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A DECISION-MAKING FRAMEWORK FOR THE SELECTION OF SUSTAINABLE ALTERNATIVES FOR ENERGY-RETROFITS

by

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B.Sc., Civil Engineering, University of Tehran, Iran 2009
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DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Doctor of Philosophy in Engineering

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July 2018

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DEDICATION

This dissertation is dedicated to my beloved grandfather, who passed away last year. His memories will remain forever in my heart.

This dissertation is also dedicated to my parents, *Zohreh* and *Mohammadali*, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

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Firstly, I would like to express my sincere gratitude to my advisor Prof. Vanessa Valentin for the continuous support during my Ph.D. study and related research, and for her patience, motivation, and immense knowledge. Her guidance helped me with the research and writing of this dissertation. I could not have imagined having a better advisor and mentor for my Ph.D. study.

Besides my advisor, I would like to thank the rest of my dissertation committee: Prof. Susan Bogus Halter, Prof. Robert Berrens, and Dr. Mark Russell, for their insightful comments and encouragement, but also for the hard questions asked which motivated me to widen my research from various perspectives. I also would like to kindly thank the Associated General Contractors (AGC) Endowment at the University of New Mexico for the support provided for this research

My sincere thanks also go to family. Words cannot express how grateful I am to my parents, Zohreh and Mohammadali, and my sisters, Leila, Ladan, and Mahtab, for all the sacrifices that you’ve made on my behalf. Your prayers for me sustained me thus far.

I would also like to thank all my friends who supported me in writing and motivated me to strive towards my goals. And, to everyone who helped me during this journey.

Finally, I would like express appreciation to my dearest, Saba, who was always my support in the moments when there was no one to answer my queries. Your support, encouragement, and patience during the final stages of this Ph.D. is very appreciated. Thank you.

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ABSTRACT

"Today's energy wastage is tomorrow's energy shortage"

Buildings are major consumers of energy worldwide. On the other hand, over 60% of the US housing inventory is over 30 years old and a large number of these homes are energy inefficient. Therefore, it is essential to target the existing building stock for energy efficient interventions as a key to substantially reduce the adverse impacts of buildings on the environment and economy.

Building energy retrofitting has emerged as a primary strategy for reducing energy use and carbon emissions in existing buildings. An energy retrofit can be defined as a physical or operational change in a building, its energy-consuming equipment, or its occupants' energy-use behavior to convert the building to a lower energy consuming facility. Energy retrofitting could result in additional sustainable benefits such as reducing maintenance costs, reducing air emissions, creating job opportunities, enhancing human health, and improving thermal comfort among others.

One of the main challenges in building energy retrofitting is that several combinations of applicable energy consumption reducing measures can be considered to retrofit a building and it is a difficult task to choose the best retrofit strategy. Although numerous resources provide advice on how to retrofit a building, decisions regarding the optimal combination of retrofitting measures for a specific building are typically complex. In addition, most of the decisions for energy retrofits are based on limited cost categories rather than environmental and social considerations.

The main goal of this study is to develop a decision support system that integrates sustainable criteria (i.e. economic, environmental, and social benefits) in decision-making in energy retrofits. This goal will achieved through following objectives: (1) Determining the impact of building life-cycle on energy retrofitting decision-making; (2) Identifying and quantifying the sustainable benefits of building energy retrofitting to be used as an

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objective function in optimization problems; (3) Developing a systematic approach to select among different sustainable decision criteria for energy retrofitting decision-making; and (4) Developing and demonstrating a decision-making optimization model to select the best energy retrofitting alternative for a specific building while maximizing its sustainable benefits.

First a life-cycle cost analysis of the case study is presented in terms of energy retrofitting. This life-cycle cost analysis is used to explore the process of decision-making in energy retrofits. Then, a comprehensive study on identifying and quantifying the sustainable benefits of energy retrofits is performed that can be used in decision-making. Different tools such as literature review, surveys, Delphi technique, concept mapping approach, hedonic price modeling, and statistical analysis are used in this step. After that, a Sustainable Energy Retrofit (SER) decision support system is proposed. Finally, the application of this decision support system on a case study of a house located in Albuquerque, New Mexico is explored.

This research contributes to the body of knowledge by: (1) Integrating sustainable impacts of building energy retrofits (i.e. Economic, Environmental, and social) in decision-making; (2) Proposing a decision matrix that guides decision-makers on how to select the objective function(s) to formulate an optimization problem that results in the selection of the best energy retrofitting strategy, considering the benefits to investors; (3) Introducing a novel simplified energy prediction method by integrating dynamic and static modeling; (4) Measuring the implicit price of energy performance improvements in the US residential housing market; (5) Identifying, categorizing, and mapping the social sustainability criteria of energy improvements in existing buildings; and last but not least (6) Developing a decision-support system for energy retrofitting projects that integrates the above approaches.

The energy retrofitting decision-making model developed in this research can be implemented for different types of buildings to help decision-makers select the optimum energy retrofit strategy that not only maximizes monetary benefits, but also maximize environmental and social benefits. The presented research can also help homeowners to plan or evaluate their retrofitting strategies.

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CHAPTER 1: Introduction

1.1. Problem Statement

Buildings are major consumers of energy worldwide. In the United States, buildings accounts for 40% of total energy consumption and 72% of total electricity consumption, where residential buildings accounted for more than half of the total (EPA 2009; eia 2018). Although construction activities consume large amounts of energy, most of the energy consumption in a building occurs during the operation phase (Menassa 2011). As such, building operation energy costs play an important role in long-term costs (Gasic et al. 2012).

On the other hand, according to the American Housing Survey by the US Census Bureau (USCB 2013), over 60% of the US housing inventory is more than 30 years old and a large number of these homes are energy inefficient (Syal et al. 2014). Therefore, it is essential to target the existing building stock for energy efficient interventions as a key to substantially reduce the adverse impacts of buildings on the environment and economy (Menassa 2011).

Building energy retrofits have emerged as a primary and low cost strategy for reducing energy use and greenhouse gas emissions from existing buildings (Kontokosta 2016, Calì et al. 2011). Energy retrofits of existing buildings represent an opportunity to upgrade the energy performance of building assets for their ongoing life by improving energy efficiency or decreasing energy demand. Energy retrofitting can also offer sustainable benefits such as reducing maintenance costs, creating job opportunities, enhancing human health, and improving thermal comfort among others (Goodacre et al. 2002; Jafari et al. 2016; Jafari et al. 2014; Ma et al. 2012; Pombo et al. 2016).

One of the main challenges in building energy retrofitting is that several hundred combinations of applicable energy measures can be considered to retrofit a building and it is not easy to determine which one is the best strategy (Gustafsson 2000). Because every building exhibits unique architectural, geographical, and operational characteristics, retrofit options must be rationally investigated for every individual building in a building stock (Rysanek and Choudhary 2013). Despite the numerous resources that provide advice on how to retrofit a building, decisions regarding the optimal combination of retrofitting measures for a specific building are typically complex. The selection process of a retrofitting strategy can be a trade-off between the capital investment (the investment

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required to implement that retrofitting strategy) and the benefits obtained from energy retrofitting (Ma et al. 2012). When choosing among a variety of sustainable benefits, the decision maker has to consider environmental, energy related, economic, and social factors to reach an optimum possible solution that satisfies the final occupant needs and requirements (Asadi et al. 2012). However, most of the decisions for energy retrofits are based on limited cost categories rather than environmental and social considerations. Despite of the significant contributions of other studies on energy retrofit decision-making, holistic decision frameworks that identify, measure, and consider multiple sustainable aspects of energy retrofits (e.g. economic, environmental, and social) are limited.

1.2. Research Questions

In this dissertation, the following research questions are addressed:

Question 1. What are the sustainable benefits of building energy retrofits?
Question 2. How can we measure the sustainable benefits of building energy retrofits?
Question 3. Which sustainable benefits of building energy retrofits are important in decision-making? and
Question 4. How can we select for the best energy retrofitting strategy for a specific building?

1.3. Research Goals and Objectives

The main goal of this study is to develop a decision support system that integrates sustainable Triple Bottom Line (TBL) criteria (i.e. economic, environmental, and social benefits) in decision-making in energy retrofits. This goal will be met by achieving the following objectives:

Objective 1. Determine the impact of building life-cycle on energy retrofitting decision-making;
Objective 2. Identify and quantify the sustainable benefits of building energy retrofit to be used as an objective function in optimization problems;
Objective 3. Develop a systematic approach to select among different sustainable decision criteria for energy retrofits decision-making; and
Objective 4. Develop and demonstrate a holistic decision-making model to select the best energy retrofitting that maximizes sustainable benefits for a specific building.

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1.4. Research Scope

The scope of this doctoral research is limited to the building itself and does not consider occupants' energy-use behavior. In other words, this research only focuses on the building as a system and considers building characteristics for decision-making in building energy retrofits.

The energy retrofit decision-making model that is developed in this dissertation is general and can be applicable to residential or commercial buildings as well. However, only its application on the case study of a residential building is demonstrated in this dissertation.

1.5. Dissertation Type

This dissertation follows a non-traditional (hybrid) format that for the most part represents a summary of the following four published articles:

Jafari, A., and Valentin, V. (2015). "Decision-making Life-Cycle Cost Analysis Model for Energy-Efficient Housing Retrofits", *International Journal of Sustainable Building Technology and Urban Development*, Volume 6, Issue 3, pp. 173-187.

Jafari, A., Valentin, V., Barrens, R. (2017). "Estimating the Economic Value of Energy Improvement in the US Residential Housing", *Journal of Construction Engineering and Management*, Volume 143, Issue 8.

Jafari, A., and Valentin, V. (2018). "Selection of Optimization Objectives for Decision-Making in Building Energy Retrofits", *Journal of Building and Environment*, Volume 130, pp. 94-103.

Jafari, A., and Valentin, V. (2017). "An Optimization Framework for Building Energy Retrofits Decision Making", *Journal of Building and Environment*, Volume 115, pp. 118-129.

These articles are not the only published papers from this dissertation; but they represent the core methodology and findings of the research. For more information, please check the "References" section.

1.6. Organization

In the next chapter (*Chapter 2*), the literature about building energy retrofits is reviewed. The chapter also summarizes previously developed models for decision-making in energy retrofits, their strength and limitations, and identifies the existing gap in the area. *Chapter 3* describes the case study used to demonstrate the different components of the proposed decision framework in different parts of this dissertation. It also shows the results

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of energy simulation for the case study. *Chapter 4* focuses on economic aspects of energy retrofitting through a life-cycle cost analysis for the case study. This life-cycle cost analysis is used in this chapter to explore the process of decision-making in energy retrofits. *Chapter 5* presents a comprehensive study on identifying and quantifying the sustainable benefits of energy retrofits that can be used in decision-making. Additional to the criteria introduced in Chapter 5, the quantification of building resale value through energy retrofits is presented in *Chapter 6*. Then *Chapter 7* proposes a Sustainable Energy Retrofit (SER) decision support system that integrates the results from Chapters 4, 5, and 6. The application of this decision support system on the case study is also explored in this chapter. Finally, *Chapter 8* provides the conclusions of this doctoral research. The organization of this research is mapped in Figure 1.1.

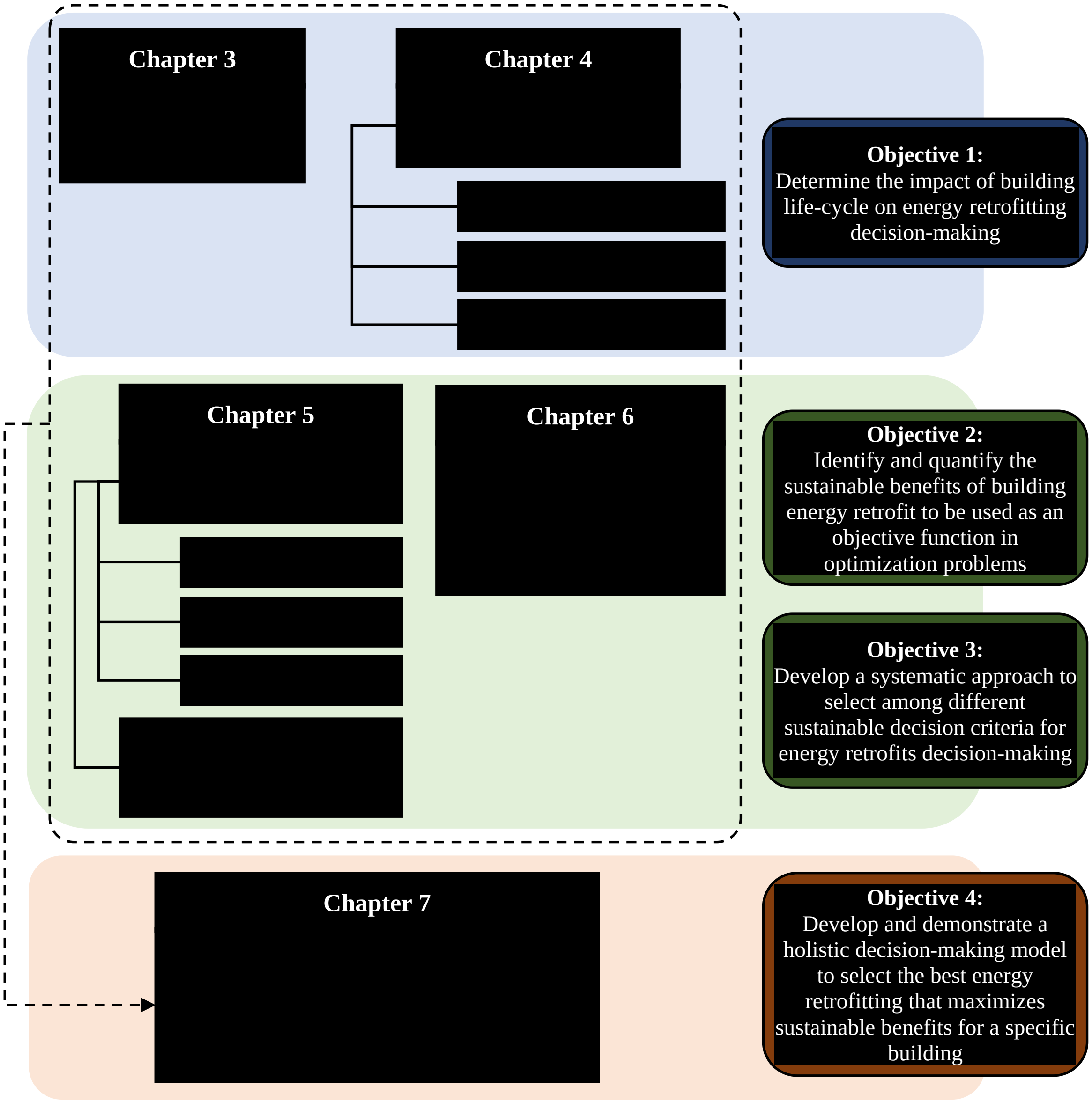

Figure 1.1: Research map

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CHAPTER 2: Review of the Literature

2.1. Building Energy Retrofits

An energy retrofit can be defined as a physical or operational change in a building, its energy-consuming equipment, or its occupants' energy-use behavior to reduce the amount of energy to convert the building to a lower energy consuming facility (Jafari and Valentin 2017; Syal et al. 2014). As mentioned in Chapter 1, building energy retrofitting has emerged as a primary strategy for reducing energy use and carbon emissions (Kontokosta 2016). Energy retrofitting can also offer sustainable benefits such as reducing maintenance costs, creating job opportunities, enhancing human health, and improving thermal comfort (Goodacre et al. 2002; Jafari et al. 2016; Jafari et al. 2014; Ma et al. 2012; Pombo et al. 2016).

Various energy retrofit measures can improve energy efficiency in buildings in different levels. These measures can be categorized in five main groups (Diakaki et al. 2008; Ma et al. 2012; Malatji et al. 2013; Marszal et al. 2011):

- *Controlling measures*: provide appropriate controls and monitors for the mechanical systems, lighting, ventilation, and the efficient use of multi-functional equipment, among others.
- *Load reduction measures*: upgrade the mechanical systems; replace fixtures, appliances, and lighting with energy efficient models, among others.
- *Enveloping measures*: insulate and air-seal the roof or ceiling, walls, and floor; replace the windows and doors with energy-efficient models.
- *Renewable energy technologies*: provide renewable-energy sources such as solar thermal systems, solar photovoltaic/thermal systems, geothermal power systems, among others.
- *Human behavior*: Alter energy consumption patterns of occupants using different methods such as education, individual metering, among others.

2.2. Decision-Making for Energy Retrofits

The selection process of a retrofitting strategy is a trade-off between the capital investment (the investment required to implement that retrofitting strategy) and the benefits

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obtained from energy retrofitting (Ma et al. 2012). These benefits can be economic (e.g., reducing operating costs), environmental (e.g. reducing air emissions), or social (e.g. enhancing occupant's comfort and health) (Jafari et al. 2016). In the construction industry, most funding decisions are often made on the basis of initial cost instead of on the basis of life-cycle cost (LCC) (Arditi and Messiha 1999; Salem et al. 2003). Syal et al. (Syal et al. 2014) stated that the reasons for low patronage of energy retrofits include perception of high upfront costs and a general lack of trust on information about the benefits of retrofits.

The decision about which retrofit measures to implement in a particular project is a single- or multi-objective optimization problem subject to many constraints and limitations (Ma et al. 2012). Several studies have used a single- or multi-objective optimization approach to select the best retrofitting measures for a specific building, using a wide variety of objective(s) such as minimizing life-cycle costs, maximizing indoor air quality, maximizing thermal comfort, and minimizing payback period, among others.

When choosing among a variety of proposed measures, the decision-maker (the corresponding building expert and representative of the investor, who could be the investor him or herself) has to reconcile environmental, energy-related, financial, legal or regulatory, and social factors to reach the best possible compromise to satisfy needs and requirements (Asadi E 2012). Table 2.1 summarizes prior studies and their limitations. In addition, Nielsen et al. (2016) provided a state-of-the-art overview of the development of decision support tools applicable in the predesign and design phase of energy retrofitting projects.

Table 2.1: Summary of literature about energy efficiency decision-making

Ref	**Model**	**Objective Function(s) Optimized**	**Limitation(s)**
(Verbeeck and Hens 2005)	Deducting measures hierarchy	• Min Life Cycle Cost o Investment Cost; o Late Investments; o Energy Cost; o Maintenance Cost	• Ranks the retrofit measures, not selecting the best strategy • Uses simulation (timely, complex, hard to extend) • Considers limited variables • No uncertainty is considered
(Diakaki et al. 2008)	Multi-objective optimization Approach	• Min Investment Cost • Min Building Load Coefficient	• Focuses on required energy for heating • Considers limited cost elements • No uncertainty is considered
(Diakaki et al. 2010)	Multi-objective decision model	• Min Investment Cost • Min Energy Consumption • Min CO2 Emission	• Focuses on required energy for heating • Considers limited cost elements • No uncertainty is considered
(Chidiac et al. 2011)	Screening methodology for implementing cost effective retrofit	• Min Payback Period	• Considers limited cost elements • Uses simulation (timely, complex, hard to extend) • No NPV method is considered • No uncertainty is considered
(Asadi et al. 2012)	Multi-objective optimization model	• Min Retrofit Cost Max Energy Savings	• Considers limited cost elements • Focuses on required energy for heating • Uses simulation (timely, complex, hard to extend) • No uncertainty is considered

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Ref	Model	Objective Function(s) Optimized	Limitation(s)
(Fesanghary et al. 2012)	Multi-objective optimization model	• Min Life Cycle Cost • Min Co2-eq	• Considers designing new buildings not retrofitting • Considers limited cost elements • No NPV is considered • Considers limited variables • No uncertainty is considered
(Kumbaroğlu and Madlener 2012)	Techno-economic evaluation method	• Min NPV of LCC	• Uses simulation (timely, complex, hard to extend) • No tax benefits are considered • Considers limited variables
(Asadi et al. 2012)	Multi-objective optimization model	• Min Retrofit Cost • Max Energy Savings • Max Thermal Comfort	• Considers limited cost elements • Only focuses on required energy for heating • Uses simulation (timely, complex, hard to extend) • No uncertainty is considered • Considers limited variables
(Malatji et al. 2013)	Multiple objective optimization model	• Max Energy Saving • Min Payback Period	• Considers limited cost elements • Uses simulation (timely, complex, hard to extend) • No uncertainty is considered
(Wang et al. 2014)	Multi-objective optimization model for life-cycle cost analysis	• Max energy Saving • Min Life Cycle Cost • Min Payback Period	• Considers limited cost elements • Focuses on electricity • Considers limited variables • No uncertainty is considered
(Asadi et al. 2014)	Multi-objective optimization model	• Min Retrofit Cost • Min Energy Consumption • Min Thermal Discomfort Hours	• Considers limited cost elements • Focuses on required energy for heating • Uses simulation (timely, complex, hard to extend) • Considers limited variables • No uncertainty is considered
(Antipova et al. 2014)	Systematic tool for the optimal retrofit	• Min Total Cost • Min Environmental Impact (LCA)	• Considers limited cost elements • Focuses on required energy for heating • Considers limited variables • No uncertainty is considered
(Murray et al. 2014)	Multi-variable optimization model	• MIN payback • MIN Carbon Emissions • MIN Energy Cost	• Considers limited cost elements • Considers limited variables • No uncertainty is considered
(Mauro et al. 2015)	SLABE (Simulation-based Large-scale uncertainty/sensitivity Analysis of Building Energy performance)	• Min Life Cycle Cost	• Considers limited cost elements • Considers limited variables • Uses simulation (timely, complex, hard to extend)
(Pombo et al. 2016)	Multi-Criteria Methodology	• Min NPV of LCC • Min Environmental Impact (LCA)	• Considers limited variables • Uses simulation (timely, complex, hard to extend) • Assesses the retrofitting strategies not selecting the optimum
((BSI) 2007)	Economic evaluation procedure for energy systems	• Min Global Cost • Min Annuity Cost	• Assesses the retrofitting strategies not selecting the optimum • No uncertainty is considered

As summarized in Table 2.1, different proposed models have been proposed to optimize different single objective or multiple objectives, such as energy consumption, energy saving, CO_2 emission, thermal comfort, and life-cycle impact, to find the optimal retrofit strategy. However, prior models use at least one economic aspect (in terms of retrofitting investment cost, energy cost, life-cycle cost, or payback period) to find the

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optimal retrofit strategy. Life-cycle cost has been considered most frequently as the objective for optimal building retrofitting planning.

2.3. Energy Retrofits Decision Parameters

Literature shows that the following features are included in decision-making model for energy retrofitting: decision variables; single- or multi-objective functions; a method to assess energy performance; and retrofitting uncertainties in some cases.

2.3.1. Decision Variables

In a decision-making model for selecting the optimal retrofitting strategy, the decision variables are defined as energy retrofit measures. These variables can be related to natural gas consumption of a building (Asadi et al. 2012; Diakaki et al. 2010; Diakaki et al. 2008; Mauro et al. 2015), electricity consumption of a building (Wang et al. 2014), or can consider renewable energy measures (Antipova et al. 2014; Asadi et al. 2014; Verbeeck and Hens 2005). A decision-making model developed by Chidiac et al. (2011) considering all types of energy retrofitting measures (including energy measures related to natural gas consumption, electricity consumption, and renewable energy) at the same time (Chidiac et al. 2011). A reliable decision-making model needs to consider all types of retrofitting measures at the same time.

2.3.2. Objective Function(s)

The decision-making model for a retrofitting project can be a single-objective or a multi-objective optimization problem. These objectives usually involve the capital investment and benefits of energy retrofitting. When choosing among a variety of objective functions, the decision-maker has to reconcile environmental, energy related, financial, legal regulation and social factors to reach the best possible compromise to satisfy the final occupant needs and requirements (Asadi et al. 2012). Proper selection of these objectives and their accurate estimation is one of the main decision-maker's challenges. As mentioned in Section 2.2, different models try to optimize one or multiple objectives to find the optimal retrofit strategy such as energy consumption, energy savings, CO_2 emissions, thermal comfort, and environmental impacts (see Table 2.1 for references). However, the available models use at least one economic aspect (in terms of retrofitting investment cost, energy cost, life-cycle cost, or payback period) to find the optimal retrofit strategy. In terms of economic benefits of energy retrofits, life-cycle cost analysis (LCCA) is one of the most common tools used to compare the initial investments and the future benefits of retrofit alternatives in building energy efficiency. However, the detection of cost-optimal levels for an entire building stock is still a complex task (Mauro et al. 2015). Although there are a few studies which try to consider a wide range of cost elements during the service life of a building (Pombo et al. 2016), there is still lack of research considering additional life-

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cycle cost items (such as tax credits and building resale value) for an energy retrofit decision-making model. Considering not only economic benefits comprehensively (including all cost-related components of building during its service life), but also all other sustainable benefits of energy retrofits can improve reliability of any decision-making model.

2.3.3. Energy Assessment Method

The energy analysis of a building is essential when estimating the baseline energy consumption of existing buildings, or to give general indications about the cost-effectiveness of energy measures (Heo et al. 2015; Mauro et al. 2015). Reliable estimation and quantification of energy benefits are essential in a sustainable building retrofitting decision-support system for prioritization of retrofit measures (Ma et al. 2012). For example, The European Union (EU) initiated the energy performance of building directive (EPBD) in 2002 to improve the energy performance of buildings using two different ratings: (1) asset rating, which is the absolute evaluation method for building energy performance based on the physical properties of buildings, such as building design elements; and (2) operational rating, which is the relative evaluation method for building energy performance based on the actual energy consumption (Hong et al. 2015). There are two types of energy estimation methods in the literature: dynamic modeling (energy simulation programs) and static modeling (mathematical methods). Although many sophisticated energy simulation programs (e.g., TRNSYS, Energy Plus) are valuable tools to study the impact of alternative scenarios on building performance (Hall et al. 2013), the iterative trial and error process of searching for the best retrofit action is time consuming and ineffective due to the inherent difficulty in exploring a large decision space (due to its combinatorial nature) (Asadi et al. 2012). Additional challenges of simulation models in energy retrofitting decision-making models are mentioned by Rysanek and Choudhary (Rysanek and Choudhary 2013). However, there are studies that have used mathematical methods instead of simulation to improve effectiveness of energy consumption assessment in decision making (Antipova et al. 2014; Asadi et al. 2012; Diakaki et al. 2010; Wang et al. 2014). These studies have limited number of variables, do not consider the interaction of energy measures, and lack accuracy, among others. Therefore, there is still a need for an energy assessment method that overcomes weaknesses of each modeling method in energy retrofitting decision-making.

2.3.4. Uncertainties

The process of decision-making for energy retrofitting include many uncertainties, such as changes in service life, human behavior change, market value of the building, financial limitations and barriers, perceived long payback periods, interruptions to operations, among others. These uncertainties, directly affect the selection of optimal retrofitting strategy and hence the success of a retrofit project (Ma et al. 2012). There are

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a few studies that try to address uncertainties present in energy retrofitting decision-making such as uncertainties associated with life cycle cost and perceived benefits of this investment (Menassa 2011), uncertainties associated with energy price (Kumbaroğlu and Madlener 2012), and uncertainties associated with potential rebound effects (Booth and Choudhary 2013). Although no decision-making model have incorporated these uncertainties concurrently.

2.4. Social Impact of Energy Retrofits

The literature about the economic and environmental impacts of building energy efficiency is quite rich. There are numerous studies that highlight the impacts of building energy efficiency in terms of the environment (Dong et al. 2005; Jafari et al. 2014; Junnila and Horvath 2003; Junnila et al. 2006; Thiel et al. 2013; Wang et al. 2010; Wu et al. 2012) and the economy (Abdallah et al. 2014; Chai and Chen 2013; Jafari and Valentin 2015; Jafari et al. 2014; Jafari et al. 2016; Kansal and Kadambari 2010; Karatas and El-Rayes 2014; Kumbaroglu 2012). However, the definition and quantification of social impacts of energy retrofitting is still under-developed (Jafari et al. 2017; Jafari et al. 2016).

Social sustainability has been defined in different ways (Zuo et al. 2012), such as: “a series of processes for improving the health, safety, and well-being of current and future generations” (Valdes-Vasquez and Klotz 2013); “a life-enhancing condition within communities, and a process within communities that can achieve that condition” (McKenzie 2004); and “the social and cultural consequences to the society in various aspects from both short-term and long-term perspectives” (Marafa 2002). The topic of social sustainability in construction processes is not new. Several prior studies have tried to identify social criteria in construction projects. Gilchrist and Allouche (Gilchrist and Allouche 2005) outlined 22 sources of social costs associated with construction projects in urban environments and grouped them under four headings: traffic, economic activities, air and water pollution, and damage to the physical environment. Valdes-Vasquez and Klotz (Valdes-Vasquez and Klotz 2013) identified 50 social considerations in construction projects, based on input from 25 experts in academia, industry, and government. They also used the concept-mapping method to organize the identified criteria into six categories defining social sustainability in construction projects: stakeholder engagement, user considerations, team formation, management considerations, impact assessment, and place context. Sierra Leonardo, et al. (Sierra Leonardo et al. 2016) identified 36 social sustainability criteria assessed at each stage of the lifecycle of Chilean public infrastructure, using the Delphi method with 24 Chilean experts consulted in a series of three rounds. They concluded that the most relevant criteria, considering life-cycle stages, were stakeholder participation (design and demolition stages), external local population (design stage), internal human resources (construction and demolition stages), macro-social action of socioenvironmental activities (construction stage), and macro-social action of

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socioeconomic activities (operation stage). Zuo et al. (Zuo et al. 2012) highlighted 26 criteria to measure social sustainability in the context of construction by conducting interviews with 16 industry professionals. They also grouped these indicators into three categories: internal stakeholders, external stakeholders, and macro level issues. Valentin and Bogus (Valentin and Bogus 2015) investigated the correlation between social sustainability and public opinion for building and infrastructure projects.

With respect to the contribution of the above studies, there is still lack of research when considering social aspects of sustainability, specifically in energy retrofit projects. Recently, Jafari et al. (2016) identified some of the social benefits of a sustainable building and classified the social impact area of a retrofitting project into three different levels:

- *Building Level*: The occupants of the building are the key stakeholders involved in a retrofitting project. They are directly affected by the process and results of retrofitting.
- *Community Level*: The neighborhood surrounding a retrofitting project may indirectly be affected by the process and results of the project.
- *Society Level*: The government and utility companies are indirectly involved in retrofitting projects. They are responsible for production and regulation of energy as well as providing the project requirements.

2.5. Gaps in the Previous Studies

Despite the significant contributions of previous studies, a comprehensive decision-making model is still required to select the optimal energy retrofitting strategy by (I) considering multiple sustainable benefits (e.g. economic, environmental, and social) of energy retrofitting; (II) selecting the most proper objective function(s) systematically (III) calculating a simple estimation of building energy performance; (IV) performing a comprehensive life-cycle cost analysis, and then (V) selecting the optimal cost retrofitting strategy for a specific building based on the maximization of these sustainable benefits.

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CHAPTER 3: Case Study

3.1. Description

The proposed decision support model is developed and demonstrated through the use of a case study house. The house was originally constructed in 1964 as a ranch style home (which is one of the most popular styles in the area) in Albuquerque, New Mexico. The house is owned by the Department of Civil Engineering at the University of New Mexico. Essentially, all the repairs on the home have been intended to keep the facility habitable and no major energy conserving features have been added. Figure 3.1 shows some pictures of the house.

Figure 3.1. View of the case study

The home is 150 m^2, has 3 bedrooms, 2 bathrooms, and is made of concrete blocks constructed on a crawlspace. There is a relatively flat gable roof with a 1:12 pitch. The ridge of the roof runs through the middle of the building in a north south direction. Roofing construction is a ballasted built up roof system using bituminous material. The house has a built-up tar and gravel roofing system and brick floors. The current heating is by gas furnace and cooling is provided by an evaporative cooling (swamp cooler) system. The house also uses gas water heater and electric kitchen and laundry appliances. The building site is a 1,200 square meter lot that has a grass lawn and several planted landscaped areas.

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There is a covered carport and external storage shed. Figure 3.2 demonstrates the layout of the house.

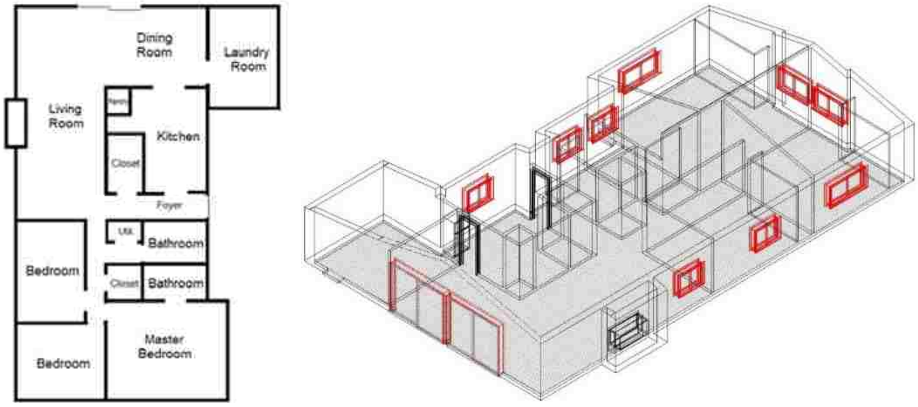

Figure 3.2. Case study layout

Currently, the performance and features of the electrical system of the house can be described as follows: there are ceiling fans on the bedrooms, the living room and dining room areas do not have ceiling lighting and lamps are not enough for providing appropriate lighting to these large spaces. The electricity provided through the electric outlets does not provide adequate power for a single portable heater or 2 small kitchen appliances working at the same time.

To demonstrate the proposed framework, this residential building is used as an exercise. The estimation of energy usage for the case study is explained in detail in the next section.

3.2. Energy Usage

The building was occupied by a family of three from 2011 to 2012. During that time, the annual utility usage was 9,000 kWh of electricity, and 700 therms of gas. The average Albuquerque, New Mexico utility usage provided by PNM, the local utility company, for a similar size and age of home is: 9307 kWh per year and 755 therms of natural gas (PNM 2013). Therefore the actual usage of utilities for the home is directly in line with the average Albuquerque utility usage for a similar constructed and age of facility.

3.3. Energy Simulation

To simulate the annual energy consumption for the case study house, an energy simulation software developed be the US Department of Energy, called eQuest (Quick Energy Simulation Tool), was used. eQuest calculates hourly building energy consumption over an entire year using (hourly) weather data for the location under consideration (DOE2 2013). Input to the program consists of a detailed description of the building being

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analyzed, including hourly scheduling of occupants, lighting, equipment, and thermostat settings.

The result of energy simulation is used as the baseline of the case study annual energy consumption. Figure 3.3 shows the output of the case study house model in terms of electricity and natural gas consumption of the building.

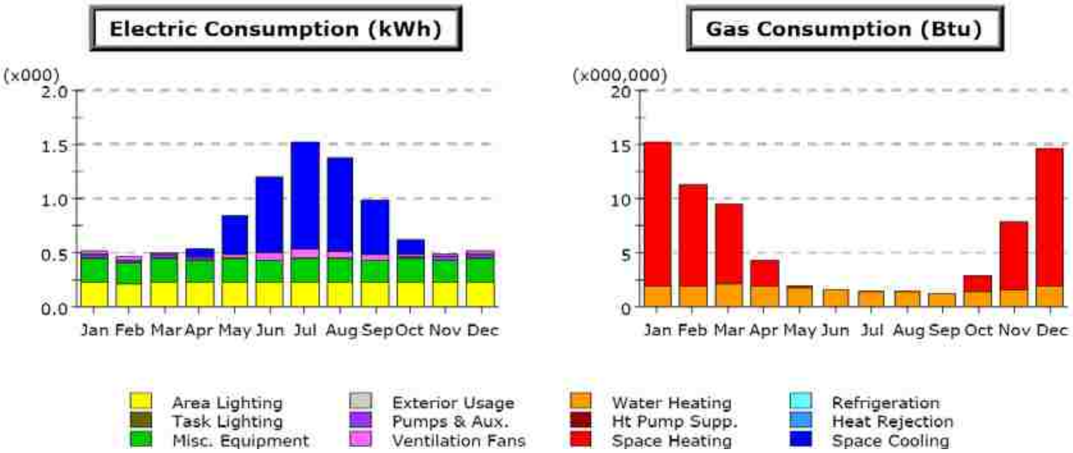

Figure 3.3. Energy Simulation Output

Figure 3.4 compares the percentage of energy usage in an US average home by end user and the outputs of eQuest for the case study. Similarity between the results with a US average home could support overall simulation validity.

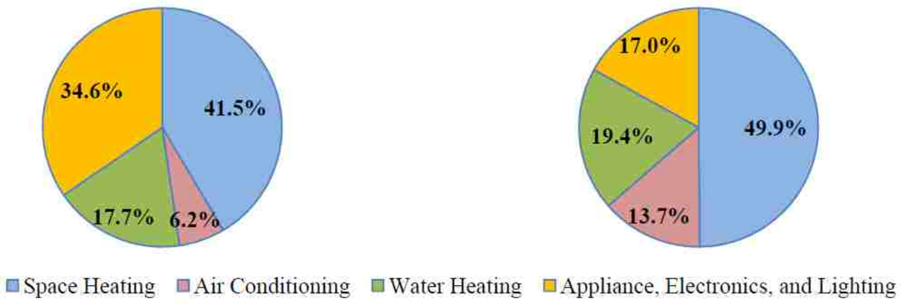
A. Average US energy usage (2009) *B. eQuest results for the case study*

Figure 3.4. Comparison of energy consumption by end users and case study simulation

The results of the simulation also revealed that the annual electricity and gas consumption of the case study house are 9,550 Kilowatt hour (Kwh) and 77,462 Kilo Joule (Kj), respectively, which is in line with the average actual usage of the utilities (9,000 Kwh of electricity, and 73,854 Kj of gas, respectively) (Jafari et al. 2014). Considering the energy unit price in New Mexico ($0.113/KWh and $0.01/Kj for electricity and gas, respectively (EIA 2014)), the average annual energy cost of the house is equal to $1,857.20 per year during the studied years.

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CHAPTER 4: Life-Cycle Cost Analysis for Energy Retrofits

4.1. Introduction

A significant barrier to sustainable design and construction are the cost premium of the project and the long pay back periods from sustainable practices (Ahn et al. 2013). Sustainable projects often have higher initial costs than conventional projects even though they can reduce annual building operating costs by reducing energy consumption (Abdallah et al. 2014). As a sustainable development, energy retrofitting projects usually require high initial costs. However, annual building operating costs can be reduced by reducing energy consumption. These sustainable types of improvement are now widely seen as long-term investments that cause lower life cycle costs (LCC).

A typical approach to consider life-cycle benefits of energy retrofits is to conduct a life cycle cost analysis (LCCA). The decision-maker can then select a plan with the minimum life-cycle costs as the optimal housing retrofit strategy. However, LCCA can be a hard and time-consuming process if performed for all possible alternatives for each building.

The objective of this chapter is to introduce an approach for evaluating housing energy retrofit alternatives, using data from the case study. First, a detailed LCCA is performed for implementing a combination of 15 different retrofitting activities - varying from low to high cost efforts for the case study. Then, a simplified LCCA approach is proposed to illustrate the trend of retrofitting costs and benefits. By defining three different retrofitting zones (e.g., cost efficient zone, energy efficient zone, and improvement needed zone) instead of providing a single optimum solution, this chapter can help home owners to evaluate their retrofitting investment and may lead them to select appropriate retrofitting investment plans.

4.2. Life Cycle Cost Assessment

LCCA is an analytical method of project evaluation in which all costs of the project (i.e., construction, operation, maintenance and disposal) are considered (Kansal and Kadambari 2010). The first step in a LCCA is to define the cost elements and structure. Each element correlates to several life cycle assumptions such as the replacement cycle,

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operational costs, and quantity of the element. Every assumption is a variable in life cycle costing; therefore, making accurate assumptions is the most difficult step in life cycle costing due to the complex cost breakdown structure and uncertainties in predicting future events at the long term (Wang et al. 2012). Table 4.1 summarizes assumed factors in previous studies on LCCA in construction projects, focusing on building projects.

Table 4.1: Cost elements in previous studies (building projects)

Reference	Studied Case	Elements Studied
(Bromilow and Pawsey 1987)	University building	Replacements cost, maintenance cost, cleaning costs, energy cost, other cost
(Kansal and Kadambari 2010)	Green building versus an ordinary building	Initial cost of building, annual maintenance cost, special repairs, annual operation cost
(Menassa 2011)	Sustainable retrofits for existing buildings	Energy upgrades investment costs, annual costs of operating and maintaining
(Gasic et al. 2012)	Architectural projects	Utility costs, maintenance costs, administration costs, periodic costs, taxation costs, repair and replacement costs, renovation, alteration, and addition costs, miscellaneous costs and expenses
(Wang et al. 2012)	School rehabilitation project	Replacement cost rates
(Ammar et al. 2013)	Water mains and sewer infrastructure rehabilitation project	Initial capital costs, operating and maintenance costs, disposal cost, service life of the asset + discount rate

Another main step in life cycle cost analysis is to define the service life of a building. The determination of the time horizon for the assessment needs to consider aspects such as the physical, technological, and economic life of projects and it can vary according to client expectations and project characteristics (Wang et al. 2012). Time spans typically range from 25 to 50 years (Wang et al. 2012), but also may be expanded to more than 70 years (Ammar et al. 2013; Kansal and Kadambari 2010). In addition, Emrath showed that, based on a long-run calculation that averaged the available data over the years 1985 through 2007, the typical buyer could be expected to stay in a single-family home from 12 to 18 years on average (Emrath 2009).

4.3. Simplified LCCA for Building Energy Retrofit

In order to simplify the process, among various cost elements for considering LCCA of a house, this chapter only considers initial investment costs and energy consumption costs as the elements of the LCCA for energy retrofits:

- *Initial Investment Cost*: Initial costs refer to cost of implementing a retrofitting activity including materials, equipment, labors, etc.
- *Energy Consumption Cost*: the average cost of gas and electricity consumption of the house per year.

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The total LCC can be calculated by adding the initial investment cost of implementing a retrofitting strategy and the present value of the house energy consumption during its whole service life (equation 4.1).

$$LCC = IC + NPV(EC) \tag{4.1}$$

Where *LCC* is the objective function, *IC* is the initial investment cost, and *NPV(EC)* is the net present value of the building energy consumption cost during its whole service life.

The Net Present Value (NPV) of the house energy consumption cost during its whole service life can be calculated by equation (4.2):

$$NPV(i, N) = \sum_{t=1}^{N} \frac{EC_t}{(1+i)^t} \tag{4.2}$$

Where *NPV* is the Net Present Value of the building energy consumption cost, *i* is the interest rate, *N* is service life of the building, and EC_t is annual energy consumption cost of the building in the year *t*. If we consider that the energy consumption of the building would be constant per year, then annual energy consumption cost (EC_t) can be calculated by equation (4.3):

$$EC_t = EC \times (1+k)^t \tag{4.3}$$

Where *EC* is energy consumption cost in the first year and *k* is the annual rate of energy cost increase per year.

The interest rate and energy cost increase rate may not be constant each year; since these two factors typically fluctuate with the economy. For example according to US Energy Information Administration (eia 2014) residential electricity price in United States has changed 3.2% from first half of 2013 to first half of 2014 (This rate for West South Census where New Mexico is located is 2.4%). On the other hand, based on the US Treasury (TreasutyDirect 2014) the average interest rate for August 2014 is 2.402. In order to simplify equation (4.3) it was assumed that interest rate and energy cost increase rate will be equal each year (i=k). Therefore, the Net Present Value of the house energy consumption cost can be calculated by equation (4.4):

$$NPV(i, N) = \sum_{t=1}^{N} \frac{EC \times (1+k)^t}{(1+i)^t} = \sum_{t=1}^{N} EC = EC \times N \tag{4.4}$$

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As such, the total LCC can be calculated by summing up the initial investment cost of implementing a retrofitting strategy and the house energy consumption cost multiplied by the expected service life (equation 4.5).

$$LCC = IC + EC \times N \tag{4.5}$$

A key assumption underlying this methodology is that an increased amount of money spent on initial cost can considerably reduce future costs (in this case, energy consumption cost) of a building (Wang et al. 2012) in a housing retrofit project.

4.4. Energy Retrofits Cost Data

In order to determine the potential sequence of retrofitting activities for the LCCA of the case study, this chapter starts by identifying the basic least expensive alternatives for the house, works up through more complex items, and finishes with on-site renewable energy systems. The “Build Green New Mexico criteria for a Green Building” (BGNM 2012) document is used as a reference. Considering the homeowner’s preferences, 15 different major retrofitting activities - varying from low to high cost efforts - are selected as possible retrofitting activities for the case study. Figure 4.1 provides a summary of the selected activities for retrofitting the case study house.

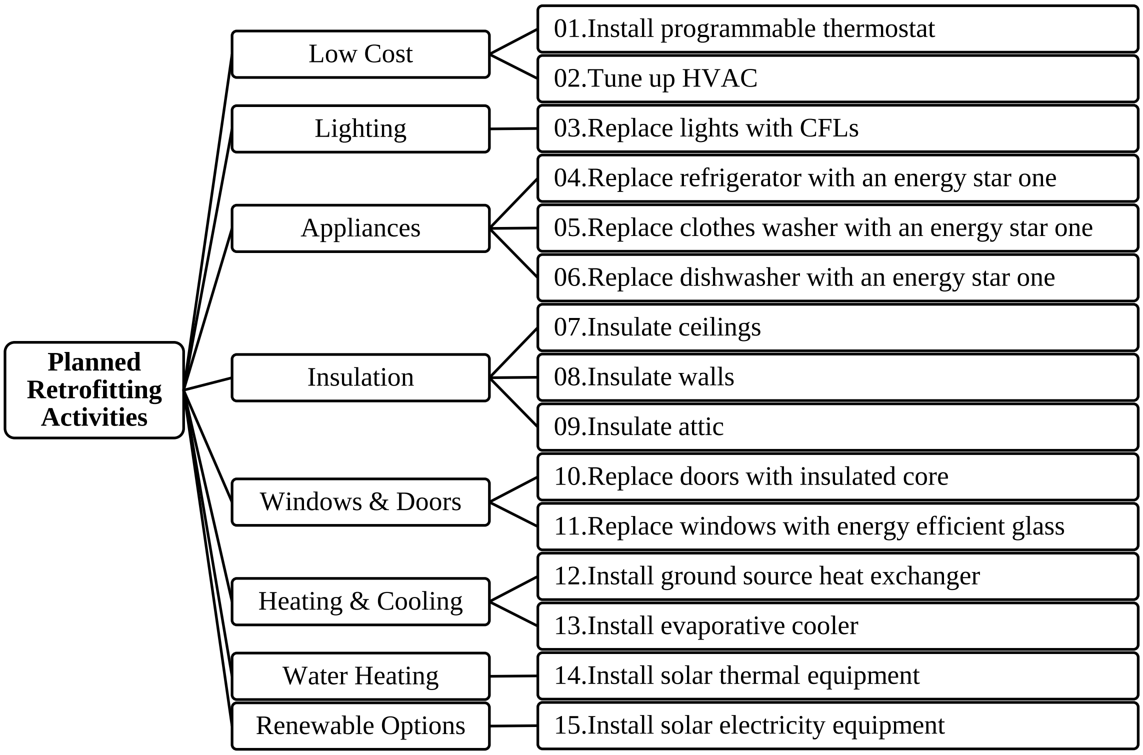

Figure 4.1: Planned retrofitting activities

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In order to estimate the initial retrofitting investment costs, different tools are used including RS Means Green Building Cost Data (RSMeans 2012) and the Housing and Urban Development Website Energy Efficient Rehab Advisor (HUD 2013). Table 4.2 shows the activities (in the first two columns), the estimated initial investment cost to implement each activity to the house, and the impact of implementation of that activity on electricity and gas consumption of the house, respectively, according to the eQuest simulation. Some activities have a negative impact on gas consumption due to the fact that replacing the appliances and lighting features with energy efficient products may cause a decrease in amount of heat generated by these products. Therefore, the impact on electricity consumption is positive, yet the gas consumption may have a small increase (to generate more heat). Nevertheless, the impact of such activities on the total energy consumption (sum of gas and electricity consumption) will be positive.

Table 4.2: Energy simulation results and cost data

Group	**Activity**	**Initial Investment Cost ($)**	**Impact on Electricity**	**Impact on Gas**	**Annual Savings ($)**	**Pay Back (year)**
Low Cost	Install programmable thermostat	79.2	2.6% Decrease	-	28.3	2.8
	Tune up HVAC	164.8	8.2% Decrease	7.6% Decrease	147.0	1.1
Lighting	Replace lights with CFLs	55.3	24.0% Decrease	4.2% Increase	226.4	0.2
Appliances	Replace refrigerator with an energy star one	725.7	2.3% Decrease	0.5% Increase	21.3	34.1
	Replace clothes washer with an energy star one	526.0	2.3% Decrease	0.5% Increase	21.3	24.7
	Replace dishwasher with an energy star one	385.0	1.2% Decrease	0.2% Increase	10.5	36.7
Insulation	Insulate ceilings	1,521.7	5.5% Decrease	6.5% Decrease	110.8	13.7
	Insulate walls	1,915.6	1.0% Decrease	17.7% Decrease	149.1	12.8
	Insulate attic	1,297.7	5.8% Decrease	8.9% Decrease	131.7	9.9
Windows & Doors	Replace doors with insulated core	2,680.7	0.2% Decrease	3.8% Decrease	31.8	84.3
	Replace windows with energy efficient glass	5,240.7	4.9% Decrease	13.5% Decrease	158.1	33.1
Heating & Cooling	Install ground source heat exchanger	20,000.0	50.0% Decrease	50.0% Decrease	928.6	21.5
	Install evaporative cooler	1,460.0	15.4% Decrease	9.9% Decrease	243.3	6.0
Water Heating	Install solar thermal equipment	4,572.3	-	Provide 20.8 MBtu	220.5	20.7
Renewable	Install solar electricity equipment	23,500.0	Provide 8.3 KWh	-	937.9	25.1

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Table 4.2 also shows energy saving costs, which represent the amount of saving in terms of energy consumption cost results from implementation of each activity in comparison to basic house energy consumption cost. The payback period of each activity, calculated by dividing the initial investment cost to annual saving, is also shown in Table 4.2. The results show that the initial investment cost of implementation of an activity has almost no significant impact on its payback period.

4.5. LCC Analysis

After identifying all major retrofitting activities that best match to the case home, each combination of different retrofitting activities may be considered as a possible retrofitting strategy. Therefore 2^{15} (32,768) different strategies are considered in this study. The initial investment costs of these different strategies vary from zero (meaning that no retrofitting activity will be implemented) to the highest value (meaning that all retrofitting activities are implemented). The underlying assumption indicates that a larger amount of money spent on initial investment cost can considerably reduce future costs (in this case, energy consumption cost) (Wang et al. 2012) in a housing retrofit project.

To analyze the data, an approach consisting of eight steps was used: First, the initial investment cost of each retrofitting strategy is calculated as the sum of the initial investment costs of all retrofitting activities that are included on that specific retrofitting strategy. Then, the energy consumption cost of each retrofitting strategy during the service life of the project is calculated. After that, the total LCC of each retrofitting strategy is calculated as the sum of initial investment cost and energy cost. Then, the values for initial investment costs of retrofitting strategies are arranged in descending order, and an index is defined for each retrofitting strategy based on the order, named "Development Level" (DL). Therefore, the strategy of having no retrofitting activity has a development level of 0% and the strategy of having all retrofitting activities has a development level of 100%. After that, in order to decrease the number of points (32768 different strategies) to reduce the computational complexity of the model, a new data set is created in which each sorted 8-point bin of initial investment cost, energy cost, and total LCC is averaged and used as a new point (which decreases the number of points to 4096). And finally, the values for initial investment cost, energy cost, and total LCC are represented as three polynomial trend lines to illustrate the different cost category trends.

When a service life of 50 years is assumed, the results are shown in Figure 4.2. A second-order polynomial trend line is estimated to obtain the best-fitting curve (R^2=0.88 for LCC trend line). As shown in Figure 4.2, the retrofitting strategy with development level of 0% (i.e., no retrofitting activity) has zero initial investment cost and maximum amount of energy cost. In contrast, the retrofitting strategy with development level of 100% (includes all retrofitting activities) has a maximum amount of initial investment cost and zero energy cost. The minimum LCC is a strategy that lies between these two points.

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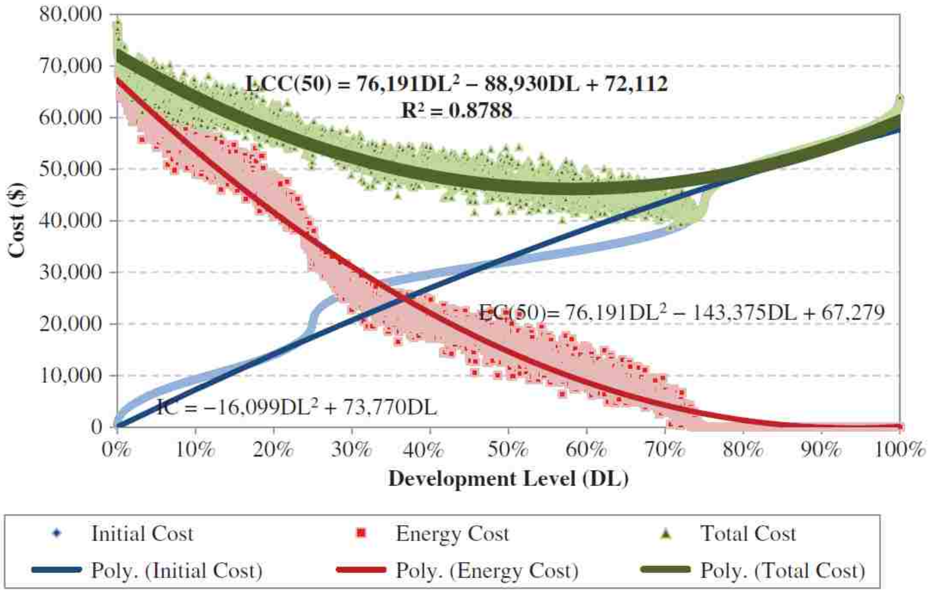

Figure 4.2: Fitting the costs curve for service life of 50 years

By using the LCC equation shown in Figure 4.2, the minimum value of the LCC is determined as:

$$\frac{\partial LCC(50)}{\partial DL} = 0 \tag{4.6}$$

As result, the DL value for the minimum LCC is 58%. By substituting this value in the equations shown in Figure 4.2, the total LCC for a service life of 50 years is calculated as $46,163, and the initial investment cost is calculated as $37,371.

4.6. LCC Evaluation Zones

Assuming that Figure 4.2 shows the behavior of investment on housing retrofits, we can define three separate cost evaluation zones. As shown on Figure 4.3 for the case study (which has a service life of 50 years), these zones include:

Cost Effective Zone: This zone is the adjacent area of the minimum LCC. In this zone, there is a balance between investment cost of retrofitting and energy consumption cost, which causes a decrease in total LCC.

Energy Efficient Zone: This zone is the area in which the energy consumption of the house approaches zero. However, the retrofitting investment cost (and commensurate LCC) is high, because the house is converted to a Net Zero Energy (NZE) house, which means the total amount of energy used by the house is equal to the amount of renewable energy

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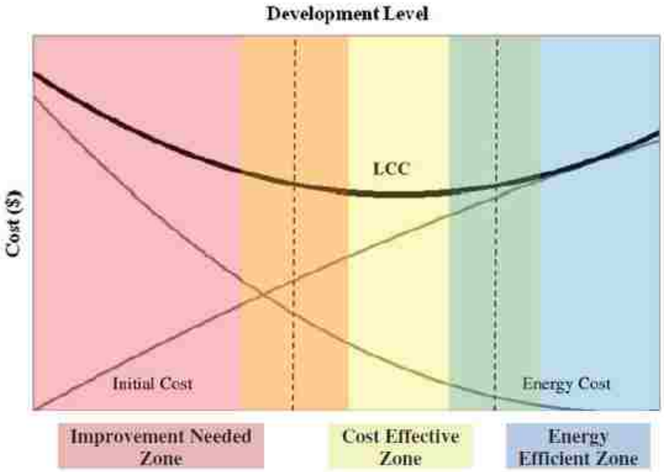
created on the site. Therefore, the house does not have a negative impact on environment, from an energy perspective.

__Improvement Needed Zone__: In this zone, the retrofitting investment cost is not as high as the energy efficient zone, as well as energy saving; however, the LCC is still less than having no retrofitting activity. In this zone the retrofitting project could undertake more improvements, which may increase initial investment costs but decrease total LCC as a result.



*Development Level**	≈ 0–40%	≈ 40–75%	≈ 75–100%
*Initial Cost**	≈ < $27,000	≈ $27,000–$46,000	≈ > $46,000

**The values are approximations.*

Figure 4.3: Cost evaluation zones for the case study

It should be mentioned that the zones borders are calculated for the case study and for a service life of 50 years. Changing the service life may shift the borders of the zones. Therefore, based on the number of years that a homeowner wants to stay the building, the retrofitting investment evaluation zones can be calculated and used for decision-making.

The proposed zones can help decision-makers select an appropriate retrofitting investment plan according to project goals. Considering the initial investment for retrofitting and the number of years for service life, decision-makers can figure out that where they are located, and how much more investing they need to meet their goals. Using these evaluation zones, it is also possible to evaluate different retrofitting strategies, based on their initial investment costs for the studied case.

4.7. Impact of Service Life

This section considers the effect of different building/housing service life periods on the cost evaluation of the retrofitting project. Three scenarios (service life of 15, 30 and

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70 years) are considered and compared to the reference case (service life of 50 years). Typical life-cycle cost analyses are performed for 15, 30, 50 and 70 years, however, this study considers that homeowners could be expected to stay in a single-family home from 12 to 18 years on average (Emrath 2009). The initial investment costs in all scenarios are the same; however, the energy cost and LCC may differ. Therefore, the optimum point of LCC (and consequently the best retrofitting strategy) may change according to the designed project service life. Figure 4.4 illustrates cost trend lines for the different scenarios.

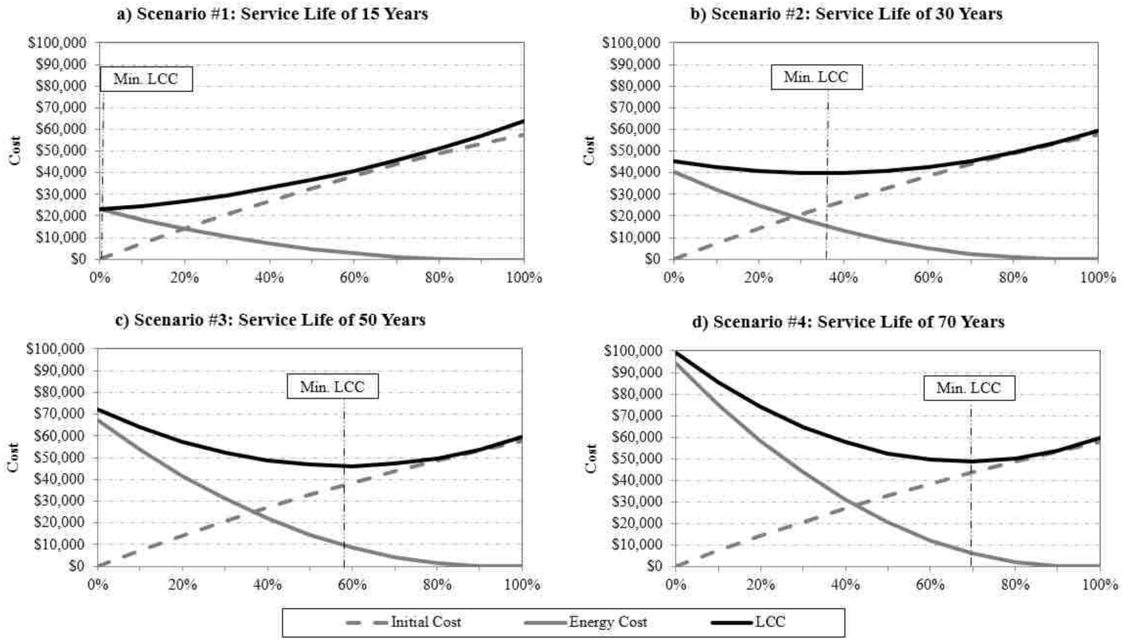

Figure 4.4: Cost evaluation for service life of (a) 15; (b) 30; (c) 50: and (d) 70 years

As shown in Figure 4.4, the minimum LCC occurs in development levels of 0%, 35%, 58%, and 69% for service lives of 15, 30, 50, and 70 years, respectively. This implies that for short term use of the house such as 15 years has no cost-effective zone for retrofitting. In other words, if the homeowner wants to stay in the building for a short amount of time, it is not cost effective to implement a retrofitting plan. This results also suggests that by increasing the service life of a house, the retrofitting investment cost according to an optimal retrofitting strategy will increase. Therefore, if an owner plans to operate a house for a longer time, it would likely be better to have a higher retrofit investment (see Figure 4.5). By expanding the service life of the house, it is expected that the payback of the retrofit investment becomes more important than the initial investment cost in terms of life cycle costs. Therefore, it would be more economical to have more investment to result in more saving per year for a longer operation period. In addition, if the homeowner plans to stay less than 20 years in the house, implementing the retrofitting plan would not be cost-efficient. Results also show that by extending the service life of the house, the optimal strategy for retrofitting in terms of minimum LCC approaches to NZE strategy (approximately Development level of 75%). Effectively, converting the case study

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home to a NZE building is economically feasible, if the house is planned to have a service life of more than 70 years.

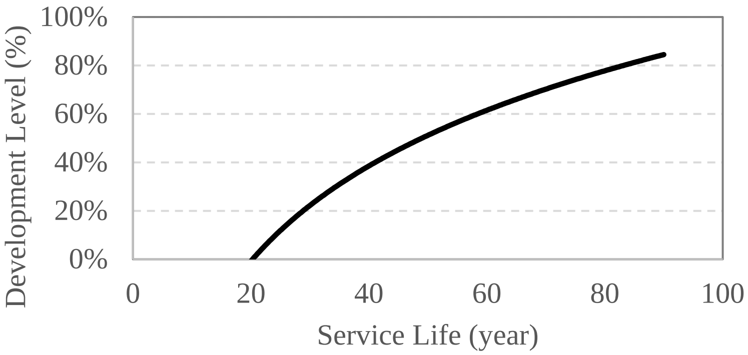

Figure 4.5: Trend of optimum LCC development level based on the service life

4.8. Chapter Conclusion

This chapter introduced an approach for evaluating energy-efficient housing retrofit alternatives, based on the investment cost and energy performance. Using a life cycle cost assessment for a case study house in Albuquerque, New Mexico, three separate cost evaluation zones are defined: (1) a *cost effective zone* where there is a balance between investment cost of retrofitting and energy consumption cost, which cause a decrease in total LCC; (2) an *energy efficient zone* where the total amount of energy used by the house is equal to the amount of renewable energy created on the site; and (3) an *improvement needed zone* where the retrofitting project could undertake more improvements, which may increase initial investment costs but decrease the total LCC as a result. These defined zones can potentially be used not only in decision-making for retrofitting, but also in evaluation of projects related to energy retrofits.

Results of the case study also suggest that by increasing the service life of a house, the retrofitting investment – even for the optimal, lower LCC strategy – will increase, which implies that if an owner plans to operate a house for a longer time, it would be likely better to financially plan for higher energy-related retrofitting investments for the house.

This chapter introduced an approach to evaluate the investment cost and the energy consumption for housing retrofit decision-making. However, based on data availability at the moment for the case study, only energy consumption costs and initial investment cost were considered. Maintenance costs, applicable rebates, and tax incentives will be considered as additional cost items in future chapters. The next chapter will focus on the other factors that can be considered in decision-making for energy retrofits.

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CHAPTER 5: Decision-Making Factors in Energy Retrofits

5.1. Introduction

The decision about which retrofit measures to implement in a project can be formulated as a multi-objective optimization problem. This process is a trade-off between the capital investment (the investment required to implement that retrofitting strategy) and the benefits obtained from energy retrofitting (Ma et al. 2012).

Several studies have used single- or multi-objective optimization approach to select the best retrofitting measures for a specific building. However, most of the decisions for energy retrofits are based on costs rather than environmental and social considerations. As a sustainable development, building energy retrofits require the consideration and integration of the three sustainability dimensions: environmental, economic and social (Jafari et al. 2016; Santoyo-Castelazo; Asadi et al. 2012 and Azapagic 2014). A review of literature about decision-making for energy retrofits shows that despite the contribution of previous studies, there is no study that integrates the sustainable impacts of energy retrofits in buildings (i.e. economic, environmental, and social benefits). The first step in integrating the sustainable benefits in decision-making is to identify and measure economic, environmental, and social criteria in energy retrofits. Therefore, this chapter focuses on identifying possible sustainable criteria of energy retrofitting projects.

On the other hand, in this field of study, the “decision-maker” usually refers to the professional building owner, who has knowledge and experience in the field of building energy retrofits, and who has a professional team of specialized advisors and designers (Nielsen et al. 2016). However, as Kontokosta (Kontokosta 2016) stated, ownership type does, in fact, influence the retrofit decision. The author believes that the concept of “investor benefits” is neglected in previous literature for the selection of decision parameters for building energy retrofits.

This chapter first identifies the sustainable criteria in energy retrofits and then proposes a process for selecting decision parameters (i.e. objective function/functions) taking into consideration the benefits to investors. The approach used in this study includes three main stages: (1) identifying different potential investors in energy retrofitting projects, (2) identifying possible sustainable benefits of energy retrofitting projects, and (3) developing a matrix that relates the identified energy retrofitting benefits to different

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identified investors. The developed matrix will help decisions-makers to select adequate objective function(s) in any single- or multi-objective energy retrofit decision-making process.

5.2. Potential Investors in Energy Retrofits

Retrofitting an existing building in terms of energy efficiency has many benefits. These highly beneficial retrofits will pay for themselves over time and will provide direct benefits to the investor. However, the required initial investment often deters building owners from improving the energy efficiency of their properties, or else limits the retrofits to a smaller scope, which is often suboptimal (Moder 2013). This problem does not exist for new construction, where the costs of green development are barely noticeable. However, when retrofitting existing buildings, the upfront costs of energy-efficiency retrofitting may overwhelm the long-term savings possibilities (Jafari and Valentin 2016).

Investors in energy retrofit measures are not limited to the building owners. This study categorizes the investors of an energy retrofit project into four main groups:

- ***Owner-occupant***: an occupant of a property who also holds the title to that property. In most residential retrofitting projects, the owner-occupant is an investor in the project.
- ***Absent Owner***: an individual who owns a property but does not occupy it. The property held by an absent owner can range widely—from a single condominium or apartment to a large property such as an apartment building or shopping mall. The primary motivation of absent owners is to generate returns from their properties.
- ***Leaser***: an occupant of a property who does not own it but occupies it by paying rent. The leaser could be a renter in a residential building (condominium or apartment) or leaser of a commercial building (office or mall).
- ***External Stakeholder***: a federal, state, or local agency or other lender that provides loans to owners to eliminate energy retrofit upfront costs. Energy efficiency policies and programs can help to drive the implementation of energy retrofit projects that minimize or reduce energy use of a building during its operation. US federal, state, and local financial incentives and programs help building owners execute energy efficiency projects by lowering cost burdens through public benefits funds, grants, loans, or property-assessed clean energy financing; and providing personal, corporate, property, and sales tax incentives; or assistance with permitting fee reduction or elimination (Energy. 2017). These energy efficiency financing incentives resources can be found in the US Department of

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Energy Database of State Incentives for Renewables and Efficiency (DSIRE).

Each one of the aforementioned potential investors might provide initial budget for a building energy retrofit project and could, therefore, be considered a decision-maker. In any energy retrofit project, investor benefits should be considered during the decision-making process for any energy retrofit measures. Maximizing investor benefits when implementing specific retrofitting activities could encourage the investor to invest in building energy efficiency.

5.3. Sustainable Benefits of Building Energy Retrofits

The selection of retrofit measures is a trade-off between capital investment and life-cycle benefits. As a sustainable development, the benefit of building energy retrofits can be categorized into economic, social, and environmental (Jafari and Valentin 2017). For example, by increasing the energy efficiency of buildings, energy retrofits could reduce air emissions (environmental benefits), reduce building operating and energy costs (economic benefits), and enhance occupant comfort and health by improving thermal comfort and indoor air quality (social benefits) (USEPA). Numerous studies have targeted the environmental benefits of energy-efficient buildings (Dong et al. 2005; Jafari et al. 2014; Jiang et al. 2012; Junnila and Horvath 2003; Thiel et al. 2013; Wang et al. 2010) as well as the economic benefits (Abdallah et al. 2014; Chai and Chen 2013; Jafari et al. 2014; Kansal and Kadambari 2010; Karatas and El-Rayes 2014; Kumbaroğlu and Madlener 2012). However, the measurement of social benefits of building energy retrofits is less well developed (Jafari et al. 2016). This study categorizes the economic, environmental, and social benefits of an energy retrofit project.

5.3.1. Economic Benefits

The economic benefits of energy retrofits can be calculated in terms of the change in life-cycle cost (LCC) of the building during its service life. The LCC, which sums all costs of the building during a certain period of time, provides a criterion for finding the best solution, i.e., when the LCC is as low as possible (Gustafsson 2000). As it is stated, the defining the cost elements and structure is the most difficult step in life-cycle costing due to uncertainties in predicting future events at the long term.

Two groups of costs are always being considered in any LCCA: *initial investment cost* and *future cost*. Initial investment costs refer to the costs of implementing a retrofitting measure, including materials, equipment, and labor. Future costs refer to the costs of operating the building during its service life. These costs include:

- *Energy consumption cost*: the total cost of energy (i.e., gas and electricity) that a building consumes during its service life.

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- *Maintenance and replacement cost*: the average cost of service, repair, or replacement of equipment in specific periods to keep them performing as intended during the building's service life duration.
- *Resale benefits*: the benefits to the owner from reselling the building after its service life. The housing markets capitalize improved energy performance into home value (Jafari et al. 2017).
- *Property tax*: the total amount of property taxes that the owner must pay during the building's service life. There are government incentives for "green" programs that have an important role in providing tax incentives for homeowners to install environmentally preferred equipment.

Among the economic benefits of energy retrofits, "resale benefits" is the one that is hard to measure and quantify. The next chapter (Chapter 6) focuses on estimating the marginal cost of energy efficiency improvements in housing market.

5.3.2. Environmental Benefits

Energy-efficient buildings provide many environmental benefits, such as reduced CO_2 emission through energy consumption reduction, reduced damage to nature, and reduced pollution loads. The environmental benefits of energy efficiency can be categorized into three groups:

Life-cycle environmental impacts: Sustainable buildings reduce the influences of buildings on the environment during their service lives. It is vital to take into consideration the environmental influences of a building through its whole life (Wang et al. 2010). Environmental assessments of buildings can provide information necessary for a systematic and comprehensive reduction of environmental impacts from the building sector. Life-cycle assessment (LCA) is a methodology considered by the building industry for finding answers on how to assess the environmental impacts of energy-efficient buildings.

Fossil fuel conservation: Fossil fuels, including coal, oil, and natural gas, are currently the world's primary energy sources. Although fossil fuels are continually being formed via natural processes, they are considered to be non-renewable resources because they take millions of years to form and the known viable reserves are being depleted much faster than new ones are being produced. Increasing the energy efficiency of buildings, changing attitudes and behavior towards energy consumption, and using resources such as water, biomass, wind, geothermal, and solar energy, which can supply clean, renewable energy to replace fossil fuels, can play an important role in conserving fossil fuel sources (IPCC 2017).

CO_2 emissions: The commercial and residential building sector accounts for 39% of carbon dioxide emissions in the United States per year, more than any other sector. Most of these

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emissions come from the combustion of fossil fuels to provide heating, cooling, and lighting, and to power appliances and electrical equipment ((EIA) 2016). By transforming the built environment to be more energy efficient and climate friendly, the building sector can play a major role in reducing CO_2 emissions and the threat of climate change.

In the US, electricity is generated in many different ways, and therefore, environmental impacts vary. According to the US Environmental Protection Agency (EPA), power emissions factors are determined based on the power grid region; and air emission rates of the electricity generated in the region are compared with those of the national average. However, burning natural gas instead of other fossil fuels emits fewer harmful pollutants, and an increased reliance on natural gas can potentially reduce the emission of many of these harmful pollutants (NaturalGas 2013). For example, Table 5.1 summarizes the air emissions quantities resulting from electricity and natural gas generation, for the state of New Mexico.

Table 5.1: Energy emissions factors

Energy	**Reference**	**Air Emissions**		
		NO_x	**SO_2**	**CO_2**
Electricity (E_i)	(EPA 2013)	1.52 lbs/MWh	0.62 lbs/MWh	1,191 lbs/MWh
Natural Gas (G_i)	(NaturalGas 2013)	0.092 lbs/MBtu	0.001 lbs/MBtu	117 lbs/MBtu

Considering the energy savings associated with energy retrofits, the amount of air emission reductions resulting from implementation of retrofitting activity can be estimated.

5.3.3. Social Benefits

Prior studies have identified the social impact of sustainable buildings and energy-efficient facilities. However, the measurement of these social impacts and their implementation during decision-making are less well developed. In order to identify the social sustainability criteria of energy improvements in existing buildings and then develop an empirical framework to organize and categorize these criteria, a series of survey approaches were used. First, a pre-evaluation survey was used to select the most qualified experts in the field of social sustainability. Then, a Delphi technique was employed to identify criteria for measuring social sustainability in energy retrofit projects and to create a list of these social sustainability criteria, using a series of two survey rounds. Finally, a concept-mapping approach (consisting of multidimensional scaling and hierarchical cluster analyses) was used to organize the identified social criteria and develop an empirical framework for considering social sustainability criteria in energy retrofit projects, using another survey round. In total, four surveys were deployed and completed. A total of 11 expert panelists participated in the surveys. The results identified 19 social sustainability criteria that can be categorized in six clusters: "occupants' health and comfort impact," "society enhancement," "cultural and community education," "project stakeholder enhancement," "building quality and technology enhancement," and "socio-economic

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growth." The results are shown in Table 5.2. In order to develop a more practical framework, the authors again analyzed the content and the relationships among these clusters. Based on this information, an empirical social sustainability framework was formed in three different levels: *building level*, *community level*, and *society level*, which represents the area of social impact of the energy retrofit projects on building occupants, people living in a community, and the whole society, respectively. The author believes that there is no clear definition line among these three levels; therefore, a Venn diagram can represent the framework better. This framework is shown in Figure 5.1.

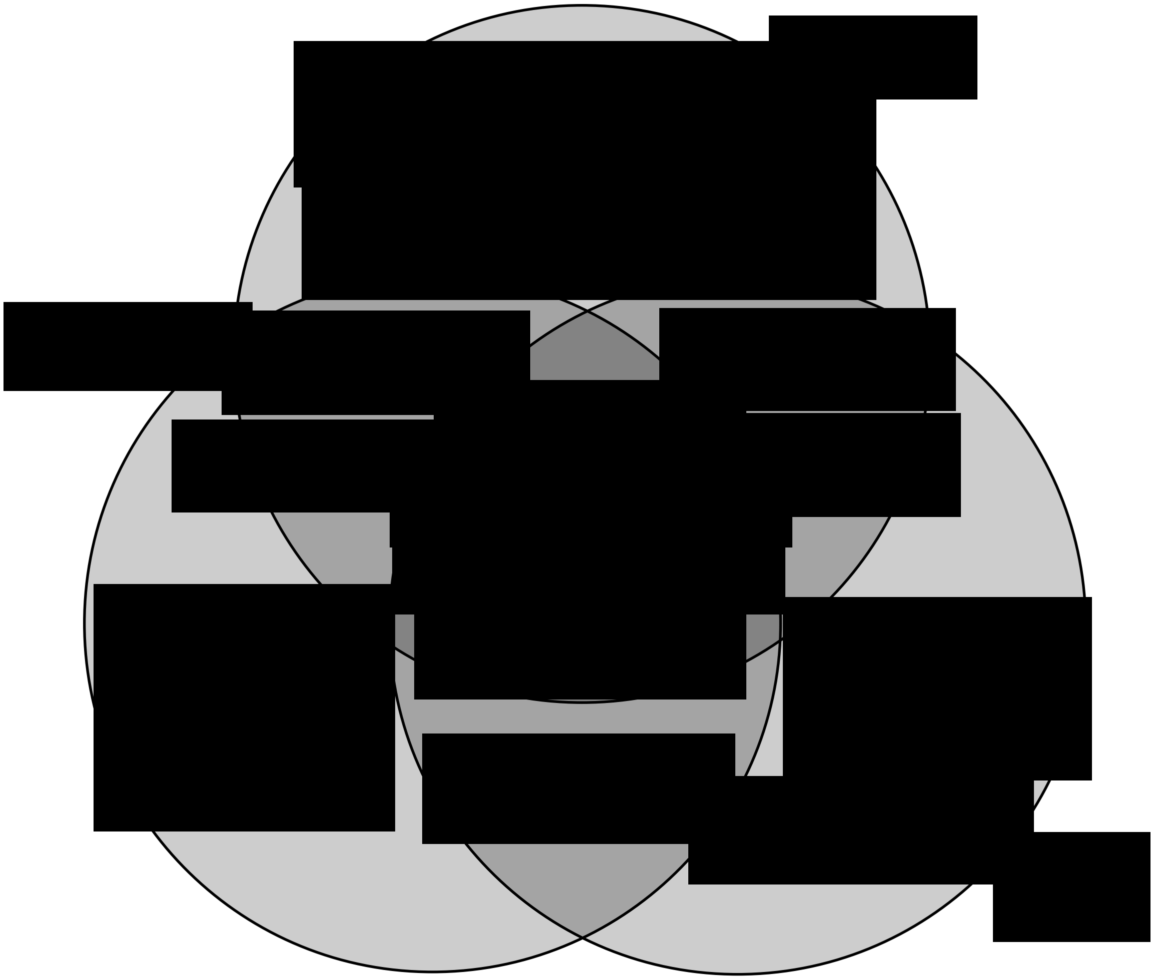

Figure 5.1. Proposed social sustainability framework in energy retrofit projects

The proposed framework (Figure 5.1) can be used by decision-makers who are seeking social impacts of energy retrofitting, as well as by policy makers who investigate the social aspect or social costs of energy reduction programs.

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Table 5.2. Social sustainability framework

ID	**Social Sustainability Criteria**
Cluster A: Occupants' Health and Comfort Impact	
SC01	Impacting occupants' health
SC16	Reducing occupant fatigue through improved artificial lighting and increased use of natural lighting
SC02	Impacting occupants' thermal comfort
SC17	Decreasing the occupants' and community's exposure to noise
SC03	Enhancing productivity and efficiency of occupants in working environments
Cluster B: Society Enhancement	
SC05	Enhancing stakeholders' feeling of well-being and satisfaction through the positive contribution to the environment
SC08	Improving social equity when providing energy efficient facilities for low-income occupants
Cluster C: Cultural and Community Education	
SC10	Encouraging neighbors and community to the culture of energy efficiency
SC11	Improving the connection among people in a community
SC12	Increasing energy efficiency literacy among occupants and communities
Cluster D: Project Stakeholder Enhancement	
SC13	Educating the next generations of stakeholders for enhancing the trend of energy efficiency culture
SC19	Enhancing collaboration and education opportunities among the design, construction and operation teams in the energy retrofitting sectors
Cluster E: Building Quality and Technology Enhancement	
SC04	Improving reliability through diverse power generation sources
SC09	Improving durability related issues of the buildings
SC14	Improving the application of energy efficiency technologies and innovative ideas
Cluster F: Socio-Economic Growth	
SC15	Reducing the exposure to risk of increases in energy prices
SC18	Increasing the marketability of the building
SC07	Reducing the dependence on external energy providers and foreign nations
SC06	Providing job opportunities for local, regional, or national sustainable renovation and manufacturing companies

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5.4. Decision Matrix Development

The proposed decision matrix shows how the different types of potential investors for an energy retrofit project could benefit from energy retrofits in terms of economic, environmental, and social benefits.

In terms of economic objectives, when the investor occupies the building, the energy consumption costs and increased value of the building become important. On the other hand, when the investor owns the building, maintenance and replacement costs and property tax could affect his/her decision about energy retrofit measures. When the investor is an external stakeholder, based on type of organization, different cost categories, such as environmental or social impact costs, may affect the decision.

In terms of environmental objectives, all project stakeholders would benefit from improving energy efficiency in the built environment. However, this global effect on environment may not convince owners or occupiers to participate in improvement by retrofitting their buildings. Making policies to improve global air quality, preserve the environment, and conserve fossil fuel is a large-scale or governmental responsibility. For example, Executive Order (E.O.) 13693, which was signed by US President Barack Obama on March 19, 2015, offers a holistic approach for federal agencies to lead by example in making the federal government’s operations more sustainable, efficient, and energy-secure, while saving taxpayer dollars. This policy significantly increases targets for reducing greenhouse gas emissions in federal operations. The E.O. states that “we have the opportunity to reduce agency direct greenhouse gas emissions by at least 40 percent over the next decade while at the same time fostering innovation, reducing spending, and strengthening the communities in which our federal facilities operate.” Therefore, the main investor beneficiaries from the environmental benefits of energy efficiency will be governmental agencies (as owner or occupant) as well as external stakeholders.

In terms of social objectives, when the investor occupies the building, the community-level impact and the building-level impact can affect his/her decision for performing energy retrofits. Similarly, when the investor owns the building, the community-level impact and the building-level impact (especially those impacts increasing marketability of the property) become important. When the investor is a governmental agency, the social benefits at the society level might affect the energy retrofit decision.

The proposed decision matrix is illustrated in Figure 5.2. The selection of retrofit measures is a trade-off between initial investment and benefits that can be achieved due to implementation of energy retrofit measures. Therefore, in any decision-making process for energy retrofitting, the amount of investment cost plays an important role.

The goal of any optimization problem for an energy retrofitting project will be maximizing the benefits while minimizing the initial investment costs required for energy retrofits. For example, an owner-occupant might decide on optimum energy retrofit measures such as minimizing total LCC, minimizing investment cost while maximizing

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energy cost saving, or minimizing investment cost while maximizing comfort and satisfaction (e.g., thermal comfort), among others.

		Investor			
		Owner-occupant	**Absent Owner**	**Leaser**	**External Stakeholder**
Objective	**Economic**	• Investment Cost	• Investment Cost	• Investment Cost	• Investment Cost
		• Energy Consumption Costs • Maintenance & Replacement Costs • Property Tax • Resale Value	• Maintenance & Replacement Costs • Property Tax • Resale Value • Rental Value	• Energy Consumption Costs	• Property Tax • Environmental Costs • Social Costs
	Environmental	• CO_2 emissions • Environmental Impacts Fossil Fuel Conserving	• CO_2 emissions • Environmental Impacts Fossil Fuel Conserving	• CO_2 emissions • Environmental Impacts Fossil Fuel Conserving	• CO_2 emissions • Environmental Impacts • Fossil Fuel Conserving
	Social	• Community impact • Building impact o Health o Comfort & Satisfaction o Productivity o Security o Pride & Satisfaction	• Community impact • Building impact o Comfort & Satisfaction o Security	• Community impact • Building impact o Health o Comfort & Satisfaction o Productivity o Security o Feeling of proud	• Society impact

Figure 5.2: Decision matrix for decision objective(s) selection

The goal of any optimization problem for an energy retrofitting project will be maximizing the benefits while minimizing the initial investment costs required for energy retrofits. For example, an owner-occupant might decide on optimum energy retrofit measures such as minimizing total LCC, minimizing investment cost while maximizing energy cost saving, or minimizing investment cost while maximizing comfort and satisfaction (e.g., thermal comfort), among others.

The decision matrix illustrated in Figure 5.2 could help any energy retrofitting decision-maker to select the optimization objective(s). However, it does not provide guidance about measuring these benefits. After selecting the optimization objective(s), the next step in decision-making will be measuring the benefits that can be achieved due to the implementation of energy efficiency measures.

5.5. Chapter Conclusion

While several studies have used different objectives to optimize retrofitting strategies, the possible list of objectives and the process of how to select the specific objectives remains unclear. The author believes that the concept of investor benefits is

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neglected in previous literature on decision-making for building energy retrofits. This study listed the potential sustainable benefits (e.g. economic, environmental, and social) of energy retrofits and proposed a process for selecting the objective function(s) in an optimization problem used for energy retrofit decisions for a specific building, taking into consideration investor benefits. Different potential investors in energy retrofitting projects were identified and possible benefits of energy retrofit projects were determined, based on the literature, and a matrix that relates the energy retrofit benefits to different identified investors was proposed. This matrix could help decision-makers to select the optimization objective(s) for energy retrofitting.

The application of this proposed matrix will be demonstrated in Chapter 7. Also, the quantification of resale value of a building due to energy retrofits (as an economic benefit) remained unclear in this chapter. The next chapter will focus on estimation of the economic value of energy improvement in the US residential housing.

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CHAPTER 6: Economic Valuation of Energy Retrofits

6.1. Introduction

Upgrading a home to improve its energy performance could, depending on the property, involve a significant financial investment (Hyland et al. 2013; Jafari and Valentin 2016). On the other hand, energy retrofits could generate economic benefits or savings (e.g., reduce operating costs and optimize life-cycle economic performance), environmental benefits (e.g., reduce air emissions and prevent fossil fuel depletion), and social benefits (e.g., enhance occupant comfort and health as well as create job opportunities in the home improvement sector) (Goodacre et al. 2002; Jafari et al. 2016; Ma et al. 2012; Pombo et al. 2016). All these effects can contribute to increases in value, advantages in tendering processes and increases in the marketability of a building (Popescu et al. 2012), such as raising housing prices or the monthly rental equivalent.

The objective of this chapter is to apply a hedonic pricing model (HPM) (Freeman et al. 2014; Taylor 2003) to measure the marginal value or implicit price for improvements in the energy performance of a house in US residential housing markets. Further, using the HPM estimation results, a prediction cost model is developed for estimating the market value of a housing unit through specific energy performance improvements.

6.2. Hedonic Pricing Model

Three methods can be used for estimating a property's incremental or added value due to energy performance improvement: (1) a revealed preference approach, such as an application of the hedonic pricing method; (2) direct comparison between transaction prices method; and (3) a stated preference approach, such as a contingent valuation or choice experiment survey for evaluating willingness to pay (Alberini and Bigano 2015; Popescu et al. 2012).

The hedonic pricing method (HPM) attempts to econometrically decompose the observed variation in the price of a heterogeneous good in order to isolate the value of individual attributes (Rosen 1974; Taylor 2003). Hedonic pricing regression techniques are commonly used to estimate the value of individual attributes of a residential property whose prices are not directly observed. The marginal implicit prices of specific

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characteristics can be estimated by regressing the observed price of the product (e.g. house price) on its attributes (e.g., size, number of bedrooms/bathrooms, location, etc.) (Hyland et al. 2013; Rosen 1974). The basic assumption of this approach is that if the quality and character of a house (with a similar cost of construction) are kept constant, then the difference in market price is due to the difference on that characteristic (Surahyo and El-Diraby 2009). Such methods can be used to derive the quantitative impact for a chosen measure of energy performance (as an attribute) on the value of the property (Popescu et al. 2012).

Several recent studies have used a hedonic pricing approach to estimate the impact of energy efficiency on the valuation of residential houses. Brounen and Kok (Brounen and Kok 2011) reported evidence on market adoption and economic implications of energy performance certificates implemented by the European Union. Hyland et al. (Hyland et al. 2013) analyzed the effect of energy efficiency ratings on the sale and rental prices of properties in the Republic of Ireland. Koirala et al. (Koirala et al. 2014) estimated the net implicit price of International Energy Conservation Code, IECC 2003 through IECC 2006, for American households. Finally, Fuerst et al. (Fuerst et al. 2015) investigated whether energy performance ratings, as measured by mandatory Energy Performance Certificates are reflected in the sale prices of residential properties. In addition, Eichholtz et al. (Eichholtz et al. 2012) studied the economics of sustainable building practices and private returns to recent large-scale investments in energy-efficient office buildings, as certified under the US Green Building Council or Environmental Protection Agency (EPA)'s Energy Star program. Results showed that, within the population of certified buildings, attributes associated with greater thermal efficiency and sustainability contribute to increases in rents and asset values. These studies mostly focused on the *presence* of energy codes or certification procedures. According to their results, the presence of energy efficiency certification will increase the selling or rental price. These studies provide evidence on the discrete effects of certification or building codes, but cannot be directly connected to the actual effects of energy consumption or its costs to residents.

6.3. Methodology

This chapter employs a hedonic pricing model (HPM) to estimate the effect of building energy performance on value of a house. The theoretical framework of the HPM has been developed through many works, including related recent studies such as Brounen and Kok (Brounen and Kok 2011), Hyland et al. (Hyland et al. 2013), Koirala et al. (Koirala et al. 2014), and Fuerst et al. (Fuerst et al. 2015). A five-step approach is used: (1) measuring building energy performance, as proxied by energy expenditures (cost in dollar terms) index; (2) defining HPM framework; (3) collecting data; (4) defining variables; and (5) running the regression to illustrate the results.

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6.3.1. Measuring building energy performance

The Building Energy Index (BEI) is a common metric used to track and compare the performance of energy consumption in buildings (Abu Bakar et al. 2015). Generally, BEI can be defined as the ratio between energy input to some chosen factor related to the energy using component (such as number of occupants, building size, or usage hours per day). In order to manage and improve energy consumption in buildings, BEI is typically expressed in terms of kilowatt hour per square meter (kWh/m^2), which measures the total annual energy consumption used in a building divided by the gross floor area (Ahmad et al. 2012) as shown in Equation (6.1):

$$BEI = \frac{Annual\ Energy\ Consumption\ (KWh)}{Area\ (m^2)} \tag{6.1}$$

Often, direct measurement of the BEI is not available (e.g., as the case for the AHS). As a result, in this study, a new index called Building Energy Cost Index (BECI) is defined in terms of cost per floor area unit ($/$m^2$) which measures the annual energy consumption cost of the building divided by the gross floor area as follows:

$$BECI = \frac{Annual\ Energy\ Consumption\ Cost\ (\$)}{Area\ (m^2)} \tag{6.2}$$

This measure is dependent on the profile of energy prices in an area over the period of interest (which are later accounted for in its estimation).

6.3.2. Defining HPM framework

House market values are estimated by applying the HPM and assuming that prices are determined by the housing unit characteristics and location characteristics, in addition to the energy performance index (e.g., BECI in this study). As Dinan and Miranowski (Dinan and Miranowski 1989) stated, a linear functional form limits the amount of information that can be obtained about the impact that efficiency improvements have on housing resale values and may bias the resulting implicit prices. The literature shows that the semi-log function is commonly used (Brounen and Kok 2011; Fuerst et al. 2015; Hyland et al. 2013; Koirala et al. 2014); therefore, the HPM is estimated as follows, using a semi-log functional form (which fit our data well), as an example:

$$Ln(P) = \delta + \alpha X + \beta N + \lambda E + \varepsilon \tag{6.3}$$

In this case, *Ln(P)* refers to the natural log of price of the residential housing unit in dollars, *X* represents a vector of housing unit characteristics (such as age, size, number of rooms, etc.), *N* represents a vector of location characteristics (such as region, city or suburban status, etc.), *E* represents a generic energy performance index of the building, and

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ε is the error term. Similarly, δ, α, β, and λ are the intercept, and corresponding conformable vectors of estimable coefficients, respectively.

While commonly employed, the use of single-equation regression equations for price of the residential unit and energy index fails to account for the possibility that many explanatory variables in such models are not truly exogenous, independent variables. Econometric theory suggests that in modeling one of these events using an equation, ignoring the other (sister) equation is imprudent because the single-equation estimator will be biased (Bhargava et al. 2010). In Equation (6.3), it can be claimed that energy index is endogenous variable, which can vary due to regional variation in energy unit prices and climate. In other words, the error term ε is correlated with independent variable E. Fortunately, there are ways to address simultaneity bias and thus to consistently estimate the coefficients in the system of equations. The most common approach is termed the method of instrumental variables. When several instrumental variables are available, they are combined via regression (the first stage) and then used in a second regression (Bhargava et al. 2010). Thus, in this situation, a two-stage least squares (2SLS) regression method is suggested (Dinan and Miranowski 1989; Laquatra et al. 2002).

In the first stage, a regression model is used to estimate the energy performance index, using a semi-log functional form, as follow:

$$Ln(E) = \delta' + \alpha' X + \beta' N + \lambda' Z + \nu \tag{6.4}$$

where *Ln(E)* refers to the natural log of energy performance index, X represents a vector of housing unit characteristics, N represents a vector of location characteristics, Z represents a vector of energy-related climate features (such as a regional energy unit price, regional climate measures (for cooling and heating), number of persons in the household, etc.), and v is the error term. Similarly, δ', α', β', and λ' are the intercept, and corresponding conformable vectors of estimable coefficients, respectively.

Then in the second stage, the estimated energy index (Ê) derived from Equation (6.4) replaces the energy index (E) in Equation (6.3), as follow:

$$Ln(P) = \delta + \alpha X + \beta N + \lambda \hat{E} + \nu \tag{6.5}$$

In Equation (6.5), the error term will be uncorrelated with independent variables of X, N, and Ê.

With this two-stage least squares regression approach, using our chosen proxy BECI (and corresponding BÊCI) to replace the generic energy performance index E (and Ê), we can return to the question of interest – how is energy efficiency capitalized into housing markets? While a variety of functional forms were evaluated, a semi-log functional form is used to fit Equation (6.5); the estimated coefficient of energy performance index, λ, measures the marginal implicit price or the marginal effect on housing market value in

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percentage terms, if we change the corresponding explanatory variable by one unit. The estimated value quantifies the marginal implicit price of improving building energy performance that households are willing to pay.

6.3.3. Collecting Data

Data for this study were obtained from the American Housing Survey (AHS) 2013 Metropolitan Public Use File (PUF). These micro-data contain individual responses to survey questions, for which the basic unit is an individual housing unit (CensusBureau 2016).

The published AHS micro-data for household level information contain 84,355 responses or data points, of which 27,547 data points were selected. The selection process was based on data points having no missing information about property market value, electricity and gas consumption bills, along with economic and demographic information, housing unit characteristics (i.e., age, size, number of rooms), region, among others. Such information richness at the micro-level is appropriate for an empirical analysis of the effects of energy performance on housing market value at the household level.

6.3.4. Defining Variables

The dependent variable is defined as the AHS survey respondent's self-reported market value for single family residence, which measures the current market value of a specific housing unit in 2013 US dollars.

In order to estimate the effect of energy performance on the housing unit value, the primary focus of this analysis, the Building Energy Cost Index (BECI) is defined in Equation (6.6):

$$BECI = \frac{(AMTE \times 12) + (AMTG \times 12) + (AMTO) + (AMTF)}{AREA} \tag{6.6}$$

where AMTE is average monthly cost of electricity, AMTG is average monthly cost of gas, AMTO is annual cost of fuel oil, AMTF is annual cost of other fuels, and AREA is the floor area unit in m^2. The BECI is a dollar cost per square meter index. So that, for example, a $1 reduction in the annual BECI would equate to a total annual energy cost reduction of $207 for the typical home in our AHS data.

Housing unit characteristics considered in this analysis include: age of building (BUILT) which considers the year when unit was built; the total number of rooms (ROOMS); the number of stories in the building where unit is located (FLOORS); and floor area of unit in m^2 (AREA). Neighborhood and location characteristics considered include: Census regional division that the unit is located (DIVISION); and central city or suburban status that the unit is located (METRO). Energy related features considered include: average January temperature (TEMPJAN) and July temperature (TEMPJUL) in degrees Celsius (°C) to estimate the cold and warm climate effect, respectively (as

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suggested by (Laquatra et al. 2002), and unit price of electricity (ELECPRICE) and natural gas (GASPRICE) in dollars per kilowatt hour (kWh), to control energy price are considered for each regional division (see Table 6.1).

Table 6.1. Regional climate and energy unit price data for 2013

DIVISION	**Average January Temp. (°C)**	**Average July Temp. (°C)**	**Average Electricity Unit Price ($/kWh)**	**Average Natural Gas Unit Price ($/kWh)**
New England	-4.7	22.6	16.2	49.1
Middle Atlantic	0.7	24.0	15.6	39.2
East North Central	-3.4	21.7	12.1	30.0
West North Central	-5.4	22.4	10.8	30.4
South Atlantic/East South Central	9.2	25.3	10.9	43.3
West South Central	7.6	26.6	10.8	35.5
Mountain and Pacific	-2.6	22.3	12.4	32.8

In addition, the number of persons in household (PER) and the main heating equipment system (HEQUIP) is also considered in this analysis. Variable definitions and descriptive statistics are given in Table 6.2 and Table 6.3.

Table 6.2. Descriptive statistics for continuous variables

Variable	**Description**	**Mean**	**S.D.**	**Min**	**Max**
VALUE	Current market value of unit ($)	258,174	283,768	10,000	2,520,000
BECI	Annual energy consumption cost per floor area ($/m^2)	14.82	19.79	0.08	1694.89
AREA	Floor area of unit in m^2	207.2	215.2	9.3	2290.8
ROOMS	Number of rooms in unit	6.6	1.7	1	15
FLOORS	Number of stories in building	2.1	1.5	1	21
TEMPJAN	Average temperature of January (°C)	1.0	5.4	-5.4	9.2
TEMPJUL	Average temperature of July (°C)	23.5	1.6	21.7	26.6
ELECPRICE	Electricity unit price ($/kWh)	12.5	1.9	10.8	16.2
GASPRICE	Natural gas unit price ($/kWh)	36.5	5.8	30.0	49.1
PER	Number of persons in household	2.6	1.4	1	14

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Table 6.3. Descriptive statistics for categorical variables

Variable	Description	Category	Frequency	% of Total
BUILT	Year unit was built	1919 or earlier	1,711	6.2%
		1920 to 1949	3,801	13.8%
		1950 to 1979	11,498	41.7%
		1980 to 1989	3,269	11.9%
		1990 to 1999	3,273	11.9%
		2000 to 2009	3,674	13.3%
		2010 or after	321	1.2%
GARAGE	Whether unit has garage / carport or not	Yes	22,967	83.4%
		No	4,580	16.6%
REGION	Census region that the unit is located	New England	1,116	4.1%
		Middle Atlantic	5,325	19.3%
		East North Central	6,477	23.5%
		West North Central	1,756	6.4%
		South Atlantic and East South Central	6,001	21.8%
		West South Central	2,381	8.6%
		Mountain and Pacific	4,491	16.3%
METRO	Central city or suburban status in which the unit is located	Central city of MSA[*]	6,272	22.8%
		Inside MSA[*], but not in central city – urban	11,953	43.4%
		Inside MSA[*], but not in central city – rural	4,087	14.8%
		Outside MSA[*], urban	1,688	6.1%
		Outside MSA[*], rural	3,547	12.9%
HEQUIP	Main heating equipment system	Forced warm-air furnace	19,106	69.4%
		Steam or hot water system with radiator	3,331	12.1%
		Electric heat pump	3,060	11.1%
		Built-in electric baseboard heating	728	2.6%
		Pipeless furnace built into the building	589	2.1%
		Vented room heaters burner	157	0.6%
		Unvented room heaters burner	175	0.6%
		Portable electric heaters	164	0.6%
		Woodburning stove	237	0.9%

[*] MSA: Metropolitan Statistical Area

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6.4. Energy Performance Model Results

Following the analytical framework and using the data described above, a semi-log energy performance modeling was estimated for the first stage of 2SLS, using Statistical Package for the Social Sciences (SPSS) (statistics package, version 24). The results are presented in Table 6.4.

The natural log of BECI for residential unit is explained as a function of six housing unit attributes, including: size, age, number of rooms, number of stories in building, whether there is a garage, and main heating equipment system (vector X in Eq. 6.4), one location attributes, including: central city or suburban status of unit (vector N in Eq. 6.4), and five energy-related climate features, including: warm climate effect, cold climate effect, electricity price control, and natural gas price control, and the number of persons in household (vector Z in Eq. 6.4). For the categorical variables, a set of indicator variables (binary dummy variables) are used. The category with the highest frequency of occurrence is noted as “hold-out” as a baseline for coefficient comparison. In terms of explanatory power, the adjusted R-square value is nearly 40% and the estimated coefficients of the independent variables are mostly significant at the 1 percent level.

In terms of housing unit characteristics, the results show that, evaluated at the sample mean, if the floor area of the house is increased by 1 square meter, then its BECI decreases by 0.2%. Further, buildings built in 1919 or earlier, and from 1920 to 1949, have a higher BECI by 5.6% and 7.2%, respectively, compared to homes built in 1950 to 1979 (which include the predominant share of US housing units). Similarly, the buildings built in 1980 to 1989, 1990 to 1999, 2000 to 2009, and 2010 or after, have a lower BCEI by 8.3%, 13.2%, 15.7%, and 25.6%, respectively, compared to homes built in 1950 to 1979. Additionally, if the housing unit includes garage or carport, its BECI decreases by 3.2%. Residential houses located in taller buildings have a lower BECI (2.8% decrease for one more story in the average building). In addition, there is no significant relation between the number of rooms and BECI.

In terms of main heating equipment, the residential units using steam or a hot water system with a radiator have a higher BECI by 22.0% compared to residential units using forced warm-air furnace. Similarly, residential units using an electric heat pump, a pipeless furnace built into the building, or a woodburning stove have lower BECI by 2.2%, 7.8%, and 26.6%, respectively, compared to residential units using a forced warm-air furnace.

In terms of housing unit location characteristics, the results show that increasing 1 degree Celsius in average January temperature decreases BECI by 1.8%, and increasing 1 degree Celsius in average July temperature increases BECI by 5.5%. In addition, increasing the unit price of electricity by $1 per kWh increases BECI by 4.8%, and increasing the unit price of natural gas by $1 per kWh increase BECI by 1.5%. Further, housing units located in a Metropolitan Statistical Area (MSA) but not in the central city (i.e., of a more suburban or rural nature) have a significantly higher BECI. Finally, increasing the average number of persons in the household by one person increases BECI by 6.6%.

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Table 6.4. Results of semi-log energy performance modeling and HPM

Vector/Index	**Variable**		**Stage 1: Energy Model**	**Stage 2: Pricing Model**
	INTERCEPT		0.329(0.127) ***	10.761(0.037) ***
Energy Performance Index (E)	BECI		-	-0.020(0.002) ***
Housing Unit Characteristics (X)	BUILT	1919 or earlier	0.055(0.014) ***	-0.102(0.018) ***
		1920 to 1949	0.070(0.010) ***	-0.040(0.013) ***
		1950 to 1979	Hold-out	Hold-out
		1980 to 1989	-0.087(0.010) ***	0.080(0.013) ***
		1990 to 1999	-0.142(0.011) ***	0.123(0.014) ***
		2000 to 2009	-0.171(0.010) ***	0.157(0.013) ***
		2010 or after	-0.296(0.030) ***	0.283(0.038) ***
	AREA		-0. 002(0.000) ***	$9.116{\times}10^{-5}$(0.002) ***
	ROOMS		-0.001(0.002)	0.152(0.003) ***
	FLOORS		-.029(0.002) ***	0.078(0.003) ***
	GARAGE		-0.033(0.009) ***	0.151(0.011) ***
	HEQUIP	Forced warm-air furnace	Hold-out	-
		Steam or hot water system with radiator	0.199(0.011) ***	-
		Electric heat pump	-0.022(0.011) **	-
		Built-in electric baseboard heating	0.006(0.020)	-
		Pipeless furnace built into the building	-0.081(0.022) ***	-
		Vented room heaters burner	-0.024(0.042)	-
		Unvented room heaters burner	0.014(0.040)	-
		Portable electric heaters	-0.014(0.742)	-
		Woodburning stove	-0.310(0.035) ***	-
Location Characteristics (N)	DIVISION	New England	-	0.814(0.029) ***
		Middle Atlantic	-	0.651(0.017) ***
		East North Central	-	Hold-out
		West North Central	-	0.011(0.018)
		South Atlantic and East South Central	-	0.227(0.012) ***
		West South Central	-	0.089(0.016) ***
		Mountain and Pacific	-	0.716(0.013) ***
	METRO	Central city of MSA	-0.011(0.008)	-0.116(0.011) ***
		Inside MSA, but not in central city – urban	Hold-out	Hold-out
		Inside MSA, but not in central city – rural	0.023(0.010) **	-0.072(0.012) ***
		Outside MSA, urban	-0.024(0.014) *	-0.384(0.017) ***
		Outside MSA, rural	-0.015(0.011)	-0.254(0.013) ***
Energy-Related Features (Z)	TEMPJAN		-0.018(0.002) ***	-
	TEMPJUL		0.054(0.006) ***	-
	ELECPRICE		0.047(0.003) ***	-
	GASPRICE		0.015(0.001) ***	-
	PER		0.064(0.002) ***	-

* Indicate that the estimated coefficients are significant at 10% levels.
** Indicate that the estimated coefficients are significant at 5% levels.
*** Indicate that the estimated coefficients are significant at 1% levels.

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6.5. Hedonic Pricing Model Results

A semi-log HPM was estimated for the second stage of 2SLS, using the estimated value for BECI from the first step (BÊCI). Results are presented in Table 6.4. The natural log of current market value of residential unit is explained as a function of five housing unit attributes, including: size, age, number of rooms, number of stories in building, and whether there is a garage (vector X in Eq. 6.5), two location attributes, including: Census regional division of unit and central city or suburban status of unit (vector N in Eq. 6.5), and most importantly the level of energy performance (Ê in Eq. 6.5), measured by estimated BECI, that is BÊCI from the first stage. For the categorical variables, a set of indicator variables (binary dummy variables) are used to compare the coefficient of each category in the hedonic pricing model. The category with the highest frequency of occurrence is noted as "hold-out" as a baseline for coefficient comparison. In terms of explanatory power, the adjusted R-square value is nearly 40% and the estimated coefficients of the independent variables mostly are significant at the 1 percent level. The signs and significance of the estimated coefficients, in both stages of 2SLS, support overall model validity. For example, this is seen in the significance of all energy-related features in stage 1 (all positive except for TEMPJAN as expected). In stage 2, the hedonic price function, this is seen for example in the significant negative estimated coefficient on BECI, and the significant positive estimated coefficients for housing unit characteristics such as ROOMS, AREA, GARAGE and FLOORS.

As it is shown in Table 6.4, the estimated coefficient on annual energy consumption cost per floor area (BÊCI) is negative and significant at the 1 percent level. This result indicates that US housing markets capitalize higher energy performance into home's value; decreasing the amount of annual energy consumption per floor area by \$1 per m^2 increases the unit market value by 2%. Improving energy performance of a building through energy retrofit requires an initial investment, but homeowners could benefit from these costs when they sell (or equivalently rent) their homes. On the other hand, buyers (or renters) are willing to pay more for a house that has a higher level of energy performance (potentially due to aforementioned benefits such as reducing operating costs, reducing air emissions, and enhancing occupant comfort).

In addition to the effects of energy performance on housing unit prices, there are other determinants. In terms of housing unit characteristics, the results show that, evaluated at the sample mean, if the floor area of the house is increased by 100 m^2, then its value increases by 1%. Further, buildings built in 1919 or earlier, and 1920 to 1949, have a lower market price by 9.7% and 4.7%, respectively, compared to homes built in 1950 to 1979, which includes the predominant share of US housing units. Similarly, the buildings built in 1980 to 1989, 1990 to 1999, 2000 to 2009, and 2010 or after, have a higher market price by 8.3%, 13.1%, 17.0%, and 32.7%, respectively, compared to homes built in 1950 to 1979. In addition, as expected, if the number of rooms is increased by one, the housing price

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increases by 16.4%. Additionally, according to the results, if the housing unit includes garage or carport, its market price increases by 16.3%. Also, multi-stories homes have higher market prices (8.1% increases in price for having one more stories in the building).

In terms of housing unit location and neighborhood characteristics, residential housing units located in the New England, Mountain and Pacific, Middle Atlantic, South Atlantic and East South Central, and West South Central US Census regional divisions have higher market price by 125.7%, 104.6%, 91.7%, 25.5%, and 9.3%, respectively, compared to the housing units located in the East North Central US Census regional division. However, there was no significant relation between price of the houses located in West North Central division and East North Central division. Further, housing units located in MSA but not in the central city (urban) had a significantly higher price.

6.6. Value Added Through Energy Performance Improvement

After estimating HPM, a prediction model can be developed for estimating the marginal or added value to a residential housing unit from energy performance improvement. Based on the HPM estimation, and assuming that other house characteristics remain the same after energy retrofits (excepted BECI), the change in unit market value can be calculated as:

$$Ln(VALUE^{*}) - ln(VALUE) = -0.020 \times (BECI^{*} - BECI) + (\varepsilon - \varepsilon^{*}) \qquad (6.7)$$

Where *VALUE* is predicted housing price before energy retrofit, *VALUE** is predicted housing price after energy retrofit, *BECI* is building energy consumption index before energy retrofit, *BECI** is building energy consumption index after energy retrofit, and ε and ε^{*} are the error terms. The value $\lambda = -0.020$ is the corresponding estimated coefficient of BÊCI, driven from Table 6.4. Assuming that the difference between error terms in Equation (6.7) is small enough to be neglected, this equation can be simplified as:

$$\frac{VALUE^{*}}{VALUE} = e^{0.020\times(BECI-BCEI^{*})} \qquad (6.8)$$

Where *the left side* represents the ratio of the residential house price when implementing energy retrofits to pre-retrofit residential house price.

The developed model in Equation (6.8) estimates the change in market price of a house (or its equivalent rent) immediately after the implementation of energy retrofits. Consider the following example, using an average housing unit (using mean values) in our 2013 US national sample from the AHS, with floor area of 207.2 m^{2}, current market value of $258,174 and energy consumption cost of $2,382 per year (BECI of $11.50 per m^{2}). If investing in an energy retrofit results in cutting energy bills by 50% (reducing energy consumption cost to $1,191 per year), then the market value of the residential house unit

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would be calculated to increase to \$289,638 which represents an increase of 12.2% (\$31,464). This added value through energy performance improvement represents the marginal implicit price or value for that example house for a specific improvement in building energy performance (50% reduction in energy costs). For comparison, and to give an idea about how the housing market is capitalizing energy performance improvements, the implied discount rate to equate an annual cash stream (or cost savings) of \$1,191 over 15 years to a present value \$31,464 would be 6.363%. Figure 6.1 illustrates the relation of housing added value across a range of energy performance improvements (in terms of energy consumption cost reduction percentage) for the average housing size example case. As shown, the relation is close to linear and based on energy performance improvement ranging from 0 to 100 percent, the marginal implicit price would change from 0% to 25.8% of the unit market value for the average home example case.

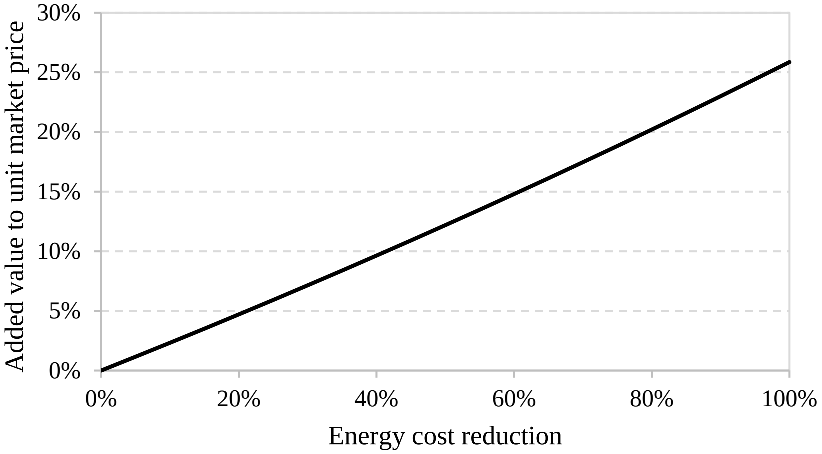

Figure 6.1. Housing added value through energy efficiency for example case

6.7. Chapter Conclusion

Energy retrofitting can improve the building in terms of economic, environmental, and social aspects, and lead to a higher capitalized present value (as reflected in market price). The extent of such capitalization is an empirical question. To help answer this question, this analysis used a hedonic pricing model (HPM) to measure the marginal value or implicit price for improvements in energy performance in the US residential housing markets. Econometric results of the HPM indicate that US housing markets capitalize higher energy performance into higher home value. For example, decreasing the BECI by \$1 per m^2 (or a \$207 reduction in annual energy expenditures for a typical home in our 2013 AHS sample), increases the US unit market value by 2%. Further, using the HPM estimation results, a prediction cost model is developed for estimating the market value of a housing unit through specific energy performance improvement. Therefore, for an assumption of energy performance improvements through retrofitting that cut the typical

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energy cost by 50%, ceteris paribus, this would increase the expected sale price by 12.2% for the average home in our sample. This model can help planners and homeowners estimating the change in market price of a house (or its equivalent rent) through implementation of energy retrofits.

An important limitation of this investigation is the lack of detailed housing attribute variables in the AHS. It is expected that a number of avenues could improve estimation: (1) Improved parcel-level information controlling for a greater number of neighborhood and regional characteristics; (2) Investigation of possible spatial interdependencies (e.g. spatial correlation effects). But, most importantly for this line of HPM research, is the need for large sample surveys that link direct, continuous measures of energy consumption and efficiency with housing prices. But, as shown here using AHS data, an energy consumption cost index can provide a reasonable proxy measure, and illustrates how energy efficiency investments are getting *broadly and rationally capitalized* into current US housing markets.

In addition to the above limitations, the impact of occupants' behavior is not considered as a control component of observed energy usage, due to the lack of data. The occupants' lifestyle in terms of energy consumption can impact on developed BECI index. The authors' hope is that this investigation spurs additional research into the economic value of energy retrofitting for residential buildings.

The next chapter will use the LCCA presented in Chapter 4, the sustainable criteria and selection matrix presented in Chapter 5, and the economic value of energy retrofit presented in this chapter to focus on developing a decision support system for decision-making in energy retrofits.

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CHAPTER 7: Sustainable Energy Retrofit (SER) Decision-Support System Development

7.1. Introduction

This chapter introduces the Sustainable Energy Retrofit (SER) decision support system (DSS) that combines sustainable triple bottom line criteria (TBL) criteria (i.e. economic, environmental, and social) in decision-making for energy retrofits. The proposed model answer basic decision-making questions such as: what is the best amount of investment required for retrofitting a specific building? and, which retrofitting measures should be implemented (as the best retrofitting strategy) to maximize the sustainable benefits of retrofitting based on an available budget? Specifically, SER decision support system: (1) calculates the sustainable benefits of energy retrofitting during its service life; (2) determines the optimum retrofitting budget that maximizes the sustainable benefits during the building's service-life; and (3) selects the optimum energy retrofitting strategy (among available energy retrofitting measures) to maximize the sustainable benefits during service-life of the building based on available budget.

In addition, the proposed DSS in this study contributes to the body of knowledge in three aspects: (1) integrating all sustainable dimensions (i.e. economic, environmental, and social) for decision-making in energy retrofits; (2) introducing a novel simplified energy prediction method by integrating the dynamic modeling (by simulating the current energy performance of a building) and static modeling (by using the results of simulation as a mathematical input); and (3) considering energy retrofitting decision-making uncertainties including facilities life-span, energy unit price change, rebound effect, the interaction of energy measures, and market values of energy efficiency to reach more accurate results. Finally, the application of the SER decision support system is demonstrated using the case study.

7.2. Methodology

The main goal of this chapter is to introduce the SER decision support system, which includes four main phases (Figure 7.1):

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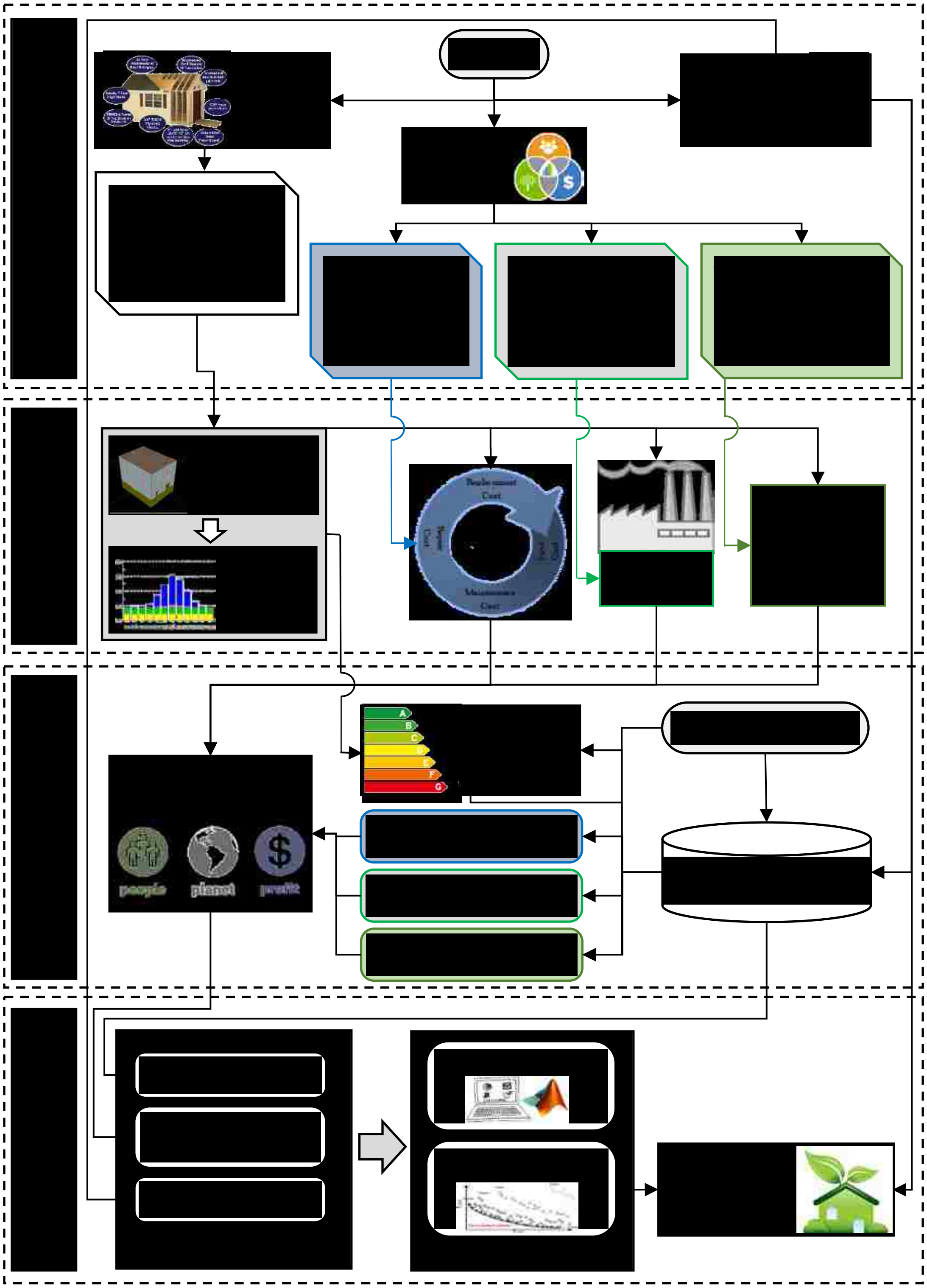

Figure 7.1. SER Decision Support System Framework

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- ***Phase 1. Data Collection***: The required data is collected including building information, owner’s requirements, and related sustainable information.
- ***Phase 2. Building Evaluation***: The building energy consumption is simulated, and the economic, environmental, and social baseline status of the building is evaluated.
- ***Phase 3. Analysis of Energy Measures***: A database of potential energy retrofitting measures is created according to the building characteristics, owner’s requirements, and expert knowledge. Then the impact of each energy efficiency measure is evaluated considering sustainable criteria.
- ***Phase 4. Decision-Making***: The data collected from previous stages is integrated into a decision-making optimization model that selects the optimum energy retrofitting strategy to maximize sustainable criteria. To solve this multi-objective problem, a Pareto optimal solution is suggested and the optimum solution is selected based on the owner’s expectations.

Following the proposed SER decision support system will help decision makers to select the optimum building energy retrofitting strategy based on the maximized economic, environmental, and social benefits for the owner. To evaluate sustainable criteria, three indicators have been defined (see Table 7.1). To find the optimum energy retrofitting strategy for a specific building, SER requires different type of data collection methods (i.e., observation, investigation, survey, and interview), energy consumption simulation (e.g. eQuest or DesignBuilder software), expert knowledge and judgment, and computerized programming (e.g. Matlab or Paython) to solve the multi-objective optimization problem. In the next section, each phase in the SER decision support system and available tools are described in detail.

Table 7.1. Sustainable indicators

Indicator	Description
Economic	Savings in life cycle cost (LCC) of the building through energy retrofits.
Environmental	Reduction in total air emissions (TAE) resulting from the production of the required energy when operating the building.
Social	Improving the occupants’ comfort and satisfaction level (OCL) through the improvement of indoor air quality, temperature, humidity, and controllability.

7.3. Development of SER Decision Support System

7.3.1. Data Collection

The first phase in SER decision support system includes collecting the required data such as building features, owner’s requirements and the sustainable TBL data. This data includes the described criteria in Chapter 5. The suggested data collection methods are explained in this section.

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Building Features. The data collected in this step will be then used as input in the building energy consumption simulation. Therefore, based on the selected software for energy simulation, the types of required data can be determined. In general, the following information is required: (1) building location and weather data; (2) building physical features such as size, shape, wall heights, size and location of doors and windows, among others; (3) the number of occupants and their energy consumption behavior; (4) type of envelopes that are used in walls, roof, floor, doors and windows; (5) HVAC system and related information for heating, cooling, and ventilation; and (6) lighting and main appliances data. Usually, this data can be obtained through site observation and/or the review of as-built documents.

Owner's Needs and Requirements. Like any other construction project, the needs and requirements of the owner play an important role in decision making for energy retrofits. This information can be obtained through interviewing the owner during the early stages of decision making. The required information in this step may be different based on the type of project, however, in general this data includes the following information: (1) available budget for the project; (2) expected service life of the building; (3) expected return period; and (4) important requirements or expectations about the project.

Sustainable TBL Data. The data resulting from this step will be used to evaluate the sustainable indicators in the SER decision support system.

Since the economic indicator is defined as the savings in LCC of the building through energy retrofits, the economic data related to the building needs to be collected. Generally, this data can be grouped into two main categories: building related information (e.g. house value, maintenance cost, repair and replacement cost, required property tax, among others) and location information (e.g. unit price of electricity, unit price of natural gas, discount rate, expected rate of energy cost increase, etc.).

One of the most important environmental impacts of buildings is the amount of greenhouse gases that are released to the atmosphere through energy production (Jafari and Valentin 2017). Therefore, in this study the environmental indicator is defined as the reduction in total air emissions resulting from producing the required energy for operating the building. The data to evaluate this environmental indicator generally includes the amount of air emission released for producing one unit of electricity (which is published by the Environmental Protection Agency (EPA) in each state), and the amount of air emission releases for consuming one unit of natural gas.

Since the social indicator is defined as improving the occupants' comfort and satisfaction level, a pre-retrofit survey may be required to evaluate the current level of comfort and satisfaction of the building occupants. The survey should include different OCL criteria such as thermal comfort, indoor air quality, ability of the user to control in temperature or humidity, and noise, among others. Likert scale responses could be used to evaluate the current OCL in the building.

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7.3.2. Building Evaluation

The second phase in the proposed SER decision support system is to evaluate the current situation of the building in terms of the sustainable criteria. Two main steps are required in this phase: energy consumption simulation and quantification of the sustainable indicators.

Energy consumption simulation. The energy analysis of a building is essential when estimating the baseline energy consumption of existing buildings. Reliable estimation and quantification of energy performance are necessary in a sustainable building retrofit decision-support system for prioritizing energy retrofit measures (Ma et al. 2012). There are two types of energy estimation methods in the literature: dynamic modeling (energy simulation programs) and static modeling (mathematical methods). Jafari and Valentin (2017) compared the cons and pros of these methods. To overcome weaknesses of each modeling method in energy retrofitting decision-making, a simplified energy assessment method is proposed that integrates dynamic modeling and static modeling. This method simulates the energy consumption of the building as the baseline of analysis and then uses the simulation output as input for mathematical energy consumption prediction. This method is explained in more detail in Section 7.5.

There are many options for energy simulation software that could be used in this step. DesignBuilder and eQuest are amongst the most popular options. The output of this simulation generally included the building energy consumption over an entire year (categorized by different zones such as space heating, water heating, appliance and electric devices, lighting, air conditioning, among others) and considers the weather data for the location under consideration.

Sustainable Indicators. In order to consider sustainable criteria in decision making, three main indicators are defined as: economic indicator, environmental indicator, and social indicator. The energy consumption of the building calculated in the simulation step can be used for more accurate estimation.

As the *economic indicator*, LCC can be estimated as described in Chapter 4. Also, additional cost factors that are described in Chapter 6 can be added to LCC formulation. For example, LCC can be formulated as:

$$LCC = EC + MR + TX - RV \tag{7.1}$$

Where *EC* is the net present value of building total energy costs during its service life; *MR* is the present value of building maintenance and replacement costs during its service life; *TX* is the present value of the total amount of property taxes that the homeowner has to pay in the building's service life; and *RV* is the present value of reselling the building after it achieves its service life. Implementing any energy retrofitting measure

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may add an initial cost (IC) to the LCC, however it may reduce the total LCC by reducing the energy consumption of the building, causing tax credits, or increasing the building resale value.

As the *environmental indicator*, TAE can be calculated based on greenhouse gases that are released to the atmosphere through energy production. In the US, electricity is generated in many different ways, and therefore, environmental impacts vary. Electricity generation from the combustion of fossil fuels contributes towards air pollution, acid rain, and global climate change (EPA 2013). According to the US Environmental Protection Agency (EPA), power emissions factors are determined based on the power grid region and the air emission rates of the electricity generated in the region are compared to those of the national average. However, burning natural gas instead of other fossil fuels emits fewer harmful pollutants, and an increased reliance on natural gas can potentially reduce the emission of many of these harmful pollutants (NaturalGas 2013). Jafari and Valentin (2017) defined the term of "CO_2-equivalent reduction" to analyze the environmental impact of energy retrofitting measures as follow:

$$CO_2 - Eq = \sum_i \alpha_i (AES \times E_i + AGS \times G_i) \tag{7.2}$$

where CO_2-Eq is the CO_2-equivalent reduction per year, i is a specific air emission (e.g. carbon dioxide, sulfur dioxide, nitrogen oxide, among others), *AES* is the expected annual electricity saving in Kwh, *AGS* is the expected annual natural gas saving in MBtu, E_i is the amount of i^{th} air emission releases for producing 1 KWh of electricity (lbs/KWh), G_i is the amount of i^{th} air emission releases for consuming 1 MBtu of natural gas (lbs/MBtu), and α_i is the conversion factors (in terms of global warming impact) of i^{th} air emission, in CO_2-Equivalent calculation. For example, α is equal to 1, 1/0.005, and 1/0.0025 for CO_2, SO_2, and NO_x, respectively (Jafari and Valentin 2017). The authors suggest the use of CO_2-equivalent reduction per year for calculating the TAE during the service life of the building.

As the *social indicator*, OCL can be calculated based on the results of surveys among occupants, as follow:

$$OCL = \frac{1}{A} \times \sum_i W_i \times \frac{IF_i}{N} \tag{7.3}$$

Where i is the social criteria (e.g. thermal comfort, indoor air quality, amount of control in temperature or humidity, noise, among others), W_i is the average importance of that criteria (from 1: very low importance to 5: very high importance) from survey results, IF_i is the evaluation of occupants for the i^{th} social criteria before implementing any retrofitting measure, A is the highest weight possible (i.e., 5); and N is the total number of survey respondents.

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7.3.3. Analysis of Energy Measures

The third phase in the proposed SER decision support system is to select potential energy efficiency measures and analyze the impact of these measures on the sustainable criteria. Three main steps are required in this phase: energy efficiency measures selection, evaluation of energy efficient measures, and formulation of sustainable benefits. These steps and suggested tools are explained in this section.

Energy efficiency measures selection. In this stage, potential retrofitting measures that can be implemented are identified as well as their impact on energy consumption and their interactions. To select the energy retrofit measures that are available for the project, two approaches are suggested: analyzing homeowner needs for energy efficiency improvements, and considering home upgrade possibilities for the existing inefficiencies based on consultation with experts. Various energy retrofitting measures can be categorized in the following main groups: controlling measures (which provide appropriate controls and monitors for the mechanical systems, lighting, ventilation, and the efficient use of multi-functional equipment, among others); load reduction measures (which upgrade the mechanical systems; replace fixtures, appliances, and lighting with energy efficient models, among others); enveloping measures (which insulate and air-seal the roof or ceiling, walls, and floor; replace the windows and doors with energy-efficient models); and renewable energy technologies (which provide renewable-energy sources such as solar thermal systems, solar photovoltaic/thermal systems, geothermal power systems, among others) (Jafari and Valentin 2017). Syal et al. (2014) summarized several construction and home energy efficiency-related information portals and databases currently exist, including National Residential Efficiency Measures (NREM) Database; Building America (BA) Portal; Energy Star Portal; and Database of State Incentives for Renewables and Efficiency Portal.

Evaluation of energy efficiency measures. To build the energy simulation model, several energy consumption zones impacted by different retrofitting measures need to be defined as a first step. As an example, five main energy consumption zones are defined: space heating (SH), water heating (WH), appliance and electric devices (AE), lighting (LI), and air conditioning (AC).

In order to estimate the impact of different energy measures on total energy consumption of a building (as well as other sustainable criteria) accurately, it is important to consider that energy measures are not independent and in reality, they interact with each other. For example, it is proven that replacing lights with energy efficient ones would decrease the required energy in the lighting zone. However, it would also increase the required energy for space heating because of a decrease in heating burden. To consider these interactions of energy retrofits, the impact of each energy measure on different energy consumption zones were estimated (as a percentage of increase or decrease in consumption

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value for each energy zones) as a network. Different tools and sources can be used to estimate these interactions. Then, the interaction logic of identified retrofitting measures can be determined and embedded into the model through the calculation of energy consumption cost.

Different energy retrofitting measures may have different impacts on energy consumption of a building. Based on how retrofitting measures may impact energy consumption, two different groups of measures can be defined:

- *Consumption-Reducing (CR) Measures*: Those activities that improve energy performance of a building. Their impact can be illustrated by the percent of decrease in energy consumption of each effected zone.
- *Energy-Producing (EP) Measures*: Those activities that produce energy for the building using renewable sources. Their impact can be illustrated by subtracting the amount of energy they can produce during a year from each effected zone.

The author suggests this method to analyze the impact of different energy retrofit measures on energy consumption of the building, since this method avoids the iterative trial and error process of searching for the best retrofit action when exploring a large decision space; considers the interaction of energy measures; and estimates energy consumption accurately (Jafari and Valentin 2017).

Formulation of Sustainable Indicators. After analyzing the impact of different energy retrofit measures on energy consumption of the building, the impact of these measures should be formulated in terms of sustainable criteria. First, a set of $X=[x_i]$ is considered as binary indicator variables for representing the selected energy measures. Then, the sustainable benefits should be formulated based on sustainable criteria and these indicator variables. These formulations may change case by case; however, they follow a similar approach. As an example, the LCC formulation is presented in this section.

For the purpose of this section, the following cost elements are selected for the LCC equation formulation:

- Initial Investment Cost (IC): Initial costs refer to cost of implementing a retrofitting activity including materials, equipment, and labor.
- Energy Consumption Cost (EC): the total cost of gas and electricity that the building consumes during its service life.
- Maintenance and Replacement Cost (MR): the average cost of service, repair, or replacement of an equipment in specific periods (MR period) to keep it performing as intended in the building's service life duration.
- Resale Benefits (RV): The benefits of homeowner from reselling the building after its service life (See Chapter 6).

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- Property Tax (TX): Total amount of property taxes that the homeowner has to pay in the building's service life duration. There are government incentives for "green" programs which can play a substantial role in providing tax incentives for home owners to install the environmentally preferred equipment during their building's service life.

Therefore, the change in LCC of a building due to energy retrofits can be calculated as follow:

$$LCC = IC + PV_{EC} + PV_{MR} - PV_{RV} + PV_{TX} \tag{7.4}$$

Where LCC is the net present value of the total life-cycle cost of the building during its service life, IC is the initial investment cost due to energy retrofits, PV_{EC} is the present value of total energy consumption cost of the building during its service life, PV_{MR} is the present value of total maintenance and replacement cost of the building during its service life, PV_{RV} is the present value of the benefits from building resale value after its service life, and PV_{TX} is the present value of the total property tax that the homeowner needs to pay during the building's service life.

To calculate the initial investment cost of an energy retrofit strategy, the following equation is used:

$$IC = \sum_{i=1}^{m} C_{Ii} \times x_i \tag{7.5}$$

Where C_{Ii} is estimated cost of implementation of i^{th} retrofitting measure, and x_i is a binary or indication variable indicating whether the i^{th} retrofitting measure is selected in the energy retrofit strategy (a measure with a value of "1" implies that this measure is part of the retrofitting strategy, and a "0" value, implies that the measure is not part of the retrofitting strategy). In addition, m is the total number of potential energy retrofit measures.

To calculate the present value of energy consumption cost of a building due to energy retrofits, the following Equation is used:

$$PV_{EC} = AEC \times \left[\frac{(1+\left(\frac{d-k}{1+k}\right))^{n} - 1}{\left(\frac{d-k}{1+k}\right) \times \left(1+\left(\frac{d-k}{1+k}\right)\right)^{n}} \right] \tag{7.6}$$

Where *AEC* is the estimated annual energy consumption cost of the building in the first year, d is the interest rate, k is the annual rate of energy cost increase (a rate of 5% is reported for the state of New Mexico (EIA 2014)), and n is the service life of the building.

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The annual energy consumption of a building in the first year can be calculated as the sum of the estimated electricity and natural gas consumption per year as follow:

$$AEC = AEC_0 - (1 - RB) \times \left[AEC_0 - \left(EL \times U_{EL} + NG \times U_{NG} \right) \right] \tag{7.7}$$

Where AEC_0 is the annual energy consumption of the building before energy retrofit implementation, EL is the estimated annual electricity consumption of the building in the first year, U_{EL} is the electricity unit price, NG is the estimated annual natural gas consumption of the building, and U_{NG} is the natural gas unit price in the first year. In addition, RB is the rebound effect of energy consumption. The rebound effect assumes that people increase their use of energy as a result of reduction in energy cost, thereby reducing the energy saving s achieved. Nadel (Nadel 2012) estimated a rebound effect of 20% for energy efficiency in buildings (Nadel 2012) that means only 80% of energy efficiency benefits can be achieved because of increase in users' usage.

To calculate the estimated electricity consumption of the building due to energy retrofits, the following Equation is used:

$$EL = \left(\prod_{i=1}^{n_{CR}} (1 - C_{SHi} \times x_i) \right) E_{SH} + \left(\prod_{i=1}^{n_{CR}} (1 - C_{WHi} \times x_i) \right) E_{WH} + \left(\prod_{i=1}^{n_{CR}} (1 - C_{AEi} \times x_i) \right) E_{AE} + \left(\prod_{i=1}^{n_{CR}} (1 - C_{LIi} \times x_i) \right) E_{LI} + \left(\prod_{i=1}^{n_{CR}} (1 - C_{ACi} \times x_i) \right) E_{AC} - \sum_{j=1}^{n_{EP}} C_{Ej} \times x_j \tag{7.8}$$

Where n_{CR} represents the consumption-reducing measures, n_{EP} represents the energy-producing measures, C_{SHi} is the impact of i^{th} activity from the CR group on building space heating energy consumption zone, E_{SH} is the electricity consumption of the building for space heating before retrofitting, C_{WHi} is the impact of i^{th} activity from the CR group on building water heating energy consumption zone, E_{WH} is the electricity consumption of the building for water heating before retrofitting, C_{AEi} is the impact of i^{th} activity from the CR group on building appliance and electric device energy consumption zone, E_{AE} is the electricity consumption of the building for appliance and electric device before retrofitting, C_{LIi} is the impact of i^{th} activity from the CR group on building lighting energy consumption zone, E_{LI} is the electricity consumption of the building for lighting before retrofitting, C_{ACi} is the impact of i^{th} activity from the CR group on building air conditioning energy consumption zone, E_{AC} is the electricity consumption of the building for air conditioning before retrofitting, and C_{Ej} is the amount of electricity-equivalent energy that can be produced per year by j^{th} activity from the EP group. C_{SHi}, C_{WHi}, C_{AEi}, C_{LIi}, and C_{ACi} represent the impact of energy measures on energy consumptions as well as the interaction between energy measures.

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To calculate the natural gas consumption of a building based on a retrofitting strategy, the following Equation is used:

$$NG=\left(\prod_{i=1}^{n_{CR}}(1-C_{SHi}\times x_i)\right)G_{SH}+\left(\prod_{i=1}^{n_{CR}}(1-C_{WHi}\times x_i)\right)G_{WH}+\left(\prod_{i=1}^{n_{CR}}(1-C_{AEi}\times x_i)\right)G_{AE}+$$
$$\left(\prod_{i=1}^{n_{CR}}(1-C_{LIi}\times x_i)\right)G_{LI}+\left(\prod_{i=1}^{n_{CR}}(1-C_{ACi}\times x_i)\right)G_{AC}-\sum_{j=1}^{n_{EP}}C_{Gj}\times x_j \tag{7.9}$$

Where G_{SH} is the natural gas consumption of the building for space heating before retrofitting, G_{WH} is the natural gas consumption of the building for water heating before retrofitting, G_{AE} is the electricity consumption of the building for appliance and electric device before retrofitting, G_{LI} is the natural gas consumption of the building for lighting before retrofitting, G_{AC} is the electricity consumption of the building for air conditioning before retrofitting, and C_{Gj} is the amount of electricity-equivalent energy that can be produced per year by j^{th} activity from the *EP* group.

If the annual estimated electricity or natural gas consumption cost is calculated to be a negative number (which means that by using renewable sources, the project can produce more power than is required), a zero consumption is assigned (Jafari and Valentin 2015). In this case study, based on the selected energy retrofitting measures, the natural gas consumption cost cannot get a negative value.

To calculate the maintenance and replacement cost due to energy retrofits, the number of replacements during service life of the building is calculated using the following equation:

$$m_{MRi}=Round_{Down}\left[\frac{n}{n_{MRi}}\right] \tag{7.10}$$

Where m_{MRi} is the number of maintenance and replacements need to be done for the i^{th} measure during service life of the building, and n_{MRi} is the maintenance and replacement period for the i^{th} measure. Then to calculate the present value of maintenance and replacement cost due to energy retrofits the following equation is used:

$$PV_{RC}=\sum_{i=1}^{m}\left[\left(\sum_{j=1}^{m_{MRi}}\frac{C_{MRi}}{(1+d)^{(j\times n_{MRi})}}\right)\right]\times x_i \tag{7.11}$$

Where C_{MRi} is the estimated maintenance and replacement cost of implementation of the i^{th} activity after its *MR* period.

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To calculate the present value of resale benefits due to energy retrofits, first the value of the building after implementing the energy retrofits is calculated using Chapter 6 results. The marginal value or implicit price for improvements in the energy performance of a house in US residential housing markets is measured using a hedonic pricing model and a two-stage least squares approach, along with 27,547 household observations from the American Housing Survey (AHS) 2013. The value of the building after implementing the energy retrofits as follow:

$$V = V_0 \times e^{0.020 \times \frac{(AEC_0 - AEC)}{Area}} \tag{7.12}$$

Where *V* is the resale value of the building with improvement in energy efficiency, V_0 is the resale value of the building with no energy retrofit, and *Area* is the floor area of the building in square meter. In order to calculate the present value of the benefits from building resale value after its service life, the following equation is used:

$$PV_{RV} = (V - V_0) \times \frac{1}{(1 + d)^n} \tag{7.13}$$

New Mexico State's average property tax rate is 0.96% of the assessed home value. Increasing the value of the building may increase the amount of annual property tax, however there are federal tax incentives for improving the energy efficiency of a building. According to US Department of Energy(DOE 2015), taxpayers who upgrade their homes to improve their energy efficiency or make use of renewable energy may be eligible for tax credits to offset some of the costs. The federal government offers two of such credits:

- *Residential Energy Efficiency Property Credit*: can be claimed for solar, wind and geothermal equipment. The tax credit is equal to 30% of the cost of the equipment, including installation. There is no upper limit on the amount of the credit for solar, wind and geothermal equipment.
- *Nonbusiness Energy Property Credit*: can be claimed for qualified energy efficiency improvement equipment and materials, including home insulation, exterior doors, exterior windows and skylights, among others. The tax credit is equal to 10% of the cost of qualified energy efficiency improvements. There is a maximum credit for insulation of $500, and a maximum credit for changing door and windows of $500 (a maximum of $200 can be for windows).

To calculate the present value of property tax due to energy retrofits, the following equation is used:

$$PV_{TX} = 0.0096 \times V \times n - PV_{TI} \tag{7.14}$$

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Where PV_{TI} is the present value of the amount of tax credits that can be applied to the building from the time of energy retrofitting to its service life due energy efficiency improvement. The PV_{TI} can be estimated based on the two aforementioned federal government credits and their applicability to the selected energy retrofitting measures.

7.3.4. Decision-Making

The final phase in the proposed SER decision support system is to develop an optimization decision-making framework that selects the optimum energy retrofitting strategy to maximize benefits of sustainable criteria. Two main steps required in this phase: model formulation, and optimization and interpretation. These steps and suggested tools are explained in this section.

Model formulation. The binary indicator variables are used as the decision variables in the proposed SER decision support framework. The goal is to maximize the sustainable benefits (i.e. economic, environmental, and social benefits) which are defined in Phase 3. The model also needs to fulfill a main constraint: the maximum budget (MB) that the owner plans to invest for energy retrofits. The initial investment cost of retrofitting strategy should be less than the available budget. The optimization model developed for the selection of the optimum energy retrofit strategy that maximize the sustainable benefits is defined as follows:

$$\begin{cases} Maximize \quad LCC(x), TAE(x), OCL(x) \\ Subject\ to \quad IC \leq MB \end{cases} \tag{7.15}$$

Optimization and interpretation. The optimization in the SER decision support system is defined as a multi-objective decision problem. In this case, a Pareto optimal solution approach that corresponds to the Pareto frontier is suggested. This approach helps determining the trade-off relationships between the optimization objectives.

The formulated problem is a constrained nonlinear optimization with a non-differentiable objective function. Genetic algorithm (Goldberg 1989) is a method able to solve nonlinear constraint problems (MathWorks 2015). Therefore, in order to optimize the objective functions of the model and to find the Pareto optimal solution for optimum energy retrofit strategies that optimize the sustainable benefits of energy retrofits, genetic algorithm (Goldberg 1989) is proposed as optimization algorithm (Cho and Hastak 2012; Hegazy and Kassab 2003; Karatas and El-Rayes 2014; Kim and Ellis 2008; Que 2002). After calculating the Pareto optimal solutions, the last step is to find the optimum energy retrofit strategy among the ones in the Pareto frontier. The weights in the multi-objective optimization will be determined through input from the decision-maker (owner or investor) on the importance level of each sustainable criteria (i.e. economic, environmental, and social).

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Optimum Energy Retrofit Budget. In terms of economic benefits, the total LCC of a building due to energy retrofits is equal to sum of initial investment cost (IC) and future cost (FC). Future cost is the sum of net present value of energy cost, maintenance cost, replacement cost, tax incentives earning, and resale earning. Figure 7.2 from Chapter 4 shows the relationship between initial investments, future cost, and the total LCC associated with energy retrofits. As it is illustrated, low investments for energy retrofits are associated with high future cost, implying that homeowners would not benefit economically if they cannot provide enough budget for energy retrofitting. On the other hand, large investments reduce building's future costs and increase the economic benefits of the homeowner. The optimum initial investment would minimize the total LCC of the building.

In order to find the optimum energy retrofitting investment that minimize the total LCC of the building, the optimization model is run for different budgets, varying from no retrofitting budget to the required budget to implement all energy measures. Then the Figure 7.2 can be built based on the results.

After finding the optimum budget for energy retrofits, the associated retrofitting strategy can be extracted from the model. That strategy will be the most economically beneficial energy retrofitting plan that the homeowner can use as a reference for an energy retrofit project.

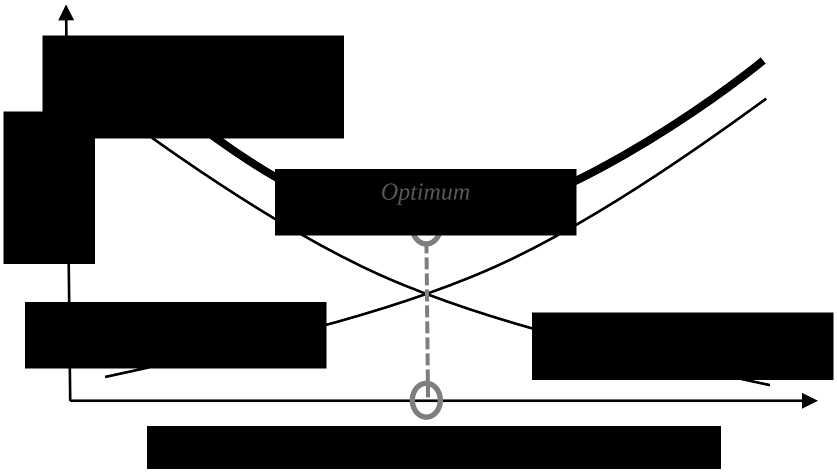

Figure 7.2. Optimization of energy retrofits investment

7.4. Application of SER Decision Support System

In order to validate the application of the proposed SER decision support system, the author implemented the model to the real case study. This case study is described in detail in Chapter 3. Because of data limitation, the economic section of SER was implemented in this chapter.

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7.4.1. Data Collection

In this section, potential retrofitting measures that can be implemented are identified as well as their impact on energy consumption and their interaction. For the purpose of this study, the “Build Green New Mexico criteria for a Green Building” (BGNM 2013) document is used to evaluate measures that could be implemented to retrofit the case study house. This document suggests retrofitting measures from the basic least expensive items from the house, works up through more complex items, and finishes with on-site renewable energy systems. Same as Chapter 4, for the case study, 15 different retrofitting measures - varying from low to high cost efforts - are selected as possible retrofitting measures for the case study. Figure 7.3 provides a summary of the selected potential retrofitting measures for the case study.

In order to collect data for the case study, different tools and resources are used. For each identified retrofitting measure, the initial investment cost for implementation is estimated using RS Means Green Building Cost Data (RSMeans 2012) and the energy star website (EnergyStar 2013). For example, for energy measure 08: Insulate walls, the cost of demolition of current insulation, purchase of new specific materials for insulation, and installation of that insulation for external walls were estimated. However, this estimation can be adapted if the decision-maker wants to consider a different option such as improving the current insulation as an alternative. In this case, a new energy measure can be added with its respective cost estimation.

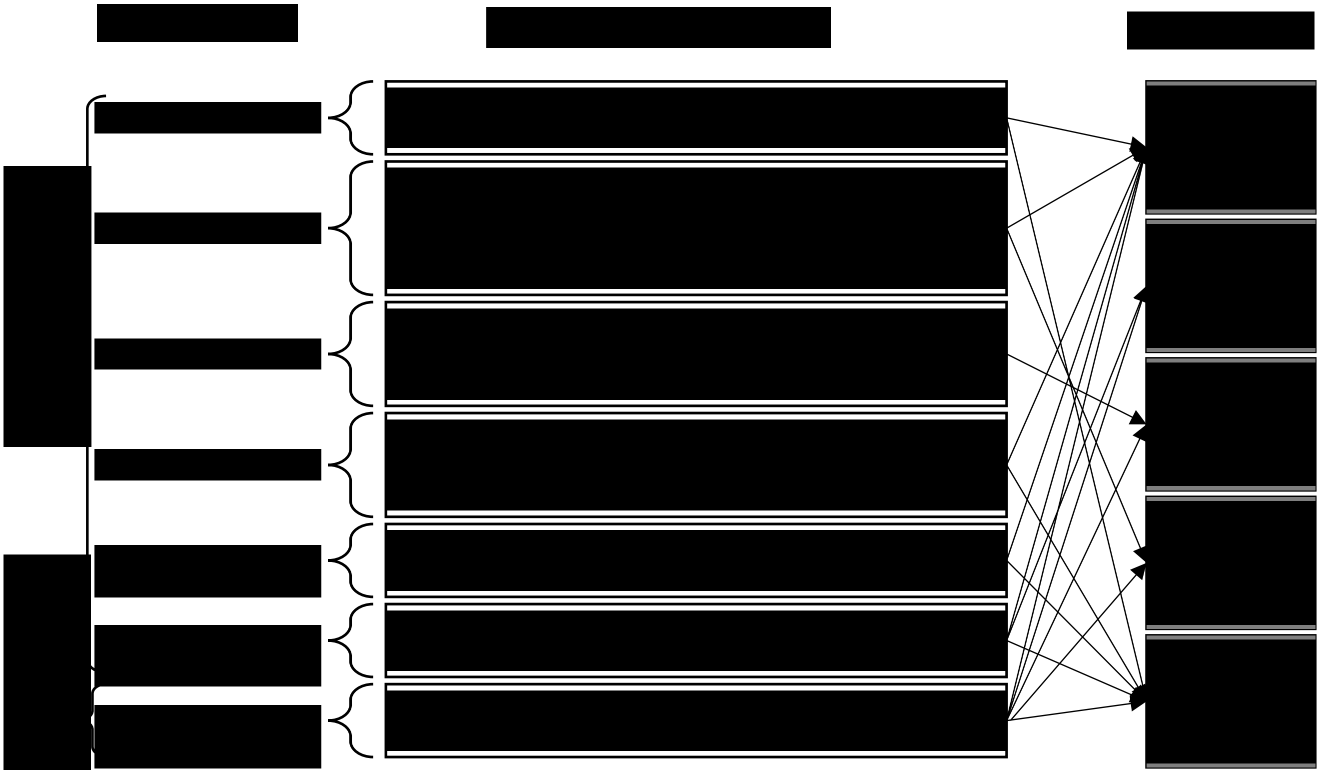

Figure 7.3. Selected Retrofitting activities and their interactions

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In order to account for the interaction of energy measures, the impact of implementation of a specific energy measure on each energy consumption zone is determined using the energy star website (EnergyStar 2013), the eQuest (Quick Energy Simulation Tool) software (DOE2 2013), and the Housing and Urban Development Website Energy Efficient Rehab Advisor (HUD 2013). Finally, the maintenance period and maintenance and replacement cost are calculated, and the tax rebates are evaluated for implementing each activity based on the case study. The interaction logic of identified retrofitting measures are also presented in Figure 7.3.

7.4.2. Optimum Energy Retrofit Budget

In this study, Matlab R2014a is used for implementing genetic algorithm (GA) optimization for the model.

After gathering data about possible retrofitting activities and related information, the optimum energy retrofit investments for the case study is identified. The model is run for investment budget of $1,000 to $50,000 with intervals of $1,000. For each case, the best selected retrofitting measures are selected to minimize the future cost of the case study. Then the initial investment cost, future cost, and total LCC of the optimum retrofitting strategy according to each budget case is calculated and plotted. As the results show in Figure 7.4, the minimum LCC is reached on the energy retrofitting budget of $11,000 for the case study. In other words, the budget of $11,000 for energy retrofitting of the case study can minimize the total LCC of the building for the homeowner. The calculated optimum retrofitting budget is specifically for the example case and for the aforementioned assumptions. The optimum budget would be different for any other cases.

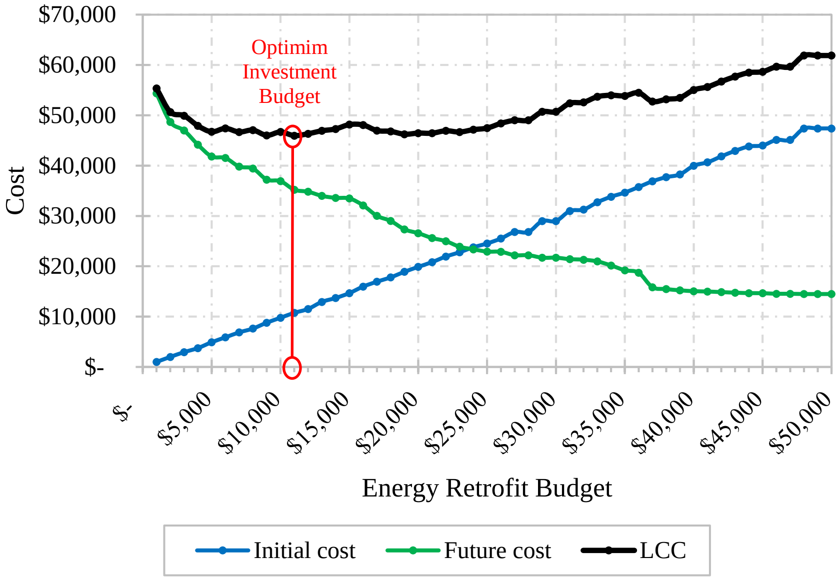

Figure 7.4. Optimization investment budget selection

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7.4.3. Energy Retrofit Strategy

After estimating the optimum retrofitting budget for the case study, the model is used to select the best energy retrofitting measures. In order to compare the results, four different scenarios are considered for the case study: (1) below optimum budget ($5,000); (2) optimum budget ($11,000); (3) above optimum budget ($20,000); and (4) very above optimum budget ($30,000). For a service life of 15 years for the case study and discount rate of 2.6%, the results of the model are presented in Table 7.2. The results of the selected retrofitting strategies presented in Table 7.2 are specifically for the example case and for the aforementioned assumptions. The results would be different for other cases; however, the process for performing such analysis will be the same. As the results show, in scenario #1, the selected low-cost measures were able to decrease the energy consumption cost by 40% with a low investment cost and therefore, the LCC of the building also decreased. In scenario #2, which is the optimum one, the model suggests the installation of solar thermal equipment, which decreases the expected energy consumption of the building by 51%. However, the change in LCC is not very significant and it can be concluded that the budgets around selected optimum budget could have been selected based on the financial situation of the owner.

Table 7.2: Results of the developed model for the case study

Scenarios	1	2	3	4
Investment Budget	$5,000	$11,000	$20,000	$30,000
Measure 01. Install programmable thermostat	✓	✓	✓	✓
Measure 02. Tune up HVAC				
Measure 03.1. Replace lights with energy efficient ones (HALOGEN)				
Measure 03.2. Replace lights with energy efficient ones (CFL)		✓	✓	
Measure 03.3. Replace lights with energy efficient ones (LED)	✓			✓
Measure 04. Replace refrigerator with an energy star one				✓
Measure 05. Replace clothes washer with an energy star one				
Measure 06. Replace dishwasher with an energy star one	✓	✓	✓	✓
Measure 07. Insulate ceilings	✓	✓	✓	✓
Measure 08. Insulate walls	✓	✓	✓	✓
Measure 09. Insulate attic	✓	✓	✓	✓
Measure 10. Replace doors with insulated core		✓		
Measure 11. Replace windows with energy efficient glass				✓
Measure 12. Install ground source heat exchanger			✓	✓
Measure 13. Install evaporative cooler				
Measure 14. Install solar thermal equipment		✓		✓
Measure 15. Install solar electricity equipment				
Initial Investment Cost	$ 4,906	$ 10,752	$ 19,887	$ 28,993
Annual Energy Cost Reduction	40.2%	51.3%	62.4%	71.9%
LCC	$ 46,730	$ 45,967	$ 46,464	$ 50,706

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In scenario #3, the model suggests the installation of ground source heat exchanger that is able to decrease the expected energy cost by 62% but needs high amount of investments. In this scenario, the LCC increases, however the amount of change in LCC is not significant. Finally, scenario #4 suggests the installation of both solar thermal equipment and ground source heat exchanger to decrease the energy cost by 72%. However, the required investments and LCC are considerably high.

The analysis of the developed model results will help a decision-maker to select an optimal energy retrofitting budget and according combination of retrofitting measures that best fits the specific project. It also provides details about the amount of required budget as well as the amount of savings and rebates that can be obtained, which can help homeowners evaluating retrofitting alternatives for a building.

7.4.4. Impact of Different Types of Investors

The presented case study can be also used to illustrate how different types of investors (described in Chapter 6) may impact the selection of optimization objective functions and, therefore, the final decisions on which building energy retrofitting measures (optimum energy retrofits). The developed decision matrix presented in Figure 1 is applied to the case study for selecting the optimization objectives, considering different types of investors and the potential economic benefits of building energy retrofits.

In this section, different scenarios considering the goals of different decision-makers were explored, using the same case with the same data. Since the data collected relates to only the economic aspects of building energy retrofits, this study limits the optimization objective functions of each scenario to economic functions.

In addition to the aforementioned cost factors, this study defined two more categories: total annual rent (TR) and carbon dioxide reduction benefits (CR).

Total annual rent (TR)*:* the present value of the total amount of annual rent during the study period. To calculate the annual rent, the ratio of rent to value was used. This ratio (12 months of rent/home price), called “rental yield,” is similar to the earnings-to-price ratio in the stock market, and implies that higher rents would make it less important for the property to appreciate in value in order to meet a certain expected return target set by the investor. Rental yield was estimated to be 21.9 for the case study location of Albuquerque, NM (smartasset 2017).

Carbon dioxide cost (CC): the present value of the total cost of carbon dioxide (CO_2) that is produced as a result of providing energy for the building during the building’s service life. Carbon dioxide emissions from burning fossil fuels are warming our planet and changing our climate in harmful ways, which generates costs for our society economy and environment. Transitioning to a lower carbon economy is an essential step toward reducing these costs. Energy efficiency in buildings could lead to a lower carbon economy by

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reducing the carbon dioxide that is released to the air. The social cost of carbon (SCC) is a tool that helps federal agencies decide which carbon-reducing regulatory approaches make the most sense. The SCC is a range of estimates, in dollars, of the long-term damage generated by one ton of carbon emissions. Carbon dioxide cost per year (ACC) can be calculated as follows:

$$ACC = (AEC \times E_{CO2} + AGC \times G_{CO2}) \times SCC \tag{7.16}$$

where AEC is the annual electricity consumption of the building (KWh), AGC is the annual natural gas consumption of the building (MBtu), E_{CO2} is the amount of carbon dioxide released to provide a unit of electricity (lbs/KWh), and G_{CO2} is the amount of released carbon dioxide to burn a unit of natural gas (lbs/MBtu).

The E_{CO2} and G_{CO2} were estimated to be 0.876 (lbs/KWh) and 117 (lbs/MBtu), respectively, for the state of New Mexico. In addition, EPA estimated an annual SCC value of $39.7/ton (≈$0.02/lbs) for regulatory analyses, for the year 2017, and a discount rate of 2.5% (the discount rate of Albuquerque, NM is 2.6%) (USEPA).

Four different scenarios were considered, to analyze the impact of different types of investors on energy retrofit decisions:

Scenario 1. When the investor is the owner-occupant, he/she would pay energy costs, maintenance and replacement costs, and property taxes. The owner-occupant would also receive the resale price of the building. Equation 7.17 shows the LCC objective function, which was selected based on the proposed decision matrix. In this case, the objective function is the same one proposed in Jafari and Valentin (Jafari and Valentin 2017):

$$LCC_{Owner-Occupant} = IC + EC + MR - RV + TX \tag{7.17}$$

Scenario 2. When the investor is an absent owner, he/she would pay maintenance and replacement costs and property taxes. Additionally, an absent owner would receive annual rents and the resale price of the building. Equation 7.18 shows the LCC objective function, which was formulated based on the proposed decision matrix:

$$LCC_{Absent\ Owner} = IC + MR - RV + TX - TR \tag{7.18}$$

Scenario 3. When the investor is a leaser, he/she would pay the energy costs (no change in the annual rent is assumed when the leaser is investing for energy retrofits). Equation 7.19 shows the LCC objective function, which is selected based on the proposed decision matrix:

$$LCC_{Leaser} = IC + EC \tag{7.19}$$

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Scenario 4. When the investor is an external stakeholder, which for the case study is assumed to be a carbon dioxide reduction program, the investor would be responsible for the carbon dioxide reduction cost. According to the proposed decision matrix, the LCC objective function is given in Equation 7.20.

$$LCC_{External\ Stakeholder} = IC + CR \tag{7.20}$$

For a service life of 15 years and a discount rate of 2.6%, the model was run for investment budgets of $1,000 to $25,000, considering intervals of $1,000. For each case, the optimal retrofitting measures that minimized future costs were selected for the case study. Then, the percentage of change in the LCC and the reduction in the percentage of energy-consumption (ECR) of the optimum retrofitting strategy was calculated and plotted for each budget case. The results are shown in Figure 7.5.

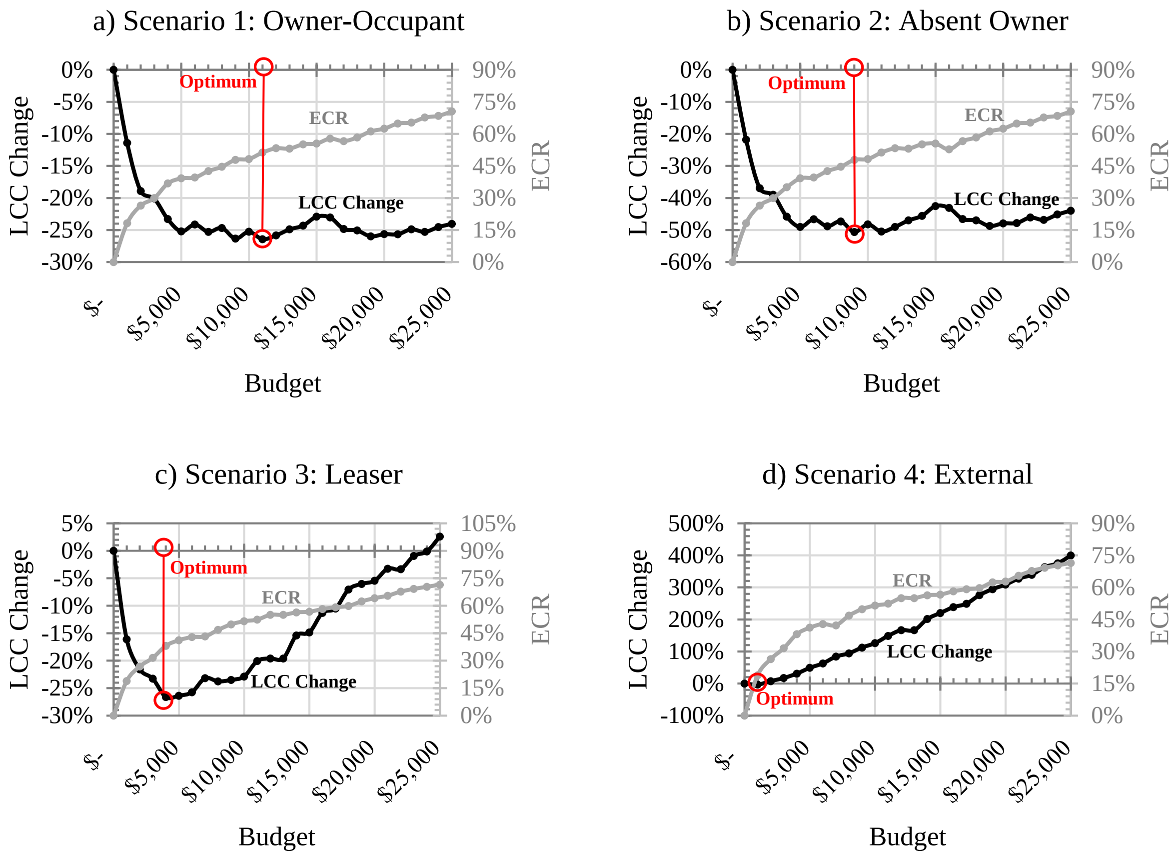

Figure 7.5: Optimized investment budget scenarios

As illustrated in Figure 7.5, since the objective function (which corresponds to the total LCC in this case) is different for each retrofitting scenario, the calculated LCC change and ECR values corresponding to the same budget are different for each scenario,

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accordingly. The minimum LCC was reached for energy retrofitting budgets of $11,000, $9,000, $4,000, and $1,000 when considering the investor as owner-occupant, absent owner, leaser, and external stakeholder (carbon dioxide reduction program), respectively. In other words, these budgets for energy retrofitting of the case study can minimize the total LCC of the building for the investor (or the main stakeholder). The calculated optimum retrofitting budget is specifically for the example case and for the aforementioned assumptions.

The results show that when the investor is the owner (i.e., owner-occupant or absent owner), investing more in energy retrofits may still keep the LCC close to optimum; that is because of the high economic benefits to the owner that result from energy efficiency improvements. On the other hand, when the investor is not the owner (i.e., leaser or external investor), more than optimum investment for energy retrofits may not be feasible, since the investor would not own the building and could not utilize the related economic benefits through energy efficiency improvement.

The results also show that when the investor is an owner-occupant, he/she would need to invest more in energy retrofits to achieve optimum benefits. On the other hand, when the investor is a carbon dioxide reduction program external stakeholder, less investment in energy retrofits would be desired.

After estimating the optimum retrofitting budget for the different types of investors, the best energy retrofitting measures were selected for each scenario, assuming a service life of 15 years and discount rate of 2.6%. The results of the model are presented in Table 7.3. Even though results will vary for different case studies, the proposed process for performing such analysis will be the same.

As shown in Table 7.3, when the investor is the owner-occupant (Scenario #1), the selected measures include a high number of energy-related activities. The selected strategy would decrease the energy consumption cost by more than 50%, with an optimum investment cost of $10,752. Scenario #2, where the investor is an absent owner, differs from scenario #1 (owner-occupant) primarily with a suggestion not to replace doors with insulated core (measure 10). In this scenario, the selected strategy would decrease the energy consumption cost by around 48%, with an optimum investment cost of $8,792. In Scenario #3, where the investor is the leaser, a smaller number of activities are selected as the best retrofitting strategy and this selected strategy would decrease the energy consumption cost by less than 40%, with an optimum investment cost of $3,874. Finally, in Scenario #4, where the investor is a carbon dioxide reduction program, a smaller investment (less than $1,000) is suggested, resulting in less than 20% of energy consumption reduction for the case study.

Analysis of the results could help emphasize the impact that a decision-maker has on selecting an optimal energy retrofitting budget and the combination of retrofitting measures that best fits a specific project. The case study also shows how the developed

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decision-matrix works and how different investors may affect the selection of optimum energy retrofits strategies.

Table 7.3: Optimum energy measure selection for different scenarios

Scenarios	1	2	3	4
Investor/decision-maker	Owner-Occupant	Absent Owner	Leaser	CO$_2$ Reduction Program
Optimum Investment Budget	$11,000	$9,000	$4,000	$1,000
Measure 01. Install programmable thermostat	✓	✓	✓	✓
Measure 02. Tune up HVAC			✓	✓
Measure 03. Replace lights with energy-efficient ones				
Measure 03.1. Replace lights with energy-efficient ones (HALOGEN)				
Measure 03.2. Replace lights with energy-efficient ones (CFL)	✓		✓	✓
Measure 03.3. Replace lights with energy-efficient ones (LED)		✓		
Measure 04. Replace refrigerator with an Energy Star one			✓	✓
Measure 05. Replace clothes washer with an Energy Star one				
Measure 06. Replace dishwasher with an Energy Star one	✓	✓	✓	
Measure 07. Insulate ceilings	✓	✓		
Measure 08. Insulate walls	✓	✓	✓	
Measure 09. Insulate attic	✓	✓	✓	
Measure 10. Replace doors with insulated core	✓			
Measure 11. Replace windows with energy-efficient glass				
Measure 12. Install ground source heat exchanger				
Measure 13. Install evaporative cooler				
Measure 14. Install solar thermal equipment	✓	✓		
Measure 15. Install solar electricity equipment				
Initial Investment Cost	$ 10,752	$ 8,792	$ 3,874	$ 932
Annual Energy Cost Reduction	51.3%	47.8%	38.1%	18.8%

7.5. Chapter Conclusion

This chapter introduced SER decision support system to select an optimum energy retrofitting strategy for a specific building. The main contribution of SER is to adopt sustainable triple bottom line criteria in the decision-making process by defining the economic, environmental and social indicators. Then using a multi-objective optimization model, SER is able to find the best energy retrofitting strategy for a specific building that optimizes sustainable criteria. The main phases in the SER decision support system process are: (1) data collection, which collects the required data and related sustainable information; (2) building evaluation, which simulates the energy consumption of the building and evaluates its current sustainable situation; (3) analysis of energy measures, which selects the potential energy efficiency measures and analyzes their impact on sustainable criteria; and (4) decision-making, which proposes an optimization tools to find the optimum energy retrofitting strategy based on maximized sustainable benefits.

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Following the described steps of SER decision support approach could help decision makers considering and optimizing sustainable criteria in energy retrofit projects.

In order to validate the application of the developed SER, the application of SER was also demonstrated. The economic component of the SER decision support system was implemented on the case study to show how the SER decision support system can guide decision-makers to select appropriate retrofitting budget and associated strategy to achieve maximum economic benefits of energy retrofitting for a specific building. Also, the case study showed how different types of investors may affect the selection of the optimization objective function, and therefore the final decisions for optimum energy retrofits. The results showed that when the investor is the owner-occupant, he/she needs a higher investment to meet the optimum benefits of energy retrofits. On the other hand, less investment is desired when the investor is a carbon dioxide reduction program.

The framework allows selecting the optimum housing retrofit measures to maximize the owner’s sustainable benefits. However, the proposed model can be more effective by improving it to consider a database of retrofitting measure instead of just limited activities for a specific project. It can also be more realistic by estimating the costs (e.g. cost implementation cost, maintenance and replacement cost) as probabilistic data to consider uncertainty in the estimated information. As the future research, the author will implement the other aspects of SER (i.e. environmental and social) in the same case study.

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CHAPTER 8: Conclusion

8.1. Summary of Conclusions

The primary goal of this research was to develop a holistic decision support system for energy retrofitting projects that integrates sustainable criteria (i.e. economic, environmental, and social benefits). To achieve this goal, this research first introduced an approach for evaluating life-cycle cost of building energy retrofits, based on the investment cost and energy performance of the building. Results of the LCCA of the case study house in Albuquerque, New Mexico demonstrated that if an owner plans to operate a house for a longer period of time, higher energy-related retrofitting investments for the house are optimum.

Then, this research identified and measured the sustainable decision criteria (i.e. economic, environmental, and social criteria) of energy improvements in existing buildings. In terms of economic criteria, this research focused on life-cycle costs of buildings. It also used a hedonic pricing model to measure the marginal value or implicit price for improvements in energy performance in the US residential housing markets. The results of the hedonic pricing model demonstrated that when assuming energy performance improvements through retrofitting that cut the typical energy cost by 50%, ceteris paribus, the expected sale price increases by 12.2% for the average home in our sample. In terms of environmental criteria, this research focused on the reduction of total air emissions resulting from producing the required energy for operating the building. In terms of social criteria, this research adopted a combination of a Delphi method and a concept-mapping approach to develop an empirical social sustainability framework through energy retrofits. This framework categorized the social sustainability criteria in energy retrofits into three different levels: *building level, community level, and society level*, which represents the area of social impact of the energy retrofit projects on building occupants, people living in a community, and society, respectively. Finally, this research proposed a decision-matrix for the selection of the objective function(s) in an optimization problem used for energy retrofit decisions for a specific building, taking into consideration investor benefits.

Then, this research introduced SER decision support system to select an optimum energy retrofitting strategy for a specific building. The main contribution of SER was to adopt sustainable triple bottom line criteria in the decision-making process by defining the

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economic, environmental and social indicators. Using a multi-objective optimization model, SER was able to find the best energy retrofitting strategy for a specific building that optimizes sustainable criteria. The main phases in the SER decision support system process were: (1) data collection, which includes the gathering of the required data and related sustainable information; (2) building evaluation; which simulates the energy consumption of the building and evaluates its current energy performance situation; (3) analysis of energy measures; which selects the potential energy efficiency measures and analyzes their impact on TBL criteria; and (4) decision-making, which proposes an optimization tool to find the optimum energy retrofitting strategy based on maximized sustainable benefits. This model also contributes to the body of knowledge by formulating the sustainable objective for decision-making in energy; and by introducing a novel simplified energy prediction method by integrating dynamic modeling (by simulation of the current energy performance of a building) and static modeling (by mathematical methods using the result of simulation as an input). Following the described steps of SER decision support approach could help decision makers considering and optimizing their sustainable benefits in energy retrofit projects.

Finally, the application of proposed SER decision support system and introduced decision-matrix was demonstrated using a case study house built in 1960's in Albuquerque, New Mexico. Because of data limitations, the economic section of the SER was implemented.

8.2. Contributions to the Body of Knowledge

The primary contributions to the body of knowledge of this research include the following:

- Integrating sustainable impacts of building energy retrofits (i.e. economic, environmental, and social) in decision-making;
- Proposing a decision matrix that guides decision-makers on how to select the objective function(s) to formulate an optimization problem that results in the selection of the best energy retrofitting strategy, considering the benefits to investors;
- Introducing a novel simplified energy prediction method by integrating dynamic and static modeling;
- Measuring the implicit price of energy performance improvements in the US residential housing market;
- Identifying, categorizing, and mapping social sustainability criteria of energy improvements in existing buildings; and last but not least
- Proposing and demonstrating a holistic decision-support system that integrates the aforementioned contributions for energy retrofit projects.

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8.3. Contributions to the Body of Practice

The energy retrofitting decision-making model developed in this research can be implemented in any other buildings to help decision-makers select the optimum energy retrofit strategy that not only maximizes monetary benefits, but also maximize the environmental and social benefits through energy retrofits. The presented research can also help homeowners to plan or evaluate their retrofitting strategies in a simple and effective way. This approach can also guide them to select appropriate retrofitting budget and associated strategy to achieve maximum sustainable benefits of energy retrofitting for a specific building.

In addition, following the presented approach in this research, any decision-maker can identify and quantify the environmental and social decision criteria and incorporate them in his own decision-making problem. Sustainable decisions in all aspects of a society can make it a healthier, more productive, and more environmental friendly society.

8.4. Research Limitations

In Chapter 4, an approach to evaluate the investment cost and the energy consumption for housing retrofit decision-making was introduced. However, based on data availability for the case study on the research period, only energy consumption costs and initial investment cost were considered. Maintenance costs, applicable rebates, and tax incentives could be considered as additional cost items. These costs, however, were considered in Proposed SER decision support system in Chapters 7. Chapter 4 showed how the life-cycle c cost analysis could be performed for energy retrofit alternatives.

In Chapter 5, sustainable decision criteria were identified but not all of them were quantified. Because of the scope of this research, only the most significant decision factors were formulized in economic, environmental, and social criteria. In addition, to developing the social sustainability framework, this research considered the input of only academic experts and not industry professionals. However, 8 out of 11 panelists had a professional engineering registration, which could imply that.

In Chapter 6, the marginal value or implicit price for improvements in the energy performance of a house in US residential housing markets was estimated. An important limitation of this investigation was the lack of detailed housing attribute variables in the AHS. For this line of research, there is a need for large sample surveys that link direct, continuous measures of energy consumption and efficiency with housing prices. In addition, the impact of occupants' behavior was not considered as a control component of observed energy usage, due to lack of data.

In Chapter 7, the SER decision support system allowed selecting the optimum housing retrofit measures to maximize the decision-maker's sustainable benefits. However, the proposed model could be improved by considering a database of retrofitting measures

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instead of limited activities for a specific project. It could also be improved by incorporating uncertainty through probabilistic criteria values (e.g., costs, occupants' satisfaction, etc.) In addition, because of data limitations, only the economic section of SER was implemented. Undergoing research by the authors is focusing on demonstrating the remaining components of the SER decision support system using a real energy retrofit case study to validate the system and show its applicability.

8.5. Future Research Opportunities

Even though energy retrofits are usually beneficial and can pay for themselves over time and provide direct benefits to owners, the upfront costs of energy retrofits may deter owners from investing on energy efficiency improvement and overwhelm the long-term savings possibilities. For this purpose, many governmental policies target reducing energy consumption of buildings through cost-effective retrofit interventions; such as the Property Assessment Clean Energy (PACE) program; or the Energy Efficiency Revolving Loan (EFRL) program. An increasing number of government and utility programs are established to subsidize or eliminate the upfront costs of energy retrofits in order to promote the reduction of energy consumption of buildings. While the presented research focused on evaluating optimum energy retrofit strategies for individual buildings, scaling up the analysis of decision-making for energy efficiency improvement at the building portfolio level is a natural future research. In order to address this scaling up decision-making problem that might be faced by subsidizing entities or owners of building portfolios, new approaches are needed. These new approaches should be able to prioritize energy retrofits investment in an optimal way and within acceptable computation costs.

To fill this gap, future research opportunities could propose a framework that defines a reference building for predicting energy consumption and then prioritizes energy retrofit investments for a portfolio of buildings at the urban level.

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