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Net-Zero Energy Residential Building Component Cost Estimates and Comparisons

Joshua Kneifel
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Abstract

Homeowners and builders have increasingly strived to build low energy homes. As building materials, equipment, and methods have improved and renewable energy systems have become commonplace, the goal of net-zero energy homes has become technologically viable. Such an example of these capabilities is on display in the Net-Zero Energy Residential Test Facility (NZERTF), located at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. While the NIST NZERTF has shown that net-zero energy performing homes are technologically feasible using conventional technologies, questions related to costs continue to arise. Economic performance evaluation is reliant on accurate construction cost data, which may change significantly over time as industry learns how to implement energy-efficiency measures into building design and more energy-efficient technology diffuses into the marketplace. In order to update the underlying data in NIST's economic analysis, a NIST-funded contract was completed to estimate the costs of building components designed to meet current Maryland building energy code based on 2015 IECC as well as higher efficiency building components that are either currently installed in the NZERTF or will be installed in the NZERTF in the near future.

The purpose of this study is to summarize the cost estimates generated by the outside contractor. These estimates will then be compared to those from multiple existing data sources. Findings from this study will help provide a reasonable range of cost estimates for different building components that can be used for future research related to the low- and net-zero energy building designs – in particular, research related to the NZERTF and the Building Industry Reporting and Design for Sustainability (BIRDS) software tool.

Keywords

Building economics; cost estimation; energy efficiency; residential buildings; low-energy buildings; net-zero energy buildings

Preface

This study was conducted by the Applied Economics Office in the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). The study is designed to estimate the construction costs of energy efficiency measures (EEMs) in new residential construction. The intended audience is researchers and policy makers in the residential building sector, and others interested in residential building energy efficiency.

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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Table of Contents

List of Figures

List of Tables

List of Acronyms

ACH	Air changes per hour
AEO	Applied Economics Office
ASHRAE	American Society for Heating, Refrigeration, and Air-Conditioning
BC3	Building Component Cost Community
BIRDS	Building Industry Reporting and Design for Sustainability
COP	Coefficient of Performance
CPUC	California Public Utilities Commission
DEER	Database for Energy Efficiency Resources
DOE	Department of Energy
EER	Energy Efficiency Ratio
EL	Engineering Laboratory
HRV	Heat Recovery Ventilator
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
ICC	International Code Council
IECC	International Energy Conservation Code
LBNL	Lawrence Berkeley National Laboratory
NAHB	National Association of Home Builders
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NREMD	National Residential Energy Measure Database
NZERTF	Net-Zero Energy Residential Test Facility
OC	on center
OCMI	O'Connor Construction Management Inc.
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
SEER	Seasonal Energy Efficiency Ratio
SFCE	Square Foot Cost Estimator
SHGC	Solar Heat Gain Coefficient
SIP	Structural Insulation Panel
WHD	whole house dehumidifier
XML	Extensible Markup Language
XPS	Extruded polystyrene

1 Introduction

Homeowners and builders have increasingly strived to build low energy homes. As building materials, equipment, and methods have improved and renewable energy systems have become commonplace, the goal of net-zero energy homes has become technologically viable. Such an example of these capabilities is on display in the Net-Zero Energy Residential Test Facility (NZERTF), located at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland (see Figure 1-1). In the completion of its second phase (February 2015 through January 2016), the facility demonstrated that a home of similar size, aesthetics, and amenities to those in the surrounding communities can generate as much energy as it consumes on an annual basis using conventional technology while meeting the needs of a family of four. The facility will subsequently serve as a test bed to facilitate the development and improvement of methods of test and performance metrics for existing and future energy-efficient technologies.

Figure 1-1 NIST Net-Zero Energy Residential Test Facility

While the NIST NZERTF shows that net-zero energy homes are technologically feasible using conventional technologies, a recurring question remains, "What does it cost?" Since 2012, NIST has pursued this question in a number of studies focusing on the life-cycle costs of alternative levels of energy-efficiency in residential buildings.

Some analyses have taken a nationwide perspective and focused on state residential building energy codes, which are based on different editions of the International Energy Conservation

Code (IECC), and the potential gains of state adoption of more restrictive energy codes. Kneifel and O'Rear (2015) analyzed 9120 whole-building energy simulations included in the Building Industry Reporting and Design for Sustainability (BIRDS) new residential database. The database covers 10 building types in 228 cities located across the U.S. for 9 study periods. The performance of buildings designed to meet current state residential energy codes is compared to their performance when meeting 2012 IECC requirements for their state.

Other analyses have focused on the performance of the NIST NZERTF relative to Maryland code requirements. Kneifel (2014) uses cost estimate data from a NIST-funded contract (Matlock 2013) to estimate the cost performance of the NZERTF relative to the same house built to meet Maryland residential energy code, which was based on 2012 IECC for residential buildings at the time of construction.

Kneifel and O'Rear (2015) combined cost data developed in Kneifel (2014) and Kneifel et al. (2015), and compared the sustainability performance (energy, economic, and environmental) metrics of the NIST NZERTF design to a 2015 IECC compliant building design using whole-building energy simulation, life-cycle costing, and life-cycle impact assessment. Additionally, a preliminary analysis was conducted to evaluate the impacts of incrementally adopting energy-efficient measures on a building design's sustainability performance.

Kneifel et al. (2016) expanded on Kneifel and O'Rear (2015) by analyzing sustainability performance of the 75 million records in the recently released BIRDS v3.0 database that analyzes 240 000 building designs based on the NIST NZERTF across multiple of study periods, home financing options, levels of building construction quality, and discount rates. Building design specifications included in the database are based on the five most recent IECC editions, as well as other design cases which lead to low-energy or net-zero energy performance.

Economic performance evaluation is reliant on accurate construction cost data, which may change significantly over time as industry learns how to implement energy-efficiency measures into building design and more energy-efficient technology diffuses into the marketplace. In order to update the underlying data in NIST's economic analysis, a NIST-funded contract (OCMI 2016) was completed to estimate the costs of building components designed to meet current Maryland building energy code based on 2015 IECC as well as higher efficiency building components that are either currently installed in the NZERTF or will be installed in the NZERTF in the near future. This study will summarize the cost estimates developed in (OCMI 2016), as well as compare those estimates to cost data used in Kneifel's 2014 study (Kneifel 2014), the data from two residential construction cost databases (National Renewable Energy Laboratory 2012, RS Means 2016), solar PV system installation cost data collected by Barbose and Darghouth (2015), and an industry report on structural insulation panels (SIPs) produced by RS Means (RS Means 2006). Recommendations on an average/best guess estimate will be generated, as well as a reasonable range of cost estimates for future analysis related to net-zero energy home design – particularly related to the NZERTF and BIRDS.

2 Cost Data Sources

The cost estimate data sources considered in this study include: (1) two cost reports developed under NIST-funded contracts; (2) two public construction cost databases; (3) one subscription-based construction cost database; (4) an annual report on average installed solar PV costs; and (5) a structural insulated panel industry (SIP) association report. Each of these data sources are described in detail below.

2.1.1 OCMI

O'Connor Construction Management, Inc. (OCMI) developed cost estimates for NIST on energy-efficiency measures that were incorporated into the NZERTF design or will be installed in the NZERTF in the near future. Cost estimates were derived using OCMI's internal cost database and predefined scopes of work provided by NIST on the NZERTF and the 2015 IECC for the current construction market for Gaithersburg, MD. A full quality control process including independent internal reviews was implemented to verify those cost estimates. OCMI also obtained external estimates from subcontractors capable of completing the installation of a given building component. When subcontractors could not be identified or were not willing to participate, OCMI used industry pricing databases (Sayer and RS Means) for the external estimate. OCMI compared the external estimates to the internal estimates for confirmation or identification of line item differences. The differences were investigated and consolidated into final cost estimates for each component alternative, which are the basis for this study and will be compared to alternative data sources to determine the potential variability in these cost estimates. The cost estimates assume all building components are installed by a subcontractor with a 30 % mark-up, general conditions mark-up of 10 %, and overhead and profit mark-up of 10 % (compounding to 21 %).

2.1.2 VESTA

Kneifel (2014) used the cost estimates reported in Matlock (2013), a government contracted report completed by Multinational Group, LCC. The report documented the approach used to estimate the costs of constructing the NZERTF and a comparable 2012 IECC Maryland code-compliant design. Multinational Group hired a LEED-certified contractor (VESTA) to create a bid as though it was a private sector project in Maryland being built to meet both the NZERTF design as being operated during the demonstration phase (proving net zero energy performance over an entire year), as well as a Maryland code-compliant design built according to the 2012 design specifications for ASHRAE Climate Zone 4. The cost estimates to the contractor for each house design were delivered to NIST in spreadsheet form with the report, which include the sub-contractor mark-up that are not specified in the report. VESTA assumes a general contractor mark-up for overhead and profit of 17.5 %, which is included in the estimates reported in Kneifel (2014). For direct comparison purposes, the general contractor mark-up is changed to match the OCMI mark-up of 21 % and the estimates are inflated from 2014 to 2016 dollars (factor of

1.0111) using the RS Means historical construction cost indexes (RS Means 2016a). The inflation factor is different for the cost of the solar PV system. See Section 2.1.6 for details.

2.1.3 Building Component Cost Community (BC3)

The Building Component Cost Community (BC3) database was developed by Pacific Northwest National Laboratory (PNNL), and provides costs for primary building components, including walls, fenestration, equipment, and energy-efficiency measures (BC3 2016). BC3 is a publicly available repository of building component costs, and includes three cost databases. PNNL developed a residential energy efficiency measure (EEM) database through a contract with Faithful and Gould (2012) that includes the incremental costs of meeting different requirements across editions of IECC, as well as detailed cost data for building components. The American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) developed an economic database for the energy-efficient design of low-rise residential buildings through a contract with the National Association of Home Builders (NAHB) Research Center (National Association of Home Builders 2009). The California Public Utilities Commission (CPUC) developed the Database for Energy Efficiency Resources (DEER) database (California Energy Commission 2008) focused on residential building costs in California. All three databases can be used depending on the specific cost data needed for a given cost analysis. BC3 estimates are national average costs to the general contractor including the sub-contractor mark-up (unknown values), and are adjusted using the location factor for Washington, D.C. (0.9992) developed for BC3 and the OCMI general contractor mark-up of 21 % and RS Means construction cost index for 2011 data of 1.0834 (RS Means 2011). The inflation factor is different for the cost of the solar PV system. See Section 2.1.6 for details.

2.1.4 National Residential Efficiency Measures Database

The National Residential Efficiency Measures Database (NREMD) is a publicly available, centralized resource of residential building retrofit measures and costs for the U.S. building industry (National Renewable Energy Laboratory 2012). With support from the U.S. Department of Energy (DOE), the National Renewable Energy Laboratory (NREL) developed an online tool (National Renewable Energy Laboratory 2016) to help users of the database to determine the most cost-effective retrofit measures for improving the energy-efficiency of existing homes. This database of retrofit measures provides information in a standardized format (Extensible Markup Language (XML)) that improves consistency and accuracy of cost estimates to support building science research and development. NREL developed a set of rules to construct a list of measures based on component properties and action types. Version 1 of the Database was publically released in February 2010. The second and third versions were released in October 2010 and July 2012, respectively. See (National Renewable Energy Laboratory 2012) for details on the structure of the database, information regarding the collection and processing of underlying data, and information utilized in developing and assembling the database. The NREMD provides national average and range of cost estimates, which include the sub-contractor mark-up. Note that the sub-contractor mark-up values are unknown for this database. The general contractor mark-up is assumed to match the OCMI mark-up of 21 % and the estimates are inflated from 2014 to 2016 dollars (factor of 1.0111) using the RS Means historical construction cost indexes (RS Means 2016a).

2.1.5 RS Means

RS Means Online (RS Means 2016) includes two residential construction cost databases that can be used to estimate the cost of energy-efficiency measures: (1) residential new construction and (2) residential square foot assemblies. These datasets include the most widely used construction assemblies and units, but do not always include less common building components or the same level of detail for differentiating some higher efficiency equipment. RS Means cost data includes both the "bare total" without any mark-up, as well as a "total O&P" estimate that includes subcontractor mark-up. For this study, the "bare total" estimate is used and adjusted using the OCMI 30 % sub-contractor and 21 % general contractor mark-up for consistency across estimates. No location factor or construction cost indexing is necessary since the RS Means data is for 2016 construction data for the College Park, Maryland location (includes ZIP codes beginning with 208 and 209).

2.1.6 SunShot

Lawrence Berkeley National Laboratory (LBNL) publishes "Tracking the Sun," an annual report on trends in the solar PV system market (Barbose and Darghouth 2015). Given the fast-changing market conditions in the solar PV market that has led to significant reductions in the installed cost of a solar PV system, it is necessary to use the most up-to-date cost data. The installed cost includes all expenditures associated with the system including the sub-contractor and contractor mark-up (unknown values). Installed cost data is available by type of system (residential, commercial, or utility), size, and location, allowing for more precise estimates than cost databases that focus on national average costs with location factors. Additionally, general construction costs have been increasing over time while solar PV system costs are trending downward. Therefore, the historical installed cost data for Maryland in Barbose and Darghouth 2015 is used to develop an inflation factor for solar PV system cost estimates for the BC3 (0.63) and VESTA (1.00) data sources.

2.1.7 Structural Insulation Panel Association (SIPA)

RS Means generated a report for BASF (RS Means 2006) that compares the time and effort required to install residential structural insulation panels (SIPs) to those of typical wood-framed residential wall construction. Within this report characteristics of SIPs are explained in detail, including the SIP assembly and differences in material and labor.

3 Building Component Alternatives

The construction cost data in OCMI (2016) includes line item cost estimates for 13 building components with a range of one to six alternatives for each component, totaling 37 building component cost estimates. Seven of the building components are associated with the building envelope (e.g., exterior enclosure), while 6 are associated with building systems (e.g., heating and cooling equipment and renewable systems). Each component alternative is discussed in detail below.

3.1 Building Envelope

The OCMI cost estimates include one to four alternatives for each aspect of the building envelope: exterior wall assembly, roof/ceiling assembly, basement insulation, whole house air leakage rate, and fenestration (i.e., windows). Since the building envelope of the NZERTF would be difficult to change over the lifetime of the facility, the focus of the alternatives selected is to allow for comparison between current Maryland residential energy code requirements and the specifications of the NZERTF. In some cases, additional alternatives may also be reported. Each is discussed in Section 3.1.1 through Section 3.1.5.

3.1.1 Exterior Wall Assembly

Two types of exterior wall assemblies are considered: (1) framing installed first (constructed on-site or prefabricated) and then insulation installed second (i.e. "stick-built" framing) and (2) prefabricated assembly with continuous insulation within plywood structure (i.e., structural insulation panels or SIPs). The exterior wall "stick-built" framing estimates include three alternatives: 5.1 cm x 10.2 cm – 40.6 cm studs on center (OC) (2 in x 4 in – 16 in OC), 5.1 cm x 15.2 cm – 40.6 cm studs OC (2 in x 6 in – 16 in OC), and "advanced framing" that uses 5.1 cm x 15.2 cm studs installed 61.0 cm studs OC (2 in x 6 in – 24 OC). These three alternatives will be referenced as **2x4-16OC**, **2x6-16OC**, and **2x6-24OC**, respectively, for the remainder of this study.

The exterior wall insulation alternatives for "stick-built" wall framing include: (1) R-13 batt fiberglass insulation in the wall cavity and R-5 of extruded polystyrene (XPS) rigid exterior insulation (**R-13+5**); (2) R-20 of cellulose insulation in the wall cavity (**R-20**); and (3) R-20 cellulose insulation in the wall cavity with R-24 of polyisocyanurate rigid exterior insulation (**R-20+24**).[1] The first two are both compliant with 2015 IECC requirements while the third is the insulation installed in the NZERTF. The line item estimation by OCMI allows for an additional alternative between the performance of the Maryland code and NZERTF designs to be estimated

[1] Units for R-value are h·ft2·°F/Btu for customary units and K·m2/W for metric units. The conversion is 1 h·ft2·°F/Btu = 0.176110 K·m2/W.

by adding R-12 of the exterior rigid insulation to the R-20 cellulose in the wall cavity (**R-20+12**), which is an alternative included in the BIRDS low-energy residential database.

Given the dependency between the structural support and the insulation alternatives, it is necessary to consider the installed costs of the entire assembly. The combinations of framing and wall insulation that are estimated by OCMI are shown in Table 3-1. Also included in the wall insulation alternatives is a SIP with R-44 of rigid insulation (**R-44 SIP**), which includes both the structural sheathing in place of framing and the insulation in an assembly that is installed as a single unit.

Table 3-1 Building Component Alternatives: Exterior Wall Assembly

Exterior Wall	MD Code	Alt. MD Code 1	Alt. MD Code 2	Incremental Alt.*	NZERTF	Alt. - SIPs
Insulation**	R_{SI}-2.29+0.88 (R-13+5)	R_{SI}-23.52 (R-20)	R_{SI}-3.52 (R-20)	R_{SI}-3.52+2.11 (R-20+12)	R_{SI}-3.52+ 4.23 (R-20+24)	R_{SI}-3.52 SIP (R-44 SIP)
Framing***	5.1x10.2-40.6OC (2x4-16OC)	5.1x15.2-40.6OC (2x6-16OC)	5.1x15.2-61.0OC (2x6-24OC)	5.1x15.1-61.0OC (2x6-24OC)	5.1x15.2-61.0OC (2x6-24OC)	

*Alternative calculated using line item cost estimate for NZERTF wall assembly.
** R_{SI}-value units is kelvin square meters per watt (K·m^2/W). R-value units is degree Fahrenheit square feet hours per Btu (ft^2·°F·h/Btu)
***Framing characteristics are expressed in centimeters (inches)

3.1.2 Roof/Ceiling Assembly

As with wall assemblies, the roof assembly alternatives include both "stick-built" framing and SIPs. Three different approaches to insulating the attic space are shown in Table 3-2: (1) cellulose insulation on the attic floor (**R-49**) to meet 2015 IECC requirements; (2) R-45 cellulose insulation in the roof rafter cavity in combination with R-30 polyisocyanurate rigid exterior insulation (**R-45+30**) to match the specifications of the NZERTF; and (3) prefabricated SIP assembly with comparable levels of thermal performance to that of the NZERTF (**R-75 SIP**). An additional alternative can be estimated using the OCMI line item estimates for an incremental increase in thermal performance between the Maryland-code compliant and NZERTF designs (**R-45+15**).

Table 3-2 Building Component Alternatives: Roof/Ceiling Assembly

Roof/Ceiling	MD Code	Incremental Alt.*	NZERTF	Alt. - SIPs
Insulation**	R_{SI}-8.63 (R-49)	R_{SI}-7.92+2.64 (R-45+15)	R_{SI}-7.92+5.28 (R-45+30)	R_{SI}-13.21 SIP (R-75 SIP)

*Alternative calculated using line item estimate for NZERTF roof assembly.
** R_{SI}-value units is kelvin square meters per watt (K·m^2/W). R-value units is degree Fahrenheit square feet hours per Btu (ft^2·°F·h/Btu).

3.1.3 Basement Insulation

Three alternatives for basement insulation are shown in Table 3-3: (1) the 2015 IECC compliant option of R-10 rigid insulation in the basement wall assembly with no insulation under the slab (**R-10/R-0**); (2) the insulation installed in the NZERTF with R-22 rigid insulation in the basement wall assembly and R-10 rigid insulation in the basement slab assembly (**R-22/R-10**); and (3) an incremental alternative that installs R-22 in the basement wall assembly with no insulation under the basement slab assembly (**R-22/R-0**).

Table 3-3 Building Component Alternatives: Basement

Basement	MD Code	Alt. MD Code*	Incremental Alt.*	NZERTF
Wall Insulation**	R_{SI}-1.76 (R-10)	R_{SI}-1.76 (R-10)	R_{SI}-3.87 (R-22)	R_{SI}-3.87 (R-22)
Slab Insulation**	R_{SI}-0.0 (R-0)	R_{SI}-0.0 (R-0)	R_{SI}-0.0 (R-0)	R_{SI}-1.76 (R-10)

*Alternative calculated using line item estimate for NZERTF basement wall assembly.
** R_{SI}-value units is kelvin square meters per watt ($K \cdot m^2/W$). R-value units is degree Fahrenheit square feet hours per Btu ($ft^2 \cdot °F \cdot h/Btu$).

3.1.4 Air leakage Rate

Two alternatives for the air leakage rate are shown in Table 3-4: (1) spray-on air barrier membrane that reduces the air leakage rate to 3.0 air changes per hour at 50 Pa using a blower door test to meet 2015 IECC requirements (**3.0 ACH**), and (2) peel-and-stick air barrier membrane that reduces the air leakage rate to 0.63 air changes per hour at 50 Pa using a blower door test to meet the measured performance of the NZERTF (**0.63 ACH**).

Table 3-4 Building Component Alternatives: Air leakage Rate

Air leakage	MD Code	NZERTF
ACH	3.0 ACH	0.63 ACH

3.1.5 Windows

Two alternatives for windows are shown in Table 3-5: (1) window with specifications that meet 2015 IECC U-value and SHGC requirements (**U-0.35/SHGC-0.40**) and (2) windows comparable in performance to those installed in the NZERTF (**U-0.20/SHGC-0.25**).

Table 3-5 Building Component Alternatives: Windows

Windows	MD Code	NZERTF
Thermal Performance	U_{SI}-2.00 (U-0.35) SHGC=0.4	U_{SI}-1.14 (U-0.20) SHGC=0.25

3.2 Systems

The OCMI cost estimates include two or more alternatives for each of the building systems: domestic hot water system, heating, ventilation, and air conditioning (HVAC) system, and renewable energy systems. The electrical system is not considered because energy-efficiency for lighting in residential buildings is primarily increased by replacing light bulbs with CFLs or LEDs without changing the electrical system design, which is a straightforward cost estimate that does not require the expertise of a construction cost estimator.

Duplicate HVAC systems were installed in the NZERTF, including ground-source (geothermal) loops, small-duct, high-velocity ductwork as well as two separate solar thermal systems. Additional equipment has been (e.g., small-duct high-velocity heat pump), or will be installed (e.g., ground-source heat pump and gas storage water heater), over the lifetime of the facility to test alternative system configurations. Therefore, there are additional alternatives considered that allow for both comparisons between current Maryland residential energy code requirements and the specifications of the NZERTF, as well as future system configurations. Each system component alternative is discussed in detail below.

3.2.1 Domestic Hot Water System

Two alternatives for the domestic water heater are shown in Table 3-6: (1) an electric water heater that meets the federal minimum efficiency requirement of 95 % (**ElectWH**) and (2) a heat pump water heater comparable in performance to that installed in the NZERTF (**HPWH**) with a rated coefficient of performance (COP) of 2.33.

Table 3-6 Building Component Alternatives: Water Heater

Domestic Hot Water System	MD Code	NZERTF
Water Heater	ElectWH	HPWH

3.2.2 HVAC System

The HVAC systems described in Table 3-7 include up to three different components depending on the system type. These three components are: (1) a heat pump with ductwork, (2) a ground-source loop, and (3) ventilation equipment and/or ductwork. All HVAC system costs estimates include the cost of a heat pump with rectangular ductwork. A total of six different 2-ton heat pump options are considered. The first four are air-to-air heat pump units with one of the four following characteristics: (1) a federal minimum efficiency Seasonal Energy Efficiency Ratio (SEER) rating of 13 Btu/W-hr and a Heating Seasonal Performance Factor (HSPF) of 7.7 Btu/W-hr (**SEER 13/HSPF 7.7**); (2) a comparable efficiency to that of the system installed in the NZERTF (**SEER 15.8/HSPF 9.05/DM**) with dedicated dehumidification mode; (3) a comparable efficiency to that of the system installed in the NZERTF without dedicated dehumidification mode (**SEER 15.8/HSPF 9.05**); and (4) an efficiency level comparable to that of the Lennox XP 25 series (**SEER 23.5/HSPF 10.2**).

Heat pump option 1 is a single-speed, "standard efficiency" system which meets IECC requirements, has a SEER of 13 Btu/W-hr for cooling mode, and a HSPF of 7.7 Btu/W-hr for heating mode. Heat pump options 2 and 3 are multi-speed heat pump systems with SEER and HSPF ratings of 15.8 Btu/W-hr and 9.06 Btu/W-hr, respectively. The former includes dehumidification-only mode which helps to reduce the humidity in the house, making it more comfortable for the occupants. The latter does not include this feature. The fourth heat pump option is an air-to-air heat pump with a SEER rating of 23.5 Btu/W-hr and a HSPF rating of 10.2 Btu/W-hr.

The remaining two heat pump options considered are water-to-air heat pumps. The first is comparable to that of Water Furnace 3 with an Energy Efficiency Ratio (EER) of 22.3 Btu/W/hr and is representative of entry-level ground-source heat pumps. The second (**EER 43**) has a performance comparable to the Climate Master Trilogy 40 Q with an EER of 43 Btu/W/hr, and the capability of both space conditioning and water heating. In the case of a water-to-air heat pump, a ground-source loop is required for heat exchange. Three ground-source loops sized to match a 2-ton water-to-air heat pump are considered: vertical U-loop, horizontal loop, and "slinky" loop. All three have been installed in the ground surrounding the NZERTF.

Under current Maryland code, outdoor air ventilation is required for all new residential building construction. Two approaches for providing dedicated outdoor air ventilation are considered. The first incorporates supply only utilizing the heat pump ductwork, while the second uses a balanced system with dedicated ductwork with energy recovery equipment. Three alternative setups are considered for the latter approach: (1) a heat recovery ventilator (**HRV**) only; (2) a HRV with additional economizer (**HRV+ECO**); and (3) a HRV with a whole-house dehumidifier (WHD) (**HRV+WHD**). The purpose of these three different combinations is to allow for consideration of different HVAC configurations. For example, an air-to-air heat pump without dehumidification only mode may require the HRV with a WHD in order to maintain the indoor relative humidity level.

Table 3-7 Building Component Alternatives: HVAC Components

Components	Type	Characteristics / Efficiency
Heat Pumps	Air-to-Air	SEER 13 / HSPF 7.7
	Air-to-Air	SEER 15.8 / HSPF 9.05 with Dehumidification Only Mode
	Air-to-Air	SEER 15.8 / HSPF 9.05 without Dehumidification Only
	Air-to-Air	SEER 23.5 / HSPF 10.2
	Water-to-Air	EER 22.3
	Water-to-Air	EER 43
Ground-Source Loop	Vertical	2 - 150’ Bore Holes
	Horizontal	4 - 230’ trenches and tubing (6’ deep)
	Slinky	2 - 130’ trenches with 801’ tubing (5’ deep)
Ventilation	Dedicated Outdoor Air	No Energy Recovery
	Separate Ductwork	HRV
		HRV with Economizer
		HRV with Whole House Dehumidifier
Conversion: 1’ = 0.3048 m		

3.2.3 Renewable Energy Systems

Two different types of renewable energy systems have been installed in the NZERTF, a solar thermal system and solar photovoltaic system. Two different indirect solar thermal systems are currently installed on the porch roof of the NZERTF: (1) two flat plate solar collector panels with 303 L (80 gal) storage tank and (2) two flat plate solar collector panels with 454 L (120 gal) storage tank. Both solar thermal systems are indirect systems that use a glycol/water mix in the solar thermal loop to allow for year-round operation and a heat exchanger that transfers energy from the solar loop fluid to the water in the storage tank. OCMI developed cost estimates for the 303 L (80 gal) solar thermal system as well as two alternatives, replacing the flat plate collectors with evacuated tube collectors and replacing the entire solar thermal system and installing a 2.0 kW solar PV system in its place on the porch roof. The latter was included because the electricity generation from the PV system may be a more cost-effective use of the porch roof area than using it for pre-heating domestic water with the solar thermal system. OCMI developed an estimate for the 10.2 kW solar photovoltaic system with two inverters currently installed on the roof of the NZERTF as well as estimates for down-sizing the solar PV system to 2.55 kW, 5.1 kW and 7.6 kW with appropriately matched inverters. Each of these renewable system alternatives is shown in Table 3-8.

Table 3-8 Building Component Alternatives: Renewable Energy Systems

System	Alternative
Solar Thermal System	Two Panels w/ 80 gal storage tank
	Two Panels w/ 120 gal storage tank
	Replaced with 2.5 kW Solar PV System
Solar PV System	2.5 kW
	5.1 kW
	7.6 kW
	10.2 kW

4 Building Component Cost Comparisons

The OCMI cost estimate for each of the alternatives described in Chapter 3 is reported in this chapter. These costs are compared to the cost estimates from other data sources discussed in Chapter 2. Any cost estimates reported on a per unit basis are converted to total costs using the specifications of the NZERTF (e.g., exterior wall area). Cost comparisons are focused on the incremental total costs to account for differences in fixed costs across data sources. All cost estimates are total installed costs, which include both material and labor costs. Mark-ups for overhead and profits are also included, and adjusted where necessary to remain consistent across data sources.

4.1 Building Envelope Cost Estimates

OCMI cost estimates for the building envelope are estimated on a per square foot basis. In order to compare the OCMI estimates to other data sources (i.e., VESTA), it is necessary to calculate the total costs for each building component. This is accomplished by multiplying the cost per unit of area by the area for each building envelope component in the NZERTF, which are shown in Table 4-1.

Table 4-1 Building Envelope Area by Component

Building Envelope Area	Exterior Wall	Basement Wall	Basement Floor	Roof	Ceiling	Exterior Framing	Total Exterior Area	Windows
m^2 (ft^2)	303.4 (3266)	151.7 (1633)	148.8 (1602)	187.2 (2015)	135.8 (1462)	303.4 (3266)	490.6 (5281)	38.6 (416)

Conversion: 1 m^2 = 10.76391 ft^2

4.1.1 Building Envelope Cost Estimates – OCMI

OCMI cost estimates per unit of area are shown in Table 4-2. The cost of exterior wall construction is lowest with **R-20 2x6-24OC**, followed by **R-13+5 2x4-16OC**. This is because **R-20** thermal performance is achieved using only batt or loose-fill insulation, which is far less expensive than the rigid insulation that must be paired with batt insulation to achieve comparable thermal performance. **R-20 2x6-16OC** is comparable in cost to **R-13+5 2x4-16OC** because the lower insulation costs are offset by the greater costs for the framing. The NZERTF design (**R-20+24 2x6-24OC**) is significantly more expensive than either of the Maryland-code compliant designs due to the additional rigid insulation. The line item estimation by OCMI allows for estimating the cost of an incremental energy efficiency measure between the

Maryland-code compliant and NZERTF designs (**R-20+12 2x6-24OC**).[2] Comparing the insulation costs per ft^2 for the **R-20 2x6-24OC** and **R-20+12 2x6-24OC** exterior wall constructions, reveal that use of the additional R-12 rigid insulation increases ft^2 costs by roughly $1.43. The change in cost using the structural insulation panel for the wall assembly (**R-44 SIP**) is almost a factor of 10 greater than **R-20+24**. Even after combining the wall framing and insulation costs, **R-44 SIP** is approximately five times more expensive than **R-13+5** and three times more expensive than **R-20+24**.

Table 4-2 OCMI Exterior Wall Cost Estimates

Building Envelope		Cost ($/ft²)* R-13+5 2x4-16	R-20 2x6-16	R-20 2x6-24	R-20+12 2x6-24	R-20+24 2x6-24	R-44 SIP
Exterior Wall	Insulation	$1.71	$1.44	$1.44	$2.87	$4.19	$29.62
	Framing	$4.76	$5.06	$4.71	$4.71	$4.71	
	Total / ft²	$6.47	$6.50	$6.15	$7.58	$8.90	$29.62
	Total	$21 131	$21 229	$20 086	$24 756	$29 067	$96 739
	Delta Cost	$0	$65	-$1078	$3592	$7904	$75 575

*Conversion: 1 US$/m² = 0.09290304 US$/ft²

Table 4-3 OCMI Roof/Ceiling Insulation Cost Estimates

Building Envelope		Cost ($/ft²)* R-49	R-45+15		
Roof/Ceiling	$/ft²	$2.30	$3.74	$5.90	$23.25
	Total	$3363	$7536	$11 889	$46 849
	Delta Cost	$0	$4173	$8526	$43 486

*Conversion: 1 US$/m² = 0.09290304 US$/ft²

shows the four OCMI cost estimates for each of the roof/ceiling alternatives. The cost of the insulation in the attic space is lowest for the Maryland code-compliant design (**R-49**), which is a result of not requiring any rigid insulation. The NZERTF design (**R-45+30**) is significantly more expensive than the Maryland code-compliant design, while the cost of the incremental alternative design (**R-45+15**) is approximately the midpoint between the Maryland code-compliant and NZERTF designs. The structural insulation panel for the roof assembly (**R-75 SIP**) is nearly five

[2] Note that this alternative has been estimated for use in future analysis (e.g. BIRDS database) and will not be discussed further.

times more expensive than **R-45+30**. However, much of this higher cost is attributed to the additional cost of the structural rafters.

Table 4-3 OCMI Roof/Ceiling Insulation Cost Estimates

Building Envelope		Cost ($/ft^2)*			
		R-49	R-45+15		
Roof/Ceiling	$/ft^2	$2.30	$3.74	$5.90	$23.25
	Total	$3363	$7536	$11 889	$46 849
	Delta Cost	$0	$4173	$8526	$43 486

*Conversion: 1 US$/m^2 = 0.09290304 US$/ft^2

Table 4-4 shows OCMI cost estimates for the three basement insulation alternatives. The cost of the basement insulation (wall and floor combined) is seven times greater for the NZERTF design (**R-22/R-10**) relative to the Maryland code-compliant design (**R-10/R-0**), while the design with the wall insulation of the NZERTF with no insulation under the slab (**R-22/R-0**) is almost five times the Maryland-code compliant design. The alternative Maryland code-compliant design that uses XPS to meet the R-10 requirement (**Alt. R-10/R-0**) is almost four times as expensive.

Table 4-4 OCMI Basement Insulation Cost Estimates

Building Envelope		Cost ($/ft^2)*			
		R-10 / R-0	Alt. R-10 / R-0*	R-22 / R-0	R-22 / R-10
Basement	Wall Insulation	$1.22	$2.94	$5.81	$5.81
	Floor Insulation	$0.00	$0.00	$0.00	$2.88
	Total	$1992	$7552	$9488	$14 101
	Delta Cost	$0	$5560	$7496	$12 109

* Conversion: 1 US$/m^2 = 0.09290304 US$/ft^2
**Uses R-10 of XPS in place of concrete block polystyrene to match NZERTF specs.

Table 4-5 shows the two air leakage rate alternatives. The cost of the air leakage rate for the NZERTF design (**0.61 ACH**) is significantly more expensive than the Maryland-code compliant design (**3.0 ACH**). Note that the wall and roof SIPs are assumed to meet the NZERTF air leakage rate at no additional cost.

Table 4-5 OCMI Air Leakage Rate Cost Estimates

Building Envelope		Cost ($/ft^2)*	
		3.0 ACH	0.61 ACH
Air Leakage Rate	Membrane	$0.96	$2.49
	Total	$5070	$13 150
	Delta Cost	$0	$8080

Note: Assumes SIPs meet 0.61 ACH50
*Conversion: 1 US$/m^2 = 0.09290304 US$/ft^2

Unlike the rest of the building envelope components, which are priced out on a cost per unit of area, OCMI estimated the total cost for the windows as shown in Table 4-6. The use of higher efficiency windows by the NZERTF design (**U-0.20/SHGC 0.25**) drives up costs by roughly 45 % relative to the Maryland-code compliant design (**U-0.30/SHGC 0.40**).

Table 4-6 OCMI Window Cost Estimates

Building Envelope	Cost ($)	
	U-0.30 / SHGC 0.40	U-0.20 / SHGC 0.25
Windows	$18 560	$26 880
Delta Cost	$0	$8320

OCMI assumes that the building envelope construction will be bid by subcontractors and the subcontractor will include a 30 % mark-up for their overhead and profit. Table 4-7 shows the costs for the Maryland-code compliant and NZERTF designs for each component of the building envelope accounting for the subcontractor mark-up. The incremental costs for the entire building envelope of the NZERTF design to the general contractor is $58 463 more expensive than the Maryland-code compliant design. After accounting for the general conditions and overhead and profit mark-ups by the general contractor (10 % and 10 %, respectively, for a total of 21 %), the cost to the homebuyer is $70 740. The compounding mark-up from the subcontractor (30 %) and general contractor (21 %) increases the total incremental costs for the building envelope by 57.3 % ($25 748) from $44 971 to $70 740.

Table 4-7 OCMI Building Envelope Cost Estimate including Mark-Up

Building Envelope	Area (ft^2)*	MD Code	NZERTF
Exterior Wall	3266	$33 239	$45 723
Basement Insulation	1633	$3134	$22 182
Roof/Ceiling	2015 / 1462	$5289	$18 701
Air Leakage Rate	5281	$7975	$20 684
Windows	416	$24 128	$42 282
Total Incremental Costs		$65 194	$123 613
Cost Difference to General Contractor		$0	$58 463
Cost Difference to Homebuyer		$0	$70 740

*Conversion: 1 m^2 = 10.76391 ft^2

4.1.2 Building Envelope Cost Estimates – Alternative Sources

The VESTA cost estimates for the building envelope were reported in total costs while the cost estimates from BC3, NREMD, and RS Means are on a per unit of area basis. In some cases, an exact match is not possible (e.g., window U-factor and SHGC) and the cost data for the component with the closest match to those specifications is selected. There is no data for the exterior framing in the alternative data sources, but since the change in costs is minimal and negative for the OCMI estimate it is reasonable to assume the change in cost will be approximately zero for the estimates for the alternative data sources. The total cost estimates including mark-ups are reported in Table 4-8 for each building envelope component for each available data source as well as a comparison to the OCMI estimates.

Estimates across the different data sources are similar for exterior wall insulation, roof/ceiling insulation, and exterior framing. The additional costs from building to the NZERTF design for the exterior wall assembly is comparable with a range of -18 % to +2 % relative to the OCMI estimate. The roof/ceiling insulation cost estimates are similar for the OCMI and alternative data sources, with the additional cost to meet the NZERTF roof and ceiling assembly ranging +/- 20 %. There is no data for the exterior framing in the alternative data sources, but since the change in costs is minimal and negative for the OCMI estimate it is reasonable to assume the change in cost will be approximately zero.

Significant differences are realized for the air leakage rate, windows, and basement wall and floor insulation. The air leakage rate cost estimate is higher for OCMI than the alternative data sources except for RS Means. The reason for these differences is the assumed method to reach the lower air leakage rate through the building envelope. The OCMI and RS Means estimates are based on changing the type of continuous air barrier installed on the exterior of the house while the BC3, NREMD, and VESTA estimates assume the use of spray foam insulation in combination with or in lieu of the air barrier. The use of spray foam on areas of high air leakage could reduce air leakage more significantly while using less material and labor, leading to lower costs to meet the target air leakage rate. The cost estimates for changing the windows vary significantly, -46 % to +73 %, which could be driven by the underlying source of the data in combination with the window characteristics. Since the performance specifications (U-factor and SHGC) of the windows installed in the NZERTF cannot be matched exactly, it is possible that the cost of windows can vary significantly.

The largest differences in costs across the alternative sources are for the additional costs incurred by building to the NZERTF design specifications for the basement wall insulation and basement floor insulation, with estimates being 53 % to 76 % and 44 % to 55 % lower, respectively. Some of these additional costs are a result of the assumed insulation approach to reach the R-10 basement wall requirement for the MD Code design. If the R-10 requirement is met using R-10 of XPS instead of concrete block polystyrene, then it leads to the OCMI estimate being 24 % to 62 % higher. The remaining difference may be due to some unforeseen complexity in the insulation installation. The difference in the estimates for the basement floor insulation may be due to the lack of available cost data for the specific installation of insulation under a basement slab. The wall insulation cost data is used from the alternative cost data sources to develop the cost estimate, potentially not accounting for the complexities of installation under the slab.

Excluding wall framing, cost estimates were completed for all building envelope components using the BC3 and NREMD databases.[3] RS Means does not have detailed data for windows, for which an average of the other alternatives is used as a proxy. VESTA does not have a line item breakdown for the basement insulation as well as additional costs for a combination of the roof and wall framing. In total, the additional costs for the building envelope range from \$50 708 to \$75 411 with an average of \$61 108, which is 13 % lower than the OCMI estimate. The sum of the minimum cost differences for each building envelope component is \$37 646, which is the lowest potential estimate at 47 % lower than the OCMI estimate. The sum of the maximum cost differences for each building envelope component is \$73 884, which is less than the VESTA estimate at \$75 411 and 7 % higher than the OCMI estimate.

[3] Since the total cost estimates are not comparable across data sources, the total for each building design is excluded.

Table 4-8 Alternative Building Envelope Cost Estimates including Mark-Up

Building Envelope	Data Source	MD Code	NZERTF	Additional Cost	Additional Cost (OCMI)	Difference relative to OCMI	Percent Difference relative to OCMI
Exterior Wall	VESTA	$2447	$12 846	$10 399	$12 741	-$2342	-18%
	BC3	$11 188	$23 786	$12 598	$12 741	-$143	-1%
	NREMD	$14 473	$26 052	$11 579	$12 741	-$1163	-9%
	RS Means	$7038	$19 985	$12 947	$12 741	$206	2%
Exterior Framing	VESTA	NA	NA	NA	-$257	NA	NA
	BC3	NA	NA	NA	-$257	NA	NA
	NREMD	NA	NA	NA	-$257	NA	NA
	RS Means	NA	NA	NA	-$257	NA	NA
Basement Wall	VESTA	NA	NA	NA	$11 790	NA	NA
	BC3	$3315	$7743	$4427	$11 790	-$7363	-62%
	NREMD	$5996	$11 579	$5582	$11 790	-$6208	-53%
	RS Means	$3802	$6575	$2773	$11 790	-$9017	-76%
Basement Floor	VESTA	NA	NA	NA	$7 258	NA	NA
	BC3	$0	$3252	$3252	$7 258	-$4005	-55%
	NREMD	$0	$4057	$4057	$7 258	-$3201	-44%
	RS Means	$0	$3730	$3730	$7 258	-$3528	-49%
Roof / Ceiling	VESTA	$3059	$19 330	$16 272	$13 412	$2860	21%
	BC3	$3159	$16 549	$13 389	$13 412	-$22	0%
	NREMD	$3332	$14 032	$10 700	$13 412	-$2712	-20%
	RS Means	$5166	$17 751	$12 586	$13 412	-$826	-6%
Air Leakage Rate	VESTA	$1835	$8319	$6484	$12 710	-$6226	-49%
	BC3	$2144	$12 140	$9996	$12 710	-$2714	-21%
	NREMD	$0	$3477	$3477	$12 710	-$9233	-73%
	RS Means	$1246	$13 624	$12 378	$12 710	-$332	-3%
Windows	VESTA	$26 915	$40 373	$13 458	$13 087	$370	3%
	BC3	$12 245	$19 289	$7044	$13 087	-$6043	-46%
	NREMD	$18 435	$41 083	$22 648	$13 087	$9561	73%
	RS Means	$17 723	NA	NA	$13 087	NA	NA
Total			**VESTA**	$75 411	$70 741	$4669	7%
			BC3	$50 708	$70 741	-$20 034	-28%
			NREMD	$58 043	$70 741	-$12 699	-18%
			RS Means	$60 272	$70 741	-$10 469	-15%
			Average	**$61 108**	**$70 741**	**-$9354**	**-13%**
			Min*	$37 646	$70 741	-$33 096	-47%
			Max*	$73 884	$70 741	$3143	4%

*The min and max estimates are the sum of the minimum and maximum estimates for each building component, which does not include the VESTA roof and wall framing costs.

The NREMD database includes a range of values leading to the minimum and maximum values shown in Table 4-9. The additional costs of constructing the building envelope to meet the NZERTF requirements vary by +/- 20 % to +/- 58 % relative to the average value depending on the building envelope component. The minimum total additional costs vary by +/- 27 % relative to the average value and -40 % to 4 % relative to the OCMI estimate, which are similar to the minimum and maximum values estimated in Table 4-8 at -47 % and 7 %.

Table 4-9 Range in Building Envelope Cost Estimates including Mark-Up for NREMD

Building Envelope		MD Code	NZERTF	Additional Cost	Percent Variation	Additional Cost (OCMI)	Difference relative to OCMI	Percent Difference relative to OCMI
Exterior Wall	Average	$14 473	$26 052	$11 579		$12 741	-$1163	-9%
	Min	$9221	$17 367	$8 146	-30 %	$12 741	-$4595	-36%
	Max	$18 194	$33 495	$15 301	32 %	$12 741	$2560	20%
Exterior Framing	Average	NA	NA	NA		-$257	NA	NA
	Min	NA	NA	NA		-$257	NA	NA
	Max	NA	NA	NA		-$257	NA	NA
Basement Wall	Average	$5996	$11 579	$5582		$11 790	-$6208	-53%
	Min	$4549	$8684	$4135	-26 %	$11 790	-$7655	-65%
	Max	$7650	$14 679	$7029	26 %	$11 790	-$4761	-40%
Basement Floor	Average	$0	$4057	$4057		$7258	-$3201	-44%
	Min	$0	$3245	$3245	-20 %	$7258	-$4013	-55%
	Max	$0	$4868	$4868	20 %	$7258	-$2389	-33%
Roof / Ceiling	Average	$3332	$14 032	$10 700		$13 412	-$2712	-20%
	Min	$2221	$10 461	$8240	-23 %	$13 412	-$5172	-39%
	Max	$4443	$17 604	$13 161	23 %	$13 412	-$250	-2%
Air Leakage Rate	Average	$0	$3477	$3477		$12 710	-$9233	-73%
	Min	$0	$1471	$1471	-58 %	$12 710	-$11 239	-88%
	Max	$0	$5482	$5482	58 %	$12 710	-$7228	-57%
Windows	Average	$18 435	$41 083	$22 648		$13 087	$9561	73%
	Min	$11 588	$28 442	$16 855	-26 %	$13 087	$3767	29%
	Max	$23 175	$51 090	$27 915	23 %	$13 087	$14 828	113%
	Total		**Average**	$58 043		$70,741	-$12 699	-18%
			Minimu	$42 092	-27 %	$70,741	-$28 649	-40%
			Maximu	$73 758	27 %	$70,741	$3,016	4%

Note: Minimum and maximum are the sum of the minimum and maximum values for each building component.

4.2 Building System Cost Estimates

OCMI cost estimates for building systems include components of the domestic hot water system, HVAC system, and renewable energy systems. OCMI developed detailed line item estimates, allowing for isolation of the costs for individual pieces within a building system, such as alternative heat pumps, ventilation equipment, or water heaters. This section will report these OCMI estimates and compare them to the alternative data sources when available.

4.2.1 Domestic Hot Water System Cost Estimates

Cost estimates including the subcontractor and contractor mark-ups for domestic water heaters are shown in Table 4-10. OCMI estimated the cost for two water heaters, an electric water heater that meets minimum federal efficiency requirements, and a heat pump water heater comparable to that installed in the NZERTF. Based on these estimates, the heat pump water heater is $1587 more expensive than the electric water heater. The alternative data sources do not include the cost of plumbing, which is assumed to be constant across the two alternatives. Therefore, the difference in costs across data sources should be directly comparable. As shown in the table, the OCMI estimated difference in cost is slightly lower (15 %) than the NREMD estimate, but higher (12 %) than the BC3 estimate. There was no cost estimate in VESTA for the water heater and RS Means does not have cost data on residential heat pump water heaters.

Table 4-10 Water Heater Cost Estimates with Mark-Up

DHW	Electric Water Heater	Heat Pump Water Heater	Difference
OCMI	$2345	$3933	$1587
VESTA	NA	NA	NA
BC3	$1009	$2355	$1346
NREMD	$747	$2532	$1785
	($494 to $975)	($1773 to $3292)	($798 to $2798)
RS Means	$1826	NA	NA
Range	NC	NC	$1346 to $1785

Includes 30 % subcontractor mark-up.
NC = Not Comparable

4.3 HVAC System Cost Estimates

OCMI cost estimates for the HVAC system include heating and cooling equipment, ventilation equipment, and ground-source heat exchanger loops. The OCMI estimates will be explained in detail and then compared to available estimates for alternative data sources.

OCMI estimated the cost of six heat pumps, four air-to-air heat pumps and two water-to-air heat pumps, including the ductwork for the system. The more efficient the air-to-air heat pump, the greater the cost of the installed system. One of the heat pump system estimates includes dehumidification-only mode, which will allow for comparison of the system operated during the first year of operation for the NZERTF, to the installation of a whole-house dehumidifier, which was operated during the second year. See Section 3.2.2 for additional details.

Table 4-11 includes the contractor cost of each heat pump system, cost of each system adjusted for a 21 % contractor mark-up, and the difference in costs relative to the MD Code building component design. Based on Table 4-11, the following is revealed: (1) increases in heat pump efficiency correspond with increases in cost; (2) inclusion of the dehumidification-only mode option raises the price of an air-to-air heat pump by $750; (3) the typical high-efficiency water-to-air heat pump is similar in price to the highest efficiency air-to-air heat pump; (4) the water-to-air heat pump with a variable speed compressor and water heating is significantly more expensive than any other heat pump. The difference in cost between the MD Code and NZERTF building component designs is $1930.

Table 4-11 Heat Pump Cost Estimates - OCMI

Heat Pump	Contractor Cost	Price w/ Mark-Up	Diff. from MCC
HP13/7.7	$16 677	$26 233	$0
HP15.8/9.05 No Dehum	$17 007	$26 752	$519
HP15.8/9.06 w/ Dehum	$17 904	$28 163	$1930
HP23.5	$22 754	$35 792	$9559
Geo Water Furnace 3 EER 22.3*	$22 032	$34 656	$8423
Climate Master Trilogy 40 Q EER 43**	$33 264	$52 324	$26 091

*Must be combined with ground-source loop.
** Must be combined with ground-source loop; includes DHW capabilities

Table 4-12 shows the cost estimates available from the alternative data sources. Notice that some cost data is not available for some of the heat pump alternatives depending on the data source, and those with available data cannot be compared directly to the OCMI estimates because it is uncertain whether the costs include all the same line items. However, it is reasonable to compare the cost difference across systems for each data source. VESTA is the only data source with cost estimates for both the Maryland code-compliant heat pump and NZERTF heat pump, and includes the cost of installing the ductwork. According to VESTA, the cost difference is estimated at $11 623. The BC3 and NREMD data sources have data for the heat pump installed in the NZERTF except for the dehumidification mode capability. The difference between the MD Code and NZERTF heat pump is $709 and $1246, respectively.

Table 4-12 Heat Pump Cost Estimates – Alternative Sources

Heat Pump	Price w/ Mark-Up			
	VESTA	BC3	NREMD*	RS Means
Air-to-Air 13/7.7	$16 516**	$1558	$3439 ($2368 to $4675)	$5348
Air-to-Air 16.5/9.1 No Dehum	NA	$2267	$4685 ($3401 to $6407)	NA
Air-to-Air 16.5/9.1 w/ Dehum	$28 139**	NA	NA	NA
Air-to-Air 23.5	NA	NA	$6204 ($4343 to $8534)	NA
Water-to-Air EER 22.3	NA	$5348	$9002 ($5824 to $12 636)	$3854
Water-to-Air EER 43	NA	NA	NA	NA

*Closet match
**Includes cost of ductwork

Cost estimates for the ventilation component of the HVAC system include a dedicated outdoor air system built into the heat pump ductwork and 3 system alternatives that include separate ductwork. The system installed in the NZERTF is an HRV system with separate ductwork. The two other alternatives incorporate an economizer and a dehumidifier into the HRV system. As displayed in Table 4-13, use of a separate ductwork for whole-house ventilation increases ventilation costs by $3736. Inclusion of an economizer, a dehumidifier, or both, will only lead to further increases in ventilation costs.

Table 4-13 Ventilation Cost Estimates - OCMI

Ventilation	Contractor Cost	Price w/ Mark-up	Diff. from MCC
DOA	$557	$876	$0
HRV	$2932	$4612	$3736
HRV w/Econ	$3308	$5203	$4327
HRV w/Dehumid.	$3762	$5918	$5041
HRV w/Econ & Dehumid.	$4138	$6509	$5633

Only the VESTA and NREMD data sources have cost data for an HRV system. The estimates based on VESTA is $14 681 while the estimates based on NREMD is $2102 with a range from $1760 to $2583.

Table 4-14 Ventilation Cost Estimates – Alternative Sources

Ventilation	Price w/ Mark-up			
	VESTA	BC3	NREMD	RS Means
DOA	NA	NA	NA	NA
HRV	$14 681	NA	$2102 ($1760 to $2583)	NA
HRV w/Econ	NA	NA	NA	NA
HRV w/Dehumid.	NA	NA	NA	NA

The water-to-air heat pumps must be combined with ground-source heat exchanger loops. Three cost estimates were developed for each of the loop options available. The estimates in Table 4-15 include mark-up. The cost estimates based on VESTA are significantly lower than the OCMI cost estimates. For both data sources, the vertical system has the greatest cost because it requires drilling a deep well to install the vertical U-tube instead of a long trench.

Table 4-15 Ground-Source Loop Cost Estimates

Ground-Source Loops	Vertical U-Tube	Horizontal U-Tube	Slinky
OCMI	$27 778	$24 506	$24 539
VESTA	$19 575	$12 846	$12 846
BC3	NA	NA	NA
NREMD	NA	NA	NA
RS Means	NA	NA	NA

4.3.1 Renewable Energy System Cost Estimates

Two types of renewable energy systems are considered: solar thermal and solar PV systems. OCMI estimated the cost for two solar thermal systems, one using flat plate collectors and another using evacuated tube collectors. Both systems include the same pumping loop, heat exchanger, and storage tank. An alternative to a solar thermal system is to install additional solar PV panels to generate electricity instead of pre-heating water going to the domestic water heater. The cost estimates in Table 4-16 include all mark-up. The OCMI cost estimate shows that the flat plate collector system ($6824) is cheaper than the evacuated tub collector system ($9304). The cost estimates from VESTA ($4894) and BC3 ($7134) for the flat plate collector system are similar to the OCMI estimate. The OCMI solar PV system alternative is significantly more expensive at $20 265 while the alternative cost estimate based on data from SunShot is only $7800.

Table 4-16 Solar Thermal System Cost Estimates

Solar Thermal	2 Panels w/ 80 gal tank	2 Panels w/ 120 gal tank	Evac. Tubes w/ 80 gal tank	Replace w/ 2 kW PV
OCMI	$6824	NA	$9304	$20265
VESTA	$4894	$7341	NA	NA
BC3	$7134	NA	NA	NA
NREMD	NA	NA	NA	NA
RS Means	NA	NA	NA	NA
SunShot	NA	NA	NA	$7800

The solar PV system installed on the NZERTF is a 10.2 kW system, which includes four horizontal rows of eight 320 W panels with two inverters. The OCMI cost estimates include 4 incremental increases in the size of the installed system (2.55 kW, 5.1 kW, 7.65 kW, and 10.2 kW). These incremental increases are based on adding an additional string of panels, with adjustments to the size and number of inverters accordingly.

Table 4-17 shows the solar PV system installation cost estimates compiled from the different cost data sources. All cost estimates include markup and are absent of any federal or state incentives like the Solar Investment Tax Credit. Both the OCMI and BC3 data sources show that system costs increase with system size. The discrepancies in the cost estimates between the two data sources are rather significant. Even though both the OCMI and VESTA cost estimates were developed specifically for the NIST NZERTF, the difference in the estimated cost of a 10.2 kW system is more than $24 843. The BC3 cost estimate also shows lower costs than the OCMI estimate at $41 598. The most up-to-date data source is SunShot, which estimates the 10.2 kW system to cost $39 780 ($3.90/W). Based on the alternative cost estimates, it appears that the OCMI estimate is relatively high at $5.76/W of installed capacity for the 10.2 kW system.

Table 4-17 Solar PV System Cost Estimates

Solar PV	2.55kW	5.1 kW	7.65 kW	10.2 kW
OCMI	$22 944	$32 571	$45 486	$58 723
VESTA	NA	NA	NA	$33 880
BC3*	$10 399	$20 799	$31 198	$41 598
NREMD	NA	NA	NA	NA
RS Means	NA	NA	NA	NA
SunShot**	$9 945	$19 890	$29 835	$39 780
Range	$9945 to $22 944	$19 890 to $32 571	$29 835 to $45 486	$33 880 to $58 723

*Includes the installed cost of PV panels and inverters only.
**Based on the average price of installed capacity for Maryland ($3.90/W)

4.3.2 Cost Comparison by Building Design - Building Systems

Table 4-18 shows the cost estimates for each building system component for the Maryland Code design and NZERTF design, the cost difference between the two designs, and the total building system cost differences between the two designs for each of the alternative data sources. As in the case for RS Means window cost data, for data sources missing cost estimates for a given system component, the average of the other alternative data sources is used as a proxy.

The difference in building system costs for OCMI is higher than any of the alternative data sources at $71 616. However, once this estimate is adjusted to use solar PV cost data that seems more accurate (SunShot), the estimate decreases to $52 673 and brings it in line with the alternative cost estimates. The alternative data sources range from $49 719 to $66 950 with an average of $59 069, which is within 12 % of the OCMI estimate with the adjusted solar PV cost data. The extreme minimum and maximum are only slightly outside these estimates at $43 237 to $76 821.

Table 4-18 Alternative Building System Cost Estimates

Building Envelope	Data Source	MD Code	NZERTF	Difference
Domestic Hot Water System	OCMI	$2345	$3933	$1588
	VESTA	NA	NA	NA
	BC3	$1009	$2355	$1346
	NREMD	$747	$2532	$1785
	RS Means	$1826	NA	NA
Heating and Cooling Equipment	OCMI	$26 233	$28 163	$1930
	VESTA	$16 516	$28 139	$11 623
	BC3	$1558	$2267*	$709
	NREMD	$3439	$4685*	$1246
	RS Means	$5348	NA	NA
Ventilation Equipment	OCMI	$876	$4612	$3736
	VESTA	$0	$14 681	$14 681
	BC3	NA	NA	NA
	NREMD	$0	$2102	$2102
	RS Means	NA	NA	NA
Solar Thermal System	OCMI	$0	$5639	$5639
	VESTA	$0	$5200	$5200
	BC3	$0	$7134	$7134
	NREMD	NA	NA	NA
	RS Means	NA	NA	NA
Solar PV System	OCMI	$0	$58 723	$58 723
	VESTA	$0	$33 880	$33 880
	BC3	$0	$41,598	$41,598
	NREMD	NA	NA	NA
	RS Means	NA	NA	NA
	SunShot	$0	$39 780	$39 780
Total Building System Costs	OCMI	$29 454	$101 070	$71 616
	OCMI using SunShot for Solar PV			$52 673
	VESTA**			$66 950
	BC3**			$59,179
	NREMD**			$49 719
	Sum of Average			$59 069
	Sum of Minimum			$43 237
	Sum of Maximum			$76 821

*Heat Pump does not include cost of dehumidification mode capability.
**For missing values, used the average of the other alternatives for that category.

5 Building Design Cost Comparisons

The total additional costs to meet the NZERTF specifications relative to the Maryland-code compliant specifications shown in Table 5-1 are calculated by combining the results from Table 4-8 on the building envelope and Table 4-18 on the building systems. The total cost to the homeowner using the OCMI estimate with the adjusted solar PV costs is $123 414 with the alternative data source estimates ranging from $107 762 (-13 %) to $142 360 (+15 %). The average of the alternative data sources is within 1.4 % at $125 591. The most extreme combinations of cost estimates lead to a minimum of $80 883 (-34 %) and a maximum of $150 705 (+22 %).

Table 5-1 Alternative Building Design Cost Estimates including Mark-Up

Incremental Costs	Difference to Homeowner	Difference to Contractor	Difference to Subcontractor
OCMI	$142 357	$117 651	$90 501
OCMI using SunShot	$123 414	$101 995	$78 458
VESTA*	$142 360	$117 653	$90 502
BC3*	$109 886	$90 815	$69 858
NREMD*	$107 762 ($89 439 to $126 540)	$89 059 ($73 916 to $104 579)	$68 507 ($56 859 to $80 445)
Average	$125 591	$103 435	$79 565
Min Combination	$80 883	$66 845	$51 420
Max Combination	$150 705	$124 550	$95 808

*Proxies required when no value is available.
Note: Assumes subcontractor mark-up is the same as OCMI assumption.

These additional costs of reaching net-zero energy performance can be put into perspective by comparing the change in the total costs of purchasing a home in the Gaithersburg, Maryland area. Assuming the specifications of a 2015 IECC compliant design, the cost of constructing a 2700 ft^2, luxury two-story home in Gaithersburg, MD would cost approximately $418 965 ($155.17/ft^2)[4]. Adding together the incremental costs from Table 5-1, the cost of the constructing a code-compliant home in Gaithersburg, and the cost of land in the area, will give the total cost to the homeowner of constructing a net-zero energy home. The lot size is assumed to be 0.4 acres with a cost of $100 000, which is a conservative estimate based on current listings of land lots

[4] The RS Means Online Square Foot Calculator was used to generate this cost. The RS Means calculator accounts for differences in construction cost based on location in the U.S. The user has the ability to account for these location-based adjustments in their cost calculations by clicking on a dropdown and selecting from a list of U.S. cities. Since Gaithersburg, MD is not included as an option, the city of College Park, MD was chosen given its close proximity to Gaithersburg relative to other Maryland cities listed in the dropdown.

for sale southwest of the NIST campus in the Quail Run community between Darnestown, MD and Kentlands, MD vary from $260 000 per acre to $753 000 per acre according to Redfin 2016.

Table 5-2 shows the total cost to the homeowner of building a net-zero home in the Gaithersburg area, as well as the required monthly mortgage payment given the different data sources. Monthly mortgage payments were calculated based on a 30-year loan payback period and 80 % financing of the initial investment cost of the total property at 4.88 % APR (Annual Percentage Rate). The OCMI estimate leads to mortgage payments that are $754 more expensive than those for the house built to Maryland code compliance.

The table reveals that the differences in monthly mortgage payments for the net-zero energy home across the alternative sources, with the largest difference being only $183 (OCMI and NREMD). Although proxy data was used in cases where no data was available for some sources, Table 5-2 does highlight the importance of not only using accurate cost data when formulating cost estimates of net-zero energy building designs, but also the importance of using cost data that is consistent with existing industry cost trends.

Table 5-2 Alternative Building Design Cost Estimates including Mark-Up

Data Source	Cost to Homeowner (Sale Price)		Mortgage Payment (Monthly)*		Additional Mortgage Payment	
	MD Code	NZERTF	MD Code	NZERTF	Relative to MD Code	Relative to OCMI
OCMI	$518 965	$661 323	$2748	$3502	$754	$0
OCMI using SunShot	$518 965	$642 380	$2748	$3401	$653	-$101
VESTA	$518 965	$661 325	$2748	$3502	$754	$0
BC3	$518 965	$628 851	$2748	$3330	$582	-$172
NREMD	$518 965	$626 727	$2748	$3319	$571	-$183
Average	$518 965	$644 121	$2748	$3411	$663	-$91
Min Combination	$518 965	$599 848	$2748	$3176	$428	-$326
Max Combination	$518 965	$669 670	$2748	$3546	$798	$44

*Assumes 30-year mortgage, 80 % financing, and 4.88 % APR.

6 Summary, Limitations, and Future Research

This study compares the recent cost estimates developed by OCMI related to building components incorporated into a Maryland 2015 IECC code-compliant design, as well as higher efficiency building components currently incorporated or soon to be incorporated in the NIST NZERTF, to alternative cost data sources related to these buildings. The purpose of this study is to reveal differences in component cost estimates across data sources, as well as provide reasonable ranges for building component cost approximations that can be incorporated into future studies related to low-energy and net-zero energy residential building designs.

6.1 Results Summary

The alternative cost estimates for the building envelope reveal similarities across data sources for the exterior wall assembly and the roof/ceiling insulation building component categories. The additional costs incurred by building to the NZERTF design specifications ranges between -18 % and 2 % for the exterior wall assembly, and -20 % to 21 % for roof/ceiling insulation, relative to the OCMI estimates. More noticeable differences, however, are realized for the air leakage rate, windows, and basement (wall and floor) insulation. Air leakage rate cost estimates differ by as much as -73 % relative to OCMI, with RS Means showing the least amount of deviation (-3 %). These differences are primarily linked to differences in the assumed approach to achieving the lower air leakage rate.

The wide range in window cost estimates across the alternative data sources (-46 % to 73 %) is likely the result of differences in the underlying cost data, as well as the use of proxy data in cases where window specifications cannot be matched exactly across data sources. Of any of the building envelope components the biggest differences in incremental costs between OCMI and the alternative data sources are for basement wall and floor insulation, with OCMI estimates being 56 % to 76 % and 44 % to 55 % lower, respectively. Alternative assumptions for the method to reach the R-10 basement wall requirement for the Maryland code-compliant design are partly responsible for these considerable differences. The additional costs of building the entire building envelope to that of the NZERTF specifications range from $50 708 to $75 411. The average incremental cost ($61 108) is roughly 13 % lower than that of the OCMI estimate.

The significant differences in cost estimates do not occur for the building envelope only, but for the domestic hot water system, HVAC system, and renewable energy systems as well. According to the OCMI estimates, changing to a heat pump water heater from a minimum efficiency electric water heater would cost the homeowner an additional $1587. This incremental cost estimate is about 15 % lower than the NREMD estimate and 12 % higher than the BC3 estimate.

The HVAC system configurations considered in this study include at least two out of the three system components: heat pumps for heating and cooling, ventilation equipment, and ground-source heat exchanger loops. Data sources show that increases in heat pump system efficiency coincide with increases in system costs. Differences in cost for the Maryland code-compliant heat pump and NZERTF heat pump based on VESTA estimates ($11 623) is roughly six times greater than the difference based on OCMI ($1930). Similar trends are seen with regards to the ventilation system and ground-source loop options. The addition of the HRV system with separate ductwork (based on the NZERTF specifications) leads to an additional cost of $14 681 based on VESTA estimates, which is roughly four times higher than the incremental cost found using OCMI data ($3736). The difference in costs for the ground-source heat exchanger loops differ by as much as $11 660 between the VESTA and OCMI data sources depending on the loop type.

The two types of renewable energy systems considered in this study are solar thermal and solar PV systems. OCMI estimates suggest that at an additional cost of $6824 the two-panel flat plate collector system with 80-gallon storage tank is the least expensive solar thermal system configuration. Both the VESTA and BC3 estimates for the same system are close to OCMI estimates with cost estimates of $4894 and $7134, respectively. In regards to a roof-mounted solar PV system, the alternative data sources reveal that system costs increase with system size. However, large discrepancies between the data sources exist for a 10.2 kW system with OCMI estimate being roughly $25 000 higher than the VESTA estimate for a similar system. OCMI estimates are slightly more than $17 000 higher than BC3 and almost $19 000 more than SunShot.

The differences in total building system cost (sum of domestic hot water, HVAC, and renewable energy systems) between the Maryland code-compliant and NZERTF designs is highest with OCMI data with an estimated cost of $71 616. This falls outside of the $49 719 to $66 950 cost range defined by the alternative data sources. The OCMI estimates only fall within this range when it is adjusted using the SunShot estimate for the 10.2 kW solar PV system instead of the original OCMI estimate.

The incremental building envelope and building systems costs incurred by the homeowner for building to NZERTF specifications relative to the code-compliant design range between $107 762 and $142 360, with an average cost of $125 591. The magnitude of this cost gap, however, is reduced once the total costs of building the property is calculated and converted into a monthly mortgage payment. Assuming a 30-year mortgage at 4.88 % with 20 % down payment, monthly payments range between $3319 and $3502 across the alternative data sources, with an average monthly payment of $3411. Regardless of the data source, the additional mortgage payment of purchasing a home designed to reach net-zero energy performance relative to Maryland code compliance is between $400/month and $800/month based on the characteristics of the NIST NZERTF.

6.2 Limitations and Future Research

The analysis in this study is limited in scope and would be strengthened by including more accurate, up-to-date data sources as they become available. Recent technological innovation and improvements in production efficiency should be considered in the future because they have been found to be two key drivers behind declining installed costs of building products. Since all of the cost data sources, except OCMI and RS Means Online, are based on data before 2016, it is probable that the costs of some building components have fallen as a result of these factors and/or others.

Also limiting the scope of this study is the lack of consistency in building specifications across data sources, as well as the lack of available cost data for all building components considered. In a few instances, building component cost data from an alternative source was compared to the corresponding OCMI estimate despite the specifications of the component not matching exactly between the two sources. As a result, the accuracy of the cost comparison can be improved in the future with additional data and information. A majority of the alternative data sources had missing estimates for multiple building components. The use of proxy data to fill in these gaps also limits the accuracy of the analysis. Future analyses should consider only using data sources that: (1) include cost data on all building components being considered in the study; and (2) have a one-to-one matching of building component specifications with the other data sources being used. These two requirements help to ensure that a direct comparison can be made across alternative data sources.

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