THE COST-EFFECTIVENESS OF ZERO-ENERGY AND NEAR ZERO-ENERGY HOMES IN WASHINGTON STATE

by

Floyd Beaman

A Thesis
Submitted in partial fulfillment
of the requirement for the degree of
Master in Environmental Studies
The Evergreen State College
June 2013

This Thesis for the Master of Environmental Studies Degree

by

Floyd Beaman

has been approved for

The Evergreen State College

by

Edward A. Whitesell
Member of the Faculty

Date

ABSTRACT

The Cost-Effectiveness of Zero-Energy and
Near Zero-Energy Homes in Washington State

Floyd Beaman

Zero-energy buildings achieve a net-zero use of electricity from the grid or from any source that is non-renewable. Such buildings are significant in that they provide an opportunity for a sustainable energy future. Currently, buildings consume 40% of total U.S. energy. Thus, a reduction in this sector could have a significant impact on our energy consumption as a whole. While the building sector includes both commercial and residential buildings, this thesis focuses on residential buildings in Washington State. As of now, the technology is available to build such homes, but the question remains whether it is cost-effective. A number of factors come into play when determining cost-effectiveness, such as climate, type of renewable energy, cost of energy by location, etc. The purpose of this research is to determine the cost-effectiveness of modeled zero-energy homes in nine locations throughout Washington. While zero-energy homes are the end goal, several levels of energy efficiency are analyzed along the path to net zero. "BEopt" (Building Energy Optimization software) was used as the primary tool. The findings show that as energy efficiency increases, zero-energy homes become less cost-effective. Additionally, as energy efficiency increases, the return on investment decreases. The greatest determinant of cost-effectiveness, in both cases, is the substantial cost of photovoltaic systems, which were used to produce the renewable energy for all zero-energy homes modeled in this thesis. Since the cost-effectiveness analysis provided no distinct answer to whether zero-energy homes are cost-effective, compared to a similar conventional home, the return on investment was used as a proxy. It was concluded that homes on the path to net zero are cost-effective (i.e., provide utility bill savings that cover the increase in energy efficiency costs), up to the point at which photovoltaic is implemented, which represents an average of 34.3% energy efficiency.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my thesis reader, Dr. Edward Whitesell for his valuable and constructive suggestions during the writing process of this thesis. His willingness to give his time so generously has been very much appreciated. I would also like to thank the Master of Environmental Studies Program at The Evergreen State College for the opportunity to develop my interests and conduct this research. My grateful thanks are also extended to my wife, my family, and my friends for their support and encouragement throughout my study.

LIST OF ABBREVIATIONS/ACRONYMS

BAB	Building America Benchmark
BEopt	Building Energy Optimization
BPS	Building Performance Simulation
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CER	Cost-Effectiveness Ratio
DOE	Department of Energy
DOE2	Department of Energy Building Energy Analysis Program
EISA	Energy Independence and Security Act
EPBD	Energy Performance of Buildings Directive
GHG	Green House Gas
HERS	Home Energy Rating System
HPH	High Performance Homes
HVAC	Heating, Ventilation, Air Conditioning
IECC	International Energy Conservation Code
IPCC	International Panel Climate Change
kW	Kilowatt
KWh	Kilowatt Hour
LC-ZEB	Life Cycle Zero-Energy Building
MWh	Megawatt Hour
NREL	National Renewable Energy Laboratory

NZEH	Near Net Zero-Energy Home
PPMV	Parts Per Million by Volume
PV	Photovoltaic
ROI	Return on Investment
SIP	Structurally Insulated Panels
TMY3	Typical Meteorological Year Weather Data 3rd edition
TRNSYS	Transient System Simulation Tool
ZEB	Zero-Energy Building
ZEH	Net Zero-Energy Home

Introduction

Currently, 40% of the energy used worldwide is being consumed in buildings (Kolokotsa et al. 2011). In the United States, buildings are responsible for 39% of energy consumption, 68% of electricity use, and 38% of the carbon dioxide emissions found in the atmosphere (Srinivasan et al. 2012). The U.S. residential sector alone accounts for 20% of national energy consumption, 35% of electricity use, and 18% of all greenhouse gas emissions (Danny 2009). As the population continues to grow, the energy usage in the building sector is expected to rapidly increase. At the same time, the evidence for global climate change and for the impacts of greenhouse gas emissions are increasingly calamitous. The fourth assessment report by the Intergovernmental Panel on Climate Change (IPCC) shows that 11 of the 12 years between 1995 and 2006 were the warmest years in the record of global surface temperature (since 1850) (IPCC 2007). The consequences for this century if we continue "business as usual" could be drastic. However, at the same time, the IPCC is very optimistic about the ability of the building sector to reduce carbon dioxide emissions through energy efficiency (Verbruggen et al. 2011). A report by the McKinsey Global Institute found that the U.S. could reduce energy use in new and existing buildings by more than 25% by 2020 with measures that pay for themselves in less than 10 years (ASE 2010). Additionally, with the global building sector accounting for over 1/3 of the global energy consumed, this is fast becoming a very viable option in terms of working towards a clean and sustainable future.

The objective of this thesis is to determine the cost-effectiveness of building highly energy efficiency buildings known as zero-energy homes in the state of Washington. In doing so, Building Energy Optimization (BEopt) software, were used to model a home design on the path to achieving net zero-energy efficiency for nine locations throughout Washington State. The cost data for these homes was then analyzed to determine the cost effectiveness per unit of energy efficiency as well the return on investment provided by a reduction in utility bills over the life of the mortgage. This research provides insight into the current technological and economical feasibility of zero-energy homes.

The findings presented in this thesis are significant in that it is now necessary that we identify and become acquainted with every avenue of carbon mitigation and energy efficiency, particularly those that can be done quickly and cost-effectively first. The scope of this paper is limited to energy efficiency in the residential building sector, but the ideas and concepts could be extrapolated to all built environments. Given the benefits that zero-energy buildings provide, this concept has received special attention around the world. Not only do such buildings provide a more sustainable future, but they can also provide specific benefits for the consumer. Through purchasing or building a zero-energy home, the consumer achieves a reduction in total net monthly cost of living and becomes protected from the future increase in non-renewable energy costs. In some cases, zero-energy buildings may produce more energy than is consumed, in which case, homeowners may receive payment for exports to the grid, depending on where they live. If this were the case, it would make sense for someone looking to invest in a new home to consider a zero-energy building. The technology is already available to contstruct net zero-energy buildings (ZEBs), but the question remains whether it is currently cost-effective for the average consumer to consider investing in this alternative. While the price of purchasing a zero-energy home is likely to have more upfront costs than a conventional home, there is a possiblilty that the initial increase in cost could be reimbursed during the life of the mortgage (typically 30-40 years). In answering these questions, we deploy the use of cost-effectiveness analysis and return on investment analysis to compare zero-energy homes (ZEH) and near zero-energy homes (NZEH) to similar conventional homes. The findings presented in this thesis suggest that as energy efficiency increases, energy efficient homes become less cost effective. It is also the case that as energy efficiency increases, the return on investment decreases. Additionally, the findings show that the greatest determinant of cost-effectiveness, in both cases, is the substantial cost of photovoltaic systems (PV), which were used to produce the renewable energy for all zero-energy homes modeled in this thesis. Thus, if the price of PV were to come down or if financial incentives were provided to lower the overall costs of PV, zero-energy homes would become more cost-effective as well. Nevertheless, the results show that energy efficient homes on the path to net zero are cost-effective until the point at which the marginal cost of energy savings equals the cost of producing PV energy, at an average of 34.3% energy efficiency. This suggests that the cost-effectiveness of ZEHs will mirror that of PV into the future.

In determining the cost-effectiveness of zero-energy homes, it is first necessary to begin with an indepth review of the current literature. This provides the background needed to understand the current state of research as well as setting the stage for the research presented in this thesis. Much of the literature focuses on understanding and defining what it is to be a zero-energy home. This includes specific definitions as well as studies on the technological feasibility and applications of such homes. Additionally, a look into the current paradigm describes the political, social, and economic barriers of implementing ZEHs and why they have not begun to take hold.

After reviewing the literature, the next chapter covers the methods used in conducting the research and analysis presented within these pages. As menetioned above, BEopt software was used to model home designs on the path to net zero for nine locations throughout Washington State. BEopt generated cost data for each location at several points along the path to net zero. A Benchmark home, representing a typical convnetional home, was used as the reference case in which the modeled homes were compared to. This cost data was then analyzed in the following chapter, using cost-effectiveness analysis and return on investment analysis. Utilizing these two methods of analysis, one is able to ascertain how cost-effective each ZEH or NZEH is at each point along the path to 100% energy efficiency. One is also able to see at which point purchasing an energy efficient home can one expect to see a complete return on investment over the life of the mortgage. The return on investment is used as a proxy for cost-effectiveness since it does a better job of comparing the cost versus benefits than does the cost-effectivness analysis. Thus, a home that achieves an ROI equal to 1, represents a home that is able to completely offset the additional increase in cost due to increases in energy efficiency through the reduction in utility bills over the life of the mortgage.

Lastly, a discussion of the importance of building codes in relation to improving our nation's energy efficiency in the building sector is presented. It may be that market forces are yet unwilling to promote the implementation of energy efficient buildings, especially with low cost fossil fuels being the primary energy source for the world. Nevertheless, building codes provide a tried and true method of systematically implementing energy effciency as we move into the future. Thus, building codes may provide the best mode of implementing energy efficient measures, particularly those that are already cost-effecttive.

Literature Review

Advancements in photovoltaic and efficient building technologies are now proving, after several decades, that it is technologically feasible to build a home that uses net zero-energy. Nevertheless, there is still much uncertainty pertaining to the implementation and economic feasibility of zero-energy homes (ZEH). Much of what we know currently has come out of experimental studies in which ZEHs are built and observed to determine their annual energy demand and supply. These feasibility studies provide great insight into the functionality and possibilities of ZEHs, but do not answer the question of how we can build such homes in a cost effective way. Since it could be assumed that cost is one of the greatest barriers of ZEH implementation, a greater understanding of what it takes to design, build, and operate these types of homes in a cost effective manner is needed before we can expect to see such homes compete for a share of the market place. In reviewing the literature, I cover the most common definitions of what it means for a home to be zero energy. I also analyze the current market and institutional paradigms as well as review the technological feasibility. Lastly, how this research and the current body of literature contribute to a more sustainable future is explored.

Defining Net Zero-Energy Homes

Currently, there is no nationally or internationally agreed upon definition of what it means for a home to be zero-energy. Nevertheless, this major impediment has been recognized and effort is being put forth to define the parameters and standards of what a zero-energy home will look like and to establish a consistent framework for all zero-energy buildings. In fact, zero-energy buildings have already been discussed in the U.S.'s Energy Independence and Security Act of 2007 (EISA 2007) and in Europe with the recast of the Directive on Energy Performance of Buildings (EPBD) (ASE 2010). Much of this initial attention has been focused in the commercial arena, but the same concepts and goals apply. In essence, a zero-energy home could be achieved by taking a conventional home and adding a very large solar array, or any renewable energy source, that would offset the home's energy use through its renewable energy generation. For example, if the goal were only to achieve net zero energy, and an installed photovoltaic system delivers more energy than a home uses, then this home is potentially a "net zero-energy home" under a very loose standard. Thus, the purpose behind building a zero-energy home or the goals of a zero-energy home must be considered before a given definition can be settled upon. So, in many cases, the definition or type of zero-energy home will be largely dependent on the individual project and its objectives. It is with this understanding that we can define several different types of zero-energy homes.

With no prior understanding of the potentials of zero-energy homes, one might envision a compact minimalist hut set remotely off the grid. Several solar panels and a few golf cart batteries, to store the excess energy, would be tucked away to provide this self-sustaining home with some of the little energy it would need. Although these types of homes are definitely zero energy, they should really be considered as the jumping off point for the modern day zero-energy home. That is to say, they were simply an intermediate step on the path towards the true potential of zero-energy that can be achieved through net metering. In simple terms, net metering uses the power grid like a massive battery. All the excess energy that the home produces through its renewable energy generation is exported to the grid to be used by others, since it must be used as it is being generated. This output is accounted for like money in a bank account, to be used at a later time. For example, at night and during the dark winter months when PV (photovoltaic) generation is lacking or non-existent, a home can hypothetically import the energy it produced back, thus resulting in a net-balance. It is with this technology that we are beginning to see the potential of zero-energy homes unleashed. Beforehand, all excess energy must have been stored in batteries or used as it was being generated. That was until 1983, when Minnesota enacted the first net-metering law in the world (DSIRE 2012) So, if you wanted to put a PV system on your home, economically it wouldn't have been feasible given the immense amount of batteries needed. Unless your goal was to be off the grid, in which case you probably don't require much energy to begin with. Although off-grid ZEHs are truly zero-energy, they are not practical for the purposes of this thesis. If we are to work towards zero-energy homes on a massive scale, it is necessary that they be connected to the grid and able to utilize net metering. Thus, from now on, all zero-energy homes referred to in this thesis as "ZEH" will refer to any net zero-energy home and those denoted, as" NZEH" will be considered nearly net zero-energy homes. These latter are homes on the path towards net zero, not to be confused with homes that have achieved a net zero standing. Separately, "ZEB" will be used to denote any zero-energy building (i.e., not just residential buildings), although the focus of this thesis is on zero-energy homes. Lastly, photovoltaic (PV) is consistently referred to in this thesis as the primary source of renewable energy generation for ZEHs. This is because of its general acceptance as the most cost-effective form of renewable energy, its widespread implementation, compatibility with net metering, as well as its inclusion in most building performance simulation (BPS) software programs, including BEopt, the program used in this thesis.

With this in mind, the heart of defining zero-energy homes comes down to the different methods of calculating the "zero" balance i.e., "a condition that is satisfied when weighted supply meets or exceeds weighted demand over a period of time, nominally a year" (Sartori et al. 2012, p. 222). This balance is influenced by a variety of measures and each must be taken into account when defining the net zero home. For example, one might select end-use energy, CO2 emissions, energy, or cost of energy as the metric of balance. If one of these is given priority over the other or weighted more heavily, then this will impact the balance calculation methodology and ultimately how we define the home. Torcellini et al. (2006) provide an overview of the different ZEB designs and how specific objectives can determine the type of ZEH. Torcellini et al (2006) is considered the first publication to document and discuss the different zero-energy definitions and is often cited in publications on ZEBs. Additional research concluded that the definitions proposed by Torcellini are being continually used in this field of reseach, particularly by the Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL). The definitions that are proposed reflect how differences in project goals, intentions of investors, climate change and greenhouse gas (GHG) objectives, as well as energy costs impact the understanding of what a ZEB actually is. This is because each of these concerns is going to mean different things to different people. For example, a general contractor is going to have a different objective than the Department of Energy and a designer is going to have a different goal than someone whose main concern is reducing emissions. Thus, Torcellini et al. (2006) presents four different definitions of ZEBs. A site ZEB produces as least as much energy as it uses in a year, when accounted for at the site. A source ZEB produces as least as much energy as it uses in a year when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year. A net zero-emissions building produces GHG (greenhouse gas) emissions-free energy in an amount that is at least as much as it uses from emissions-producing energy sources. Each one has its own unique advantages and disadvantages. What they all share, however, is the idea that energy efficiency is the first priority and once that is achieved, the addition of renewable energy sources can be added to reach the zero balance. Each of the definitions assumes that they will use the grid for net metering.

The site ZEB produces as much energy as it consumes when accounted for at the site (Torcellini et al. 2006). Like the others, it can generate energy through a variety of renewables suitable to the given location. This could be roof-mounted PV, a small-scale wind turbine, low-imapct hydroelectricity etc. To better guide in the selection of different supply-side technologies Torcellini et al. (2006) provide a ranking of renewable energy sources based on minimizing environmental impact through energy-efficient designs and reducing transportation and conversion losses. Additionally, whether they will be available over the buildings lifetime and whether they show high replicable potential for future ZEBs were also taken into account.

Regardless of type of renewable, the first option is always to reduce the site energy through low-energy building technologies. This is usually a given but can be easily overlooked. After this, the best option is to use renewable energy sources available within the building's footprint e.g., using PV, solar hot water, and wind located on the building. Ideally, this is the best option after all efficiency measures have been met. This is primarily due to the renewables not requiring additional resources, but instead taking advantage of available space, such as the roof, in cases of PV and wind generation. Next is the use of renewables from energy sources at the site. These could be PV, solar hot water, low-impact Hydro, and wind that are on site but not on the building. While still a stellar option, there may be additional environmental impacts when dealing with sources away from the building. The last two options are to utilize renewable energy from off-site sources. For example, one could bring in biomass, ethanol, and biodiesel from another site or waste stream and process it on site to generate electricity. Lastly, once could purchase off-site renewables, for example, by buying utility-based wind, PV, emissions credits, or even hydroelectric energy. However, in the last two cases, one could potentially purchase all power from hydroelectric or biomass and declare their home "zero energy," which is not quite what a ZEH is attempting to reach. Rather it would be best practice to utilize as much of the first options as possible and only consider the off-site renewables as a last resort, to reach Zero Energy. Figure 1 is representative of the different renewable energy supply options as discussed above.

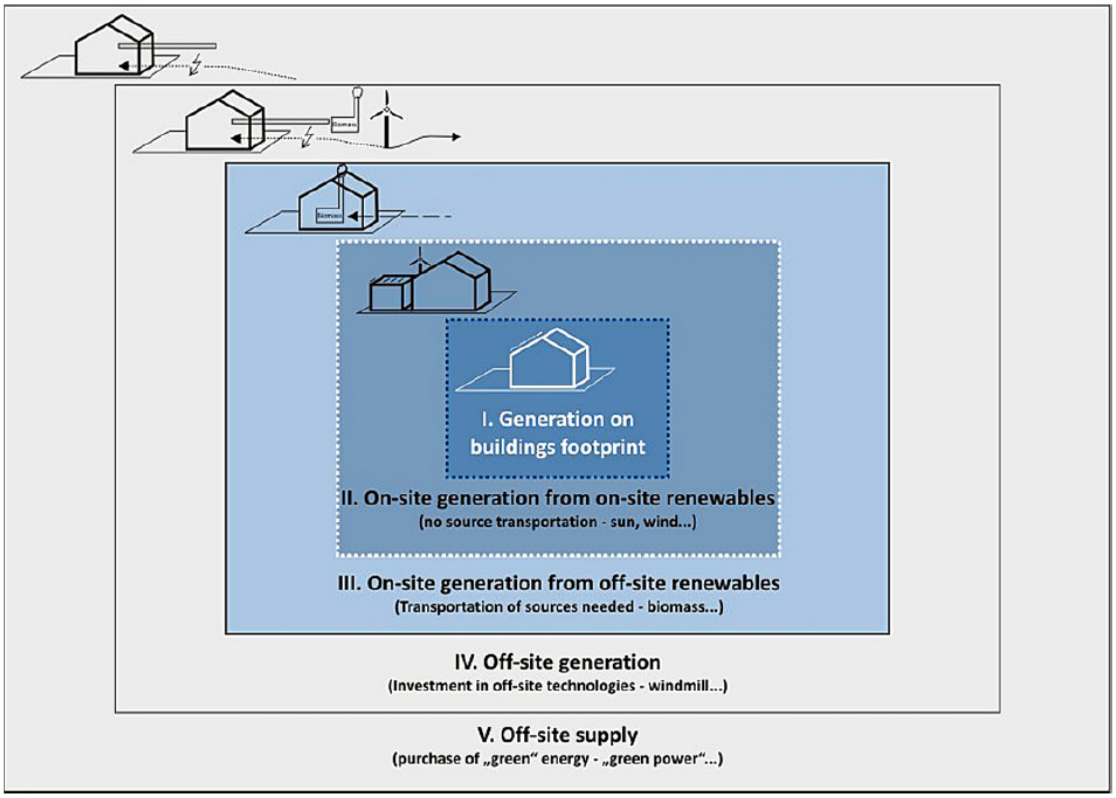

Figure 1. Overview of possible renewable supply options (Marszal et al. 2010)

All four definitions have different goals in mind, each with their own strengths and weaknesses. One limitation of a site ZEB is that the differing values of various fuels at the source are not considered. This is because the building site energy is typically measured at the utility meters and is the total of the electrical, gas, and other types of energies delivered to the home. In this case, one unit of electricity is equivalent to one unit of natural gas, despite electricity being 3 times as valuable at the source (Torcellini et al. 2006). Site energy can be useful in understanding the overall performance of a home, but it does not take into account the whole story of environmental impacts resulting from the home's energy use and thus should generally not be used as a metric to compare homes with different mixes of energy types e.g., homes with on-site PV generation. For example, whether a home is using a site or source ZEB definition will determine the amount of on-site electricity needed to offset gas use. In the case of a site ZEB, this would need to be on a 1 to 1 basis and result in a larger PV system than a source ZEB would require. This is because a site ZEB does not take into account the differences in energy sources, such as transportation costs; it only compares energy used at the site. This definition also favors electric equipment, since under this definition; it is more efficient at the site than its gas counterpart. For example, an electric heat pump would be favored over natural gas furnaces despite cases where a natural gas furnace may be more suitable e.g., very cold climates. Nevertheless, a site ZEB is easily verified through measurements on-site, which makes it an easily repeatable and consistent definition. In terms of meeting a ZEB policy goal, this definition might be something to consider.

On the other hand, a source ZEB produces as much energy as it consumes as measured at the source (Torcellini et al. 2006). In order to calculate the building's total source energy, the imported and exported energy need to be multiplied by an appropriate site-to-source energy factor. The NREL used a life cycle assessment to determine national electricity and natural gas site-to-source energy factors of 3.37 and 1.12 (Deru and Torcellini 2006). Thus, site gas energy use will have to be offset by onsite electricity generation on a 3.37 to 1 ratio for source ZEBs. This means that for every 3.37 units of gas used at the site, 1 unit of electricity must be exported to offset it. In most cases, the national average site-to-source energy factors are used so that projects can be consistently compared across the nation. However, this definition has the potential to encourage the use of gas in as many end uses as possible in order to reach the net zero-energy goal. For example, gas could be used to power gas boilers, domestic hot water heaters, or dryers. This kind of fuel switching and source accounting is one currently economically feasible way to reach net zero-energy. That is, the higher the total energy use at the site that is natural gas, the smaller the PV system has to be, thus lowering costs. While natural gas can't power everything and it is still a fossil fuel, it is relatively cheap and clean in terms of non-renewables.

Another potential weakness of this definition has to do with how the site-to-source energy factors were calculated. If we use national averages, this might not reflect regional differences in electricity generation. For example, here in the Pacific Northwest, hydropower is a significant portion of our energy portfolio and thus the site-to-source multiplier is somewhat lower than the national average. Deru and Torcellini (2006) provide multipliers for three primary grid interconnects and for each individual state.

An additional issue with this definition occurs when gas from fossil fuels is used to generate electricity on site. Since nearly all ZEB definitions state that a building must use renewable energy to offset its energy use and reach the ZEB goal, any electricity generated from fossil fuels cannot be exported and counted towards reaching net zero. However, taking into account the most cost-optimal methods, this scenario is unlikely to play out given that buildings will usually need more electricity than they do heat. However, if energy costs go unmanaged, despite reaching site or source net zero, then a building may not realize energy cost savings. Thus, cost will likely determine the best combination of energy efficiency, co-generation, and renewable energy generation at the site.

With this in mind, the third definition of a ZEB can be understood i.e., the net zero-energy cost building. A cost ZEB is one that receives as much financial credit for exported energy as it is charged on the utility bills (Torcellini et al. 2006). Thus, the credits received for exported electricity will need to offset the charges incurred for energy, distribution, peak demand, taxes, and metering for both electricity and gas. This definition provides an even comparison of different fuel uses at the site and thus the energy availability and competing fuel costs will be the main determinant of optimal solutions. One issue with this is that as utility rates vary widely and change constantly, a building with consistent energy use might meet the ZEB goal one year and not the next. In terms of wide scale implementation, this definition may not be suitable because utility rates have the potential to change dramatically. Eventually, as energy efficient buildings and renewable technologies increase, the effects they will have on the utilities service area must be taken into account. Not only do utilities purchase fuel to generate their electricity they also pay to maintain the infrastructure and to provide profitability to their stakeholders. Thus, if or when significant numbers of buildings reach net zero, the utility may not have the financial resources to maintain the infrastructure and thus would need to raise the fixed costs and demand charges. This may or may not impact a buildings goal, but it is an eventuality that will need to be taken into account. So, while this definition may not be suitable over the long-term, in all practicalities, cost will be the greatest determining factor for many when deciding whether or not to build a zero-energy building, especially in the residential sector.

To achieve a cost ZEB, it is necessary to first reach a certain threshold energy savings. The less energy required by a building, the less renewable energy it has to produce and thus, the less costly the home is overall. Since cost ZEB is primarily interested in balancing the cost of renewable energy exported to the grid with the amount the owner pays to the utility, the differences in costs are the main determinant in a homes ability to reach net zero-energy costs. With this comes the need for aggressive demand management in order to reduce demand to the point at which the renewable energy source could offset it. In this case, in order to achieve a cost ZEB, it would be necessary to know when peak demand charges occur and manage energy use around these. Since peak demand charges cost more, more renewable energy would be needed to offset the higher rates. Thus, a utility rate that factors energy use and not peak demand charges would be more favorable.

Additionally, a net-metering agreement that credits excess electricity generation at avoided generation costs without PV capacity limits would be ideal. Most states that have net metering laws require utilities to purchase the excess energy back, although with different stipulations based on location. The avoided generation costs would be a valuation of the costs associated with the utility not having to generate energy. It could also be credited back at the full retail rate, which is usually more than the avoided generation costs. In Washington, the utilities will pay $0.15/kWh for electricity generated from PV equipment manufactured out of state and $0.54/kWh for solar generated electricity from equipment manufactured locally. This program known as Washington State's 6170 program expires on July 2020 (DSIRE, 2012). With the average retail rate of electricity in Washington State being $6.66/kWh in 2010, this incentive program could offer significant incentives for people to build zero-Energy homes as soon as possible (DOE and EIA 2012). Nevertheless, if demand charges account for a large portion of the utility bills, then a cost ZEB can be difficult to achieve. Thus, demand savings, as described above, becomes very important in order to reduce overall costs and allow for greater payback.

Lastly, and perhaps the most suitable in terms of reaching climate change objectives is the net zero emissions building. It produces emissions-free renewable energy in an amount that is at least as much as the amount of emissions-producing energy it uses (Torcellini et al. 2006). While it could be argued that there is no such thing as emissions-free renewable energy technology, this would assume that we are taking into account the life cycle of the technology. For the purposes of this thesis, we are only interested in the process of energy generation. While it would be more accurate to include life cycle cost analysis, it is beyond the scope of this paper. Thus, renewable energy could be considered emissions free because it does not release climate-altering elements into the atmosphere; the central idea with this definition is that the emissions free energy balances the energy used from conventional sources. Thus, in this way, it reduces its emissions through using supply side options as mentioned above. Potentially, an all-electric building that gets all its electricity from an off-site zero-emissions source is already zero-emissions and thus does not have to generate any on-site renewables. This would be considered an off-site building. However, if the building utilized natural gas, it would then need to offset this with renewable generation. It could do this by purchasing enough renewable energy from a hydro utility, for example, to offset this. So, if one lived in a region with a predominantly renewable energy generation mix, then that ZEB would need a smaller PV to offset emissions than it would need in a region that used predominantly coal. However, in both cases, purchasing emissions offsets from other sources is considered an offsite ZEB, which is generally not what the net zero-energy goal entails. Lastly, since utilities often use mixes of energy sources, it could be hard to calculate the generation source of electricity.

Apart from these definitions, which encompass the main components of what it means to be zero-energy, other considerations must be taken into account.
For example, the period of time that the building calculation is performed, known as the period of balance, must be determined (Marszal et al. 2011). This could be the full life cycle of the building, which would take into account all energy from the moment construction began. It could also be the operating time of the building (e.g., 100 years or until demolished), the mortgage period (e.g., 30 years), or most commonly, the annual balance. The yearly balance is suitable in most cases because it covers all operation settings with regards to the succession of the seasons. Seasonal or monthly balances have also been put forth as options. In reviewing several studies, Marszal et al. (2011) found that the most favored balancing period is the annual balance.

However, the life cycle of a building could be more appropriate because it takes into account not only the energy use but embodied energy in the building materials, construction, demolition, and installation (Hernandez and Kenny 2010). This sort of methodology and type of balance is more in line with evaluating the true environmental impacts of the building. However, due to the scope of this thesis, we will not be taking into account life-cycle costs. Nevertheless, this life-cycle analysis does not restrict calculation of annual energy use to any particular methodology. Instead, any consistent building energy calculation could be expanded to include a life-cycle perspective. We would then be considering a life-cycle zero-energy building or LC-ZEB. LC-ZEBs are buildings “whose primary energy use in operation plus the energy embedded in building materials and systems over the life of the building is equal to or less than the energy produced by renewable energy systems within the building” (Hernandez and Kenny 2010, p. 817).

While life-cycle assessments try to take into account all the energy use encompassed in the life of the building, many of the publications do not even specify the type of energy use that is included in their balance (Marszal et al. 2006). These discrepancies add to the issues that come with having no agreed upon definition of ZEBs or the type of balance to be used in the calculation methodologies. While the literature shows the most favored balance being between the energy consumption and the renewable generation, we noted other definitions above that could be used given the goals of the project (Marszal et al. 2006). However, even with specified definitions, there are still other requirements buildings must meet before being constructed. These are energy efficient requirements, indoor climate requirements and grid-interaction requirements. We noted that although some definitions do not require energy efficiency before implementing renewables, it only makes sense that this be the first priority on the path to net zero. Torcellini et al. (2006, p. 3) give the definition that “a ZEB is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies.” This provides a stripped down, jargon-free definition of what it ultimately means to be on the path towards net zero-energy. This thesis will largely be guided by the precepts of this framework.

In terms of indoor climate requirements, the literature has been largely quite. Of course, the comfort of the indoor climate is “always the first priority in building design” (Sartori et al. 2012, p. 229). Thus, requirements for a good and healthy indoor climate should be understood and specified. For example, buildings should utilize daylight and supply sufficient artificial light control, maintain proper atmospheric indoor climate through temperature and air quality control, and utilize healthy materials with good acoustics and sound. Marszal et al. (2011) point out that out of the 12 publications reviewed, only two mentioned indoor climate requirements. Sartori et al. (2012) also only briefly cover it by pointing out that the climate and comfort standards need to be accounted for because any variations in the expected outdoor and indoor climates will affect energy demand (e.g., different temperature settings or hotter/colder years). These specifications are useful in that they allow one to design a ZEB for a given climate, which is best because most renewables are climate dependent. However, if ZEBs are designed properly, most will take this into account regardless of whether or not this is made explicit.

Lastly, grid interaction requirements are also taken for granted when ZEBs are being discussed. Most definitions require that the ZEB be connected to the grid without any details describing the interaction. In most instances, as long as net metering is available in the location, the perception is that the grid is capable of unlimited energy storage with no losses. However, this idea is changing with more research investigating the interaction that would be best for both building and infrastructure (Marszal et al. 2011). The issue lies with the grid-building interaction being hard to define. Since the approaches depend on which perspective you take (e.g., the grid, the building, or the nation), there are going to be different objectives. Two indexes were defined in the literature to characterize this interaction from the building perspective. One is the load match index, which describes how much demand is covered by on-site generation or how much stress is put on the grid. The other is the grid interaction index, which describes the fluctuation of the energy exchange between the grid and the ZEB. These analyses, however, require many measurements that may be hard to come by, including the grid characteristic, location, type and load profile of the building, and time resolution. Nevertheless, one basic requirement has been identified in the literature i.e., the energy fed back to the grid has to have the same usability as the energy taken from the grid (Marszal et al. 2011). This will be assumed to be the case in most instances.

Although the concept of zero-energy buildings is generally inferred, there is still no agreed upon-definition or standard. Nevertheless, it is now accepted that the definitions for a ZEH depend on an individual's objective or the targets that lie behind the promotion of any zero-energy building. One commonality for all ZEBs, and one that is used in this thesis is the concept of balancing the weighted demand and supply. Without the ability to balance the buildings energy consumption with its renewable energy supply i.e., net-metering, zero-energy buildings may not have reach the potential that they have today.

Understanding the Current Paradigm

As of May 9 2013, CO_2 readings from the Mauna Loa Observatory showed atmospheric carbon dioxide levels had reached 400 ppmv (parts per million volume) (Tans and Keeling 2013). This is an increase of 40% relative to preindustrial levels of approximately 280 ppmv. These levels have never been seen in human history. This rise in carbon dioxide has led to observed increases in the global average surface temperature and ocean temperature as well as widespread melting of snow and ice, resulting in a rising global average sea level. Thus, there is clear evidence that the warming of the climate system is unequivocal. Many natural systems around the world are being affected by regional climate changes, including the ocean, which faces increasing levels of acidity due an increase in anthropogenic CO_2 (IPCC 2007). The Intergovernmental Panel on Climate Change (IPCC) reported that "unmitigated climate change would, in the long run, be likely to exceed the capacity of natural, managed, and human systems to adapt" (IPCC 2007, p, 65). Thus, it is necessary for us to identify the barriers, limits, and costs of adaptation and mitigation strategies if we are to take this issue seriously.

The IPCC fourth assessment report found that energy use in buildings offers the greatest potential for reducing carbon emissions over any other single sector in the US and abroad (IPCC 2007). Taking this into account, our current housing paradigm is in great need of a transformation. In understanding the challenges of making this shift, Farhar and Coban (2008) tease apart some of the misconceptions that they call "conventional wisdom" from what they term the "new market paradigm." They interviewed and sent questionnaires to homebuyers of high performance homes (HPH) (30-50% savings in utility costs) in the Scripps Highlands development of San Diego as well as to comparative conventional homeowners. This was the first development in the U.S. to be built of high performance homes attached to the grid and the first development to implement net metering. From this study, they identified several misconceptions associated with HPHs that can also be extended to ZEHs. For example, conventional wisdom would lead us to believe that HPHs cost more to build and that only innovators and early adopters will buy them. It also suggests that homeowners are motivated to purchase HPHs based on economic payback and that satisfaction with the home is contingent on this payback. Additionally, given the poor aesthetics of solar panels affecting home values, production builders should only offer these homes as an option. However, the results of this study show quite the opposite and suggest what may be a new market paradigm. For example, they report that production builders can market HPHs competitively and profitably where subsidies are in place and may even sell them faster than nearby conventional homes, as was the case with this study. They also note that buyers of HPHs are the same types of consumers attracted to new production homes in their price range and that when a homebuyer likes their home's location, appearance, and layout, they tend to be unconcerned about the aesthetics of solar features. Lastly, when it comes to purchasing HPHs, homeowners perceived three major benefits: altruistic, financial, and personal satisfaction. While the energy saved plays a huge role in all of these, it is not the determining factor. This study exemplifies some of the main misunderstandings that we see in terms of the current paradigm and what a possible shift may look like.

Apart from some of the common misconceptions that we have about consumer choices on this issue, there is additional research being done in order to understand some of the barriers perceived by builders. The National Renewable Energy Laboratory, in an effort to meet the DOE's ZEH performance goals, is looking into all barriers and has identified some notable characteristics about builders. In terms of technology, they tend to avoid those that increase risks, increase overall costs, have potential for customer complaints, require additional training and oversight, require new and unfamiliar materials, require additional planning and codes, and lastly, have the potential to increase future home warranty or callback costs (Anderson and Roberts 2009). For the most part, builders are risk-averse in respect to new technologies, however, if they are to continue to respond to consumer and policy-driven demand, then they are going to need credible information to decide for themselves whether they can successfully use these new technologies and products that come with unknown risks and, so far, unproven benefits.

In the United Kingdom, the Code for Sustainable Homes has set a target for all new homes to be zero-carbon from 2016 on. While technically not referred to as a zero-energy home, these buildings are expected to produce as much energy as they consume. With this ambitious target set, there has been an effort to identify some of the challenges faced by UK builders. Osmani and O'Reilly (2009) conducted a study looking at the main drivers and barriers from the perspective of builders in the UK. They performed interviews and sent surveys to the largest homebuilders in England; their results identified several cultural, financial, and legislative barriers. For example, most homebuilders revealed a lack of confidence in emerging green technologies, while close to half of them reported that a lack of widespread customer demand is a significant barrier. One interviewee pointed out "there is a substantial amount of education that needs to happen for the general public to appreciate the benefits of zero carbon homes" (Osmani and O'Reilly 2009, p. 1922) Additionally, homebuilders identified a lack of data related to the cost of zero-carbon homes and a lack of sales data as financial barriers for the implementation of ZEHs. Lastly, the definitions of zero-carbon homes as well as too many government policies (68%) were also perceived as barriers. This study indicates that some of the main concerns that builders have are related to a lack of trust in new technologies as well as a lack of cost data and consumer demand. Since these homes are a relatively new technology, it seems correct to assume that builders may have a challenging time leaving the current paradigm behind.

In addition to understanding barriers that UK builders had, Osmani and O'Reilly (2009) were also interested in influential driving forces that would lead to reaching the goal of zero-carbon homes. Nearly all builders reported that compliance with environmental legislation as well as government policies on building practices are key driving forces to the implementation of zero carbon homes. The overall consensus in the interviews was that "making zero carbon standards mandatory would be the most effective way of driving the industry to build zero carbon homes" (p. 1920) While other drivers were identified, legislative drivers had the highest impact on house builders current work practices. Although this study was done in England, many of the same barriers and drivers could apply to U.S. homebuilders. Most significantly, the recognition that government policy plays a driving role in the development of implementing highly efficient homes is important to consider. As we reach a point where research and development are making zero-energy homes a viable option to combat climate change, the current paradigm may need a nudge in terms of groundbreaking environmental policy.

On the other hand, what may be applicable in the U.K. might very well be different in the United Sates. The goal of reaching zero-energy in the building sector is evident in many developed nations around the world, yet the way in which each country will transition into this new paradigm may be dependent on the culture itself. An example of how cultures influence building practices is presented by Koch et al. (2010) in a study that compares Swiss building practices to that of the U.S. The study was framed within the context of moving towards zero-energy homes. They report that Swiss home building standards are more similar to the commercial standards than the residential standards in the U.S. In Switzerland, it is common practice to use thick masonry brick-type components that create more thermal mass than it is to use the U.S. style wood frame. They also pay significant attention to optimizing the building envelope as well as taking advantage of highly efficient mechanical systems such as air-to-air heat recovery, radiant slab heating and cooling, and solar domestic hot water, which are common in U.S. commercial applications. Swiss homes typically cost $600,000 to purchase and people tend not to purchase new homes, but rather inherit them.

In order to compare these different standards, this study used the U.S. Energy Star standards and the Swiss Minergie standards, both of which are categorized as the current "best practices" in each country, thus represent a starting point for zero-energy. They modeled a home design that was found in both countries using the software tool RemRate. This tool predicts annual utility costs and provides a Home Energy Rating Systems (HERS) index based on a reference building built to specifications of the 2006 International Energy Conservation Code. A home meeting the reference building standards gets a score of 100 while a net zero-energy home receives 0. The lower the score, the more efficient a home is. In this, study, the U.S. Energy Star home scored 79, with the standard U.S. home scoring a 98. The Swiss Minergie home scored a 37, while the standard Swiss home scored 54. Lastly, two hybrids of each type of home, a hybrid energy star home and a hybrid Minergie home were modeled. They scored a 45 and 69, respectively. Thus, the Swiss building practices, both standard and efficient types, were more successful in reducing overall energy consumption than those of the U.S.

However, energy performance does not provide a complete picture of overall performance. This is clearly recognized by the fact that we are capable of building highly efficient buildings without regard to cost, but once cost is taken into account a different picture may play out. For example, Koch et al. (2010) calculated which home would be most cost-effective based on cost of construction and annual energy costs. They found that the standard U.S. home would be the most cost effective until year 13, with lower construction costs offsetting energy expenditures for these early years. After this, the hybrid energy star home would be most cost effective until year 43 at which point the Minergie home becomes cost effective. These calculations indicate that more expensive energy-efficient homes can become more cost effective if energy prices were to increase, as may occur in the future. In terms of culture, people in the U.S. tend to move frequently and thus a less expensive home may be cost-effective because they do not stay long enough to experience any of the energy saving benefits that occur down the road. On the other hand, a Swiss home is a once-in-a-lifetime investment therefore it makes sense to purchase a home that is cost-effective over a longer period of time.

It is important to consider the implications that culture will have on the implementation of zero-energy buildings. As was shown above, it will likely be a much smoother transition for those countries that already practice energy-efficiency as a standard in their construction practices to move towards zero-energy. It may even be less costly, since the building industry in these countries is already familiar with green technologies and there is consumer demand to push the market. On the other hand, cultures such as the U.S. could face additional barriers, especially when you take into consideration that the average home in the U.S. is 50% larger than the average home in all other developed nations. This is also 50% larger than the average homes built 25 years ago in the U.S., despite average household size decreasing from 3.1 people in 1970 to 2.6 people in 2007 (Gray and Zarnikau, 2011). Additionally, a major incentive for purchasing a zero-energy home is the expected payback in terms of the annual energy production. If homeowners cannot justify making that long-term investment, they may opt for less efficient homes that are more cost-effective in the short run. This may be the case in the United States given the fact that 50.2% of homeowners had only been in their house 10 years at the least, while 27.6% had been in their homes for 20 years (U.S. Census Bureau, 2007). Thus, it's necessary to keep in mind barriers that are presented by our current paradigm and how we may overcome these given the accelerating pace of research and development into new cost-optimal designs of zero-energy homes.

Lastly, in understanding our current paradigm and how we can make the transition to zero-energy, further barriers and challenges to implementation need to be considered. In their book, "*Getting to Zero: Green Building and Net Zero-energy homes*" Gray and Zarnikau (2011) identify some additional key barriers. The most obvious and the one that this thesis will be addressing is the initial cost of the home. It's generally the case that the most efficient technologies require premium initial costs and this will be reflected in the total price of new, zero-energy homes. Additionally, the on-site renewable technology that is needed to reduce net consumption is presently (and will remain for some time) more expensive than purchasing power from the utility grid. Nevertheless, there are many ways in which this barrier can and is being addressed. It also remains to be known exactly how much of an increase in cost zero-energy homes will have compared to a similar conventional home.

Technological Feasibility

With advancements in new building technologies and efficiency gains, zero-energy homes are no longer a thing of the past. There are many combinations of materials and technologies that can be used to construct a ZEB, which are usually reflective of the type of ZEB being built. With many different possible configurations and variables, it is often hard to know beforehand whether the ZEB being designed will perform in the real world as expected. Since this is a relatively new concept and not many ZEBs have been built, it is often argued that the technology hasn't caught up yet. This is in fact untrue. While much of the research relies on modeling and simulation software, mainly because of the high costs of construction, there still exists research on the construction and monitoring of experimental ZEBs or highly efficient near zero-energy buildings (NZEBs). The examples of these types of homes are being built and monitored with the goal of learning the best and most optimal designs. It has been these experimental and simulated cases that have provided much of the current measured and predicted data. Thus, it is in this section that a number of these homes and buildings are highlighted in order to display the capabilities and feasibility of ZEBs.

In terms of large-scale developments, there have been several projects, which are highlighted in Gray and Zarnikau (2011). "Solutions Oriented Living" development is a housing development in Austin, Texas designed by the firm KRDB. It is a mixed-income development with the goal of building homes that generate as much energy as they draw from the grid. The main technologies that allow for this are passive ventilation and day lighting, thermally efficient windows, structurally insulated panels for the framing system, modular construction, geothermal heating and cooling, and of course, PV panels. Also in Texas, “Discovery at Springs Trails” claims to be “Houston’s first solar powered hybrid community”(Gray and Zarnikau 2011, p. 247). This project utilizes whole house energy efficiencies and solar power to guarantee that energy bills will be lower than comparable energy star homes. Some homes are even equipped with battery storage capable of discharging for several hours at 2 kW. The first homes in the development will be equipped with GE energy monitoring dashboards to monitor their energy and water use. In Boulder, Colorado, “ Solar Village Homes” are near zero homes that utilize passive solar design, Icynene foam insulation, fiberglass windows, solar hot water, and have PV panels on the roof. Based on modeling, the design team estimates that these condominiums will save 67,400 kWh a year of electricity. In Chicago, the EcoPower Project designed zero-energy plans with hopes of creating affordable low-income housing. To do this they designated the homes as residential solar generation stations in order to utilize renewable energy credits. They had proposed 100 homes, but only seven were built. Nevertheless, these achieved 67% energy efficiency, with 33% of that coming from solar power. Separately, “Premier Gardens” in Sacramento, California, is a 95-home zero-energy community, which exceeds California’s Title 24 energy cooling requirements by 50% and utilizes PV, a tankless water heater, mechanically designed heating and air conditioning, spectrally selective glass windows, and tightly sealed air ducts. Overall, these homes are expected to save $600 more than the average U.S. homeowner in energy bills. Lastly, in Germany, the “Solar Settlement” is a housing community where all the buildings produce a positive energy balance, thus they are all net zero. These buildings were built between 2000 and 2005 and use a tenth of the energy of a conventional house. The extra energy they produce through their PV array is sold back to the citywide grid.

These examples from Gray and Zarnikau (2011) display that the technology is here and, in some instances, is being implemented by innovators in production homes. However, as the examples indicate, those in the United States are working towards net-zero, but have yet to make the leap. Effort is being made here in the U.S., but not on the same scale or as precociously as in places like Germany's Solar Settlement, However, this may simply be due to market barriers that have yet to be overcome. The National Renewable Energy Laboratory identified three levels of market maturity and risk reduction that it suggest needs to be reached before ZEH technology can be successfully implemented by builders, contractors, and homeowners (Anderson and Roberts 2008). First, the technology must meet minimum builder, contractor, and homeowner performance and reliability requirements. Second, the design, construction, and commissioning details for integrating the new technology into homes need to be understood and validated across the board. Lastly, field training, quality assurance/control, commissioning, and operations/maintenance requirements for the technology must be integrated into the process of production building. This would ensure that potential savings and benefits could be achieved once the technologies are broadly implemented. Whatever barriers remain in the U.S., the fact remains that we can build and operate homes at net zero-energy.

Apart from the above examples, several studies have been done all around the world to determine the feasibility of ZEBs and to measure their actual performance. They provide invaluable information and at the same time shine light on areas where information or technology is lacking and areas where we need further research. One study explores the feasibility of a 110m^2, two-bedroom, single-family ZEH in the mild climate of southern Europe, utilizing solar as its renewable energy source (Carrilho da Graca et al. 2012). This study used dynamic thermal simulation for two representative house designs in order to size solar thermal and PV collector systems that would meet the annual energy needs. They found that the initial increase in cost was between 11% and 22%, with a payback time of 13-18 years. Thus, the study found that, for a southern European climate, a ZEH is feasible with a moderate increase in initial cost. However, they also found that the size of the PV system varies by a factor of three depending on the efficiency of the building and electrical appliances used. This shows how important efficiency is when it comes to the design process, and this extends to efficient appliances. Lastly, they calculated a payback taking into account a micro-generation subsidy and found that it could possibly lead to a faster payback in the range of 8-10 years. In terms of incentives, subsidies can help considerably for both the builder and homeowner.

Another study was done in the United Kingdom to investigate the feasibility of ZEH and provide specific design methods to achieve the zero-energy goal (Wang et al. 2009). This study relied on computer simulations of building systems to model zero-energy house design. EnergyPlus was used to model hourly energy consumption and for building envelope design while TRANSYS was used for building systems and renewable energy systems design. They found that it is theoretically possible to achieve ZEH in the

UK. The annual electricity generated is expected to be 7305.9 kWh, with the energy consumption being only 6008.9 kWh. The remaining electricity could be used to charge an electrical vehicle or to sell back to the grid, which, through net metering, is now becoming widely available. This study, not only showed that is was theoretically possible; the authors also identified several solutions for U.K. house design that are particularly suited for that region and that climate. As part of this process, they recognized three steps that need to be considered: analysis of local climate conditions, application of passive and advanced designs to minimize load requirements, and the use of modeling software to investigate various mechanical and renewable energy systems.

In Australia, there has been research conducted from actual measured data from an off-ground detached family home in southeast Queensland. Miller and Buys (2012), described their energy goals as the "triple bottom line of sustainability": economic (self-sufficiency, resilience, adaptability), environmental (passive solar design, low embodied energy), and social (thermal comfort, universal design). The house easily meets the annual net energy balance with a total energy consumption of 1.8 MWh and a total renewable energy electricity generation of 2.77 MWh, thus making this a net-positive energy home. With Australia's "Solar Bonus Scheme," which pays $0.44/kWh of electricity exported to the grid, the house actually makes money. Rather than paying the average annual electricity cost of a Queensland resident of $1600, they make a net income of $829. Considering that the local electric prices have increased nearly 50% from 2007-2010, this household is relatively unaffected. If it continues in this direction, the economic benefit of energy efficiency, renewable energy, and ZEHs will grow over time.

In the United States, research is also being conducted across the varying climatic regions. In Las Vegas, a study was conducted looking at the energy and economic performance of a conventional house versus a ZEH (Zhu et al. 2009). Two identical floor plans were built side-by-side. One used conventional methods meeting minimum requirements for building codes, and the other was built utilizing energy efficiency technologies and solar applications. It was found that four items have a competitive cost of electricity compared to the commercial rate, i.e., high performance windows, compact fluorescent lights, air conditioner with water-cooled condenser, and a highly insulated roof. In the desert climate of Las Vegas, with high solar radiation, the use of high performance windows is the best for energy savings and it offers a fast payback. Roof mounted PV tiles allow the ZEH to have a net zero electricity consumption on an annual basis and with rebates can be more cost-effective. They found that thermal mass walls would provide better insulation but are too costly to be competitive in the market. Although they used real houses for their study, they still relied on ENERGY10 and eQUEST3.6 for simulations of energy utilization. The climate data were also collected at the site in 2006, but they employed TMY2 data as well.

Separately, but also in Las Vegas, a study was done to simulate the energy consumption of the heating and cooling loads of two residential homes and compare these results to actual experimental results (Madeja and Moujaes 2008). Trace700, was the software used for simulated data. The two homes were identical, except one is a ZEH with the latest technology and the other a baseline of common construction practices. During their testing phase, the homes served as model homes, to be unoccupied, but subject to foot traffic from visitors. The goal of the study was to see whether a widely used building load and energy analysis software package could accurately predict the energy consumption of two constructed homes in heating and cooling. They also looked at comparing the differences in energy consumption between the two homes. What they found was that although Trace700 had some over-and-under predictions based on the day-by-day simulations, it was quite accurate for the entire monitoring period, with a range or error being between 2% and 11%. While this study was primarily concerned with comparing the simulated data with real data, it shows that the modeling software designed to simulate energy performance can be a reliable and useful tool on the path towards designing ZEHs. Since it is extremely costly to build homes for research purposes, it is absolutely essential that we have accurate and effective technological resources, such as these widely used models.

Most of the previous examples have been cases of warmer or mild climates. However, ZEHs are and can be built in areas where one might not expect. A study done in Denver, Colorado shows the performance results from a 1280 ft^2, three-bedroom ZEH (Norton and Christensen 2008). This ZEH was the result of collaboration between the NREL and Habitat for Humanity and was designed using an early version of the BEopt building optimization software. To exceed the net zero goal, it utilized envelope efficiency; efficient equipment, appliances, lighting; a PV system; and solar thermal features to exceed the net zero goal. From April 2006 to March 2007, the home's 4kW PV system produced 5127 kWh of electricity and only used 3586 kWh of electricity and 57 therms of natural gas. Overall, it produced 24% more energy than it used. They found that the most difficult design challenge is sizing a PV system to achieve net zero when the majority of energy used is dependent on plug loads, which are dependent on occupant choices and behavior. Thus, if someone likes to maintain their furnace at 70 F°, rather than 65 F°, this could have an impact on the net-balance regardless of design. The authors also note that the economics of excess annual PV production is dependent on net metering agreements and thus ZEHs will be more cost-effective in areas where utilities offer reimbursements for exported electricity.

Net zero-energy homes are also being built in Massachusetts, by a production builder who has been building them since 2008 (Bergey and Uneo 2011). The builder is currently working on multiple, small-scale subdivisions of 20 or more houses, utilizing solar, super-insulated, double-stud above grade walls, triple-glazed, low-emissivity krypton-filled windows; and very high airtightness. The homes range from 1100 to 2600 ft^2, with one to two stories, and all have roof-mounted PV systems. In terms of fuel selection, they utilize solar and natural gas. Based on the Building America Benchmark assumptions of hot water and appliance use, using gas saves more than $350 a year relative to electric heating. Two-thirds of this savings is in water heating, with the other third being split between cooking and clothes drying. This large energy and costs savings, due to avoiding electric heating, often supports installing gas appliances wherever feasible. However, it is noted that some designers have preferred to steer away from gas combustion appliances, believing that their present advantage in reaching net zero will eventually fade away as grid electricity is increasingly produced by renewables. While this could eventually occur, as of now, natural gas has provided a stepping-stone for cost-effective zero-energy homes.

As is seen in the above examples, these homes are being built using today's technology. Some are being built for the purpose of research, while others are being built by innovative green builders. In both cases, it is clear that we are beyond questions of technological feasibility; what remains to be investigated lies within the realm of cost-effectiveness. Now that we have the technology and it can meet our goals, we need to figure out the least-costly way to implement these technologies. It may be some years before we see net zero-energy homes being built on a production scale, but it will not be because of a lack of available technology. Perhaps the biggest challenge to overcome is how to make widely available the information and tools that are already out there.

In the United States, the Department of Energy is the federal agency heading much of the research in this area, with its Building America Program, whose goal is to demonstrate how cost-effective strategies can reduce home energy use by up to 50% for both new and existing homes, in all climate regions by 2017 (Bianchi 2011). As part of this process, the DOE have developed the Building America House Simulation Protocols, which are aimed at assisting researchers in tracking the progress of multi-year energy reduction against specific research goals for new and existing homes. These protocols come preloaded in the Building Energy Optimization (BEopt) software tool, developed by the NREL to help create market-ready energy solutions that improve the efficiency of homes on the path towards net zero. This specialized computer program is designed to identify the most optimally efficient designs at the lowest possible cost. It is technologies like this that will become invaluable in helping the building industry become aware of how to build zero-energy homes cost-effectively. Without being able to accurately predict how much a ZEH will cost and how it will perform, the risk associated with ZEHs may be too high for the building industry to consider.

In sum, the literature on zero-energy homes is still lacking in key areas. This becomes clear after taking into account the literature as a whole. There is a general consensus as to what a "zero-energy home" would require depending on ones objective. There are also several working definitions with more likely yet to come. From the literature, one get's a sense that we have grasped the technology and can build zero energy homes relatively easily. However, what is lacking is the need for more data and information, particularly on the sides of the consumer and producer, i.e., the homebuyer and homebuilder. They need to know what it is going to cost to build and operate this new breed of homes. At what cost can the homebuilders build an energy-efficient home, and what information do they need to provide the homebuyer to make them understand the increase in costs due to energy efficiency measures. Oftentimes, a homebuilder just complies with new building codes, generally increasing energy efficiency, but with no regard for the homeowner's awareness. Perhaps, homebuyers would be interested in purchasing an energy-efficient home if there were options in their price range. It is obvious that these homes will cost more initially, but they do provide a return on investment in terms of money that homeowners will save on lower energy bills, and create an avenue in which we can reduce the carbon footprint of our built environments. As we surpass a global atmospheric carbon dioxide concentration of 400 ppmv, it is becoming increasingly more apparent that a paradigm shift is needed in the building industry. Apart from climate change, however, is the inevitability of rising energy prices. If energy prices rise, as they are expected to, these homes will become more cost-effective the further we move into the future, as well as provide security from unforeseen energy crises. In terms of the homeowner, there are clear incentives for purchasing an energy-efficient home. For the homebuilder, there is room for profit as in any business. They just require the assurance and the cold hard numbers that an investment in this arena will not disappoint. In terms of our government, whose role it is to guide our country's direction, there is an urgency to pass measures that directly address climate change. What better way than to begin with an industry that has a thirst for energy. In determining the cost-effectiveness of ZEHs in Washington, this thesis is attempting to identify, for a given climate, where we stand in terms of incentivizing these homes to both sides of the market. We can build the homes; we now need to know if we can afford them.

Methods

The objective of this research project is to determine the cost-effectiveness of net zero-energy homes and near net zero-energy homes for several locations throughout Washington State. In doing so, it was necessary to develop house designs that integrated energy-efficiency and on-site renewable PV generation that could be successfully used on a production basis. The house designs are location-specific and meant to achieve whole house energy savings for the varying levels of energy efficiency on the path to net zero. In order for these types of innovative building energy technologies to compete viably with conventional homes, it is necessary that they be demonstrated to cost-effectively increase overall product value and quality while at the same time reducing energy use significantly. The research approach taken includes the use of the Building Energy Optimization (BEopt) software to provide cost and performance data for individual house designs. BEopt utilizes a sequential search technique that measures system performance and cost trade-offs as they relate to the whole building energy performance and cost optimization. This includes interactions between advanced envelope designs, mechanical and electrical systems, lighting systems, appliances, plug loads, energy control systems, renewable energy systems, and on-site power generation.

All energy savings in this thesis are defined in terms of source energy, or primary energy, as discussed earlier in the literature review, rather than site energy. This allows for the use of a source-to-site energy ratio, which determines the percentage of source energy that is saved. The energy efficiency measures that BEopt evaluates save more energy than just the amount saved at the site. This is sometimes referred to as "downstream efficiency." For example, if the source-to-site ratio is 3:1, then one unit of energy saved at the site will save three units of source energy. Thus, when PV is added to the home, one unit of electricity produced could offset three units of source energy that doesn't have to be produced from other sources (e.g., natural gas). In order to assess the relative efficiencies of buildings with varying proportions of site and source energy consumption, it's necessary to convert these two types of energy into equivalent units of raw fuel consumed to generate the one unit of energy consumed at the site.

In analyzing the least-cost path to homes that produce at least as much energy as they use annually, we begin with a base case, which is often a current practice building or code-compliant building. This ensures a well-defined reference for the evaluation of energy saving goals. The chosen base case or reference building for this project is the Building America (BA) B10 Benchmark, which was developed by the DOE and NREL (Hendron and Engebrecht 2010). The B10 benchmark, referred to as the Benchmark for this project, is consistent with the 2009 International Energy Conservation Code (IECC). The Benchmark represents typical construction at a fixed point in time so it can be used as the basis for multi-year energy savings goals without the complications of chasing a moving target. A series of user profiles that represent the behavior of a typical set of occupants is used in conjunction with the Benchmark, providing a standard set of occupant behavior as well. Since BEopt, the tool utilized in this thesis, has been specifically developed and tailored to meet Building America's needs, it is the simulation tool recommended for this type of systems analysis. Thus, for each analysis in this project, the reference building will be the BA Benchmark. Given that this research is attempting to compare the cost-effectiveness of ZEHs to a typical conventional home with average energy use profiles, the BA Benchmark seemed appropriate. This is because of the significant research and effort that went into developing a national base case based on the IECC, the primary residential model energy code used in the U.S. Thus, it represents the current standard of energy efficiency in the residential building sector. This works for research in Washington State because it maintains a statewide building code program and has a history of adopting the latest energy codes. In turn, most current conventional homes in Washington have to be built to the IECC standard. To see a complete list of B10 Benchmark Specifications, see the Building America House Simulation Protocols (Hendron and Engebrecht 2010). It is not included here for the sake of space.

In order to evaluate the cost required to reach a specific energy target in BEopt, the energy and cost results can be plotted in terms of annual costs (the sum of utility bills and mortgage payments for different energy options) versus the percent energy savings as shown in Figure 2. The optimal least-cost path can then be determined by connecting the points for building designs that achieve varying levels of energy savings at minimal cost i.e., the cost that establishes the lower bound of results from all possible building designs for a given location. While this type of building energy simulation is often used for trial and error and "what-if" options of building designs, the applications do not stop there. This project uses BEopt in order to generate cost data for a Benchmark building on the path towards zero-energy for several locations throughout Washington. While not intending to build the designs, the software provided cost data for designs that would otherwise be difficult or near impossible to determine.

For each location, BEopt identifies the design with the minimum annual cost that balances investments in efficiency versus utility bill savings. This point could be identified in purely economic terms as the most cost-optimal design; however, there are often other energy savings targets that are important as well. In this case, the focus is on designs that achieve varying levels of energy savings on the path to zero-energy. The method used by BEopt does not currently include models to evaluate the impacts of non-energy market drivers such as durability, reliability, ease of install, local supply availability, warranty callbacks etc. Thus, the data provided is limited to determining the minimum requirement based on marginal cost and energy performance for a given design. An example of the least-cost optimization results are given in Figure 2 (Hendron and Engebrecht 2010).

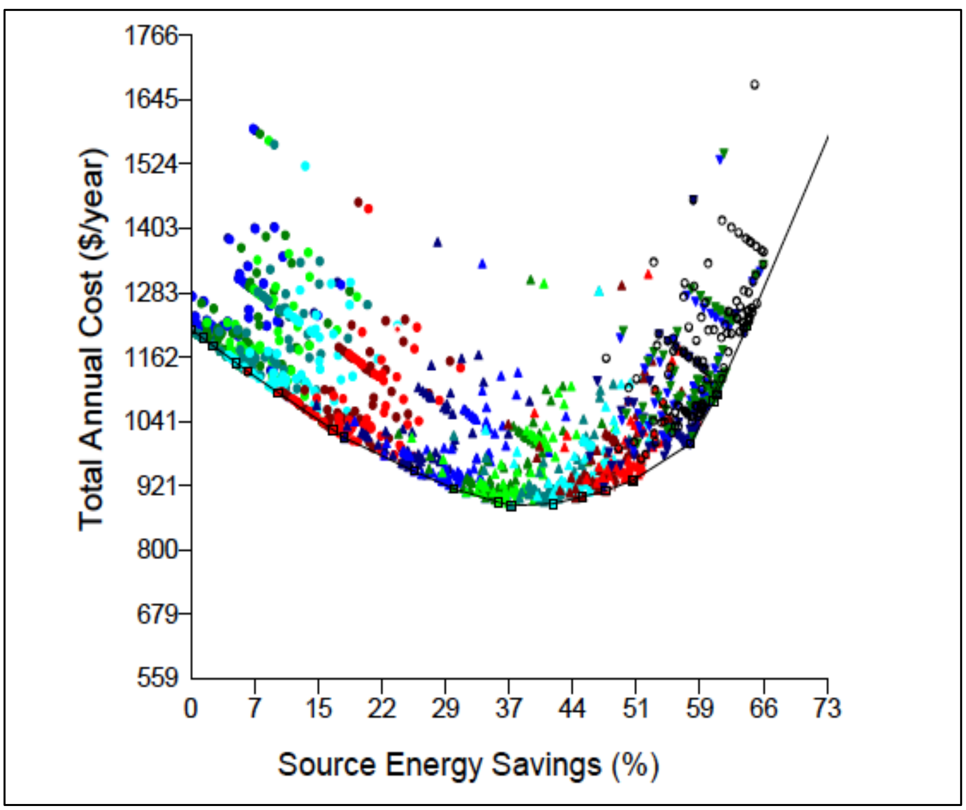

Figure 2. Sample results showing all points in neighborhood of least-cost curve

In the above example, each symbol represents a particular simulation in the optimization search, with different iterations represented by different colors. This allows the user to pick through the results one iteration at a time to see how the optimization progressed. It should be noted that the points on the least-cost curve represent potential performance that can be achieved by homes that are fully optimized in terms of energy cost performance and should not be used as a predictor.

BEopt and Modeling Cost Optimal Designs

In order to deliver zero-energy homes, the barriers between building design, performance, and cost-effectiveness need to be overcome. One of the most effective ways of doing this is through the use of building performance simulation tools (BPS), such as BEopt. Since there are so many options to reduce energy in buildings, it can be difficult to determine which are the most appropriate technologies to implement and/or which are the most cost-effective. Even with the proper tools, designing a ZEH can be a complex, costly, and tedious task with a high level of uncertainty that comes with not knowing the occupant's energy use, for example, or even how climate change will play out. Despite these uncertainties, all sorts of tools are currently available and each offer different capabilities depending on whether they are design oriented (HEED, e-Quest, ENERGY-10, Vasari, Solar Shoebox, Open Studio Plug-in, IES-VE-Ware, Design Builder, ECOTECT etc.) optimization oriented (Opt Plus, Genet, DER-CAM, Homer, BEopt etc.) or a bit of both (Brown et al 2010, Attia and De Herde 2011). Depending on ones motivations or purpose, there likely exists a tool that is capable of helping reach it. With the design goal of zero-energy buildings being mostly performance based, the energy performance goals must be taken into account early in the design process. This is where these tools can offer the greatest support particularly since 20% of the design decisions made early on will influence 80% of the rest of the design (Attia et al. 2012). Thus, being able to predict or model different designs using software tools is absolutely fundamental. While much work is being done to create more useful tools, particularly in the early architectural design phase, the existing tools can be very useful depending on ones purpose.

If an individual is primarily concerned with optimization, that is, a ZEH that is both energy-efficient and cost-effective, then a tool such as BEopt might be the most suitable. There exist other tools that are capable of similar simulation results, however, BEopt is unique in that a major component of it focuses on cost-optimal designs. Thus, if cost is a major motivation for the designer, then BEopt, the freeware developed by the NREL with funding from the DOE, may be the best tool, especially since it is readily available and user friendly. Widely used as part of the Building America Program, BEopt uses the simulation software DOE2 and TRNSYS or EnergyPlus to determine the optimal energy use of a given building design and TMY2/TMY3 for weather data. It provides a consistent method for comparing costs, energy savings, and interactions between large numbers of different combinations of energy saving options that can potentially be used to achieve whole-building energy savings on the path to reaching net zero.

In terms of meeting specific energy-efficiency targets, BEopt is particularly helpful. Since it plots points along the path to net zero, one can determine the percentage of whole building energy savings that corresponds to a reduction in their annual energy costs. Such a plot also shows the incremental increase in costs associated with increase in percent energy savings. Figure 3, from Christensen et al. (2006) shows this conceptually. The X-axis represents the percent energy savings that a home could potentially achieve on the path to net zero, 100% being the achievement of net zero. The Y-axis represents the annualized mortgage payments plus the utilities, which for the purposes of this thesis, refers to only those utilities related to energy e.g., electric and natural gas. The green curve, or cash flow, is the total annual cost of both mortgage and utilities at each level of energy savings. The blue downward sloping curve represents the utility bill costs as a function of energy efficiency. Thus, this graph is essentially showing what happens with increased energy efficiency, particularly for those homes on the path to net zero.

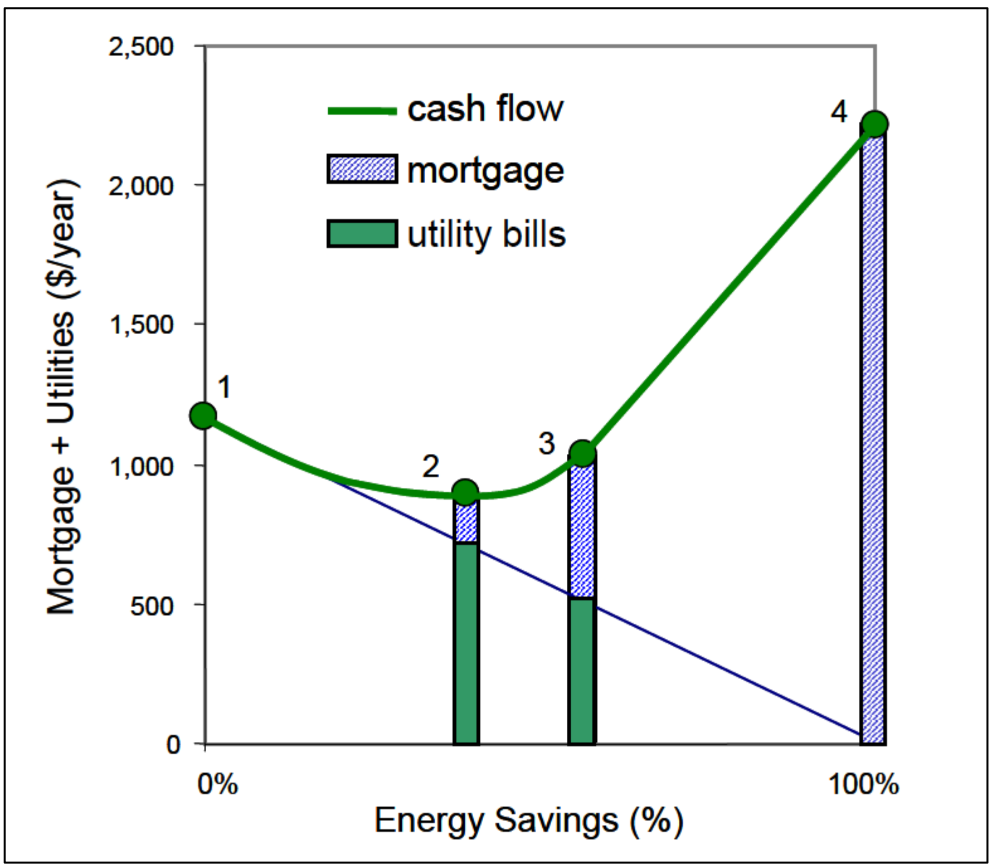

Figure 3. Conceptual plot of the least-cost path to a ZEH

Point 1, on the graph, represents the reference building. That is, a building that is a user defined base case or a climate specific Building America Benchmark building that is generated by the BEopt software. Often times, the reference building will be a conventional home built to the current building codes for that region. Point 2 represents the least-cost point on the path towards zero-energy. Here, one is able to achieve a lower annual cost compared to the reference building by making efficiency gains that result in lower energy bills. The increase in cost, due to beyond code changes is reflected in a higher mortgage payment, but still results in a lower cost than the reference. Point 3 represents higher energy savings; lower utility bills, but a slightly higher mortgage than points 1 and 2. This point results from implementing additional efficiency gains from point 2 until the marginal cost of energy savings equals the cost of producing PV energy at point 3. After point 3, there is a constant increase in "cash flow", or combined utility and mortgage, until a home reaches net zero. This is because, after point 3, it is just a matter of adding additional PV or renewable energy generation until zero-energy is achieved at point 4. Thus, the additional increase in cost due to achieving additional energy savings becomes reflected in a higher cash flow, although corresponding with a constant decrease in utility bills. When the net zero point is reached, the home no longer has any utility bills but is subject to the highest mortgage rate of all. What is not represented in this graph is the cost-savings over the life of the home, which, if total utility savings are taken into account, could result in a home of comparable cost-effectiveness to that at point 1. The difference would be that instead of paying utility bills every year, the owner would pay a higher mortgage that incorporates the initial increase in costs, but would enjoy a partial return on that investment in the form of energy savings. One could also think of it as paying the utility bills 30 years in advance. There are additional benefits, other than costs, such as reduction in green house gases, but these can be difficult to quantify. Nevertheless, if these benefits could be quantified or if a carbon tax were to be implemented, then one could realize a faster return on investment than they would through energy savings alone. Figure 3 essentially represents what the BEopt software is capable of doing by determining building energy optimization for every possible point along the curve.

There are two types of energy optimization - global and constrained (Christensen et al. 2006). If the goal were purely economics, then energy optimization would be about finding the global optimum. This is the minimum annual cost that balances investments in energy efficiency with utility bill savings (point 2 in Figure 3). On the other hand, there can be reasons other than economics to target a specific energy savings goal. With a target in mind (e.g., 50% efficiency) economic optimization can be used to determine the optimal design to achieve this target. This type of constrained optimization can be used for any target on the path to zero-energy and, in terms of policy, could help establish what an optimal path would look like. It is also advantageous for the optimization process to include multiple solutions for optimal and near-optimal designs. Near-optimal designs achieve the zero-energy goal or another level of energy savings with the total costs close to, but not at, the optimal design total cost. Given the uncertainties that are embedded in cost assumptions and energy use predictions, near-optimal points could be as good as optimal points, in terms of being within a similar range. These designs are identified in BEopt and could be used for a variety of non-energy and cost reasons.

Although BEopt's design purpose was to find optimal building designs along the path to zero-energy, it is also meant to accelerate the process of developing these high-performance building designs in an effort to move towards a cleaner and more sustainable future. As we tackle this challenge, more advanced tools will be needed and BEopt happens to be one of these. Figure 4 provides a basic diagram of how the BEopt software utilizes established and well-known simulation engines such as TRNSYS and DOE2 (Christensen et al. 2006). For example, TMY2 weather data are needed for each given location, which are then used by TRNSYS to run simulations for PV generation based on the inputs in BEopt. DOE2 is used in a similar way, but uses the weather data to generate heating, cooling, lighting and appliance requirements based on BEopt inputs. All together, they can systematically provide optimal zero-energy home designs.

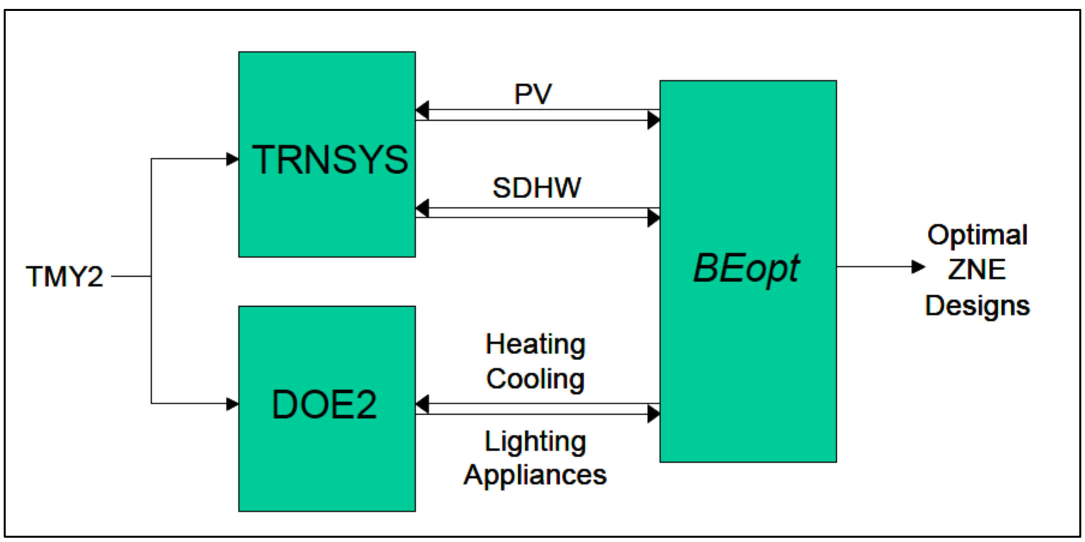

Figure 4. Optimization with multiple simulation programs

The software includes a main input screen that allows the user to select, from many predefined options (Building geometry, PV system parameters, economic parameters, and energy savings options), which are then used in the optimization. The options are intended to represent readily available products and construction techniques and have a first cost and lifetime cost associated with them. Costs are retail and include national average estimated costs for hardware, installation labor, overhead, and profit. The lifetime for building construction options is assumed to be 30 years but, as with everything, this can be user defined (Christensen et al. 2006). It also includes an output screen that allows users to display their results for many optimal and near optimal designs. Lastly, it includes an options library spreadsheet, where the user can review and modify the information on all available options, such as cost assumptions, etc.

Utilizing the above simulation engines, BEopt automates the process of identifying optimal designs, using a sequential search technique. At each step along the path, BEopt runs a series of simulations incorporating every user-selected option, one at a time, and searches for the most cost-effective combination of options. This technique has several advantages. First, it is able to find the intermediate optimal points along the path. These are the minimum-cost designs for different energy savings targets and not just the global optimum. It also utilizes discrete, rather than continuous, building options, thus providing realistic construction choices. Lastly, it is able to provide multiple near-optimal designs that are identified at each energy-savings level, which provide alternate designs close to the optimal. BEopt is also capable of up to 20 user-defined cases in a single project file. These can be used to analyze building performance as a function of climate and thus location. Cases could also be used to study how building performance is affected by different economic parameters, such as fuel costs. Multiple cases are also useful in determining PV systems for a given design, different heating, windows, or any options selected for optimization.

There are several published reviews of the BEopt software with it being regarded as having a high accuracy rate because of its reliable and well-known simulation engines as well as its sequential search technique. (Attia and De Herde 2011). Attia and De Herde (2011) analyzed several simulation tools and rated them according to their Intelligence, Interoperability, process adaptability, and accuracy. BEopt had a low rating for interoperability, because it has its own built-in-3-D modeler, without any exchange with CAD, gbXML, BIM, or other drawing tools. This limits it to certain building geometries, but as a tool for residential homes, this limitation may not be a big concern for most users. They rated BEopt as having medium intelligence and usability as well as a high process adaptability. Intelligence mainly refers to its function capacity while process adaptability is the ability to support different levels of data. A separate study also analyzed several tools for optimization and found that BEopt is currently the most effective tool, in terms of achieving quick optimization for both efficiency measures and different renewable alternatives for various building types (Brown et al. 2010). The hurdles BEopt faces are that it is used solely for residential buildings and utilizes only solar applications as its renewable energy source.

Lastly, BEopt was mentioned in a report by the Federation of American Scientists on the "America Clean Energy and Security Act of 2009" (Talapatra 2009). This bill, also known as the Waxman-Markey Bill, did not pass, but had the goal of achieving 30% reduction in energy use in new buildings compared to the IECC 2006 baseline code by 2010. It also targeted 50% by 2014, and 5% for every additional three years following, with an end goal of net zero-energy. The report mentions BEopt as a critical tool that could help developers meet targets such as these. The paper even suggests a portable

BEopt application that could have been used by building inspectors to examine the cost-effectiveness of making specific changes to a building's design had these codes been passed. While the Waxman-Markey Bill did not pass, these targets will eventually be set and BEopts potential will likely be realized.

BEopt Inputs

BEopts method of analysis is capable of including any system option or component whose performance can be defined in the context of EnergyPlus or DOE2 and TRNSYS and for which first costs, installation costs, operation and maintenance costs, and replacement costs can be specified over a 30 year life span. For this project, Energy Plus was used as an alternative to the DOE2 and TRNSYS simulation engines, for the simple reason that it required only one additional piece of software. As is the case in any analysis, the results are subject to the assumptions used during this project. For the purpose of evaluating the cost performance tradeoffs for different energy performance targets, costs and performance for a range of currently available production building materials and components were used.

The same building characteristics were used for each location throughout Washington State. It was a simple two-story, 2496 ft^2 residential building with an attached two-car garage (see Figure 5).

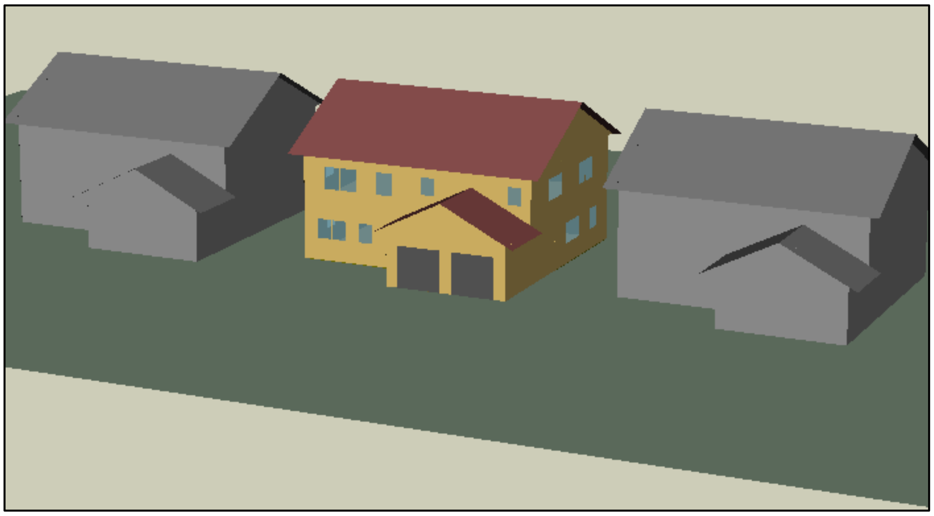

Figure 5. Graphical representation of the modeled ZEH

The building was modeled with a foundation typical of the Washington climate; slab on grade for the attached garage and a four-foot ventilated crawlspace for the rest of the living area. The building has two-foot eaves. Window area is assumed to be 15% of floor area and is distributed with 20% on the front and sides and 40% on the back of the house. Adjacent buildings, 15 feet to the north and south provide shading of sidewalls. This study was limited to an Eastern orientation for each location (i.e., the compass direction of the front door). Other orientations may have an impact, however, they were not considered due to modeling time constraints. The heating set point was set at 71 degrees F, while cooling set point was set to 76 degrees F. Humidity was constant at 60%. These are the Benchmark heating and cooling comfort requirements that were assumed to model each home on the path to net-zero.

The energy options considered in this study include space-conditioning systems (up to SEER 24.5 i.e., seasonal energy efficiency ratio), envelope systems, hot water systems, lighting systems, major appliances, and residential PV up to 8 kW (see Figure 6). No options that contribute to miscellaneous electric loads other than major appliances were included. This is allows the same usage for all homes. The homeowner's costs calculated for this project assumed a 30 year mortgage at 7% interest rate with a 3% general inflation rate and 3% discount rate. No maintenance costs were used in this study assuming all inputs have a lifetime of 30 year. The occupancy and operational assumptions are defined in the Building America Benchmark and include time-of-day profiles for occupancy, appliance and plug loads, lighting, domestic hot water use, and ventilation. All results are calculated relative to a base case or reference building for each location. This reference building, known here as the Benchmark, defines wall, ceiling, and foundation insulation levels as well as framing factors, window areas, U-factors and solar heat gain factors, interior shading, overhangs, air infiltration rates, duct characteristics, and heating, cooling, and hot water system efficiencies. The Benchmark represents standard building practices for the given location.

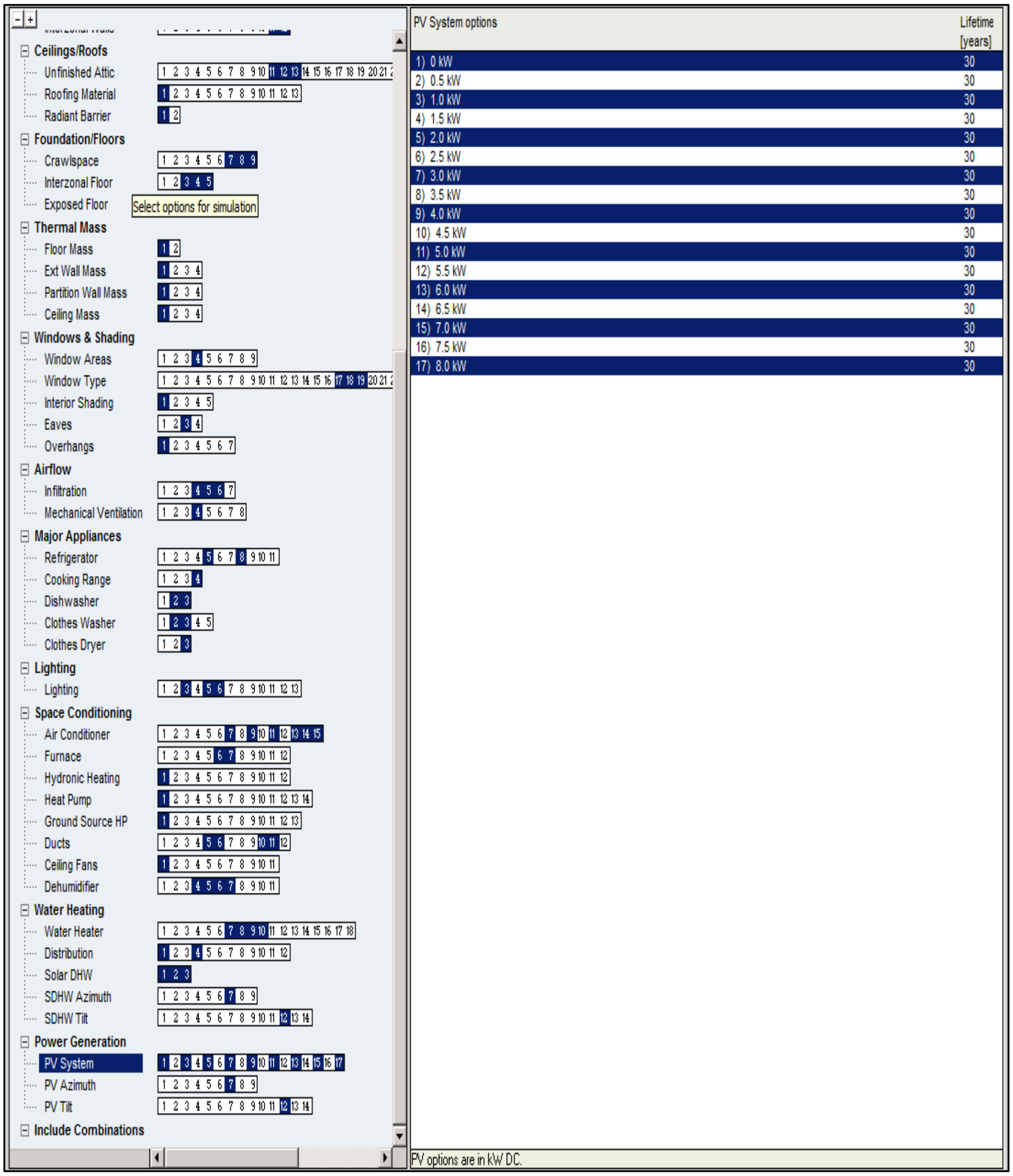

Figure 6. BEopt input selection screenshot

Each option has an assumed initial cost and lifetime cost. Costs are retail and include national average estimated costs for hardware, installation labor, overhead, and profit. Some costs are input as unit costs that are multiplied by a category constant. For example, ceiling insulation cost is an input measured per square foot and automatically multiplied by ceiling area. Other cost inputs are energy option specific such as the cost of solar water heating systems. Additional inputs are based on total costs e.g. the cost of wall construction with different insulation values. This can be done because BEopt will calculate the difference between the option costs. Construction costs are based on average national cost data. Windows and HVAC systems are based on quotes from the manufacturer's suggested retail price. All building construction options are assumed to have a 30-year lifetime, which is the typical span of a mortgage. Equipment and appliance options typically have a 10 to 15 year lifetime and lighting options are based on the cumulative hours of use.

Utility costs are assumed to escalate at the rate of inflation, so they are constant in real terms. The mortgage interest rate is 4% above the rate of inflation. The on-site power option used was a residential PV system, up to 8 KW, with installed cost of $5.50 per peak wattDC, including value of operation and maintenance costs. This cost is independent of PV system size. Additional costs that might be associated with mounting large PV systems were not taken into account. Natural gas is assumed to cost $1.19/therm, which is taken from the state average. Electricity costs were also taken from state average and are $0.07/kWh. The cost data was based on the latest EIA data, which BEopt updates with each new release. The costs estimates used from BEopt do not include the initial costs required to reengineer home designs, state and local financial incentives and rebates, or hidden costs, such as warranty and call back costs that are not accounted for as part of the operational and maintenance costs.

In order to provide an assessment of the differences between location and weather patterns throughout Washington State, system optimizations were run for nine locations - Seattle, Bellingham, Fort Lewis, Olympia, Whidbey Island, Spokane, Yakima, Port Angeles, and Walla Walla. Locations were chosen from a list of available TMY3 weather data for Washington State with an emphasis on choosing a variety of localities from every corner of Washington (Figure 7).

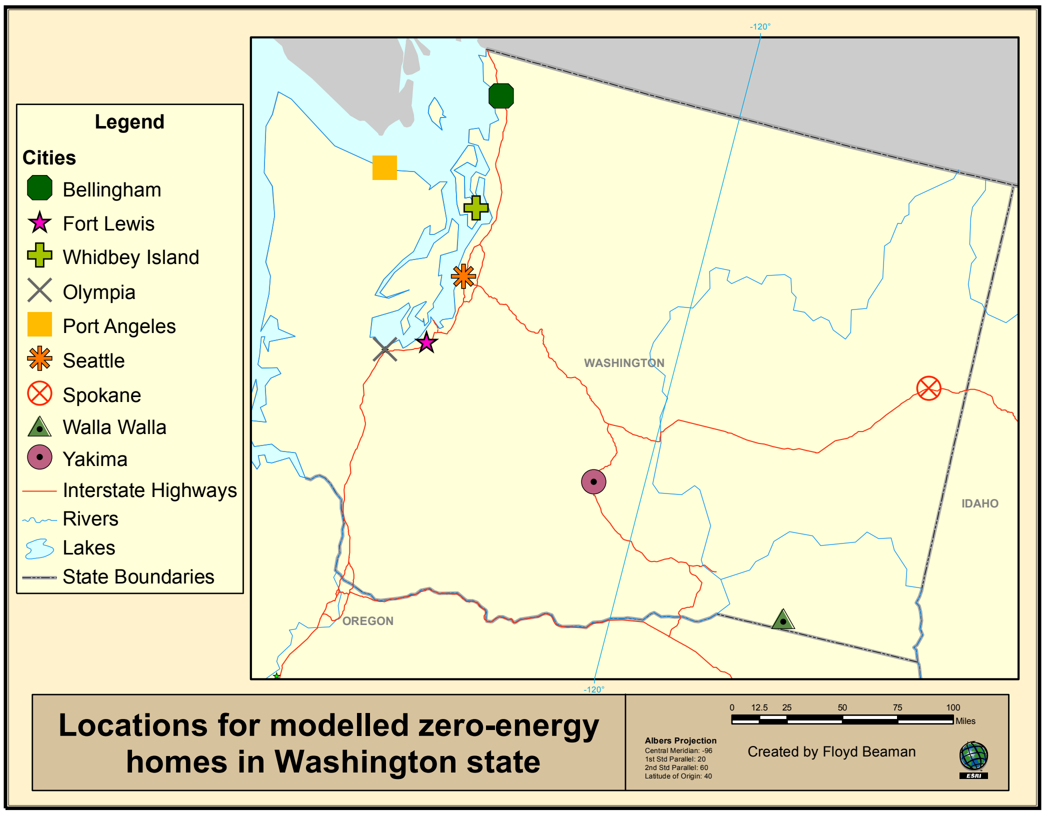

Figure 7. Locations for modeled zero-energy homes in Washington State

Cost-Effectiveness Analysis and Return on Investment

Cost-effectiveness analysis (CEA) refers to the evaluation of specific alternative interventions in which costs and consequences are taken into account in a systematic way. It is most often used as a decision-oriented tool, in that it is designed to ascertain which particular intervention will be the most cost-effective, i.e., the most economical based on the tangible benefits produced by money spent. For example, there are many alternative approaches for pursuing such goals as production-scale net zero-energy homes or even a minimum level of home energy-efficiency. These could include the adoption of new building codes, new building materials and technologies, educational training, computer and modeling assistance, and so on. One cost-effective solution to this challenge is to determine the costs and effects of building zero-energy homes for alternative locations throughout a given region, in this case, Washington State. In doing so, we can then determine which alternative shows the greatest impact of achieving a cost-effective zero-energy home and determine whether any of the alternatives are cost-effective compared to doing nothing at all, which is here referred to as the null alternative. That is, rather than building a zero-energy home, what would the costs and effects be of building a new, up-to-code, production home compared to that of a ZEH?

Cost-effectiveness analysis is very similar to cost-benefit analysis (CBA) in that they both represent economic evaluations of alternative resource use and measure costs in the same way. However, they differ in that CBA is used to address only those types of alternatives whose outcomes can be measured monetarily. This means that all costs and benefits are monetized and everything is essentially translated into dollars. However, CEA focuses on non-monetary outcomes, which is why it is so prevalent in the health sector where risk reduction, changes in health status, weight loss, etc., are primary goals that are difficult to monetize. Thus, the difference between CBA and CEA depends mostly on what is being measured, with CEA looking at the incremental cost per unit of effectiveness for each alternative rather than the ratio of benefit to cost and return on investment.

The purpose of cost-effectiveness analysis is to determine which alternative or combination of alternatives can achieve a particular objective at the lowest cost. The underlying assumption is that the different alternatives have different associated costs and different effects. By choosing those with the least-cost for a given outcome, society can use its resources more effectively. The resources that are saved through using more cost-effective solutions can be devoted to expanding other goals or to other important social endeavors. In this project, CEA is used to first compare the cost-effectiveness of several ZEHs throughout Washington to that of the null alternative, which is the Benchmark. In determining the cost-effectiveness of ZEHs compared to the Benchmark, one can determine the potential cost-effectiveness of building these homes presently. Additionally, the alternatives can be compared to each other, in order to determine which of all the alternatives is the most cost-effective.

There are varying techniques for doing cost-effectiveness analysis, however, the basic technique has been to derive results for effectiveness of each alternative using standard evaluation procedures or studies and to combine such information with cost data that are derived using the ingredients approach. The ingredients approach was developed to provide a systematic way for evaluators to estimate the costs of social interventions (Levins and McEwan 2001). The general idea is that every intervention uses ingredients that have a value or cost. If the ingredients can be identified and their costs can be ascertained, we can estimate the total costs of the intervention as well as the cost per unit of effectiveness, benefit, and utility. The ingredients approach goes by other names in the literature on cost analysis and may sometimes be referred to as the "resource cost model." Nevertheless, both require that each intervention or alternative be exhaustively described in terms of their ingredients or the resources that are required to produce the outcomes that will be observed. Thus, all ingredients must be carefully identified for purposes of placing a value or cost on them. In this particular project, BEopt allows us to choose which ingredients we would like to use in our simulations as well as the optimal ingredients for a home on the path to net zero. It also provides us with cost data for each ingredient or input, such as the costs of different water heating systems or different HVAC systems. In this regard, BEopt allows one to model designs on the path to zero-energy and thus identify the ingredients that change along the way as well as the costs. It is also able to provide effectiveness results in terms of the percentage of energy saved compared to the benchmark. Thus, we can determine the cost-effectiveness of each alternative by relating the total cost to that of the effectiveness, or in this case, the percent of energy saved.

This is done using, what is termed, the cost-effectiveness ratio, which can be obtained by dividing costs by units of effectiveness:

$$\text{Cost-Effectiveness Ratio} = \frac{\text{Total Cost}}{\text{Units of Effectiveness}}$$

Units of effectiveness are simply a measure of any quantifiable outcome central to the objective of the project. For example, in the case of mandating air bags in cars, one could use the number of lives saved as the unit of effectiveness (Wholey et al. 2010). Using the formula above we could generate a cost-effectiveness ratio that would give us dollars per life saved. One could then compare this ratio to the cost-effectiveness ratios of other transportation safety policies, to determine the most cost-effectiveness in terms of lives saved.

It is ordinarily the case that the focus in a CEA is on one primary outcome; however, CE ratios can be calculated for additional outcomes as well. For instance, in this project, CE ratios are calculated for nine zero-energy home locations throughout Washington State, each with 10 outcomes. The objective here is to compare the CE ratios of building a home along the path to net zero to that of building a conventional or status quo home i.e. the Benchmark. Thus, CE ratios are also calculated for 10 outcomes, including the Benchmark. That is, in addition to looking at the cost-effectiveness of ZEHs (homes with 100% energy savings), this project is also interested in determining the cost-effectiveness at different points along the path to zero-energy. So, CE ratios are calculated for each location given designs with outcomes of varying percent of energy savings. This allows us to compare the cost-effectiveness of different outcomes rather than just looking at complete ZEHs. These different outcomes of energy saved also serve as a measure of effectiveness. Since the ultimate objective is to reach 100% energy savings or net zero, determining the cost per unit of energy saved provides us with a valuable measure by which we can understand the current cost-effectiveness of ZEHs.

Once the ingredients have been identified and the associated costs and measurements of effectiveness have been quantified, it is important to discount costs and obtain present values. It is also important to recognize that by purchasing a home that is more efficient than the Benchmark, an individual will be spending more money upfront for the energy-efficient technology. While they will receive a payback in lower energy bills, they pay more now than they would by purchasing a Benchmark home. Since they will not have that money to spend in other ways, an opportunity cost incurs when purchasing a ZEH that should be recognized in the analysis. The idea is that even without inflation, $100 today is worth more to a person than the same $100 promised to that person one year from now, and much more than the same $100 promised ten years from now. The reason is that that money has an opportunity cost. One could take that same money and invest it to receive more money in the future; how much money would depend on the interest rate and many other factors. This could be said about all costs and benefits. People have a tendency to value costs and benefits incurred today more than those that they may incur in the future. This is generally why many people purchasing new homes opt for the Benchmark, where they can receive a new home at the lowest cost while still being up to code. The reason is that the cost of the ZEH results in a higher opportunity cost in the present, while at the same time, offering future benefits with a lower present value. In order to include this concept in the analysis, all monetary values are converted to their present value, or the equivalent value at the beginning of the project, or year one. Instead of using an actual interest rate, CEA uses what is known as a social discount rate (r), for example 0.03 or 0.06. The discount rate is meant to reflect society's impatience or preference for consumption today over consumption in the future. This can sometimes be considered a barrier to entrance into the market.

In CEA, the costs of the project is used as the numerator in the cost-effectiveness ratio. To do this, all the costs are aggregated in each year, with each years costs as C_t where *t* indicates the year from one to T or the last year in the analysis. In this case, "T" would be at the end of the 30-year mortgage. The values in each year need to be converted to their year 1 equivalent, which is done by dividing C_t by $(1+r)^{t-1}$. For example, using a 3% discount rate, $1,000 in costs accruing in year 4, would be converted to present value by dividing $1,000 by $(1.03)^3$. Summing the present value of the costs in each year, the present value of costs (PVC) is obtained for the whole project, as indicated in Figure 8 (Levin and McEwan 2001):

$$PVC = C_1 + \frac{C_2}{(1+r)^1} + \frac{C_3}{(1+r)^2} + \ldots + \frac{C_r}{(1+r)^{r-1}} = \sum_{t-1}^{T} \frac{C_r}{(1+r)^{t-1}}$$

Figure 8. Present value cost formula

The PVC is then used to calculate the CE ratio that was mentioned above.

It is important to note that an appropriate discount rate is critical to a CEA, however, there is much debate over what rate is appropriate. A study done by the Asian Development Bank found that developed nations tended to use real rates between three and seven percent depending on the project, where developing nations used a higher rate of eight percent or more, reflecting higher risk and uncertainty in investments in those nations (Wholey, Hatry, and Newcomer 2010). On the other hand, a World Bank paper has argued for a real rate of 3 to 5 percent (Lopez, 2008). On the far end of the spectrum, the Stern Report argued for a rate near zero percent for long-term projects involving the environment (Stern 2006). Thus, there is a broad range of discount rates that can be used and, in many cases, great resources are poured into determining the appropriate rate. One of the most common discount rates is three percent, which is what is used in this thesis. However, we can test the sensitivity of the project by doing sensitivity analysis with higher rates of five to seven percent.

An additional analysis, one that can goes hand in hand with CEA, is return on investment (ROI). ROI is an analysis done to calculate the net financial gains or losses of a given investment or improvement action, taking into account all the resources invested and all the amounts gained through an increase in revenue, reduced costs, or both. The ROI is calculated as the ratio of two financial estimates, as follows:

ROI = net-returns from improvement actions/investment in improvement actions

"Net-returns from improvement actions" refers to financial gains made from the implementation of the improvements actions. These are generated by net changes in quality, efficiency, utilization of services, or payments for those services. In this case, it would refer to the money saved on utility bills due to energy efficiency improvements. The investment in improvement actions refers to the costs of developing and operating the improvement actions. This is the cost of the improvements or efficiency upgrades in our case. In analyzing the ROI Index, a value greater than one means the returns generated by improvement actions are greater than the costs of implementation. Thus, ROI is positive in this case. If ROI is less than zero, then improvement actions yield a net loss from the changes made. This is considered a negative return on investment. Lastly, if ROI is between zero and one, the improvement actions yielded a positive return from the changes made, but it is too small to fully recover the implementation costs.

The same data can also be used to calculate the total cost savings of an improvement by using the following formula:

Cost savings = returns – investment

This is useful to determine whether any money was actually saved over the life of the investment. For example, would purchasing a ZEH now provide net cost savings, when all utility bill savings are taken into account over the life of the home? In calculating ROI, it is also necessary to discount the returns on investment since they are occurring over the lifetime of the mortgage, which in this case is 30 years. Thus, the discounted ROI is reflected in the following formula:

Discounted ROI = net present value benefits/total present value of costs

Additionally, it is of utmost importance that a sensitivity analysis be performed to test the sensitivity of the analysis to particular assumptions. Sensitivity analysis is an essential feature of any cost analysis, however, it is less common in the literature than it should be. A review done by Levin and McEwan (2001) of numerous CE and CB studies in health showed that two thirds did not conduct a sensitivity analysis. Another found that only 14% of health studies provided good analysis of uncertainty. If a cost study completely ignores the issue of uncertainty, the results should be interpreted with some caution. Even a simple sensitivity analysis is better than none.

For example, a one-way sensitivity analysis is done rather intuitively. First, one identifies which parameters or inputs reflect the greatest uncertainty. This could be any aspect of the analysis such as the discount rate, the cost of an ingredient, or the estimate of effectiveness. Second, one identifies the range over which each parameter might vary. The middle value is usually the baseline estimate that was calculated in the original analysis. For example, the cost assumptions used in this thesis are based on national averages and thus represent a baseline that may vary by region. The high or low values can be ascertained in a number of ways. Oftentimes, the evaluator uses professional judgment to estimate the high and low values of the input in question. Parameters that are derived from statistical analysis of a sample include a confidence interval, whose upper and lower bounds could be used as the high and low estimates. Once one of the inputs has been changed, the cost-effectiveness or ROI ratios should be re-estimated for that input, with this being repeated for each outcome with an uncertain estimate. The main purpose for sensitivity analysis is to see if the ranking changes when we change a given assumption. If cost-effectiveness is invariant with regard to changing assumptions about any one of the inputs, then the results could be characterized as highly robust with respect to different assumptions in estimating costs (Levin and McEwan 2001). If, on the other hand, the ranking of outcomes change with different assumptions, it will be necessary to decide among alternatives by deciding which assumptions are the most reasonable. If it seems as though there is great uncertainty, the conclusion may be postponed in order to seek new sources of data that provide additional certainty.

Lastly, it is often the case that the purpose of doing certain cost analyses is to make some sort of recommendation in terms of policy or decision-making. In the case of a CEA, there is no real decision rule when evaluating a given project. Usually policymakers must use their own judgment as to whether the cost per unit of effectiveness indicates the need for a decision or in the case of an ROI, whether it is a solid investment. However, when two or more outcomes are being evaluated against the same units of effectiveness, the policy with the lowest CE ratio would be indicated. However, it is not just total costs and benefits that matter when suggesting a policy; who benefits and who pays are also important. Sometimes it’s difficult to determine whether there are strong distributional consequences but, if there are, they should be noted. For example, rising income inequality is a major issue that has made the effects of policy decisions on low-income populations an essential consideration. In this project, we are primarily concerned with the costs associated with purchasing a ZEH. However, in terms of policy, the cost imposed on all parties is a necessary consideration for all policymakers.

Results

The least-cost curve for all nine locations is shown as a function of source energy savings in Figure 9. At zero source energy savings, the first points on the vertical axis, represent zero source energy savings i.e., the annual utility bill for a homeowner with a Building America Benchmark home. Each point along the curve in Figure 9 represents a different combination of equipment and envelope options for a home. BEopt runs an annual energy simulation for a large number of possible option combinations in approximation to the least-cost curve, which represents the lower bound of all the combination options. While Figure 9 shows only the least-cost curve for each location, there are many option combinations surrounding the least-cost curve that have near equivalent costs and performance. While this is not taken into account in this analysis, these data may be useful in other scenarios where one is interested not only in those option combinations on the least-cost-curve, but those surrounding it as well.

The marginal cost of increased energy efficiency is equal to the marginal cost of electricity from residential PV when source energy savings reaches an average of 34.3%. That is, it becomes cost effective, on average for each location, to implement PV technology once efficiency measures have brought the house to an energy savings level of 34.4%. The average was calculated using the points in which PV becomes cost-effective for each location. The straight line that begins at source energy savings of 34.3% represents the cost of using a net-metered, grid-connected PV system to meet the remaining home energy needs on the path to net zero. The minimum average annual energy-related cost point for all nine locations is $361/year less than the Benchmark and occurs on average at 19.4% source energy savings. The average maximum level of source energy savings occurred at 97.9% with the annualized energy-related costs adding up to $1,976 more than the Benchmark. As is shown in Figure 9, the benchmarks for each location begin at different starting points. This is not due to differences in Benchmark characteristics, but rather differences in climate and energy-related costs associated with different energy requirements.

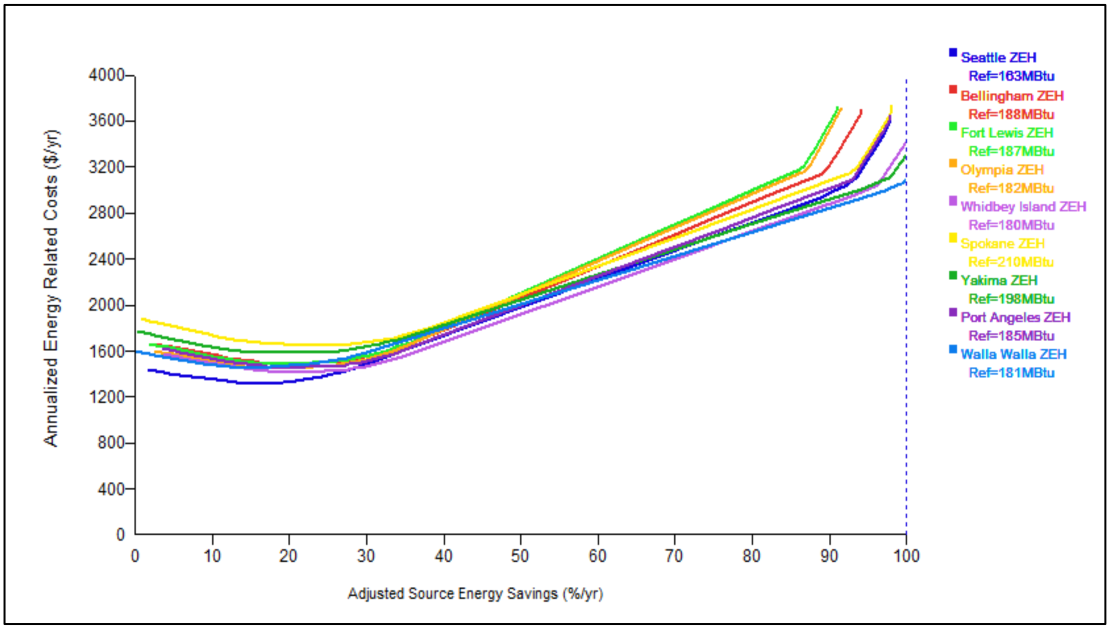

Figure 9. Least-cost curve for nine home locations in Washington State

The costs that accrue according to the different levels of source energy savings on the least-cost curve that go above and beyond the benchmark are reflected in the annualized energy-related costs. The annualized energy-related costs are calculated by annualizing all the energy-related cash flows associated with that location over the analysis period of 30 years, or the life of a typical mortgage. The values displayed in the least-cost curve, if broken down, include full-annualized utility bills plus incremental annualized values for every cash flow. BEopt calculates the cash flows by determining the mortgage/loan payments, replacements costs, utility bill payments, mortgage tax deductions, and residual values. The costs, excluding mortgage/loan payments are inflated using a 3% inflation rate. The annualized costs provide insight into what a homeowner would actually pay in energy-related costs spread over the lifetime of the home.

Table 1 provides the cost data that is associated with the least-cost curve in Figure 9. It provides the cost in US dollars of what the annualized energy-related costs would be, in US dollars, for each location as they reach different points on the path to net zero. These points include the reference building or benchmark (BAB), 10% energy efficiency (10%), the minimum cost point (MIN COST), 20% efficiency (20%), the point in which photovoltaic becomes more cost effective than energy efficiency upgrades (PV START), and the point in which photovoltaic ends (PV ENDS), which is a modeling limitation, since BEopt only allows PV systems of up to 8 kW. Nevertheless, additional, often more costly energy efficiency measures, such as highly insulated walls, could allow a home to reach zero-energy despite PV sizing limitations. Additional points include 90% energy efficiency (90%) and the point at which each home reaches its maximum level of energy efficiency (MAX SAVINGS). The points of MIN COST, PV START, PV END, and MAX SAVINGS are different for each location and thus the average level of percent energy savings will be considered for overall results.

Table 1. Annualized energy-related costs ($/yr.) for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	1441	1349	1317	1349	1477	2935	2978	3662
Bellingham	1722	1566	1492	1494	1683	3132	3210	3694
Fort Lewis	1709	1557	1494	1495	1693	3174	3585	3727
Olympia	1658	1500	1445	1447	1652	3137	3518	3709
Whidbey Island	1647	1500	1418	1420	1549	2956	2913	3575
Spokane	1914	1736	1652	1666	1788	3140	3099	3731
Yakima	1796	1635	1585	1600	1690	3011	2979	3640
Port Angeles	1691	1539	1454	1459	1598	3019	3016	3644
Walla Walla	1616	1497	1453	1487	1620	2929	2888	3598

Table 2. Total marginal costs ($/%) for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0	839	1317	1349	9419	53419	54829	72143
Bellingham	0	480	2615	2740	12951	56951	59021	71062
Fort Lewis	0	443	2615	2949	13337	57337	67334	71038
Olympia	0	480	2615	2797	12732	56732	66154	71038
Whidbey Island	0	849	2615	2310	10706	54706	52905	66562
Spokane	0	620	5751	3371	13118	57118	55317	72143
Yakima	0	616	2904	3428	10931	54931	53210	63398
Port Angeles	0	849	2615	2442	11092	55092	54873	71062
Walla Walla	0	908	2442	4025	11280	53768	50921	59622

If we were to consider the total costs (Table 2) associated with increasing a Benchmark home's efficiency by 10%, we would find it would require an additional $676 while a 20% increase would be $2,823 more relative to the Benchmark. This 20% increase in efficiency results in an average annualized cost of $209 less than the Benchmark. However, if we take into account the average minimum cost point of 19.4%, we find that it results in an even greater reduction of annualized cost of $361 less than the Benchmark. While the minimum cost point is just 0.6% below 20% efficiency, it results in an additional savings of over $150 compared to the homes at 20%. This is because the minimum cost point is an average of the nine locations with a range of 13.9% to 26.1 %. However, these findings suggest that a home that cost-optimally achieves a level near 20% source energy savings is actually cheaper than the Benchmark, when the costs are annualized. At the point in which the marginal cost of energy efficiency equals the marginal cost of PV-generated electricity, i.e., 34.3%, the total costs increase an average of $11,720 over the Benchmark. While this may seem like a substantial increase, the average annualized cost is still less than that of the Benchmark by $49. Thus, one could potentially build a home that is 30% more efficient relative to the benchmark at an annual cost that is just slightly less.

The point at which PV ends is averaged around 90.4%, with an average increase in cost over the Benchmark of $55,561. In annualized terms, this would result in an average additional cost of $1,360 over the Benchmark. At 90% efficiency, we see an average increase in total costs of $54,341, with an additional annualized cost over the Benchmark of $1,653. While 90% efficiency is closely linked to the point in which Photovoltaic ends at 90.4%, it results in a more expensive annualized cost. This is because the point at which PV ends is averaged, with a low of 86% and a high of 94.3%, resulting in a range of costs that brings the annualized cost down. Lastly, the point at which max energy savings occurs is averaged at 97.9%, with three locations reaching a positive net-energy balance Walla Walla, Yakima, and Whidbey Island at 104%, 102.5%, and 101.1% respectively. The other locations were very near net zero with Seattle at 97.9%, Bellingham at 94.1%, Fort Lewis at 91.1%, Olympia at 91.5%, Spokane at 98.1%, and Port Angeles reaching 98%. The average annual increase in cost over the Benchmark for the point at which max energy savings occurs for all locations (i.e., the point at which each location reaches net zero or near net zero) is $1,976 as mentioned above.

The findings in Table 2 represents the additional cost of energy-efficiency were one to improve the energy-efficiency of a benchmark home using standard construction practices until it reaches a level of maximum energy savings or net zero. It does not take into account the estimated costs of a benchmark building. Thus, the benchmark represents the reference case for each location and has a total cost of $0. This is consistent with the BEopt calculations since we are mainly interested in the cost of increasing energy-efficiency and not the cost of the reference. On the other hand, in Table 1, the annualized energy-related costs are calculated for the Benchmark because these data are necessary for the analysis.

Apart from annualized costs and total costs, annualized utility bills are presented in Table 3. While Table 1 shows annualized energy-related costs, Table 3 presents annualized utility bills ($/yr.) for each location on the path to net zero. The first column in both Tables 1 and 3 contain the same data. This is because they both start where the benchmark buildings' annual energy-related costs bare equal to their annual energy bills. However, once energy-efficiency improvements begin to be made, the trend follows that of generally increasing energy-related costs (after reaching the minimum cost point) and a continually decreasing utility bill (as energy costs are shifted from the utility over to efficiency measures).

Table 3. Annualized utility bills ($/yr.) for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	1441	1311	1249	1158	1047	476	456	333
Bellingham	1722	1544	1374	1371	1093	513	496	415
Fort Lewis	1709	1537	1376	1363	1086	538	470	448
Olympia	1658	1490	1327	1321	1072	529	459	431
Whidbey Island	1647	1460	1316	1300	1067	445	485	336
Spokane	1914	1707	1395	1514	1191	514	557	402
Yakima	1796	1606	1454	1444	1193	485	536	400
Port Angeles	1691	1499	1336	1348	1099	491	497	365
Walla Walla	1616	1454	1342	1304	1107	453	538	367

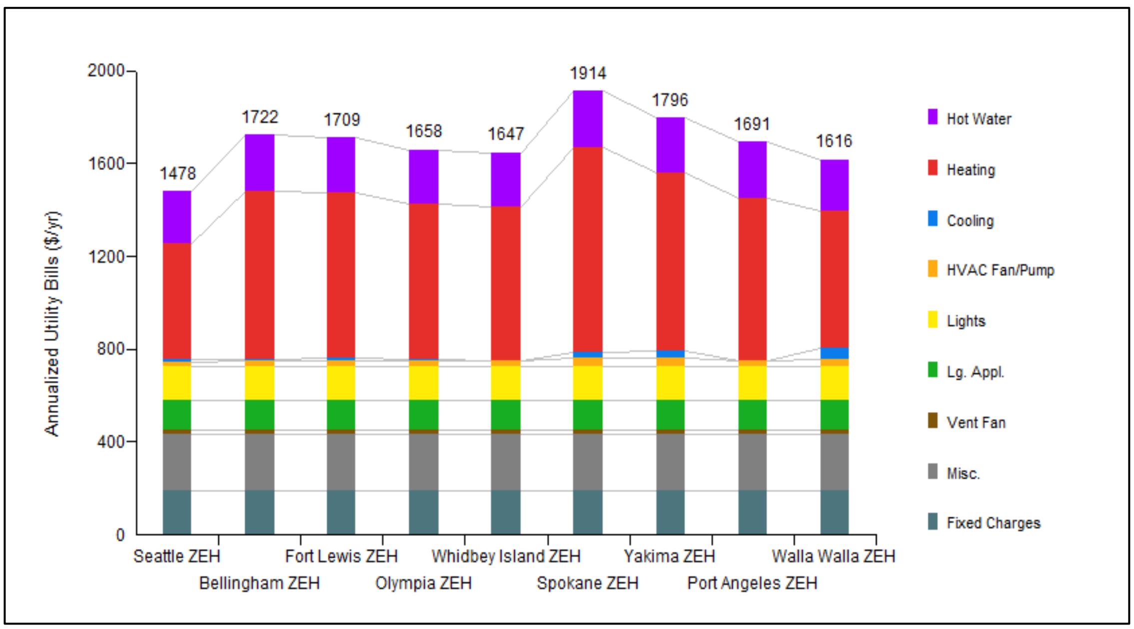

Figure 10. Annualized utility bills for nine locations at benchmark

The effect that increasing energy efficiency has on utility bills is evident when comparing the annualized utility bills for each location in Figure 10 to those in Figure 11. Figure 10 represents the annual utility bills for the benchmark at each location. That is, it is the utility bills for what a typical home built up to code might be for each given Washington location. Figure 11 represents the annual utility bills for the same locations after they've implemented the most cost-optimal energy efficiency improvements in order to reach the goal of net zero. The figures break down the annual utility bills by end use, thus providing insight into the end uses that are most affected by changes in energy efficiency. As is evident, heating results in the greatest reduction in terms of end uses as well as contributing the greatest reduction to utility bills.

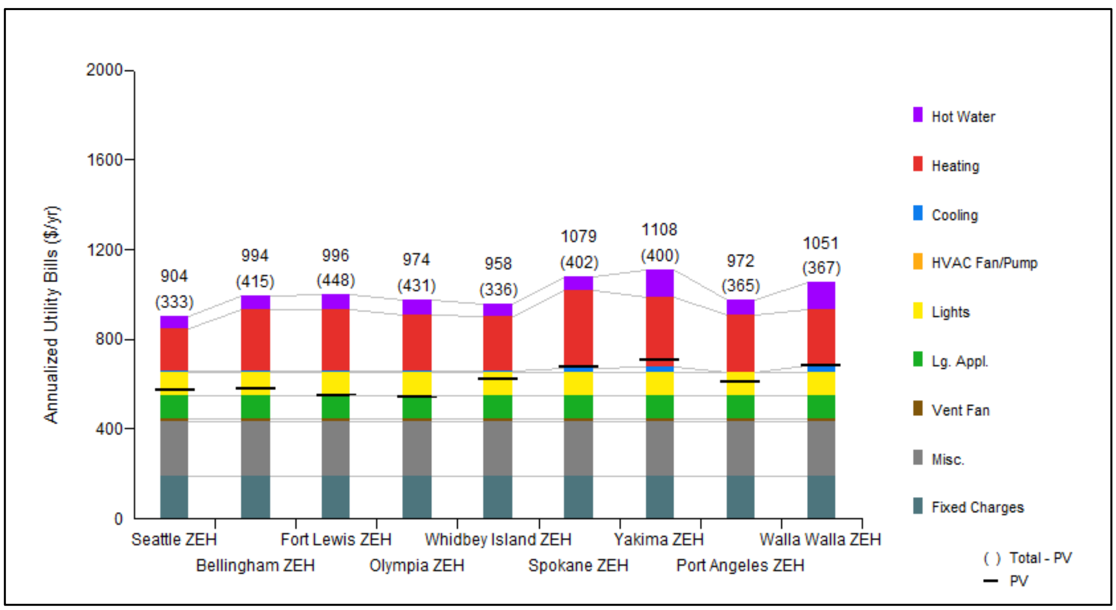

Figure 11. Annualized utility bills for nine locations at max energy savings

Overall, each location in Washington State took a similar path to net zero as is indicated in Figure 11. The variation that occurs is due to differences in climate and weather patterns for each given location thus resulting in different PV generation and energy efficiency requirements. Had this project been done for nine locations around the country, the results would be significantly different. Nevertheless, there is still some variation with some homes surpassing the net zero goal and others just barely missing it. The inputs that showed the most variation among the different locations had to do with the walls, window type and shading, space conditioning, and water heating. However, for the most part, many of the inputs remained the same as the home designs moved along the path. For example, all home locations utilized the full 8.0 KW PV systems, which had a cost of $44,000 for each location. Since PV was necessary to reach net zero, had there been an option to increase the size of the PV system, it is likely that each home would have achieved the goal. The PV system also contributed the greatest cost in terms of energy-efficiency inputs. Also, necessary in reaching net zero was the type of walls used. In particular, structurally insulated panels (SIPs) or double-studded walls were needed in several of the cases with a cost of $9,832 and $11,009 respectively, ranking walls as the second highest cost next to PV. Lastly, the use of solar water heating was also needed in most cases with a cost of $8,817, which turned out to be the third highest input cost. Some locations, for instance, Whidbey Island were able to get by without SIPs, which is reflected in their total cost. These differences in inputs offer great insight into how paths to the same outcome can be made up of different inputs, which correspond largely with location.

Analysis

In order to determine the cost-effectiveness of zero-energy homes in Washington State, a cost-effectiveness analysis was performed on the cost data generated by BEopt. As mentioned before, the purpose of a cost-effectiveness analysis is to determine which alternative or combination of alternatives can achieve a particular objective at the lowest cost. The underlying assumption is that the different locations of ZEHs in Washington will have different associated costs and different effects. Thus, we can determine in what locations might a ZEH be more cost effective. Also, by taking into account multiple locations throughout Washington State, one can determine the overall cost-effectiveness of building such homes in Washington by aggregating the data. By understanding the overall cost-effectiveness and which locations provide the least-cost for a given outcome, society can use its resources more effectively.

The analysis requires that an ingredients list as well as the associated costs for each outcome be determined. An outcome, in this case, is defined as a specific point on the path to net zero. Thus, each location will have several outcomes, represented by the data in the results. We are interested in which points or outcomes along the least-cost curve provide the most-cost-effectiveness, i.e., at 20%, 30%. PV STARTS, PV ENDS, 90%, etc. We can determine this by calculating the cost-effectiveness ratios for each outcome using the costs of each ingredient required for each outcome as well as the measurement of effectiveness, which, in this project, is the percent of energy saved. The ingredients or inputs that were used for each location and each simulation were the same for all locations. The input screen for BEopt is indicated in Figure 12. Differences in effects result from differences in weather and climate, which, together, are among the great determinants of the cost-effectiveness for ZEHs. This has much to do with the need for renewable generation, particularly photovoltaic, as well as the existence of different envelope and heating requirements. These three can be the most costly in terms of energy efficiency upgrades.

To continue the analysis in the same fashion in which the results were presented, the cost-effectiveness ratios were calculated for each of the nine locations along with 10 different outcomes. The CER was calculated using the total present value costs for each outcome over the percent of energy saved at that outcome. Thus, cost-effectiveness ratios for specific levels of percent energy savings (i.e., 10%, 20%, 90%) were calculated using the given percent as the denominator. However, for outcomes with different percent energy savings (i.e., MIN COST, PV START, PV END, MAX SAVINGS), the percent energy savings that was achieved for each outcome per location was used as the denominator. Nevertheless, we are able to determine, for each outcome, what home locations are the most cost-effective. Table 4 presents the cost-effectiveness ratios for each outcome per location. The CER represents the cost per unit of effectiveness or in other words, the cost per unit of percent energy saved (i.e., $/% energy savings).

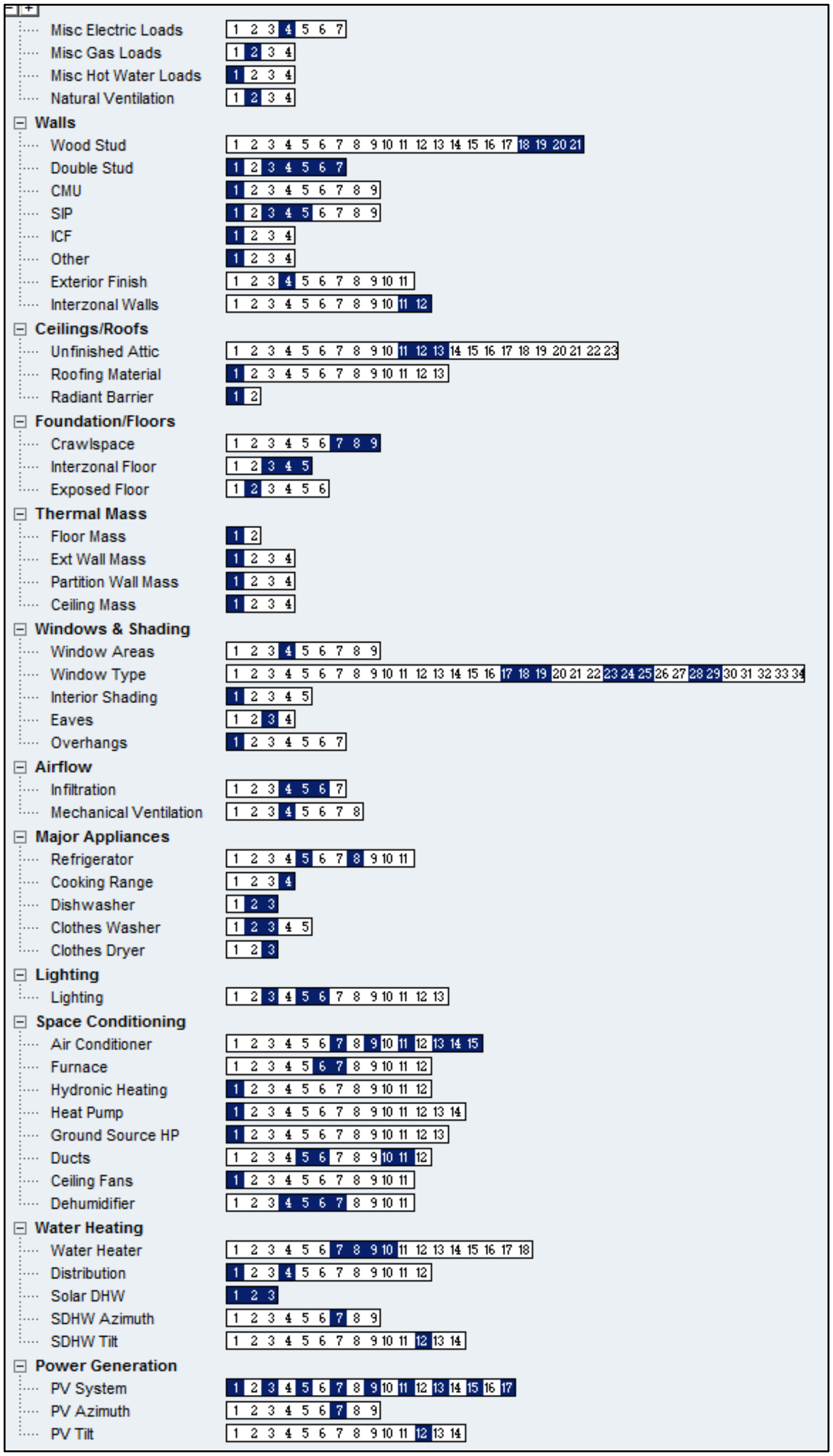

Figure 12. BEopt input screen indicating the ingredients (inputs) used for each location. (Single selections indicate inputs that were held constant)

Table 4. Cost-effectiveness ratios ($/%) for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0	83.9	86	67	319	601	609	694
Bellingham	0	48	131	137	356	642	656	725
Fort Lewis	0	44.3	136	147	366	666	748	696
Olympia	0	48	133	140	361	660	735	724
Whidbey Island	0	84.9	125	116	309	586	588	659
Spokane	0	62	220	169	349	618	615	788
Yakima	0	61.6	160	171	326	583	591	696
Port Angeles	0	84.9	126	122	322	610	610	755
Walla Walla	0	90.8	153	201	356	570	566	609

Depending on the location and the outcome, different cost-effectiveness ratios were calculated using the formula in the methods. What we find is that although most locations follow the same general pattern in terms of increasing CERs as % energy savings increases (see Figure 13), their CERS are different from each other with the same outcomes. For all locations at the Benchmark or reference outcome, the CERs were $0/% energy savings. At 10% energy savings, the most cost-effective location is Fort Lewis with a CER of $44.30/% energy savings. The least-cost-effective location is Walla Walla Washington with a CER of $90.80/% energy savings. For the minimum cost outcome, Seattle has the lowest CER of $86.10/% energy savings. This is only $2.10 more than Seattle's CER at 10%, however, Seattle reached its minimum cost outcome at the lowest percent of energy savings, which was 15.3%. The least-cost effective at the minimum cost outcome was Spokane at $220/% energy savings. However, Spokane was able to reach their minimum cost point at the highest percent of energy savings compared to all locations, which was 26.1%. This explains why, in Figure 13, Spokane's CER is so much higher than the rest.

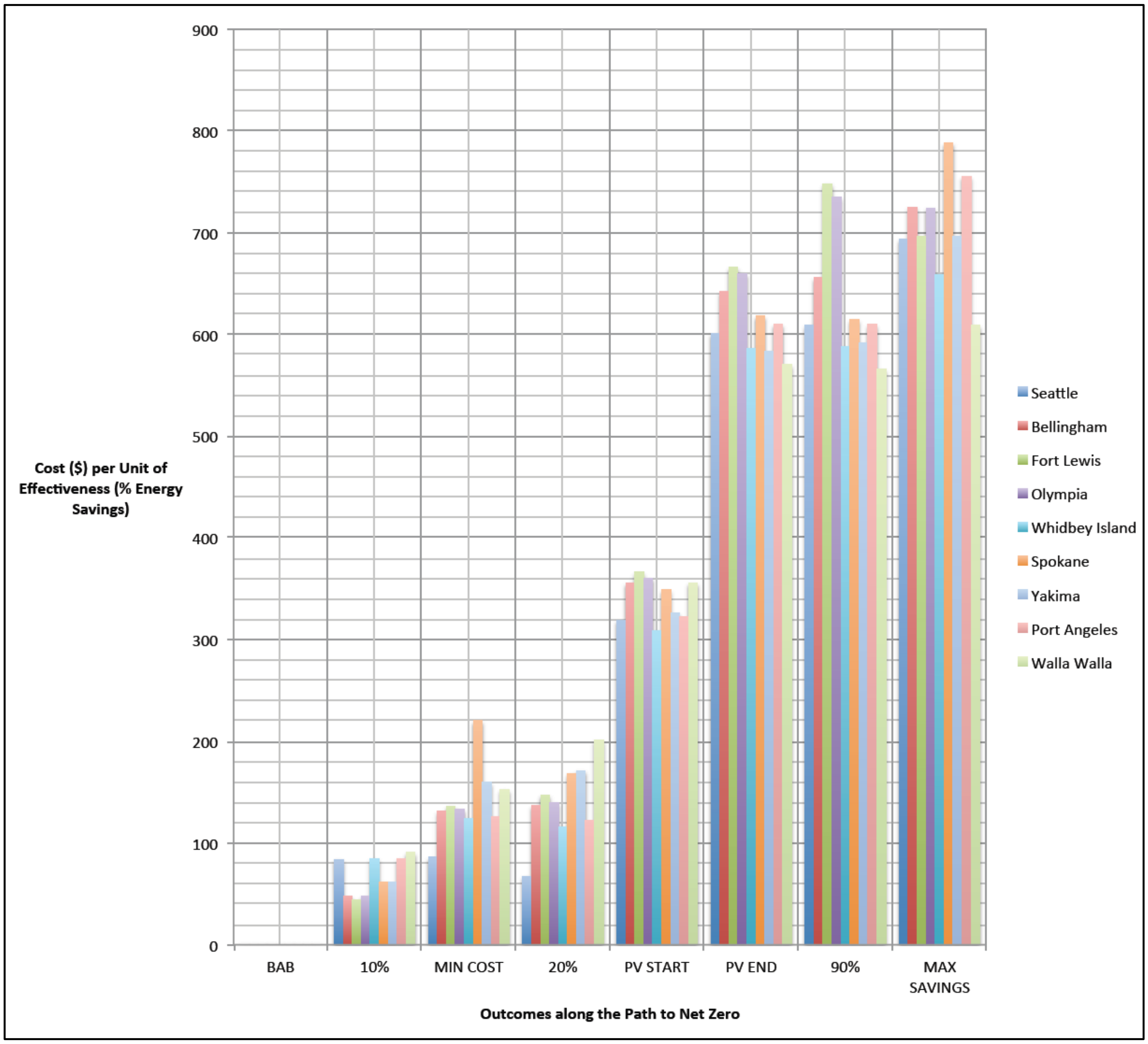

Figure 13. Cost-effectiveness ratios for nine locations on the path to net zero

It is also important to note that the average minimum cost point for all locations was 19.4%, which is very close to the 20% outcome of all locations. However, there is noticeable variation between some of the CERs at the minimum cost outcome and the 20% outcome because of the differences in how each location was able to reach its minimum cost. For example, at the 20% outcome, the most cost-effective location is Seattle with a CER of $67/% energy savings. The least cost-effective at 20% was Walla Walla with a CER of $201/% energy saving. The next most cost-effective location after Seattle was Whidbey Island with a CER of $116/% energy savings, indicating that Seattle, at the 20% outcome, is significantly more cost-effective than the other locations. Interestingly, Seattle was one of the least-cost effective at 10%.

At the outcome in which the marginal cost of increased energy efficiency is equal to the marginal cost of electricity from residential PV (i.e., PV START), the most cost-effective location is Whidbey Island with a CER of $309/% energy savings. The average point at which PV becomes cost-effective to implement is 34.3%, with Whidbey Island implementing it at 34.7%. The least cost-effective is Fort Lewis with a CER of $366/% energy savings and achieving this at 36.4%. As we move to the outcome at which PV ends, or the point where the 8.0 KW PV system maxes out, we find that the most cost-effective location is Walla Walla with a CER of $570/% energy savings. The least-cost effective for this outcome is still Fort Lewis with a CER of $666/% energy savings. The average point in which PV ends for all locations is 90.4%, with Walla Walla stretching it to the maximum level of efficiency at 94.3% and Fort Lewis reaching it at the lowest, 86%. This explains why some of the locations have CERs at PV END that are very similar to the levels reached at the 90% outcome. For example, in Figure 13, Olympia and Fort Lewis show the greatest increase in their CERs from PV END to 90%, which is mainly due to their photovoltaic systems both ending at 86%, whereas the rest were near 90% or above. The 90% outcome results in Walla Walla achieving the greatest cost-effectiveness with a CER of $566/% energy savings and Fort Lewis achieving the least-cost effective CER at $748/% energy savings.

Perhaps the most significant CERs calculated are those relating to the maximum level of energy savings or net zero-energy homes. The average maximum level of energy savings for all locations was achieved at 97.9%. The location with the most cost-effectiveness is Wall Walla, with a CER of $609/% energy savings and a max energy savings of 104%, resulting in a positive net zero-energy home. The least cost-effective was Spokane, with a CER of $788/% energy savings while reaching a total energy savings of 98.1%. It is also interesting to note that both Fort Lewis and Yakima had CERs of $696/% energy savings, while reaching energy savings levels of 91.1% and 102.5%, respectively. This goes to show that although a given location has the potential to achieve 100% zero energy, it may not be the most cost-effective location in which to do so.

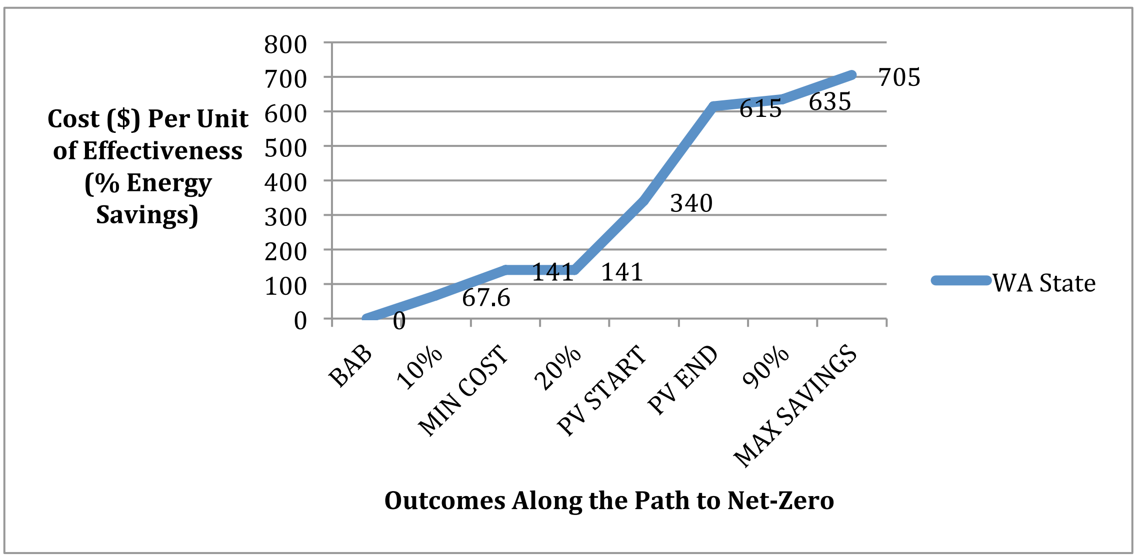

Figure 14. Cost-effectiveness for homes on the path to net zero in Washington State

Taking the average CERs for each outcome, we are left with a generalized cost-effectiveness for the state of Washington, based on nine locations throughout the state.

Looking at Figure 14, we can see the average cost per unit of effectiveness as we move along the path to net zero. Starting with a benchmark building, at 0% energy savings, the line graph covers each major outcome along the path to net zero. The average CERs are indicated above each outcome near the line. One sees that the cost-effectiveness of energy-efficiency improvements decreases the further you move along the path to net zero. That is, as a home continually becomes more energy-efficient, the cost of each additional percent of energy saved costs more than the last due to the increase in cost of more expensive technologies. However, most of the increase in the CER is seen after photovoltaic is implemented, which makes sense, since it is the most costly energy efficient upgrade. At the same time, PV also provides renewable energy, thus driving the cost of utility bills down and providing a payback on investment. This isn't reflected in the CER because it only takes into account what it costs per unit of energy-efficiency to build a home along the path to net zero and not the payback provided by lower utility bills over the life of the mortgage. This is more accurately reflected in a Return on Investment Analysis (ROI), which is discussed in the methods, and will now be presented.

The ROI was calculated using data from Tables 2 and 3. Table 2 provides the annualized utility bill costs for all locations at each point along the path to net zero. This table includes the annualized utility bills for the benchmark at each location as well as the utility bills for each level of energy savings. In order to calculate how much is being saved at each point along the path, the utility bill costs at each point were deducted from the benchmark utility, to get the total annual utility bill savings from energy-efficiency upgrades at each point. Since this is money that is being saved, it represents a return on the investment. While it may not seem like much initially, the money saved on utility bills adds up over the life of a mortgage and, thus, is a good estimate of how cost effective an investment will be over its life. Since purchasing a home is often the biggest investment people make in their lives, it makes sense to determine what kind of return they could receive by purchasing a ZEH. Table 5 provides the discounted (0.03) present value of utility bill savings over the 30-year life of the mortgage. It is the amount of money, in present-value terms, which one could expect to save on utility bills for each home design along the path to net zero.

Table 5. Net present value of total utility bills savings on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0	2548	3763	5547	7723	18914	19306	21717
Bellingham	0	3489	6821	6880	12329	23697	24030	25618
Fort Lewis	0	3371	6527	6782	12211	22952	24285	24716
Olympia	0	3293	6488	6605	11486	22129	23501	24050
Whidbey Island	0	3665	6488	6801	11368	23560	22776	25696
Spokane	0	4057	10173	7840	14171	27441	26598	29636
Yakima	0	3724	6703	6899	11819	25696	24697	27362
Port Angeles	0	3763	6958	6723	11603	23521	23403	25990
Walla Walla	0	3175	5371	6115	9977	22795	21129	24481

Once the values in Table 5 were calculated, the figures in Table 2 were used to determine the ROI for each point along the path to net zero. Since ROI is calculated using the formula: *Discounted ROI = net present value benefits/total present value of costs* , we determined ROI by dividing the figures in Table 5 by the corresponding figures in Table 2. Thus, total utility bills savings were divided by the total marginal costs of energy efficiency upgrades to give us Table 6, the ROI index for each point along the path to net zero. The ROI index is a number that represents the point at which an investment has paid for itself and is designed to simplify and standardize return on investment. An ROI index of 0.5, for example, means that the improvement action recovered 50% of its costs. An ROI index of 1 means that the investment has paid for itself in full, but the savings did not exceed the investment. An ROI index greater than 1 means that savings exceeds investment. For example, an index of 3 means that the savings have reached 3 times the amount of the investment. Thus, if we look at Table 6, we can see that at 10% energy efficiency, all locations recovered the costs several times over, with Fort Lewis providing the best ROI. At MIN COST, the ROI for all locations except Spokane was greater than 2, resulting in a return greater than twice the amount of the investment.

Table 6. Return on investment for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0.00	3.04	2.86	4.11	0.82	0.35	0.35	0.30
Bellingham	0.00	7.27	2.61	2.51	0.95	0.42	0.41	0.36
Fort Lewis	0.00	7.61	2.50	2.30	0.92	0.40	0.36	0.35
Olympia	0.00	6.86	2.48	2.36	0.90	0.39	0.36	0.34
Whidbey Island	0.00	4.32	2.48	2.94	1.06	0.43	0.43	0.39
Spokane	0.00	6.54	1.77	2.33	1.08	0.48	0.48	0.41
Yakima	0.00	6.05	2.31	2.01	1.08	0.47	0.48	0.43
Port Angeles	0.00	4.43	2.66	2.75	1.05	0.43	0.43	0.37
Walla Walla	0.00	3.50	2.20	1.52	0.88	0.42	0.41	0.41

At 20%, the investment in energy-efficiency is still cost-effective in terms of ROI, with all but Walla Walla having an index greater than 2. At PV START, where the average level of energy efficiency is 34.3%, 4 of the 5 homes had an ROI Index greater than 1, while least-cost-effective was Walla Walla with an Index of 0.88. As we move into greater levels of energy-efficiency, it becomes clear that the investment becomes less appealing. This is primarily due to the increase in costs of technology, particularly PV, relative to the payback provided by savings on utilities. As is shown above, after PV ENDS until MAX SAVINGS for all locations, the ROI index is below 0.5 for all locations. Thus, after PV START, or an average energy savings level of 34.3%, the energy efficient upgrades do not provide a significant payback.

Figure 15 shows these data more clearly as an average ROI for the state, while Figure 16 presents a bar graph of ROI for each location. These figures show that, at every energy savings level, there is a return, although in the cases of highest energy efficiency this tends to be less than a 50% payback. In both representations, it becomes clear that the 10% energy savings level provides the greatest return on investment by a substantial amount compared to all other levels of savings. The only case where it does not is Seattle, where 20% energy savings provides the best ROI. This could suggest that Seattle is the best place to invest in a home at that energy savings level. It also suggests that anything before PV implementation is going to provide a positive return, i.e., greater than 1. This suggests that in the future, as the price of PV comes down, return on investment will rise.

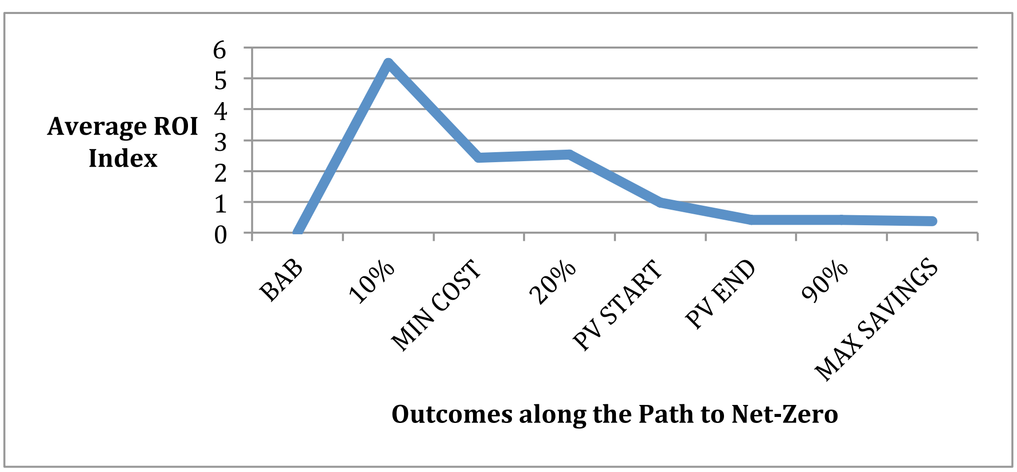

Figure 15. Average ROI index for nine locations on the path to net zero

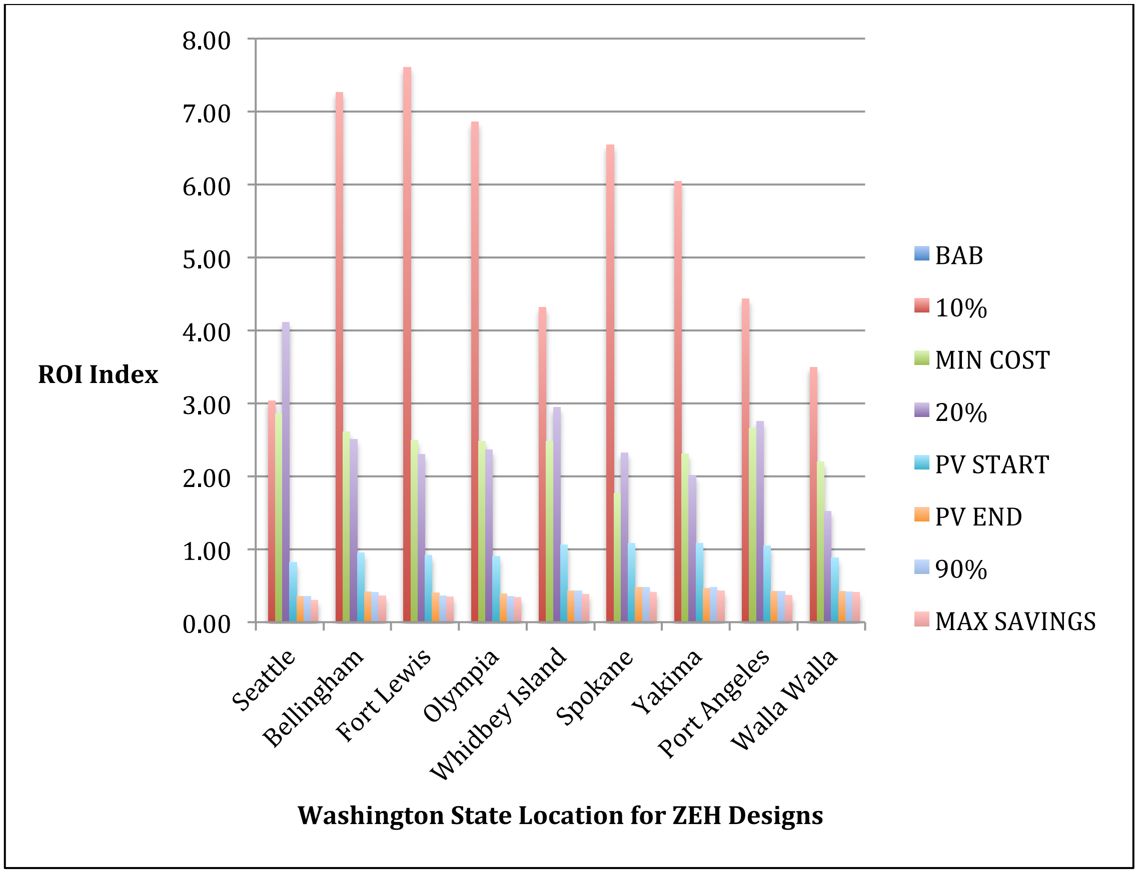

Figure 16. Return on investment index for nine locations on the path to net zero

Lastly, a sensitivity analysis was performed on the data for both CEA and ROI to gauge levels of uncertainty and to see how changing assumptions could lead to changes in results. This approach varies one assumption at a time, holding everything else constant. For example, in the case of the CEA, we assumed no incentives in our cost calculations for the implementation of our photovoltaic systems. However, there currently exists a federal residential renewable energy tax credit that could be applied to the price of this PV system, thus lowering the overall marginal cost of a home design once it reaches the point at which PV becomes cost-effective (DSIRE 2012). This federal tax credit applies to solar water heat, photovoltaic, wind, fuel cells, geothermal heat pumps, other solar electric technologies, as well as fuel cells using renewable fuels. The tax credit applies to 30% of the total price, with no maximum size for solar electric systems placed in service after 2008. This tax credit expirees on December 31, 2016 and, so, would apply only to those systems installed within the next few years, unless the tax credit is extended. Using this renewable tax credit to test our initial analysis, we deduct 30% from the price of the PV installation for each location at PV END, 90%, and MAX SAVINGS. At these points along the path to net zero, the full 8.0 kW PV system was needed to reach the energy savings level, with a total cost of $44,000 for the system. Thus, 30% deducted from the total price of the installed PV system at $44,000 is $13,200. This is a substantial savings and one that could realistically apply. See Table 7 for adjusted total costs.

Table 7. Total costs — 30% tax credit for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0	839	1317	1349	9419	40219	41629	58943
Bellingham	0	480	2615	2740	12951	43751	45821	57862
Fort Lewis	0	443	2615	2949	13337	44137	54134	57838
Olympia	0	480	2615	2797	12732	43532	52954	57838
Whidbey Island	0	849	2615	2310	10706	41506	39705	53362
Spokane	0	620	5751	3371	13118	43918	42117	58943
Yakima	0	616	2904	3428	10931	41731	40010	50198
Port Angeles	0	849	2615	2442	11092	41892	41673	57862
Walla Walla	0	908	2442	4025	11280	40568	37721	46422

After adjusting the total price for those points that utilized PV, we also calculated the cost-effectiveness ratio for each as well, which is indicated in Table 8. As is shown below, the CERs only changed for PV END, 90%, and MAX SAVINGS, with all locations having the same reduction in price and thus an equivalent reduction in their cost-effectiveness. Nevertheless, this could significantly impact decision-making in terms of a maximum level of cost-effectiveness. For example, if someone was limited to a CER of 600, then under our original analysis, they could not afford to reach the level of energy efficiency attained at PV END and beyond. However, under our sensitivity analysis, they could now afford a home in several locations that achieve MAX SAVINGS. The only locations, in which they could not, would be Spokane and Port Angeles. Under the original analysis, they could only reach PV END and only in a limited number of locations, i.e., Whidbey Island, Yakima, and Walla Walla. Thus, adjusting the price of PV can significantly impact the cost-effectiveness for those homes beyond PV START. However, adjusting for the tax credit did not affect the ranking of the locations, indicating the results hold despite changes in the greatest cost determiner. Figure 14 indicates the change in the average CERs for Washington, which follows the same path as Figure 12.

Table 8. CERs adjusted for 30% tax credit for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0	83.9	86	67	319	452	463	567
Bellingham	0	48	131	137	356	493	509	590
Fort Lewis	0	44.3	136	147	366	513	601	567
Olympia	0	48	133	140	361	506	588	590
Whidbey Island	0	84.9	125	116	309	445	441	528
Spokane	0	62	220	169	349	475	468	644
Yakima	0	61.6	160	171	326	443	445	551
Port Angeles	0	84.9	126	122	322	464	463	615
Walla Walla	0	90.8	153	201	356	430	419	474

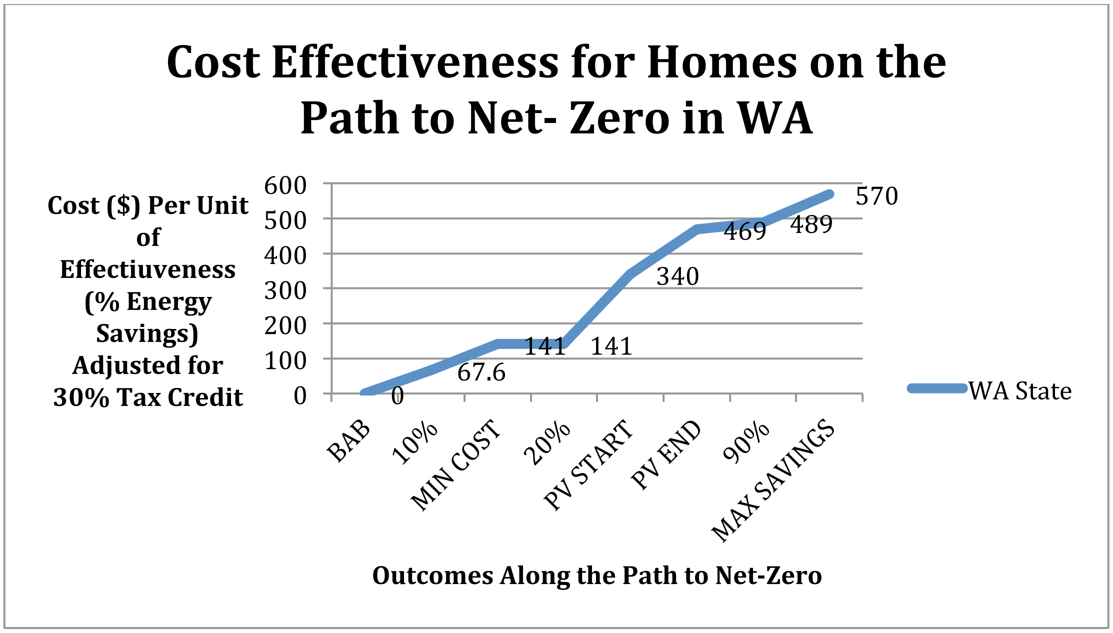

Figure 17. Adjusted cost-effectiveness for homes on the path to net zero

An additional sensitivity analysis was performed by adjusting the discount rates for the data in the return on investment analysis. Taking a 1% and 5% discount rate, we can see what a 2% change in either direction would look like. Since the payback, in terms of utility bill savings, is highly dependent on the value we place on future payments, changing the discount rate could provide very different results. Table 9 represents the ROI index with a discount rate of 1%. This would represent someone who places a very high value on the money that they will receive in the future. A discount rate of 0% would represent placing the same value on returns several years from now as one would today. There are reasons to value returns differently and, in fact, depending on the party, discount rates could vary widely. Perhaps, someone who values the environment would value the future returns from utility bill savings more highly because it includes a non-monetized value of emission reduction on their part. Thus, at 1%, ZEHs could provide a substantial ROI as indicated in Table 9.

Table 9. ROI index (1% discount rate) for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0.00	9.11	8.57	12.34	2.46	1.06	1.06	0.90
Bellingham	0.00	21.81	7.83	7.53	2.86	1.25	1.22	1.08
Fort Lewis	0.00	22.83	7.49	6.90	2.75	1.20	1.08	1.04
Olympia	0.00	20.58	7.44	7.08	2.71	1.17	1.07	1.02
Whidbey Island	0.00	12.95	7.44	8.83	3.19	1.29	1.29	1.16
Spokane	0.00	19.63	5.31	6.98	3.24	1.44	1.44	1.23
Yakima	0.00	18.14	6.92	6.04	3.24	1.40	1.44	1.29
Port Angeles	0.00	13.30	7.98	8.26	3.14	1.28	1.28	1.10
Walla Walla	0.00	10.49	6.60	4.56	2.65	1.27	1.24	1.23

Under this scenario, we find that every location at every point, except for Seattle at MAX SAVINGS, provides an ROI greater than 1. Thus, if someone were to place a high value on utility bill savings over the life of the home, a ZEH or one on the path to net zero could provide a complete return on investment in nearly all cases. It was also the case that changing the discount rate does not change the ranking of any location at any point. As is shown, 10% energy savings still provides the greatest ROI, with Bellingham, Olympia, and Fort Lewis achieving returns 20 times greater than what was invested.

While changing the discount rate had no effect on ranking, it is a good test of sensitivity, in that it points out how important the discount rate can be in terms of making decisions that involve future payouts. This is even more apparent when we apply a discount rate of 5% as is shown in Table 10. A 5% discount results in greatly reduced ROIs, with no locations receiving a positive return at PV Start, whereas before 4 of the 5 locations were able to. Additionally, all location were able to achieve a ROI greater than 1 at 20% energy savings before, whereas now, Walla Walla, does not. Nevertheless, the rankings still do not change, as was the case with the 1% discount rate. This can be seen more clearly by comparing Figure 16 and Figure 18.

Table 10. ROI Index (5% discount rate) for nine locations on the path to net zero

Cities	BAB	10%	MIN COST	20%	PV START	PV END	90%	MAX SAVINGS
Seattle	0.00	1.82	1.71	2.47	0.49	0.21	0.21	0.18
Bellingham	0.00	4.36	1.57	1.51	0.57	0.25	0.24	0.22
Fort Lewis	0.00	4.57	1.50	1.38	0.55	0.24	0.22	0.21
Olympia	0.00	4.12	1.49	1.42	0.54	0.23	0.21	0.20
Whidbey Island	0.00	2.59	1.49	1.77	0.64	0.26	0.26	0.23
Spokane	0.00	3.93	1.06	1.40	0.65	0.29	0.29	0.25
Yakima	0.00	3.63	1.38	1.21	0.65	0.28	0.29	0.26
Port Angeles	0.00	2.66	1.60	1.65	0.63	0.26	0.26	0.22
Walla Walla	0.00	2.10	1.32	0.91	0.53	0.25	0.25	0.25

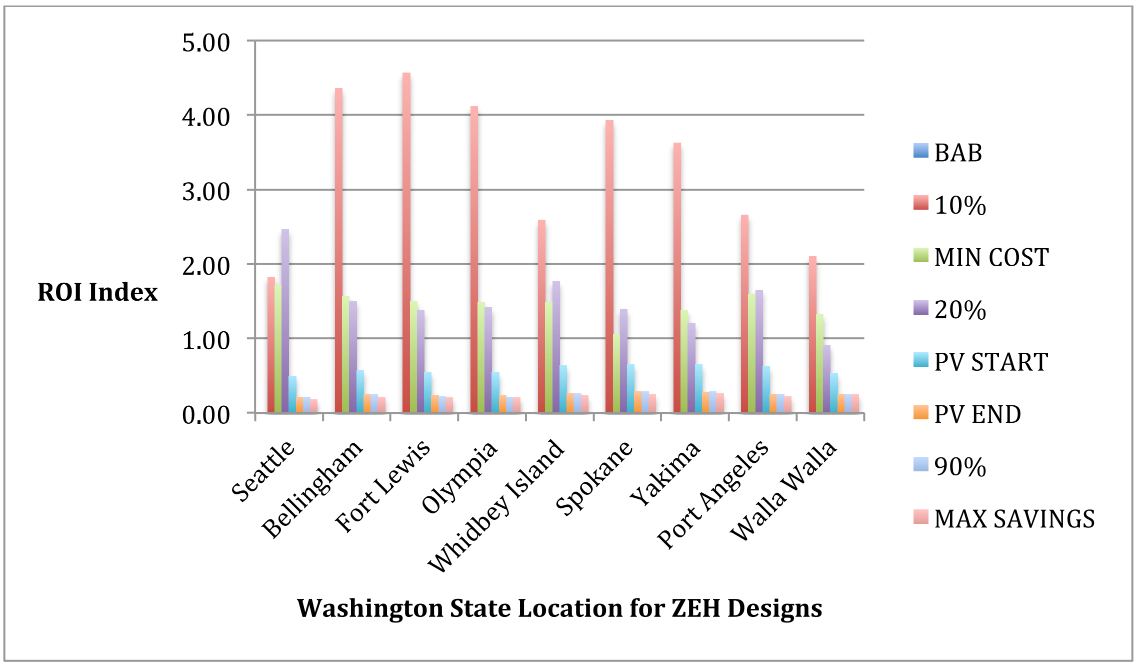

Figure 18. ROI (5% discount rate) for nine locations on the path to net zero

In conclusion, Figures 14 and 15 provide an overall average summary of cost-effectiveness and return on investment for zero-energy homes in Washington State. It is clear from the data that cost-effectiveness decreases as the percent in energy savings increases. That is, as homes become increasingly energy-efficient the price per unit of effectiveness - in this case, price per percent energy savings - continues to increase as well. This is particularly significant after PV begins to be implemented as is noted by the sharp rise in the CER after PV START. This large decrease in the cost-effectiveness is primarily the result of the PV systems, after PV START, since these payments represent such a large portion of the overall cost of energy-efficiency improvements. This is also the reason why the CER before PV START is fairly low, with it more than doubling by the time it reaches PV END. It is also important to note that the rise in CER levels off after PV END to a very gradual increase, ending at MAX SAVINGS. Thus, it would be most beneficial for the government or any party interested in increasing the cost-effectiveness of ZEHs, to focus on research and policy that would contribute to lowering the cost of photovoltaic systems. This is because PV systems result in the greatest increase in CERs as well as the largest portion of overall costs. As is shown in our sensitivity analysis, the federal tax credit substantially lowered the CER for the homes in which PV was implemented, simply by providing a tax incentive.

However, while cost-effectiveness allows us to see the incremental increase in cost per unit of effectiveness, it does not provide the consumer with enough information to make an informed investment decision. Since it is often consumers, and not the government, that drive changes in the marketplace; it may be the consumers that drive the production of new zero-energy homes. Thus, it is necessary that we get information such as the ROI of ZEH into the hands of those that could use it. This is helpful because, as one can see in Figure 15, investing in energy-efficient homes does provide significant payback. It is clear here that the greatest returns are provided early on at 10% energy efficiency and slowly decline until the investment drops below full reimbursement near PV START, which makes sense, since PV implementation results in the greatest increase in the total cost of investment. However, this is largely dependent on how we value the future payback in terms of utility bill savings. For someone who places a much higher value on their dollar today than that dollar tomorrow, then ZEHs may not be a very good investment. However, for someone who places a much higher value on their future utility bill savings because they represent a lower carbon footprint, then ZEHs may be a very successful investment. Although this analysis makes many assumptions, it is essential to do these sorts of calculations if we are to provide credible and informative information on the capabilities and potentialities of ZEHs as well as providing insight for new and innovative policy measures.

Discussion

The purpose of this research was to determine the cost-effectiveness of ZEHs in Washington State. After taking the results into account, it is clear that energy-efficiency can be cost-effective and could provide a return on the investment, particularly for levels before PV START or an average energy-efficiency level of 34.3%. This is primarily due to the cost of photovoltaic systems being what they are despite this technology becoming increasing less expensive. Nevertheless, this research has shown that energy-efficiency does pay, not only in terms of financial benefits but in positive environmental impacts as well. Thus, while we may not see ZEHs become implemented on a production basis right away, it is important that we work to make our homes more energy-efficient than the Benchmark building or code-compliant house.

Furthermore, it should be noted that all assumptions in this thesis inherently leave room for uncertainty and while a sensitivity analysis was performed on the data, changing the assumptions of this project would undoubtedly change the results to a degree. For example, had the definition of ZEHs been changed from source energy to site energy, the use of a source-to-site-ratio would not have been permitted and the need for a larger PV array would have been required to reach the same outcomes. Additionally, the benchmark home could have been user defined, in which case, every result would have been different. This is because all home designs begin at the benchmark and move upward through energy-efficiency to reach net zero. Thus, a different benchmark would have resulted in different housing requirements and, in turn, different starting utility rates. Also part of the benchmark, were the user profiles, which were based on a typical occupancy behavior. Such user profiles could have been changed to reflect more conservative behavior and thus result in a home that could have reached net zero earlier on the path. The same could be said for changing the comfort heating and cooling set points so that they reflected a cooler/warmer environment. Changes in the study period, or length of mortgage, from 30 years to a different length of time would affect the results, particularly, in terms of return on investment.

Apart from changes in the study period, changes in the interest rate, inflation rate, and discount rate can have significant effects on the costs, especially as they change over time. An example of changing the discount rate was presented in the sensitivity analysis, which showed great degrees of change in terms of return on investment. Lastly, changing in the floor plan used in this thesis, or of any housing characteristics, such as compass direction, size of eaves, house size, etc., that were held constant, could change the entire parameters of the study. Thus, while the benchmark used in this thesis is representative of a typical conventional American home, the assumptions associated with it may not be representative of all homes in Washington. Nevertheless, projections, as are provided by the results of modeling studies, would not be possible without certain assumptions. They allow us to predict in what ways we can reach certain levels of energy efficiency and at what cost. This type of information is invaluable when it comes to implementing energy efficiency, particularly at the state and national levels.

One of the most effective ways of accomplishing energy efficiency in the building sector is through the adoption and implementation of energy efficient building codes i.e., energy codes. It is through the use of these codes that we have a viable avenue of softening the environmental impact of buildings as well as generating energy and cost savings that extend far into the future. These codes are also responsible for driving much of the wide scale implementation of energy efficiency in buildings, even though much of the public is unaware of this until they are confronted with purchasing a new home or renovating an existing one. Even then, the long term benefits and/or additional cost may not be completely understood by current and prospective homeowners. Those not “in the know” might consider these codes unnecessary or too costly. It is true that they can come at an additional cost, but the costs offer paybacks, not only in terms of energy saved, but also in the reduction of climate impacts and the protection of our environment. This is clear after looking at the data analysis done in this thesis, particularly for the lower energy savings levels.

Energy codes establish the criteria for a buildings thermal envelope, HVAC systems (heating, ventilation, and air conditioning), water heating systems, lighting, and other areas dealing with energy use. These codes serve as a baseline from which both residential and commercial buildings can achieve a minimum level of energy-efficiency. The two most commonly adopted energy codes are the International Energy Conservation Code (IECC) and ANSI/ASHRAE/IES standard 90.1 (ASHRAE 90.1). The IECC can be applied to all buildings while ASHRE 90.1 only applies to commercial buildings. Both IECC and ASHRAE standard 90.1 are maintained and updated in open public forums. This kind of transparency is of utmost importance to the widespread acceptance of the resulting energy codes. Those participating in the maintenance and upkeep of these energy codes include a wide array of interests. Representatives from the design community, code enforcement community, policy makers, builders, industry, utilities, advocacy groups, academia, and federal agencies, such as the DOE, are all involved

(DOE 2010). Through collaboration, all stakeholders have an opportunity to participate and voice their technological, economic, and policy concerns as they relate to the maintenance of the codes. Without organizations like ICC and ASHRAE, each government agency, from federal down to the local government, would need to develop its own, similar standards. This would lead to an immeasurable amount of additional work and would threaten code uniformity, which is essential for the building industry. Thankfully, the development and maintenance process of these model codes and standards is not as much of a concern as is the adoption of these codes.

In the United States, there is no national energy codes or standard. This means that the responsibility of adopting model codes, such as the IECC and ASHRAE 90.1 fall to the state and local levels of government. Adoption occurs through legislative action or regulatory agencies authorized by the legislative body. Once they are adopted through regulation, the building energy codes become law within that state or local jurisdiction. At the federal level, the DOE's Building Energy Codes Program (BECP) provides the technical support to state and local governments in order to help assist in the adoption process (DOE 2010). This assistance includes energy savings and cost analysis, comparative analysis of future code options, potential modification of model code, educational materials, training, and compliance resources. They also provide a State Energy Program (SEP) that provides grants to states so that they may carry out their own renewable and energy-efficiency programs.

While the main goal of energy codes is to conserve energy, there are a number of additional benefits that are also realized. From the national government to states and local municipalities, all the way down to the homeowner, there are a range of energy, economic, and environmental benefits to be had from energy codes. This has been recognized by the national government, and, although there is no national building code, Congress has been trying for decades to encourage states and local authorities to adopt progressively stronger energy codes for all new buildings. Two major contributing statutes are the 1992 Energy Policy Act, which directs the states to consider the model residential energy code (IECC) and to adopt the model commercial energy code (ASHRAE standard or equivalent) with updates (U.S. House 1992) The other is the American Recovery and Investment Act of 2009, which requires states to commit to adopting and improving compliance with the 2007 ASHRAE Standard and the 2009 IECC as a condition for receiving their share of the $3.2 billion State Energy Program grants (U.S. House 2009).

Thus, while there are many recognized benefits of adopting energy efficient building codes, this doesn't necessarily mean that the benefits will lead to adoption. This has to do with the fact that every benefit comes at a cost and sometimes states or localities must weigh them according to their own goals and motivations. This is partly why one of the most easily recognized and appreciated benefits is the substantial money savings that results from the adoption of energy codes. It is estimated that building codes could potentially produce a financial benefit to homeowners of $2 billion annually by 2015, rising to $15 billion by 2030 (DOE 2013). This is the result of saving over 14 quadrillion Btu of energy from 2009 to 2030. Studies also show that transforming the building sector so that it employs more energy efficient designs and equipment as well as solar could cut projected household energy expenses from $285 billion down to $130 billion by 2030. While there could be a modest initial increase in cost for these improvements, the investment will offer a payback in lower energy bills and even make homes more affordable to the consumer by lowering their total monthly cost i.e. mortgage plus utility bills. This initial increase in cost for a new home often pays for itself in as little as 12 months (Mississippi Development Authority 2013). In California, the state has saved businesses and residents more than $15.8 billion in electricity and natural gas costs since 1975, with these savings expected to climb to $59 billion in 2011 (EPA 2012) Apart from the obvious savings, however, energy-efficient buildings can also result in reduced maintenance costs. These result from improvements that reduce total building maintenance due, for example, to problems that occur from condensation, excessive runtimes of heating/cooling equipment, pest infestations from improper sealing, and the additional cost that comes from fixing such problems post construction. On the other hand, failing to take advantage of the building sectors potential savings could raise the cost of meeting our long-term climate goals by at least $500 billion per year globally (Houser 2009).

With climate change as a major motivation for many entities to adopt energy codes, the resulting emission reductions also become a great benefit. Buildings use a significant amount of energy and thus result in a significant amount of pollution, particularly carbon from our substantial coal use in electricity generation. Projected savings from energy code adoption could reach 800 million metric tons of CO_2 by 2030, which is equivalent to removing 145 million vehicles from our roadways (DOE 2013). It was also found that states that adopted the federal building energy codes reduced household GHG emissions by 16% from 1986 to 2008 (DOE 2013). States are also realizing the benefits of reducing pollution through energy efficiency. The New York

Energy Conservation Construction Code (ECCC) reduces CO_2 emissions by more than 500,000 tons annually and reduces SO_2 by nearly 500 tons per year (EPA 2006). Also, the 2001 Texas Building Energy Performance Standards are projected to reduce nitrogen oxide emissions statewide by more than two tons each peak day and over one ton each average day, which helps the state meet Clean Air Act requirements for nonattainment areas (EPA 2006). While it may be difficult to quantify these benefits in monetary amounts, they are still a great benefit of energy codes particularly in regards to climate change goals.

Building energy codes also provide jobs and economic stability as a benefit. The use of innovative and improved technology in buildings and the need for energy code experts will create new job opportunities around the country. New codes means new technical experts will be required in areas such as duct and air leakage, quality control, building and systems commissioning, energy auditing, and compliance (DOE 2013). Even requirements for retrofitting and weatherization could create new employment opportunities. Also, instead of sending money out of the state, as is often the case with energy services, dollars saved from efficiency tend to be re-spent locally, thus booting the economy (EPA 2012). As for the consumer, reducing heating and cooling costs allows more money to be saved and thus spent on other good and services, which are essential to a healthy economy. The same also goes for business owners who have more money to spend on business improvements such as additional investments or employee benefits. Another aspect of building codes is that that they have the potential to support grid reliability through system sizing and increased controls. By decreasing the impact of peak loads, these codes help reduce the stress on the grid, thus creating a reliable grid and a reliable economy. When the lights are out, it is hard to keep things running. Lastly, reducing our nations dependency on foreign energy sources is one of the greatest benefits energy codes can have on our economy. In a global market, things can be hard to predict and control, so making us less reliant on other country's resources secures our economic stability.

Additional benefits are realized come from the positive health aspects of energy codes. By reducing pollution, including GHG emissions, and by improving the indoor air quality of buildings, energy codes keep consumers comfortable and healthy. The Center for Disease Control and Prevention found that burning fossil fuels contributes to numerous health issues such as asthma, bronchitis, pneumonia, and low birth rate (CDC 2013). As a result, people that may not have gotten sick under lower emissions levels may end up at the hospital, resulting in higher health costs overall. By reducing our fossil fuel emissions we can actually lower the risk of related health problems. Apart from the environmental pollutants, energy-efficient buildings often reduce other health risks from things like mold, dust, radon, pollen, rodents, insects, and combustion products (Mississippi Development Authority 2013). These health concerns are often seen in old houses and those that are not up to code. Further health benefits arise from the fact that energy codes result in a more comfortable home and can help alleviate problems with outdoor noise, muggy air, condensation, and hot and cold areas. These examples go to show that improving building efficiency in energy codes can have far-reaching benefits that extend all the way to anyone who interacts with our built environments i.e., basically everyone.

While there are numerous benefits that these continual energy code improvements provide, they do not come without a price. Improving efficiency requires making new investments and making investments requires spending money now so that we may save or make money in the future. Thus, one way to understand building codes is to think of them as an investment. They are an investment that provides numerous benefits, including energy and cost savings, but at the same time, must come with an initial increase in cost. With each new model code, the Department of Energy performs its own evaluation to determine whether the new codes will actually save energy and, in turn, save money. If it weren't required that building codes utilize a minimum level of cost-effectiveness, then they would likely be extremely difficult to implement and enforce. However, as it turns out, building codes are one of the most fundamental, affordable, and effective methods for increasing long-term efficiency of our nations buildings despite any increase in costs they may have. It is a great misconception that upgrading our building energy codes requires an increase in cost that is not easily offset. While it is true that building a home to meet a new code or retrofitting an old house up to code is going to cost more, this increase will quickly be paid back through lower utility bills. The long-term savings this provides will actually make the energy-efficient home more affordable than the same home not built to code.

Looking at the whole picture, building energy codes provide great benefit with relatively little cost. Thus, while climate change impacts become increasingly severe, there is an urgent need for viable, cost-effective solutions that target key areas of great energy consumption and pollution. With buildings consuming about 40% of energy, building energy codes seem a suitable place to start. The process is in place and model codes are continually being designed and implemented. However, there are still costs that are keeping some states and localities from adopting up-to-date model codes. There are also those states that have adopted the new codes, but are lacking in enforcement resources. This goes to show that at each point along the energy code path there is room for improvement. Much of it has to do with identifying places or areas where the costs are too high and pouring resources that way, as is the case with photovoltaic. When we look at the final product of building codes, namely the code-compliant house, we see that the increase in cost that is passed onto the homeowner is repaid within a year or two. This shows that great benefits can be achieved nationwide, with relatively little or no cost to the consumer. Thus, the questions we should be asking are how do we get states and localities to adopt the latest codes? How can we shift resources and bring all the states up to date? More importantly though, how do we expand our ecological responsibilities cost-effectively and how are we going to redefine our relationship with the environment, moving forward?

These are questions that we don't have answers for yet. However, as time goes on, I suspect the red carpet will be rolled out for energy-efficiency. It's clear from this thesis that energy-efficiency measures can be cost effective and provide a substantial payback, we now need to get our building codes on board in the best way we can. It could be said that zero-energy homes are the goal and building codes are the path by which we get there. Thus, it may not be long before we see building codes that require PV installs as part of their energy code compliance or perhaps a Benchmark that requires a home to meet a net zero balance of energy.

Conclusion

One could imagine a world in which the current building practices no longer apply. Instead, all new buildings would be required to achieve a high level of efficiency and utilize renewable energy generation so that they contribute as much energy back to the grid as they consume. Of course, an advanced smart grid would be required and perhaps a complete expansion of our ecological responsibilities would be needed, but it is not impossible and in actuality, not very far off. In the face of climate change, population growth, and unsustainable energy use, zero-energy homes offer a fast, viable, and cost-effective path for moving forward into a clean-energy future. Much research has been and is being done on the potentialities of energy-efficiency, which is at the core of the ZEH philosophy. As money and effort are being poured into discovering new renewable technologies and new deposits of carbon-based energy sources, energy-efficiency is showing its face as the leader of a cleaner, more sustainable, and hopeful future. It's not just the built environment that is undergoing this change, but everything that requires energy will be looked at in a new light. Once it is widely recognized that it is easier to save energy than it is to produce it, then many objectives and motivations will change.

The objective of this thesis was to determine whether ZEHs and NZEHs are cost-effective in Washington. In doing so, energy-efficient home designs on the path to net zero were modeled for nine locations around the state. While each location showed similar results, this was primarily due to the scope being limited to one geographical region and, thus, a narrow range of climatic conditions. Nevertheless, it has been shown that, depending on several factors, a complete ZEH is possible to build and is cost effective. Cost-effectiveness ratios were calculated for each location thus indicating the price per percent energy-efficiency. These figures, while not particularly useful to consumers, could be used in developing policy or in comparing other regions ZEHs cost-effectiveness. It was shown that, as energy-efficiency increases, homes become less cost-effective to build. The greatest decrease in the cost-effectiveness comes at the point in which PV begins to be implemented, with it leveling off again once the PV limit is reached (this thesis was limited to an 8 kW system). This goes to show that the greatest determiner of cost-effectiveness has to do with the renewable energy generation, indicating that, as PV becomes more cost-effective, so will ZEHs.

Additionally, the return on investment was identified for each home at each location on the path to net zero. While the cost-effectiveness ratios are a great method of evaluation and comparison, they do little for the consumer curious about what to expect from a home that might provide a payback. In most cases, a home will be the greatest investment a family makes in their life. It is usually the most costly expense one incurs but, often, has the potential to provide a return in the future, depending on several factors. This is why it is so essential that an understanding is cultivated of what we can expect from a home with little to no energy bills. The data in this thesis suggests that, early on, on the path to net zero, the greatest returns will be provided below 30% energy efficiency, with those returns declining once PV is implemented. This, of course, is due to the high cost of PV relative the savings one receives from utility bills. However, the ROI is highly dependent on the discount rate as well as a number of other factors that were not considered in this thesis. For example, if conventional energy prices were to rise, as they continually do, within the time in which someone built a ZEH, they would begin to receive an even greater return on investment. Thus, ZEHs also provide an additional benefit, one that was not quantified here, namely security from rising energy prices. Also, as was mentioned in the analysis, under a 3% discount rate, ZEHs may not provide a 100% payback over their lifetime. However, people value things differently and, although a monetary quantification is usually a good standard, the benefits that come from having a home with little to no carbon footprint will be highly valuable to some people, especially as we observe the increasing effects of climate change.

Thus, hopefully this research serves as a starting point to encourage more economical evaluations of what one could expect from energy-efficiency buildings, particularly in the residential sector, where the consumer tends to drive demand. As with any investment, people want to see what they are getting themselves into and are wary of new and innovative concepts. This is why information can be used as a powerful incentive to drive market changes. In the meantime, however, the government, both federal and local, has a responsibility to drive change through building codes. As was covered in the discussion, this is the standard method of driving change in the building sector. Of course, there will be innovative builders at the forefront some were mentioned in the literature review but most change will be forced and it will be slow. However, if we are to take climate change and carbon mitigation seriously, small incremental changes every three years are not going to do it. Perhaps multiple building codes with varying levels of energy efficiency could be required. This way, consumers would have the option to choose a higher energy-efficiency package without all the misinformation or worry of what they are getting themselves into. Thus, in effect, we could create a standard building code as well as an energy-efficient code that could then be adopted as the standard after three years. Whatever happens, we need change and it needs to happen quickly. We've now surpassed an atmospheric CO_2 concentration of 400 ppm a first in human history. We can't expect to go on living the way we are, but we can't expect everyone to give up all of their luxuries either. Thus, compromises need to be made. We can have the luxuries of a typical home without requiring the combustion of fossil fuels. Since buildings have the potential to greatly reduce energy consumption and do it cost-effectively, why not start here?

References

Alliance to Save Energy. 2010. Building Energy Code Fact Sheet. <http://ase.org/resources/building-energy-codes-fact-sheet>.

Anderson, R., C. Christensen, and S. Horowitz. 2006. Analysis of residential system strategies targeting least-cost solutions leading to net zero-energy homes. ASHRAE Transactions **112**:330–341.

Anderson, R., and D. Roberts. 2008. Maximizing residential energy savings: net zero-energy home technology pathways. TP-550-44547.DOE. NREL. Golden, CO, US.

Attia, S. G., and A. De Herde. 2011. Early design simulation tools for net zero-energy buildings: a comparison of ten tools. 12th Conference of IBPSA. Sydney, Australia. November, 2011.

Attia, S., E. Gratia, A. De Herde, and J. L. M. Hensen. 2012. Simulation-based decision support tool for early stages of zero-energy building design. Energy and Buildings **49**:2–15.

Bergey, D., and K. Uneo. 2011. New England net zero production houses. Building Science Information. Research Report 1303. <http://www.buildingscience.com/documents/reports/rr-1103-new-england-net zero-production-houses/view>.

Bianchi, M. V. 2011. Challenges and opportunities to achieve 50% energy savings in homes: national laboratory white papers. GO-102011-3242. DOE.

Brown, C., Glicksman, and M. Lehar. 2010. Toward zero-energy buildings: optimized for energy use and cost. Massachusetts Institute of Technology. Fourth Conference of IBPSA. New York City, NY. August, 2010.

Carrilho da Graça, G., A. Augusto, and M. M. Lerer. 2012. Solar powered net zero-energy houses for southern Europe: feasibility study. Solar Energy **86**:634–646.

Christensen, C., Anderson, Ren, Horowitz, Scott, Courtney, Adam, and Spencer, Justin. 2006. BEopt software for building energy optimization: features and capabilities. TP-550-39929. U.S. DOE. NREL. Boulder, CO, US.

Danny S., P. 2009. Very low energy homes in the United States: perspectives on performance from measured data. Energy and Buildings **41**:512–520.

Deru, M., and P. Torcellini. 2006. Source energy and emission factors for energy use in buildings. TP-550-38617. DOE. NREL. Golden, CO, US.

DOE and EIA. 2012. State Electricity Profiles 2010. 0348(01)2. DOE. EIA. Washington, D.C., US. <http://www.eia.gov/electricity/state/pdf/sep2010.pdf.>.

DSIRE. 2012. Renewable energy cost recovery incentive payment program. <http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=WA27F>.

EPA. 2006. Clean Energy- Environment Guide to Action. 430-R-06-001. EPA. OAP. Washington, D.C. US <http://www.epa.gov/statelocalclimate/resources/action-guide.html>.

Farhar, B., and T. Coburn. 2008. A new market paradigm for zero-energy homes: a comparative case study. Environment. **50**:18–32.

Gray, M., and J. Zarnikau. 2011. Getting to Zero: Green Building and Net Zero-Energy Homes. Butterworth-Heinemann, Boston.

Hendron, R., and C. Engebrecht. 2010. Building America house simulation protocols. GO-102010-3141.U.S. DOE. NREL.

Houser, T. 2009. The economics of energy efficiency in buildings. Policy Brief 09-17. Peterson Institute for international Economics, Washington, D.C, US.

Hernandez, P., and P. Kenny. 2010. From net energy to zero-energy buildings: defining life cycle zero-energy buildings (LC-ZEB). Energy and Buildings **42**:815–821.

IPCC. 2007. AR4 SYR synthesis report summary for policymakers - observed changes in climate and their effects. <http://www.ipcc.ch/publications_and_data/ar4/syr/en/spms1.html.>.

Koch, D. C., W. J. Hutzel, J. M. Kutch, and E. A. Holt. 2011. Toward a zero-energy home: applying Swiss building practices/attitudes to U.S. residential construction. Journal of Technology Studies **37**:18–26.

Kolokotsa, D., D. Rovas, E. Kosmatopoulos, and K. Kalaitzakis. 2011. A roadmap towards intelligent net zero- and positive-energy buildings. Solar Energy **85**:3067–3084.

Levin, H. M., and P. J. McEwan. 2001. Cost-Effectiveness Analysis: Methods and Applications. Sage Publications, Thousand Oaks, CA.

Lopez, H. 2008. The social discount rate: estimates of 9 Latin American countries. Policy Research Working Paper WPS4639. The World Bank. Latin American and Caribbean Region.

Madeja, R., and S. Moujaes. 2008. Comparison of simulation and experimental data of a zero-energy home in an arid climate. Journal of Energy Engineering **134**:102–108.

Marszal, A. J., P. Heiselberg, J. S. Bourrelle, E. Musall, K. Voss, I. Sartori, and A. Napolitano. 2011. Zero-energy buildings – a review of definitions and calculation methodologies. Energy and Buildings **43**:971–979.

Miller, W., and L. Buys. 2012. Anatomy of a sub-tropical positive energy home (PEH). Solar Energy **86**:231–241.

Mississippi Development Authority. 2013. Energy Codes Create Better Homes. <http://www.mississippi.org/assets/docs/energy/homeowner-faq.pdf>.

Norton, P., and C. Christensen. 2008. Performance results from a cold climate case study for affordable zero-energy homes. ASHRAE Transactions **114**:218–229.

Osmani, M., and A. O'Reilly. 2009. Feasibility of zero carbon homes in England by 2016: a house builder's perspective. Building and Environment **44**:1917–1924.

Sartori, I., A. Napolitano, and K. Voss. 2012. Net zero-energy buildings: a consistent definition framework. Energy and Buildings **48**:220–232.

Srinivasan, R. S., W. W. Braham, D. E. Campbell, and C. D. Curcija. 2012. Re(De)fining net zero energy: renewable emergy balance in environmental building design. Building and Environment **47**:300–315.

Stern, N. 2006. The Stern Review Report on the Economics of Climate Change. HM Treasury. London, England.

Talapatra, A. 2009. Implementing energy efficiency in building codes based on the America clean energy and security act of 2009. Federation of American Scientists. Washington, D.C, US.

Tans, P., and R. Keeling. 2013. Recent monthly mean CO2 at Mauna Loa. NOAA/ESRL, Scripps Institution of Oceanography. <www.esrl.noaa.gov/gmd/ccgg/trends/, scrippsco2.ucsd.edu/>.

Torcellini, P., S. Pless, M. Deru, and D. Crawley. 2006. Zero-energy buidlings: a critical look at the definition. ACEEE Summer Study, Pacfic Grove, California. US.

U.S. Census Bureau. 2007.American Fact Finder. <http://factfinder2.census.gov>

DOE. 2010. Building Energy Codes 101: An Introduction. PNNL-SA-70586. <http://www.energycodes.gov/>

DOE. 2012. National energy and cost savings for new single-and multifamily homes: a comparison of the 2006, 2009, and 2012 editions of the IECC. PNNL-21329. DOE. Washington, D.C. US <http://www.energycodes.gov/sites/default/files/documents/NationalResidentialCostEffectiveness.pdf>

DOE. 2013. Building Energy Codes Program. <http://www.energycodes.gov/>

CDC. 2013. Climate and Health Program. Health Effects. <http://www.cdc.gov/climateandhealth/effects/default.htm>

EPA. 2006. National Action Plan for Energy Efficiency Report. DOE. EPA. http://www.epa.gov/cleanenergy/energy-programs/suca/resources.html

EPA. 2012. Consumer Energy Efficiency Fact <http://www.epa.gov/cleanenergy/energy-programs/suca/resources.html>

U.S. House.1992. 102nd Congress. H.R.776.ENR. Energy Policy Act of 1992

U.S. House. 2009. 11th Congress. H.R.111-5.ARRA. American Recovery and Reinvestment Act of 2009

Verbruggen, A., M. A. Marchohi, and B. Janssens. 2011. The anatomy of investing in energy efficient buildings. Energy and Buildings **43**:905–914.

Wang, L., J. Gwilliam, and P. Jones. 2009. Case study of zero-energy house design in UK. Energy and Buildings **41**:1215–1222.

Wholey, J. S., Harry P. Hatry, and K. E. Newcomer. 2010. Handbook of Practical Program Evaluation, 3rd edition. Jossey-Bass, San Francisco, CA.

Zhu, L., R. Hurt, D. Correa, and R. Boehm. 2009. Comprehensive energy and economic analyses on a zero-energy house versus a conventional house. Energy **34**:1043–1053