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Sustainability Performance of the NIST Net-Zero Energy Residential Test Facility Relative to a Maryland Code-Compliant Design

Joshua Kneifel
Eric O'Rear

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Abstract

The National Institute of Standards and Technology (NIST) received funding through the American Recovery and Reinvestment Act (ARRA) to construct a Net-Zero Energy Residential Test Facility (NZERTF). The initial goal of the NZERTF is to demonstrate that a net-zero energy residential design can “look and feel” like a typical home in the Gaithersburg area. The purpose of this report is to compare the sustainability performance including energy, economic, and environmental metrics, of the NZERTF design to a comparable Maryland code-compliant building design using whole building energy simulations, life-cycle costing, and life-cycle assessment.

Keywords

BIRDS; energy efficiency; net-zero energy; residential buildings; sustainability; whole building energy simulation

Preface

This study was conducted by the Applied Economics Office (AEO) in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). The study is designed to compare the sustainability performance of the NZERTF design to a comparable Maryland code-compliant building design using the results of EnergyPlus (*E+*) whole building energy simulations, life-cycle costing, and life-cycle assessment. The intended audience includes researchers in the residential building sector concerned with net-zero energy residential performance.

Disclaimers

The policy of the National Institute of Standards and Technology is to use metric units in all of its published materials. Because this report is intended for the U.S. construction industry that uses U.S. customary units, it is more practical and less confusing to include U.S. customary units as well as metric units. Measurement values in this report are therefore stated in metric units first, followed by the corresponding values in U.S. customary units within parentheses.

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Contents

Abstract ... **iii**
Preface ... **v**
Acknowledgements ... **vii**
Author Information ... **vii**
List of Acronyms ... **xiii**
1 Introduction ... **1**
2 Building Specifications for the 2012 *IECC* and NZERTF Homes ... **3**
3 Performance Estimation Approaches ... **7**
3.1 Energy ... 7
3.2 Economic ... 7
3.3 Environmental ... 8
4 Sustainability Performance ... **11**
4.1 Energy Performance ... 11
4.2 Economic Performance ... 11
4.3 Environmental ... 19
4.3.1 Environmental Impact Categories ... 19
4.3.2 BIRDS Normalization and Weighting ... 24
5 Variances in the Relative Efficiency of Simulated Building Designs ... **31**
5.1 Isolating the Optimally Efficient Building Design ... 31
5.2 Sustainability Performance of the Optimal Efficient Design ... 34
6 Discussion, Limitations, and Future Research ... **37**
6.1 Discussion ... 37
6.1.1 Energy Performance ... 37
6.1.2 Economic Performance ... 37
6.1.3 Environmental Performance ... 38
6.1.4 Optimal Building Design ... 38
6.2 Limitations and Future Research ... 39
References ... **41**

List of Figures

Figure 4-1 Present Value of Total First Costs for the MCC and the NZERTF Housing Designs 12
Figure 4-2 Present Value of Additional First Costs by Energy Efficiency Measure 13
Figure 4-3 Present Value of Total Electricity Costs by Study Period 14
Figure 4-4 Present Value of Total Maintenance, Repair, and Replacement Costs by Study Period 15
Figure 4-5 Present Value of Maintenance, Repair, and Replacement Costs by Component by Study Period 16
Figure 4-6 Present Value of Total Residual Value by Study Period for both Building Designs 17
Figure 4-7 Life-cycle Cost Measures for the Maryland Code-Compliant and NZERTF Building Designs 18
Figure 4-8 Life-cycle Impact Assessment Results for (a) GWP (b) acidification (c) smog and (d) energy for the Maryland design and NZERTF design 20
Figure 4-9 Life-cycle Impact Assessment Categories ((a)-(d)) Directly Influenced by Building Construction Inputs and Operation for the Maryland and NZERTF designs 22
Figure 4-10 Relative Differences in Environmental Impacts for the Net-Zero and Maryland Code Compliant Designs 23
Figure 4-11 Weighted Normalized Impact Scores for the MCC and NZERTF Building Designs using Equal Weights 26
Figure 4-12 Weighted Normalized Impact Scores for the MCC and NZERTF Building Designs using BEES Weights 27
Figure 4-13 Weighted Normalized Impact Scores for the MCC and NZERTF Building Designs using SAB Weights 28
Figure 5-1 Changes in Life-Cycle Costs and Energy Use Reductions for Simulated Building Designs 31
Figure 5-2 Cost of Additional EEM Investment for Simulated Buildings 33
Figure 5-3 Relative Differences in Environmental Impacts for the Optimally Efficient, NZERTF, and MCC Designs 35

List of Tables

Table 2-1 Electricity Consumption and Solar PV Production by Design (kWh) 4
Table 3-1 Environmental Impact Categories and Units 9
Table 4-1 Electricity Consumption and Solar PV Production by Design (kWh) 11
Table 4-2 Annual Net Electricity Consumption and Electricity Costs 13
Table 4-3 Normalization References: Annual U.S. Contributions 24
Table 4-4 Normalization Impact Assessment Scores 24
Table 4-5 Relative Importance Weights (%) 25
Table 4-6 Weighted Impact Scores 29
Table 5-1 Breakdown of Energy Efficiency Measures for Simulated Buildings 34
Table 5-2 Economic Performance Measures 34
Table 5-3 Weighted Impact Scores 36

List of Acronyms

Acronym	**Definition**
ACH	air changes per hour
AEO	Applied Economics Office
AIRR	Adjusted Internal Rate of Return
ARRA	American Recovery and Reinvestment Act
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	Building America
BSC	Building Science Corporation
BEES	Building for Environmental and Economic Sustainability
BIRDS	Building Industry Reporting and Design for Sustainability
CFA	conditioned floor area
CFC-11	Trichlorofluoromethane
CFL	compact fluorescent lamp
CFM	cubic feet per minute
CO2	carbon dioxide
CO2e	carbon dioxide equivalent
COP	Coefficient of Performance
CTUe	Equivalent Comparative Toxicity Units for ecological receptors
CTUh	Equivalent Comparative Toxicity Units for human health receptors
DHW	Domestic Hot Water
E+	EnergyPlus
EERE	Office of Energy Efficiency & Renewable Energy
EEM	Energy Efficiency Measure
EIA	Energy Information Administration
EIS	Environmental Impact Score
EL	Engineering Laboratory
ELA	effective leakage area
EPA	Environmental Protection Agency
GWP	Global Warming Potential
H+	Hydrogen Ion
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilator

Acronym	**Definition**
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Conservation Code
MCC	Maryland Code-Compliant
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
N	Nitrogen
NIST	National Institute of Standards and Technology
NOx	nitrogen oxide
NS	Net Savings
NZERTF	Net-Zero Energy Residential Test Facility
O3	Ozone
OC	on center
PM10	particulate matter less than 10 micrometers in diameter
MRR	Maintenance, Repair, and Replacement
PV	photovoltaic
SAB	Science Advisory Board
SEER	Seasonal Energy Efficiency Ratio
SIR	Savings-to-Investment Ratio
SHGC	Solar Heat Gain Coefficient
SO2	sulfur dioxide
VT	Visual Transmittance

1 Introduction

The National Institute of Standards and Technology (NIST) received funding through the American Recovery and Reinvestment Act (ARRA) to construct a Net-Zero Energy Residential Test Facility (NZERTF). The initial goal of the NZERTF is to demonstrate that a net-zero energy residential design can "look and feel" like a typical home in the Gaithersburg area. The purpose of this report is to compare the sustainability performance including energy, economic, and environmental metrics, of the NZERTF design to a comparable Maryland code-compliant building design using whole building energy simulations, life-cycle costing, and life-cycle assessment.

Kneifel (2012) documents the assumptions made to create a whole building energy simulation model in the *E+* simulation software estimating the energy performance of the NZERTF. The geometry, building envelope, and hard-wired lighting design as well as some energy performance requirements are based on the specifications defined by the NZERTF project's architectural firm, Building Science Corporation (BSC).[1] Based on the BSC specifications, the contractor selected interior equipment and lighting to meet those specifications. Occupant behavior assumptions for the NZERTF are defined based on Phase I operation. For some operating conditions, the model uses assumptions defined in Hendron and Engebrecht (2010). Additional documents that assist the model design are *American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.2-2007, ASHRAE 62.2-20*10, and the *ASHRAE* Fundamentals Handbook.

Kneifel (2013) compares the energy performance of the NZERTF design to a comparable Maryland code-compliant building design using whole building energy simulations. The analysis includes a total of eleven EnergyPlus (*E+*)[2] simulations, starting with the Maryland code-compliant design, which requires building to *2012 International Energy Conservation Code* (*IECC*),[3] and then adding energy efficiency measures incrementally until all measures are included to reach the NZERTF design. This approach allows for a comparison across energy efficiency measures to determine the incremental impact of each energy efficiency measure on energy consumption.

Kneifel (2014) compares the life-cycle cost performance of the NZERTF design to a comparable Maryland code-compliant building design using the results of *E+* whole building energy simulations and a contractor report estimating the associated construction costs. The use of life-cycle cost analysis is important because the cost flows associated with the NZERTF design and a Maryland code-compliant house design are different, with the NZERTF design realizing greater initial costs, but lower (negative) annual energy costs. By accounting for all costs

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[1] Building Science Corporation (2009)

[2] Department of Energy (2013)

[3] International Code Council (2011)

associated with both building designs for the home owner’s investment time horizon, it is possible to allow a direct comparison of the economic performance across designs.

This study expands on the analysis in Kneifel (2013) and Kneifel (2014) by analyzing the sustainability performance of the NZERTF design and comparing it to the performance of the alternative Maryland code-compliant design based on 2012 IECC. The analysis uses the recently developed low-energy residential database that will be incorporated into NIST’s BIRDS (Building Industry Reporting and Design for Sustainability) web interface, and includes detailed comparisons in energy, economic, and environmental performance of the two designs to determine the benefits and costs of going beyond current residential energy code requirements to reach net-zero energy consumption in a single-family dwelling. The analysis includes some preliminary analysis of the incremental energy efficiency measure adoption that is available in the BIRDS low-energy residential database.

2 Building Specifications for the 2012 *IECC* and NZERTF Homes

The current residential code adopted by the state of Maryland is based on the 2012 International Energy Conservation Code (*IECC*) for residential buildings. The *IECC* defines minimum construction requirements for various aspects of a building that impact its energy demand. Our analysis compares the simulated performance of a house that is compliant with 2012 *IECC* to the same house built to the NZERTF specifications. The inclusion of ten energy efficiency measures (EEMs) distinguishes the NZERTF design from the Maryland Code-Compliant (MCC) home. They come in the form of improvements to the building envelope, interior equipment and lighting systems, as well as the installation of an on-site solar photovoltaic (PV) system. Table 2-1 provides a simple breakdown of the building specifications for each home design.

The building envelope is different across the two building designs. The wall assembly in the MCC design is typical framing with R-13 batt insulation in the wall cavity and R-5 rigid exterior insulation while the NZERTF design implements advanced framing (Lstiburek 2010) with R-20 blown-in cellulose insulation in the wall cavity and R-32 rigid exterior insulation. The MCC design includes R-38 of blown-in insulation on the attic floor while the NZERTF has the insulation installed in the roof assembly with R-45 blown-in insulation in the rafters and R-30 of rigid exterior insulation on the outside of the roof. The windows installed in the NZERTF design have a lower U-factor and solar heat gain coefficient (SHGC) than those installed in the MCC design. The building envelope in the NZERTF design is much “tighter” than the MCC design, leading to less air flow through the building envelope.

Table 2-1 Electricity Consumption and Solar PV Production by Design (kWh)

Building Category		MCC	NZERTF
Windows	U-Factor	1.99 W/m^2-K (0.35 Btu/h*ft^2-F)	1.14 W/m^2-K (0.20 Btu/h*ft^2-F)
	SHGC	0.35	0.25
	VT	0.40	0.40
Exterior Wall Assembly	Framing	5.1 cm x 10.2 cm - 40.6 cm OC (2 in x 4 in - 16 in OC) 23 % Framing	5.1 cm x 15.2 cm - 61.0 cm OC (2 in x 6 in - 24 in OC) 15 % Framing
	Insulation†	R_{SI}-3.5 or R_{SI}-2.3+0.9 (R-20 or R-13+5)*	R_{SI}-3.5+4.2 (R-20+24)*
Basement Wall	Insulation†	R_{SI}-1.8 (R-10)	R_{SI}-3.9 (R-22)
Roof/Ceiling Assembly	Framing	11 % Framing	11 % Framing
	Insulation†	Ceiling: R_{SI}-8.6 (R-49)	Roof: R_{SI}-7.9 + 5.3 (R-45 + 30)*
Infiltration	Air change rate	3.00 ACH_{50}	0.61 ACH_{50}
	Effective Leakage Area	1st Floor = 403.6 2nd Floor = 368.1	1st Floor = 98.8 2nd Floor = 90.2
Lighting		75 % efficient built-in fixtures	100 % efficient built-in fixtures
HVAC	Heat/Cool	Air-to-air heat pump (SEER 13/HSPF 7.7)	Air-to-air heat pump (SEER 15.8/HSPF 9.05)
	Outdoor Air**	Min. Outdoor Air (0.04 m^3/s)	Separate HRV system (0.04 m^3/s)
Domestic Hot Water	Water Heater	189 L (50 gal) electric water heater (0.98 efficiency)	189 L (50 gal) heat pump water heater (COP 2.6)
	Solar Thermal	None	2 panel, L(80 gal) solar thermal storage tank
Solar PV system		None	10.2 kW

* Interior Wall Cavity + Exterior Continuous Insulation

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

†Units: m^{2}K/W (ft^{2}F/(Btu/h))

The 2012 *IECC* requires that at least three-quarters of built-in lighting be efficient (energy conservative bulbs). This analysis assumes that the MCC and NZERTF designs use 75 % and 100 % efficient built-in lighting, respectively. All heating and cooling demands for the MCC design are met using a standard efficiency (Seasonal Energy Efficiency Ratio (SEER) of 13 and

Heating Seasonal Performance Factor (HSPF) 7.7) air-to-air heat pump system. The NZERTF design uses a higher efficiency (SEER 16.5/HSPF 9.05) air-to-air heat pump system and incorporates a separate Heat Recovery Ventilator (HRV) system. The HRV system is necessary for the NZERTF design in order to maintain the required outdoor air exchange as defined in ASHRAE 62.2-2010. The domestic hot water system installed in the MCC is a 189 L (50 gal) electric water heater (efficiency of 0.98 with uniform skin loss coefficient of 0.41 W/m^2-K). A 189 L (50 gal) heat pump water heater (HPWH) with a coefficient of performance (COP) of 2.6 is installed in the NZERTF. An electric back-up element (thermal efficiency of 0.98) internal to the water heater tank is installed in the case that the HPWH fails to bring the water temperature to setpoint levels. An additional EEM installed in the NZERTF includes two solar thermal panels and a 302.8 L (80 gallon) storage tank that preheats water entering the HPWH. A solar PV system sized according to the surface area of the roof (10.2 kW) is installed on the north side of the NZERTF. The solar PV system installation and operation offsets the household electricity demands.

3 Performance Estimation Approaches

The approaches implemented to calculate performance for each category of sustainability (energy consumption, economic competitiveness, and environmental impacts) are discussed below.

3.1 Energy

Energy performance is evaluated using results from *EnergyPlus* ($E+$) *8.0.0* (DOE 2013) whole building energy simulations designed to the specifications of the NZERTF as operated during the demonstration phase and a comparable home built to meet 2012 *IECC* energy efficiency requirements. Energy consumption is estimated by $E+$ using the 3rd iteration of the Typical Meterological Year (TMY3) data for the weather station located at the Dulles International Airport near Sterling, Virginia. See Kneifel (2012) and Kneifel (2013) for additional details on the whole building energy simulations.

3.2 Economic

Economic performance is evaluated using the life-cycle cost methodology defined in Handbook 135 (Fuller and Petersen 1996). Life-cycle costing accounts for all costs (in present value terms) associated with constructing and operating a building over the selected study period. Four different LCC metrics are used in the analysis: LCCs, net savings (NS), savings-to-investment ratio (SIR), and adjusted internal rate of return (AIRR). Life-cycle costs (LCC) are the sum of the costs (C_t) realized in each year (t) of the study period (N) discounted using discount rate d into present value terms as shown in Formula 1. The alternative that has the lowest LCC is the best option.

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

For a building design, LCC can also be analyzed as shown in Formula 2, where LCC is the present value initial investment costs (I) plus present value capital replacement costs (RC) minus present value building residual value (RV) plus present value energy-related operating costs (E) plus present value non-energy related operating, maintenance, and repair costs ($OM\&R$). Residual value is the value of the building at the end of the study period (i.e., resale value).

$$(2)\ LCC = I + RC - RV + E + OM\&R$$

Net savings (NS) is the difference between the LCC for the baseline (LCC_{base}) and the LCC for alternative i (LCC_i) as shown in Formula 3. Positive NS means that alternative i is preferable to the baseline case.

$$(3)\ NS_i = LCC_{base} - LCC_i$$

Formula 4 shows that SIR is the difference in present value costs of future non-investment related costs over the study period relative to the baseline case (ΔE + $\Delta OM\&R$) divided by the difference in present value investment costs relative to the baseline case (ΔI+ΔRC-ΔRV) where Δ is the alternative case investment costs minus the baseline case investment costs. An SIR of greater than 1.0 occurs when an alternative leads to greater present value cost savings than the additional present value investment costs required to obtain those savings.

$$(4)\ SIR = \frac{\Delta E + \Delta OM\&R}{\Delta I + \Delta RC - \Delta RV}$$

AIRR uses the SIR to calculate an annualized return on investment using Formula 5, where *r* is the reinvestment rate at which realized savings is reinvested, which is the minimum acceptable rate of return (MARR). An AIRR greater than the MARR, which is often the assumed discount rate (*d*), means that the alternative leads to greater returns than the baseline case.

$$(5)\ AIRR = (1 + r) * (SIR)^{1/N}$$

Each of these four metrics will be used in the economic analysis within this report assuming a 3 % discount rate (Rushing, Kneifel et al. 2014) and a study period ranging from one year to 40 years. The economic analysis excludes any incentives offered to the homeowner for energy efficiency gains or renewable energy production, including the 30 % tax credit for the installed cost of the solar PV system. See Handbook 135 (Fuller and Petersen 1995) for additional information on LCC methodology.

3.3 Environmental

Environmental performance is evaluated using a hybrid life-cycle assessment (LCA) approach, which combines "top-down" LCA input-output environmental flow data with "bottom-up" process-based environmental flow data to calculate the total environmental flows associated with constructing and operating each design over the study period of interest (Suh and Lippiatt 2012). The flows for a "baseline" single-family dwelling (i.e., MCC design) are estimated using the input-output environmental flows. Since input-output environmental flows are based on a per dollar basis, the baseline construction costs ($Const_{base}$) and the baseline maintenance and repair costs ($M\&R_{base}$) are multiplied by the associated flows (*Flow Per $*) as shown in Formula 6 where *i* is an array of 12 environmental impact categories.

$$(6)\ LCA_{base,i} = Const_{base} * Flow\ Per\ \$_{Const,i} + M\&R_{base} * Flow\ Per\ \$_{M\&R,i}$$

The flows for the building design changes associated with the energy efficiency measures implemented in the NZERTF design not included in the MCC design are derived from "bottom-up" process-based LCA data. The flows for building envelope products are based on a per square foot basis while the flows for building equipment are estimated on a per installed unit basis. See Suh and Lippiatt (2012) for additional details on the hybrid LCA approach.

The consideration of only a building design's carbon footprint could miss other important environmental impacts. For this reason, building designs will be analyzed across the twelve environmental impact categories in Table 3-1. Global Warming Potential (GWP) serves as a measure of the degree to which human activities (e.g., the building and use of a small family dwelling) contribute to the greenhouse gas effect phenomenon through the releasing of heat-trapping gases or greenhouse gases (GHG) like carbon dioxide and methane. Acidification involves the mixing of acidifying compounds, such as nitrogen oxides (e.g., NO_x) and sulfur dioxide (SO_2), in water to form acid rain which can be detrimental to both local and global ecosystems. A common source of acidification of water is the pollution released into the atmosphere (SO_2 and NO_x) from the burning of coal to produce electricity. Smog formation is the result of sunlight reacting with nitrogen oxides and volatile organic compounds released by local industries and vehicles including fossil fuel-based electricity production. This by-product has proven to be harmful to individuals suffering from chronic respiratory issues and to local vegetation. Primary energy consumption includes energy consumption from building operation as well as the energy embodied within the building products. The thinning of earth's ozone layer – referred to as "ozone depletion" – results in more radiant energy reaching the planet's surface. The implications of this can be detrimental, with agriculture and human health being at risk. Eutrophication refers to the depositing of additional mineral nutrients to soil or water. The harming of surrounding ecosystems from industrial pollutants is accounted for in the "ecological toxicity" or "ecotoxicity" impact category. The potential impacts on human health can occur from the exposure to both industrial and natural substances.

Table 3-1 Environmental Impact Categories and Units

Category	Unit
Global Warming Potential	kg CO_2e
Acidification	mol H+ eq
Ozone Depletion	kg CFC-11 eq
Ecotoxicity	CTUe
Water	kg
Land	Acre
Smog	kg O_3 eq
Eutrophication	kg N eq
Energy	1000 Btu
Carcinogens	CTUh
Non-Carcinogens	CTUh
Respiratory Effects	kg PM10 eq

The additional components incorporated into the NZERTF design have embodied environmental flows. There are two approaches to allocating these flows over a study period. First, the flows can be treated as "sunk flows" associated with the initial year of construction. This approach tends to overweight the embodied environmental flows for short study period lengths. Second, the flows can be split equally across all years of the product’s or component’s lifetime, which is more consistent to the life-cycle costing residual value calculation approach. This study treats environmental flows on an annualized basis to maintain consistency across both the life-cycle costing and life-cycle assessment methodologies.

4 Sustainability Performance

The sustainability performance results for the MCC design and NZERTF design are compared and contrasted in this chapter across the three metrics (energy consumption, LCC, and LCA) defined in Chapter 3.

4.1 Energy Performance

Both the NZERTF and MCC designs are assumed to operate solely on electricity. The annual electricity consumption, production, and net consumption of the two designs are shown in Table 4-1. Given the assumed occupant activity and setpoint conditions, the MCC design consumes 23 604 kWh of electricity annually while the NZERTF design consumes 11 231 kWh of electricity annually. The solar PV system installed on the roof of the NZERTF design produces 15 474 kWh of electricity, which leads to net consumption of -4243 kWh, or 38 % more production than its consumption. In other terms, 8 of the 32 solar PV panels could be removed and the NZERTF design would still reach net zero energy consumption.

Table 4-1 Electricity Consumption and Solar PV Production by Design (kWh)

	MCC	NZERTF
Electricity Consumption	23 604	11 231
Electricity Production	0	15 474
Net Consumption	23 604	-4243

4.2 Economic Performance

Total first costs (initial investment costs) for the MCC and NZERTF designs are shown in Figure 4-1. Total first costs are the sum of all costs of construction, which can be broken down into two categories: incremental costs associated with energy efficiency measures (EEMs) and costs independent of EEMs. Cost of purchasing and preparing the land for construction is excluded from the analysis because those costs are a constant across the two designs. Constructing to meet the NZERTF design costs an additional $108 049 (26 %) relative to the MCC design ($521 722 versus $413 673) due to the additional expenses of incorporating more energy conservation technologies and on-site electricity production.

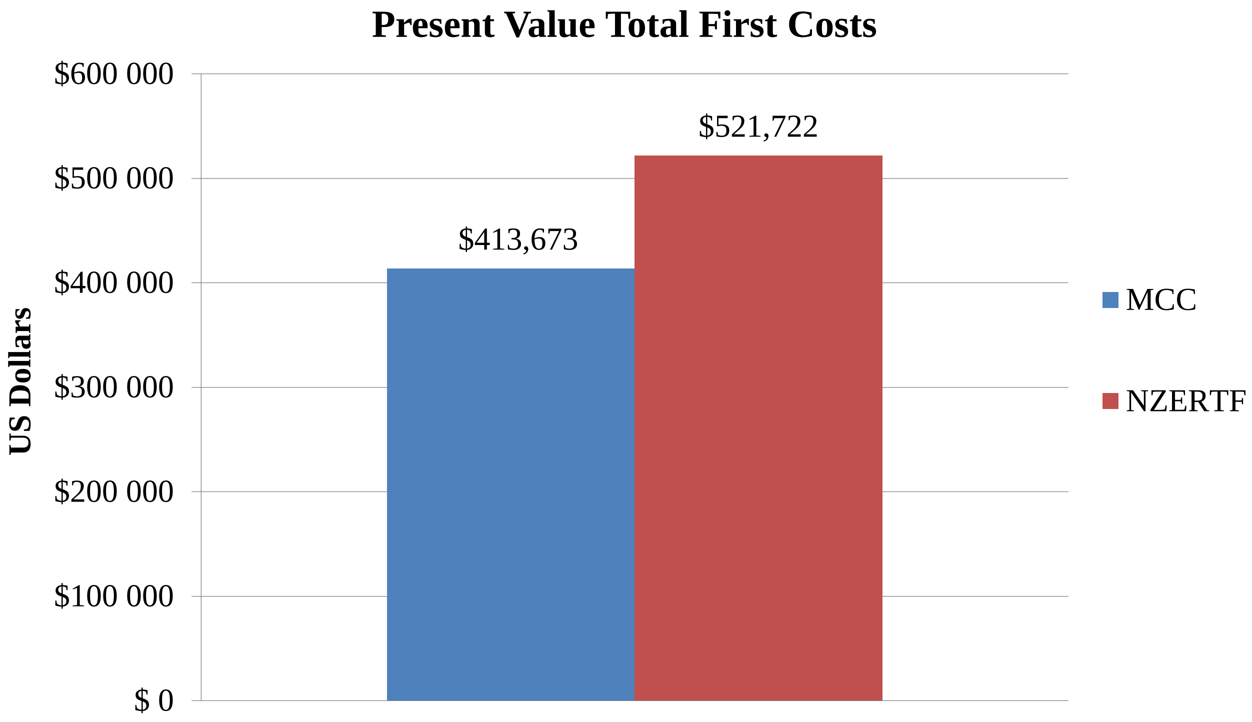

Figure 4-1 Present Value of Total First Costs for the MCC and the NZERTF Housing Designs

Figure 4-2 provides a breakdown of the additional first costs related to the EEMs included in the NZERTF design relative to the MCC design. The on-site solar PV system costs an additional $58 091 – the most expensive of all seven adopted energy efficiency measures. The advanced framing and additional insulation in the walls ($14 807) and roof ($11 597) combine to cost $27 440 while the installation of a more efficient HVAC system (combination of the air-to-air heat pump, electric resistance heating element, and separate HRV) costs an additional $12 945. The additional cost of reducing infiltration is $2766 while the HPWH and solar thermal system cost an additional $1504 and $5963, respectively. Shifting the 25 % of built-in light fixtures from incandescent bulbs to high efficiency lighting (compact fluorescent bulbs) is inexpensive at an additional cost of $30.

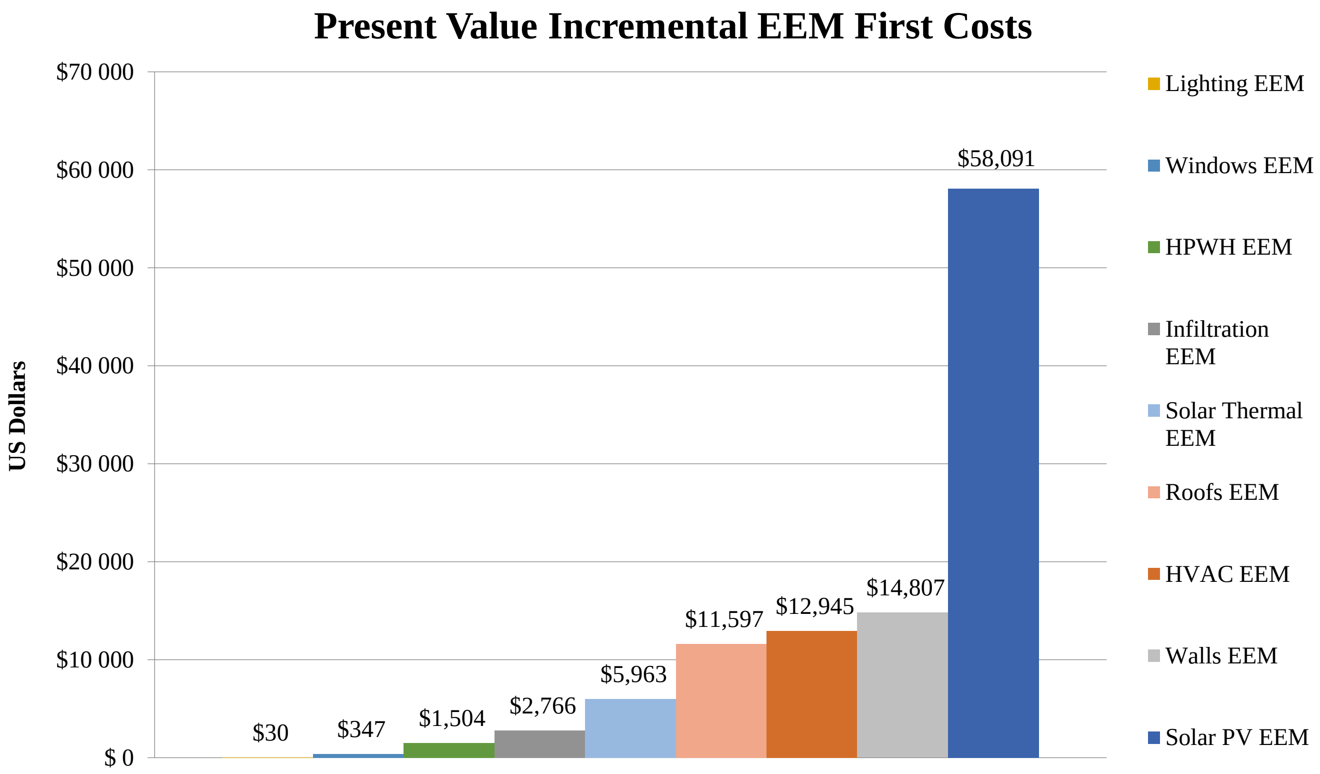

Figure 4-2 Present Value of Additional First Costs by Energy Efficiency Measure

Annual net electricity consumption and electricity costs for both designs are shown in Table 4-2. Net annual consumption for the MCC design is 23 604 kWh at a cost $3153.[4] The operation of the solar PV system by the NZERTF design provides enough on-site electricity to more than offset annual energy consumption, leading to a production surplus of 4243 kWh of electricity. The NZERTF design realizes annual energy costs of -$567, or annual energy cost savings of $3720 relative to the MCC design.[5]

Table 4-2 Annual Net Electricity Consumption and Electricity Costs

	MCC	NZERTF
Net Electricity Consumption	23 604 kWh	-4243 kWh
Electricity Costs	$3153	-$567

Figure 4-3 displays total present value electricity costs across study periods ranging from 1 year to 40 years. Household electricity expenditures are steadily increasing in the case of the MCC design given the projected annual increases in electricity prices. The opposite occurs for the NZERTF design with energy costs growing increasingly negative (cost savings) as the study

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[4] Based on the state average residential cost per kWh of electricity for Maryland (EIA 2012)

[5] The value of the excess electricity sold back to the utility is also based on EIA (2012).

period length increases. The divergence in costs between the two building designs grows larger over time. By year 40, there is a difference of more than $95 000 – once again showcasing the present value of potential energy cost savings that can be recouped by constructing the NZERTF design.

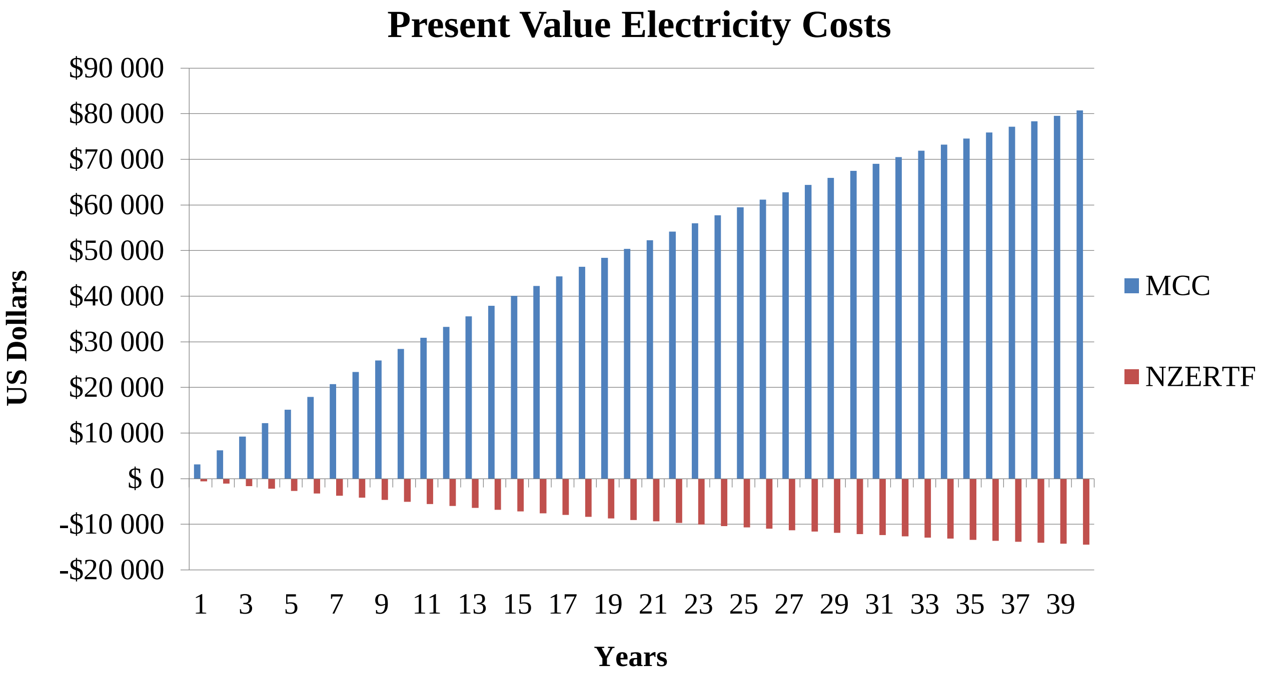

Figure 4-3 Present Value of Total Electricity Costs by Study Period

All future maintenance, repair, and replacement costs are necessary to complete life-cycle cost analysis. Figure 4-4 shows the total maintenance, repair, and replacement (MRR) costs for the two building designs. The NZERTF design realizes notably larger MRR costs than the Maryland compliant home in all study periods. The most significant differences occur in study periods longer than 25 years where NZERTF MRR costs are between 2 to 3 times higher than the MCC design.

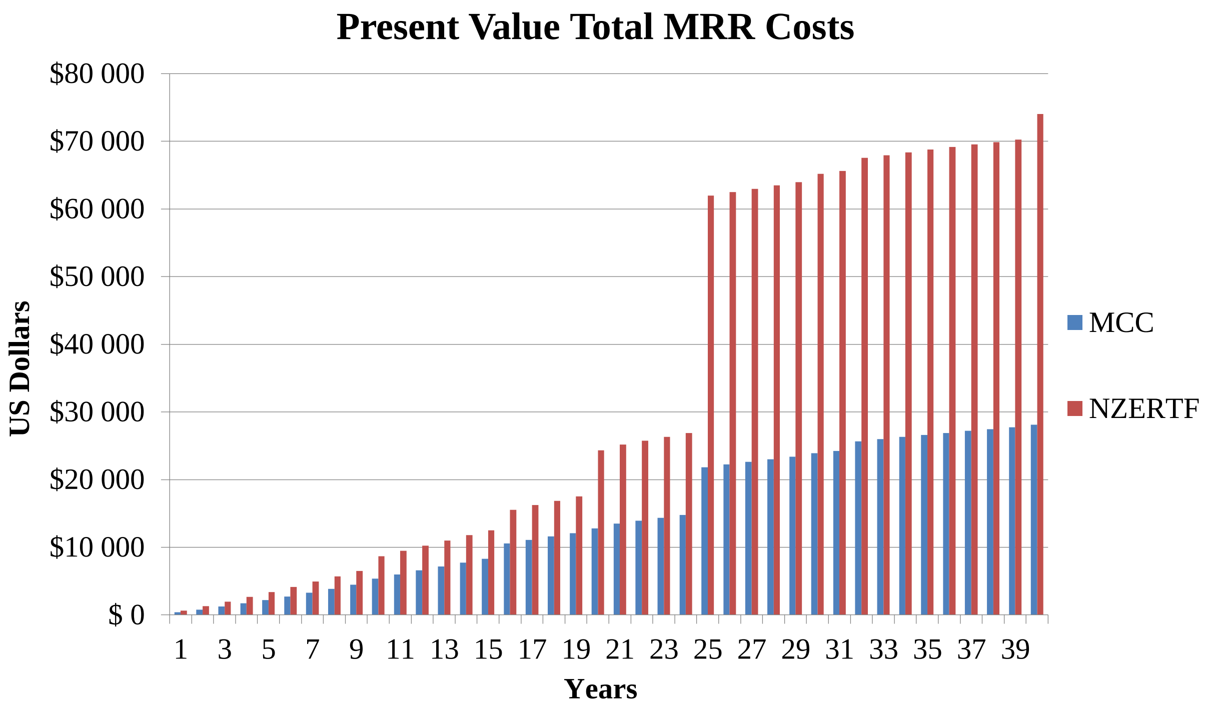

Figure 4-4 Present Value of Total Maintenance, Repair, and Replacement Costs by Study Period

Figure 4-5 reveals that the significantly higher MRR costs for the NZERTF building design are associated with the replacement of the home's solar PV system, which has an assumed lifetime of 25 years. Higher MRR costs seen in earlier periods (before year 25) are primarily related to the costs of replacing other technologies adopted under the NZERTF design, such as the high efficiency HPWH, solar thermal system, and the high efficiency HVAC. The annual cost of maintaining the buildings' heat pump comprise the majority of the MRR costs for the MCC design from year 0 to year 16 at which time the air-to-air heat pump is replaced. Non-EEM related costs (baseline costs) have not been included Figure 4-5. Baseline cost is the money spent maintaining, repairing, and replacing house components not associated with the adopted EEMs (windows, HVAC, DHW, and lighting systems) and is the same for both designs. Lighting system MMR costs proved to be negligible for the two designs and are not included in Figure 4-5.

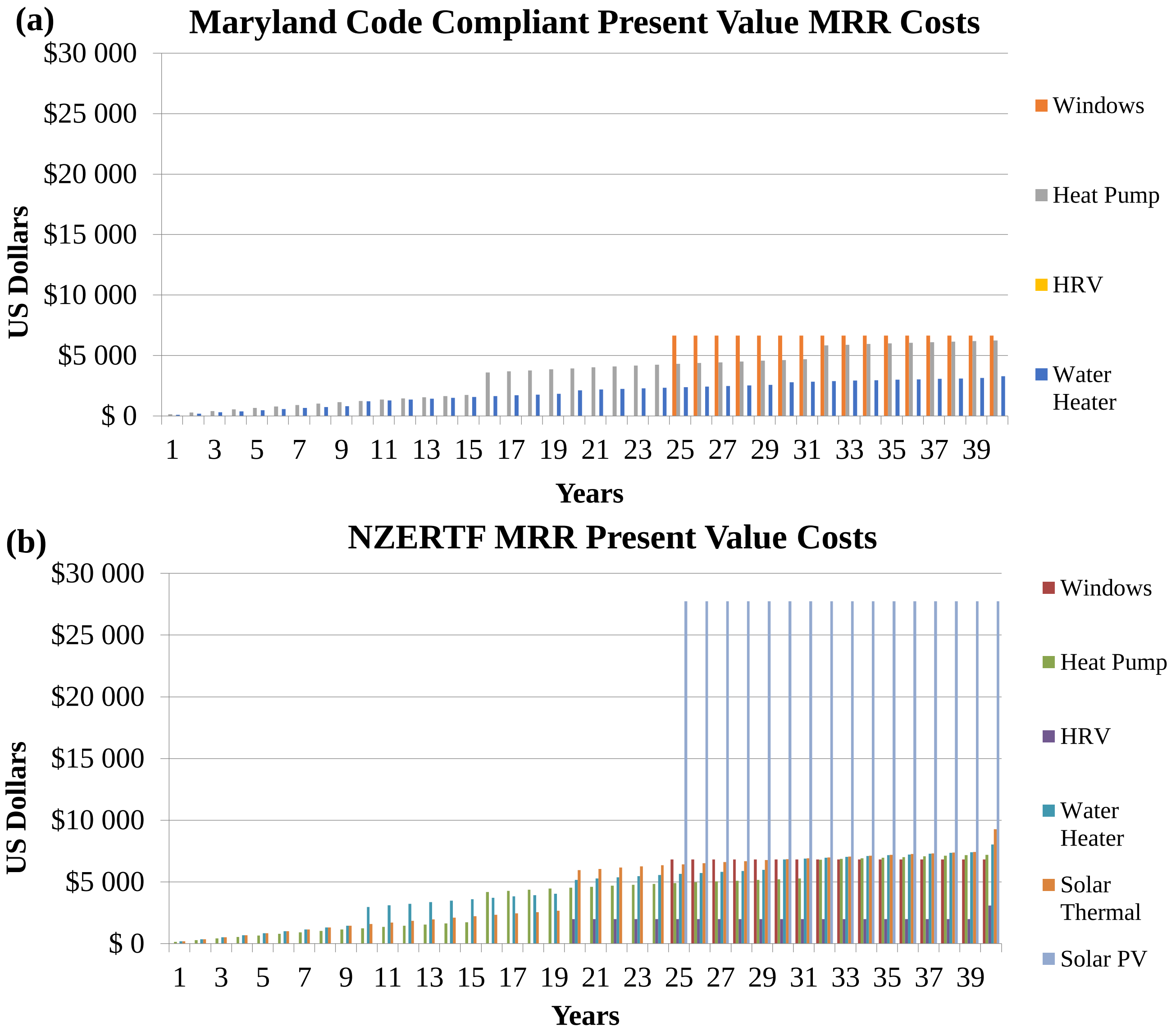

Figure 4-5 Present Value of Maintenance, Repair, and Replacement Costs by Component by Study Period

A house has a long lifetime (assumed to be 100 years), which is much longer than the maximum study period considered in this analysis (40 years). As a result, both designs have some value at the end of the study period (residual value or resale value). Figure 4-6 illustrates the residual value for both building designs across all study periods. Residual values for the NZERTF design are consistently higher than the MCC design across all study periods given the additional EEMs incorporated into the NZERTF design.[6] Residual values for both building designs are steadily declining as the study period increases except in year 25 where the residual value for the newly replaced solar PV system drives up the residual value for the NZERTF design.

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[6] Assumes the homeowner can realize the additional residual value at resale of the house

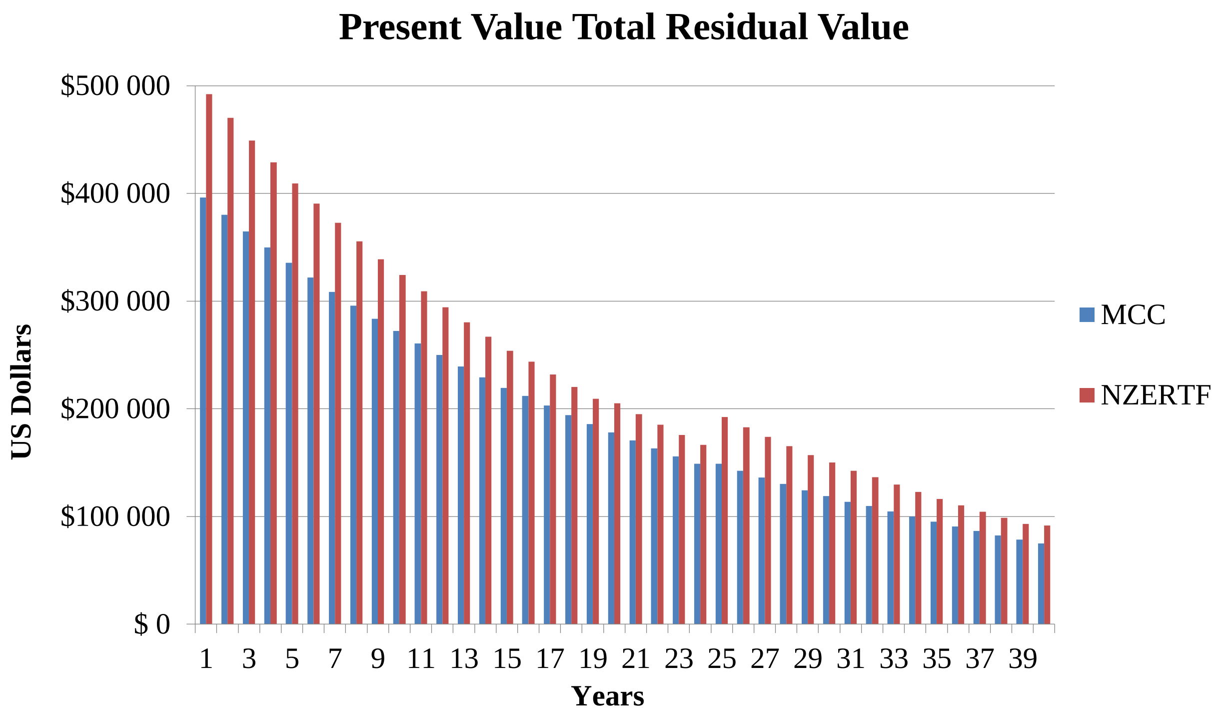


Figure 4-6 Present Value of Total Residual Value by Study Period for both Building Designs

Total LCCs are the sum of first costs, replacement costs, maintenance and repair costs, and energy costs minus the residual value. It is used in this analysis to gauge the economic feasibility of the NZERTF design. Figure 4-7 shows (a) total LCC and (b) the changes in LCC between the two building designs. According to Figure 4-7(a) the NZERTF consistently has a higher LCC than the MCC design. Differences in costs grow wider as study period length increases. Future energy cost savings realized by the NZERTF are not large enough to offset the higher initial and future investment costs associated with the energy efficiency measures incorporated in its design.

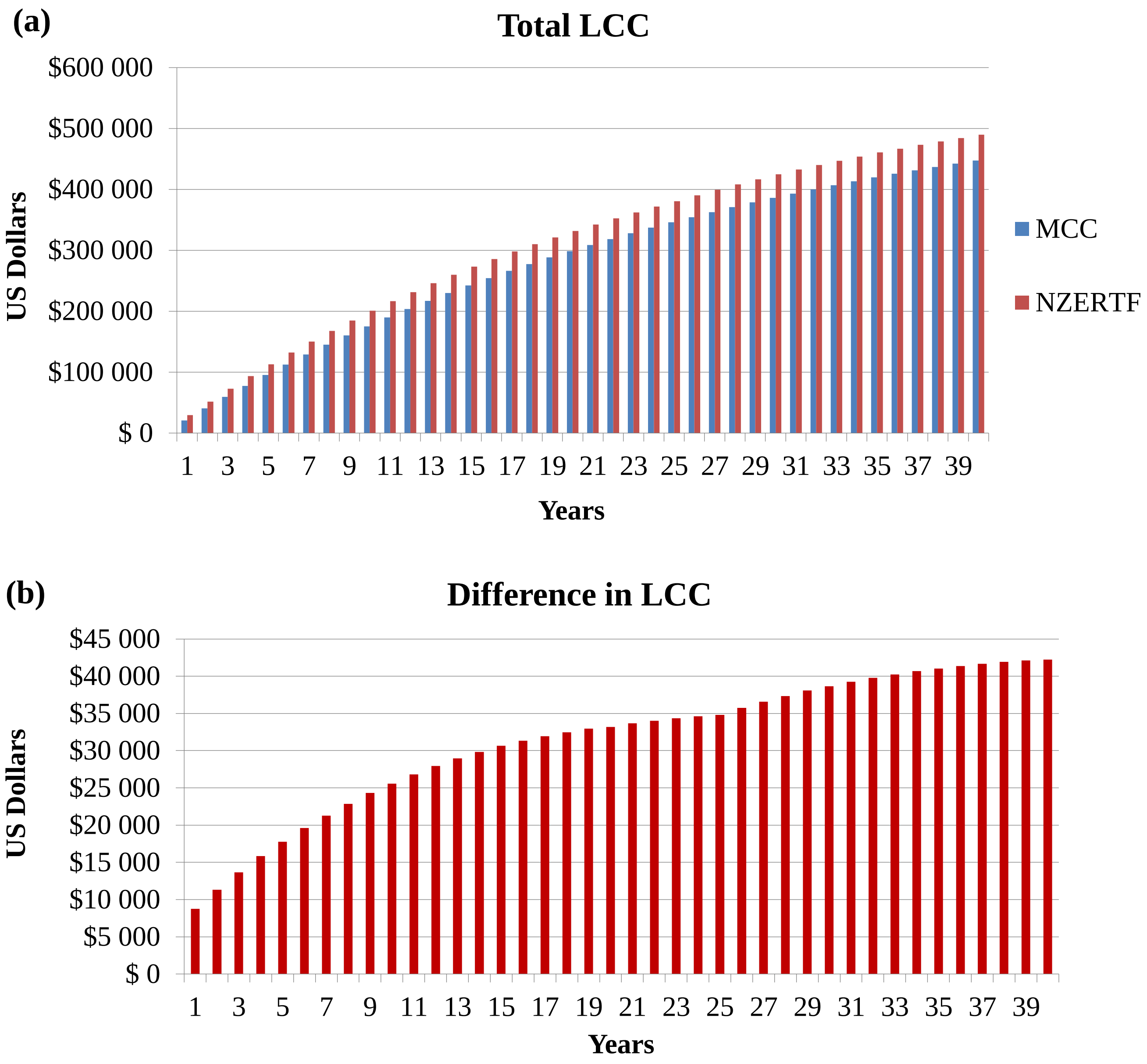


Figure 4-7 Life-cycle Cost Measures for the Maryland Code-Compliant and NZERTF Building Designs

Changes in LCC between the designs captured in Figure 4-7(b) further supports the above conclusion that the MCC design is more economical than the NZERTF design. The difference in LCCs begins to plateau near year 25, at which point the solar PV system is replaced. However, a homeowner could build and live in the NZERTF design, consuming no net energy over a year at additional present value costs of $20 000 (6 years) to $35 000 (40 years), which excludes any financial incentives offered to homeowners for building a more energy efficient house or installing the solar PV system.

4.3 Environmental

The environmental performance of the NZERTF design and MCC design are analyzed by individual environmental impact category as well as a combined environmental impact score (EIS) based on a weighted average of all impact categories. The EIS takes into account the environmental benefits of lower energy consumption and the additional environmental impacts embodied within the EEM components.

4.3.1 Environmental Impact Categories

The environmental performance of the NZERTF design relative to the MCC design varies depending on the environmental impact category. Because of this result, it is imperative that all environmental impacts are considered as opposed to a single impact such as GWP. Twelve impact categories are assessed for both building designs: GWP, Primary Energy Consumption, Human Health (Respiratory Effects, Cancer Effects, and Non-cancer Effects), Water Consumption, Ecological Toxicity, Eutrophication Potential, Land Use, Smog Formation, Acidification Potential, and Ozone Depletion.

Figure 4-8 provides an illustration of the four impact categories primarily affected by operating energy consumption: global warming potential, ozone depletion, smog, and primary energy consumption. The GWP impacts (in kg CO2 eq.) in Figure 4-8(a) for both the MCC and NZERTF designs show continuous growth in emissions as the study period length increases – with the MCC design having significantly greater CO_2e emissions because of the greater electricity consumption. In the case of a 40-year study period, the impacts of the MCC design on GHG emissions are more than five times that of the NZERTF design. As shown in Figure 4-8(b), both designs contribute to acidification levels (mol H+ eq.). The contributions of the NZERTF design are considerably lower than the MCC design for all study periods. Figure 4-8(c) shows that the NZERTF design contributes less to smog formation than the MCC design across all assumed study period lengths. MCC design impacts are as much as five times greater (40-year study period) because of its higher electricity consumption. Since electricity production relies on fossil fuels, at least partially as a fuel source, increasing the energy efficiency of a house will impact fossil fuel resource supplies. The “Primary Energy Consumption” metric in Figure 4-8(d) shows that the contributions of the NZERTF design are consistently lower than the less energy-efficient MCC design. The difference is considerable for a number of study periods. For example, the difference is 1725 kWh for a 40-year period. Since the metric includes both energy embodied within the building materials and operating energy consumption, the NZERTF GWP value is still positive even though the NZERTF is a net producer of energy.

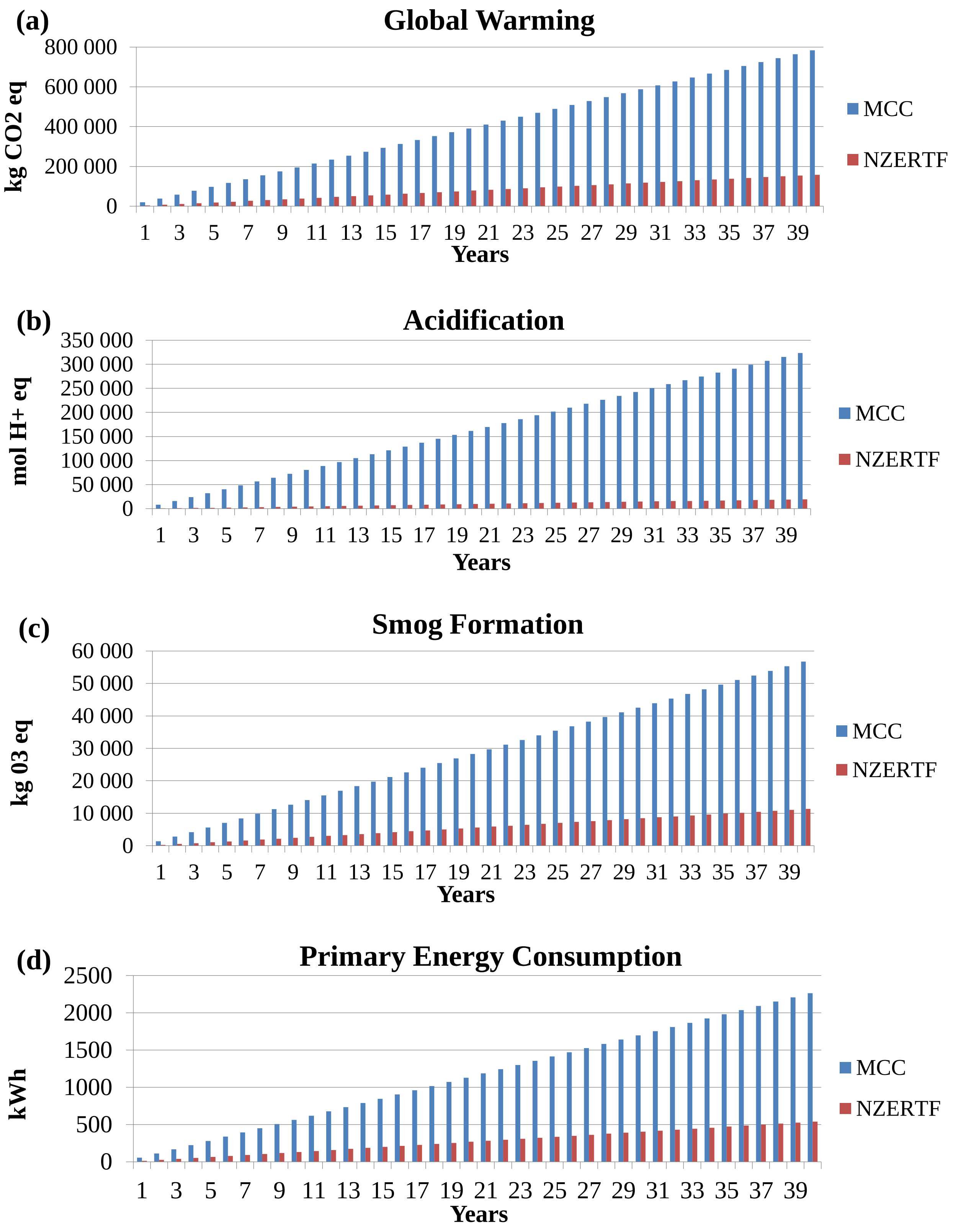
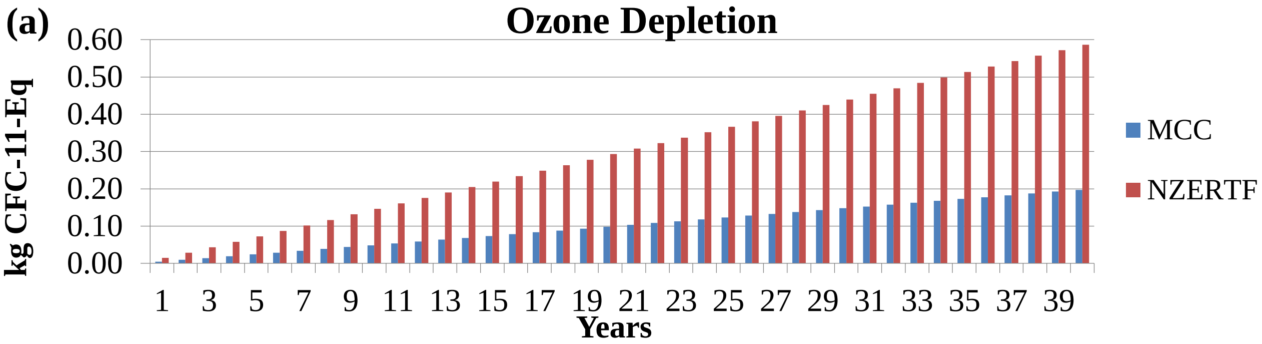
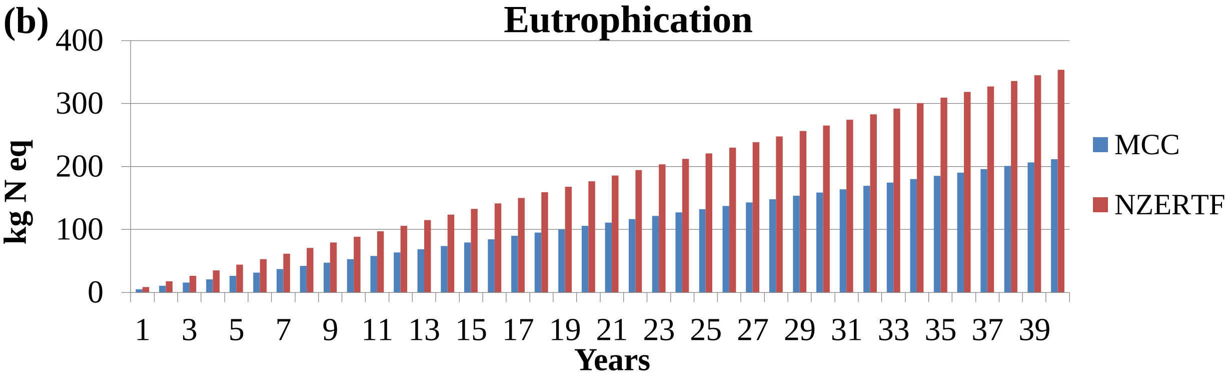


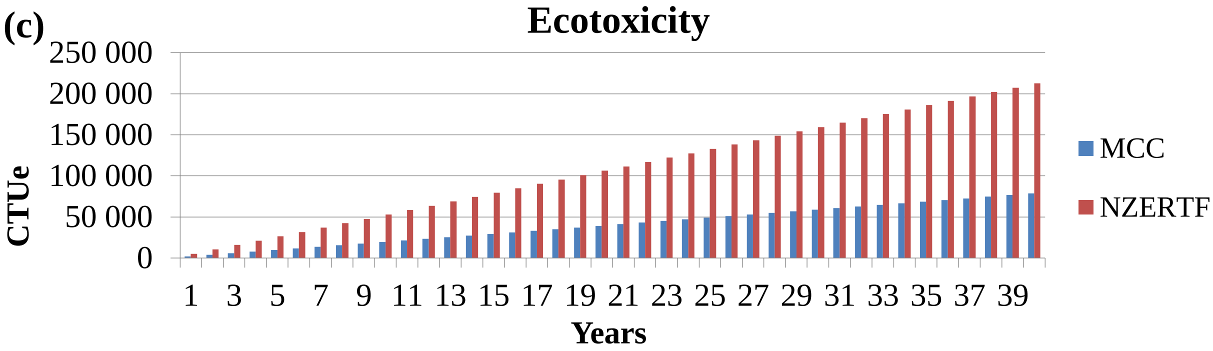
Figure 4-8 Life-cycle Impact Assessment Results for (a) GWP (b) acidification (c) smog and (d) energy for the Maryland design and NZERTF design

Given the above results, the NZERTF design will fare better than the MCC design in impact categories driven by energy consumption (GWP, Ozone Depletion, Smog Formation, and Primary Energy Consumption). Its impact on the remaining impact categories must also be considered in order to evaluate the overall "environmentally-friendliness" of the NZERTF design relative to the MCC design.

Household energy demands somewhat influence the impact categories associated with Figure 4-9. However, the embodied environmental flows in the building materials and components themselves are primarily responsible for these impacts. Figure 4-9(a) shows that the NZERTF design has a much larger impact on ozone depletion than the MCC design, which is driven by the embodied emissions in the additional rigid insulation in the roof and wall assemblies. The divergence in impacts grows larger over time to 0.40 kg CFC-11-eq given a 40-year study period. Figure 4-9(b) shows that the NZERTF design has a consistently greater impact on eutrophication levels than the MCC design. The building and operation of both the MCC and NZERTF designs are likely to contribute to ecotoxicity. Figure 4-9(c) shows that the potential contributions of the NZERTF design will be more than twice as high as that of the MCC design in most study periods due to the emissions embodied in the solar PV system. Figure 4-9(d) highlights differences in impacts for the NZERTF and MCC designs on human health – more specifically, the non-carcinogenic effects. Construction and use of the NZERTF design lead to greater (non-cancerous) human health impacts than the MCC design. Impact differences grow as large as 0.011 CTUh (assuming a 40-year study period length).







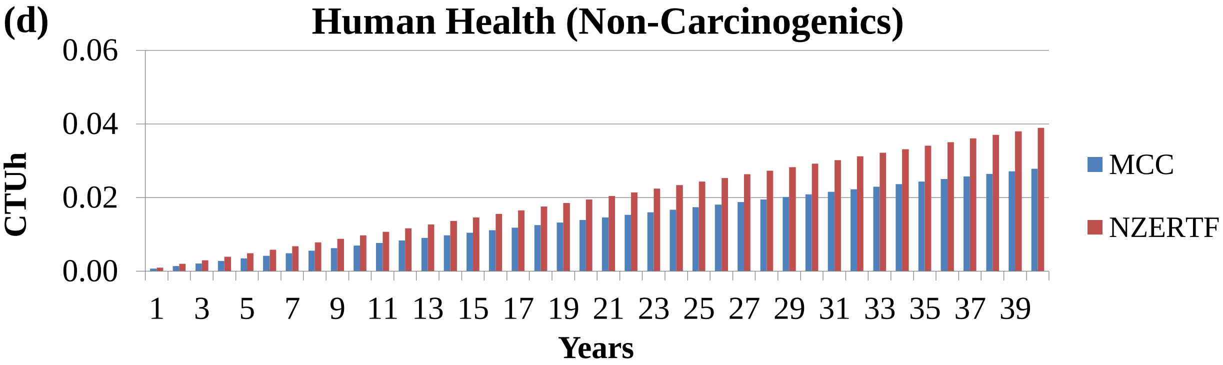


Figure 4-9 Life-cycle Impact Assessment Categories ((a)-(d)) Directly Influenced by Building Construction Inputs and Operation for the Maryland and NZERTF designs

Only 8 of the 12 impact categories have been accounted for in Figure 4-8 and Figure 4-9. The effects of the two designs on the remaining 4 categories (land, water, human health – carcinogenics, and respiratory effects) are relatively small. Both the NZERTF and MCC designs will increase the potential for the occurrence of these impacts; however, there is no real benefit of building and operating one home over another in regards to minimizing its impact on one of the five categories.

Figure 4-10 summarizes the above results by measuring the impacts of the NZERTF on all 12 environmental impact categories relative to the MCC design (in percentage terms) given a 40-year study period. The most noticeable difference in impacts occurs for ozone depletion. The contributions of the NZERTF are three times greater (a 200 percentage point difference) than that of the MCC design. Similar impacts are seen with ecotoxicity, where the NZERTF impacts are 172 percentage points greater than the MCC design. The effects of the NZERTF on GWP, acidification, and smog formation are 20, 6, and 19 percentage points less than the MCC alternative.

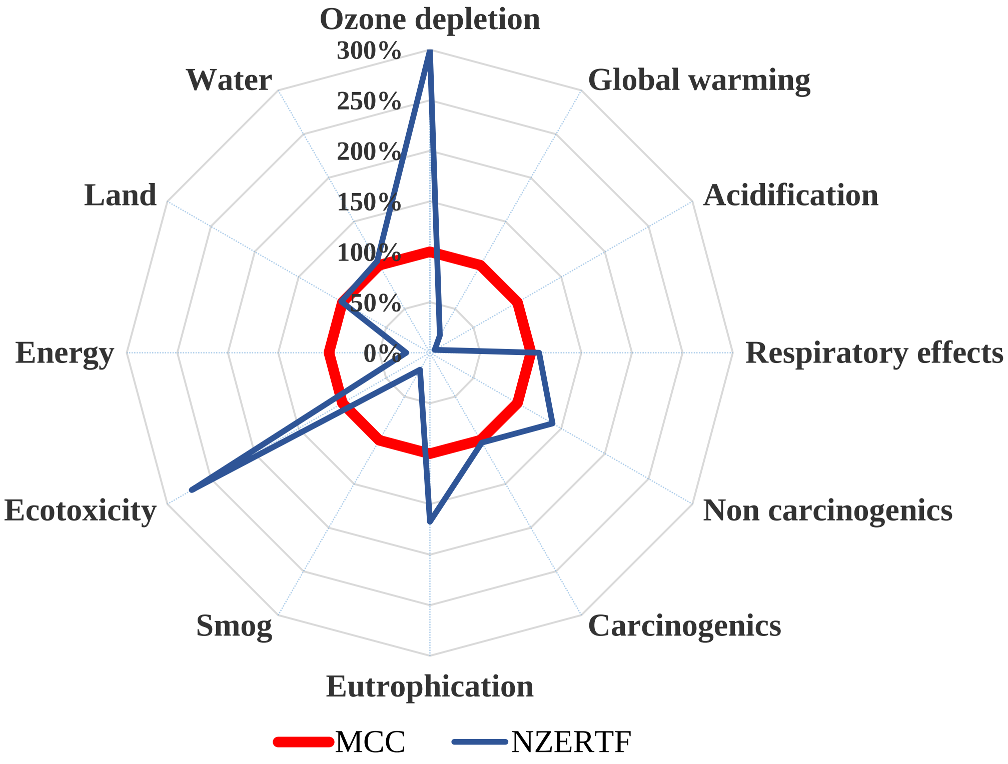


Figure 4-10 Relative Differences in Environmental Impacts for the Net-Zero and Maryland Code Compliant Designs

Large differences between the impacts of MCC and NZERTF designs on individual environmental flows make it difficult to gauge which home is more environmentally-friendly. The following section discusses a reliable approach to reaching a more holistic conclusion about each design’s overall environmental impact.

4.3.2 BIRDS Normalization and Weighting

As mentioned in the previous section, impacts are expressed and measured in different units, which prevents adequate comparisons across environmental flows. This analysis implements a technique that allows such comparisons to be made through normalized impact scores, which can then be used to compare impacts. Fixed scale normalization references based on the relative annual contributions of total U.S. economic activity to each of the 12 environmental flows shown in Table 4-3 are used in calculating the scores (Lippiatt, Kneifel et al. 2013).

Table 4-3 Normalization References: Annual U.S. Contributions

Impact Category	Normalization reference (Annual)	Units
Global Warming	7.16E+12	kg CO_2 eq.
Primary Energy Consumption	3.52E+13/1.20E+14	kWh/kBTU
HH – Criteria Air	2.24E+10	kg PM10 eq.
HH – Cancer (Carcinogenic)	1.05E+04	CTUh
Water Consumption	1.69E+14	L
Ecological Toxicity	3.82E+13	CTUe
Eutrophication	1.01E+10	kg N eq.
Land Use	7.32E+08/1.81E+09	hectare/acre
HH – Non-cancer (Non-Carcinogenic)	5.03E+05	CTUh
Smog Formation	4.64E+11	kg O_3 eq.
Acidification	1.66E+12	mol H+ eq.
Ozone Depletion	5.10E+07	kg CFC-11-eq.

Dividing each initial impact assessment by the total US contribution to that particular flow normalizes the results to permit direct comparisons. Table 4-4 lists the first series of normalized impact assessment scores for the MCC design and NZERTF design assuming a 10-year study period length, which is the same study period used for the life-cycle cost analysis.

Table 4-4 Normalization Impact Assessment Scores

Impact Category	MCC	NZERTF
Global Warming	2.73E-08	5.47E-09
Primary Energy Consumption	1.60E-08	3.73E-09
HH – Criteria Air	3.05E-09	3.31E-09
HH – Cancer (Carcinogenic)	3.93E-08	4.04E-08
Water Consumption	7.14E-09	7.47E-09
Ecological Toxicity	5.10E-10	1.39E-09
Eutrophication	5.22E-09	8.74E-09
Land Use	6.89E-09	6.97E-09
HH – Non-cancer (Non-Carcinogenic)	1.38E-08	1.93E-08
Smog Formation	3.04E-08	5.91E-09
Acidification	4.86E-08	2.81E-09
Ozone Depletion	9.73E-10	2.95E-09

An overall environmental impact score (EIS) can then be calculated by taking a weighted average of the normalized scores. The higher the EIS, the more impact the building will have on the environment. The selected weights for the impact categories will affect the relative environmental performance. Weights developed by the EPA Science Advisory Board (SAB) and a stakeholder panel hosted by NIST for the Building for Environmental and Economic Sustainability (BEES) software[7] (referred to as the BEES Stakeholder Panel through the remainder of this document), along with a set of equal weights (8.3 % for each category), are three examples of weighting approaches that are used to assess environmental flows. The "Equal Weighting" approach assumes that each impact category is valued the same. GWP is just as important as Ecotoxicity, Smog, and so forth. However, it is likely that some impacts are considered more important than others. The Science Advisory Board weights consider land use and global warming as the "highest-risk problems" and therefore are weighted more heavily than the others. Weights based on BEES Stakeholder Panel judgments attribute higher weights to GWP and energy consumption. For further discussion on the BIRDS normalization and weighting approaches, please refer to Lippiatt et al. (2013). Weights based on the SAB and BEES panel are shown in Table 4-5.

Table 4-5 Relative Importance Weights (%)

Impact Category	Science Advisory Board	BEES Stakeholder Panel
Global Warming	18	29.9
Primary Energy Consumption	7	10.3
HH – Criteria Air	7	9.3
HH – Cancer (Carcinogenic)	8	8.2
Water Consumption	3	8.2
Ecological Toxicity	12	7.2
Eutrophication	5	6.2
Land Use	18	6.2
HH – Non-cancer (Non-Carcinogenic)	5	5.2
Smog Formation	7	4.1
Acidification	5	3.1
Ozone Depletion	5	2.1

Figure 4-11, Figure 4-12, and Figure 4-13 are graphical illustrations of how the different weighting approaches generate noticeably different EISs. The equal weighting of normalized environmental flows in Figure 4-11 produces an overall higher EIS for the MCC design. Because all environmental flows are assumed to be valued the same, impact categories more negatively affected by the NZERTF design than the MCC design, like ecotoxicity and ozone depletion, end up contributing less to the overall EIS.

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[7] Lippiatt, B., et al. (2010). BEES Online: Life cycle analysis for building products, National Institute of Standards and Technology, US Department of Commerce.

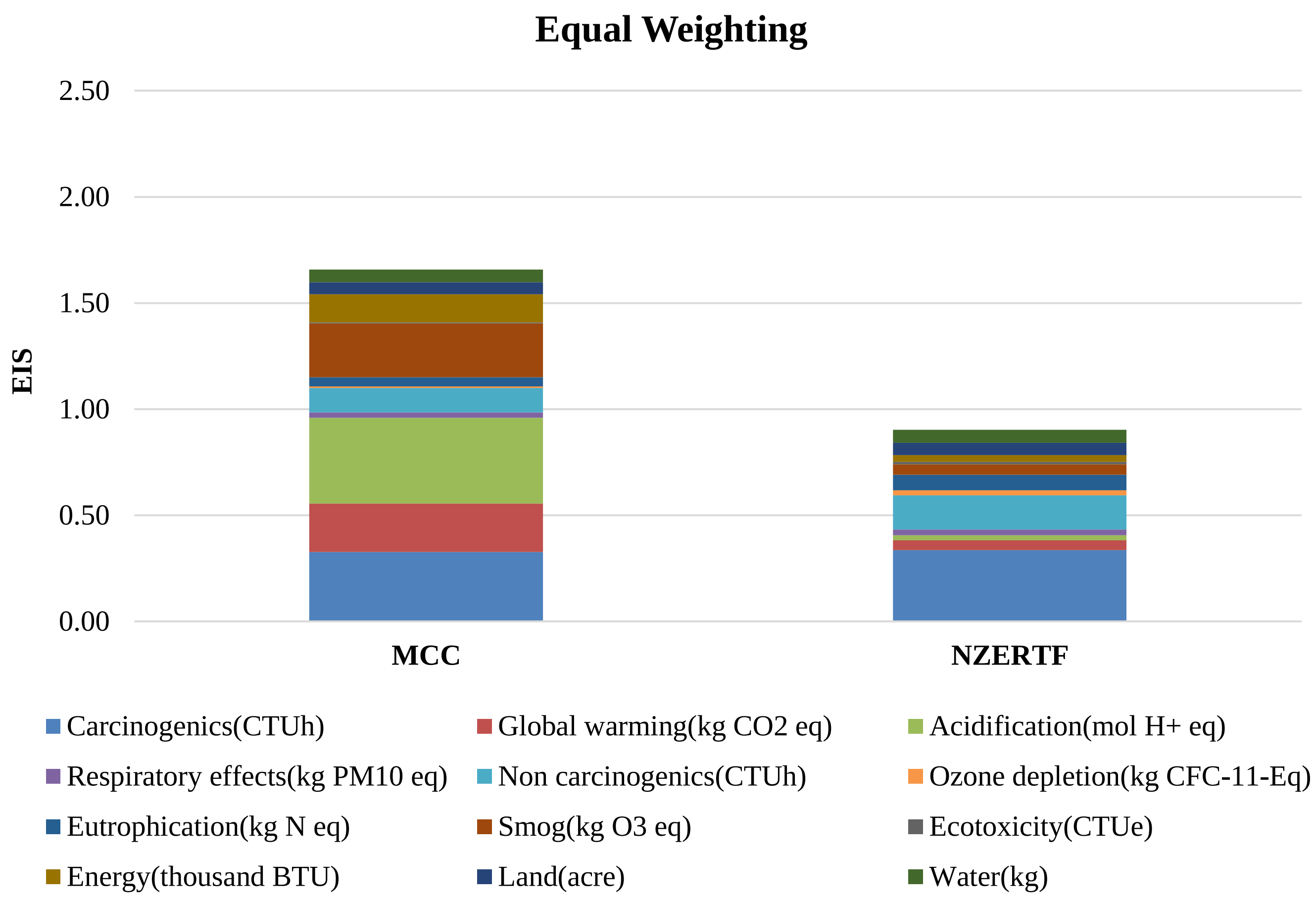

Figure 4-11 Weighted Normalized Impact Scores for the MCC and NZERTF Building Designs using Equal Weights

Figure 4-12 and Figure 4-13 show how different weighting approaches can change the EIS. The MCC design generates a higher EIS under both approaches. In the case of the BEES Stakeholder panel, impact categories in which the NZERTF design performs worse than the MCC design (i.e., ecotoxicity and ozone depletion) are not heavily weighted, leading to small EIS contributions. The contributions of GWP and primary energy consumption to the EIS are 40 %. Better performance by the NZERTF design in these impact categories drives down its EIS relative to the MCC design.

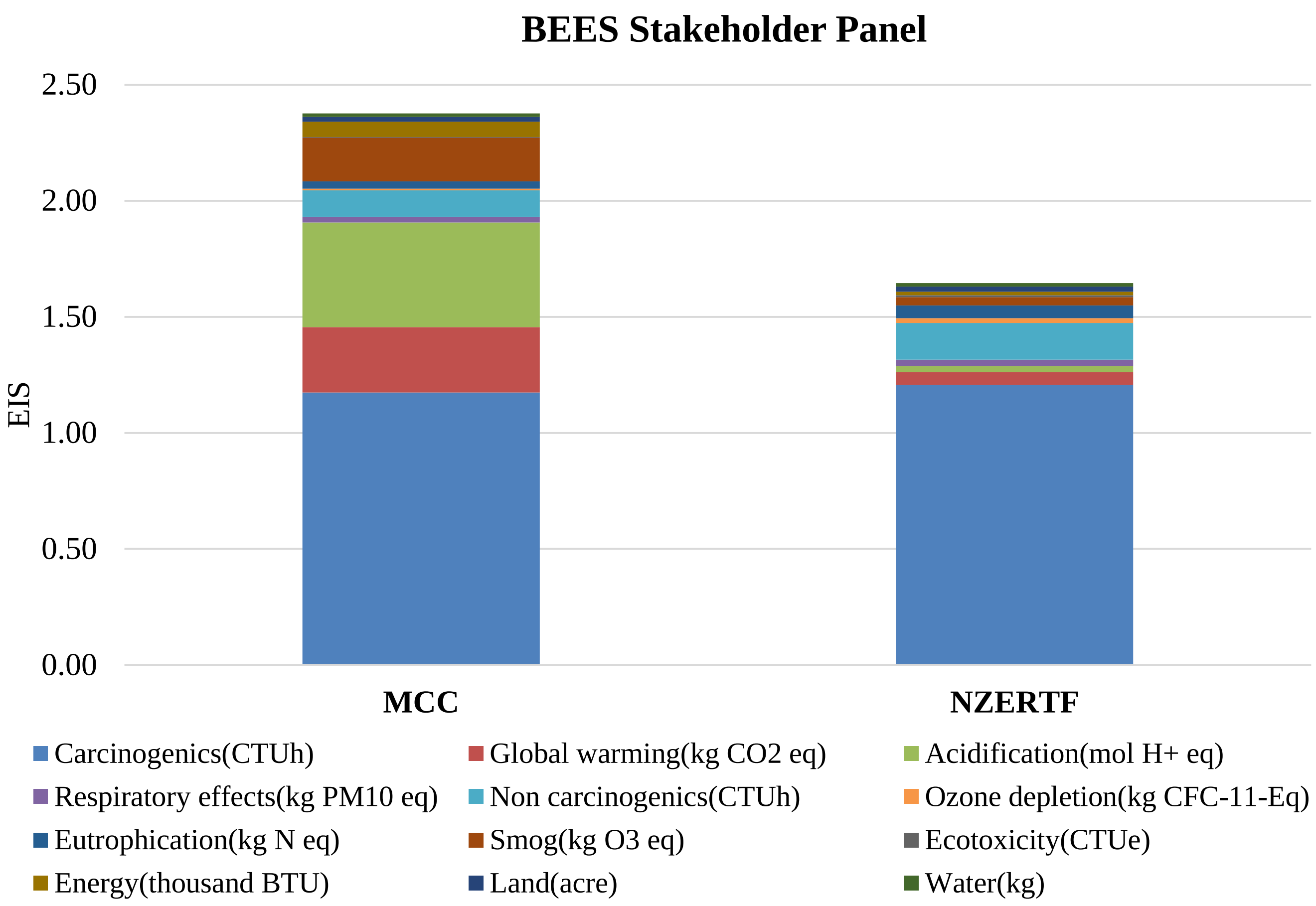

Figure 4-12 Weighted Normalized Impact Scores for the MCC and NZERTF Building Designs using BEES Weights

A similar outcome occurs with the SAB weights. Environmental flows more negatively impacted by the NZERTF design compared to the MCC design are not weighted heavily (with the exception of ecotoxicity), leading to rather small contributions to the EIS than other impact categories where the NZERTF design performs better. The EIS for the MCC design is more than two times higher than the NZERTF design.

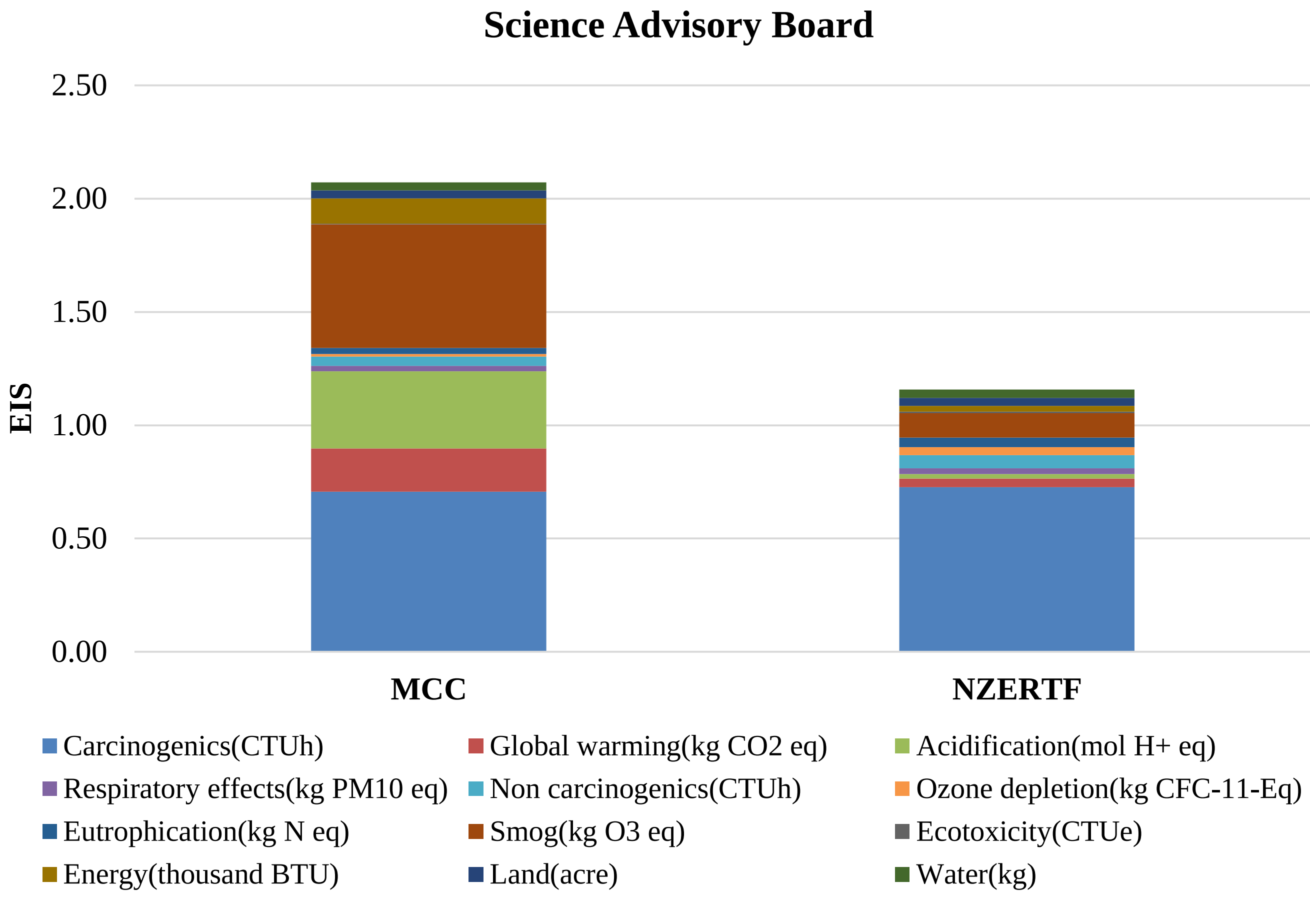

Figure 4-13 Weighted Normalized Impact Scores for the MCC and NZERTF Building Designs using SAB Weights

Computed impact scores using the three aforementioned weighting systems for both the MCC design and NZERTF design are shown in Table 4-6. All 3 EIS estimates suggest that the NZERTF design will have less of an overall environmental impact than the MCC design. The MCC design fairs just as well or better than the NZERTF design in 8 of the 12 impact categories. However, large divergences in GWP, acidification, and smog formation impacts make the NZERTF design more environmentally-friendly than the MCC design. Under the equal weighting approach, the NZERTF design realizes an EIS that is 41 % smaller than the MCC design. This divergence is further exacerbated by the SAB and BEES weights since both place great emphasis on GWP. All results must be considered with caution. Our results are based only on three weighting systems. Alternative weighting approaches could produce significantly different outcomes. Since environmental flows for building components are annualized, the study period length would impact the magnitude of the results. Additionally, the relative performance of the building designs would change as the study period increases in length because the fraction of total flows associated with operating energy consumption increases.

Table 4-6 Weighted Impact Scores

	Equal Weighting		**Science Advisory Board**		**BEES Stakeholder Panel**	
Impact Category	**MCC**	**NZERTF**	**MCC**	**NZERTF**	**MCC**	**NZERTF**
HH – Cancer	0.33	0.34	0.71	0.73	1.17	1.21
Global warming	0.23	0.05	0.19	0.04	0.28	0.06
Acidification	0.40	0.02	0.34	0.02	0.45	0.03
HH – Criteria Air	0.03	0.03	0.02	0.03	0.03	0.03
HH – Non-cancer	0.11	0.16	0.04	0.06	0.11	0.16
Ozone depletion	0.01	0.02	0.01	0.04	0.01	0.02
Eutrophication	0.04	0.07	0.03	0.04	0.03	0.05
Smog Formation	0.25	0.05	0.55	0.11	0.19	0.04
Ecological Toxicity	0.00	0.01	0.00	0.01	0.00	0.01
Primary Energy Consumption	0.13	0.03	0.11	0.03	0.07	0.02
Land Use	0.06	0.06	0.03	0.03	0.02	0.02
Water Consumption	0.06	0.06	0.04	0.04	0.02	0.02
Total	1.66	0.90	2.07	1.16	2.38	1.64
Pct. Difference	59 %		57 %		36 %	
Note: All values listed in the table have been scaled by 10^8						

5 Variances in the Relative Efficiency of Simulated Building Designs

Design of the NZERTF requires the implementation of seven additional EEMs. Chapter 4 revealed that these additional measures lower household electricity demands relative to the MCC design, but at a significantly higher cost to the homeowner. Ideally, homeowners wanting to improve the energy efficiency (relative to the MCC) of their new home are seeking cost-effective solutions. Alternative designs that are less costly to construct and still lead to considerable reductions in energy use could be considered. This chapter includes preliminary analysis of the incremental adoption of the EEMs in the NZERTF design as are found in the BIRDS low-energy residential database.

5.1 Isolating the Optimally Efficient Building Design

Figure 5-1 is a scatterplot of 864 incremental designs assuming a ten-year study period. Each point represents the observed level of energy efficiency and change in life-cycle costs associated with a specific combination of EEMs specified in Section 2 relative to the baseline case of the MCC design (Point A). All designs or "points" captured on the lower envelope of the solution set (points along the black line) are the most inexpensive combination of EEMs for a given level of energy reduction. We characterize a design as being closer to optimal the lower its change in LCCs. Based on this characteristic, Point B proved to be the LCC optimal building design. The design lowers annual energy use by 46 % while decreasing life-cycle costs by $6304 relative to the MCC design and nearly $32 000 less than the NZERTF design (Point F). Four of the seven EEMs described in Section 2 (i.e., high efficiency windows, high efficiency HVAC system, 100 % efficient lighting, and improved infiltration) are implemented in the optimal design.

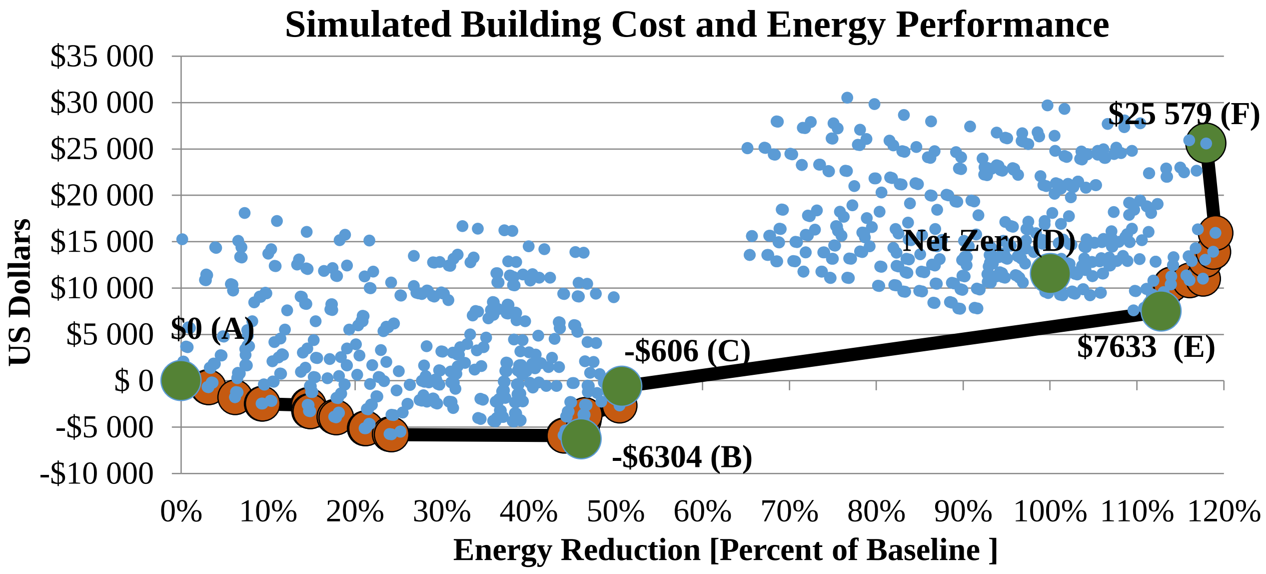

Figure 5-1 Changes in Life-Cycle Costs and Energy Use Reductions for Simulated Building Designs

Homeowners may be willing to select a design alternative that is not LCC optimal in order to gain additional energy efficiency as long as the LCC will not increase relative to the MCC design. Point C is an example of a combination of EEMs (6 in total) that produce noticeable energy savings (51 %) at roughly the same LCC as the MCC design. In fact, homeowners will save $606 over the course of ten years.

Homeowners driven by reducing their energy use and/or environmental impacts are likely to consider house designs that are more expensive to build and operate, but are more energy efficient and sustainable in nature. Figure 5-1 shows reductions in energy consumption beyond 51 % are achievable but come at higher LCCs to the homeowner. Points further to right of the graph incorporate the 10.2 kW solar PV system in its design. Additional electricity produced on-site is enough to offset most or all of the household energy demands. However, the additional cost of the system makes these designs much less economical. Point D and Point E are examples of building designs that reach net-zero energy performance using different EEM combinations. A home built to the specifications of Point D will just reach net-zero. However, a different combination of EEMs, used in the design at Point E, generates an additional 10 % of net energy consumption reductions for approximately $4000 less in LCCs.

Figure 5-2 captures, for a given level of energy efficiency, the additional investment costs associated with the adoption of various combinations of EEMs. Only designs located on the lower envelope of the solution set displayed in Figure 5-1 are shown. According to the figure, homeowners incorporating higher efficiency windows, 100 % efficient lighting, and/or improvements in infiltration in their home, assume only slightly higher investment costs. Integrating a high efficiency HVAC system in the home has a considerable impact on investment costs. The first noticeable jump in initial investment costs (and resulting jump in energy consumption reduction) is a result of the high efficiency HVAC system being implemented and requires an initial investment of approximately $13 000 (Figure 5-2). The additional investment costs incurred ($16 280) by moving from the Point B design to Point C is directly related to the inclusion of both advanced framing with additional insulation for the walls and a HPWH in the building design. The greatest increase in first costs is related to the installation and use of the solar PV system, which drives up investment costs by approximately $58 000 while increasing energy reduction by about 60 percentage points. Our findings suggest that additional investment costs are not necessarily a function of the number of measures adopted, but more so the types of EEMs adopted.

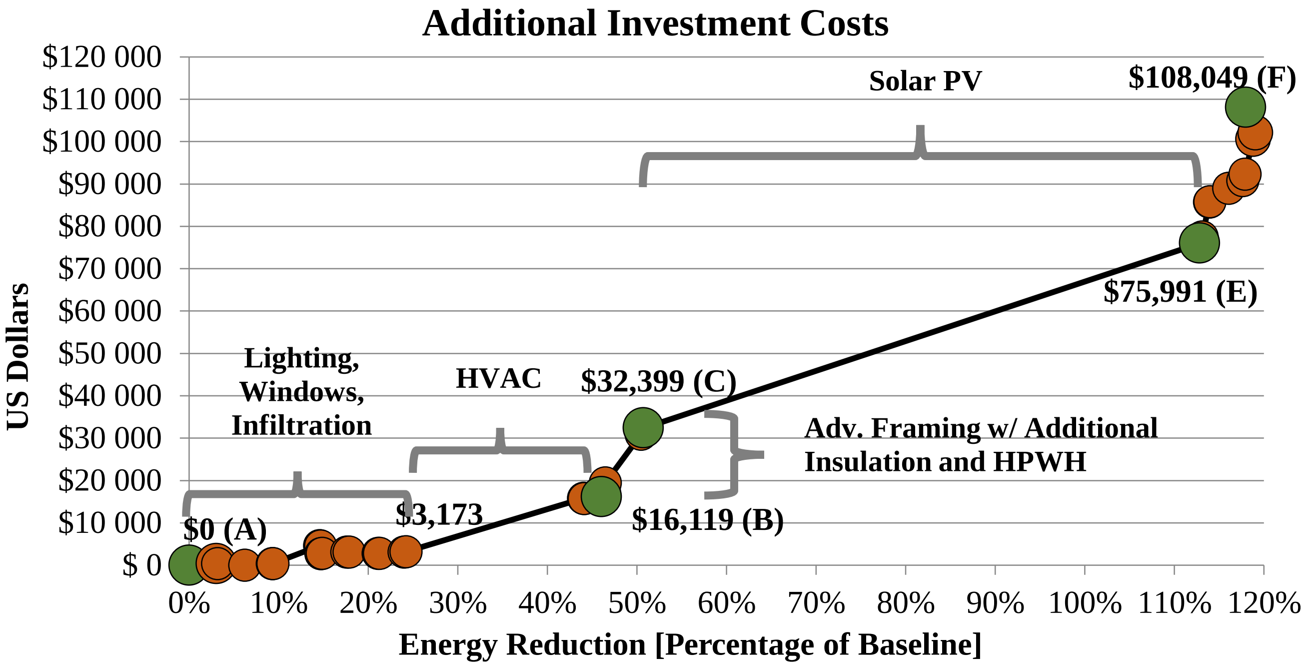

Figure 5-2 Cost of Additional EEM Investment for Simulated Buildings

A breakdown of the different combinations of EEMs employed by four of the simulated building designs is shown in Table 5-1. The four are: (1) MCC design; (2) a design that is more energy efficient than the MCC design with comparable LCCs (MCC*); (3) LCC optimal design; and (4) NZERTF design. Relative to the MCC design, a 51 % improvement in energy efficiency can be attained by implementing 6 of the 9 EEMs at no additional LCC to the homeowner (MCC*). The inclusion of the high efficiency HVAC system is largely responsible for the reductions in energy use. Only four measures are adopted by the LCC optimal design (high efficiency HVAC system, high efficiency windows, air infiltration improvements, and 100 % efficient lighting). The NZERTF adopts all EEMs and improves energy efficiency by 118 %, but is one of the least cost-effective of all the building designs considered in the BIRDs low-rise residential database.

Table 5-1 Breakdown of Energy Efficiency Measures for Simulated Buildings

Building Design	Energy Reduction	Change in LCC	Additional Energy Efficiency Measures
MCC	-	-	-
MCC*	51 %	-$606	(1) High efficiency windows; (2) High efficiency HVAC system; (3) improved air infiltration; (4) 100 % energy efficient lighting; (5) HPWH; and (6) advanced framing with additional insulation.
Optimally Efficient	46 %	-$6304	(1) High efficiency windows; (2) High efficiency HVAC system; (3) improved air infiltration; and (4) 100 % energy efficient lighting.
NZERTF	118 %	$25 579	1) High efficiency windows; (2) High efficiency HVAC system; (3) improved air infiltration; (4) 100 % energy efficient lighting; (5) solar PV system; (6) HPWH with (7) additional solar thermal storage; (8) shift from ceiling to roof insulation with additional exterior rigid insulation; and (9) advanced framing with additional insulation in wall.

5.2 Sustainability Performance of the Optimal Efficient Design

Isolating the optimal building design was done by comparing its relative cost-effectiveness with those of the other 863 designs. In this section, we provide an in-depth analysis of the LCC optimal design by considering both its economic and environmental performance relative to the MCC and NZERTF designs. Along with LCC, the 3 metrics described in Section 3.2 (NS, SIR, and AIRR) can be used to compare design alternatives to the established baseline case (MCC design).

Table 5-2 lists the NS, the SIR, and AIRR for the optimal and NZERTF designs under the assumption of a ten-year study period. The optimal design generates a positive net savings ($6304), a SIR greater than one (1.9), and an AIRR greater than 3 % (10.0 %). All three measures suggest that our LCC optimal building design is a cost-effective alternative to the MCC home. The NZERTF produces a NS of -$25 570, a SIR of 0.54, and an AIRR of -3.1 %, implying that it is in fact not a cost-effective project alternative.

Table 5-2 Economic Performance Measures

Economic Performance Measures	LCC Optimal	NZERTF
Net Savings	$6304	-$25 579
Savings-to-Investment Ratio	1.9	0.5
Adjusted Internal Rate of Return	10.0 %	-3.1 %

Energy efficiency improvements can be cost-effective, as the results have shown, given the correct combination of EEMs. However, homes built close to or in complete accordance with the NZERTF specifications, will not be economical after 10 years.

Figure 5-3 shows the impacts of both the LCC optimal and NZERTF designs on all twelve environmental impact categories relative to the MCC design. The LCC optimal design performs just as well or better than the MCC design in all but four impact categories (Human health - non-carcinogenics, eutrophication, ecotoxicity, and water consumption). The additional impacts on human health, eutrophication, ozone depletion, and water consumption are marginal, i.e. 1 % to 2 %. Only in the case of ecotoxicity are the impacts considerably larger (a difference of 17 %), although much lower than the NZERTF design because the optimal design does not include the solar PV system. The NZERTF performs better than the optimal design in the global warming, acidification, smog formation, and energy use impact categories.

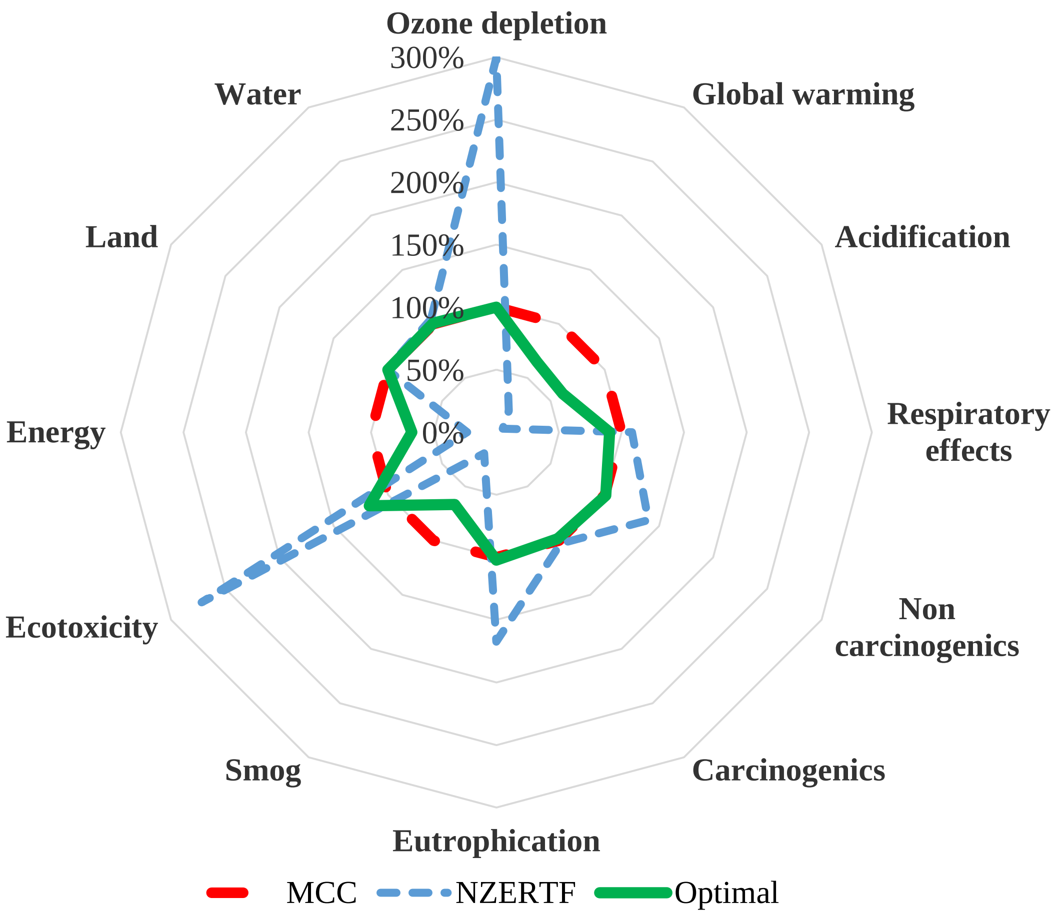

Figure 5-3 Relative Differences in Environmental Impacts for the Optimally Efficient, NZERTF, and MCC Designs

The results of Figure 5-3 do not provide an adequate measure by which to determine if the optimal building design is more environmentally-friendly overall compared to the MCC design.

Similar to Section 4.3.2, environmental flows must be normalized and weighted to develop meaningful impact scores. Table 5-3 shows the weighted impact scores for all three designs. The LCC optimal design has lower EISs than the MCC design across all three weighting systems, while the NZERTF design continues to be the most environmentally-friendly alternative.

Table 5-3 Weighted Impact Scores

	Equal Weighting			**Science Advisory Board**			**BEES Stakeholder Panel**		
	MCC	**NZERTF**	**Optimal**	**MCC**	**NZERTF**	**Optimal**	**MCC**	**NZERTF**	**Optimal**
Score	1.66	0.90	1.29	2.07	1.16	1.64	2.38	1.64	2.00

6 Discussion, Limitations, and Future Research

6.1 Discussion

This study uses whole-building energy simulations, life-cycle costing, and life-cycle assessment to compare the sustainability performance of the NIST NZERTF design relative to that of a Maryland code-compliant design constructed according to the 2012 *IECC*. Comparisons are made based on the energy, economic, and environmental performance of the two designs. This section discusses key findings, research limitations, and future research interests.

All key findings are categorized and described according to the three aforementioned metrics: energy, economic, and environmental performance. Additionally, there is a preliminary discussion of the variations in the relative performance for the 864 different building designs included in the BIRDs low-energy residential database.

6.1.1 Energy Performance

The MCC design and NZERTF design are assumed to rely solely on electricity to satisfy energy demands. Annual electricity consumption by the MCC design and NZERTF designs are 23 604 kWh and 11 231 kWh, respectively. The installed solar PV system incorporated into the NZERTF design produces 15 474 kWh, resulting in an annual net consumption of -4243 kWh. The NZERTF design proves to not only be net-zero, but actually a net producer of electricity (38 % excess production).

6.1.2 Economic Performance

Incorporating all nine EEMs into the NZERTF design increases initial investment costs by $108 049, an increase of 26 % relative to the MCC design. More than half of these additional first costs are due to the installation of the on-site solar PV system ($58 091). Use of advanced framing, additional roof and wall insulation, and a high efficiency HVAC system collectively raises first costs by another $40 385.

The added costs of the NZERTF, however, are partially offset by the 4243 kWh production surplus and the consequent energy cost savings each year. Annual savings for the NZERTF design is $3720 relative to the MCC design. The divergence in cumulative energy cost savings between the two designs increases as the assumed study period length increases, with the NZERTF design saving a homeowner a total of $95 000 (in present value terms) in energy costs over the course of 40 years.

Total LCCs consider initial investment costs, replacement costs, maintenance and repair costs, energy costs (savings in the case of the NZERTF), and the residual value of the house at the end of the study period. Using this metric to compare the economic feasibility of the designs, the NZERTF design will have a higher LCC than the MCC design across all assumed study period lengths. In other words, the MCC design will consistently be the more economical alternative of the two designs. The additional $108 049 investment required by the NZERTF design coupled with consistently higher maintenance, repair, and replacement costs more than offset the potential energy cost savings and residual value recouped by the homeowner. Differences in LCC range from $8746 after 1 year to $42 224 after 40 years. Even though the NZERTF design is not more cost-effective, the LCC premium is not as significant as some may expect even without considering the financial incentives available for building a more energy efficient house or installing renewable energy systems.

6.1.3 Environmental Performance

A life-cycle assessment of the environmental performance for the MCC design and NZERTF design is conducted based on twelve different impact categories described in Section 4.3.1. Under the assumption of a 40-year study period, the NZERTF design performs better than the MCC design in the four impact categories primarily affected by household energy consumption (i.e., GWP, acidification, smog formation, and primary energy consumption). The effects of the MCC design on acidification levels are roughly seventeen times greater than the NZERTF design. Additionally, its impacts on GWP, smog formation, and the availability of primary energy sources are four to five times greater.

Dissimilar findings are seen in regard to the performance of the NZERTF design in categories mainly influenced by the actual construction of the building and the incorporated technologies (i.e., ozone depletion, eutrophication levels, ecotoxicity, and human health (non-carcinogenic)). The NZERTF design performs worse than the MCC design in all four categories with ozone depletion and ecotoxicity being the most negatively affected at close to three times those of the MCC design. The impacts of the two building designs on the remaining four categories are minimal and fail to exploit the preference of one design over the other.

Environmental flow impacts cannot be adequately compared across flows of different types. An EIS can be generated for each design by normalizing and weighting flows based on different weighting assumptions. These scores can then be compared to determine which design will be the least harmful to the local ecosystem and environment. The Equal Weighting, BEES Stakeholder Panel, and EPA Science Advisory Board series of weights all lead to a similar conclusion – construction and operation of a home built according to NZERTF specifications will be more environmentally-friendly than the less energy-efficient MCC design. EISs between the two designs differ by as much as 59 % (Equal Weighting). Although the results are robust across the 3 selected weighting approaches, other weight sets could lead to a different conclusion depending on which environmental impact categories are determined to be of most importance.

6.1.4 Optimal Building Design

All 864 different designs included in the BIRDS low-rise residential database were analyzed, each of which is representative of a different combination of adopted EEMs, leading to different levels of energy consumption reduction and LCCs. Assuming a 10-year study period length, the

LCC optimal design, or the one that provides the most "bang-for-your-buck", lowers annual energy use by 46 % at $6304 and $32 000 less in LCCs than the MCC design and NZERTF design, respectively. The LCC optimal design incorporates only four of the nine EEMs (i.e., high efficiency windows, high efficiency HVAC system, 100 % efficient lighting, and improved infiltration).

A number of other design alternatives improve energy efficiency, each with a different impact on total life-cycle costs. At roughly the same LCC as building and operating the MCC design for ten years, a more energy efficient design incorporating six of the nine EEMs can generate 51 % in energy savings each year. Alternative designs that achieve net-zero include the 10.2 kW on-site solar PV system as one of its adopted EEMs and raise overall LCC significantly despite the additional energy cost savings recouped through excess electricity generation. The alternative design that reaches net-zero energy performance at the lowest cost leads to an additional $7633 in LCCs.

Net Savings, the Savings-to-Investment Ratio, and the Adjusted Internal Rate of Return measures shed some light on the relative cost-effectiveness of the LCC optimal design. Assuming that the MCC design is the baseline case, the LCC optimal design generates a net savings of $6304, an SIR of 1.92, and an AIRR of 10.0 % for a 10-year study period, suggesting that the LCC optimal design is a cost-effective alternative. In contrast, the NZERTF design is not cost-effective with a negative net savings (-$25 570), a SIR less than one (0.54), and an AIRR less than 3 % (-3.1 %).

Based on the EIS, the optimal building design performs better than the MCC design. Differences between the two differ by as much as 22 % when relying on the Equal Weighting system. The environmental impact scores for the NZERTF are lower than both the MCC design and LCC optimal design, showcasing its ability to be the more environmentally-friendly design despite being more costly.

6.2 Limitations and Future Research

The analysis in this study is limited in scope and scale, and future research should consider a number of factors: updated simulation models, alternative assumption values, additional cost data and approaches, and more increments for EEM alternatives.

Since the creation of the database used in this analysis, an updated NZERTF simulation model has been developed and documented in Kneifel (2015). The validated model is significantly different than the model developed before the demonstration phase used in Kneifel (2012), Kneifel (2013), and Kneifel (2014). The new NZERTF model should be used as the basis to update the existing low-energy residential database to ensure the results are consistent with the measured performance of the NZERTF.

Although all costs associated with the building designs are included in the current analysis, there are several assumptions that should be analyzed in greater detail. The assumed discount rate may not be representative of the typical homeowner. Other discount rates should be considered to determine the sensitivity of the results. This study assumes an all cash purchase of the house even though financing of a new house is more typical of the market. Financing options should be considered in future analysis. The state average electricity price may vary significantly from the local electricity price, both in terms of magnitude as well as complexity because actual electricity rates often vary by time of year and/or day. Additionally, the compensation for net production sold back to the utility is not always equivalent to the electricity price. Local electricity pricing schedules, including net metering rates, should be included in future research. Financial incentives (i.e., federal tax credits) have been excluded from the current analysis, but could have significant impacts on the LCC analysis. LCC methodology clearly defines how to calculate the residual value of a building at the end of a study period, which assumes a linear depreciation of the house value. It is unclear what the market value is for reductions in energy consumption. Alternative approaches to valuing the resale value of a house should be considered in future research. Each of these factors is accounted for in Kneifel (2014), and should be used as a basis for testing the sensitivity of the results to these assumptions.

The underlying cost data for the current analysis is based on a publically available database that is becoming outdated. Alternative data sources should be identified to see how sensitive the results are to up-to-date data. This study uses an engineering cost approach to estimating the incremental costs of EEMs while contractors may deal with different costs due to unforeseen factors (e.g., uncertainty or non-energy related “green” products). The engineering approach defined in this study should be compared to the contractor estimate in Kneifel (2014). The non-energy related features in the NZERTF design that lead to a LEED Platinum Certification are ignored even though these amenities may add value at the time of resale. Future research should consider both the additional first cost as well as the future value of these “green” amenities to incorporate them into the NZERTF design LCC analysis.

Although this study does consider incremental combinations of EEMs, each EEM only includes two or three levels. For example, the wall insulation R-values either meet the 2012 IECC requirements or the specifications of the NZERTF design even though the optimal R-value for wall insulation may be somewhere in between the two R-values. Future research should include incremental options between the MCC design and NZERTF design.

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