A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in partial fulfillment of the Degree of Master of Science

The cost margins of new high energy performance buildings: a comparison based analysis

Jonathan BRENES SALAZAR

July, 2014

Budapest

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ABSTRACT OF THESIS submitted by:

Jonathan BRENES SALAZAR

For the degree of Master of Science and entitled: The cost margins of new high energy performance buildings: a comparison based analysis.

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The Global Energy Assessment attributes one-third of global final energy use and energy-related CO_2 emissions to buildings. This thesis investigates how the investment costs of high energy performance buildings compare to their conventional alternatives from an investment, energy efficiency and climate mitigation perspective. The study considers data for forty-eight buildings in temperate climate regions and three single family homes in a warmer climate region of Europe, taking a comparison-based approach that weighs cost data of new high energy performance constructions against their conventional alternatives. In addition to the additional investment costs, the research analyses the cost of conserved heating and total energy and the cost of conserved carbon where calculable. An important limitation for this study was the lack of detailed reference energy and cost data, which leads to a recommendation that building data gathering and reporting should be improved to enable more precise and comparable assessments. The results provide evidence that it is possible to build new high energy performance buildings—such as those meeting the passive house standard—at similar to lower construction costs than their current conventional alternatives. Energy savings of up to 90% are reachable with negative investment costs. Given the high share of energy use and greenhouse gas emissions, and the never ending expansion of the building stock, a transition towards lower energy demand frontiers is imperative. This thesis helps bridge the awareness gap that comes in the way of this transition by providing evidence that high-performance, low-cost new buildings are possible.

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Keywords: energy efficiency, new buildings, cost-effectiveness, cost of conserved energy, cost of conserved carbon.

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Table of Contents

CEU eTD Collection

List of Tables

List of Figures

List of Appendices

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1 Introduction

1.1 Background

The Global Energy Assessment reports that energy use in buildings constitutes roughly one-third of total global final energy use as well as energy-related CO_2 emissions (Ürge-Vorsatz *et al.* 2012; Hamdy *et al.* 2011; Paumgartten 2003). Growth in wealth, population, and urbanization therefore makes energy efficiency in the building sector key for mitigation and a low-carbon future given the rise of energy services demanded (Ürge-Vorsatz *et al.* 2012, 663). Compared even to the most stringent national building codes, recent developments of building design promise substantial energy savings (Harvey 2013). According to the Global Energy Assessment, highly efficient commercial buildings have reduced energy use by at least 50% compared to local conventional practice at the time of the assessment (Ürge-Vorsatz *et al.* 2012, 689). Looking at the European Union, Balaras *et al.* (2007) points out that reducing energy demand is of importance in the region for energy independence, where fuel import projections for 2020 go up to two-thirds of total demand. Moreover, high energy performance design has also been noted to provide additional benefits such as improvements in health and productivity of occupants (Kats 2010).

In order to avoid a substantial "lock-in" of energy intensive design as the building stock is renovated and expanded, experts recommend the adoption of state-of-the-art energy performance standards in new and retrofit buildings (Ürge-Vorsatz *et al.* 2012, 654). Though there are different levels of what can be understood as high-performance buildings, they are characterized by low-energy demand. The most stringent labels in this sphere are

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the Passive House and Zero Energy Building (ZEB) standards (Harvey 2013; Rodriguez-Ubinas et al. 2014; Mlecnik *et al.* 2010). The adoption of the Passive House standard has been spreading in Europe, with roughly 57 thousand buildings according to Feist (2012). In Austria, for example, several cities use this standard for new municipal buildings (Harvey 2013). Several German cities have taken a similar approach; Frankfurt, for example, has applied the passive house standard to its public buildings for a decade (Linder 2014). After several years of providing financial support for exemplary buildings, the city of Brussels have required the passive house standard for all new public buildings since 2010 and will extend the requirement to private constructions beginning in 2015 (Clerfayt 2014).

According to the International Panel on Climate Change (IPCC), climate mitigation should aim to reduce energy demand, implement energy efficiency technologies, and switch to low and zero-carbon energy sources (Lucon *et al.* 2014, 54). However, the panel laments that models and consequent mitigation plans do not prioritize nor give the adequate level of importance to energy demand reduction methods.

Energy use projections for the building sector forecast a decline in OECD countries, and a significant rise in developing nations due to population growth, urbanization, and changes in wealth and lifestyle (Lucon *et al.* 2014). With this in mind, the IPCC warns that “without action, global building final energy use could double or even close to triple by mid-century” and estimates range from roughly 75% compared to 2010, to 150% growth from baseline energy use (Lucon *et al.* 2014, 48). Therefore, the rate by which high-performance constructions can contribute to reach climate mitigation goals is directly linked to how fast and how wide these constructions can spread, which is in turn linked to both political will

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and cost-effectiveness.

Despite an overall agreement that energy demand reduction by high-performance buildings can be cost effective, high-performance constructions are perceived to be much more costly than conventional buildings, which pushes energy and climate policy attention away from energy efficiency (Kats 2010). This perception needs to be refuted if high-performance construction is to be mainstreamed. Nevertheless, there is insufficient evidence available to policy makers and investors to provide a convincing case about the investment costs—and thus cost-effectiveness—of new high-performance buildings to create the political will necessary to proliferate these practices at the rate and scale needed for climate mitigation purposes (Harvey 2013).

1.2 Aim of research

The aim of this thesis is to contribute to filling this information gap by analyzing examples of new high energy performance buildings—with a focus on energy demand reduction measures—and compare investment costs of high-performance buildings to their conventional alternatives and determine their cost-effectiveness. Aiming to gain insights on new commercial and public constructions, the research considers a sample of 51 buildings—new constructions—49 of which are commercial and/or public, and 50 of which are in Europe (Table 2). This research is important given that it can provide useful insights to decision makers and encourage the proliferation of high-performance design for buildings and of more stringent building codes to levels that are more favorable for climate mitigation purposes. Thus, the thesis aims at answering the question:

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How do the investment costs of high energy performance buildings compare to their conventional alternatives from an investment, energy efficiency, and climate mitigation perspective?

The main objectives of this thesis therefore include the following:

1. To consider the marginal additional investment costs for high energy performance construction.
2. To analyze the cost of conserved energy and the cost of conserved carbon in order to contextualize investment cost margins from an energy efficiency and climate mitigation perspective.
3. To question the possibilities of negative cost margins for high energy performing buildings.
4. To consider factors influencing the cost-effectiveness of high energy performance buildings from an investment standpoint.

1.3 Structure of Research

The thesis begins with an overview of the literature with regards the role of the building sector in energy efficiency and climate mitigation, and introduces high energy performance design, relevant policies, and important economic principles to be considered for high energy performance constructions. Section 3 describes the methodology. Section 4 presents the results of the analysis on the cost margins for high energy performance buildings from various perspectives, and includes a case study on a new high energy performance commercial building in Austria. The discussion comments on negative cost margins and factors that influence the cost-effectiveness of high energy performance buildings. The thesis concludes with an overview of the findings and a recommendations that can help bridge the existing gap between energy demand reduction potentials and conventional construction practice.

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2 Literature Review

2.1 Energy demand reduction and climate change mitigation in buildings

Given the high share of final energy demand by the building sector and the resulting carbon emissions, an aggressive approach towards energy efficiency in buildings is much needed on a global scale for energy security and climate mitigation purposes. Whereas renewable technologies reduce the carbon intensity of energy supply, they are only one part of the solution. The literature agrees that energy demand reduction through investments in efficiency are the most logical first step to take towards a more sustainable energy system. For example, global estimates of greenhouse gas emission reduction potential from energy efficiency in buildings for 2020 are estimated at 29% of global CO_2 emissions by Ürge-Vorsatz and Novikova (2008). The building sector should first reduce energy demand by utilizing more efficient components, and the outstanding energy demand can then be supplied by renewable sources, which further reduces greenhouse gas emission (Zhu *et al.* 2009).

The majority of a building's energy demand is directed to meeting internal comfort levels of temperature, ventilation, and lighting; which means that climate conditions determine the extent to which building design should focus on heating and cooling (Ürge-Vorsatz, Eyre, et al. 2012; Lucon et al. 2014). Climate classification developed by Ürge-Vorsatz *et al.* (2012) illustrates the intermal comfort requirements by climate (Figure 1). Hamdy *et al.* (2011) point out that building energy consumption is largely dependent on thermal comfort criteria while pointing out that 77% of CO_2 emissions from heating the EU building stock at the turn of the century came from the residential sector.

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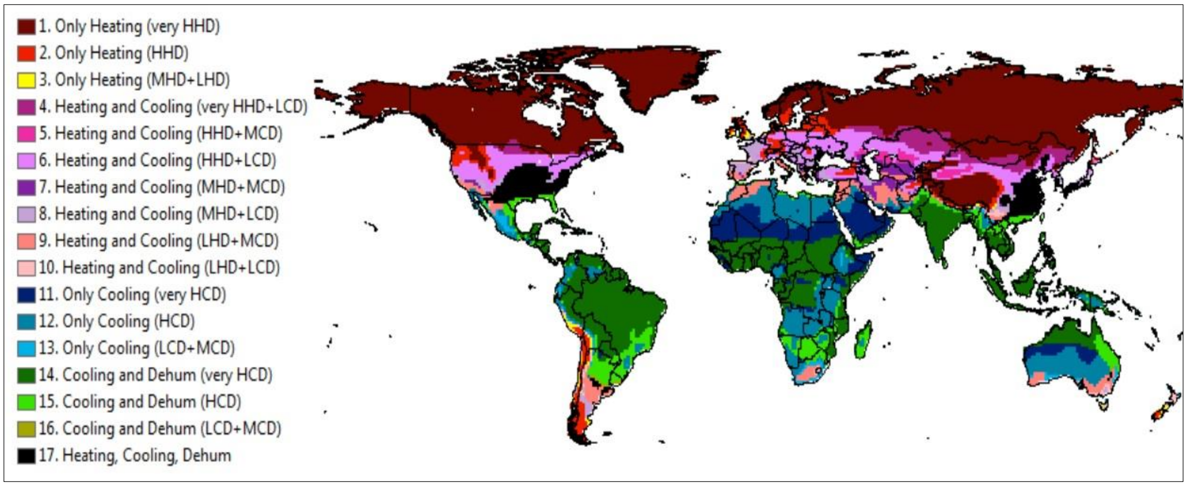

Figure 1: Composite Climate classification; climate identification number (1-17) according to this classification is referred to as "CID" from hereafter. Source: Ürge-Vorsatz, Petrichenko, *et al.*(2012)

Despite the high share of energy and related carbon emissions corresponding to the residential sector, commercial buildings have significant opportunities for energy demand reduction (Harvey 2013). Considering the relative scarcity of so-called "ecological buildings," Kimmo Kuismanen (2012)—from Ab Case Consulting Ltd. and architect of a high-performance office building in Finland included in the sample of this study—comments that the different uses and needs, combined with heat load contributions of office and commercial equipment are part of the reason why high energy performance in buildings is more complicated than for the residential sector. Similarly, the IPCC points out that behavioral and cultural influences can alter energy use by a factor of 3-5 (Lucon et al. 2014, 6). Conventional practice often meets comfort levels in buildings through *active*—energy consuming—technologies, such as heating and cooling units and fans (Sadineni *et al.* 2011). However, innovations in design have brought back an emphasis on *passive* methods of construction, which aim to meet comfort demands through passive building envelopes and ventilation methods, as well as prioritizing options for natural lighting (Sadineni *et al.* 2011).

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The application of energy efficiency technologies—both active and passive—contributes significantly to the reduction of final energy demand in buildings. Looking at new commercial buildings in the United States, Kneifel (2010) concluded that applying energy efficiency design can achieve 20-30% and up to 40% of energy savings on average with conventional technologies. However, the IPCC (Lucon *et al.* 2014, 16) estimates that really high energy performing buildings—using existing technologies—can achieve energy demand reductions of 50-90% in new buildings and 50-75% in retrofits, compared to their conventional alternatives.

Carbon mitigation interests are served as a side benefit to energy efficiency construction (Kneifel 2010). Nonetheless, reducing greenhouse gas emissions in buildings should be a primary goal in the long term as the building stock continues to expand. For example, Balaras *et al.* (2007) report that CO_2 emissions from buildings grew annually by 1.7% and four times as much in developing countries from 1980 and 1990. The IPCC stresses the importance of considering indirect emissions from electricity consumption and report that the highest increase in emissions from buildings are in Asia, where the building stock and energy use patterns have burgeoned (Lucon *et al.* 2014). Energy efficiency in buildings can also be translated into a reduction of carbon emissions. Kneifel (2010) estimates these reductions to average 16% for 10 years for all buildings.

2.1 Building design for energy demand reduction in buildings

There are various standards by which the construction sector aims to reduce energy demand in buildings. Conventional approaches incorporate low-energy design, which can feature a combination of active and passive improvements for efficiency and contribute significantly

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to energy demand reduction goals. Kneifel (2011) studied the cost-effectiveness of 12 commercial building types across the United States looking at conventional energy efficiency measures on roof, wall and window insulation to be code-compliant under ASHRAE 2004, 2007, and a Low Energy Case (LEC) design standards. He concludes that these technologies can reduce energy demand by 20% from 2004 standards and up to 30% using additional measures to those in LEC design. Whereas conventional design for energy demand reduction can be the best feasible alternative for demand reduction, a problem stemming from not maximizing the energy performance of buildings is the fact that less efficient buildings are "locked in" for the length of their life, thus reducing the potential for energy reduction and climate mitigation (Lucon *et al.* 2014). As Harvey (2013, 286) describes, "state-of-the-art buildings have energy requirements that are two to four times smaller than the most recent minimally code-compliant buildings."

There are various labels across Europe aiming to minimize building energy demand, such as the klima:active haus in Austria, casa clima in Italy, minergie in Switzerland, and effinergie in France (Mlecnik *et al.* 2010; Harvey 2013). However, the most ambitious standard for this purpose is the passive house standard, which was introduced in Germany and requires a heating and cooling load of no more than 15kWh/m^{2}yr regardless of climate and assuming a consistent indoor temperature of 20°C (Harvey 2013; Lucon *et al.* 2014, 19). Low-energy buildings in Europe are considered to use 30-60kWh/m^{2}yr for heating (Harvey 2013). The design approach for both passive house and low-energy buildings is known for substantially reducing heating and cooling loads by using passive design methods of construction and energy efficient technologies for insulation (Sadineni *et al.*

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2011). As a voluntary label, the passive house standard, and passive house technologies and design principles have been applied throughout Europe and other parts of the world.

As the terminology implies, Zero Energy Buildings take a step beyond the target of minimizing energy demand towards a virtual elimination of energy demand. Rodriguez-Ubinas *et al.* (2014) illustrate the design for the three classifications of the Zero Energy Buildings, which require energy generation as part of the construction to approach or attain zero-energy criteria (Figure 2). Based on the literature, the definition of what constitutes a zero energy building is still under discussion and there are varying terms and classifications in circulation. For example, Cortese *et al.* (2014, 56) criticize that the near ZEB approach advanced in the European Union only accounts for building energy use but excludes plug loads, and suggest that net zero energy buildings should be defined as including all energy used within a building. Whereas the abbreviations and terms for Zero Energy Building design vary slightly in the literature, Rodriguez-Ubinas' classification provides a clear description of this general category of construction.

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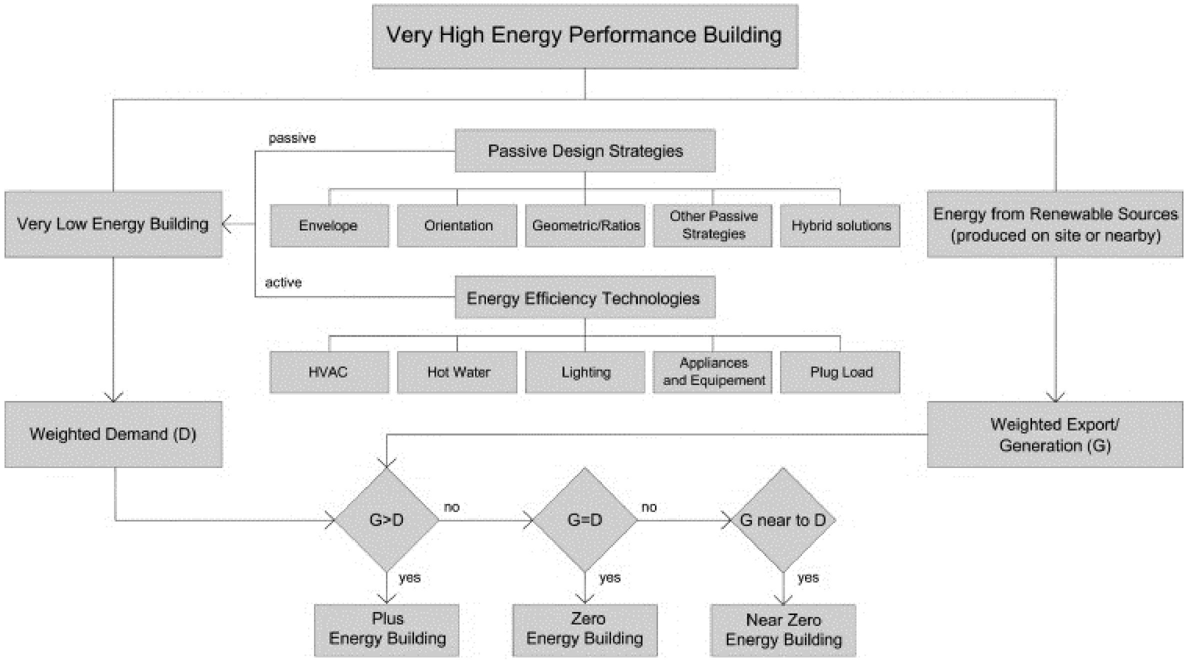

Figure 2: Zero energy building (ZEB) design approach. Source: Rodriguez-Ubinas *et al.* (2014).

The Nearly Zero Energy Building standard (NZEB) requires that a significant portion of energy use in the building be supplied by on-site or nearby renewable sources (Sartori *et al.* 2012; Kumitski *et al.* 2011; Rodriguez-Ubinas *et al.* 2014). This standard is implemented in the European Union as part of the Energy Performance in Buildings Directive (Rodriguez-Ubinas *et al.* 2014). Zero Energy Buildings have a more ambitious and clear definition than NZEB, and require the entirety of the building's energy demand within a year's time to be generated by renewable sources (Rodriguez-Ubinas *et al.* 2014). Lastly, a Plus Energy Building (PEB) is yet another classification of high-performance construction within this framework; as the name suggests, the energy produced by the building exceeds its own demand within a year (Rodriguez-Ubinas *et al.* 2014). Zero energy buildings can go hand in hand with the passive house standard, as the latter necessitates passive house design principles in order to reduce demand to a level that can be reached by renewable sources.

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2.1.1 Integrated Design Process

According to the literature, the most effective approach to reduce energy demand—and consequently greenhouse gas emissions—in buildings is through a holistic, systems-oriented design approach which is known as Integrated Design Process (IDP) (Lucon et al. 2014; Pacheco *et al.* 2012; Kneifel 2011; Kats 2010; Omer 2008; Levine et al. 2007; Lewis 2004). Pope and Tardiff (2011) describe the complexities and stages of IDP. As opposed to a traditional linear design where architects first develop plans for the building and then engineers chose the appropriate mechanical systems to meet internal comfort criteria, IDP uses energy modeling and involves all players in the construction and operation of a building in iterative charettes of design from the beginning stages of design, with a focus on reducing heating and cooling loads (Rodriguez-Ubinas et al. 2014; Lucon et al. 2014; Harvey 2013; Pope and Tardif 2011; Montanya, Keith, and Love 2009; Gowri 2005). Harvey (2013) discusses the effects of IDP on building costs and explains that IDP can downsize or eliminate systems needed to meet thermal comfort criteria. Commenting on a passive house school in the United States aiming to disprove the perception that energy-efficiency is costly, an architect is quoted by Ernst (2014), saying that "The investigational process is the most important aspect of designing an affordable Passive House" because it helps identify the best technologies for site-specific climactic conditions, and downsize mechanical systems. With this in mind, lack of expertise in IDP for energy efficiency can often be a barrier for the expansion of high-performance design (Harvey 2013; Mlecnik *et al.* 2010).

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2.1.2 Elements of design for energy demand reduction

Pacheco *et al.* (2012) provide an extensive overview of the design principles and objectives of high-performance design, which are also illustrated by Rodriguez-Ubinas *et al.* (2014) in Figure 2. The most important features are shape and orientation, envelope, passive heating, cooling and ventilation systems, but other passive features such as day-lighting can also reduce energy demand (Levine et al. 2007; Lucon et al. 2014; Ürge-Vorsatz et al. 2007). Climatic conditions define the technologies and design principles that—through an integrated design process—are to be used to minimize energy demand while meeting comfort criteria (Levine *et al.* 2007; Lucon *et al.* 2014). For example, long and cold winters in northern climates require heat-gaining design whereas longer and warmer summers in tropical and subtropical climates require particular attention to heat-blocking design principles.

2.1.2.1 Shape and Orientation

The shape of a building is fundamental for passive design, given that it determines the surface exposure to radiation, which in turn influences thermal exchange options (Pacheco *et al.* 2012). Similarly, the primary objective with regards to orientation is therefore to position the sides of the building in an angle that either maximizes or minimizes exposure to solar radiation for heating or cooling purposes depending on the climate (Pacheco *et al.* 2012). In northern latitudes with cold climate, for example, the largest surface area faces south so that solar radiation passively warms the building (Cortese *et al.* 2014; Pacheco *et al.* 2012).

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2.1.2.2 Envelope

A high-performance envelope in a building is arguably the most fundamental element of passive design because it controls internal comfort through insulation, air tightness, and eliminates thermal bridges where heat exchanges between the exterior and interior of a building can occur (Cortese *et al.* 2014; Pacheco *et al.* 2012). For example, a large portion of heat loss occurs in glazed areas, making them among the most thermal bridge-susceptible components of a building (Pacheco *et al.* 2012). Although Pacheco *et al.* (2012) discuss glazing as a separate element of design, glazing constitutes a part of a building's external layer and therefore of the envelope (Rodriguez-Ubinas *et al.* 2014). Depending on climate conditions and cost options, designers use different envelope technologies to increase the compactness (external surface area/volume) to drive down the heat transfer coefficient—known as U-value—of components (Pacheco *et al.* 2012). This is done by controlling the thickness, position, and material of the insulation layer (Pacheco *et al.* 2012).

A significant portion of the literature on high-performance design focuses on building envelope technologies. Sadineni *et al.* (2011) provide a thorough overview of the different technologies for the components of a building's envelop with energy demand reduction in mind, and make some references to the economics of some of these technologies. Some of the literature points to a potential problem of overheating due to tight and well-insulated envelopes in areas with high or rising temperatures (Ridley *et al.* 2014; Hamdy *et al.* 2011).

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2.1.2.3 Passive heating, cooling and ventilation

There are several technologies available, discussed by Pacheco *et al.* (2012), which provide passive methods for thermal gains exchanges for heating and cooling purposes, as well as ventilation methods. Hamdy *et al.* (2011) propose that designers pay equal attention to energy sources, ventilation and heat recovery as they do to the building envelope because regulations focusing on energy demand reduction in buildings are not linked to energy supply emissions.

2.2 Building energy performance requirements and high perceived costs

Building codes, regulations, and energy and climate policy should include energy performance requirements that encourage energy efficiency, especially given climate and energy security concerns. In the European Union, this purpose is encouraged by the Energy Performance of Buildings Directive (EPBD), which was introduced in 2002 and recast in 2010 (EC 2002; Rodriguez-Ubinas et al. 2014; Ploss et al. 2013). This directive prompts all member states to establish a minimum energy performance standard for public buildings by 2019 and by 2021 for all buildings, such that only nearly zero energy buildings are constructed by the latter (Ploss *et al.* 2013; Rodriguez-Ubinas *et al.* 2014).

The ambition of the EPBD along with the private sector involved in high-performance design has begun to spread passive design measures across Europe. For example, insulation and heat recovery requirements have yielded energy savings of up to approximately 30% according to Hamdy *et al.* (2011, 109). Moreover, initiatives at the municipal level have been among the most effective in leading by example and increasing the stock of very efficient buildings. Mlecnik *et al.* (2010) give an overview of initiatives in Austria,

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Germany, Belgium, France, and Italy aiming to mainstream energy-efficient design in buildings. For example, the city of Brussels has led an exemplary building campaign that has resulted in 350 000m^2 of passive buildings claiming not to have significant additional costs; and the city will set the passive house standard as the requirement starting in 2015 (Clerfayt 2014). These efforts are not limited to Europe; in the United States, for example, the District of Columbia has an ambitious goal of reaching carbon neutrality by 2032, which has given birth to various incentives for investments in high-performance design such as ZEB (Cortese *et al.* 2014).

Despite exemplary initiatives in cities, a significantly larger energy policy transformation is required in order to maximize energy efficiency and emission reduction potentials. In a presentation at the 18th international passive house conference, Diana Ürge-Vorsatz (2014), coordinating lead author for the third working group of the IPCC fifth assessment report, laments that placing building energy policies in the context of overall climate policy reveals that energy efficiency and building energy demand reduction is not a priority in the climate and energy policy agenda. Similarly, the United Nations Economic Commission for Europe (2012) comments on its web page that "in many countries, the regulatory and policy framework for energy efficiency market formation has not been developed and/or implemented yet." An important barrier to the transition towards a high energy performing building stock is the notion that the cost margins for demand reduction measures are too high (Kats 2010; Harvey 2013). Whereas energy efficiency is the most logical first step in the energy transition, the perception on investment costs is hindering the energy policy transformation that is required (Lucon et al. 2014; Harvey 2013). Nonetheless, according to a country-wide study in the United States by Kneifel (2011), state building code decisions

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are not based on energy or cost saving prospects. Therefore, an important policy objective to build the case for constructions that push the frontiers of energy demand reduction is to ensure that the cost margins do not come in the way of investors as the reason why less efficient buildings are locked into the building stock.

2.3 Costs of energy demand reduction in buildings

Determining the costs of energy demand reduction is difficult to separate from the total costs of the project. As Cortese *et al.* (2014, 22) state, "While energy efficiency and renewable technologies do have specific costs […] the design and technology tradeoffs due to the advanced systems can blur the line of incremental costs" (Cortese *et al.* 2014, 22). Vaidya *et al.* (2009) note that a fragmented, incremental costing approach creates a higher first cost barrier for high-performance design. Harvey (2013) agrees and explains that whereas regular design procedures are less costly, the costs for IDP can be higher given that engineers are involved since the early stages of design as opposed to after architectural plans have been completed. Whereas these balance out in the end by reducing other construction costs, Vaidya *et al.* (2009) lament that energy efficiency incentives often require investors to still bear some of these higher costs. This approach to cost projects often leads construction projects with a fixed budget to opt out of IDP, and thus for lower-performing constructions, which illustrates the need for an integrated approach (Vaidya *et al.* 2009; Harvey 2013; Cortese *et al.* 2014).

Cost-effective construction for energy demand reduction is possible. Lucon *et al.* (2014, 37) understand cost-effective, low-energy buildings as those where additional investments are "optimized with regard to the additional vs. reduced (e.g. simplified or no heating

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system, ductwork, etc,) investment requirements and no non-energy related 'luxury' construction investments are included." Studies claim that very high-performance new buildings are being constructed with very low to even negative marginal additional costs—compared to conventional buildings that meet current required standards, as can be seen in studies presented by Lucon *et al.* (2014), Harvey (2013), Ürge-Vorsatz *et al.* (2012, 691), Pope and Tardiff (2011), Kneifel (2010) and Montanya *et al.* (2009). These agree that cost margins are low given that reduced costs from smaller or avoided mechanical and electricity equipment can offset and even exceed any extra cost for high-performance envelope and any other energy efficiency construction methods. Estimates of cost savings from high performance constructions range between 50-80% for new constructions and between 25-70% for retrofits (Lucon *et al.* 2014; Levine *et al.* 2007; Harvey 2009). Zhu *et al.* (2009) conducted an energy and economic analysis for two homes with identical floor plans whereby one met zero energy standards and the other was a conventional baseline comparison. By comparing elements to the baseline building, they found that windows, lights, cooling, and roof technologies for the zero energy house are the most cost-effective passive technologies in reducing energy demand. Furthermore, although the literature suggests that negative upfront cost margins are attainable, the topic is still under debate; as Kolstad *et al.* (2014) warn, the extent to which negative margins exist can be overstated as a result of uncertainty and imprecise assumptions. Whereas the high costs of new technologies drive up the costs of high-performance buildings, low and negative cost premiums are believed to be more dependent on the design process than they are on the level of ambition in terms of energy efficiency (Lucon *et al.* 2014, 39; Harvey 2013; Kats 2010).

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2.3.1 Cost of conserved energy

Considering the cost margins of energy conservation can be an influential factor in promoting high-performance design. An insightful approach to estimate the cost-effectiveness of energy demand reduction measures is the cost of conserved energy (CCE), which accounts for the extra costs for every kWh/m^2 saved each year (Harvey 2009, 292; Stoft 1995). This measure is weighed against the lifetime of the project and is therefore heavily influenced by discount rate and assumed lifetime assumptions (Harvey 2013, 292; Lucon *et al.* 2014, 39). Krey et al. (2014) speak to the utility of the CCE and point to Suerkemper et al. (2012) who note that the value is not linked to the price of energy, which helps compare CCE to different energy prices (Figure 3).

Determining the cost of energy demand reduction is difficult to separate from the total costs of the project; Cortese *et al.* (2014, 22) state that although "energy efficiency and renewable technologies do have specific costs […] the design and technology tradeoffs due to the advanced systems can blur the line of incremental costs" (Cortese *et al.* 2014, 22). Moreover, the link to reference, less efficient, building technologies makes the valuation of the CCE very susceptible to the choice of reference (Krey et al. 2014).

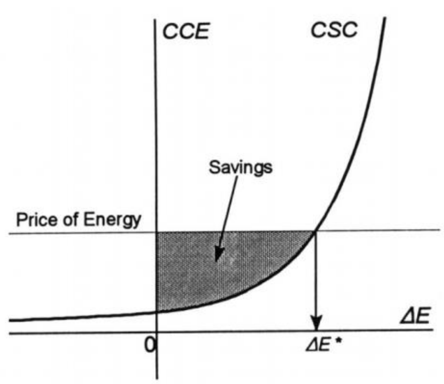

Figure 3: Conservation supply curve (CSC) based on the cost of conserved energy (CCE); the curve highlights the attainable savings from a cost-effectiveness perspective by comparing CCE to energy price. Source: (Stoft 1995)

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2.3.2 Cost of conserved carbon

Accounting for the costs of carbon emission reductions can deem high-performing building more attractive, particularly in regions where electricity generation has high greenhouse gas emissions (Kneifel 2010). Cost-effectiveness from an emissions reduction perspective can be measured by accounting for the costs of avoided emissions due to high-performance design through the cost of conserved carbon (CCC) (Lucon *et al.* 2014, 38). Though CCC has limitations due to assumptions necessary for emission factors, it can provide useful insights on how high-performance measures are contributing to climate mitigation (Lucon *et al.* 2014, 38). Negative cost margins are possible according to Ürge-Vorsatz and Harvey (Ürge-Vorsatz et al. 2007b), as a function of the life-cycle cost reductions of high-performance design.

Despite the challenges of assessing the cost-effectiveness of high-performance construction for energy demand reduction purposes, there is still a need to question the construction cost margins of energy efficiency in buildings, and to give reference to their energy and climate interests. Building political will to invest in high energy performance buildings is arguably the most important imperative to increase mitigation efforts on energy efficiency. However, financial barriers, and a lack of awareness and information induce significant limitations to the spread of energy-efficient design in buildings (Lucon *et al.* 2014). The most comprehensive attempt to address this issue on a global scale has been carried by Harvey (2009). Nonetheless, there is a lack of research on the costs for high energy performance constructions to determine their cost-effectiveness from an investment standpoint. Secondly, more awareness on the factors influencing the cost-effectiveness can be

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beneficial. Moreover, any insights with regards to negative cost margins can be useful in light of the debate on negative investment costs.

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3 Methodology

3.1 Design of research

Considering the frontiers of best practices from a cost and energy perspective, this study is based on the hypothesis that it is possible to build new high energy performance buildings, such as those meeting the passive house standard, at similar to lower construction costs than their current conventional alternatives. The research is designed under a comparison-based, quantitative approach, whereby energy cost data of new high energy performance constructions are compared to reference per-area energy and cost values in the same region (Harvey 2013). An effort was made to focus on new commercial buildings in Europe. However, data for other cases was also welcomed in order to leverage the limitations for the collection of detailed cost data within the timeframe of this research and the scope of buildings considered was ultimately expanded to include two new commercial buildings in the United States and three new residential buildings in Portugal (Table 2). Data analysis aims to identify the additional investment cost of each building compared to a reference building in the same region that does not meet high-performance energy demand criteria, based on construction cost data. The cost-effectiveness is not only assessed for investment costs, but also from a conserved energy perspective. It is important to note that since building costs are essentially compared to a less efficient version of themselves in the same region, geographical restrictions within the sample are not essential for cost-effectiveness deductions.

Whereas the ultimate goal of high-performance design should undoubtedly aim towards zero energy building standards, focusing on energy demand reduction is important in the

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short term given that renewable energy technology components push any possible higher initial costs even further away from cost-effective levels. As stated before, energy efficiency investments should in principle precede renewable energy investments in the sustainable energy pathway. Looking at the current energy-demand reduction options from a cost-effectiveness perspective can therefore help bridge the gap between current conventional energy standards and what they could become using existing technologies.

3.2 Data collection

With an aim to gain insights on the construction cost margins for new high energy performance buildings, data collection consisted of contacting architects, contractors and building-related institutions. In order to build a contact base to gather data for specific projects, I traveled to the 2014 World Sustainable Energy Days (WSED) international conference in Wels, Austria, and the 18th International Passive House Conference in Aachen, Germany. Correspondence with contacts for data collection occurred in person, via e-mail, and by phone (Table 1). During the WSED conference, I participated in a site visit to a new commercial building in Hörsching, for which I was able to collect detailed cost, energy and carbon emission values that allow for a more precise look at the cost margins of high-performance buildings (Table 5). Moreover, by virtue of attending these conferences, proceedings, materials and presentations provided useful insights for this research.

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Table 1: List of companies, organizations, and that were contacted for data collection purposes.

Company/ Organization	**Country**
Schachinger Logistik	Austria
Lang Consulting	Austria
Brussels Environment	Belgium
Baumann Consulting Lucerne	Czech Republic
Centrum Dasivního Domu	Czech Republic
Skanska	Czech Republic
Czech Green Building Council	Czech Republic
Architect	Czech Republic
Passivhaus Institut	Germany
Construction Office of Frankfurt a.M.	Germany
Advanced Building & Urban Design Ltd. (ABUD)	Hungary
Michael Bennett & Sons Building Contractors	Ireland
Architect	Italy
Wielkopolski Dom Pasywny (Passive House Poland)	Poland
Homegrid	Portugal
Minergie Association Switzerland	Switzerland
Econcept AG	Switzerland
Elemental Solutions- Energy & Water	United Kingdom
Passive House Trust	United Kingdom
Structures Design Build LLC	United States
Passive House Academy	United States
US Department of Energy	United States

Newly collected data was joined with a database for European advanced buildings, received from the Budapest-based consultancy Advanced Building and Urban Design (ABUD), which conducted studies in high-performance buildings in conjunction with the Center for Climate Change and Sustainable Energy Policy (3CSEP) of the Central European University. I also received data from past studies within the 3CSEP, which was also referenced during this research for climate and cost-related assumptions. A data collection

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template was developed based on this database and was consequently sent out to the contact base (Appendix 1).

The collection of detailed cost data that would allow for precise comparisons between the high energy performance buildings and their reference conventional alternative was one of the main challenges during this research. The European advanced buildings database was screened in order to exclude cases where actual cost or energy use data was questionable or missing, and when reference data for assumptions could not be applied. Ultimately, the sample of buildings considered include 23 cases from the European advanced building database and 29 newly collected cases. All buildings in the sample of this study are in the temperate climate conditions under Köppen-Geiger climate classification with the exception of one building in Finland, which is in a cold climate (see Appendix 2). The data was also classified under the composite climate classification developed by Ürge-Vorsatz *et al.* (2012), which has references to thermal comfort requirements (see Figure 1).

Table 2: Selected buildings considered in this study

Country	**No. of Buildings**	**Köppen-Geiger climate classification**	**Assumed CID Climate classification**	**CID Comfort demands**
Austria	1	Cfb	2	Only heating (High heating demand)
Belgium	23	Cfb	8	Heating and Cooling (Moderate heating demand and Low cooling demand)
Finland	1	Dfb	1	Only Heating (Very high heating demand)
France	2	Cfa & Cfb	8	Heating and Cooling (Moderate heating demand and Low cooling demand)
Germany	14	Cfa & Cfb	2 & 6	Heating and Cooling (High heating demand and Low cooling demand)
Italy	1	Csa	8	Heating and Cooling (Moderate heating demand and Low cooling demand)
Portugal	3	Csb	8	Heating and Cooling (Moderate heating demand and Low cooling demand)
Spain	4	Csa	8	Heating and Cooling (Moderate heating demand and Low cooling demand)
United States	2	Cfa	17	Heating and Cooling and Dehumidification
TOTAL	**51**			

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3.3 Analysis

The analysis of data was carried out through a comparison-based approach, which Harvey (2013) characterizes as the most common and includes the comparison of the costs for high energy performance buildings with those of a reference building in the same region that was built under conventional practice. The cost margins for energy demand reduction are analyzed through the cost of conserved energy (CCE), and cost of conserved carbon (CCC) when calculable. The level of detail for actual and reference energy and cost data determined the calculability of these values. In the face of this limitation, the analysis includes a case study for a new commercial building in Austria, for which I received detailed data (Table 5). The marginal costs for this building were estimated for total investment, conserved energy, and conserved carbon. For example, the cost-effectiveness of energy conservation is analyzed for heating energy demand reductions and total energy demand reductions based on the values provided for any specific case, and on the reference cost and energy demand values available.

In order to make building cost data comparable, cost currencies were converted to 2005 USD using annual exchange rate data from the European Central Bank (2014) (Appendix 3). Secondly, costs were depreciated with 2005 as the base year, using country-specific Construction Cost Index (CCI) values based on data released by Eurostat for Europe. Two cases from the United States were discounted using a Construction Price Index (CPI) obtained from the US Census Bureau (2014) for the two cases in the United States (Appendix 3). Specific assumptions applied to the selected cases in the sample are listed in Table 3.

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3.3.1 Cost of conserved energy (CCE)

The costs of high-performance construction from an energy conservation perspective were obtained by calculating the cost of conserved energy (CCE). The CCE weighs the investment for energy demand reduction against the energy savings over the project's lifetime (Krey et al. 2014; Worrell, Martin, and Price 2000; Stoft 1995). The assessment of conserved energy ΔE is analyzed by calculating the difference of what Cortese *et al.* (2014) refer to as the Energy Use Intensity (EUI)—namely a normalized value for a building's annual energy use per unit of area (kWh/m^{2}yr)—between high and reference energy performance. As they describe, low EUI values correspond to high energy performance, although the differences between building types and their energy use should be kept in mind. The energy conservation alternative can be regarded as cost-effective if the CCE is lower than the energy price (Stoft 1995; Krey et al. 2014). As proposed by Stoft (1995), the following equation illustrates the CCE:

$$CCE = \frac{Total\ costs\ of\ conservation\ (TCC)}{\text{Total energy saving } (\Delta E)}$$

In order to account for the lifetime of costs and savings, the cost difference between energy-conserving construction and the reference, conventional, building is annualized. With this purpose, the cost difference for high-performance construction, ΔI, is multiplied by a capital recovery factor (CRF), which considers the discount rate r and the lifetime n of the energy conservation project—and the lifetime is linked to the planned lifetime of the building—is factored in (Krey et al. 2014; Worrell *et al.* 2000):

$$CRF = \frac{r}{1-(1+r)^{-n}} \qquad TCC = \frac{\Delta I \times r}{(1-(1+r)^{-n})}$$

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3.3.2 Cost of conserved carbon

The carbon mitigation cost metric can allow cost-effectiveness comparison between different mitigation options; looking at the costs of demand reduction options in buildings can, therefore, help serve that purpose (Krey et al. 2014). By looking at the entire building's avoided carbon emissions based on energy demand reduction, no link to a specific high-performance technology can be made (Krey et al. 2014). To estimate the costs of carbon mitigation, the investment cost for high-performance construction, ΔI, is discounted over the lifetime of the building using the CRF, and divided by units of reduced emissions ΔC (Krey et al. 2014):

$$CCC = \frac{\Delta I \times CRF}{\Delta C}$$

The primary challenge in estimating the costs of avoided emissions from high-performance construction is accessing emission factors that adequately correspond to the pool of energy sources in a reason, and, therefore, represent the carbon emission levels in a particular place (Lucon et al. 2014). To avoid imprecisions within the timeframe of this study, the cost of conserved carbon was only analyzed for the case study building in Austria, for which actual and reference carbon emission values were provided.

3.4 Assumptions and limitations

An important limitation for this study was the lack of detailed reference energy and cost data. Discussing the life cycle cost-effectiveness evaluation for buildings, Ebel *et al.* (2014, 145) point to the fact that limitations of economic assessments may disfavor the cost-effectiveness of high-performance construction,

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> The main sources of major distortions [in cost-effectiveness assessments] are assignment of costs that are not related to energy efficiency, underestimation of life expectancy, failure to consider residual values at the end of the calculation period, unrealistic assumption on energy price increases, unreliable design and quality of measures, inadequate expectations on return and related discount rates, and lock-in effects.

In case reference cost data was not available for a specific project, low-end baseline assumptions were made—where possible—based on a survey of 2008 cost data for European buildings separated by building type (commercial, single family, and multiple family buildings) and climate (Table 3).

Table 3: Lowest best case heating and total energy consumption average (kWh/m^{2}yr) for typical reference building based on a study by Harvey (2013); these were summarized by Lucon et al (2014, 19) climate region and building type.

Climate Region	**Lowest Residential (Reference)**		**Lowest Commercial (Reference)**	
	Heating	Total*	Heating	Total*
Cold	60	63	75	115
Moderate	40	43	40	100
Hot-dry	0	13	20	60
Hot-humid	0	13	50	90

*Total lowest reference energy consumption, includes heating, cooling, ventilation and lighting energy demand (Lucon *et al.* 2014, 19).

Moreover, assumptions on reference heating and/or total annual energy demand by European buildings per square meter were based on energy consumption statistics provided by the Building Performance Institute Europe (BPIE) through their Data Hub for the Energy Performance of Buildings. These statistics are specific to each country and building type, and annual demand values are grouped by the ages of the buildings based on the year of construction; building stock information is also available (see Appendix 4). However, energy consumption reference data was not attainable for all the cases in the sample for this thesis.

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Table 4: List of assumptions applied to the selected sample of new high energy performance buildings

Country	References	Assumptions
Austria	Schachinger (pers.comm.); Hiebl (pers.comm.); Skarabela (pers.comm.); Building Performance Insitute Europe (BPIE)	• The reference baseline for heating energy consumption utilized for heating CCE was obtained from the BPIE Data Hub for the Energy Performance of Buildings, for commercial buildings in Austria built from 2001-2010, which only constitute education buildings.
Belgium	Hermans (pers.comm.); Timmermans (pers.comm.); Petrichenko (pers.comm.); Brussels Environment; Building Performance Institute Europe (BPIE)	• The reference baseline for heating energy consumption, according to Brussels Environment, is 106kWh/m²yr. In some cases, the source indicated an average of 150kWh/m²yr. • Reference construction costs assumed the lowest average cost for new commercial buildings in Europe in the CID climate classification 8, which corresponds to Brussels, and amounting to 2005USD 1594/m². This assumption was obtained from previous work of the 3CSEP, which developed a baseline of average construction costs for Europe based on CID climate classification from cost data for commercial buildings constructed in 2008 in the region.
Finland	Bird (2012); Egyed (pers.comm.); Building Performance Institute Europe (BPIE)	• The reference baseline total energy use was obtained from the BPIE Data Hub for the Energy Performance of Buildings, for office buildings in Finland, built between 2006 and 2010 (the latest available).
France	Hartkopf *et al.* (2009); Passivhaus Datenbank; Egyed (pers.comm.); Building Performance Institute Europe	• Reference baseline heating energy use in France was obtained from the BPIE Data Hub for the Energy Performance of Buildings for new educational buildings built after 2005 (latest available). • Reference total energy use in France for buildings constructed after 2005 was obtained from the BPIE Data Hub for the Energy Performance of Buildings
Germany	Passivhaus Datenbank; Egyed (pers.comm.); Harvey (2013); Lucon *et al.* (2014, 19)	• Final total energy demand was calculated by dividing primary energy consumption data by a factor of 2.75. • A reference baseline heating energy consumption of 40kWh/m²yr was assumed, which represents the lowest heating energy consumption for buildings in what Lucon *et al.* (2014, 19) classify as the "moderate "climate region that applies for Germany, according to Harvey (2013). • A reference baseline total energy consumption of 100kWh/m²yr was assumed, which represents the lowest total energy demand, including heating, cooling, lighting and ventilation--for "moderate" climates, according to Harvey (2013) and Lucon *et al.*(2014,19).

Italy	European High Quality Low Energy Buildings (euleb); Egyed (pers.comm.); Petrichenko (pers.comm); Building Performance Institute Europe (BPIE)	• Heating energy demand was calculated by dividing primary energy consumption data by a factor of 1.25. • The reference construction costs assumed the average cost low for new commercial buildings in Europe in the CID climate classification 8, which corresponds to the city of Empoli, where this building is located. The reference cost amounts to 2005USD1594/m². This assumption was obtained from previous work of the 3CSEP, which developed a baseline of average construction costs for Europe based on CID climate classification based on cost data for commercial buildings constructed in 2008 in the region.
Portugal	Gavião (pers.comm.); Marcelino and Gavião (2014)	• Reference heating, and total energy demand assumptions for single family houses in Portugal were obtained from the BPIE Data Hub for the Energy Performance of Buildings.
Spain	European High Quality Low Energy Buildings (euleb); Petrichenko (pers.comm); Egyed (pers.comm)	• The reference construction costs assumed the average cost low for new commercial buildings in Europe in the CID climate classification 8, which corresponds to the cities of Leida, Madrid and Navarra, where two of the buildings are located. The reference cost amounts to 2005USD1594/m². This assumption was obtained from previous work of the 3CSEP, which developed a baseline of average construction costs for Europe based on CID climate classification based on cost data for commercial buildings constructed in 2008 in the region. • Similarly, reference construction costs for a building in Sevilla, were assumed to be 2005USD 1447/m², which is the average cost low for new commercial buildings in Europe in the CID climate classification 17.
United States	Cohen (pers.comm.); Cohen (2014)	• Reference costs were obtained by calculating the average costs for dental clinic in Virginia, USA, according to the architect, which range from USD $155-$200 per ft² at the time of construction, according to the architect. Costs were converted in to $/m² and the minimal costs were assumed.

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The valuation approach of the costs of high energy performance construction is difficult in the face of data availability and the need for assumptions. Precise accounting of for the CCE in high-performance buildings requires a representative discount rate and a lifetime that matches the lifespan for which a building was designed to last (Stoft 1995). Unless precise values were received, the analysis assumes a discount rate of 3%, as assumed by Lucon et al. (2014) and Harvey (2013), and lifetime values were assumed at 30 years for retrofits, and 40 years for new constructions, to reflect the assumptions of Lucon *et al.* (2014). Moreover, Stoft (1995) explains that the costs of energy conservation are not all upfront as there are maintenance and operation costs, and points to a greater problem in matching the stream of payments to the stream of energy saving returns. Whereas a levelized cost approach as proposed by Stoft (1995) and further explained by Krey *et al.* (2014) is ideal, accounting for maintenance and operation cost data was difficult in the timeframe of this study, especially given the lack of detailed data. Nevertheless, energy efficient technologies can arguably be expected to have lower maintenance and operation costs, and even longer lifetimes than their less efficient alternatives, which lower the CCE margins (Krey et al. 2014). In such case, the CCE could be expected to decrease further.

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4 Results & Discussion

The results of a comparison based analysis of the 51 selected buildings in the study sample corroborate that there are possibilities for very low and negative cost margins for high energy performance constructions in the commercial and public sector in temperate climate regions, and for three single family homes in warmer climate regions of Europe. A wide range of costs and energy demand reduction potential within new high energy performance—primarily commercial—buildings is also evident. Based on the sample, it is difficult to assess the evolution of costs over time, although they should be expected to decrease as energy efficiency technologies become more economical. As illustrated in Figure 4, a look at the investment costs for high energy performance buildings in this sample reveal a wide spread in costs in relation to the year of construction.

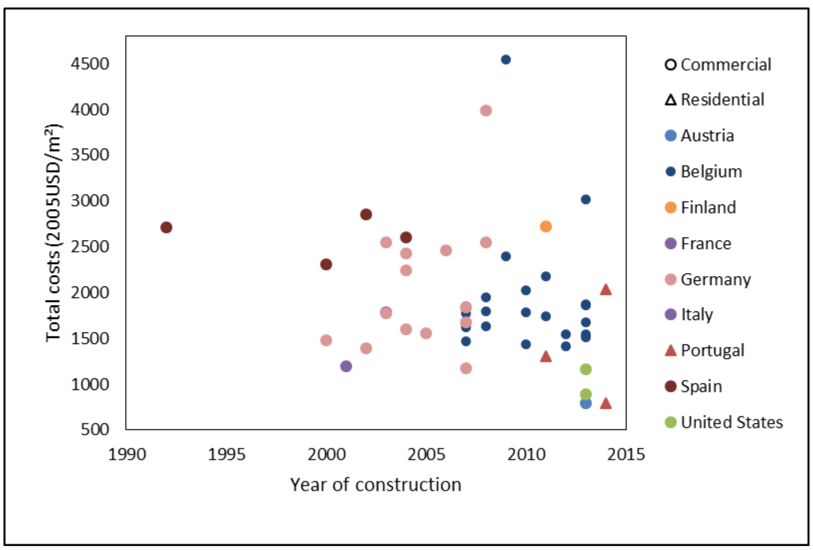

Figure 4: Total construction costs by surface area for high energy performance new construction projects in the sample according to the year of construction.

The results of the comparison analysis show that total energy savings from high-performance design can be reached with essentially no additional costs. The range of

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energy savings attainable for the selected sample of buildings, based on comparison analysis show that savings of over 50% are attainable at negative to low annualized investment costs (Table 4).

Table 5: Range of total and heating energy savings and annualized investment costs assuming a 40 year lifetime for new constructions, except for the case in Austria (25 years).

	Percentage energy savings		**Annualized investment costs**
	Total	*Heating*	
Austria		80%	2,6 2005USD/m²
Belgium		66%-92%	-7,6 to 128,8 2005USD/m²
Finland	88%		42,6 2005USD/m²
France	20%	41%-88%	8,4 2005USD/m²
Germany	7%-90%		-36,8 to 109,7 2005USD/m²
Portugal	56%-76%	91%-98%	-0,55 to 2,9 2005USD/m²
United States	50%-62%		-2,18 to -0,03 2005USD/m²

The cases in Portugal and the United States for which more precise reference costs were obtained, show energy savings of 50-76%, which were achieved with investment cost margins ranging from -5% to 5% compared to reference costs, and annualized investments that do not exceed 2005USD $2.9 per square meter (Table 4, Figure 6). Conversely, German passive house buildings in the sample show a wider range of marginal costs. Nevertheless, there is evidence for the possibility of negative and low additional cost margins. Moreover, it is important to note that energy saving estimates for German buildings in the sample are at the low end, given the assumptions made. Similarly, the cost of total conserved energy for the cases in Portugal and the United States suggest that negative marginal investments are also possible from an energy conservation perspective (Figure 6). A conversation with the architect of the two new commercial buildings from the

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United States highlighted the importance of the integrated design approach, since a fundamental element of design for these projects reportedly had no additional investment costs (Cohen pers.comm.).

Despite evidence for negative to very low cost margins, the analysis suggests that high energy performance buildings can also have significantly higher associated costs of investment. Whereas the French and Finnish cases do not have other national examples for reference, the sample-wide contextualization supports the idea that both energy savings and additional costs are fundamentally a question of design. Moreover, an important factor to highlight for the building in Finland is that the building strives to meet zero energy targets among other ecological design principles, which contribute to higher additional cost margins. Moreover, the cold climatic conditions that characterize the region may also contribute to additional requirements within the building's design to meet comfort targets.

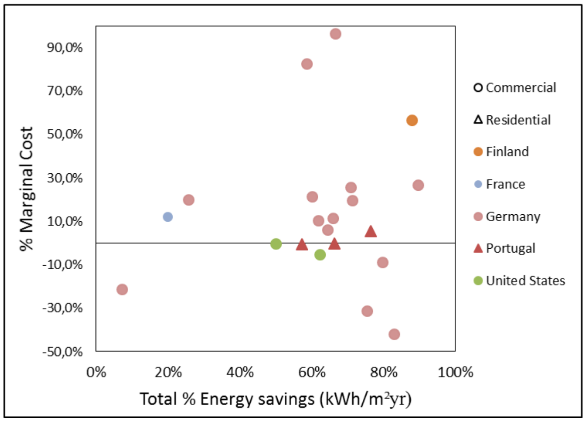

Figure 5: Additional costs for high energy performance buildings compared to energy savings by surface area.

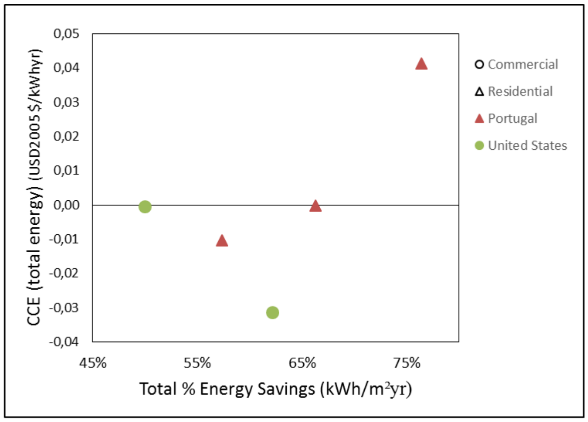

Figure 6: Cost of conserved energy (CCE) of 5 buildings as a function of the percent energy savings per surface area, compared to conventional construction in their each country.

Despite the lack of detailed data to calculate the cost of conserved energy based on total energy demand differences, heating energy demand differences can give some further

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insight into the energy conservation potential, as well as related costs. A preliminary screening of building data during this study considered data for 53 new public buildings meeting the passive house standard in Frankfurt, Germany provided by Linder (2014), which was ultimately excluded for comparability reasons. Assuming the minimal possible reference heating energy demand values for these buildings, minimum energy savings of 62.5% were achieved (Appendix 5). Cost analysis for heating energy saving for buildings in Austria, Belgium, France, and Portugal included in the sample show that heating energy demand reductions of 80% or above are possible with low and negative marginal investment costs (Figure 7). Moreover, CCE analysis reflects the same pattern and the majority of buildings in the calculation show that heating savings above 85% are possible under 2005USD $0.25%/kWhyr (Figure 8).

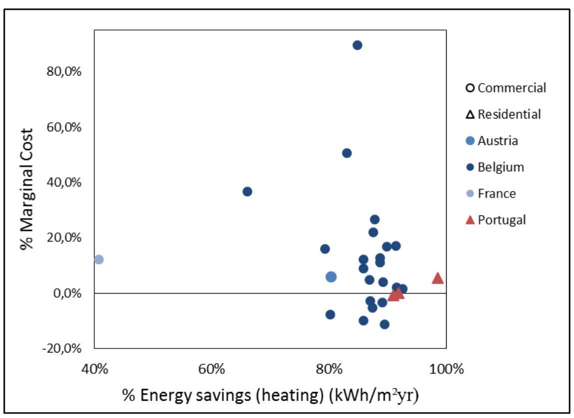

Figure 7: Additional costs compared to heating energy savings per surface area.

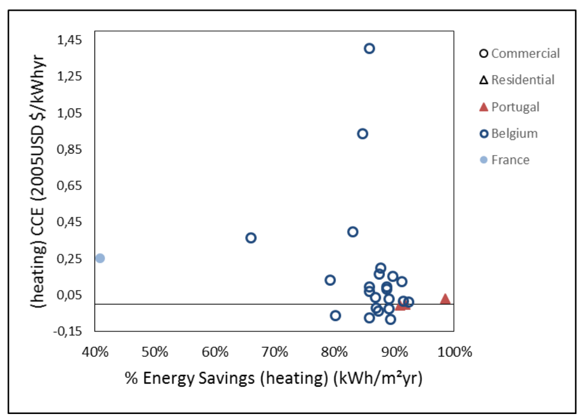

Figure 8: Cost of conserved heating energy as a function of energy savings by surface area for the high-performance buildings for which the metric was calculable.

In the face of skepticism regarding negative cost margins for high energy performance construction, the results suggest that significant energy savings are possible for a smaller investment than in case of a reference conventional building design. Whereas large

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negative marginal costs for high performance design justifiably raise questions about the assumptions made during the analysis, as Kolstad *et al.* (2014) warn, the analysis has a clear cluster of buildings with marginal costs approximating zero.

As mentioned previously, different assumptions can impact the cost-effectiveness of high energy performance construction at the marginal level. First, methodological limitations of cost analysis include lifetime and discount rate assumptions. Whereas assumptions about the lifetime applied to the selected building sample in this study arguably fall within a realistic range, matching cost analysis with the lifespan that architects assume or building owners expect can provide more useful insights from an investment standpoint. Likewise, the discount rate has a similar effect in marginal cost estimates. As sensitivity analysis presented by Lucon et al. (2014) illustrate, different discount rates can yield significant fluctuations in the CCE stemming from different discount rates (Appendix 7).

In light of these limitations of the assumptions made, it is important to keep in mind the deficit in detailed and comprehensive energy use and cost data for high energy performance and conventional buildings. Better orchestrated efforts to gather and report cost data would be extremely beneficial for the purpose of gaining a better understanding of the cost margins of high-performance constructions. Whereas different high-performance labels, certifying organizations, and governments have their own databases, detailed cost-related information is lacking. A conversation with a member of the UK Passivhaus Trust board of directors brought to light the problems of different reporting methods on costs for high-performance construction. In response, this organization is working to provide a methodology to report costs while building a cost database for the United Kingdom.

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Second, design factors may have an influencing role in the costs of high-performance design. The climatic conditions determine the technologies applied, which can vary in costs. Nonetheless, the rate by which climate can influence costs should not be emphasized given the extensive claims that an integrated design process has more significance in determining lower cost margins. With this idea in mind, the level of expertise and experience of the design team is, therefore, a fundamental factor for a low-cost, low-energy transition in the building sector, reflecting claims established by the literature (Lucon et al. 2014; Pacheco *et al.* 2012; Kneifel 2011; Kats 2010; Omer 2008; Levine et al. 2007; Lewis 2004).

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4.1 Case study: Schachinger Logistik LT1- new passive house commercial building in a temperate climate, Austria

The Schachinger Logistik LT1 building, in Hörsching, Austria, serves as a warehouse and includes 860m^2 of office space in the logistical park of Schachinger Logistik Holding, GmbH, and aims to become the benchmark for warehouses in Europe (Schachinger pers.comm.). Built to meet the passive house standard; among other ecological elements of design, wood was domestically supplied and the floor was cradle-to-cradle certified. Requirements for internal thermal and humidity levels are important given the use of the building.

Figure 9: Schachinger Logistik LT1, Hörsching, Austria

A detailed profile of the building, including a breakdown of the initial investment costs of and various energy consumption values for the Schachinger Logistik LT1 and a reference building is summarized in Table 5. A comparative analysis shows reductions in total primary energy demand by almost half through passive house design, and carbon emission reductions were also halved.

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Table 6: Detailed data for LT1 Warehouse of Schachinger Logistic Holding, GmbH. Sources: Skarabela (pers.comm); and Hiebl (pers.comm.).

Building Profile: Schachinger Logistik LT1			
Building Details			
Location	Hörsching, Austria		
Building Type	Commercial (Warehouse)		
Year of construction	2013		
Planned Lifetime	25 years		
Net floor area	11760m^2 (860m^2 office space)		
Gross volume	135105,92m^3		
Energy perfornace standard	Passive House		
Climate zone information			
CID Climate classification	2		
Köppen-Geiger Climate Region	Cfb		
CDD	<1000		
HDD	3168Kd (≥3000 and <5000 for CID climate region)		
RH	<50		
Average Temp	≤23°C		
Costs	**High performance**	**Reference**	**Savings**
Planning	€ 470 000		
Construction	€ 1 976 577		
Wood	€ 4 147 183		
Building equipment	€ 1 795 103		
Sprinklerplan	€ 314 640		
Total	€ 8 973 506		
Total costs per surface area	763,053 €/m^2 USD2005 798,02/m^2	USD2005 752/m^2	6%
Energy consumption	**High performance**	**Reference**	**Savings**
Total primary energy demand	62,7 kWh/m^{2}yr	123,0 kWh/m^{2}yr	49%
Primary energy demand including renewable energy	17,77 kWh/m^{2}yr		
Heating demand*	2,28 kWh/m^{3}yr 10 kWh/m^{2}yr	4,38 kWh/m^{3}yr 50kWh/m^{2}yr**	48%
Cooling demand*	0,54 kWh/m^{3}yr 19 kWh/m^{2}yr	0,63 kWh/m^{3}yr	14%
Total final energy demand	29 kWh/m^{2}yr		
Carbon Emissions	**High performance**	**Reference**	**Savings**
Total carbon emissions	10 kg/m^{2}yr	21,5 kg/m^{2}yr	53%
Additional notes			
Heating days	224		
Average U-value:	0,146 W/m^{2}K		
Wells and heat pumps (3 each)	340KW capacity		
Photovoltaics	200kWp capacity		
Reported side benefits	increases in productivity; workers prefer to work in this building		
Project timeframe	Planning (4 months); construction (5 months)		
*Target indoor temperature is assumed at 14°C. Internal condition requirements are 60% humidity and 14-18°C			
**Assumed			

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The cost analysis of the building compared to reference values provided by the building owners reveal an additional investment of 6% (Table 6). The cost of conserved heating energy by surface area is of USD2005 7 cents per kWh. Carbon emission values were provided by the owner, which allowed for a precise assessment of the cost margins from a climate mitigation point of view. The analysis of the cost of conserved carbon shows that additional costs for reducing carbon emissions by 53% compared to a reference building are of USD2005 17 cents.

Table 7: Results of comparison-based cost analysis for Schachinger Logistik LT1

Total Investment			Conserved Energy				Conserved Carbon		
ΔI (USD2005 $/m²)	Annualized investment (USD2005 $/m²)	Marginal cost (per surface area)		ΔE	Savings	CCE (USD2005 $/kWh)	ΔC (Kg/m²yr)	Savings	CCC (USD2005 $/kgyr
45,67	2,62	6%	Heating (kWh/m²yr)	40,14	80%	0,07	11,5	53%	0,17
			Thermal (kWh/m³yr)	2,19	44%	1,20			

From an energy efficiency and climate mitigation perspective, the Schachinger Logistik LT1 building is arguably within a cost-effective range. In addition to the low cost margins for total investment and conserved energy and carbon, the fact that the design and construction of the building was completed within 9 months speaks to some of the many additional benefits of the project; especially given the use of the building as a warehouse facility, reducing the time before the building can be used serves the economic interest of the owner. Reflecting claims in the literature about extensive side benefits from high-performance design, the owners report gains in productivity and employee satisfaction (Schachinger pers.comm.; Ürge-Vorsatz et al. 2007b).

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Both the case study and several other buildings included in the sample for this study highlight the fact that leading by example is among the most effective methods to challenge the lack of awareness and skepticism about costs that slow down the transition towards a low and zero energy building stock. Irrespective of lags in national and global policies that advance high-performance building design towards becoming conventional practice, municipal initiatives have proven to be instrumental in building the case for energy efficiency from a policy perspective. The cases from Belgium considered in this thesis are the result of an exemplary building initiative in the city of Brussels that aims to transform the city's building stock towards low energy while showcasing the range of benefits high-performance design brings (Clerfayt 2014). Similarly, buildings from the city of Frankfurt, Germany, follow a municipal commitment to the passive house standard (Linder 2014; Appendix 6). Among other cities, municipal initiatives bear witness to the idea that political will is elemental for improvements in the energy intensity profile of the building stock.

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5 Conclusion

This thesis investigated how the investment costs of high energy performance buildings compare to their conventional alternatives from a total investment, energy efficiency, and climate mitigation perspective. Considering the significant role of the building sector in reducing both energy demand and greenhouse gas emissions, it is of great importance to provide evidence about the existing possibilities for substantial energy savings at low cost margins in order to build the political will necessary for a transition towards a high-performance building stock. Aiming to focus on new commercial and public buildings in Europe, this thesis considered cost and energy use data of 51 buildings meeting the passive house standard or other low-energy targets through a comparison based approach that relates the high-performance building to a reference conventional construction in the same region. The marginal additional investments for high energy performance construction and the cost of conserved energy were calculated where possible. Additionally, a case study of a new commercial building meeting the passive house standard in Austria provides a detailed building profile and the cost analysis also estimates the cost of conserved carbon.

The results of a comparison based analysis provide evidence about the possibilities for low and negative cost margins for high energy performance constructions in the commercial and public sector in temperate climate regions, and for three single family homes in warmer climate regions of Europe. Total energy savings of up to 90% are achieved with annualized investment costs that range from 2005USD -36.8 to 109.7 per square meter. Heating energy demand reductions of 80% or above are possible with low and negative marginal investment costs. Moreover, a detailed and close look at the case study in Austria reveals

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additional investments of 6% to achieve heating energy savings of 80% and carbon emission reductions of 53% with marginal costs of 2005USD 0.07 and 0.17 respectively.

From a cost effectiveness perspective, design factors such as the climate characteristics, comfort criteria, and the level of expertise and experience by the designing team of a new construction can all cause shifts in the cost margins of energy efficient construction. From a methodological point of view, the range of assumptions required in order to analyze the costs of a building are also influential to the costs of high-performance building. Especially in response to limitations of data availability and comparability, a recommendation resulting from this study is that building cost data gathering and reporting should be improved to enable more precise and comparable assessments of the cost-effectiveness of high energy performance building. This is of particular importance from an energy and climate policy perspective given the need to address any lack of awareness or skepticism on the possibility of high-performance, low-or-negative cost buildings.

Until now, voluntary commitments by the private sector and municipal governments have been instrumental in showcasing the wide range of benefits of high-performance design. From a policy perspective, municipal initiatives bear witness to the idea that political will is elemental for improvements in the energy intensity profile of the building stock. Given the high share of energy use and greenhouse gas emissions, and the never ending expansion of the building stock, a transition towards lower energy demand frontiers is imperative. This thesis helps bridge the awareness gap that comes in the way of this transition by providing evidence that high-performance, low-cost new buildings are possible.

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Appendices

Appendix 1: Data collection template

This template was sent by email in excel format for data gathering purposes. Cells included notes clarifying the information requested. The data collection template was translated into German, French and Spanish.

Building cost data collection sheet		Please fill in the spreadsheet for each individual case with as much information as you can provide. The rows highlighted in blue are the most important; rows in white are important but not essential.		
		Example	**1**	**2**
Building characteristics	**Location (country)**	Hungary		
	City	Dunaujvaros		
	Name of building	Solanova		
	Building type (SF,MF,C&P)	MF (Multiple Family)		
	if MF, how many units (flats)			
	If C&P, what use?			
	Type of project (new construction/ retrofit)	Retrofit		
	Year of construction			
	Year of renovation	2003-2006		
	Planned Lifetime of construction/retrofit (years)			
	Floor area (m2)	2326		
Final energy use (kwh/year)	**space heating**	30		
	space cooling			
	water heating			
	other			
	Total energy use			
Final Energy use before renovation (kwh/year)	**space heating**	220		
	water heating			
	Total (previous or reference) energy use			
	Energy savings (%)	86		
Costs	**Total costs of retrofit/construction**	581500		
	currency	Euro (€)		
	Cost for energy efficiency measures			
	Components			
	Architectural			
	Legal			
	Design			
	General overhead			
	Reference Costs (same currency as costs above)			
	Key features: EE measures, RES technologies	Exterior wall, basement floor, roof, frame, glazing, entrance door, ventilation, district heating installation		
	RE production, kwh/m2			
	Notes	86, 36 % energy saving		
	Source of Data			
	Do you prefer anonymity?	No		

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Appendix 2: Description of Köppen-Geiger climate classification and defining criteria. Source: Peel *et al.* (2007, 1636)

1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 - MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 - MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

*MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

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Appendix 3: Economic assumptions

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Currency conversion factors. Source: European Central Bank (2014)																
	1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
USD/EUR	1,07	0,92	0,90	0,95	1,13	1,24	1,24	1,26	1,37	1,47	1,39	1,33	1,39	1,28	1,33	1,37
EUR/USD	0,94	1,08	1,12	1,06	0,88	0,80	0,80	0,80	0,73	0,68	0,72	0,75	0,72	0,78	0,75	0,73
Construction Cost Index (CCI) based on national construction costs. Base year= 2005. Source: Eurostat (2011); Eurostat (2014)																
		2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011***	**2012***	**2013***	**2014**
Austria		87,52	89,38	90,75	93,12	97,90	100,00	104,61	109,28	114,99	115,69	119,38	122,08	124,80	126,99	128,79
Belgium		92,28	92,83	94,50	94,90	97,23	100,00	104,90	109,58	112,30	111,08	111,07	115,43	117,57	117,89	
Finland		89,75	91,94	92,71	94,43	96,71	100,00	103,79	109,95	114,21	112,97	114,19				123,32
France		84,27	86,59	89,38	92,34	97,73	100,00	105,34	110,15	116,23	116,64	119,83	124,59	127,33	128,31	128,12
Germany		93,43	94,00	94,93	95,87	98,28	100,00	102,33	105,63	109,08	109,32	111,68	115,28	117,56	118,48	
Italy		84,34	86,22	89,62	92,28	96,16	99,99	102,78	106,54	110,58	111,65	113,34	116,77	119,44	120,19	116,66
Spain		85,59	87,92	89,36	91,28	95,57	100,00	106,86	112,20	117,47	118,69	121,71	126,32	125,98	126,36	126,66
Portugal		91,13	91,65	94,38	96,01	98,03	100,01	103,01	106,55	112,12	111,43	113,47	115,31	117,59	119,88	121,59
Construction Price Index (CPI). Base year= 2005. Source: US Census Bureau (2014)																
United States	72,80	75,60	77,90	81,40	86,00	92,80	100,00	104,70	104,90	99,50	95,10	95,00	94,30	97,60	104,70	105,90

*values for European CCI from 2011-2013 are based on values for new residential constructions due to the lack of more precise data.

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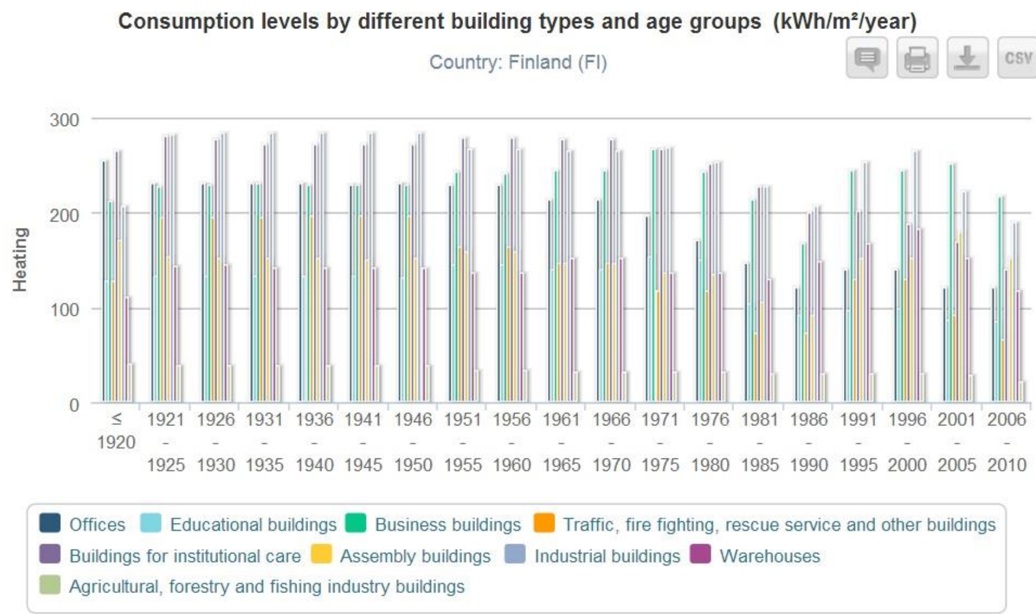
Appendix 4: Heating energy consumption for non-residential buildings in Finland. Source: Building Performance Institute Europe, Data Hub for the Energy Performance of Buildings.



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Appendix 5: Reference baseline construction cost averages for new buildings in Europe based on a survey of 2008 buildings, categorized into the composite climate split climate identification (CID), courtesy of the Center for Climate Change and Sustainable Energy Policy of the Central European University

CID	BT	Average cost: total (2005USD/m²)	Average cost: low & medium (2005USD/m²)	CID	BT	Average cost: total (2005USD/m²)	Average cost: low & medium (2005USD/m²)
1	SF	1614	1614	10	SF	1262	1172
	MF	2172	1838		MF	2771	2227
	C&P	1740	1548		C&P	2352	1501
2	SF	1390	1390	12	SF	1262	1172
	MF	1422	1223		MF	1730	1397
	C&P	2028	1711		C&P	1741	1374
3	SF	1262	1172	15	SF	1262	1172
	MF	2387	1857		MF	2043	1600
	C&P	2012	1703		C&P	1974	1576
6	SF	1011	827	16	SF	1262	1172
	MF	1121	888		MF	2693	1970
	C&P	1395	1153		C&P	2529	1931
7	SF	1262	1172	17	SF	1262	1172
	MF	2043	1600		MF	2167	1568
	C&P	1974	1576		C&P	1729	1447
8	SF	1033	855	All	SF	1262	1172
	MF	1467	1189		MF	2043	1600
	C&P	1824	1594		C&P	1974	1576
9	SF	1262	1172	SF- Single Family MF- Multiple Family C&P- Commercial & Public			
	MF	2504	1843				
	C&P	2389	1799				

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Appendix 6: Project cost data and estimated minimum energy savings for passive house public buildings in Frankfurt, Germany. Source Linder (2014).

CID Climate	Köppen-Geiger Climate	Location	Name of building	Year	Project Cost (USD2005$/m²)	Heating Energy* (kWh/m²yr)	Total Energy	Reference Heating Energy** (kWh/m²yr)	Reference Total Energy*** (kWh/m²yr)	% Energy Savings (heating)	% Energy Savings (total)
8	Cfb	Frankfurt (DE)	Zur Kalbacher Hohe 15	2004	1110	15	26,3	25	100	63%	74%
8	Cfb	Frankfurt (DE)	Berkersheimer Weg Strasse 26	2011	5001	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Sossenheimer Riedstrasse 13	2011	4507	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Platanstrasse 75	2011	3825	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Westerbachstrasse 175	2011	3622	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Schwanheimer Strasse 140	2009	3737	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Hamburger Allee 43: Bonifatiusschule Turnhalle	2009	4339	15	31	25	100	63%	69%
8	Cfb	Frankfurt (DE)	Gravensteiner-Platz 2	2011	6231	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Praunheimer Hohl 4	2011	4480	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Eichendorffstrasse 67	2012	4549	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Else-Alken-Strasse 3	2011	3821	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Pringstbrunnenstrasse 15	2012	4703	15	-	25		63%	
8	Cfb	Frankfurt (DE)	In den Schafgarten 25	2011	3794	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Kalbacher Hauptstrasse 54	2012	3175	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Friedrich-dessauer Strasse 2	2013	3564	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Idsteiner strasse 47	2011	2516	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Idsteiner strasse 47	2011	9159	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Schaumburger Strasse 66	2011	9495	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Wittelsbacherallee 6	2011	5910	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Hartmann Ibach Strasse 54	2012	14208	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Berger Marktplatz	2012	3986	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Ludwig Landmann Strasse 338	2010	4328	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Am Brunnengarten	2011	5175	15	32	25	100	63%	68%
8	Cfb	Frankfurt (DE)	West Hocher strasse 103	2011	3526	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Magda spiegl weg 10	2009	3117	15	42	25	100	63%	58%
8	Cfb	Frankfurt (DE)	valentin senger strasse 61	2011	3765	15	-	25		63%	
8	Cfb	Frankfurt (DE)	margarete susman weg 2	2010	2910	15	-	25		63%	
8	Cfb	Frankfurt (DE)	an der schwarzbachmuhle 20	2009	3891	15	-	25		63%	
8	Cfb	Frankfurt (DE)	platanenstrasse 9	2011	5519	15	-	25		63%	
8	Cfb	Frankfurt (DE)	in den aspen 2	2011	3681	15	-	25		63%	
8	Cfb	Frankfurt (DE)	deidesheimer strasse 10	2007	5053	15	-	25		63%	
8	Cfb	Frankfurt (DE)	weilbrunnstrasse 13	2012	4268	15	-	25		63%	
8	Cfb	Frankfurt (DE)	peter fischer allee 25	2008	4013	15	-	25		63%	
8	Cfb	Frankfurt (DE)	jaspertstrasse 71	2012	3301	15	-	25		63%	
8	Cfb	Frankfurt (DE)	kollwitzstrasse 3	2011	3571	15	-	25		63%	
8	Cfb	Frankfurt (DE)	boskoopstrasse 6	2007	4207	15	36	25	100	63%	64%
8	Cfb	Frankfurt (DE)	usinger strasse 24	2011	11025	15	-	25		63%	
8	Cfb	Frankfurt (DE)	niddagaustrasse 27	2011	4443	15	-	25		63%	
8	Cfb	Frankfurt (DE)	werner-bockelmann-strasse 3	2011	2550	15	-	25		63%	
8	Cfb	Frankfurt (DE)	im feldchen 26	2011	3684	15	-	25		63%	
8	Cfb	Frankfurt (DE)	landgraben 2	2011	4665	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Alexander-Riese-Weg 0	2011		15	-	25		63%	
8	Cfb	Frankfurt (DE)	Birsteiner Strasse 54	2012	3876	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Deutschherrnufer 109	2011	7605	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Gerbermuhlstrasse 110	2010		15	-	25		63%	
8	Cfb	Frankfurt (DE)	Ostparkstrasse 0	2011	9038	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Am Romerhof 9	2011	3692	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Theobald-Ziegler-Strasse 10	2011	4819	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Valentin-Senger-Strasse 9	2011	3886	15	26,5	25	100	63%	74%
8	Cfb	Frankfurt (DE)	Sossenheimer Weg 50	2011	5623	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Mierendorffstrasse 6	2011	4402	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Wilhelmshoher Strasse 124	2009	4048	15	-	25		63%	
8	Cfb	Frankfurt (DE)	Josephskirchstrasse 9	2011	2207	15	22	25	100	63%	78%
8	Cfb	Frankfurt (DE)	Alt-und Neubau: Lange Strasse 30-36	2011		15	41	25	100	63%	59%

* Assumption: Passive House standard maximum heating demand.

** Assumption: lowest possible heating energy demand for new constructions in a "moderate"climate region (Lucon et al. 2014, 19).

**Assumption: lowest possible total energy demand for new constructions in a "moderate"climate region (Lucon et al. 2014, 19).

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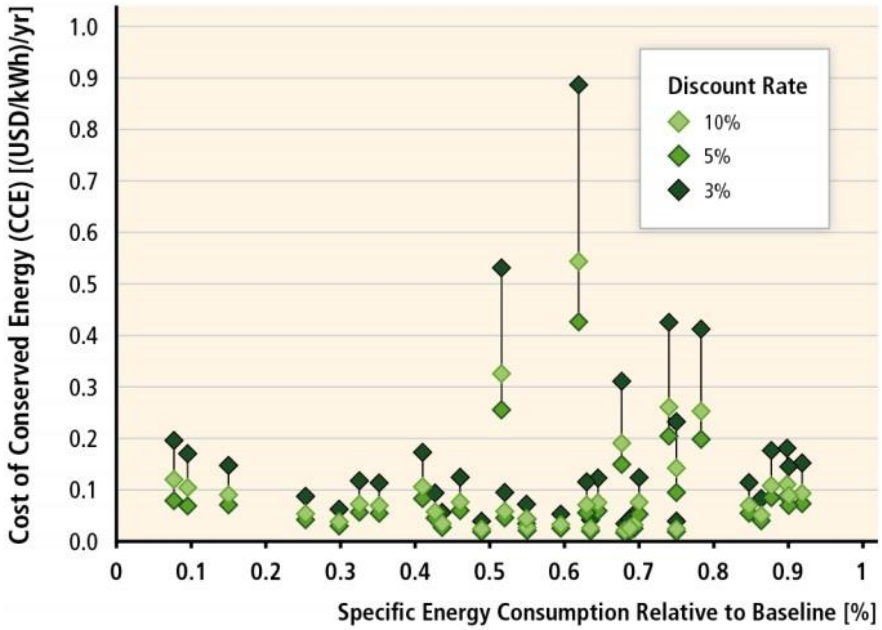
Appendix 7: Sensitivity analysis results by Lucon *et al.* (2014), illustrating the CCE for retrofit buildings in response to the variation in discount rate for selected data points.



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