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ECONOMIC EVALUATION OF SUSTAINABLE STRATEGIES FOR THE TRANSPORTATION SECTOR

by

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A THESIS

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ABSTRACT

Sustainable strategies are drawing growing attention as global environmental challenges increase concerns over energy consumption. As one of the most intensive consumers of energy, the transportation sector has a particular need to go green. Implementing alternative energy sources and applying advanced energy efficient technologies are two major approaches to achieve sustainability. Much work thus far used cost-effectiveness as an important criterion for assessing the practicability of sustainable strategies. However, few studies have evaluated such strategies systematically. This thesis has developed a framework of cost-effectiveness analysis to assess sustainability strategies. The framework summarizes the various effects of five representative alternative energy sources and calculates the costs of implementation. Combining this framework with key financial indices, this thesis specifies guidelines for systematic cost-effectiveness analysis and financial feasibility analysis. To demonstrate the functionality of the framework and the way to identify worthwhile opportunities for investment, three transportation sector case studies are presented, including an alternative energy demonstration project in Rolla, a renovation design for Rockport Welcome Center, and a strategy analysis for employing LED traffic signals in Missouri. This thesis facilitates stakeholders to generate a comprehensible comparison of multiple alternatives and to make strategy-adoption decisions based on their financial situation and preferences. This study should increase the comprehensive knowledge of energy saving practices, which will not only advance the affordability and attractiveness of sustainable strategies but also reinforce the concept of sustainability among the public.

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1. INTRODUCTION

Energy use always has an impact on the environment. The pressure of population growth drives industrial development which begins with the use of coal. Unfortunately, industry uses coal and other fuels to create a substance that the planet cannot totally digest or even bear--CO_2. The growth of the metabolism of most living creatures has upset the original balance that once existed between human activity and the ecological system. Thus, human activity has exerted undue pressure on the environment, and society has responded with policy changes [1].

Even as climate change presents environmental threats, traditional energy sources will be exhausted in the near future [2]. This prospect is driving a growing awareness of the need for sustainable development of environmentally-safe energy that can replace or supplement the current sources of supply. The solution to this problem, over the long-term, is simple: alternative energy. Although alternative energy is promising, its application is impeded by the high costs of the initial investment required for successful development and by lack of experience. Over time, however, advanced technologies are being developed that will greatly improve energy efficiency and lead to optimum use of energy. Yet the path to achieving a sustainable development remains blocked by many obstacles.

Although there is no doubt that the use of traditional energy sources, such as coal, petroleum, and natural gas, is central to the modern industrial economy, it is important to develop affordable energy sources with a manageable impact on the environment. This study focuses on sustainable energy strategies in the context of transportation, an energy intense sector of the economy. Specifically, it analyzes the costs and effects for both alternative energy sources and energy efficiency strategies for developing sustainable energy.

1.1. THE UNSUSTAINABLE TRANSPORTATION SECTOR

Interest in issues related to CO_2 emissions and energy consumption has intensified dramatically over the past years due to increasing environmental awareness and the world-wide energy crisis. According to an analysis by the United States Department of Energy in 2008 [3], CO_2 emissions, the major contributor to climate change, account for 84.6% of greenhouse gas emissions in the United States. Growing prosperity in developing countries is increasing the need for energy and generating greater CO_2 emissions. For example, China produces 10% of the globe's CO_2 emissions, and the CO_2 emissions produced by India are predicted to grow faster than in China or the United States [4]. These indigestible CO_2 emissions are generated mostly by the use of traditional energy, which results in an imbalance in the ecosystem.

The transportation sector, the primary contributor of CO_2 emissions [5], is also an extremely energy intense sector. As one of the major end-users of energy, the transportation sector consumes 29% of the world's total energy resources, second only to industry's 30%. Figure 1.1 shows the increase in total energy consumption across all end uses since 1949, and indicates that the annual growth in the rate of energy consumption by the transportation sector is 1.6%.

The need to reduce greenhouse gas emissions generated by transportation has been widely discussed since the transportation sector has such a poor environmental record. For example, Lutsey and Sperling [6] found that only 20% of cost-effective transportation strategies can contribute effectively to a 10% reduction in greenhouse gas below 1990 levels. Also, carbon fiber reinforced plastic lightens railway car bodies by 40% thereby reducing fuel consumption by 60% and lowering CO_2 emissions as well [7]. However, with the development of the world economy, rapidly growing energy demand is exhausting traditional energy sources. Energy availability has become a limiting factor in sustainable development [8], and viable energy strategies are desperately needed to quench the thirst of energy consumers without harming future generations. As a result, strategies for implementing alternative energy plans and energy efficiency measures here begun to draw wide attention.

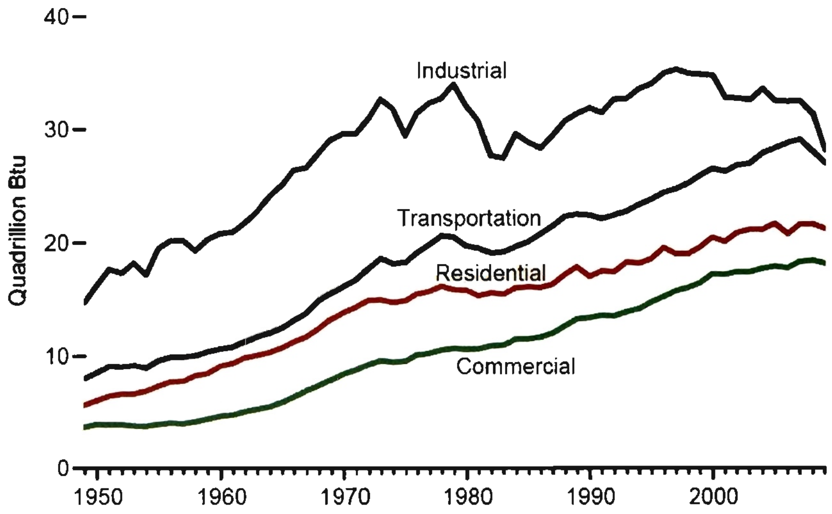

Figure 1.1. Total Consumption by End-Use Sectors 1949-2009 [9]

1.2. SUSTAINABLE STRATEGY

Sustainability, or sustainable development, is a worldwide environmental goal. The concept of sustainable development dates back to a June 1972 United Nations Conference on the Human Environment Conference where participants discussed the need for common principles to inspire and guide people to preserve and enhance the human environment [10]. Since then, the notion of sustainability has become familiar to the public. Although there are many definitions of sustainability, they all have four common attributes: environmental, economic, social/cultural, and technical. These four elements are interconnected, reflecting, for example, the interaction between society and the environment, or that between people and technology. The move toward sustainability is supported by investment in innovative and advanced green technologies. Technological change must consider both the technical potential of innovations and their social context [11].

Overconsumption of energy is the major challenge of sustainability. Energy is essential for the development of human society, and practically every turning point in human history has always involved some improvement or replacement of energy. Today, the use of alternative energy and the development of energy efficient measures are two major strategies that can achieve sustainability. Both must be evaluated based on the four attributes of sustainability mentioned above.

1.2.1. Alternative Energy Strategies. Alternative energy is drawing wide attention because traditional energy sources have created severe problems of pollution, low efficiency, and geographic dependency [12]. The alternative energy industry is experiencing unprecedented growth worldwide; however, the total alternative energy generated is far below that of traditional energy. In 2009, global renewable sources represented more than 50% of the 80 GW of newly installed power capacity. Wind and solar power reached 38 GW and 7 GW, respectively, in 2010 [13]. According to the Wind Technologies Market Report [14], cumulative total wind power capacity of the United States reached 160,000 MW in 2009, with a 28% annual growth rate. Despite this growth, traditional energy sources still account for the vast majority of energy produced in the United States. In 2009, about 19.9% of the total net electricity generated came from alternative energy sources, and a huge potential exists for further development of alternative energy.

Tremendous investments have already been made to promote energy efficiency and the use of renewable energy. The United Nations Foundation designated $451 million in environmental funding to address the world's energy problems [4], and global sustainable energy investment in 2008 reached $155 billion, surpassing investment in fossil fuels [15]. Considering the need for environmental awareness, the current economic situation, and the state of technological development, this investment must continue to increase [16]. Renewable energy is not that new; however, the knowledge is lacking to ensure an economic and environmentally friendly long-term energy supply.

The implementation of alternative energy sources involves huge investment, and its risk and advantages, in the long term, are not fully understood. Such an investment, however, would be risky without a thorough economic analysis. The complexity of alternative energy strategies requires that analytical methods focus not only on monetary issues, but also on various effects that cannot be expressed in monetary terms. Cost-effectiveness analysis (CEA) is an evaluation technique which analyzes programs and strategies for both cost and effectiveness. Specifically, it considers effects that are best measured in nonmonetary units. Alternative energy strategies can be evaluated based on effectiveness; however, this type of energy is a complex and immature product, still new to many consumers. A number of effects could too easily be overlooked with conventional use of CEA to evaluate alternative energy strategies. Thus, engineering managers need a practical and systematic CEA framework to develope alternative energy strategies.

1.2.2. Energy Efficiency Strategies. Often, alternative energy sources are automatically tagged with impressive labels: high energy efficiency, environmentally friendly, and high sustainability, for example. However, implementing alternative energy is not the only way to alleviate pollution and the energy crisis, especially when utilization of alternative energy sources is not technically feasible. In those cases, energy efficiency measures might be a better choice. High utilization efficiency translates into low energy waste, and results in low greenhouse gas emissions.

There are enormous energy losses in the electricity industry, and emissions created by this industry dramatically exacerbate the global greenhouse effect. World net electricity generation is projected to reach 25 trillion kilowatt-hours (kWh) in 2020, and bout 45% of electric power worldwide was generated from coal [17]. Generating 1 kWh of electricity from coal produces approximately 2 lbs of CO_2 emissions [18]. If there is no change in this industry, these estimations indicate that at least 22.5 lbs of CO_2 per kilowatt hours of electricity will be emitted in 2020. Stopping energy waste to alleviate pollution and end the energy crisis should be the current trend, and many companies and individuals appear to be moving in this direction.

The light-emitting diode (LED) form of lighting, a very competitive substitute for incandescent light was discovered in 1927, when Losev published his first paper on emissions from zinc oxide and silicon carbide diodes [19]. His work is considered to mark the invention of semiconductor LEDs. Today, after nearly a century of rapid and sustained LED development, the technology has been commercialized because of its many advantages over traditional lighting, including long life, durability, and high efficiency [20]. Tsao [21] has suggested that LEDs can reduce electricity use for lighting by half and save consumers more than $35 billion per year. Yenchek and Sammarco [22] found that LEDs can reduce the frequency of accidents related to the maintenance and repair of lighting systems. LEDs can also provide multiple colors and intensities to meet the requirements of modern applications. The most popular use of LEDs is in traffic light systems. Moreover, there is also a growing interest in solar-powered LEDs since this combination incorporates the advantages of both alternative energy and LEDs.

Various devices are powered by electricity, and one significant use of electricity is lighting, especially traffic lighting. Traffic light systems prevent severe accidents and deaths, but to meet adequate safety standards, traffic signals must necessarily consume a great deal of electricity. Unfortunately, traditional incandescent light bulbs transform most of the energy used into undesirable waste heat. LED technology, however, has been shown to reduce power consumption in lighting and overcome the low efficiency and high maintenance costs of traditional incandescent bulbs. Inspired by the well-known benefits of LED technology and solar-powered LEDs, with its lower power consumption, reduced maintenance and environmental benefits, departments of transportation are seeking to replace incandescent bulbs in traffic signals with sustainable alternatives, but no comprehensive and systematic means exist for evaluating such alternatives.

1.3. OVERVIEW OF THESIS

A comprehensive and systematic evaluation of the strategies of alternative energy and the energy efficiency measures to facilitate decision making is lacking. This work develops a framework for the systematic application of CEA to evaluate alternative energy and advanced energy efficiency strategies. This framework will provide consumers with a clear overview of alternative energy strategies that considers the full life cycle of the system. It will also benefit policy makers, investors, environmentalists, and analysts seeking to assess sustainability strategies. Specifically, this work investigates an existing alternative energy demonstration project, designs an alternative energy strategy for a welcome center based on known techniques, and compares among four different traffic signal systems to identify the most energy efficient application. This study examined the costs and effectiveness, of a specific alternative energy system and estimates the net present value and payback period of each case, based on a Missouri Department of Transportation traffic signal system.

The remainder of this study is organized as follows: Chapter 2 reviews the relevant literature; Chapter 3 describes the CEA framework and presents a project case study; Chapter 4 designs an alternative energy strategy for a welcome center; Chapter 5 evaluates the energy efficiency of traffic signal systems; and finally, Chapter 6 offers conclusions and recommendations for further research.

2. LITERATURE REVIEW

2.1. STRATEGY EVALUATION

Recent research addresses many aspects of alternative energy, such as market conditions [23,24], technological feasibility [25,26], and the financial feasibility of specific cases [27,28,29]. However, no comprehensive and systematic evaluation of alternative energy has yet been published to support decision makers faced with choices among various energy sources and technologies. Dalton et al. [30] made an economic evaluation of the implemtation, overhaul, replacement, operation, maintenance costs, and salvage value of a wave energy convertor using indicators such as the cost of energy, net present value, internal rate of return, and tariff rate. Their research focused on certain financial indicators and one specific alternative energy application, but ignored sustainability issues such as environmental and social effects of alternative energy usage, and does not facilitate decisions among alternative energy strategies. Heo et al. [31] offered a more complex analysis of 17 assessment factors, involved in dissemination of information about renewable energy based on five criteria (technological, market-related, economic, environmental, and policy-related). These criteria evaluated the characteristics of alternative energy, but an application was not given on how a specific energy type could be rated using these factors. Many similar financial evaluations have been made that involved various indicators [32,33], and, although these studies provide abundant information about evaluation of alternative energy, most focus on a only single monetary effect or energy strategy.

Such evaluations that do not consider a range of effects, cannot provide investors with a comprehensive picture of the value of alternative energy options, and even worse, they can create uncertainty about alternative energy strategies. Strategy evaluations should determine the technical and financial feasibility of achieving an objective, and financial criteria must be established to evaluate the financial benefits of a project. These should present the relationship between input (cost) and output (return). However, a single evaluation tool or criterion can explore only one facet of a project. In order to provide a broad range of information, a set of evaluation criteria must be identified.

There are various ways to classify financial criteria. For example, static criteria do not consider the time value of money. Classified by objectives, financial evaluation criteria can be categorized as related to either profitability or liquidity. This study relies on both types. Table 2.1 summarizes the general financial criteria and associated objectives used here.

Table 2.1. Financial Criteria

Evaluation Objects	Financial Criteria	
Profitability	Static Analysis	Return on Investment (ROI)
		Profitability Index (PI)
	Dynamic Analysis	Net Present Value (NPV)
		Internal Rate of Return (IRR)
Liquidity	Static Analysis	Simple Payback Period
	Dynamic Analysis	Discounted Payback Period

In real-world decision making, there is often no absolute best choice. These criteria permit comparison of multiple alternatives, permitting stakeholders to make an appropriate choice based on their own preferences. Given that the timing of cash flow affects the profitability of an investment, the dynamic criteria of net present value (NPV) and internal rate of return (IRR) are an optimal choice. A simple payback period and a discounted payback period evaluate the liquidity. However, the case studies outlined here are public nonprofit projects; therefore, there is no expected internal rate of return and the work relies on NPV and payback periods as measures of financial effectiveness.

2.2. COST-EFFECTIVNESS ANALYSIS FOR ALTERNATIVE ENERGY

2.2.1. Evaluation Models. Three models are commonly used in strategy evaluation: cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), and cost-utility analysis (CUA). CBA uses cost and benefit as parameters to evaluate projects. In particular, useful information is developed about the effects of public sector policies or projects [34]. Researchers have applied CBA to the generation of alternative energy [35]. This approach can discount future benefits and costs to present values [36]; however, it cannot evaluate effects that are not expressed in monetary units. For example, Diakoulaki and Karangelis [37] attempted to translate effects such as CO_2, SO_2, and NOx emissions into monetary values to examine four alternatives to electricity; however, no standard method was available to accomplish the translation. Although some nonmonetary effects can be expressed in monetary units, the process may lead to a loss of information. CEA overcomes this disadvantage by rating or ranking projects or strategies on the basis of their costs and effectiveness. This is especially useful for considering effects such as emission reductions that are best measured in nonmonetary units [38]. CUA is usually considered a special case of CEA that takes into account quality of life. It focuses on individual preferences over a lifetime [39]. However, individual preferences or satisfaction are not constant; therefore, they are difficult to measure, even for comparison. Thus, CEA is the more appropriate approach to evaluation of strategies with nonmonetary effects, such as those related to healthcare and alternative energy.

2.2.2. The Application of CEA. CEA has been used extensively as a tool for economic evaluation of strategies, policies, and programs in various fields in which the effects are not generally expressed in monetary terms. For example, when evaluating healthcare strategies it is inappropriate to place a monetary value on life [40]; therefore, Jusot and Colin [41] used CEA to combine the total costs and total number of life-years gained from nine screening strategies for hepatitis C. Expressing the cost-effectiveness ratio as cost per disability-adjusted life-year, other researchers studying humanitarian relief have analyzed the value of the treatment of visceral leishmaniasis [42]. Length of life is not the only measure of the effect of healthcare strategies. Different analytical objectives require different indicators. For example, to evaluate measles outbreak control strategies, Shiell [43] used the criterion of cost per case prevented. CEA has also been applied in other fields. To rank water management measures, for example, Aulong et al. [44] calculated the cost of one additional water supply unit to satisfy increasing demand. The reliability of the results was limited by uncertainties in cost, water output estimations, and conservation [45,46]. CEA has also been applied to study pavement projects [47]. Despite its wide use, CEA presents problems. In a systematic review of the cost effectiveness of the hepatitis A vaccination, Anonychuk et al. [48] found that use of inappropriate models and comparators affected the quality of the methodology. There is a need for a framework for systematic CEA with appropriate indicators.

CEA is also a useful tool for evaluating energy efficiency. Markandya et al. [49] analyzed the cost-effectiveness of policy options (e.g., tax incentives and subsidies) to promote energy-efficient applications (like refrigerators, washing machines, boilers, and light bulbs) in terms of cost per ton of CO_2. The energy efficiency of buildings has also received significant attention. Grobler and Heijer [50] tracked the process of energy-efficiency retrofit projects in Megawatt Park (Eksom's headquarters), and found that the appliances installed were cost-effective and generated substantial energy savings. To improve the energy efficiency of homes, Gaterell and McEvoy [51] considered the environmental and social issues associated with energy use; however, their analysis focused mainly on monetary measures such as energy savings.

The potential of CEAs as tools for decision makers, however, has been ignored by analysts [52]. Seldom has research been devoted to the systematic use of CEA to support decision making related to alternative energy sources. Research on the application of CEA to alternative energy projects has addressed the cost-effectiveness of energy policies by studying specific cases [53,54,55]. The application of CEA to alternative energy strategies has increased the number of effects measured in addition to energy savings. For example, researchers have evaluated effects related to sustainability, such as greenhouse gas emissions [56] and carbon footprint [57]. Tzeng et al. [58] used technological, social, environmental, and economic criteria to evaluate the feasibility of new energy systems. However, relatively few studies have performed complete and systematic CEA for major types of alternative energy. Researchers study the cost effectiveness of single alternative energy types on a case-by-case basis. For example, Phillips [59] addressed the negative and positive effects of a geothermal power plant. Anani et al. [60] introduced a standardized procedure for performing a cost-effectiveness study comparing solar water heating systems and wind energy conversion systems. Their work considered annual specific output, cost of energy production, fuel savings, and discounted pay-back periods, which ignored nonmonetary effects such as the cost per unit of CO_2 emissions reduction [61]. Such studies, however, have obvious limitations. For example, the lack of experience throughout the life cycle of alternative energy projects may cause decision makers to overlook many future costs of operations and maintenance. Thus, a standard that permits evaluation of different alternative energy applications based on different objectives is necessary to provide better information for good decision making.

2.3. ENERGY EFFICIENCY EVALUATION

Since the late 1990s, LED traffic light systems have drawn wide attention from many cities in the US and around the world [62]. Significant large replacements have been made including in Boston, Framingham, and Newton, Massachusetts [63,64], Denver, Colorado [65,66], Lee County, Florida [67], Portland, Oregon [68], Stockholm, Sweden [69], and Victoria, Australia [70]. A 2004 report by the California Energy Commission [71] lists 78 cities that have installed LED traffic signals. Two major advantages of LED traffic lights are remarkable energy savings and noticeable maintenance savings; the major disadvantage is the high initial cost. The present analysis shows that LED traffic lights function as well as, or better than, traditional incandescent traffic lights, and that initial costs are recovered within 2 years, after which LED systems save millions of dollars. Furthermore, from January, 2007, all traffic signals manufactured and sold in the United States had to be LED modules. This cost effectiveness study of traffic lights, therefore, provides a valuable resource for municipalities and departments of transportation. It also evaluates the other energy efficient application, the solar-powered LED, to determine if the high cost of both LEDs and solar panels are worthwhile.

The most important contributor to overall savings is reduced maintenance costs. Behura [72] analyzed survey responses from 76 government agencies and 6 industry representatives. They showed that 35% of respondents had no replacement program, and 35% had a passive program driven by complaints. The author mentioned that complaints associated with LEDs were few since LEDs do not burn out instantly. This study also found that 52% of respondents scheduled replacements at intervals greater than 6 years. LEDs are usually left alone after installation until it is time to replace them. However, a good maintenance strategy is essential for saving energy and costs throughout the long life of LEDs.

In general, there are two types of maintenance: regular or planned maintenance and emergent maintenance. Regular maintenance is implemented at regular intervals to prevent failure. Emergent maintenance responds to failure, which is especially dangerous for traffic signs, and is almost always more expensive. More frequent regular maintenance reduces the need for emergent maintenance. On the other hand, despite relatively low unit maintenance costs, too frequent regular maintenance may not be economical because it may raise total maintenance costs.

Various maintenance cost factors affect the balance between unit maintenance cost and frequency. To maintain this balance at a uniform economical level, the first step is to understand the benefits, limitations, and requirements of LED products. Information must be collected on life span, minimum light output, light distribution, and color ranges. The light output of LEDs decreases gradually over time, and their life span is measured by lumen maintenance, not by instant failure, as for ordinary light bulbs. Maintenance is widely assumed to be appropriate when the lumen decreases to 70% of the original output [73]. The loss of light output over time and with temperature change is one of the most important factors to consider in establishing an economical maintenance schedule. Once all of the details necessary for regular and emergent maintenance are determined, statistical analysis based on time elapsed since installation is applied to estimate how much it will cost to ensure that the LED products meet specific requirements. Chan and Asgarpoor [74] presented a method to establish an optimum maintenance plan for a component by applying Markov processes to calculate the statistical probability of failure and to determine the value of the mean regular maintenance time. Palma et al. [75] viewed maintenance work as a dynamic problem with numerous constraints resulting from frequent and random variations in the resources available. They applied constraints techniques like forward checking to identify better solutions. Quantitative and qualitative analysis of a maintenance schedule can provide LED investors with a comprehensive understanding of a required budget so that they can set aside adequate funding.

Other factors affecting maintenance savings are even more difficult to track. Because many LEDs are designed to be seen by the public and used for lighting and signaling, their performance and safety are major concerns [76]. The health of an LED system is important, not only in terms of potential savings but also in terms of safety. For example, failure of LED traffic signals may lead to traffic accidents, and dysfunctional LED lights cannot provide enough lumen to ensure the safety of pedestrians. The operational life span of LEDs is sensitive to junction temperature [77,78]. At cold ambient temperatures, LEDs draw more power, which can lead to system malfunction. Moreover, birds use outdoor lighting as perches, and their waste can affect the optical chambers. In addition, LEDs from different manufactures may be produced with different safety standards and may have different life spans.

Traffic signal lighting is currently a most promising application for LED technologies. The high initial investment is the major obstacle for its wide application. Therefore, careful information gathering and research is needed to evaluate its performance, maintenance strategies, and overall value.

3. CEA FRAMEWORK DESIGN

3.1. CEA METHOD

CEA measures the expected effectiveness incrementally per unit cost (E/C ratio) of a system, or the required cost per level of expected effectiveness (the C/E ratio) [36]. Decision makers, who base decisions on the maximum effectiveness per unit cost, are calculating the E/C ratio. If they focus instead on the lowest cost per level of effectiveness, they are relying on the C/E ratio.

CEA measures incremental costs and effectiveness that are expressed by the difference in costs or effects between two alternative strategies. Let B denote the base strategy and A be the alternative strategy, then CEA measures the incremental cost and effectiveness of implementing the alternative and anticipated effects. Specifically, the E/C ratio for the i^{th} effect associated with the substitution of B with A is calculated as

$$E^i/C = (E_A^i - E_B^i)/(C_A - C_B) \ \forall i . \tag{1}$$

Similarly, the C/E ratio is calculated as

$$C/E^i = (C_A - C_B)/(E_A^i - E_B^i) \ \forall i . \tag{2}$$

The values used in these equations are derived from an assessment of expected effectiveness and an estimation of associated costs. Therefore, two hierarchical structures constitute the CEA framework: an effect structure and a cost structure. The effect structure identifies the primary effects of five representative alternative energy types and organizes those effects holistically in categories (and subcategories, if needed). The cost structure lists life-cycle cost components and establishes the relationships among them based on a study of representative facilities that can be operated by alternative energy.

This paper focuses on the five most promising and representative alternative energy sources: solar, wind, geothermal, biomass, and hydrogen. Hydrogen is the most commonly used renewable source of energy. If widely used, bio-fuel could significantly reduce greenhouse gas emissions and dependence on foreign imports of fuel [79]. The use of solar, wind, and geothermal energy has increased rapidly in recent years. Solar energy has been forecasted to satisfy most energy needs in the Unites States [80]. The potential market for these energy types is huge; however, no framework exists within which to conduct a systematic evaluation of each.

3.2. CEA FRAMEWORK

3.2.1. Effects Structure Design. These five alternative energy sources generate various effects. Table 3.1 summarizes the major effects of solar, wind, geothermal, biomass, and hydrogen fuel cell energy. The effects were identified through an extensive review of the literature, including that published by governmental and organizational agencies such as the Department of Energy, the American Wind Energy Association, and the National Renewable Energy Lab. Other major sources were academic publications such as *Energy Policy*, *Renewable and Sustainable Energy Reviews*, *Energy Conversion and Management*, *Oil & Gas Journal*, *The Journal of Energy Market*, *Energy Economics,* and *Energy Sources.*

The literature shows that the effects of alternative energy are of three dimensions: environmental, social, and economic. Within each category, effects are classified as either positive (P) or negative (N). Most effects are supported or confirmed by the literature; these are indicated using a "+" sign. However, some effects are controversial; these are identified by a "–" sign for indication. For example, one source [56] claims that solar power reduces energy costs (a positive effect), so that source is marked with a "+". Another source [3] disagrees; therefore, it is marked with a "–". All numbered reference sources are presented in the Appendix.

Table 3.1. Hierarchical Structure of Effects

Effect Components			Solar	Wind	Geothermal
Environmental Impacts	P	Reduced water pollution	–[1]		+[2], –[3]
		Reduced GHG emissions	+[4-10]		+[2,3,11]
		Nitrous oxide emissions		+[21-23]	
		Sulfur dioxide emissions			+[2]
		Carbon dioxide emissions	+[25]		
		Reduced air pollution		+[30]	+[2]
		Reduced precipitation			
		Land			
		Reduced land use	–[32]	–[3]	+[2,11]
		Reduced land subsidence			+[11]
		Reduced disturbance of ecosystems	–[32]	–[3]	–[11]
		Increase in beneficial by-products			+[11]
	N	Land			
		Induced seismicity			+[11]
		Induced landslides			+[11]
		Increased bird and bat kills		+[3,36]	
		Increased noise		+[3,36,37]	–[11]
		Increased harmful by-products	+[32]		+[11]
Social Impacts	P	Technology			
		Increased energy safety	+[38]		+[57]
		Increased energy sustainability			+[3,41,42]
		Increased energy independence	+[25,46]	+[44]	
		Public			
		Increased public health conditions	– [4]	–[45]	
		Increased national security	+[4,25,46,47]		
		Increased job opportunities	+[4]	+[44,49]	
		Increased farm income			
	N	Increased visual intrusion	+[32]		
Economic Impacts	P	Costs/Savings			
		Increased tax credit & interest	+[4,5]	+[50-54]	–[55]
		Reduced energy costs	+[56], –[3]	+[57]	–[40,58-60]
		Increased market capacity	+[61]	+[62-64]	+[65]
		Increased compatibility with existing infrastructure		+[57]	+[57]
		Efficiency			
		Increased energy efficiency	+[4,25,46,67]	+[37,34,50]	+[42]
		Short installation lead time	–[69]		
	N	High initial investment			+[70]

Table 3.1. Hierarchical Structure of Effects (Contd.)

Effect Components			Biomass	Hydrogen
Environmental Impacts	P	Reduced water pollution		
		Reduced GHG emissions	+[12-16]	+[17-20]
		Nitrous oxide emissions		
		Sulfur dioxide emissions		+[24]
		Carbon dioxide emissions	+[26-28]	+ [29]
		Reduced air pollution	+[15]	+[17,19]
		Reduced precipitation	+[31]	
		Land		
		Reduced land use		
		Reduced land subsidence		
		Reduced disturbance of ecosystems	–[33,34]	
		Increase in beneficial by-products	+[35]	
	N	Land		
		Induced seismicity		
		Induced landslides		
		Increased bird and bat kills		
		Increased noise		
		Increased harmful by-products		
Social Impacts	P	Technology		
		Increased energy safety		+[39,40],–[3]
		Increased energy sustainability	+[12,14,16,35,43]	+[20]
		Increased energy independence	+[14,16,26]	+[40]
		Public		
		Increased public health conditions		
		Increased national security	+[48]	–[17,18]
		Increased job opportunities	+[48]	
		Increased farm income	+[26,43]	
	N	Increased visual intrusion		
Economic Impacts	P	Costs/Savings		
		Increased tax credit & interest	+[33]	
		Reduced energy costs	–[13,15]	
		Increased market capacity	+[66]	
		Increased compatibility with existing infrastructure	+[33], –[3]	
		Efficiency		
		Increased energy efficiency	+[13,15], –[68]	+[18,19]
		Short installation lead time		
	N	High initial investment		

Notes: 1. N: negative effects; P: positive effects.

2. "+" sign indicates the effectiveness is supported or confirmed and "-" sign indicates the opposite.

3.2.2. Costs Structure Design. The structure of costs presents all major project elements and indicates their relevant interrelationships. To support systematic collection, organization, and development of cost information, the cost structure has been designed with three layers to reflect the dependence of costs on decisions. Figure 3.1 is the general cost structure developed using a bottom-up approach [81]. It defines major cost components and the relationships among them over the project life cycle. The overall cost is first broken down as initial capital investment, operating and maintenance (O&M) costs, and final recycling and disposal costs. Capital investment costs are further divided among investments in physical assets, personnel, and other requirements (e.g., financing and incentives, such as federal, state or property taxes). O&M costs are categorized by frequency [82]. Costs for emergent or unplanned activities are usually higher than those for regular or planned activities. However, too frequent maintenance may produce higher costs than costly (but less frequency) emergent maintenance. Therefore, this scheme differentiates between unplanned and planned activities.

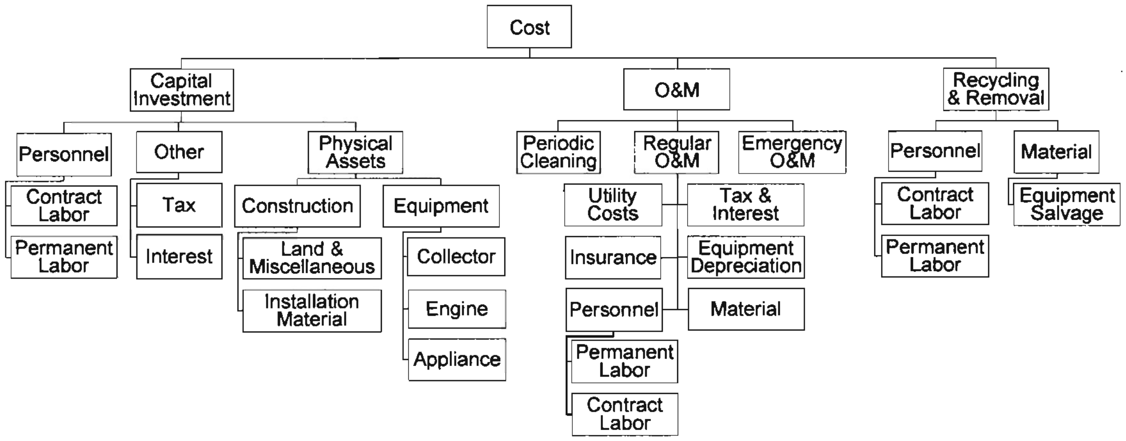

Figure 3.1. General Cost Structure

When alternative energy applications are selected, the general cost structure must be modified and expanded to obtain a more adaptive cost estimate; layer 2 permits such expansion. Figure 3.2 represents a two-layer cost structure for applying alternative energy sources to buildings. The “Recycle & Removal” cost component is in a dashed line box, indicating that it is not considered here for a case study because the history of alternative energy application is so short that most products in the market have not reached the end of their life. The few recycle or removal cases available do not provide sufficient data for analysis. Moreover, the cost factors comprising each layer of the structure will vary by applications. For example, appliance is included under physical assets and broken down into components such as ventilation and thermal distribution, heating equipment, cooling equipment, and water heater. Similarly, if alternative energy is applied to an intelligent traffic system or traffic control device, a cost component such as closed-circuit television camera and storage tank should be specified.

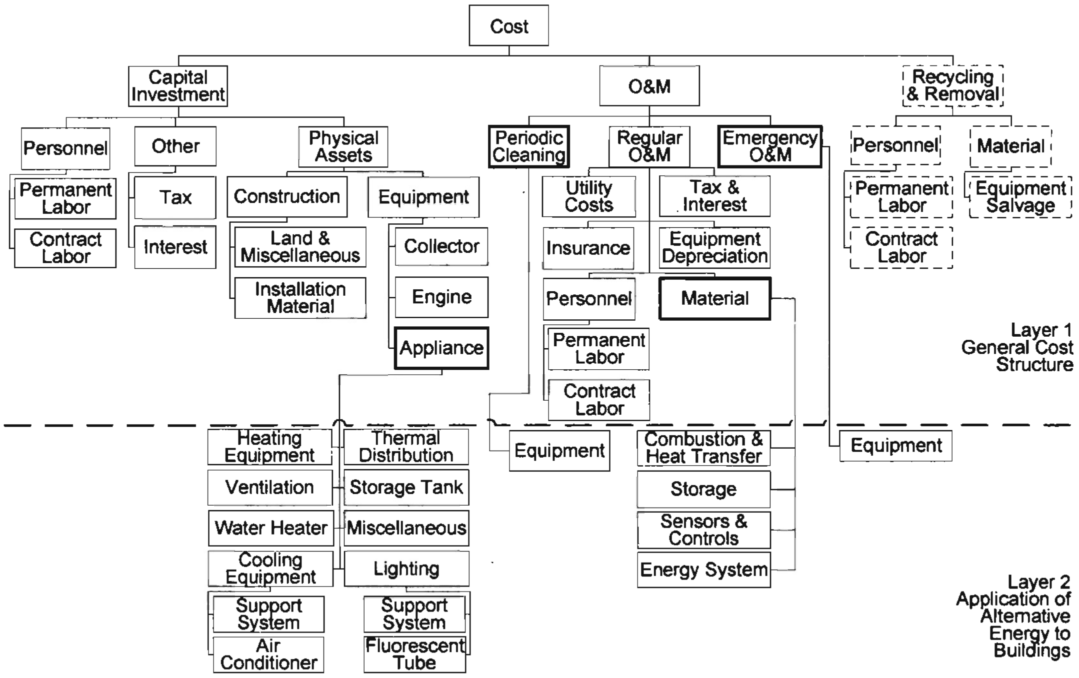

Figure 3.2. Hierarchical Cost Structure for Buildings

Notes: Regular boxes have accurate cost estimation, dashed boxes represent cost components not considered here, and bold boxes show detailed cost factors.

To obtain an accurate estimate of the equipment investment required, the cost structure can be further developed by considering specific alternative energy strategies (layer 3). Figure 3.3 uses a solar water heater system as an example to illustrate further development of the two-layer cost structure shown in Figure 3.2. The three-layer cost structure further specifies the cost components that must be precisely estimated for a solar energy system, such as those for the collector, receiver, and water heater motor. After installation of a solar water heater, additional costs arise from day-to-day operation and maintenance activities, such as glazing and sealing the collector or wiring the connection. These are exhibited on layer 3.

The three-layer framework is an efficient means for providing accurate cost estimates. As additional levels are developed, more data is collected, and accuracy typically improves; however, the cost of developing levels and collecting data increases dramatically with each layer. The appropriate number of levels strikes a balance between the need for accuracy in cost estimation and the effort required to evaluate cost factors.

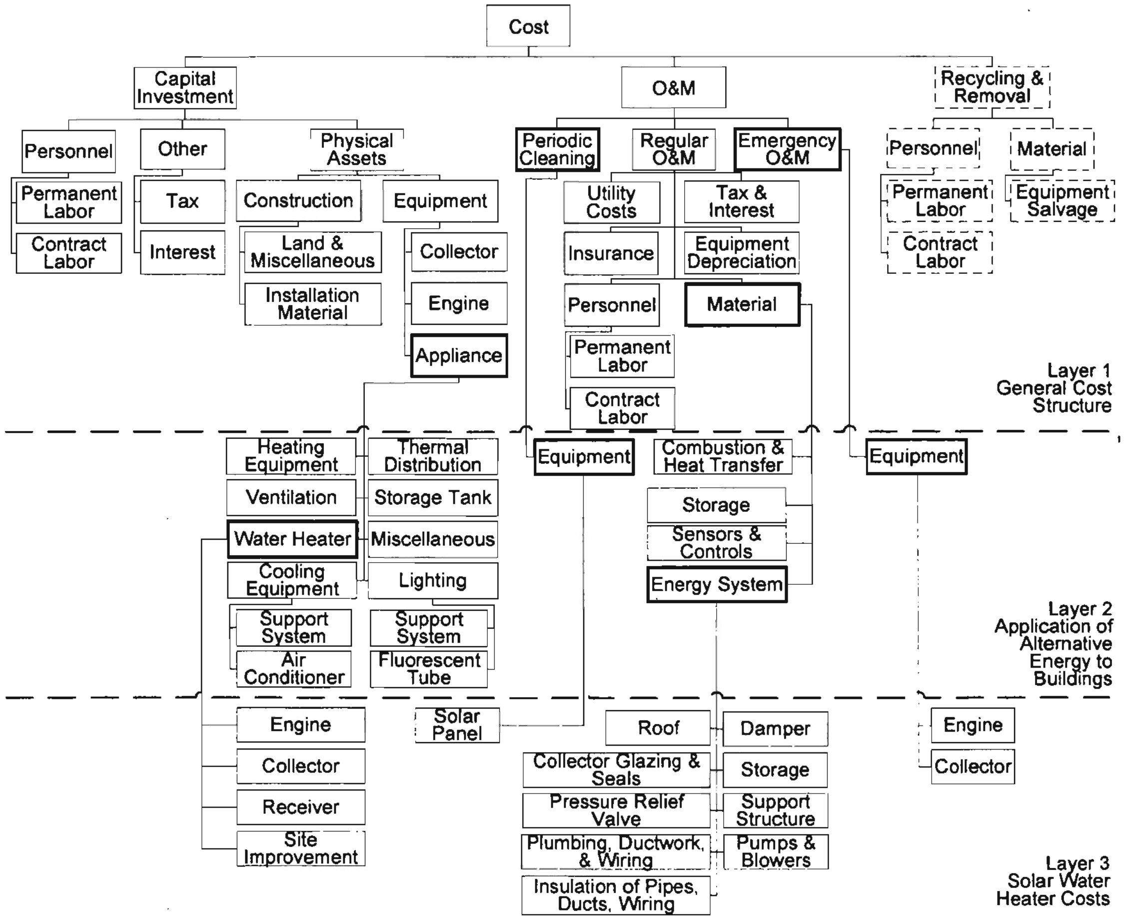

Figure 3.3. Hierarchical Cost Structure for Water Heater Installation

3.3. CEA FOR DEMONSTRATION PROJECT IN ROLLA, MISSOURI

3.3.1. Background. The demonstration project, located at the Troop I Highway Patrol Headquarters in Rolla, Missouri, was designed to show that the application of renewable energy systems has the potential to reduce the State's energy bills. The project was also intended to facilitate the development of outreach activities for secondary school students, university students, and the general public. The project involves a hybrid wind/photovoltaic (PV) system, which is composed of a wind turbine, a weather station, and a PV system. Table 3.2 shows the amount of energy produced by this system over a 17-month period. The wind turbine sits on a 120-ft lattice tower and can produce 10 kW at a wind speed of 29.3 mph. The expected annual output of this wind turbine is 14,300 kWh. The live data for this project show that the average wind speed at a height of 10 ft is 6.7 mph. The PV system can produce 2.16 kW if all panels work together. The average peak sun hours (i.e., the average number of hours during which the sun is at its maximum potential of 1,000 W/m^2 per day) is 3.04.

Table 3.2. Energy Production over 17 Months [83]

Preliminary (Unreviewed) Data					
17 months	PV Energy (kWh)	Wind Energy (kWh)	Speed (mph)	Insolation (W/m^2)	Avg.Peak Sun Hours
Total	3874.0	8460.0	114.0	2157.5	51.8
Avg.	227.9	497.6	6.7	126.9	3.0

3.3.2. Data Collection. Since complete data are not available for the project over the system's expected useful life, information was collected from multiple sources. This includes the data recorded for this and similar projects and that available in manufacturer publications. The purpose of this project is to demonstrate the environmental and economic effects of renewable energy. Table 3.1 shows an effects structure demonstrates that the use of wind power and solar power can reduce greenhouse gas emissions and air pollution, but yet they increase the noise level. Moreover, such a hybrid system promotes energy efficiency and cost savings, and can benefit from tax credits. Ideally, the system would be evaluated by measuring these reductions but, as a small-scale project for demonstration purposes, it records only the greenhouse gas emissions and energy production data. Since the system was installed on June 12, 2008, the greenhouse gas emissions have been reduced by 15,690 lbs, equivalent to the total emissions of an average passenger car over 573 days. The total energy production has been 12,334 kWh for 17 months, equivalent to an average monthly production of 725.5 kWh.

Table 3.3 summarizes the information on the equipment used in this project, including equipment types, quantities, suppliers, and costs. It indicates that the initial investment in the equipment was $69,700. Assuming all equipment qualifies as renewable energy equipment, the tax credit could reach $18,210, about 30% of the initial investment. Thus, the actual investment is estimated to have been $42,490. Construction costs of the wind system were estimated on the basis of a similar Middlebury College case [84]: $8,000 for a tilt-up tower with gin pole and all hardware, $3,000 for site improvement (concrete, concrete forms, rebar for foundations, and wire run to service panel), $800 for excavation and back-fill, and $3,000 for a data collection system (data logger, sensor, hardware). Therefore, the total installation cost was $14,800. The personnel costs (supervising electrician and labor and industry inspection) were estimated to be $2,932. The inflation rate was calculated using a Bureau of Labor Statistics tool to derive adjusted costs in 2008 dollars. The adjusted construction costs were $16,316, and the adjusted personnel costs were $3,232. Thus, the initial investment is estimated to have been $62,038.

Table 3.3. System Equipment [85]

Equipment	Quantity	Suppliers	Cost ($)
Bergey Excel S Wind Turbine (10 kW)	1	Bergey Windpower	36,700
Gridtek 10 Wind Turbine Inverter	1	Bergey Windpower	
Sharp ND216U2 Solar Panel (2 kW)	10	Carmanah Technology	13,700
Fronius IG 2000 Solar Panel Inverter	1	Fat Spaniel	
Wind Anemometers	3	Fat Spaniel	10,300
Pyranometer	1	Fat Spaniel	
Temperature Probe	1	Fat Spaniel	
Barometer	1	MetOne	

The annual O&M costs for a small wind turbine can be estimated as either $0.01-$0.05 per kWh [86] or about 1% of the installation costs [87]. Since the wind turbine needs repair, future energy production cannot be forecasted accurately based on the energy production over the past 17 months. Thus, the first method, which is based on the energy production, is not appropriate for this project. Using the second method, the annual O&M cost is estimated to be $620. The O&M costs for PV systems are generally less than $0.01 per kWh [88]. Based on energy production over the past 17 months, they are approximately $27 per year. Total annual O&M costs are $647.

Solar panels are rarely recycled [89]. With limited experience in the removal and recycling of wind turbines, the disposal and recycling costs could not be estimated for this project. The system is expected to last 30 years [90]. The historical inflation rate from January 2000 to April 2010 shows no trend of significant increases or decreases [91]. Based on these data, the average inflation rate was calculated as 2.57±1.2% per year. A constant inflation rate of 2.57% was thus assumed for this project throughout its life. A 30-year real interest rate of 2.7% on treasury notes and bonds was used as the discounting rate [92].

3.3.3. Results. Table 3.4 summarizes the effectiveness, associated costs, and E/C ratios for this project. Since solar-wind hybrid alternative energy has already been selected for this system, the results of analysis are a performance evaluation rather than an effort to select from among various alternatives.

Table 3.4. CEA of the Hybrid Alternative Energy System

Effects	Costs	E/C (the hybrid system)	E/C (the coal system)
Annual Energy Production 8,706.4 kWh	Annual Equivalent Worth: $3,545	Energy Production Cost 2.46 kWh/$	Energy Production Cost[a] 9.01 kWh/$
Annual CO_2 Reduction 8,858.2 lbs		CO_2 Emissions Reduction 2.5 lbs/$	-

a. More than 4/5 of the energy in Missouri is produced from coal, available from website: <http://tonto.eia.doe.gov>.

The E/C ratio of energy production by the hybrid system is 2.36 kWh/$, which means the cost for producing energy is $0.42 per kWh. The cost of generating energy from coal is $0.11 per kWh [93]. The energy production cost of the hybrid system is about 400% higher than the average energy production cost in Missouri, indicating that the hybrid system is less economical than a typical coal system. The wind turbine monitoring equipment is not functioning properly and currently awaits repair. This malfunction might explain why the CEA results are significantly different from expectations. Also, due to incomplete information, this analysis is based on a set of assumptions, including a 30-year life expectancy, a fixed inflation rate, and adjusted costs. Further, it disregards recycling or removal costs. Some of these assumptions might warrant change in the future with the rapid development of this industry.

The demonstration project is a small-scale system. Some effects that would be significant are not yet recorded. The reduction in greenhouse gas emissions was recorded, and the E/C ratio is 2.5 lbs per dollar. Production of 1 kWh of energy using this hybrid alternative energy system reduces greenhouse gas emissions by 1.02 lbs. The hybrid system costs more to produce energy than a coal system, perhaps due to the malfunction of the wind turbine, but positive environmental effects offer some advantages. Repair of the monitoring system will certainly lower the energy production costs.

4. ALTERNATIVE ENERGY STRATEGY DESIGN

This work designed an alternative energy project to demonstrate how the framework developed facilitates the entire CEA process and how to perform a systematic evaluation of alternative energy strategies.

4.1. CASE DESCRIPTION

Rest areas along interstate highways provide safety and convenience to travelers by offering parking, food, a view of the local landscapes, and comfort facilities. There are 19 rest areas in Missouri (Figure 4.1). Where sanitary facilities are provided, an adequate water supply, sewage disposal system, and power supply are required. An estimated 20 million travelers visit Missouri's rest areas every year [94], which makes them prime locations for testing the application of green technologies. To make the public aware of green energy technology, reduce energy costs, and improve aesthetics, the Missouri Department of Transportation (MoDOT) plans to redevelop the Rockport rest area as a modern welcome center. This new welcome center, which is expected to open in early 2012, will have some energy efficient applications, such as T-8 fluorescent lighting with occupancy sensors and exteriors painted in light colors to reflect heat back into the atmosphere. The area will be enlarged from 2,500 square feet to 5,200 square feet. This study included a CEA for this project to evaluate the financial and environmental feasibility of the proposed alternative energy system for the Rockport Welcome Center.

- Location: Southbound I-29 (40.41N, 95.516W)
- Parking space: car 30, truck and RV 9
- Other facilities: restrooms, drinking fountains, picnic tables and shelters, vending machines, information dispersal, pet accommodations, telephones, trash collectors, ADA accessible.

Figure 4.1. Missouri Rest Areas and Welcome Centers Map [95]

4.2. MODELING ROCKPORT ELECTRICITY USAGE

This project analyzed the electricity usage of the Rockport Welcome Center based on data provided by MoDOT from September 2006 to June 2010 (Figure 4.2). The data shows that its average annual energy consumption was over 70,000 kWh. The average energy consumption is 10,817 kWh per month in winter, and 3,726 kWh per month in summer. Because monthly consumption has a seasonal trend and the new size of this welcome center will be doubled after retrofit, the future monthly electricity usage is estimated based on energy consumption per square foot from existing data:

(Average monthly energy consumption/old building size) × New building size. (3)

Assuming the future energy usage falls into normal distribution, the future monthly electricity usage is predicted with a 95% probability confidence interval [L, U] as

$$L = \mu - t_{\alpha/2,(n-1)} \frac{\alpha}{\sqrt{n}}, \tag{4}$$

and

$$U = \mu + t_{\alpha/2,(n-1)} \frac{\alpha}{\sqrt{n}}, \tag{5}$$

where $t_{\alpha/2,\ (n-1)}$ denotes the $(1\text{-}\alpha/2)100$ percentile of a t-distribution with $(n\text{-}1)$ degrees of freedom, and σ is the standard deviation of available energy usage. The projection is presented in Figure 4.3, which shows that electricity consumption is estimated to be 13,160 kWh per month on average; and 157,916 kWh annually, which is twice as high as that before retrofit.

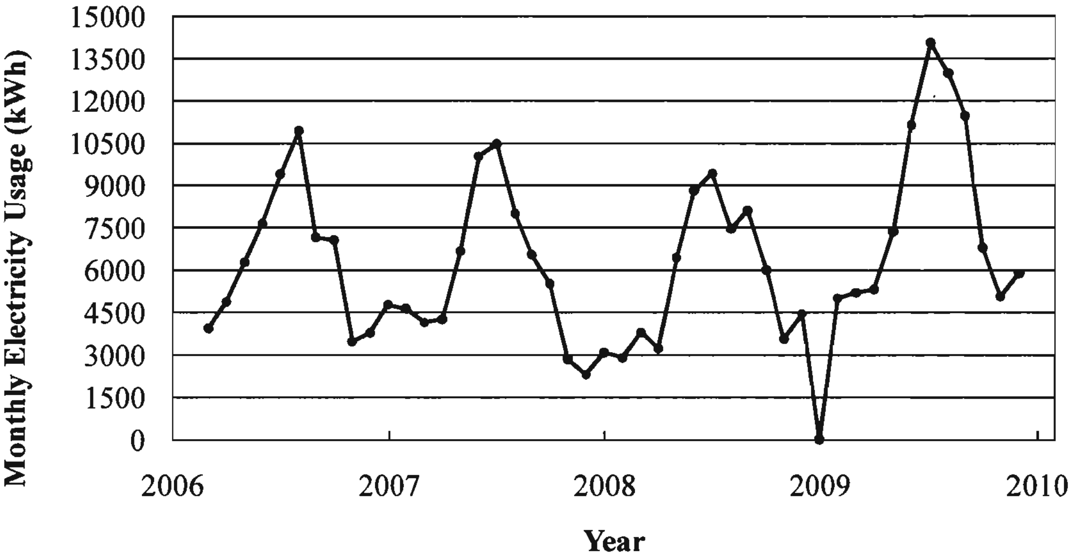

Figure 4.2. Rockport Electricity Usage

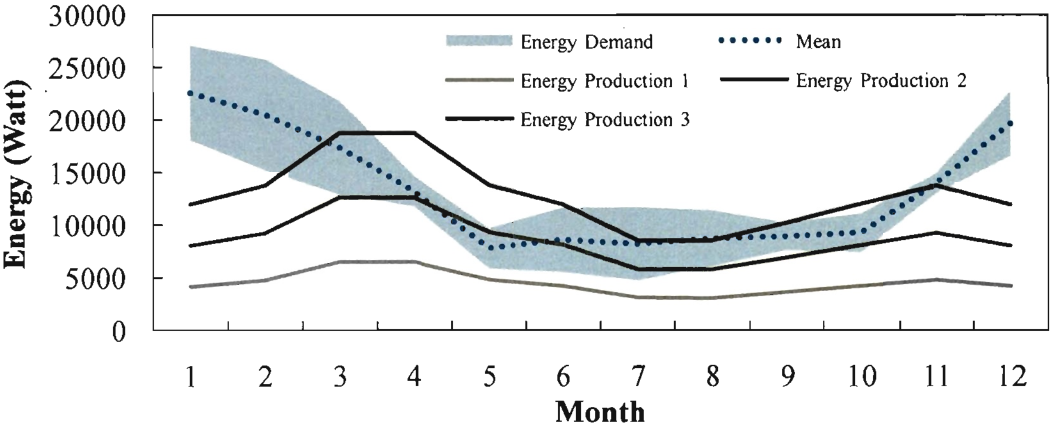

Figure 4.3. Estimate of Rockport Electricity Usage and Hybrid Alternative Energy System Production

4.3. DEVELOPING ALTERNATIVE ENERGY STRATEGIES

4.3.1. Alternative Energy Source in Rockport. The project analyzed available alternative energy sources in Missouri to select the best option. Biomass and hydrogen energy are mainly used in industry to provide power for transportation vehicles. Biomass is generally used to generate liquid transportation fuels, such as ethanol and biodiesel, and hydrogen fuel cells are usually treated as an auxiliary to power forklifts, utility vehicles, and other portable fuel cell products. Given current production technologies, therefore, biomass and hydrogen are not appropriate substitute electricity sources for Rockport Welcome Center. Other options are solar and wind power. Figure 4.4 and Figure 4.5 show the wind speed data and percentage of hours of sunshine in Rockport. According to the National Renewable Energy Lab [96], the wind power density (at 50 meters) is about 100-300 W/m^2. At a normal wind turbine height of 120 ft, annual average wind speed in Rockport is 15.5 mph [97,98]. The solar insolation map (showing the incidence of solar radiation) shows that Rockport is located in a zone with an average of 4.5 hours of insolation per day. Thus, solar and wind energy are rich in Missouri and are preferable in this case. The combination of a wind turbine and solar panels will not only ensure stable renewable energy production, but also create awareness of alternative energy. Given the limited area of this welcome center, this work considers a hybrid system that uses a wind turbine as the major power source and solar panels as a backup source.

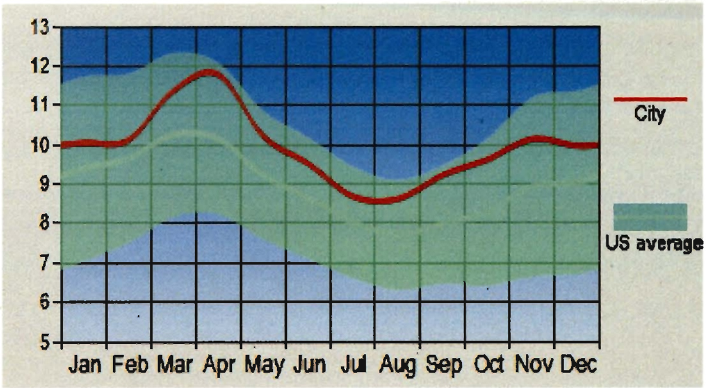

Figure 4.4. Wind Speed in Rockport [99]

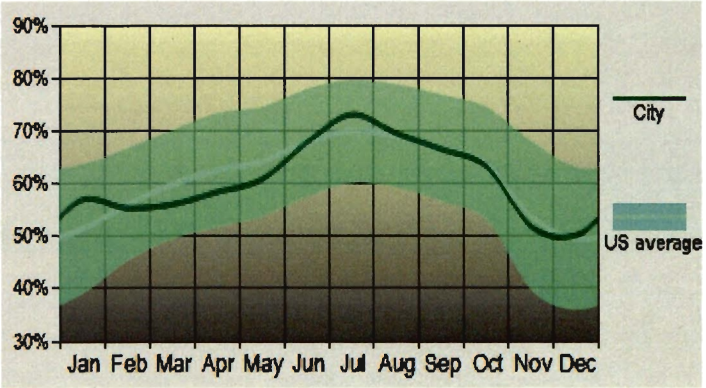

Figure 4.5. Sunshine in Rockport [99]

4.3.2. Alternative Energy Systems. The wind turbines selected here are from five major manufacturers of small wind turbines. They include Bergey Excel S 10 kW, WTIC Jacobs 20 kW, Evolve EG-12 20 kW, Aeolos H 30 kW, and Endurance E-3120 50 kW. The kilowatt number in the model names is the theoretical optimal power capacity of each wind turbine. Actual wind turbine power generation is dependent on wind speed, which increases with the height of the tower [14]. The solar energy system considered in this study uses Sharp ND-224UC1 panels, which have been used in a demonstration project in Rolla, Missouri, and have proved very efficient. All of these products are well known in the market and have an expected durability of 30 years. A wind turbine occupies only a limited area, whereas large-scale solar panels need more space. This solar system, which requires 4,032 square feet area, has a power output of 2.24 kW at its peak. The Rockport Welcome Center has a roof area of 5,200 square feet, large enough to accommodate this system.

4.3.3. Ranking Wind Energy Systems. Wind turbine power output is dependent on wind speed; therefore, the energy savings and payback period are also dependent on wind speed. The energy savings offered by the wind energy system are calculated using monthly energy production based on the recorded wind speed (Figure 4.4), which is measured at weather stations at a height of 33 ft. This speed is converted to the wind speed at the height of the wind turbine (120 ft), using the following equation:

$$V_{h2} = V_{h1} \times (h2/h1)^{\beta}, \tag{6}$$

where wind speed at the heights of $h1$ and $h2$ is characterized by V_{h1} and V_{h2} separately (h2>h1), and term β is the Hellman power law exponent [100], which is 0.27 in this case. Based on this equation, an average wind speed throughout the system life cycle is assumed to be 16 mph for comparison of the cost-effectiveness of wind energy systems. Table 4.1 lists the initial cost, annual energy savings, payback period, net present value (NPV), and profitability index (PI) for all wind turbines models at a wind speed of 16 mph. The initial costs of these five wind energy systems reflect quotes obtained from actual manufacturers.

Table 4.1. Summary of Results for Wind Energy System

Model	Initial Cost ($)	Energy Saving ($/yr)	Payback (yr)	Discounted Payback (yr)	NPV ($)	PI
Bergey Excel S 10 kW	40,256	1,555	28.8	>30	-15,816	0.61
Evolve EG-12 20 kW	56,711	4,406	14.3	22	12,536	1.22
WTIC Jacobs 20 kW	64,280	6,067	11.8	17	31,056	1.48
Aeolos-H 30 kW	65,874	5,400	13.6	20	18,988	1.29
Endurance E-3120 50kW	261,000	21,770	13.3	20	81,118	1.31

Note: Discounted payback period of Bergey Excel S 10 kW is longer than the study period of 30 years.

According to the results shown in Table 4.1, the Bergey Excel S 10 kW should be rejected because using this model will yield negative NPV. The Aeolos-H 30 kW is inferior to the WTIC Jacobs 20 kW because the additional capital investment it requires is not justified. The remaining options are the Evolve EG-12 20 kW, the WTIC Jacobs 20 kW and the Endurance E-3120 50 kW. The comparison of these three is based on the profitability index, which is calculated as

$$\text{Profitability Index} = (\text{NPV} + \text{Initial Investment})/\text{Initial Investment}. \quad (7)$$

Results show that a $1 investment in WTIC Jacobs 20 kW gains a profit of $1.48, which is the highest one among all alternative wind energy systems. Moreover, the Jacobs 20 kW has the shortest payback period. Thus, it is the most appropriate option among these five candidates.

4.4. COST ESTIMATION

4.4.1. Cost Structure. The combination of the WTIC Jacobs 20 kW and the Sharp ND-224UC1 solar energy system becomes the hybrid system. The cost of this system is systematically evaluated using the cost structure described above. Figure 4.6 incorporates these cost values into the general structure of costs to show the process of cost estimation.

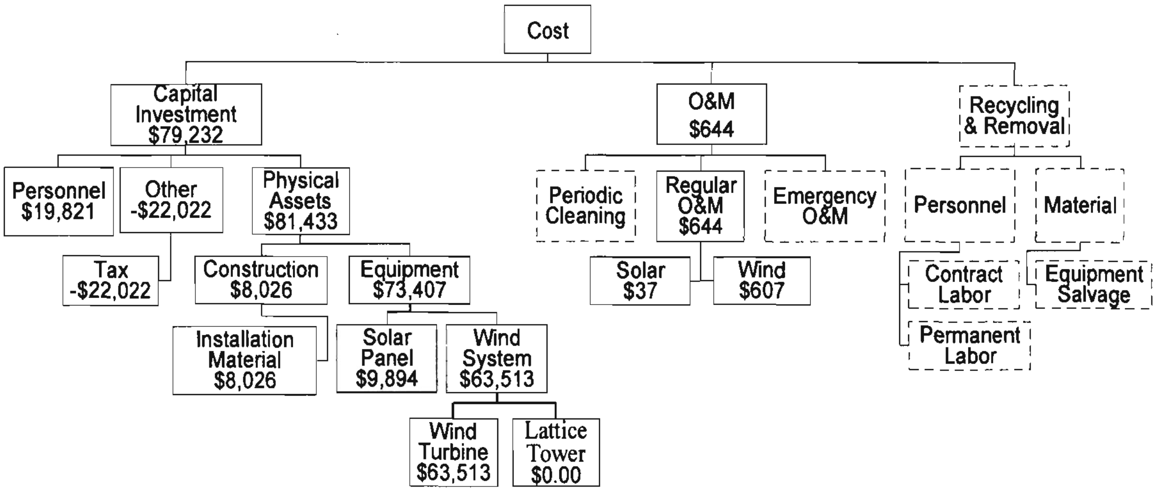

Figure 4.6. Cost Structure of Hybrid System

Solar power production depends on the number of sunshine hours. Sunshine hours are recorded on site from sunrise to sunset (Figure 4.5). However, solar panels do not fully function when the sunshine is not strong enough (i.e., at dawn and dusk). Thus, to get an effective sunshine hour (insolation hour), the hours of sunshine are normalized to the solar insolation hours using the mean value of 4.5 hours in the area [96]. For example, January has a recorded sunshine of 57.5%, which equals 428 hours. The effective insolation hours can be calculated by using the equation (8),

$$\begin{aligned} &\frac{\text{January sunshine hours}}{\text{Annual sunshine hours}} \times \text{Annual insolation hours} \\ &= \frac{428}{5{,}345} \times 4.5 \times 365 = 132\,\text{hours} \end{aligned} \tag{8}$$

The solar energy production in January can be calculated by multiplying the power of a solar panel (2.24 kW) by the monthly insolation hours (132 hours). Thus, the January solar energy production is 296 kWh. The calculation of wind energy yield follows the method used to rank wind energy systems.

In this process, the following assumptions are made. A 30% federal tax credit is applicable to the costs of alternative energy equipments, which are estimated to be \$20,946 (Figure 4.6). The price of electricity in Rockport is 0.1 \$/kWh. Here, an inflation rate is calculated using a Bureau of Labor Statistics tool to derive adjusted costs in 2010 dollars. The annual O&M cost is 0.01 \$/kWh times the annual power production [86]. The total initial cost of a solar panel system is assumed to be \$8/watt [101], and the equipment cost is \$6,310, as quoted by retailers. According to the CO_2 Emissions Report [102], the CO_2 output rate from coal is 2.1 pounds per kWh. All these assumptions are applied to the entire case study. In reality, all fees might be affected by shipping distance, site and permitting requirements, regional taxes, and other factors.

4.4.2. Hybrid Alternative Energy System. The monthly energy production of one wind turbine plus solar panels might not be able to satisfy the energy demand of

Rockport Welcome Center. Figure 4.3 plots the energy production of three types of hybrid systems, each including an array of solar panels. The first uses the WTIC Jacobs 20 kW system (expressed as energy production 1), the second uses a hybrid system with two wind systems (energy production 2), and the third uses three wind energy systems (energy production 3). The first system will produce 50 kWh annually, which cannot fully meet the predicted demand. The yield of the second is above the lower limit of the demand but below the mean value, which means that production will meet most of the demand, although only barely. The third system will produce energy that is nearly sufficient to meet demand and even above the higher bound in some months. Decision makers can choose among the three alternatives based on their project budgets. This study further analyzed the hybrid system with one wind energy system because this option requires the lowest initial investment. In winter, the system's energy output will be below the lower limit of demand, so Rockport may have to use some conventional electricity source or implement additional energy alternatives (e.g., geothermal).

Table 4.2 summarizes the initial cost, energy savings, payback period, and NPV of the hybrid system based on its estimated alternative energy generation (Figure 4.3). With a simple payback period of 13.7 years, the system will be slower to recover its initial investment than a system using only wind energy (with a simple payback period of 11.8 years). Although adding a solar panel prolongs the payback period, it ensures a more consistent renewable power supply throughout the year and fulfills the need to demonstrate the application of alternative energy. Moreover, investment in this hybrid system yields $21,920 in benefits.

Table 4.2. Summary of Results for the Hybrid System

Model	Initial Cost ($)	Energy Saving ($/yr)	Payback (yr)	Discounted Payback (yr)	NPV ($)
WTIC Jacobs 20 kW	64,280	6,067	11.8	17	31,056
Sharp ND-224UC1	17,921	370	>30	>30	-9,137
Total	79,232	6,437	13.7	20	21,920

4.5. EFFECTS OF THIS PROJECT

Table 4.3 summaries the environmental, social, and economic effects of this hybrid system. From an environmental dimension, using wind power and solar power can reduce GHG emissions and air pollution, yet this approach increases noise and kills birds. However, according to the NREL report [103], numerous factors cause avian issues, including species abundance, topography, and habitat. Avian issues, therefore, should not be a concern because potential problems can be identified and addressed before a specific location is determined. Noise issues will be addressed by the rapid improvement of wind energy technology. From an economic dimension, the hybrid system promotes energy efficiency and cost savings, and offers tax benefits. Finally, as a show case, this project has a positive social impact. Rockport has claimed an average of 72,000 visitors every year since 2005. Implementing alternative energy here could effectively increase public awareness of alternative energy. Due to the lack of data, discussion of the effects of this project is limited to CO_2 emissions, energy savings, and dissemination efficiency.

Table 4.3. Effects of Hybrid System

Effect Components			Solar	Wind	Geothermal
Environmental	P	Carbon dioxide emissions	√	√	√
	N	Increased bird and bat kills		√	
		Increased noise		√	√
Social	P	Increased awareness of alternative energy	√	√	√
Economic	P	Increased tax credit & interest	√	√	√
		Reduced electricity bill	√	√	√
	N	Increased initial investment	√	√	√

4.6. RESULTS AND SENSITIVITY ANALYSIS

4.6.1. Results. Since the system has not yet been implemented, its results can only be predicted. Table 4.4 summarizes the effectiveness, associated costs, and E/C ratios for this project. The base case is that Rockport purchase electricity from local vendors. The proposed system here is to provide part of the electricity by a hybrid energy system, and the rest of the demand is met by local vendors. Thus, the annualized incremental costs between the base case and the proposed system are the annual equivalent worth of the hybrid system. The E/C ratio of the annual electricity bill reduction is 1.1, meaning that $1 investment in the system will reduce the electricity bill by $1.1. Thus, the system can reduce the utility bill by 33% under expected conditions. The E/C ratio for CO_2 emissions reduction is 21 lbs/dollar, and 14 persons can become aware of the information on alternative energy through this welcome center every year.

Table 4.4. CEA of the Hybrid Alternative Energy System

Incremental Effects	Incremental Costs	E/C
Annual Reduction in Electricity Bill $5,890	Annual Equivalent Worth $5,351	Electricity Bill Reduction 1.1
Annual Reduction in GHG Emissions 112,450 lbs		GHG Emissions Reduction 21lbs/$
Dissemination Range 72,000 Persons		14 persons/$

Note: Annual Electricity Reduction = Annual Alternative Energy Production × Electricity Rate = 53,548 kWh × 0.11 $/kWh [93].

4.6.2. Sensitivity Analysis. Since wind energy generation is highly dependent on wind speed, a sensitivity analysis is necessary for predicting the NPV and payback period if the actual situation is different from the predicted. The project compared wind energy generation at various wind speeds (from 10 mph to 18 mph) based on manufacturer tests of energy production for the WTIC Jacobs 20 kW. Figure 4.7 clearly shows that a higher wind speed brings a shorter payback period and higher NPV. When annual wind speed is over 13 mph, this wind energy system could generate a positive NPV. The payback period could be longer than the lifespan of the energy system when annual wind speed is lower than 12 mph. Therefore, to mitigate the risk of this investment, installation of an anemometer tower in the area is recommended to record wind speed accurately and thus to determine whether the project site has enough wind energy to power a wind system.

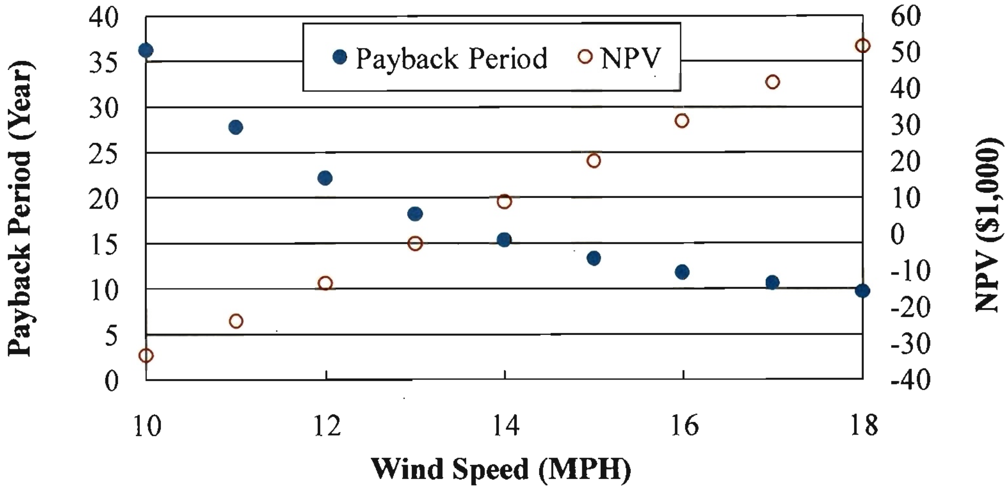

Figure 4.7. Sensitivity of NPV and Payback Period to Wind Speed

4.7. DISCUSSION

4.7.1. Wind Energy Systems. The wind turbine competition analysis shows that the WTIC Jacobs 20 kW was selected due to its outstanding economic performance. However, the wind energy yield from one wind turbine only meets about 32% of the predicted demand. A solar panel was designed to provide back-up power sufficient to meet about 2% of the demand. Thus, the hybrid system could satisfy 34% of the anticipated energy demand. A hybrid system with two or more wind turbines does reduce more CO_2 emissions than a hybrid system with only one wind turbine, but it does not provide better cost-effectiveness by electricity bill reduction and dissemination range. Although the energy yield from high-power wind turbines, like the Endurance E-3120 50 kW, may fully meet the demand, the high initial investment increases the financial risk of this project, especially since its payback is completely dependent on wind speed. In practice, small wind turbine systems are low risk and provide flexibility to decision makers who have a budget to permit installation of two or more systems to help meet the energy demand. Additional wind systems can be installed either initially or after this project is completed. Therefore, the preferred alternative energy system is based on budget any concerns and preferences of decision makers.

4.7.2. Other Possible Applications. Geothermal heat pumps for space heating and cooling are another appropriate alternative energy application, especially in winter. According to available statistical data [104], heating and cooling consume 46% of the total energy utilized in a commercial building. Heating in the winter uses 29% of the total energy consumption, making Rockport utility bills much higher in the winter than in the summer (Figure 4.3).

Geothermal heat pumps, also known as ground source heat pumps, rely on a constant underground temperature to transfer heat from below the ground surface up to a building in winter, and from the building back underground in the summer [105]. The geothermal heat pump is a quiet, clean, safe system, with low operating costs, substantial energy savings, and low greenhouse gas emissions [106]. Geothermal systems offer high energy efficiency (up to 400%) compared to the most efficient electric heaters on the market (94%), thus reducing heating bills up to 70% [107].

A geothermal heat pump costs about $2,500 per ton of capacity [108]. Considering its size, the Rockport Welcome Center would use a 6-ton unit ($15,000). Initial costs, including air conditioning, would be about twice the system price, or about $30,000. This price does not include drilling costs, which range from $10,000 to $30,000, depending on the drilling depth, terrain, and other local factors. The maintenance costs of a geothermal heat pump are much lower than those of a traditional heating device because the heat pump has no outdoor compressors and is not susceptible to vandalism [106]. The Rockport Welcome Center will use an estimated 190,000 kWh/year, 90,000 of which will be for heating and cooling. Assuming that the geothermal heat pump saves 45,000 kWh (50% of heating and cooling energy costs) annually, the simple payback period will be 8 years, much less than the life of a geothermal heat pump system (>15 years) [107]. The underground pipe even has a warranty of 50 years. A detailed analysis of this option will be part of future work.

5. ECONOMIC EVALUATION OF ENERGY EFFICIENCY STRATEGIES

This study focused on the cost and effectiveness of LED traffic lights based on a MoDOT traffic light system. This section first evaluates the effectiveness of LED traffic lights in general, and then compares four specific traffic light systems: (1) traditional lights, (2) solar-powered lights, (3) LED signals, and (4) solar-powered LED signals. The analysis demonstrates that maintenance issues are one of the key factors for improving the economic performance of traffic signal systems. This work also analyzed various scenarios to determine maintenance costs and the product life span for each of the four systems.

5.1. CHALLENGERS VERSUS BASE CASE

The traditional traffic signal system was chosen as the base case, facing three challengers. The first challenger combines alternative energy with a traditional system, using solar-powered traditional traffic lights. Solar panel technology has been widely used since the 1980s [109]. However, simply attaching a solar panel to a traditional incandescent traffic light is neither technically nor economically feasible. A typical 150W traffic light bulb needs a solar panel of at least 60 in. by 25 in., at a price ranging from $500 to $1000. To ensure that the traffic signal will work without sunshine, it also needs batteries. Ten 12V-30Ah batteries can support a traffic light bulb for approximately 24 hours. Together, these batteries cost about $1,500 and weigh 250 lbs. The weight and price of this set-up make such signals impractical in any circumstance;

therefore, no reports of solar powered incandescent traffic lights have been found, and this report offers no further analysis of this challenger.

The second challenger replaces a traditional system with advanced LED technology. LED traffic lights function better than incandescent traffic lights in several respects. First, LED bulbs have a much longer life (typically 100,000 hours) than incandescent bulbs, which last about 5,000 hours [110]. LEDs also eliminate catastrophic failure of traffic lights because each unit contains multiple LED bulbs. Unlike traditional traffic lights, LEDs do not change color when dimming, and they are more reliable than incandescent lights. At dawn and dusk, when the sunlight shines directly on traffic lights, the reflective material behind incandescent traffic lights produces an uncomfortable glare. LED traffic lights do not require this material [111]. However, LED traffic lights have more directional light beams than traditional lights, a characteristic that presents some visibility problems if traffic lights hang freely over an intersection. This problem could be solved by installing the traffic light securely [111]. Another visibility issue with LED lights is that some are too bright to be viewed comfortably in the dark. This issue could be resolved by using sensors to regulate the power input to traffic lights. LED traffic lights do not generate as much heat as incandescent lights so they do not burn the lens cover. On heavy snow days, however, the heat from LED traffic lights is usually insufficient to melt snow and ice that may accumulate on the bulb [111]. Due to their low power use, LED lights lower greenhouse gas emissions. LED power consumption is even low enough to be operated by using battery back-up during power outages. The initial cost of LED traffic lights is much higher than that of incandescent lights, typically $100 versus $3 per unit for incandescent lights [112]. However, over years of operation, LED lights save a great deal of costs involved in bulb replacement, emergency repairs, maintenance, and energy.

The rapid evolution of solar technology and the energy efficiency of LED light bulbs make possible the use of a solar panel to power LED traffic signals. This option has, indeed, drawn much attention. The combination of a renewable energy source and advanced lighting technology produces almost no greenhouse gas emissions, has no mercury content, and consumes little power. Mercury pollution is a major concern, however, in the disposal of LED lamps. Pode [113] used seven cases to persuade potential users that solar-powered LED offers significant benefits in addition to durability. These benefits include health benefits (from reductions in fumes and pollutant gases), improved quality of life, increased income, reduced monthly energy costs, high quality of lighting, and so on. Huang et al. [114] identified three factors that must be considered to ensure that these benefits are realized: (1) the efficiency of photovoltaic generation, (2) battery charge control to ensure sufficient energy storage without overcharge, (3) and battery discharge control to avoid damaging the LED. Their study also found a 14.1% probability of loss of load in winter and a 0% probability in summer for an 18W solar LED system; a 100W solar-powered LED system in spring has a 3.6% probability of loss of load. A photovoltaic array provides maximum power only at a certain voltage and current, although it can operate at wide ranges of voltage and current [115]. The whole photovoltaic system should perform consistently, efficiently capturing, converting, and storing sunlight [116]. Otherwise, low battery charge levels over long periods would reduce battery life [117] and LED life, and solar-powered LEDs could be constrained by the instability of solar power generation. Wu et al. [119] studied roadway lighting, comparing mercury lamps, grid-powered LEDs, and solar-powered LEDs. Although solar LEDs have many deficiencies in capability and reliability, Wu's group showed that the cost of solar-powered LEDs (100W) can be recovered in 3.3 years, and that of grid-powered LEDs can be recovered in 2.2 years. Unfortunately, this study used the same maintenance cost rate for all three types of lighting systems, making their results unreliable.

5.2. EFFECTS ANALYSIS

The present study addresses the functionality, environmental effects, and economic effects of both grid- and solar-powered LEDs, comparing them with traditional incandescent traffic lights. Table 5.1 summarizes the results.

Table 5.1. Effectiveness of Replacing Traditional Traffic Lights with LED Traffic Lights

Category	A/D	Description	Reference
Functionality	A	Long life span	[118]
	A	Elimination of catastrophic failure	[111]
	A	Brightness	[118]
	A	Elimination of reflection of sunlight	[111]
	A	Elimination of burnt lens cover	[111]
	A	Minimal color change when dimming	[112]
	A	Ability to use battery back-up during power outage	[71]
	D	Poor directional visibility	[111]
	D	Heat insufficient to melt covering snow and ice	[111]
	D	Excessive brightness at night if not regulated	[112]
Environmental Effects	A	Low energy consumption	[119]
	A	Low greenhouse gas emissions	[111]
Economic Effects	A	Low emergency repair costs	[111]
	A	Low bulb replacement costs	[68]
	A	Low maintenance costs	[119]
	D	High initial costs	[112]

Notes:
1. A = Advantage, D = Disadvantage
2. Most effects are reported by more than one author; referenced literature is merely a sample.

5.3. COST OF LED TRAFFIC LIGHTS

5.3.1. Cost Analysis. This cost analysis was performed using a top-down approach, which requires a host of assumptions. Data were collected from five major LED vendors (General Electric, ActOne, LeoTek, Philips, and Dial), various case studies, and reliable publications. However, in real-world conditions, reasonable adjustment of some key factors could significantly affect results. This analysis does not seek to customize investment, and it does not consider installation size or the specific area in which lights are to be installed. The results are scalable with sufficient input, including reasonable ratios and specific model numbers of LED lights. The energy consumption of LED lights was calculated here by multiplying unit wattage by average annual illumination time.

The annual energy savings is the difference in energy consumption between LED and incandescent lights. LED lights can reduce energy consumption by 90%. Table 5.2 compares the estimated price and wattage of three LED units and incandescent lights.

Table 5.2. Comparison of LED and Incandescent Lights

Display Type	Price [111]	Wattage [120]
Incandescent	3	150
LED Red	57	10.5
LED Yellow	66	13.4
LED Green	119	10.5

Based on a review of published research, this analysis assumed a 10-year life span and average electricity costs of \$0.1/kWh (based on a MoDOT electric bill for the third quarter of 2010). A smaller carbon footprint is considered one of the benefits of LED lights. The total reduction in CO_2 emissions was calculated by multiplying the reduced kilowatt hours used by LED lights with average CO_2 emissions produced by generating one kWh of electricity in Missouri (0.000685lbs/kWh, according to MoDOT records). Table 5.3 summarizes the cost and energy use of LED traffic lights.

Table 5.3. Cost Analysis of LED Traffic Lights

Factors	Red	Yellow	Green	Reference
Unit Wattage (W)	10.5	13.4	10.5	[120]
Device Cycle Time Percentage	50%	6%	44%	Assumption
Material Cost (\$/unit)	57	66	119	[111]
Installation Labor (\$/unit)	15	15	15	[121]
Total Initial Investment (\$/unit)	72	81	134	
Annual Maintenance Savings (\$/unit)	11	0	11	[112]
Annual Energy Savings (\$/unit)	60.48	7.05	53.22	\$0.1/kWh
Total Annual Savings (\$/unit)	71.48	7.05	64.22	
Payback Period (year)	1.01	11.49	2.09	
Annual CO_2 decrease (lbs/unit)	0.41	0.05	0.36	6.85×10^{-4} lbs/kWh

This work assumed a device cycle time of 50% for red lights, 6% for yellow lights, and 44% for green lights, based on observation. No reliable reference is available to verify these figures. All traffic lights are also assumed to operate 24 hours per day. In reality, some traffic lights flash after midnight, leading to a longer payback period than calculated. For example, if 50% of the traffic lights are turned off for 6 hours per day, the total annual savings would be reduced by 1/8, and the payback period could be increased by 1/8. Due to their shorter operational time, yellow lights have a much longer payback period than red and green lights; therefore, several cities that have replaced incandescent with LED lights have replaced only red and green lights [64, 122]. Some cities even replaced only red lights because they have the shortest payback time [67].

Missouri has 2,425 signalized intersections and approximately 155,000 signal indications. Combining the findings in Table 5.3 with relevant data provided by MoDOT revealed that the simple payback period for LED traffic lights in Missouri is about 4 years. This work assumed a10-year study period and a 3.92% discounted rate. Table 5.4 shows data on the defender and two technically feasible challengers.

Table 5.4. Data on Defender and Challengers

Traffic Light Bulb	Incandescent *(defender)*	LED *(challengers)*		
Color	-	Red	Yellow	Green
Unit Wattage (W)	150	10.5	13.4	10.5
Cycle Time (%)	100	50	6	44
Working Time/year (h)	8,640	4,320	518	3,802
No. of Lights	155,200	58,200	38,800	58,200
Annual Consumption (MWh)	73,919	2,640	272	2,323
		5,235		
Annual Electricity Cost ($)	7,392,000	524,00		

Considering that most states are using or plan to use LEDs, the results here prove that a LED is a superior substitute to traditional traffic signals. Table 5.5 compares a LED and a solar-powered LED to further forecast the future market for traffic signals.

Table 5.5. Summary of Results

LED Type	Grid-powered LED	Solar-powered LED
Total Initial Cost ($)	15,132,000	22,698,000
Annual Cost ($)	1,858,216	2,787,324
Annual O&M Savings ($)	1,280,400	640,200
Annual Energy Savings ($)	6,868,401	7,391,866
Total Annual Savings ($)	8,148,801	8,032,066
Net Annual Cash Flow ($)	6,290,585	5,244,741
Simple Payback Period (yr)	1.86	2.83
NPV ($)	36,094,082	20,011,473
Annual CO_2 Reduction (lbs)	47,049	50,634
CO_2 Emission Reduction (lbs/$)	0.03	0.02

5.3.2. Scenario Analysis. This analysis demonstrated that maintenance savings are an important component of the benefit of both LEDs and solar-powered LEDs. This cost analysis was conducted based on a number of assumptions. In the real world, those assumptions might be invalid, and the calculations might be different. The energy savings depend on electricity consumption (kWh) and the electric rate ($/kWh), which is highly location-specific and predetermined. However, maintenance savings can be affected by several factors.

Therefore, a sensitivity analysis of the life span of LEDs and the maintenance savings they offer was conducted to analyze their relationship. Figure 5.1 through Figure 5.3 show 15 annual operations and maintenance cost scenarios for the 155,200 LED lights in Missouri. The data include LED products with three different expected lifetimes and five standard deviations for each life span. Due to safety considerations, this report defines life span as the safe and effective operational life of a unit. It assumes that before the end of that life span, lumen output levels met the requirements of the application. Accordingly, failure means that a certain LED light failed to meet requirements, not that it burned out. Because LED traffic lights are still new on the market, little data exists to analyze real-world use. The life span of a LED is assumed to follow normal distribution. Maintenance costs under a 5-year warranty [121] would include only labor, but after expiration of the warranty, they could include both labor and materials. Labor costs for emergent repairs would be $90 per head, and average material costs for these repairs would be $88. This average represents costs for green and red LED lights only, since yellow lights are used much less often. The study period is 10 years. Bulb replacement is not included because LEDs do not usually require replacement within ten years. As shown in Figure 5.1 through Figure 5.3, good quality LED traffic lights (i.e., those with a longer mean lifetime) ensure lower total maintenance costs, which increase over time.

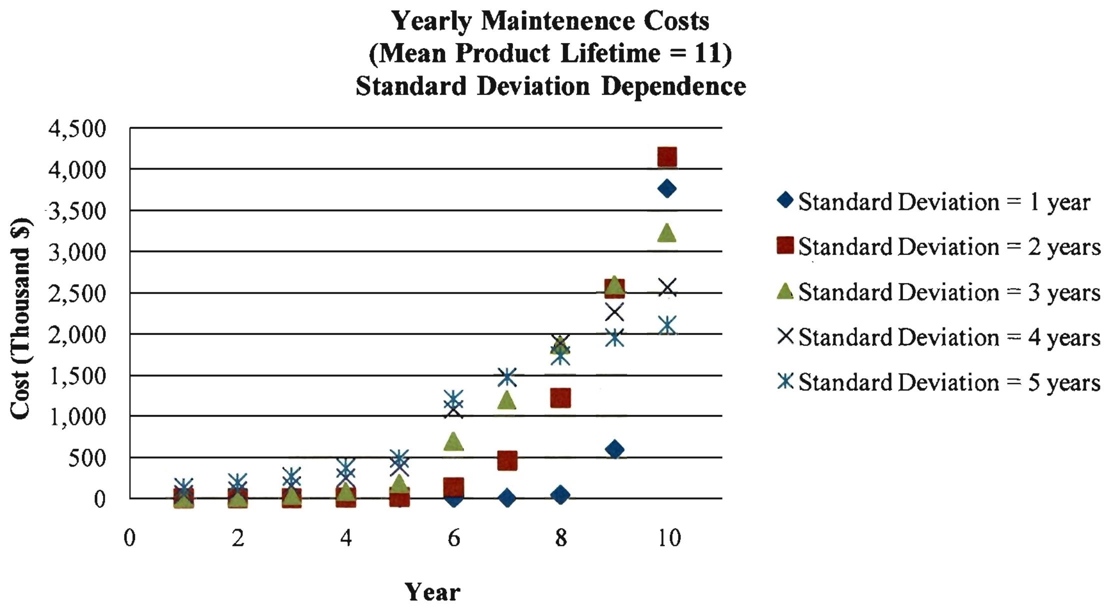

Figure 5.1. O&M Costs for Various Standard Deviations (Mean = 11 years)

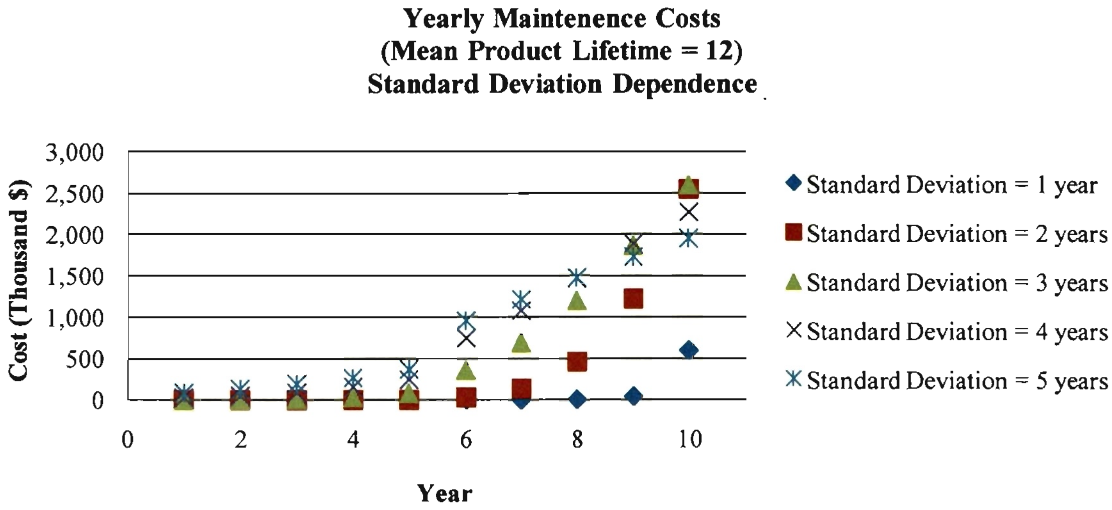

Figure 5.2. O&M Costs for Various Standard Deviations (Mean = 12 years)

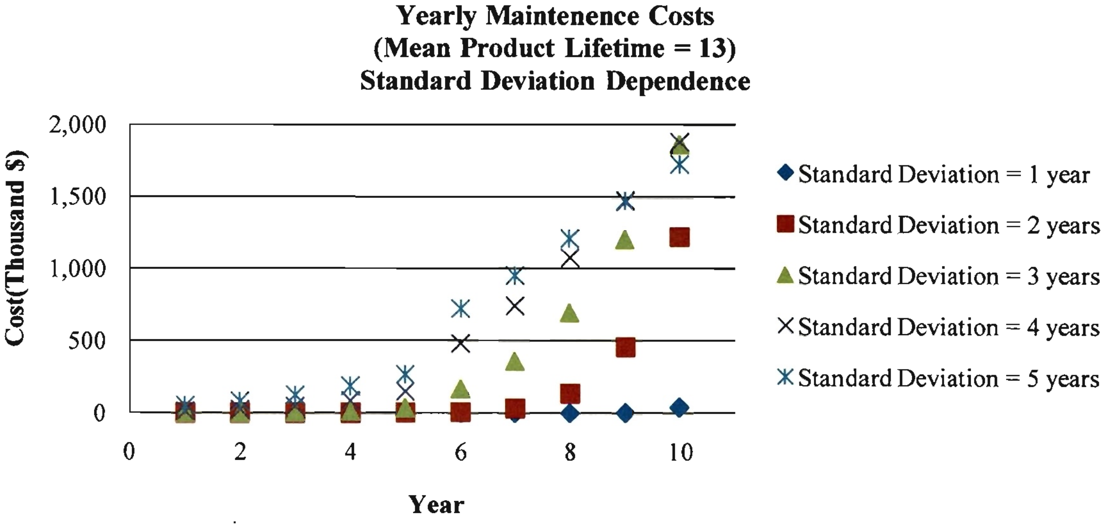

Figure 5.3. O&M Costs for Various Standard Deviations (Mean = 13 years)

5.4. DISCUSSION

In the near future, energy-efficient LEDs will likely become the major light source in all major lighting applications. Understanding and assessing LEDs is of the utmost importance for management of LED products and for the future development of LEDs themselves. The present study investigated the cost-effectiveness of LED traffic lights. Solar-powered LEDs can reduce CO_2 emissions more than grid-powered LEDs. The simple payback period for grid-powered LEDs is 1.86 years; it is less than 2.83 years for solar-powered LEDs. The longer payback period of solar-powered LEDs is the result of the higher initial investment. Sensitivity analysis shows that good quality LED products have a longer warranted life span, reducing annual maintenance costs. This analysis also demonstrated that maintenance savings are a major potential benefit of LED use. This benefit could influence decisions on adoption of LED systems because different maintenance strategies require different levels of funding after installation.

Future work will focus on modeling maintenance strategies to improve the cost-effectiveness of LEDs. A number of factors affect the choice of maintenance strategy for LED products and the balance between regular and emergent maintenance. An economical maintenance strategy not only saves money, but also makes maintenance requirements predictable, thus permitting the development of effective maintenance plans. Since 2007, many cities have replaced or are planning to replace traffic lights with LEDs, but little attention has been paid to street lighting. Future efforts will also evaluate the application of LEDs to street lighting.

6. CONCLUSION

This study was conducted to evaluate some alternative energy strategies and energy efficiency measures, especially for public transportation applications. To this end, a CEA framework was developed to facilitate the evaluation of sustainable strategies. These strategies have frequently involved huge investments and must usually remain in place over a long period before effects are realized. The case studies indicated that, by adopting this framework, analysts can effectively evaluate the costs and effects of alternative energy strategies, including defining the problems, collecting information, assessing effectiveness, estimating costs, and deriving C/E or E/C ratios. Besides CEA ratios, this evaluation also provided financial criteria in terms of profitability and liquidity, i.e., NPV, payback period, and profitability index. Stakeholders can use this framework to generate a comprehensible comparison of multiple alternatives and make strategy-adoption decisions based on their financial situation and preference. Moreover, the framework contains an effectiveness structure what can serve as an effects database to which decision makers can refer.

The validity of the framework is verified here by its application in several cases. The selection of a hybrid system for a welcome center has showed that certain significant benefits are possible without great cost to the economy. The demonstration case shows that an alternative energy strategy significantly reduces CO_2 emissions; however, the financial results of this project are far below expectations due to the dysfunction of the specific system considered here. Hence, a well-prepared feasibility study and good maintenance strategy can ensure an economically sustainable strategy that will work as planned. Although the effects would vary according to the specific climatic zone, the alternative energy type, and the application, sustainable strategies could be attractive even on strictly financial terms. The results also show that tax incentives make alternative energy strategies more affordable and attractive, while reinforcing the concept of sustainability among the public. However, the lack of data on alternative energy effects is a serious obstacle to accurate real-world analysis.

This study has built a foundation for advanced economic and financial investigation of sustainable strategies. Future work could involve more detailed studies, recording data on major effects to provide E/C ratios and comparing proposed energy portfolio strategies from a comprehensive cost-effectiveness perspective. Such work would increase knowledge of alternative energy practices.

APPENDIX

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