**, **EE**, and **LCC-NZE** designs. The negative net operating flows is a result of on-site renewable generation being greater than the operating energy consumption, which also partially offsets the embodied energy flows. Similarly, the solar PV included in the **Min-LCC** design decreases net operating energy so much (92%) that its contribution to total life-cycle energy is minimal (13%) relative to the embodied energy. The relative shares of operating and embodied energy captured in Figure 4-2 fall within ranges discovered by Sarrotori and Hestnes (2007), Gustavsson and Joelsson (2010), and Chastas, Theodosiou, et al. (2016). The share of embodied energy for the conventional

MCC design (28%) falls below the 40% maximum and within the 2-38% range of embodied energy shares for conventional buildings as defined by Gustavsson and Joelsson and Sarritori and Hestnes. The **EE-BaseLCC**, **EE**, and **LCC-NZE** designs have embodied energy shares of 128%, 129%, and 101%, respectively. At first glance, this appears to fall beyond the range of embodied energy shares for net-zero energy buildings as defined by Chastas and colleagues. But after accounting for the negative net operating energy flows for these buildings, the total life-cycle energy flows for these three designs are comprised entirely of embodied energy. Similarly, the low-energy design (**Min-LCC**) has an embodied energy share (87%) beyond the scope of what has been previously defined for low-energy buildings because of comparing embodied energy to net operating energy flows which accounts for on-site energy production.

The above research findings are consistent with much of the literature on embodied energy. Increased use of energy-efficient technologies lowers the operating energy use while generally increasing embodied energy. Each of the four key designs evaluated were more energy-efficient than the baseline and were successful in reducing total operating energy use to near zero or negative in comparison. To gain the increase in energy efficiency, additional building materials are included during construction, and therefore embodied energy is increased. The savings in operating energy more than outweighs the increase in embodied energy, leading to total savings of over 60% for all four alternative designs. Even though the 10.2 kW solar PV system leads to net excess production and a partial offset of some embodied energy, there remains 509,795 kWh of source life-cycle energy associated with building. To be net-zero life-cycle energy (source operational and embodied), an additional 8.34 kW of due south facing solar PV would be required. Such a system would meet over 239% of the operational consumption of the **EE** design and 116% of the **MCC** building design in the initial year of operation.

Identifying which EEMs are driving the increases in embodied energy is explored in Figure 4-3, which provides a breakdown of the incremental embodied energy flows relative to the **MCC** design by EEM. The same EEMs that lead to the greater operating energy savings lead to the greatest increases in embodied energy. Across all four designs, the greatest contributor to the incremental embodied energy flows is the solar PV system. Switching from no solar PV (**MCC** design) to a 10.2 kW system increases embodied energy by 120,350 kWh over the 30-year study period. The significant contributions of solar PV to total embodied energy is consistent with Cellura, Guarino et al. (2014) which determined that PV was one of the leading contributors to both initial and recurring embodied energy flows relative to other building envelope and plant components. Additionally, the results of both case studies highlight the potential of operating energy savings for net-zero energy buildings to be counterbalanced by increased embodied energy. The second largest contributor to the incremental embodied energy is the HVAC system. In this case, the “HVAC” category refers to the combination of EEMs related to the heating and cooling, ventilation, and air leakage rates for each building design.²³ Like the baseline, both the **Min-LCC** and **LCC-NZE** designs include a standard efficiency air-to-air heat pump that

²³The mechanical ventilation rate requirements are directly related to the building envelope leakage rates, and cannot be evaluated separately.

provides continuous outdoor air to meet Maryland code requirements. The additional embodied energy flows for these two designs (33,665 kWh) stem from increased use of spray-foam insulation and sealants to achieve a lower air leakage rate of 0.63 ACH₅₀. The **EE-BaseLCC** and **EE** designs realize slightly greater incremental flows (33,676 kWh) due to also switching to a higher efficiency air-to-air heat pump with separate dedicated mechanical ventilation system with HRV.

The other building components impact embodied energy to a lesser extent. Although varying in magnitude, all four optimal designs experience increases in embodied flows related to the domestic hot water system. Switching from the electric water heater in **MCC** to a heat pump water heater in **Min-LCC** and **LCC-NZE** increases embodied flows by 1,100 kWh. Use of a solar thermal system in conjunction with a heat pump water heater (**EE-BaseLCC** and **EE**) raises embodied flows by 18,665 kWh. All but one design experience increases in embodied energy associated with the roof/ceiling assembly and the wall assembly. The **EE-BaseLCC**, **EE** and **LCC-NZE** designs, unlike the baseline, use cellulose insulation in the rafters along with rigid insulation to minimize the thermal transfer through the roof, resulting in additional embodied flows of 3,270 kWh, 6,369 kWh, and 1,139 kWh, respectively. The **Min-LCC** design adopts the same insulation option as the **MCC** design – therefore, its additional embodied flows are 0 for that building component. Regarding the wall assembly, all four designs use advanced framing which should reduce overall embodied energy relative to the baseline. However, the use of R_{SI}–3.5 (R-20) in the wall cavity in combination with R_{SI}–4.2 (R-24) rigid exterior insulation by the **EE-BaseLCC**, **EE**, and **LCC-NZE** designs, lead to considerable increases in embodied energy flows. Only in the case of the **Min-LCC** design are the reduced flows from advanced framing not offset by the increased wall cavity insulation R_{SI}–3.5 (R-20), resulting in an overall reduction in embodied energy (–2,066 kWh). Only minimal reductions in embodied energy related to the building foundation (wall and floor) are realized by the **Min-LCC** and **LCC-NZE** designs (–506 kWh) because of their use of R_{SI}–1.41 (R-8) in the foundation wall instead of R_{SI}–1.8 (R-10). The use of R_{SI} –3.9 (R-22) in the foundation wall by the **EE** design leads to an increase in overall embodied energy of 1,811 kWh.

4.2.3. Environmental performance—When considering the impacts of energy efficiency on operating and embodied energy, it is also important to consider its impact on operating and embodied carbon emissions. Changes in operating carbon emissions have been found to be roughly proportional to changes in operating energy use for given fuel mixes (Ibn-Mohammed, Greenough et al. 2013); therefore, our focus will be on measurements of embodied emissions for which change may be non-proportional to embodied energy.

The analysis of total life-cycle carbon emissions (sum of operating and embodied carbon flows) for all five building designs revealed that the **MCC** design achieves the highest level of life-cycle carbon with flows totaling 582,464 kg CO_{2e}, with the most energy-efficient design (**EE**) achieving roughly a 76% reduction relative to the baseline. In comparing life-cycle energy flows with life-cycle carbon, life-cycle carbon is not quite proportional to total life-cycle energy flows in all five design cases. This outcome is directly in line with existing

literature which suggests that inconsistencies between life-cycle energy and carbon estimates are driven primarily by embodied carbon, and not operating carbon emissions (Ibn-Mohammed, Greenough et al. 2013). Even though the increase in embodied emissions are significant on a percentage basis (up to 81%), the magnitude of the increase is much smaller than the decreases in energy-related emissions.

5. Conclusion

For decades, residential buildings have been a significant contributor to U.S. energy demands and GHG emissions. Members of the building community have responded to these trends by emphasizing the importance of introducing actions that target both the operating and embodied components of life-cycle energy and emissions measures. Many of today's actions (e.g., building energy codes) have proven successful in reducing household operating flows, but ignore embodied flows incurred during the manufacturing and disposal phases of a building's life-cycle. As the introduction of new building energy codes and increasing numbers of low-energy and net-zero energy buildings continue to drive up the average efficiency of U.S. residential buildings, achieved cutbacks in operating flows will be increasingly offset by increases in embodied flows. It is because of this that the building community has directed research toward understanding the impacts of energy-efficiency improvements on levels of embodied energy and emissions. This paper further explores this relationship building upon previous work by Kneifel, O'Rear et al. (2016). Utilizing data from the BIRDS Low-Energy Residential Database, estimates of total life-cycle flows are disaggregated into its operating and embodied counterparts to examine how each of these components are directly affected by increases in building energy efficiency based on cost-optimal incremental changes in combinations of building EEMs.

Relative to the baseline Maryland code-compliant design, the inclusion of a solar PV system results in comparable net operating energy use and carbon emissions reductions of up to 60.6% (10.2 kW system), the greatest of any of the EEM options. This is followed by EEMs that reduce air leakage rates (20.6%), increase the efficiency HVAC-related equipment (15.2%), increase the efficiency of the DHW system (up to 9.2%), and improve the thermal integrity of the building envelope by coupling advanced framing with additional rigid insulation in the wall assembly (up to 6.8%). Although increases are not proportional, these same EEMs are responsible for the greatest increases in embodied energy and emissions. For example, the installation of a 10.2 kW solar PV system increases embodied energy by approximately 25.8% and embodied carbon by 31.1%. Savings in operating energy and carbon emissions from energy efficiency improvements will come at the expense of an increase (although smaller in magnitude) in embodied energy and carbon, although there is clearly a net reduction with the energy tradeoff ratios ranging from 1:1 to 89:1, and 1:1 to 29:1 for emission tradeoff ratios. Given the effects of interactions between building components, reductions in operating energy/carbon emissions for a combination of EEMs is not additive, requiring modeling of the entire building as a combination of EEMs.

Comparisons between the baseline design and the four others optimal building designs reveal tradeoffs between operating and embodied flows for different combinations of EEMs. The baseline is the greatest consumer of energy with net operating energy totaling 1,226,875

kWh. The most energy-efficient design at a level of LCC equal to that of the baseline (**EE-BaseLCC**) and most energy-efficient design overall (**EE**) both realize a 112% savings in net operating energy relative to the baseline, while the design achieving net-zero or better at least cost (**LCC-NZE**) realizes a savings of 101%. Net operating savings for these three designs is the result of their inclusion of a 10.2 kW solar PV system in combination with other EEMs. Mirroring conclusions drawn from existing research, embodied energy levels are lowest for the Maryland code-compliant design, but rise with increases in energy-efficiency. Higher embodied flows realized by the four design alternatives are driven primarily by the solar PV system, which accounts for more than half of total embodied energy.

Measurements of total life-cycle energy and carbon emissions exhibit similar trends, with the baseline design responsible for the highest level of both life-cycle energy (1,694,004 kWh) and carbon emissions (582,464 kg CO₂e) flows and the most energy-efficient design overall responsible for the least (509,795 kWh and 137,941 kg CO₂e). Like life-cycle energy, life-cycle carbon emissions for the energy-efficient designs are driven mainly by operating energy. As greater efficiency is obtained, the embodied flows have a greater importance on total life-cycle energy use and environmental impacts with the extreme case being net-zero operational energy consumption and embodied flows accounting for 100% of life-cycle flows. Although net-zero operational energy performance is achieved, there remains significant life-cycle source energy flows that would require an additional 8.34 kW of due south facing solar PV (> 80% increase) to be installed to generate enough excess electricity (27,399 kWh) to offset the remaining embodied energy flows for the **EE** design, which would generate 239% of the electricity to reach net-zero operational energy for the initial year of operation. For comparison, the 18.54 kWh solar PV system would generate over 116% of the electricity required to make the **MCC** design reach net zero operational energy performance. Attempting to change the goal from net-zero operational flows to net-zero life-cycle flows will be a daunting task both in terms of the technical and economics perspectives.

The focus of this study is on the effects of increases in residential energy efficiency on household operating and embodied energy/carbon emissions, and how embodied flows become of greater importance as energy efficiency increases. Energy demands and carbon emissions have traditionally been the focus of numerous studies and the target of many energy-efficiency policies and/or initiatives. However, there many other environmental impacts that are either directly or indirectly influenced by changes in building efficiency. Future research should broaden the current life-cycle analysis by exploring the effects of increases in residential energy efficiency on other environmental flows based on the 12 environmental impact categories in BIRDS.

Appendix

Table A1

Constructions – Roof, Ceiling, Wall and Foundation

Wall Constructions		Option 1	Option 2	Option 3	Option 4	Option 5 [•]
Exterior Wall	Framing	Typical $\ddagger$	Typical	Advanced $\ddagger\ddagger$	Advanced	Advanced
	Insulation	RSI-2.3 (R-13)	RSI-2.3+0.9 (R-13+5) [*]	RSI-3.5 (R-20)	RSI-3.5+2.1 (R-20+12) [*]	RSI-3.5+4.2 (R-20+24) [*]
Foundation Constructions		Option 1	Option 2	Option 3	Option 4 [•]	
Basement	Wall	RSI-1.41 (R-8)	RSI-1.76 (R-10)	RSI-3.9 (R-22)	RSI-3.9 (R-22)	
	Slab	RSI-0 (R-0)	RSI-0 (R-0)	RSI-0 (R-0)	RSI-1.8 (R-10)	
Roof/Ceiling Constructions		Option 1	Option 2	Option 3	Option 4	Option 5 [•]
Roof/Ceiling	Roof ^{***}	RSI-0	RSI-0	RSI-7.92+0.7 (R-45+5) ^{**}	RSI-7.92+2.64 (R-45+15) ^{**}	RSI-7.92+5.28 (R-45+30) ^{**}
	Ceiling ^{****}	RSI-6.69 (R-38)	RSI-8.63 (R-49)	RSI-0	RSI-0	RSI-0

$\ddagger$ 5.1 cm × 10.2 cm – 40.6 cm (2 in × 4 in – 16 in) on center framing

$\ddagger\ddagger$ 5.1 cm × 15.2 cm – 61.0 cm (2 in × 6 in – 24 in) on center framing

^{*} Interior Wall Cavity + Exterior Continuous Insulation

^{**} Insulation in the Rafters + Exterior Roof Insulation

^{***} Insulation blown into rafters with exterior insulation on exterior roof

^{****} Insulation blown into ceiling joists

[•] NZERTF Design

Table A2

Window Design Options

Parameter	Units	Option 1	Option 2	Option 3	Option 4	Option 5
U-Factor	W/m ² -K (Btu/h-ft ² -F)	2.57 (0.45)	2.28 (0.40)	2.00 (0.35)	2.00 (0.35)	1.14 (0.20)
SHGC	Fraction	0.60	0.60	0.60	0.40	0.25
VT	Fraction	0.40	0.40	0.40	0.40	0.40

Table A3

Design Options for Alternative Air Leakage Rates

Design Option	Assumed Effective Leakage Area (cm ²)		
	ACH ₅₀	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 A4

Design Options for Alternative Air Leakage Rates

Fraction 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 A5

Heating and Cooling Equipment Design Options

Design Option	System Components	
Option 1	Type & Efficiency	Air-to-air heat pump (SEER 13/HSPF 7.7)
	Ventilation	Min. Outdoor Air (0.04 m ³ /s)
Option 2[†]	Type & Efficiency	Air-to-air heat pump (SEER 15.8/HSPF 9.05)
	Ventilation	Separate HRV system (0.04 m ³ /s)

[†]NZERTF Design**Table A6**

Domestic Hot Water System Design Options

Design Option	System Components	
Option 1	Primary	189 L (50 gal) electric water heater (0.95 efficiency)
	Auxiliary	None
Option 2	Primary	189 L (50 gal) heat pump water heater (COP 2.36)
	Auxiliary	None
Option 3	Primary	189 L (50 gal) electric water heater (0.95 efficiency)
	Auxiliary	2 panel, 302.8 L (80 gal) solar thermal storage tank
Option 4[†]	Primary	189 L (50 gal) heat pump water heater (COP 2.36)
	Auxiliary	2 panel, 302.8 L (80 gal) solar thermal storage tank

[†]NZERTF Design**Table A7**

Solar PV System Options

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

Table A8

Design Specifications for MCC Building Simulation

Building Category	Specifications	MCC
Windows	U-Factor SHGC	1.99 W/m ² -K (0.35 Btu/h-ft ² -F); 0.40
Framing and Insulation	Framing Exterior Wall Basement Wall Basement Floor Roof/Ceiling Assembly	5.1 cm × 10.2 cm – 40.6 cm OC (2 in × 4 in – 16 in OC) R _{SI} –3.5 or R _{SI} –2.3+0.9 (R-20 or R-13+5) ^{*†} R _{SI} –1.8 (R-10) [†] ; R _{SI} –0 (R-0) [†] Ceiling: R _{SI} –8.6 (R-49)
Air Change Rate	Air Change Rate – Blower Door Test Effective Leakage Area	3.00 ACH ₅₀ 1 st Floor = 403.6 cm ² (62.6 in ²) 2 nd Floor = 368.1 cm ² (57.1 in ²)
Lighting	Efficient Lighting (%)	75% efficient built-in fixtures
HVAC	Heating/Cooling Outdoor Air ^{**}	Air-to-air heat pump (SEER 13.0/HSPF 7.7) Min. Outdoor Air (0.04 m ³ /s)
Domestic Hot Water	Water Heater Solar Thermal	50 gal (189 L) electric water heater (0.95 efficiency)

* Interior Wall Cavity + Exterior Continuous Insulation

** Minimum outdoor air requirements are based on ASHRAE 62.2-2010

† Units: m²K/W (ft²F/[Btu/h])

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Figure 3-1.
Net Operating Energy Savings vs. Absolute Change in LCC

Figure 4-1.

(a) Net Operating Energy Flows and (b) Embodied Energy Flows (30-Year Study Period)

Figure 4-2.

(a) Total Life-Cycle Energy Flows and (b) Proportions of Net Operating and Embodied Energy Flows (30-Year Study Period)

Figure 4-3.
Breakdown of the Incremental Embodied Energy Flows by Building Energy Efficiency Measure (30-Year Study Period)

Table 4-1

Change in Net Operating and Embodied Energy and Carbon Emissions relative to MCC Design

EEM	Option	Percentage Change in OENF/OEMF	Percentage Change	
			EENF	EEMF
Windows	U Factor: 2.57 W/m ² -K SHGC: 0.6	1.11%	-0.02%	-0.02%
	U Factor: 2.28 W/m ² -K SHGC: 0.6	-0.05%	0.63%	0.09%
	U Factor: 2.00 W/m ² -K SHGC: 0.6	-1.24%	≈0.00%	≈0.00%
	U Factor: 1.14 W/m ² -K SHGC: 0.25	-2.95%	3.92%	3.87%
Air leakage Rate *	0.63 ACH ₅₀ (Outdoor Air)	-20.57%	6.99%	30.32%
	7.0 ACH ₅₀ (No Outdoor Air)	31.93%	≈0.00%	≈0.00%
HVAC	Air-to-air heat pump (SEER 16.5/HSPF 9.1) **	-15.23%	1.43%	4.51%
Lighting	34% efficient built-in fixtures	0.88%	≈0.00%	-0.05%
	50% efficient built-in fixtures	0.35%	≈0.00%	-0.03%
	100% efficient built-in fixtures	-0.26%	≈0.00%	0.03%
Solar PV	2.5 kW PV system	-15.15%	6.44%	7.77%
	5.1 kW PV system	-30.30%	12.88%	15.55%
	7.6 kW PV system	-45.44%	19.32%	23.32%
	10.2 kW PV system	-60.61%	25.76%	31.10%
DHW	Electric water heater w/solar thermal	-5.93%	3.76%	3.53%
	Heat pump water heater	-7.95%	0.24%	1.63%
	Heat pump water heater w/solar thermal	-9.15%	4.00%	5.16%
Ceiling/Roof	Ceiling insulation: R _{SI} -6.69	1.02%	-0.05%	-0.05%
	Roof insulation: R _{SI} -7.92 + 0.7	-1.24%	0.24%	0.16%
	Roof insulation: R _{SI} -7.92+2.64	-1.67%	0.70%	0.44%
	Roof insulation: R _{SI} -7.92 + 5.28	-2.04%	1.36%	0.85%
Wall	Framing: Typical Insulation: R _{SI} -2.3	5.03%	-0.54%	-4.83%
	Framing: Advanced Insulation: R _{SI} -3.5	0.11%	-0.44%	-4.65%
	Framing: Advanced Insulation: R _{SI} -3.5+2.1	-4.90%	0.86%	6.68%
	Framing: Advanced Insulation: R _{SI} -3.5+4.2	-6.83%	2.17%	18.01%
Foundation *	Wall: R _{SI} -1.41 Floor: R _{SI} -0	0.05%	-0.11%	-0.94%
	Wall: R _{SI} -3.9 Floor: R _{SI} -0	-0.13%	0.39%	0.24%

EEM	Option	Percentage Change in OENF/OEMF	Percentage Change	
			EENF	EEMF
	Wall: $R_{SI}-3.9$ Floor: $R_{SI}-1.76$	3.74%	0.92%	4.87%

* Only certain combinations exist in the database at present;

** Assumes HRV ventilation system with 3.0 ACH₅₀ infiltration

OENF = net operating energy flows; OEMF = net operating emission flows; EENF = embodied energy flows; EEMF = embodied emissions flows

Table 4-2

Design Features for Optimal Building Designs

Design Category	EE-BaseLCC	EE	Min-LCC	LCC-NZE
Windows	U Factor: 1.14 W/m ² -K (0.2 Btu/h-ft ² -F) SHGC: 0.25	U Factor: 1.14 W/m ² -K (0.2 Btu/h-ft ² -F) SHGC: 0.25	U Factor: 1.14 W/m ² -K (0.2 Btu/h-ft ² -F) SHGC: 0.25	U Factor: 1.14 W/m ² -K (0.2 Btu/h-ft ² -F) SHGC: 0.25
Heating and Cooling	Air-to-air heat pump (SEER 16.5/HSPF 9.1)	Air-to-air heat pump (SEER 16.5/HSPF 9.1)	Air-to-air heat pump (SEER 13.0/HSPF 7.7)	Air-to-air heat pump (SEER 13.0/HSPF 7.7)
Ventilation	Separate HRV system	Separate HRV system	Outdoor air *	Outdoor air *
Air leakage Rate	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	10.2 kW	10.2 kW	10.2 kW
DHW	Heat pump water heater w/ solar thermal system	Heat pump water heater w/ solar thermal system	Heat pump water heater	Heat pump water heater
Roof	Roof insulation: R _{SI} -7.92 + 2.64 (R-45 + 15)	Roof insulation: R _{SI} -7.92 + 5.28 (R-45 + 30)	Ceiling Insulation: R _{SI} -8.63 (R-49)	Roof insulation: R _{SI} -7.92 + 0.9 (R-45 + 5)
Wall	Framing: Advanced Insulation: R _{SI} -3.5+4.2 (R-20 + 24)	Framing: Advanced Insulation: R _{SI} -3.5+4.2 (R-20 + 24)	Framing: Advanced Insulation: R _{SI} -3.5 (R-20 + 0)	Framing: Advanced Insulation: R _{SI} -3.5+4.2 (R-20 + 24)
Foundation Wall	R _{SI} -1.76 (R-10)	R _{SI} -3.9 (R-22)	R _{SI} -1.41 (R-8)	R _{SI} -1.41 (R-8)
Foundation Floor	R _{SI} -0 (R-0)	R _{SI} -0 (R-0)	R _{SI} -0 (R-0)	R _{SI} -0 (R-0)
Net Operating Energy Reduction (%)	112%	112%	92%	101%
Change in LCC (30- yr)	\$11	\$5035	-\$24 206	-\$20 306

* Introduced by way of air-to-air heat pump