DEVELOPMENT OF A DECISION TOOL FOR GREEN ENERGY INVESTMENT IN THE PIONEER VALLEY

A Thesis Presented

by

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ABSTRACT

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We present the process followed to create a decision-aid tool for use in renewable energy and energy efficiency investment decisions. Our tool is targeted at home and small business owners in the Pioneer Valley. We begin with the development of two prototype tools. The first was created for the Hitchcock Center for the Environment, and is an Excel-based tool that allows users to select various combinations of technologies and instantly see the financial, environmental, and educational impacts of their choice. The second examines only two technologies, solar photovoltaics and combined heat and power, and uses a cost minimization approach. These prototype tools inform the development of the Pioneer Valley Sustainability Network (PVSN) decision-aid tool. The PVSN tool allows users to compare a building's current energy consumption with the expected performance given the implementation of one or several renewable energy or energy efficient technologies. The PVSN tool evaluates financial costs along with externalities like emissions damages and health impacts. It also provides modeling of decision making under uncertain costs of damages from carbon emissions.

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1 INTRODUCTION

Climate change is a phenomenon resulting in numerous impacts upon our world. The measureable effects over recent history include rising global sea levels, thinning of sea ice in the Arctic, shrinking glaciers, and increasing land surface temperatures. According to models, the potential future effects mirror those we are seeing today: increasing sea levels, higher maximum temperatures and more hot days in nearly all areas, more intense precipitation events, an increase in drought risk (in mid-latitude continental interiors), and an increased heat index in most areas (IPCC 2008). These changes will have negative impacts on everything from natural ecosystems (Parmesan and Yohe 2003) to global food supply (Rosenzweig and Parry 1994). Analysis indicates the likelihood that the warming we are experiencing now and that we will experience in the future results from increased emission of greenhouse gasses (IPCC 2008). These gasses, including CO_2, SO_2, and NO_x, have increased in concentration over time as humans have become increasingly dependent on technologies which require the combustion of fossil fuels to generate power.

As public concern about climate change has grown, interest in means of reducing carbon emissions has increased. There is an increasing demand from individuals and industry alike to reduce their “carbon footprint,” or the amount of CO_2 and other greenhouse gasses emitted through everyday activities. Climate change is not the sole motivator of emission reductions; indeed, concerns over everything from human health impacts to rising fossil fuel costs are stimulating this interest. Various renewable energy and energy efficient technologies, which produce electricity and heat with minimal to zero emissions, are becoming prevalent. However, there is a great deal of uncertainty surrounding the best way to go about becoming "greener." Many green alternatives to traditional energy generation have higher upfront costs. In addition, there is uncertainty surrounding the degree of severity of climate change, and the corresponding level of investment toward emissions mitigation that should be made. There also exists uncertainty regarding future energy prices. While much scientific information is available on these subjects, consumers and planners alike cannot always take the needed time to research the various choices available to them.

The goal of this project is the creation of a decision support tool that can be used by the public to effectively evaluate potential investments in green energy technologies. We will create this tool in conjunction with the Pioneer Valley Sustainability Network (PVSN), an organization of community members with the common goal of enhancing sustainability in the region. For clarity, the tool we propose to create will hereafter be referred to as the "PVSN tool". The PVSN tool will allow users to select from a range of green technology options and instantly view the impacts in terms of key metrics agreed upon by the network members. These metrics will include financial costs, emissions, and health impacts. The PVSN tool will also provide users with an idea of the uncertainty associated with the results, specifically in regard to carbon damages. We will make this tool web-accessible, so that all members of the community will have equal opportunity to benefit from it.

The remainder of this thesis is structured as follows. In Chapter 2 we perform a literature review, discussing relevant existing decision tools, as well as work relating to interface design and decision making under uncertainty. This work forms the foundation upon which we will build the PVSN tool. In Chapter 3 we present a paper which discusses the creation of a decision tool developed for the Hitchcock Center for the Environment (HC tool). The HC tool will serve as a prototype for the PVSN tool. The HC tool allows the user to select implementation of solar photovoltaic, heating, lighting, and wastewater technologies, and view the impact of their selections on several metrics. Many of the methods, data, and calculations found in the HC tool will be pertinent to the creation the PVSN tool. Chapter 4 details the development of another, separate prototype tool. This tool introduces a new alternative, combined heat and power technology, in conjunction with an expansion of our analysis of solar photovoltaics. This tool also incorporates rebates and emissions trading, and works as an optimization model. Again, we will integrate parts of this prototype tool into the PVSN tool. Chapter 5 presents a detailed explanation of the PVSN decision tool, including a discussion of new technologies to be included, the user interface, the treatment of uncertainty in our calculations, as well as results and a sensitivity analysis of these results. Chapter 6 provides a summary of the ideas developed within this paper.

2 LITERATURE REVIEW

In this chapter, we provide a review of the literature as it relates to decision tools in general. We then explore past work on environment-oriented decision tools, interface design methods, and decision making under uncertainty.

Decision tools are a widely accepted means of aiding in the analysis of decisions. Typically, these computer-based tools allow users to understand various aspects of a complex decision, and to see how these different aspects combine to yield a final result. They generally have three specific components: data sources, modeling functions, and user interfaces (Shim, Warkentin et al. 2002). Decision tools have been used in the past to aid humans in a wide range of fields, including climate change impacts (Wilby, Dawson et al. 2002), medical decision making (Robinson and Thomson 2001), antibiotic therapy (Evans, Classen et al. 1995), cancer research (Breitfield, Weisburd et al. 1999), urban planning (Engelen, White et al. 1997), and agriculture (Johnsson, Larsson et al. 2002).

2.1 An overview of current Environmental Decision Tools

Many decision tools currently exist that touch upon the focus our study: green energy technology and environmental sustainability. A selection of these tools is described below.

- BIDS – The Building Investment Decision Support (BIDS) tool was developed at the Carnegie Mellon School of Architecture. The purpose of this web-based tool is to allow businesses to view the impact on overall economic value of various changes they might choose to make to their building. These changes include considerations like access to the natural environment, lighting control, temperature control, and ergonomics. Based on case studies, BIDS estimates how selected changes will impact costs associated with employee absenteeism, turnover, benefits, and energy use. Users have the ability to alter the parameters that are used in these calculations as they see fit. The output of BIDS is presented in terms of both an economic value added dollar figure, as well as a return on investment percentage (Carnegie Mellon University 2003). BIDS focuses on clients in a business environment, while our tool will focus on homeowners. BIDS also does not have a strictly technological focus, nor does it take into account uncertainty regarding future emissions damages.

- HES – The Home Energy Saver (HES) tool was developed by the Lawrence Berkeley National Laboratory. It focuses specifically on helping consumers to make decisions that will allow them to save energy in their own homes. HES is a web-based tool, and allows the user to enter parameters regarding their home, including its geographic location, number of stories, square footage, number of residents, and type and number of appliances. Based on these and other inputs, HES provides the user with a list of recommended upgrades to appliances and the home itself. An estimate of yearly cost with specific upgrades is given both numerically and graphically. HES also calculates the change in carbon emissions resulting from implementing suggested changes. Users have the ability to edit the selected upgrades, as well as the anticipated prices of these upgrades (Lawrence Berkeley National Lab 2008). HES focuses solely on efficiency, and does not deal with renewable energy technologies.

-DOE ITP tools – The Department of Energy's (DOE) Industrial Technology Program creates decision support software tools which help to identify areas of potential energy efficiency improvement in industrial systems. Tools are available for analysis of a variety of systems, including chilled water, pumping, combined heat and power, and steam systems. These tools accept user input regarding their current system, and project financial impacts of making various improvements to the system (Department of Energy 2006). The ITP tools focus strictly on industrial environments, while our tool will concentrate on the homeowner. Our tool will include cost, but focus on other metrics as well.

-SELECT – SELECT is a decision tool focusing on issues surrounding cleanup of environmental contamination, developed at the Lawrence Berkeley National Laboratory. The goals of SELECT are to provide the best possible science to support development of cleanup policies, allow remediation to be managed with minimal public risk, and communicate remediation decisions with risk managers and the public. SELECT uses a graphical user interface to allow the user to characterize the site and simulate carcinogenic exposure, risk, and cost. With SELECT, users can arrive at cost effective remediation strategies based on sound risk analysis (Lawrence Berkeley National Lab 1996). Our tool will focus on the environmental issues of green electricity generation as opposed to contamination remediation.

-RETScreen – RETScreen Clean Energy Project Analysis Software, developed by Natural Resources Canada, is a decision tool that has a close relation to the aims of the tool developed in this paper. This is a free tool that allows users to gauge the results of the implementation of different types of renewable energy and energy efficiency technologies in residential, commercial, and industrial settings. The metrics used to measure the technologies include energy production, cost, emissions, and risk (Natural Resources Canada 2008). The target user of RETScreen is a knowledgeable engineer who already understands many project requirements. The user inputs require large amounts of research, as well as strong understanding of energy production and construction. Our tool will require less of the user, thus making it easier for people of all backgrounds to engage in its use more casually.

While the tools and studies described above have some similarities to our focus, none satisfies the demand for the tool which we create. There are many ways in which our tool differs from those mentioned above. The PVSN tool is designed so that any user will be able to understand the inputs and outputs with minimal outside knowledge. Our decision making tool contains data specific to the Pioneer Valley, as its intended users reside therein. We also evaluate alternatives not only on common metrics like cost, but also include externalities like emissions and human health impacts. We present users with a broad range of technology options, allowing the user to see the combined effect of several different selections. Our tool also provides users with an understanding of the uncertainties attached to a given selection of alternatives. We also aim to keep the user interface relatively simple, and the tool fast.

2.2 Decision Tool Interface

An important factor for consideration in the development of the decision tool is the manner in which information will be displayed to users. Naturally, we want the user to be able to easily understand the results delivered by the tool, and we'd like this comprehension to occur as quickly as possible. Hence, we look to human factors literature for guidelines for effectively displaying and communicating information.

Smith, Geddes, and Beatty (2008) have produced a guide to the design of decision support systems. While their focus is on an operator interfacing with a system that is changing in real time, like an air traffic controller or a power plant operator, many of the concepts they propose can add value to our work. As a starting point in the design, they recommend creating a specification of the person for whom the tool is being designed and what goal they are trying to achieve. The design must also incorporate constraints imposed by human abilities to process information, including memory, perceptual, and information processing constraints. Smith, Bennett, and Stone (2006) suggest the use of representation aids to support both skill- and rule-based processing. Representation aids should leverage the skill-based behavior of direct perception by providing visual information that directly specifies the state of a system. In our work, we provide graphical displays to allow the user to directly perceive and compare metrics like costs, emission levels, and health impacts. The fact that humans have a limited short term memory capacity makes the use of external memory aids recommended as part of any interface. An external memory aid should provide a picture of the entire problem to be addressed, while allowing the user to work through the different parts of the problem.

Tufte (1980) has done much work in the field of visual display. We make use of several of his concepts to improve the ability of users to perceive directly the output of the decision tool. Tufte states that the best way to describe a set of numbers is with a picture of those numbers. We leverage this concept by designing graphical displays of the decision tool output. Tufte also recommends revealing data to the user at several layers of detail, from a macroscopic overview to the finer details. Tufte also advocates data transparency as a means of gaining the confidence of users by showing them exactly how results are calculated. Our use of MS Excel in the creation of our tools provides this transparency, as the savvy user will be able to step through all calculations performed by the tools.

2.3 Decision Making Under Uncertainty

This section details research that has been done on decision making under uncertainty and its influence on our work. Uncertainty can be defined as a feature of the universe over which one has no control. It is, essentially, a random variable (Savage, Scholtes et al. 2006). In the context of this project, we are primarily interested in uncertainty associated with the costs of damages due to emissions. For instance, the choice to reduce your emissions by installing expensive solar panels incorporates the risk that damages from emissions will not be as bad as currently believed. In order for community members to effectively make use of the decision tool, this uncertainty must be made easy to understand.

The approach we take to communicating uncertainty follows the work of Savage, Scholtes, and Zweidler (2006) in the area of probability management. These authors have found that people often use averages or base case numbers when representing uncertainty in metrics, which leads to misrepresentation by ignoring the underlying probability distributions behind the metrics. Savage et al recommend the use of "coherent modeling," which involves the use of interactive simulation tools to provide users with interactive visual feedback regarding uncertainty of a parameter, thus providing an experiential understanding of uncertainty and associated risk. These simulations are based on stochastic libraries, which contain probability distributions for each parameter.

We use Frontline Systems PSI technology, running through the Risk Solver Engine software add-in for MS Excel, to run simulations within our model. This technology runs all simulation trials in parallel rather than series, and thus significantly reduces the time for trials of simulations to complete. The random variable generated by the simulation will be the cost of damages due to carbon emissions. The probability distribution that drive these simulations comes from the literature. Tol (2005) has created a probability distribution of the marginal costs of damages due to carbon emissions based on a survey of 28 studies on the topic. We use his distribution as the foundation for our stochastic library.

3 HITCHCOCK CENTER DECISION MAKING TOOL

This chapter presents the initial submission of a paper to the journal Decision Analysis. We discuss the development of a prototype green energy decision tool. The development process for this tool influences the creation of the PVSN tool.

In this chapter, we discuss a collaborative process for developing a decision tool to support decisions around investment in green energy technologies. Our tool was developed specifically for the Hitchcock Center for the Environment, a local environmental education organization, and the development process began as an undergraduate student service learning project. Building on the student projects, we developed an Excel-based tool that allows users to select various combinations of technologies and instantly see the financial and environmental impacts of their choice. This tool allows the user to compute the annualized preference adjusted cost of an alternative set, which includes financial costs, costs of emissions damages, and benefits from educational value. The optimal alternative set is that which yields the lowest preference adjusted cost. Given our initial parameters and the preferences of the Hitchcock Center staff, the optimal configuration included installing a biomass heating system but avoiding investment in other green technologies, yielding an annualized preference-adjusted cost of $5,814. Sensitivity analysis indicated that the overall cost is most sensitive to the discount rate, the marginal cost of damages due to carbon emissions, the amount of electricity used at the center, and the price of electricity. We calculated the Expected Value of Perfect Information and found that the most valuable information was on the cost of maintaining a biomass heating system.

3.1 Introduction

The Hitchcock Center for the Environment (HC) is an environmental education center located in Amherst, Massachusetts. The mission of the HC is to "foster a greater understanding and awareness of our natural world and to develop environmentally literate citizens." Due to increasing program attendance and the size restrictions of their current facility, the HC has recently received funding for expansion. This expansion could take the form of renovations to the current building, or the construction of an entirely new building. As part of this expansion, the HC wants to consider the implementation of various "green" technologies. In this paper, we discuss a decision making tool developed to help the HC decide in which technologies to invest.

This was a collaborative process with an educational focus. We had multiple goals in this project. The first part of the project involved a service learning project for undergraduate students in an engineering economics class. The students gathered data and calculated the annualized costs and the carbon emissions for a range of technologies. The goals were to allow them to get a real-world application of engineering economic evaluation; to learn about a range of currently available "green" technologies; and to deepen their involvement in the local community through working with and learning about a local non-profit. The students and the research team worked closely with the building committee and the board of directors of the HC. We elicited preferences from the HC building committee and presented the results of our analysis at a number of public meetings. Our goals from this interaction were to introduce them to a formal decision making process, including elicitations of preferences and quantifying the costs and benefits of alternative technologies. The product of the process is a decision tool that the

HC can use for both designing and constructing their new building. Finally, the HC intends to pass on what they have learned and educate the public about ways to evaluate green building choices.

The results of the process indicated that the Hitchcock Center's stated goals did not match closely with their elicited preferences. The goals behind the expansion of the HC are numerous and aggressive. The overarching goal is to transform the existing building into a high performance sustainable building that is healthy, resource efficient, adaptable, and educational. To this end, the building committee hopes to work toward LEED certification, reduce their ecological footprint, reduce their net energy use to zero, and reduce their wastewater discharge to zero. They also hope to use their building as a teaching tool that can be used to demonstrate feasible ways for visitors to introduce green technologies into their own lives. However, the values that we elicited from them, and the data we collected, were not consistent with such extreme goals. Instead, we found that their current means of providing heat and electricity to their building proved to be near optimal, even considering environmental externalities. Of all the green technologies under consideration, the optimal selection included the implementation of only a biomass heater. This result stems from the relatively low amount of CO_2 produced by the HC, and hence the relatively small savings that can be gained by reducing these emissions.

We performed value of information analysis and found that the most valuable information was on the cost of maintenance for the biomass heater, and the future costs of biodiesel. This result was because the biomass heater and the biodiesel heater were very close alternatives, thus near term information could tip the decision one way or the other. The next highest value was on having better information about the future price of electricity. Given the current price, neither solar panels nor daylighting are attractive. However, we found that if the price of electricity climbs to $0.30/kWh then a 42 panel monocrystalline solar array will become cost effective.

In Section 3.2 we discuss the collaborative process, involving an undergraduate engineering economics class and the HC building committee. This process includes the development of the technology alternatives to be considered in the HC tool and the process of eliciting the HC's preferences and establishing base values for the parameters used in our tool. In Section 3 we describe the resulting decision tool. We then perform sensitivity analysis including EVPI in Section 4, and conclude in Section 5.

3.2 An Educational Collaborative Process

The first step in any decision making process is to perform an analysis of the values that drive the decision, and develop alternatives based on these values (Keeney 1992). As part of a student service learning project, we had an Economic Decision Making class of mechanical and industrial engineering undergraduates meet with the executive director and several board members of the HC to discuss their values relative to this decision problem. The three key evaluation criteria of concern to the HC were found to be the environmental impact of the center, the educational effectiveness of the center, and the financial costs to the center. Given this information, the students divided into four groups, performed initial research, and arrived at ideas for different areas of improvement that they felt might reinforce the HC's values. These selections were discussed with the HC director, and it was agreed that the technologies under consideration were in line with the HC's goals. The four areas of technology considered are daylighting, photovoltaics, heating, and wastewater.

3.2.1 Development of the Alternatives

Within each category, a variety of technologies were considered. In researching these technologies, the students considered two construction options available to the HC: either to renovate the current building or construct a new building. The primary difference between these two is size, with the new building under consideration being larger than the current one. Thus, we assume the new building will have greater heating and electricity requirements than the current building. It was also important to consider any additional costs of retrofitting a technology to the current building as opposed to including it in the construction of the new building. Daylighting fell into this category, due to the additional cost of removing old windows and installing new, larger windows at the current facility.

3.2.1.1 Daylighting

Daylighting is simply the use of additional or expanded windows, carefully placed to increase the amount of natural light allowed into a building without creating glare. This increase in natural light is generally coupled with electric lighting controls, which monitor the level of light in a room and adjust the level of illumination accordingly. Thus, instead of having electric lights turned on all day, the lights will be dimmed or off during peak daylight illumination hours and then gradually increased as the sun sets. This reduction in electricity use leads to both a financial savings and a reduction in the HC's carbon footprint.

Four alternatives were considered for the daylighting category. The first is simply to maintain the status quo, adding no additional windows. The other three alternatives involve electric lighting controls with different types of windows: double pane clear glass, double pane tinted glass, and double pane low emissivity (low-e) glass. Each of these types of window consists of a layer of air sandwiched between two layers of glass. This layer of air provides more insulation than normal single pane glass, and thus these windows provide the added benefit of heat savings on top of the electricity savings. If the windows were not double-paned, there would be a net heat loss due to the larger number of windows. (We did not consider the alternative of only replacing the current windows with double paned windows.) The significant differences between the three types of window are the price per square foot and the amount of heat transmitted through each type. Double pane clear windows are the least expensive, with a heat savings estimated at 1% of the total heat use of the building. Double pane tinted are the next most expensive, with a heat savings estimated at 2%. Tinted windows have the additional benefit of reducing the number of bird deaths. We did not account for this numerically, but it was noted as a relevant issue to the HC. Finally, double pane low-e windows are the most expensive, with a heat savings estimated at 3%. There is a significant difference between the parameters for the old retro-fit building and for constructing the new building. The total electricity savings associated with daylighting use is assumed to be 10% in the current building and 15% in the new building, as the new building could be designed and oriented for optimal daylighting conditions. Studies have shown a high variability in the energy savings due to daylighting (22%-64%) (Nicklas and Bailey 1996). Because of the high level of shading at the HC site, we have chosen more conservative estimates of savings as base parameters for our model. For the current building, a reconstruction cost of $\$5/ft^2$ was added, whereas in a new building this reconstruction cost would not be a factor. Also, the estimated square footage of required windows was set at 25% of the total area of the current building. In a new building, we assumed an additional number of windows of 15% of the total area. This difference is a result of the fact that all windows in the current building would have to be replaced, but in the new building double pane windows would be used by default, so fewer additional windows will be required.

3.2.1.2 Solar Photovoltaics

Photovoltaic (PV) technology takes energy from the sun and transforms it into useable electricity. PV panels work by absorbing photons from the sun's rays and using these photons to force the movement of electrons within the panel, thus generating electricity. The ability of a PV panel to produce electricity depends greatly on the siting of the panel (south facing in the northern hemisphere, free of shading) and the sunlight conditions of the environment (typically sunny, cloudy, etc.). While many types of photovoltaic solar panels are currently available to consumers, we chose to focus on two of the more prevalent types of panels: monocrystalline silicone panels and non-crystalline triple junction panels.

Monocrystalline panels generally have a higher generating efficiency than triple junction panels under optimal lighting conditions. They are also more expensive on a per panel basis. Triple-junction panels, while generally less efficient, are better at producing electricity under low sunlight conditions. As the siting of the HC can be considered suboptimal due to the abundance of surrounding trees and its northern, cloudy location, this type of paneling seemed to be an important consideration. One of the generating difference between these two panel types is tied to a parameter in the decision tool called the "number of useful hours", which is linked to the efficiency of the panel (the ratio of energy produced to energy input by the sun). Different sized arrays of each panel type were considered, with larger arrays having greater generating capacity. The monocrystalline panels we examined are rated at 170 W/panel, and the triple junction panels at 124 W/panel. These capacities indicate the maximum output that a panel can produce in an hour. For instance, if the sun were to shine on a 170 W monocrystalline panel under optimal lighting conditions for 10 hours, 0.17 kW*10 hours, or 1.7 kWh of energy would be produced. We also considered two scenarios: one in which unused electricity generated from the PV array is repurchased by the utility at the retail price ("buyback"), and another in which this excess electricity is not repurchased ("no buyback"). Batteries for electricity storage were not considered, as these are generally used only in rural situations where a grid connection is unavailable. Currently, utilities do not offer to buy back excess energy from solar arrays in the Amherst area. Some utilities have implemented such policies, and in the best possible situation the rate paid by the utility equals the retail price charged for electricity. Thus, the "buyback" and "no buyback" options in our decision tool provide the user with the ability to evaluate options under best and worst case scenarios. For our baseline analysis, we use "no buyback," as this reflects the current situation.

3.2.1.3 Heating

Four distinct alternatives were considered within the heating category. Propane based heat is currently used in the HC, and is the first alternative. For our analysis, we consider continued use of the current propane heater for the current building, and the purchase of a new propane heater for the new building. The remaining useful life of the current heating system is difficult to determine, as the system is comprised of four distinct propane units which were bought at different points in the history of the HC. For our analysis, we simply discount the value of the current heater as if it were a new one. This practice will overvalue the current system. However, as propane is never shown as optimal, this does not impact the results of our model. We also considered heating with biodiesel and biomass furnaces. Biodiesel is a diesel fuel made from vegetable oil, and produces lower carbon emissions than fossil fuels. Biomass furnaces simply burn wood or corn to generate heat, again producing lower carbon emissions than fossil fuel. For our analysis, we will calculate the carbon emissions of biomass as equivalent to the amount of carbon held within the fuel. Another approach would be to consider biomass as carbon neutral – taking the view that wood or corn simply releases carbon it has absorbed over its lifetime during combustion, and thus does not introduce any new carbon into the atmosphere. We will discuss the impacts of this alternate viewpoint in our analysis. The final heating alternative considered is geothermal heating, which involves digging a well to access heat below the earth's surface. Electric pumps bring the heat to the surface. Geothermal heating has the benefit of not directly requiring the combustion of any carbon based fuel, but does have significant excavation, installation, and equipment costs. Geothermal also requires the use of electricity to run the heat pumps.

3.2.1.4 Wastewater

The wastewater reduction category was broken into four possible alternatives. The first involves no changes to current water using appliances; this is the "do nothing" alternative. The second alternative involves the installation of waterless urinals. These have a low initial cost, and would be a useful way of reducing water usage from flushing the toilet for half of the population. The third alternative is the installation of a composting toilet, which has higher costs associated with purchase, installation, and maintenance, but uses no water and would also provide the HC with useful compost. The final wastewater reduction alternative is the implementation of a system known as the living machine. The living machine consists of a series of tanks, each containing organisms that break down biological waste and cleanse the water. Wastewater is gradually moved from tank to tank, becoming successively cleaner, until it can finally be reintroduced back into the system as toilet water. While it would be a valuable educational tool, the living machine would require a significant financial investment as well as a great deal of maintenance. Systems are not currently sold for low water usage facilities like the HC, so the costs associated with the living machine in our analysis are extrapolated from those of larger systems. Living machines will be produced in the future for lower water usage facilities. It is also worth mentioning that the living machine requires the construction of a greenhouse, which could yield potential heating benefits for the HC (estimated at 23% savings of total heat use).

The decision tool we develop allows for the selection of a single option from each of these four categories. The term "alternative set" used throughout this paper refers to a given combination of one of each of the daylighting, solar, heating, and water options.

3.2.2 Preference Elicitation

To effectively evaluate the relative worth of different combinations of alternatives, we examine the metrics upon which these alternatives are measured. Based on the HC's stated goals for the building project, we came up with three key metrics: financial cost, environmental impact, and educational value. While the financial costs associated with each alternative are easily quantified in terms of dollars, the same cannot be said of environmental impact and educational value. Yet, we needed to represent these two metrics in dollar values in order to accurately compare the different alternatives. Thus, we worked with the HC building committee to determine dollar values for these metrics that reflected their core values.

We focus on measuring the environmental damage through determining the amount of carbon dioxide (CO_2) released into the atmosphere by use of that alternative. CO_2 is the most prevalent greenhouse gas, and one of the biggest contributors to global warming. We asked the HC to put a value on the costs of environmental damages incurred by emission of a single ton of CO_2 in the present. Note that one approach would look at the costs of environmental damages as *information* rather than *preferences*. There is, in fact, a great deal of uncertainty involved in such a valuation. Scientists are uncertain about the degree to which global warming is impacted by human emissions; they are uncertain about how the stock of emissions in the atmosphere relates to global mean temperature; they are uncertain about how global mean temperature relates to local climate variables such as rainfall, temperature, and extreme storms. Finally, there is disagreement about how to value impacts on varying populations, species, and locales. To simplify the process, we represented both the beliefs (about the likelihood of various events) and the preferences (about the value of ecosystems for example) in a single parameter, elicited as a preference.

Using this willingness to pay technique for evaluating the cost of damages is reasonable, as both criteria for effective use of willingness to pay are met (Keeney and Raiffa 1993). First, the amount of CO_2 emitted by an alternative is independent of the other attributes of that alternative (price, educational value). Second, the marginal rate of substitution between money and other attributes does not functionally depend on the monetary level. Here we see that the monetary level associated with an alternative does not impact the rate at which money can be substituted for attributes (like CO_2 emissions). To support the HC in making this value judgment, we performed a literature review and collected an assortment of estimates of the marginal damages from climate change. The values ranged from as little at \$2/ton CO_2 (Leach, Bauen et al. 1997; Lomborg 2007) to as high as \$385/ton CO_2 (Tol 2005). This high value represents the 90^{th} percentile value from an analysis of 28 studies on the subject by Tol. We present the range of values in Table 1.

Study	$/ton CO_2
Leach, Bauen, et al. 1997 (low value)	2
Lomborg 2007	2
IPCC 2008 (low value)	6
Tol 2005 (median value)	8
Tol 2005 (mean value)	18
Leach, Bauen, et al. 1997 (high value)	51
IPCC 2008 (high value)	138
Tol 2005 (90th percentile value)	385

Table 1 - Valuations of damages from CO_2 emissions

We also wanted to consider damage from emissions other than CO_2, with the two primary pollutants being SO_2 and NO_x. While these two gases are released in much lower quantities than CO_2, they have significant environmental impacts, including contributions to both acid rain and climate change. To simplify our calculations, we estimated the approximate amount of emissions of these two gasses for every ton of CO_2 emitted. In reality these values will vary depending on the type of fuel used and the quality of the facility in which it is burned. Emissions from electricity generation in Massachusetts for these two pollutants were calculated to be 5.72 lbs SO_2/ton CO_2 and 2.15 lbs NO_x/ton CO_2 (EPA 2007).

Data collection revealed highly variable estimates at the marginal costs of damages due to these two pollutants, ranging between $341/ton (Wang and Santini 1995) and $24,670/ton (Leach, Bauen et al. 1997) for SO_2 and $256/ton (Wang and Santini 1995) and $33,378/ton (Leach, Bauen et al. 1997) for NO_x. We then translated these into an extra cost for a ton of CO_2. For instance, \$341/ton SO_2 * 1 ton SO_2/2000 lbs SO_2 * 5.72 lbs SO_2/ton CO_2 yields \$0.98/ton CO_2. The values are displayed in Table 2.

Emission	Study	$/ton	$/ton CO_2
SO_2	Wang and Santini 1995	341	0.98
	Leach, Bauen, et al. 1997	1,450	4.15
	Wang and Santini 1995	9,041	25.85
	Leach, Bauen, et al. 1997	24,670	70.56
NO_x	Wang and Santini 1995	256	0.28
	Leach, Bauen, et al. 1997	1450	1.56
	Wang and Santini 1995	17,635	18.96
	Leach, Bauen, et al. 1997	33,378	35.88

Table 2 - Estimates of costs of damages from SO_2 and NO_x

We presented these values to the HC building committee and discussed how their own environmental beliefs compared with those of the authors of the various studies. The committee noted that, even though it is an environmental center, they did not necessarily want to simply choose the most extreme number available. Part of the intention of the Green Building Project is to educate the public about the green alternatives that are available in the hopes that more people will implement them. If the HC chose an extreme value they would be likely to lose much of the public. After some discussion they decided that they would use the high valuation from the IPCC. They felt that the IPCC was a respected and valid resource; and that the higher valuation was appropriate since the HC has a firm commitment to protecting the environment, therefore their members would tend to fall on the high end of valuations for ecosystem services. They combined the IPCC's high estimate of \$138/ton CO_2 ,(IPCC 2008) with the valuations of \$25.85/ton CO_2 for SO_2 and \$18.96/ton CO_2 for NO_x (Wang and Santini 1995) for a total of \$183.

A similar method was used to put a value on water usage, though this was somewhat less subjective because water prices are readily available. However, the HC building committee felt it important to value the impact of water use at more than simply its market price. To help them arrive at a reasonable valuation, we first presented them with a study assessing national freshwater valuation by region (Frederick, VandenBerg et al. 1996). As seen in Figure 1, New England has some of the lowest valuations of any region in the nation.

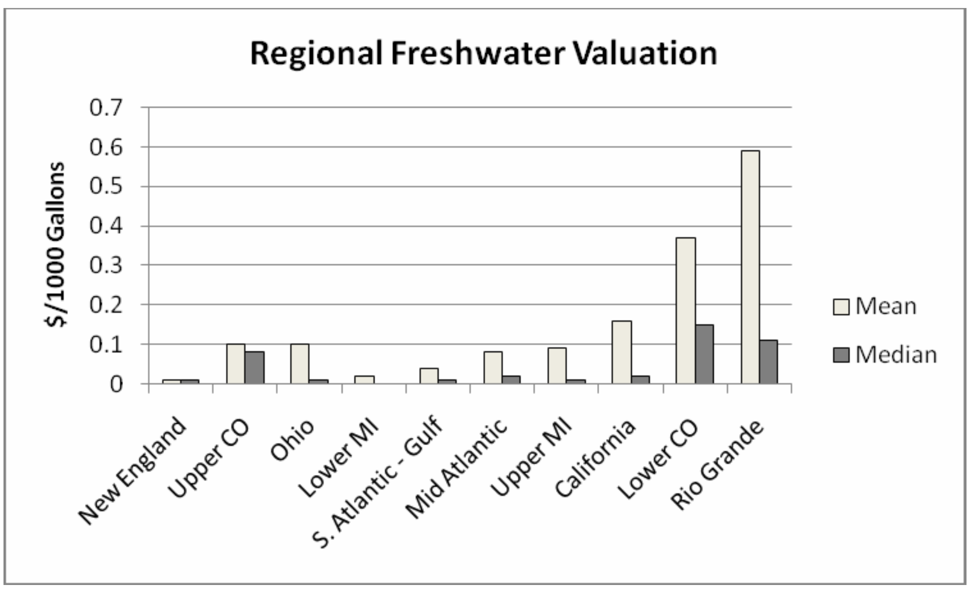


Figure 1 - US Freshwater valuation by region

We also examined local water and sewer prices, adjusted them for inflation, and made linear price projections. These projections indicate that the cost of water in Amherst has been steadily increasing over time. The current cost of water services is

$1.50/1000 gallons, and sewer services cost $1.50/1000 gallons as well. This results in a total financial cost of $3/1000 gallons of water used.

After examining local water and sewer prices, linear projections of the future prices, and national water availability/scarcity data, the building committee agreed to value water use generously at $3/1000 gallons for utility and another $3/1000 gallons for environmental impact, for a total valuation of $6/1000 gallons of water used. This is a relatively high value for what is generally considered to be a low valued commodity, and reflects the HC's high level of concern for the future condition of the environment.

Finally, the HC building committee was asked to choose their discount rate, to be used in the model to perform calculations incorporating the time value of money for each investment. The HC building committee agreed upon a discount rate of 3%, which is what is suggested by NOAA for public goods projects (NOAA 2008). This relatively low value reflects the high level of importance the HC places on the future.

Due to time and availability constraints, monetary valuations were not put on the educational value of the various alternatives. The proposed strategy for carrying out this valuation is for the educational staff of the HC to meet and discuss how different alternatives could be utilized in the HC's programming. The alternatives could be ranked in order of value as a teaching tool, and then dollar values could be applied to these rankings. At the time this paper was written, such an evaluation had not been performed. Thus, our analysis was performed with all alternatives having an equivalent educational value of $0. There is, however, a section of the decision tool in which these educational values can easily be entered, and the impact on the overall cost of the project will instantly be recalculated to reflect these values.

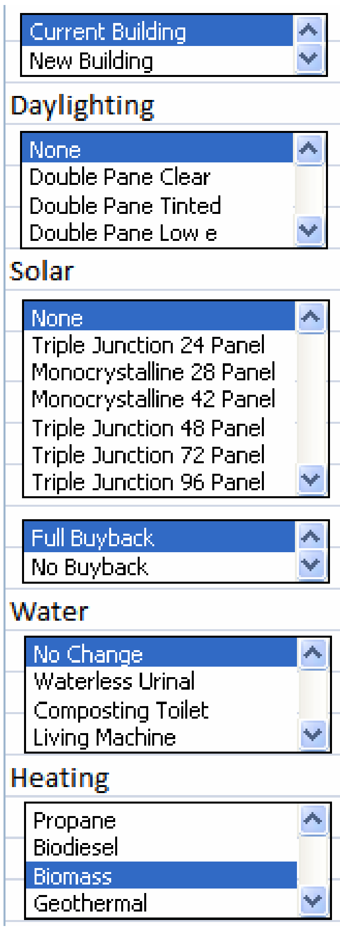
3.3 Decision Tool Description

The decision making model created for the HC takes the form of an MS Excel workbook, as Excel has the capabilities to perform all necessary calculations and also is common enough that most people are familiar with it. The model contains one tab on which users can select alternatives, change parameters, and view results, as well as several other tabs which hold the relevant data for various calculations. The model output is a numerical and graphical display of the metrics associated with a selected alternative set, including the annualized values of financial cost, carbon emissions, and overall environmentally-adjusted cost.

3.3.1 Decision Tool Inputs

The inputs to the model are twofold. The user is required to point and click on selection boxes which hold the various alternatives under each category of alternatives. They must first select whether they will be considering the current building or a new building, and then select the desired daylighting, solar (with or without buyback), wastewater, and heating options. Having selected these inputs, they also have the opportunity to change any of the many parameters used in performing the calculations. These parameters include items such as the annual utility use of the HC, which is set at a default of 12,432 kWh of electricity, 933.7 gallons of propane, and 40,050 gallons of water (based on analysis of utility bills). The prices of utility items are included as well, with electricity priced at \$0.14/kWh and propane at \$1.98/gallon. Also included are HC determined parameters, including the marginal cost of damage due to CO_2 emissions, the costs associated with water use, and the discount rate. Finally, assumptions were made regarding some parameters for which exact data was unavailable. For instance, the heat savings from use of the living machine was estimated at 23% of total heat use. These assumed values can be changed by the user. A complete view of the selection menus and parameters available to the user are displayed in Figure 2.

Selection Menus:



Parameters:

Parameters	
Prices	
Price Electricity ($/kWh)	0.14
Price Propane ($/gallon)	1.98
Price Biodiesel ($/gallon)	3
Price Biomass ($/ton)	108.57
Utility Cost/1000 gal H2O	3
Utility Use	
Yearly Electricity Use (kWh)	12432
Yearly Propane Use (gal)	933.7
Yearly Water Use (gal)	40050
HC Selected Values	
Env Cost/1000 gal H2O	3
Env Cost/ton CO2 emitted	183
MARR (%)	0.03
Assumed Values	
Reconstruction Cost ($/ft^2)	5
Daylight Elec Svg (Current)	0.1
Daylight Elec Svg (New)	0.15
Daylight Heat Savings (Clear)	0.01
Daylight Heat Savings (Tint)	0.02
Daylight Heat Savings (Low e)	0.03
Heat Savings from Liv Mach.	0.23
lbs CO2/kWh	1.34
ton CO2/kWh	0.00067

Figure 2 - Selection menus and parameters

3.3.2 Decision Tool Calculations

As the user makes changes to the set of selected alternatives and the relevant parameters, the model constantly recalculates and updates the output displayed. For each technology, we calculate the annualized financial costs. These costs include the initial investment required, recurring operation and maintenance costs for the life of the technology, and the cost of disposal at the end of the useful life. All costs are discounted appropriately using the specified discount rate to give an equivalent annual cost. The values used for the various technologies are displayed in Table 3 through Table 6.

	Solar					
	Mono-crystalline		Triple-Junction			
Number of Panels	28	42	24	48	72	96
Initial System Price	$31,359	$47,092	$18,800	$37,600	$56,400	$75,200
Installation	$840	$1,260	$720	$1,440	$2,160	$2,880
O&M Cost (per year)	$747	$1,120	$640	$1,280	$1,920	$2,560
Inverter Cost	$2,221	$2,221	$1,898	$1,898	$1,898	$1,898
Disposal Cost	$201	$301	$172	$344	$516	$688

Table 3 – Costs associated with solar technologies

			Daylighting	
		Double Pane Clear	Double Pane Tinted	Double Pane Low-e
Current building	Total Windows Cost	$19,375.00	$23,050.00	$26,725.00
	Total Lights Cost	$5,000.00	$5,000.00	$5,000.00
	Total Sensors Cost	$780.00	$780.00	$780.00
New buidling	Total Windows Cost	$13,920.00	$17,025.00	$20,130.00
	Total Lights Cost	$10,000.00	$10,000.00	$10,000.00
	Total Sensors Cost	$1,560.00	$1,560.00	$1,560.00

Table 4 - Costs associated with daylighting technologies

	Water			
	Town Water	Water Free Urinal	Composting Toilet	Living Machine
Initial Cost	$0.00	$377.94	$2,753.00	$10,814.89
Ann. Maint. Cost	$0.00	$75.82	$53.33	$300.00
Disposal Cost	$5.54	$5.54	$6.42	$205.40

Table 5 - Costs associated with water use technologies

	Heating			
	Propane	Biodiesel	Biomass	Geothermal
Initial Cost	$1000.00	$3,500.00	$3,500.00	$18,500.00
Ann. O&M Cost	$0.00	$0.00	$1,000.00	$0.00
Disposal Cost	$55.37	$55.37	$55.37	$2,768.38

Table 6 - Costs associated with heating technologies

The calculations performed by the model function in the following way. First, the total number of kilowatt hours (kWhs) of electricity and British thermal units (Btus) of heat required for the center are calculated from the parameters as follows. The amount of electricity that must come from the grid can be reduced through use of either daylighting or solar options. Thus, if the user has made a daylighting or solar selection, then utility electricity usage is reduced by the appropriate amount. Similarly, the amount of electricity required is increased by the geothermal option. The amount of heat required to be generated by the selected heating method can be impacted by the selection of one of the daylighting options or the living machine water option. If one or both of these is selected, the heat generation required is reduced appropriately. This process is illustrated in

Table 7 for an alternative set including double pane clear daylighting, a 24 panel triple junction solar array, and the living machine in the current building.

Electricity	
Total Electricity Needed (kWh/yr):	12,432.0
Need reduced by Daylighting (10% svgs):	-1,243.2
Electricity provided by Solar Selection (kWh):	-5,751.6
Remaining electricity provided by grid (kWh):	5,437.2
Heat	
Total Heat Needed (Btu/yr):	85,900,400
Need reduced by Daylighting (1% svgs):	-859,004
Need reduced by Living Mach (23% svgs):	-19,559,521
Heat requirement (Btu/yr):	65,481,875

Table 7 – Example of electricity and heat requirement calculation

The amount of fuel needed for the selected heating option to produce the required amount of heat is then calculated based on the number of Btus contained in the specific fuel type. For instance, biodiesel contains 121,000 Btu/gallon. Thus, for the above example, 65,481,874.92 Btu/yr divided by 121,000 Btu/gallon biodiesel yields an annual need for 541.17 gallons of biodiesel per year. The amount of CO_2 released through the use of electricity and heat is then calculated, as is the amount of water used given the selected water option. These values are used to calculate the environmental cost of a given alternative set. All costs associated with the selected alternative set are totaled and expressed in terms of an annual cost as detailed in the next section.

3.3.3 Model Output

The outputs of the model are both numerical and graphical. The annualized financial cost for each alternative is displayed, and all annualized financial costs are totaled to yield the total annualized cost of the selected alternative set. The utility use and associated environmental costs are also displayed and totaled, showing the user how many tons of CO_2 and gallons of water they will be using, and what the overall annual cost is for this use. The educational values of selected alternatives are displayed as well, though for our analysis these are all set to zero. The total preference-adjusted annual cost of the selected alternative set is then displayed, combining the financial, environmental, and educational costs. The numerical display seen by the user given a selection of the current building, no daylighting, no solar, town water, and biomass heating is shown in Table 8.

	Daylighting	Electricity	Water	Heating	**Total**
Ann. Fin. Cost	$0.00	$1,740.48	$120.52	$1,998.97	**$3,859.97**
		Electricity	Water	Heating	
Utility Use		12,432 kWh	40,050 gal	85,900,400 Btu	
Fuel Used				7 ton biomass	
Tons CO_2		8.33		1.69	**10.02**
Ann. Env. Cost		$1,524.29	$120.15	$310.00	**$1,954.44**
Ann. Ed. Value	$0.00	$0.00	$0.00	$0.00	**$0.00**
				Total Annual Cost	**$5,814.41**

Table 8 - Numerical output of decision tool

Here we see that the annualized financial cost of all selected alternatives is $3,859.97. We can also see that 8.33 tons of CO_2 will be emitted from electricity use, and 1.69 tons from heat use, for a total of 10.02 tons of CO_2 emitted per year. This translates to an additional annual cost of environmental damages of $1,954.44. Thus the total annualized cost of the alternative set above is calculated to be $3,859.97 + $1,954.44 = $5,814.41.

The model allowed us to find the set of alternatives for the default parameter settings that has the lowest preference-adjusted cost (including financial, environmental, and educational cost valuations). We define this set as the Optimal set. Holding all parameters at their default values, this set of alternatives is the optimal choice for the HC. The Optimal set for the current building is comprised of no daylighting, no solar array, town water, and a biomass heater, as indicated in

Table 9. It is important to note that even under the assumption of carbon neutrality for biomass this set remains preferred. The Optimal set has an annual financial cost of \$3,859.97, a total preference-adjusted annual cost of \$5,814.41, and releases 10.02 tons of CO_2 per year. The Optimal set for the new building has an annual financial cost of \$4,885.27, a total preference-adjusted annual cost of \$7,590.26, and releases 14.13 tons of CO_2 per year. For comparison purposes, we also consider a Low Carbon set of alternatives. This set has higher overall costs but very low emissions. Finally, we compare these two sets with the Status Quo set, which includes only the alternatives that the HC currently has in place.

Table 9 displays the alternatives that make up each of these sets for both the current building and a new building.

	Current Building		New Building		
	Optimal	**Low Carbon**	**Optimal**	**Low Carbon**	**Status Quo**
Daylighting	No Daylighting	Double Pane Clear	No Daylighting	Double Pane Clear	No Daylighting
Solar	No Solar	Triple-Junction 48 Full Buyback	No Solar	Triple-Junction 72 Full Buyback	No Solar
Wastewater	Town Water	Living Machine	Town Water	Living Machine	Town Water
Heating	Biomass	Biomass	Biomass	Biomass	Propane

Table 9 - Alternative sets

Having established these three distinct sets of alternatives, we designed a graphical display which would allow these three sets to be compared directly with a user-selected set. This was done with a simple bar graph, with three bars for each set. The left hand bar represents the financial cost of the set, the middle bar represents the preference adjusted cost of the set, and the right hand bar represents the tons of CO_2 released by the set (as measured on the right hand axis). Four alternative sets are displayed on the graph: the Status Quo, Optimal, and Low Carbon sets, as well as the set the user has currently selected. This User Selection set of bars will change as the user changes her selected technologies. Any change made by the user to the parameters of the model will be reflected in all four of the displayed alternative sets. Figure 3 displays the Current, Optimal, and Low Carbon alternative sets for the construction of a new building. The User Selection in this instance is an alternative set comprised of double pane clear daylighting, a 28 panel monocrystalline solar array with buyback, town water, and biomass heating. Note that this alternative set has a lower total preference-adjusted cost than the status quo and much lower carbon emissions, but higher financial cost.

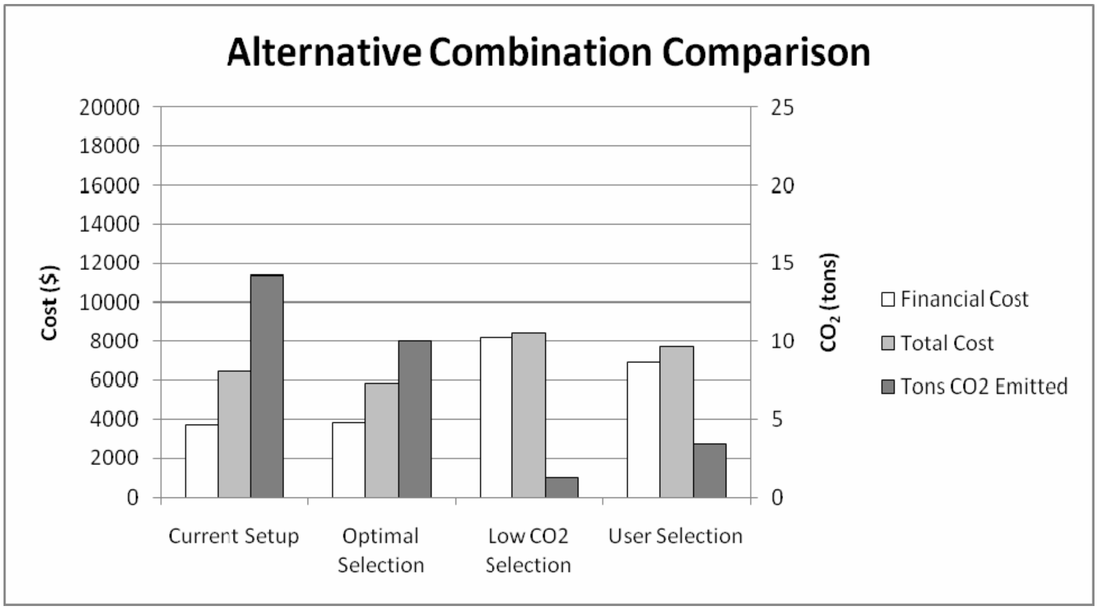


Figure 3 - Sample of graphical model output

3.4 Sensitivity Analysis

The calculations above are based on both student-collected data as well as assumptions made regarding performance characteristics of a technology when concrete data was unavailable. Thus, it is unlikely that the values entering into our calculations are precisely correct. We therefore perform a sensitivity analysis to further investigate the impact of our values and assumptions.

3.4.1 Tornado Diagrams

As a first step in performing a sensitivity analysis we constructed tornado diagrams. To construct a tornado diagram, we first must make an estimate of high and low values for all parameters deemed important. These estimates are then plugged into the model, and the resulting costs are calculated. The diagram is formed by plotting horizontal bars showing the total cost as the parameter ranges from its minimum value to its maximum value. The bars are arranged from largest to smallest, giving the overall chart a tornado-like appearance (Clemen and Reilly 2001). The minimum and maximum values used for the parameters can be found in Appendix A. Tornado diagrams give a good means of understanding to which parameters a given set of alternatives is the most sensitive.

Tornado diagrams were created for four sets of alternatives: the Low Carbon set in both the current and new buildings, and the Optimal set in both the current and new buildings. Figure 4 shows the Low Carbon and Optimal sets for the current building.

We see that the Low Carbon – Current Building set of alternatives is most sensitive to the value selected for the discount rate, the estimated reconstruction cost for daylighting implementation, and several parameters related to electricity (the annual use, as well as the number of hours per day and kW produced for the triple junction solar panels). It is least sensitive to the price of electricity, the cost of the solar panels, the electricity and heat savings estimated for daylighting, and the parameters associated with water. For the new building, the most and least sensitive parameters are identical to that for the current building, with the exception of reconstruction cost, which is not applicable to the new building.

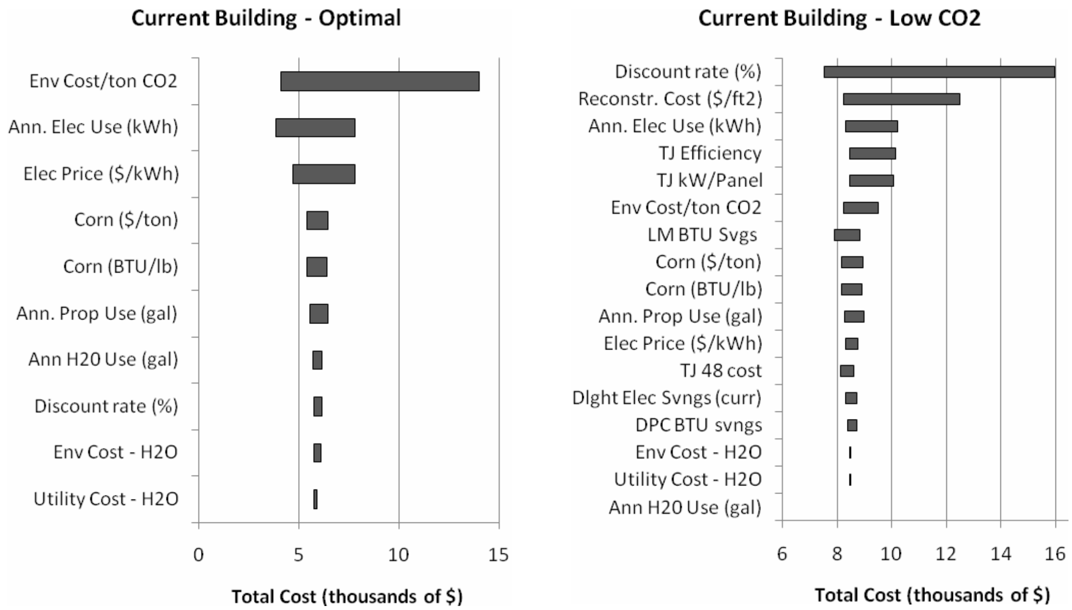


Figure 4 - Tornado diagrams for the Low Carbon and Optimal sets

Examining the Optimal set of alternatives for the current building shows a distinct change in which parameters yield the most sensitivity. As we can see in Figure 4, the most significant parameter for this alternative set is the cost associated with emitting carbon, a value chosen by the Hitchcock Center building committee. This is followed by two parameters dealing with electricity: the amount used and the price. Once again, the costs associated with water use are the least sensitive. It is also interesting to note that the discount rate, which was quite significant for the low carbon set, is now much less sensitive. This results from the fact that the low carbon set required investment in expensive solar panel technology, and thus changing the discount rate caused a significant effect in the time valuation of this option. The tornado diagram for the Optimal set in the new building yielded nearly identical results to that of the current building, and has therefore been omitted.

3.4.2 One Dimensional Analysis

Having gained an understanding of which parameters have the most power to significantly change the overall result of the model, we can now perform a more in-depth examination of these parameters. To perform this sensitivity analysis, we took individual parameters and graphed the change in overall cost to the HC resulting from a change in each parameter for several alternative sets (Clemen and Reilly 2001). We will discuss the insights gained from these graphs and the points at which one set of alternatives becomes less costly than another as a result of our changing parameter. The parameters we consider are the discount rate, the marginal damages from climate change, the amount of electricity used, the prices of electricity and biodiesel, the biomass maintenance cost, the heat savings from the living machine, and the electricity savings from daylighting. Reconstruction cost for daylighting in the current building is not considered, as alternative sets with daylighting were found to be suboptimal even when the reconstruction cost was set to a minimum of zero. In each case we consider the Optimal, Low Carbon, and Status Quo, as well as a Mid Cost/Mid Carbon sets of alternatives. The Mid Cost/Mid Carbon set will vary as we investigate different parameters.

We varied the discount rate from a minimum of 0.01 to a maximum of 0.15; and the amount of electricity used from a low of 5,000 kWh to a high of 20,000 kWh; and found in both cases that the Optimal set was always preferred.

We range the price of electricity from \$0.05/kWh to \$0.30/kWh. For the current building, the Mid Cost/Mid Carbon set included a 42 panel monocrystalline solar array; for the new building, the Mid Cost/Mid Carbon set included a 28 panel monocrystalline solar array and the living machine. These particular sets were chosen as they are optimal over some range of electricity price.

For the current building, the Optimal set is best up to a price of electricity of $0.23/kWh. At higher prices, a switch to solar becomes a more efficient choice. In the new building, an interesting interaction occurs when the price of electricity is very high. We see that should the price of electricity approach $0.30/kWh, the HC would be indifferent among the Optimal, Mid Cost/Mid Carbon, and the Low Carbon sets of alternatives.

In order to examine senstivity to the cost of biodiesel, we consider two alternative sets which are identical to the Optimal and Low Carbon sets except that they use biodiesel as the heating option. In the current and new buildings, we see that while the price of biodiesel remains below approximately $2.50 or $2.25 per gallon, respectively, the Optimal (biodiesel) set is preferable. After this point is reached, biomass provides the lowest overall cost. This would represent a significant decrease in price from the current cost of $3/gallon for biodiesel.

The Optimal alternative set recommends the use of biomass heating. Biomass is the only heating option that has a significant maintenance cost attached (i.e., the requirement that someone keep the heater stocked with corn or wood). To examine sensitivity to this maintenance cost we vary this from $500 up to $2500, around a baseline of $1000. We found that the breakeven point between biomass and biodiesel occurs when the maintenance cost is $1,300 in the current building, or $1,900 in the new building. Since $1,300 is quite close to the initial $1,000 assumption, we must therefore consider the maintenance cost to be an important uncertain parameter for the current building.

The use of the Living Machine is recommended as part of the Low Carbon set. One of the assumed benefits of the Living Machine is the ability to capture some of the heat generated by the greenhouse for use in heating the HC. The baseline estimate for the percentage of heat savings due to the living machine is 23%. We vary this savings from a low of -10% (that is, a 10% heat loss) to a high of 80%. In this comparison we consider an alternative that is the same as the Optimal set except the living machine is used instead of the town water option. In the current building, the Optimal set is preferable until the heat savings provided by the living machine reach 75%, at which point switching to the living machine provides a lower cost. In the new building, the Optimal set is preferable until the heat savings reach 55%. Thus, we see that the HC should only consider the living machine as viable if it believes it can gain a significant level of heat savings from using it.

The use of daylighting is recommended as part of the Low Carbon set. We vary the electricity savings from use of daylighting from 0% to 70% to explore the conditions under which use of daylighting might be economically optimal. We consider an alternative that includes double pane clear windows. In the current facility, the Optimal set is best until the electricity savings from daylighting reach about 45%, at which point daylighting becomes preferred. For the new building, the point of intersection occurs at an electricity savings of only 22%. This makes sense, as implementation of daylighting in the current building includes an additional reconstruction fee not present in the new building. The value of 22% is very close to our baseline assumption of 15%, and within the range of estimates for electricity savings, leading us to conclude that in the new building only a small increase in electricity savings will make the use of daylighting optimal.

The marginal cost of damage due to emitting a ton of CO_2 is a value that was set by the building committee at \$183/ton CO_2.

Figure 5 shows how changing this parameter's value affects the total cost of four sets of alternatives: Optimal, Low Carbon, Mid Cost/Mid Carbon, and the Status Quo. We will vary the marginal cost from a low of \$10/ton to a high of \$1000/ton.

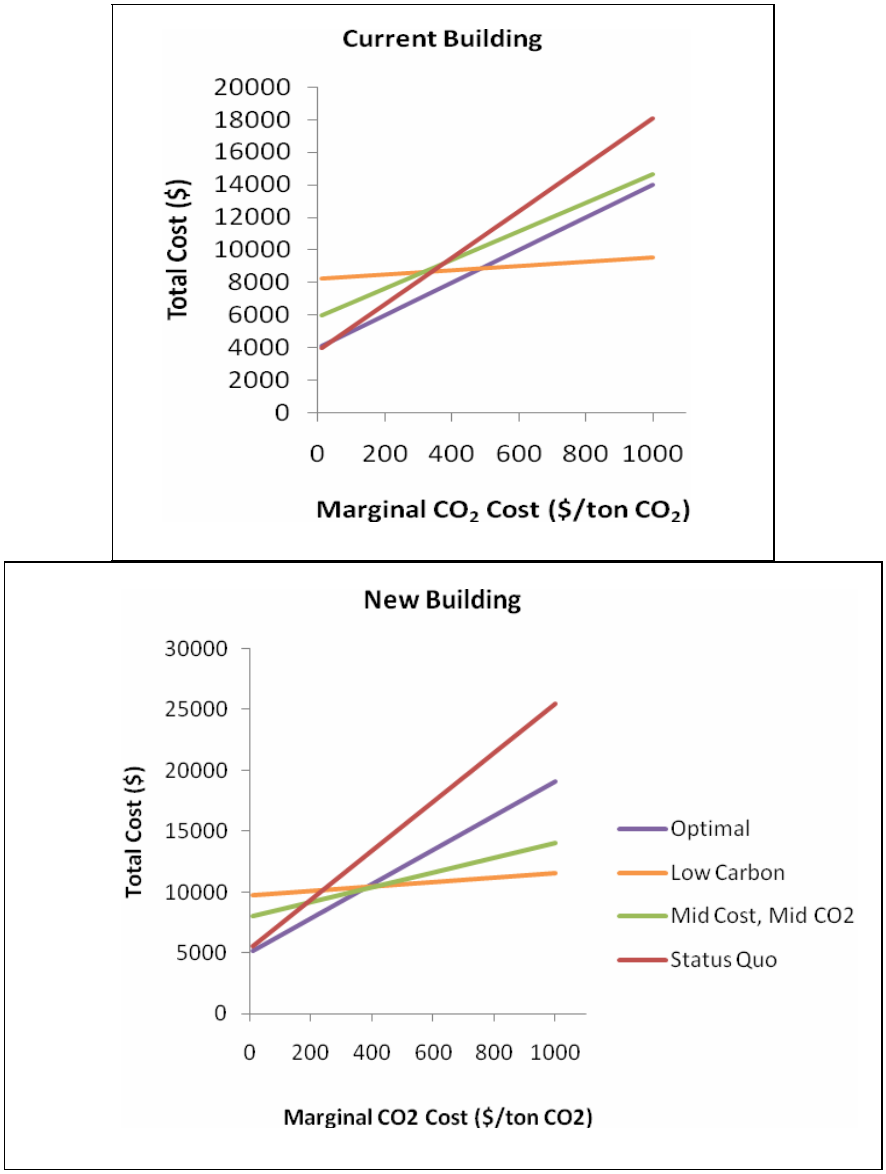


Figure 5 - Marginal cost of carbon damages sensitivity analysis

Here we see a great deal of interaction among the alternative sets. In the current building, the Status Quo and Optimal sets are equivalent at low values of the marginal cost (MC = $10/ton). The Optimal option provides the lowest cost from MC = $10/ton to MC = $500/ton. For values greater than $500/ton, the Low Carbon set provides the lowest cost. In the new building, the Optimal set provides the lowest total cost up to a valuation of about $425/ton, at which point the Low Carbon set becomes preferable. The Mid Cost/Mid Carbon set is never the least costly, but is quite close between MC = $250 and MC = $600. Thus we see that placing a higher financial emphasis on carbon emissions can seriously impact which alternative set is more desireable.

The marginal cost of carbon emission damages is an interesting parameter. This value reflects in part the values of the HC and its beliefs regarding the severity of the damage done by emitting greenhouse gases. It is also a representation of what the scientific community has concluded regarding the impact of these emissions. Thus, there is currently uncertainty surrounding the true value of this parameter. Note that in the future, when CO_2 emissions become regulated, it will be possible to put an exact value on this parameter, regardless of a decision makers' preferences over the environment.

3.5 Expected Value of Perfect Information

In this section we calculate the expected value of perfect information regarding certain key parameters. The expected value of perfect information is the difference between the expected value of costs of the alternative sets we would select given perfect information about our parameters and the cost of the alternative set we would select given no new information (Clemen and Reilly 2001). For these initial calculations we use our best guesses for the probabilities. We have built the EVPI ability into the tool, so that the HC can explore the EVPI using their own probabilities, and explore how the values change with different probabilities.

Table 10 displays the EVPI for several parameters. We can see that the HC should have the highest willingness to pay to further investigate the biomass maintenance cost and the future biodiesel price (in the current building), and the electricity savings from daylighting (in the new building). We should also note that the parameters above can be divided into two categories: those which are within the HC's power to discover (biomass maintenance cost, living machine Btu reduction, electricity use) and those that are subject to market fluctuations (biodiesel price, electricity price). As the biomass maintenance cost is somewhat within the control of the HC, we could interpret this value of $3,730 as the maximum that might be paid to guarantee maintenance costs for the life of the biomass heater. For instance, signing a maintenance contract for $214.25 per year or less would make sense. This contract would guarantee that the costs associated with stocking the heater with fuel and keeping it in good running condition would never exceed $1000 per year, but would not include the cost of the fuel itself. Given such a contract, the HC would opt to install a biomass heater, and would have hedged against higher-than-expected maintenance costs. If we assume that biomass is in fact carbon neutral, we find that the preference-adjusted cost of biomass is even lower than in our initial analysis. This, in turn, leads to a significant increase in the EVPI of biomass maintenance in both the current and new buildings.

EVPI (NPV)	Current Building	New Building
Biomass Maintenance Cost	$3,730.80	$762.29
Biodiesel Price	$3,298.60	$2,196.71
Electricity Price	$1,123.28	$1,536.92
Liv Mach Btu Reduction	$676.55	$1,276.52
Daylighting Elec Svgs	$461.05	$3,349.48
Electricity Use	$0.03	$222.37

Table 10 - EVPI for several parameters (present value)

In the event a new building is constructed, we see that it would be worth paying a consultant up to $1,277 for information regarding heat that might be captured from installation of the living machine. As shown in the sensitivity analysis above, the specific value of heat savings is not essential. Simply knowing that a minimum of 55% of required heat in the new building could be provided by the living machine would be enough to know that the implementation of the living machine provides the lowest cost. However, the heating option that will provide minimal cost in conjunction with the living machine depends on the exact value of the heat savings. We also see a significant EVPI associated with the electricity savings that can be gained from daylighting in the new building. The HC should be willing to pay a maximum of $3,349.48 to an expert to perform analysis of their proposed building site and provide a value for the percentage electricity savings they could reap from use of daylighting.

Regarding those parameters subject to market prices, one potential tactic for mitigating risk would be the purchase of a futures contract that would guarantee the commodity at a future date at a given price. Unfortunately for the HC, the futures market for biodiesel does not yet exist, and electricity futures are not available for the small quantities of electricity used by the center (Tanlapco, Lawarree et al. 2002). Thus, we must think of the EVPI values for these two parameters as the amount worth paying a well-informed expert for information. As we can see, there is very little value attached to better information regarding the center's electricity use. There is a high value attached to EVPI on the price of biodiesel, and this EVPI increases under the assumption of carbon neutrality for biomass. It is also worth noting that these values represent the willingness to pay for perfect information, so actual values for less than perfect information will be less than those presented here.

One point of interest with regard to
Table 10 is the distinct differences in values for certain parameters between the current and new buildings. The EVPI for the biomass maintenance cost in the current building, for example, is more than five times the EVPI for the new building. This results from the fact that the current building has a lower heating requirement than the new building. Thus, as the cost of maintenance associated with biomass increases it quickly becomes desirable to switch to biodiesel in the current building, while biomass remains favorable in the new building until the maintenance cost reaches a very high value ($2000/year). Thus, the savings reaped from an early switch from biomass to biodiesel in the current building yield a much higher EVPI of the cost of biomass maintenance. A similar effect is seen with regard to the EVPI of the heat savings resulting from use of the living machine in the current building as opposed to the new building. In this case, we see that it is more valuable to obtain perfect information regarding the heat savings in the new building rather than the current building. This makes sense, because the new building has a larger heating load than the current building. Thus, knowledge of heat savings will

impact the decision to invest in either of the two generally desirable heating options (biomass and biodiesel), and thus will have a more significant impact on overall costs.

3.6 Conclusion

In this paper we discuss the process of developing a decision making model to support investment choices in green energy technologies. Based on the metrics of environmental sustainability, educational applicability, and cost, student researchers gathered data in four areas of technology suited to the Hitchcock Center's goals. This research was consolidated into an Excel based decision tool, which allows users to select different technologies and view the resulting costs and impacts. Using the tool we were able to find the lowest cost alternative set, which included no daylighting, no solar array, town water, and the installation of a biomass heater, yielding a preference-adjusted annual cost of $5,814.41. We also performed sensitivity analysis, showing how the optimal choices will change with changing parameters, and an EVPI analysis, which yielded key valuations of perfect information of $3,730 for biomass maintenance in the current building and $1,277 for heat savings from the living machine in the new building. A key point of interest regarding the model is that our recommendation to the HC (the Optimal set) does not reflect the stated desires of the HC building committee. The committee is very excited to implement as many green energy technologies as possible, and yet our model suggests that they should only pursue the installation of a biomass heater. One potential reason for this discrepancy between their desires and the model's output is the lack of an educational value for each of the alternatives. Once the HC staff has placed a dollar amount on the educational value of each alternative, they may find some of the other green technologies becoming more attractive, particularly the Living Machine. Another possible interpretation of this situation is that the HC truly places a higher value on the cost of environmental damages due to emissions than they reported in our initial elicitation. A higher cost associated with environmental damages would cause green technologies to appear more favorable in the model. Finally, perhaps there are additional metrics that should be associated with the technologies in order to reflect the HC's true beliefs. On the other hand, it may simply reflect the fact that the benefits from the green technologies considered don't outweigh their costs when carefully evaluated.

This collaborative process has educational value for the undergraduate students and for members of the HC community. The students gained perspective from participating in a real project, including the difficulties in finding data and in choosing preference parameters such as the discount rate. They were introduced to the concepts of value-focused thinking and multi-objective DA as they implemented the HC's valuation of CO_2 reduction. Moreover, the students got involved in the community, learning about a local non-profit and ways in which engineering professionals can contribute to the greater good.

Members of the HC community were very interested in process. Most of the people we worked with had no exposure to quantitative-based decision making. They found the process of choosing CO_2 valuation daunting but illuminating. They are very interested in making the decision tool and the process of preference elicitation part of their educational arsenal – they want to help people make better decisions about green technologies.

This chapter has presented our Decision Analysis paper concerning the creation of a decision tool for the Hitchcock Center. We utilize many of the technologies and presentation methods created for this tool in our PVSN tool. Specifically, we include some of the same technologies (solar, heating, and daylighting), as well as present the user with a visual comparison of metrics for both their current setup and their potential implementation of green technology.

4 COST MINIMIZATION APPROACH WITH CHP

In this chapter we present another, separate decision making tool which plays a role in the development of the PVSN tool. This tool differs from the HC tool discussed in Chapter 3 in several ways. In particular, we detail the development of a new green energy alternative (combined heat and power), as well as the expansion of our treatment of an existing one (solar photovoltaics). Federal and state rebates and incentives for green energy are included, along with emissions reduction incentives. Moreover, the model presented in this chapter functions as an *optimization* model, as compared with the evaluation model presented in the previous chapter. The model can, however, allow the user to compare between specific alternatives. Cost is the sole metric output by this model. Many of the concepts developed in this chapter are relevant to the PVSN tool.

The technologies we examine in this chapter are solar photovoltaic systems and combined heat and power systems. These two technologies are well established as green technologies, with combined heat and power having existed in one form or another for many years, and solar power being relatively new to the market. Our modeling approach is from a cost minimization standpoint. When assessing these technologies we consider factors such as initial investment, lifetime costs, and carbon emissions in our analysis. We incorporate uncertainty regarding the future prices of key fuels used by combined heat and power technologies, and include federal, state, and local financial incentives applicable for the technologies. A final concern is the cost associated with environmentally harmful emissions, specifically the greenhouse gas CO_2. Our model takes the form of an Excel spreadsheet, which will accept multiple user inputs and provide an alternative set that provides the lowest cost. Through this analysis, we hope to arrive at insights regarding the conditions under which one alternative set is more attractive than another. We also will perform a sensitivity analysis to gauge which of our assumptions have the most significant impact on our final results. These assumptions will be examined further to determine the point at which the optimal alternative set changes.

4.1 Combined Heat and Power Overview

Combined heat and power (CHP) systems are those which generate both heat and electrical power from a single fuel source. This cogeneration is generally accomplished by capturing heat produced from the electricity generation process and converting it to a useful form. While CHP systems rely on the combustion of fossil fuels to create both heat and power, they require significantly less fuel to produce a given energy output. Their efficiency is further enhanced by their onsite location, reducing losses due to transmission. The lower fuel use in turn reduces emissions produced for a given level of energy output. In our model, we will consider five categories of CHP systems: steam turbines, reciprocating engines, gas turbines, microturbines, and fuel cells. While not comprehensive, this listing does cover the majority of CHP systems currently marketed. We will consider several different systems within each of these five categories.

Steam turbines are the oldest of CHP technologies, having been used for the past 100 years (Energy Nexus Group 2002). Unlike other CHP technologies, they generate electricity as a byproduct of heat, instead of vice versa. Steam turbines rely on a boiler to generate heat, and high pressure steam from the boiler is transferred to a turbine for electricity generation. Steam turbines are available in a variety of capacities, but are generally found in larger generating scenarios (> 500kW). They run on most fuels.

Reciprocating engines are a common form of power generation, found in our society everywhere from cars to power plants (Energy Nexus Group 2002). We focus purely on spark ignition internal combustion engines, rather than compression ignition (diesel) engines. These engines can be modified to run on a variety of fuels, including natural gas, propane, and oil. The capacities of these engines also vary greatly. We will look at three systems, with capacities of 100, 300, and 800 kW.

Gas turbines are the predominant choice for new power provider installations in the US (Energy Nexus Group 2002). System capacities are generally quite large, beginning at 500kW and ranging up to 250 MW. Gas turbines are also known for having in general the lowest emissions of any fossil fuel burning technology. As with the technologies mentioned above, they can run on natural gas, propane, and oil. In our analysis, we will look at gas turbines with capacities of 1, 5, and 10 MW.

Microturbines are relatively new technology, having become available commercially in 2000 (Energy Nexus Group 2002). These small electricity generators burn gaseous or liquid fuels, creating high speed rotation that results in electricity. They are generally available in capacities from 30 to 350 kW. We will examine 3 possible microturbine systems, with capacities of 70, 100, and 350 kW.

Fuel cells are by far the newest and least well tested of the technologies under consideration (Energy Nexus Group 2002). They use an electrochemical process to generate electricity, taking in hydrogen as fuel, combining it with oxygen to form water, and producing electricity in the process. The hydrogen fuel is typically generated from a hydrocarbon, like natural gas. The emissions from fuel cells are very low, as the only combustion required comes from reforming the natural gas to generate the required hydrogen. We will examine two possible fuel cell systems, with capacities of 200 and 2000 kW.

A complete set of the data collected for CHP technologies is available in Appendix B.

4.2 Photovoltaic Technology Overview

While photovoltaic systems were examined as part of the HC tool, in this section we expand the scope of the PV technologies that we will consider.

PV cells are normally fabricated using special semiconductor materials that allow electrons, which are energized when the material is exposed to sunlight, to be freed from their atoms. Once freed, they can move through the material and carry an electric current. Most PV cells in use today are silicon-based. Cells made of other materials are expected to surpass silicon-based cells in performance and cost in the future.

The PV cells that we intend to analyze are primarily silicon based PV cells. Silicon PV cells are available in the following four types: monocrystalline, multicrystalline, ribbon silicon and thin film concentrator silicon cells. Monocrystalline PV cells are made from a single cylindrical crystal of silicon. These cells have a uniform molecular structure and thus have a high efficiency (the ratio of electric power produced to the amount of sunlight available). The monocrystalline PV cells have a complicated manufacturing process and as such have a higher cost as compared to other silicon based PV cells. Multicrystalline cells are made from ingots of melted and re crystallized silicon. Multicrystalline have a simple manufacturing process and hence have a lower cost. The efficiency of the multicrystalline is less than that of the monocrystalline PV cells.

Crystalline silicon cells are mainly used by producing wafers of silicon which are obtained by cutting silicon crystals using a saw. During wafer production, a significant amount of valuable silicon is lost as sawing slurry. Ribbon sheet technology represents an alternative approach. This avoids sawing loss by producing thin crystalline silicon layers using a range of techniques, such as pulling thin layers from the melt, or melting powdered silicon into a substrate. As sawing procedures, and the material losses linked to them, are avoided, the required silicon per watt of capacity can be reduced significantly.

Concentrator cells work by focusing light on to a small area using optic concentrating devices. The small area can then be equipped with silicon or non-silicon materials like gallium arsenide to form semi conductor junctions. The two main drawbacks with concentrator systems are that they cannot make use of diffuse sunlight and must always be directed very precisely towards the sun with a tracking system. In addition, the cost of gallium arsenide cells is high. However, they do have the advantage of high efficiency.

Amorphous silicon cells are composed of silicon atoms in a thin homogenous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon, so the cells can be thinner. For this reason, amorphous silicon is also known as a "thin film" PV technology. Amorphous cells are, however, less efficient than crystalline based cells, with efficiency almost half of that of the crystalline cells. Also, the efficiency degrades much faster than that of the other silicon PV cells. They have a low manufacturing cost.

A number of other promising materials such as cadmium telluride and copper indium diselenide are now being used for PV modules. These technologies fall into the thin film category, and a generally not considered to be commercially viable on a large scale. They have a complex manufacturing process, and contain some amount of toxicity. However, these technologies are being improved continuously, and thus we feel they should be considered.

We gathered key data for each type of PV technology for use in our model. This data includes installation cost, balance of system cost (racking, inverters, accessories), and the efficiencies of various types of PV modules. A complete data set for photovoltaic technology can be found in Appendix C (Solarbuzz LLC 2008).

4.3 Fuel Prices

One factor which will greatly influence the annual operating cost of a given CHP alternative is the price of the fuel used by the technology to generate power. To make our model more realistic, we will be using prices for fuels projected out to the year 2030. This will allow us to calculate the cost for a required amount of fuel for a given year, and then convert all of these future payments into a present valuation of costs.

The fuels we will examine are those that are common to most forms of CHP: oil, propane, and natural gas. The prices we will use are those projected by the EIA (Energy Information Administration 2008), a subdivision of the Department of Energy. These projections take into account exogenous political and economic factors, and are likely to be the more accurate of the two methods. Figure 6 displays these projections.

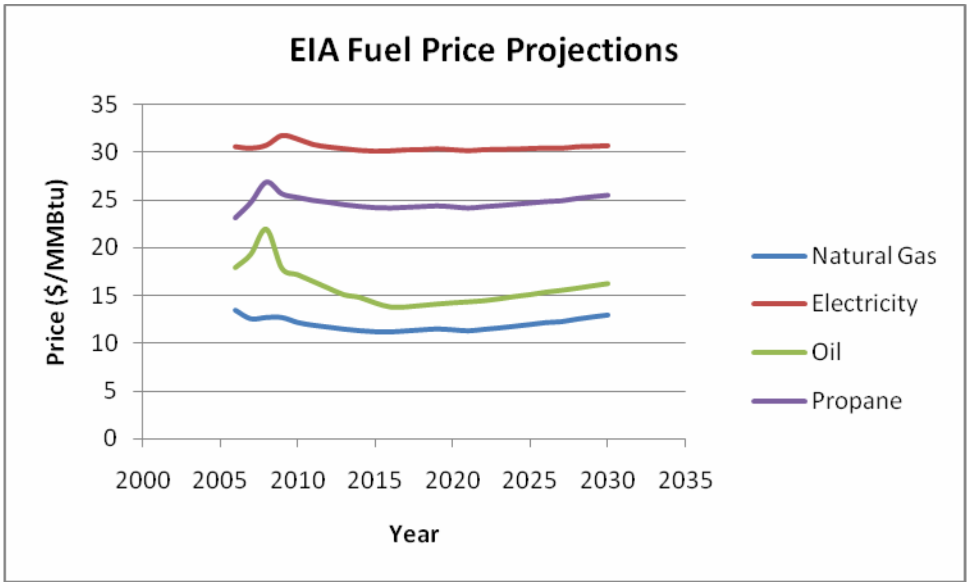


Figure 6 - EIA fuel price projections

4.4 Rebates and Incentives

The federal and state governments and local utilities offer various incentives and rebates programs to support the deployment of CHP and solar photovoltaics to various types of consumers (residential, commercial and industrial). The financial implications of various types of incentives and rebates will be discussed in the next sub-section with special reference to the solar PV market.

4.4.1 CHP Rebates

Though many states in the US offer rebates for CHP installation, no such program exists in Massachusetts. Typically, the payback period of CHP installations for large industry consumers is less than 10 years while it is more than 15-20 years for medium and small industry consumers. However, with rebates the payback period is reduced by 5-10 years which makes the technology attractive to those consumers also. We will use a dollar value as rebates for CHP installation because Connecticut offers $450/kW for CHP installation. Hence a rebate of $450/kW is considered in the calculation of the cost function.

4.4.2 Solar Rebates

While there have been marked technological developments PV technology, the cost of energy production using PV and hence the payback period remains prohibitively high. For instance, the cost of solar photovoltaics in the 1960's was an exorbitant $100/kWh.

However, the solar photovoltaic industry is growing rapidly. The International Energy Agency (2007) cites two major factors for the growth of PV market: R&D investments and financial incentives. Currently, several types of financial incentive mechanisms are used.

- Feed-in Tariffs/net metering: the electricity utility buys PV electricity from the producer under a multiyear contract at a guaranteed rate.
- Investment subsidies: the authorities refund part of the cost of installation of the system.
- Renewable Energy Certificates ("RECs")

With investment subsidies, the financial burden falls upon the taxpayers, while with feed-in tariffs the extra cost is distributed across the utilities' customer bases. While the investment subsidy may be simpler to administer, the main argument in favor of feed-in tariffs is the encouragement of quality. Investment subsidies are paid out as a function of the nameplate capacity of the installed system and are independent of its actual power yield over time, so reward overstatement of power, and tolerate poor durability and maintenance.

With feed-in tariffs, the initial financial burden falls upon the consumer. Feed-in tariffs reward the number of kilowatt-hours produced over a long period of time, but because the rate is set by the authorities they may result in perceived overpayment of the owner of the PV installation. The price paid per kWh under a feed-in tariff exceeds the price of grid electricity. "Net metering" refers to the case where the price paid by the utility is the same as the price charged, often achieved by having the electricity meter spin backwards as electricity produced by the PV installation in excess of the amount being used by the owner of the installation is fed back into the grid.

Where price setting by supply and demand is preferred, RECs can be used. In this mechanism, a renewable energy production or consumption target is set, and the consumer or producer is obliged to purchase renewable energy from whoever provides it the most competitively. The producer is paid via a REC. In principle this system delivers the cheapest renewable energy, since the lowest bidder will win. However, uncertainties about the future value of energy produced are a brake on investment in capacity, and the higher risk increases the cost of capital borrowed.

Of the incentives mentioned above, we will include state and federal installation incentives in our tool.

A list of various solar rebate programs is listed in Appendix D (NCSU 2008).

4.5 Emissions and Trading

Pollutants released through the combustion of fossil fuels, be it for electricity generation or on-site thermal energy needs, can adversely impact human health and the environment. It is also possible to derive financial benefit through the reduction of emissions via government programs, such as the EPA's emission trading program.

The emission profile will vary based upon the method used for the generation of electricity. According to ISO-New England, the electrical generating capacity in the New England states is met by approximately 28.9% Gas, 26.6% Nuclear, 12.3% Coal, 9.6% Oil/Gas, 5.1% Wood Refuse, 5% Hydro, 3.6% Oil, and 2.6% Coal/Oil. The emission factors were taken from U.S. EPA's E-GRID2000 State Data. In addition, there are emission reductions associated with on-site fuel consumption savings. The emission factors for electricity and for Natural Gas, Propane, Butane, No. 2 Oil, No. 4 Oil, and No. 6 Oil, are shown in Appendix E (EPA 2003).

Emission trading is a market-based approach the EPA has implemented to reduce overall emissions, through which industries derive financial benefit from reducing pollution. Based upon the facility's past performance, regulators give emission allowances to a facility, which in turn grants that facility the right to emit that prescribed about of a pollutant. Overall emissions are capped through the allocation of these allowances. Allowances may be sold, traded, or banked for future use. When pollution is reduced or controlled beyond what is required, an offset or Emission Reduction Credit (ERC) may be given as a reward to a facility and is based upon the amount and type of emission that is reduced. This provides an incentive to reduce emissions, as once a credit is created it can be sold on the open market for profit. Emission trading occurs when a facility reduces its emissions and then transfers ownership of the emission reduction to another party. In addition to the sale of a credit, they can also be traded or banked for future use.

4.6 Mathematical Model

This section explains the optimization model used in our tool, which centers on cost minimization. We examine all costs of choosing to implement or declining to implement a given technology to formulate our objective cost function. This function is then minimized subject to the constraints of the electricity generation requirement and heat production requirement for a given application (Varian 1992). It is important to note that this is a one period model; that is, the decision maker chooses their preferred alternative in the first period, and is allowed no choices after that. The variables used to formally define the model are as follows.

i = discount rate

t = time period

N = total periods under consideration

R_e = annual electricity requirement of facility (kWh/yr)

R_h = annual heating requirement of facility (MMBtu/yr)

U_{et} = amount of electricity provided by utility in year t (kWh/yr)

U_{ht} = amount of heat provided by utility in year t (MMBtu/yr)

E_{ct} = electricity price for year t ($/kWh)

F_{ct} = fuel price for year t ($/MMBtu)

CHP:

E_c = electricity rating of CHP technology (kW)

E_h = heat rating of CHP technology (MMBtu/hr)

I_c = install cost of CHP technology ($/kW)

M_c = maintenance cost of CHP technology ($/kWh)

FI_c = fuel input for CHP technology (MMBtu/hr)

A_c = availability of CHP technology (%)

UL_c = useful life of CHP technology

HPY_c = hours per year in year t CHP technology is running

AE_c = avoided electricity emissions

AF_c = avoided fuel use emissions

Solar:

C_s = array capacity (kW)

I_s = install cost of Solar technology ($/kW)

BOS = balance of system cost for Solar technology ($/kW)

M_s = maintenance cost of Solar technology ($/kW)

UL_s = useful life of Solar Technology

AE_s = avoided electricity emissions

Rebates:

C_{si} = CHP state incentive ($/kW)

S_{si} = solar state incentive (% of install cost)

S_{sicap} = Max payable state incentive

S_{fi} = Solar federal incentive (% of install cost)

S_{ficap} = Max payable federal incentive

Emissions:

E_p = price of tradeable permit for avoided emissions (CO_2, SO_2, NO_x) from electricity ($/kWh)

F_p = price of tradeable permit for avoided emissions (CO_2, SO_2, NO_x) from fuel use (propane, oil, or natural gas as selected) ($/MMBtu)

The model is given by the following equations:

$$(1)\quad PVCost_{CHP} = I_c E_c - C_{si} E_c + \sum_{t=0}^{UL_c} \frac{[M_c E_c HPY_c A_c + FI_c F_{ct} - AE_c E_p - AF_c F_p]}{(1+i)^t}$$

$$(2)\quad \begin{aligned} PVCost_{Solar} &= (I_s + BOS)C_s - \min(S_{si}(I_s + BOS), S_{sicap}) \\ &\quad - \min(S_{fi}(I_s + BOS), S_{ficap}) + \sum_{t=0}^{ULs} \frac{M_s C_s - AE_s E_p}{(1+i)^t} \end{aligned}$$

$$(3)\quad PVCost_{Total} = PVCost_{CHP} + PVCost_{Solar} + \sum_{t=0}^{N} \frac{U_{et} E_{ct} + U_{ft} F_{ct}}{(1+i)^t}$$

$$(4)\quad Minimize: AWCost_{total} = PVCost_{total} \left[\frac{i(1+i)^N}{(1+i)^N - 1} \right]$$

Equation (1) calculates the present value of CHP as the installation cost, minus rebates, plus the present value of yearly maintenance costs and fuel costs less the value of RECs for avoided emissions.

Equation (2) calculates the present value of solar photovoltaics as the installed cost minus any rebates or incentives plus the present value of annual maintenance costs less the value of RECs for avoided electricity emissions.

Equation (3) adds (1), (2), and the present value of annual costs associated with any excess electricity or heat which must be bought from a utility, yielding the present value of all costs associated with heat and electricity.

Equation (4) minimizes annual worth of the present value of all costs over a given time period.

Thus, we are minimizing the annual net payment that must be made to cover heating and electrical expenses. This annual net worth allows us to directly compare the costs of options with differing useful lives over the entire period under examination, N (in our case N = 23, which brings us from the present to the year 2030).

The decision variables in our model are whether to buy a CHP system, a solar array, a combination of the two, or neither. We solve this model by calculating $AWCost_{total}$ for every possible combination of CHP and solar and picking the minimum, through the iterative procedure described in the next section.

Our model is constrained by the electrical and heating requirements of the location under examination. Thus, we have constraints:

$E_h HPY_c \leq R_h$ - heat produced by CHP cannot surpasses required amount of heat

$E_c HPY_c \leq R_e$ - electricity produced by CHP cannot surpass required amount of electricity

We leave the amount of electricity produced by the solar module unconstrained. This is reasonable, as solar arrays are generally grid tied, unlike CHP systems. Thus, any electricity produced in excess of needs by a solar array will be fed back into the grid. Because net-metering laws in Massachusetts are somewhat complicated, we have excluded them from our model. This represents one limitation of our work, as any excess electricity generated by solar panels will not provide a benefit to the owner of the solar array. Another limitation is the absence of any standby charge that might be charged by the utility to a facility implementing CHP.

4.7 Model Explanation

In this section we explain the architecture and calculations of our model.

The tool we have created to solve this model takes the form of an MS Excel workbook, containing several tabs to store relevant data, perform calculations, and provide users with an interface through which to interact with the model. The model allows users to enter relevant information through the input tab. This input will include the annual electricity and heat requirements of the user, the discount rate the user wants to apply to payments made in the future, and the type of facility that is under consideration (residential, commercial, or industrial) Using these inputs, the model performs relevant calculations based on the data we have gathered and returns the alternative set that will provide the user with the lowest overall cost.

The CHP cost calculations are found on the CHP tab of the model. For each system we calculate the installed cost, the annual operation and maintenance cost, and the expected fuel cost for each of the fuels that the CHP system can run on. For most systems, this includes oil, propane, and natural gas, though for fuel cell technologies only natural gas is considered. We also calculate costs associated with downtime for each system. These calculations are tied to the availability rating of each system; when the system is not available (i.e., taken offline for maintenance), the user will be forced to meet their heating and electricity needs by buying from utilities. Here we use the selected price projection method prices to determine downtime costs, and assume that heat during downtime will be provided through use of natural gas. Combining installation cost, operations and maintenance costs (discounted to a present value), fuel costs, and downtime costs, and subtracting the benefits of reduced emissions and incentives, we arrive at a present value of costs for each technology for each type of fuel on which the technology can run.

The calculations for the photovoltaic technologies under consideration can be found on the Solar tab of the model. The costs for these technologies are all presented in terms of dollars per installed watt. The costs that we incorporate into our calculations are installation, balance of system, and annual operations and maintenance costs. The other key consideration for solar is the efficiency rating. This rating, a ratio of the energy produced by the panel to the total energy provided by the sun, is necessary to calculate the energy output of the panels. In western Massachusetts, solar panels which are perfectly oriented and have a 15% efficiency rating generally produce 1000 kWh to 1200 kWh of energy per installed kW of capacity over the course of the year. We took the average of these two values and used a value of 1100 kWh/kW at 15% efficiency in our calculations. One challenge faced with calculating solar costs is the seemingly limitless levels of installed capacity. Unlike CHP systems, which each have an installed capacity rating (be it 5 kW or 10 MW), the capacity of a solar array depends directly upon the number of panels in the array. To make this situation tractable, we discretized available array sizes to include a range of six possible selection (1, 10, 25, 100, 250, and 500 kW). We then created tables for both the present value of costs for each technology and array size, and the yearly energy output in kWh for each technology and array size. As with CHP, the present value of a given solar module can be calculated as the sum of the installation, BOS costs and the present value of maintenance costs, less the benefits of avoided emissions and government incentives.

Our treatment of PV technologies is much more thorough than in the HC tool. Here, we offer the user many different solar technologies from which to choose, whereas in the HC tool only mono- and multi-crystalline cells are available. We also separate the array size from the type of panel, giving the user the option to choose a variety of array sizes for any given technology. This represents a more realistic representation of how a consumer would purchase a solar array.

Based on the above calculations, we can use the model to quickly calculate the annual payment required for a selected set of alternatives. This value represents the annualized cost of paying for all aspects of the selected solar array, the selected CHP technology, and the utilities required to make up any difference existing between what the energy requirements are and what the selected renewable can supply. A macro for visual basic was then written which iterates through all possible combinations of alternatives for a given set of inputs (discount rate, fuel price projection method, preferred fuel type). The macro then returns the lowest possible annual cost for the user provided inputs. The user can activate this macro with the click of a button.

4.8 Results & Discussion

In this section, we discuss the results of our model for a variety of industrial users. We then present three case studies to which we applied our model, as further verification of its accuracy.

The model was run to find the optimal choice for small industry consumers. The typical electricity capacity requirements of the user is 750,000 kWh – 50,000,000 kWh and the heating requirements is 1,000 – 500,000 MMBtu. For these calculations, we used the EIA fuel price projections, natural gas as the preferred fuel, and a discount rate of 5%. Figure 7 shows the technologies recommended by the model.

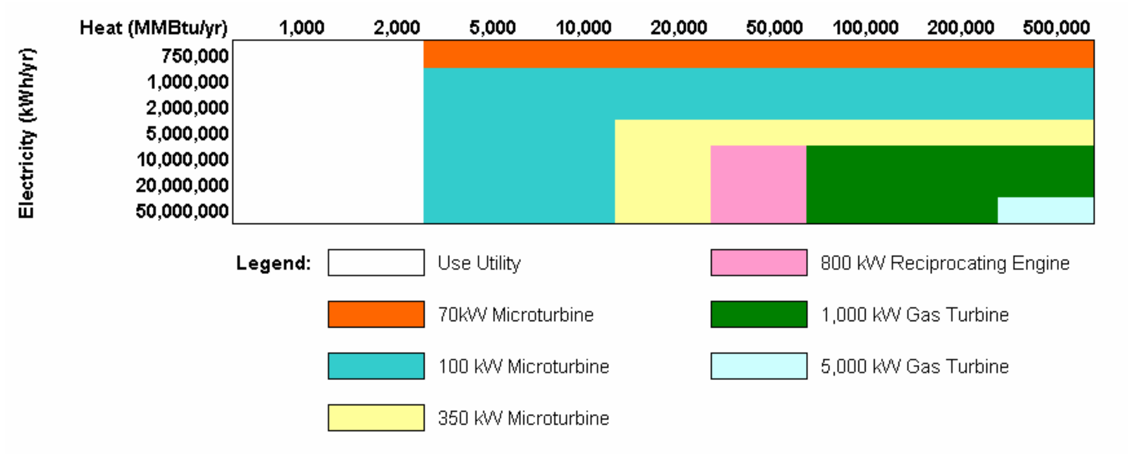


Figure 7 - Results for a Typical Small Industry User

We can gain several insights from these results. First, we see that in no case is any of the PV technology recommended. Even with rebates, incentives, and emission reductions, PV remains uneconomical. This is consistent with the findings of the tool created for the HC (although the HC tool considered non-financial metrics as well). We will explore the point at which PV becomes feasible in the sensitivity analysis. We also see that CHP technologies are recommended for all users aside from those with very low heating requirements. This indicates that in order to be economically feasible, a CHP system should be serving relatively large heat and electrical loads.

4.8.1 Case Studies

Three case studies were done to further test the model. The energy requirements of the three users are given in Table 11. The users are involved in manufacturing paper and electroplating. We chose these users because they had simultaneous heating and electricity requirements. The third column shows the model results for the three users. As expected, CHP was the predominant choice.

	Electricity (kWh/year)	Heat Requirement (MMBtu/year)	Model Recommendation
User 1	47,000,000	350,000	5000 kW Gas Turbine
User 2	10,000,000	123,000	1000 kW Gas Turbine
User 3	3,000,000	35,000	300 kW Reciprocating Engine

Table 11 - Energy Requirements of the Users

4.9 Sensitivity Analysis

In this section, we perform sensitivity analysis based on the three case studies presented in the previous section. The purpose of this analysis is to gain insight into the circumstances under which the model's output might change from one alternative to another. Parameters examined include PV technology efficiency, state and government rebates and incentives, emissions trading permit price, and PV installation cost. Our focus centers on PV technologies, with the aim of discovering the point at which PV becomes an economically viable option.

4.9.1 Change in Emissions Trading

We examined optimal selection for User 1, a paper mill, under the condition of changing emissions trading prices. Recall that under the initial model parameters the optimal technology selection for User 1 is a 5000 kW gas turbine. We varied the price of emitting a ton of CO2 from $0/ton up to $1500/ton, and examined the impact this had on a variety of technological combinations. The results are shown in Figure 8.

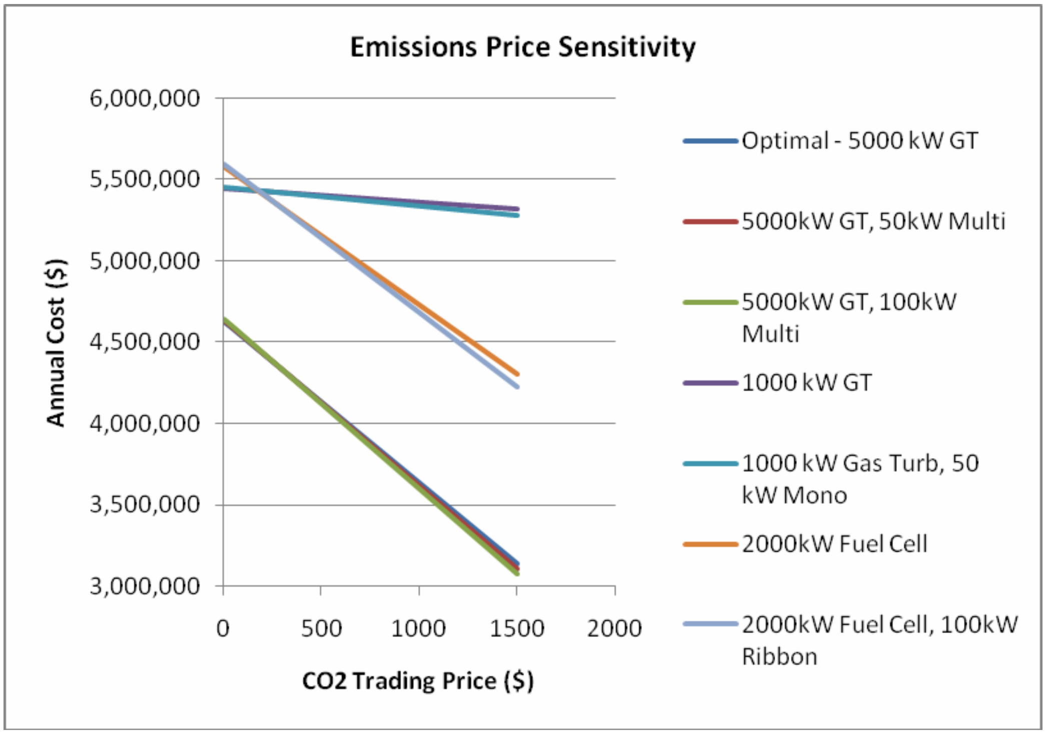


Figure 8 - User 1 sensitivity to emissions price

We see that the 5000 kW gas turbine remains the optimal choice until the trading price of CO2 reaches $300/ton. At this point, use of a 100 kW monocrystalline solar array in addition to the gas turbine becomes optimal. Addition of a 50 kW monocrystalline array also provides cost savings at this point, though not to the same degree as the 100 kW array. However, the difference in savings between the 5000 kW gas turbine and the 5000 kW gas turbine plus 100 kW solar array is so small that it is unlikely that a company would choose to go through the trouble of implementing solar. Thus, we see that for User 1 emissions will not play a role in the adoption of photovoltaic technology.

4.9.2 Change in PV Installation Cost

We used the case of User 2, a metalworking firm, to study the sensitivity of our selection to the installation cost of various photovoltaic technologies. User 2's initial optimal selection is a 300 kW reciprocating engine. We take combinations of this CHP option and different PV options and range the installed PV cost from a 0% reduction to a 60% reduction. Results are shown in Figure 9.

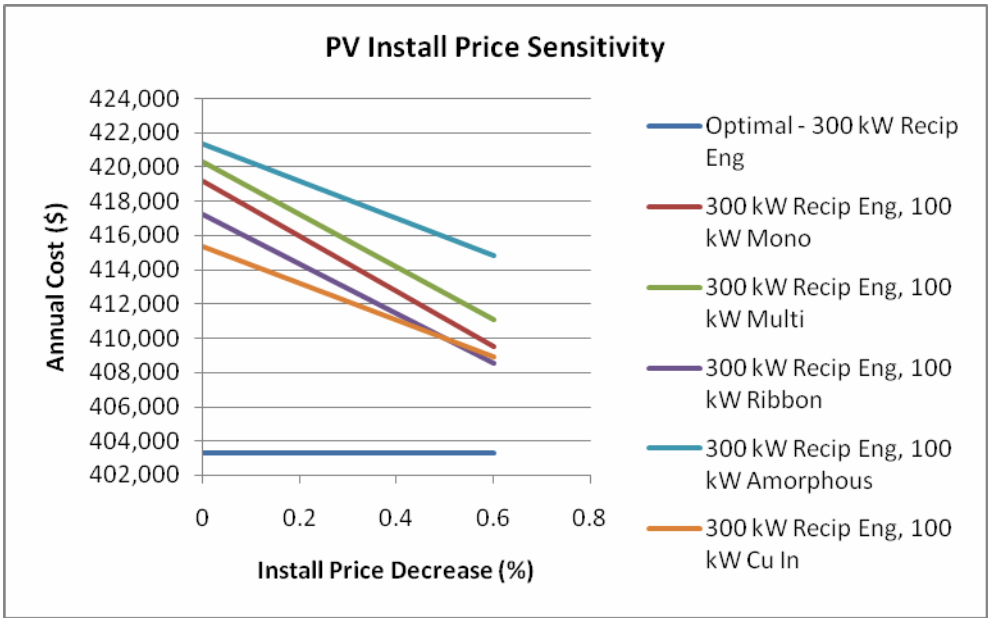


Figure 9 - User 2 sensitivity to pv install price

We see that while a reduction in cost brings all of the CHP-PV combinations closer to optimal, at no point does an alternative using PV become optimal. Thus, we see that for User 2 a reduction in PV install cost alone will not make PV a viable selection (though it certainly makes it more attractive).

4.9.3 Change in PV Efficiency

User 3, another paper producer, is used to examine the effects of increasing panel efficiency on the optimal technology selection. We combine the initial optimal choice, a 1000 kW gas turbine, with a variety of pv technologies, and vary their efficiency from 0% to 300% of the initial efficiency. Results are shown in Figure 10.

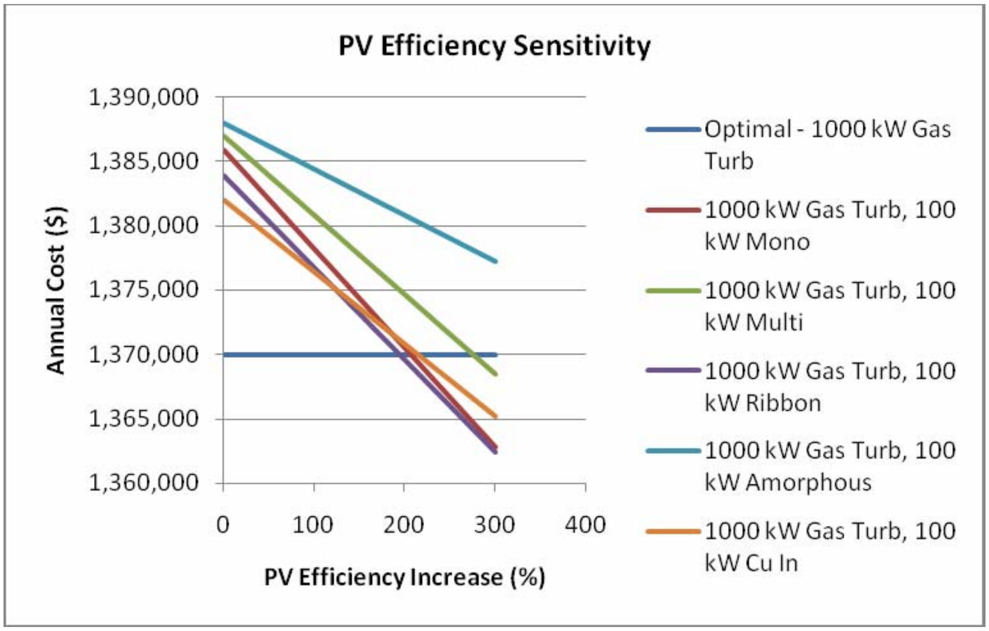


Figure 10 - User 3 sensitivity to pv efficiency

Here we see some significant interaction among the alternatives. At about 200% of its original efficiency (14%), the addition of a 100kW string ribbon array becomes optimal. We also see that addition of 100 kW arrays of both amorphous silicon and copper indium diselenide follow quickly behind the string ribbon array as superior to the 1000 kW on its own. We thus conclude that large increases in efficiency of solar cells will allow them to become more economically viable.

4.9.4 Change in PV Rebates

We examine User 3 once more to look at the potential impact of changes to governmental rebate policy. We look specifically at the rebates offered which cover 50% of installation cost, capped at $580,000. We vary the percent of installation cost covered from 50% to 100%, retaining the cap of $580,000. The results are displayed in Figure 11.

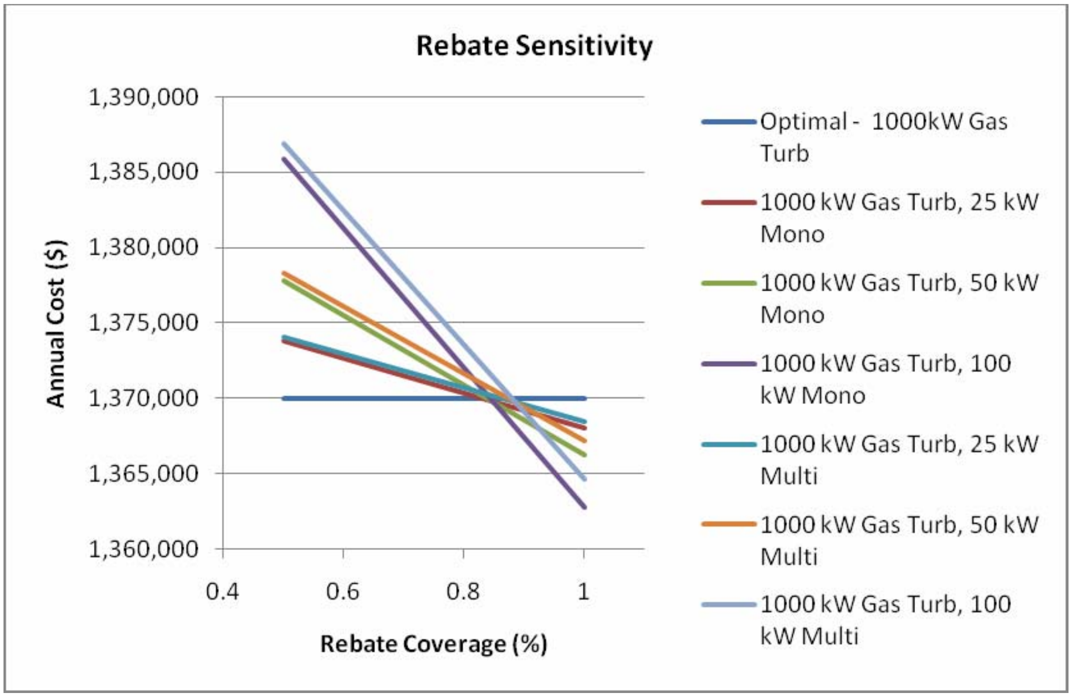


Figure 11 - User 3 sensitivity to rebates

Again, we see a significant amount of interaction among the alternatives on display. Addition of a 100 kW monocrystalline array to the 1000 kW gas turbine becomes optimal at 85% coverage of installation cost. Several other PV technologies and array sizes follow closely behind, including 50 kW and 25 kW monocrystalline arrays, as well as various multicrystalline array sizes. From this analysis, we can see that a change in rebate policy can seriously impact the market for photovoltaic technologies.

4.10 Conclusion

In this chapter, we demonstrate a tool that can be used to help a decision maker choose the optimum capacity and the set from a portfolio of CHP and photovoltaic technologies. The tool is based on a simple cost minimization model and can be extended to include other technologies. We used the tool to find the optimal technology selection for a variety of sample industrial cases, and then looked at three real cases as a means of verifying the accuracy of our tool. One significant conclusion of the analysis is that the solar PV technologies are not yet cost effective, as their use was never recommended by the model. Through sensitivity analysis, we found that increased use of solar technologies can be effectively spurred on through increased government rebates, as well as increased panel efficiencies. Decreasing installed PV costs and increasing the trading price of emissions were seen to be less effective at stimulating interest in PV for the cases we reviewed.

The creation of this tool provides many valuable advancements over the HC tool that will be useful in building the PVSN tool. First, data has been collected and calculation methods created for implementation of CHP technologies as part of a decision tool. Second, the manner in which we approach solar photovoltaic technology has evolved to be more realistic than in the HC tool, allowing users to select from a variety of technologies independent of array sizes. We also incorporate rebates and incentives into determining the financial costs associated with a given alternative set, which were absent from the HC tool. Many of these features will be carried forward into the PVSN tool.

5 PVSN TOOL

In this chapter, we explain the final segment of this thesis project. Specifically, we present the green energy decision tool created for the Pioneer Valley Sustainability Network. This tool targets homeowners and small business owners interested in green energy. We discuss the necessary inputs, the user interface, the technologies that will be included as selections in the tool, and the output of the tool.

Like the two prototypes discussed in chapters 3 and 4 of this proposal, the PVSN decision tool is created as a Microsoft Excel spreadsheet. There are multiple reasons for this choice. First, most users are familiar with spreadsheets, and thus an Excel based tool will be familiar and non-threatening. Second, using Excel will allow a level of transparency not generally present in other, similar web applications. With Excel users will have the capability to download the entire tool, view all assumptions and calculations made by the tool, and alter the tool to suit their own purposes as they see fit. Finally, the simulation software, which will play a role in our treatment of uncertainty, runs in Excel.

Like the previous two tools, this one will focus on green energy technologies. Users will be presented with a number of green energy technology alternatives, and will be able to select from among them to see how their choice will impact key metrics. Many of these technologies have already been explained in previous sections of this proposal. These include solar photovoltaics (PV), geothermal, biodiesel, biomass, and daylighting. We will update data and calculations associated with each of these alternatives to ensure accuracy and realism, and make appropriate changes to ensure a residential, rather than industrial, focus. Several new energy efficient technologies will be included as well, such as re-insulating, replacing windows, using compact fluorescent lights, and refrigerator replacement.

5.1 User Input

When initially using the PVSN tool, we require users to enter data about their building in order to get a baseline idea of their current energy use. A key factor in keeping the model accessible and useful to the public is to minimize the amount of information we require. If the information we ask for is excessive or difficult to obtain, users may decide that the tool is not worth using. With this in mind, we require the following information from the user:

1. Annual Electrical Load – the amount of electricity used on an annual basis, in kilowatt-hours.
2. Heating Fuel Type – select their current heating fuel from a menu of None, Oil, Propane, Natural Gas, and Electric.
3. Heating Fuel Use – enter amount of fuel used annually for heating, in gallons or therms.
4. Heater efficiency – enter value for efficiency of current heating unit (0.75 as default).
5. Annual Maintenance Cost – enter the annual cost of upkeep to heating unit.
6. Remaining Life (yrs) – enter years of useful life remaining for current heating unit.
7. Replacement Cost – amount they expect to pay to replace current heating unit.

8. Water heating method - select their water heating method from a menu of None, Same as Heating Fuel, and Electric.
9. House square footage – enter approximate square footage of living space.
10. Type of Building – select from menu of Residential and Commercial.
11. Number of Occupants – enter number of occupants of building.
12. Discount Rate – the rate to be used to discount future costs (default of 5%).

The majority of these inputs will likely be known by the user with no additional research. Electrical and fuel usage should be accessible from utility bills, while heating unit replacement costs and efficiency may rely on the user's experience and/or maintenance reports. Given this user information, we have a good idea of their energy usage, as well as the information we need to compute the performance of green technologies.

5.2 Technology Calculations

5.2.1 Solar Photovoltaics

As previously discussed, solar photovoltaic panels convert energy from the sun into useable electricity. In an effort to improve upon the HC model and cost minimization model, the PVSN tool's solar PV offerings are expanded and the modeling of technologies improved. The following types of modules are available for selection in the PVSN model:

Brand	Wattage
BrightWatts	135
Sharp	170
Mitsubishi	180
BrightWatts	200
Kyocera	205
Sharp	216

Table 12 - Solar photovoltaic modules

We also allow the user the freedom to enter the number of panels they wish to install. Costs for panels and inverters were gathered from online sources (Ecobusinesslinks ; Solarbuzz LLC 2008). Project installation costs, which include the costs of racking, wiring, other balance of system items, and labor, were estimated from actual panel installation projects. The installed cost of a solar photovoltaic installation can be reduced by rebates and incentives offered by state and federal agencies. We include the ability for the user to make use of the Commonwealth Solar rebate program, which offers rebates starting at $1/W installed (Massachusetts Technology Collaborative 2009), as well as the federal Residential Renewable Energy tax credit, which covers 30% of installed costs (NCSU 2008).

The performance calculation for solar PV panels follows the method used by General Electric in their publicly distributed environmental calculator (General Electric 2008). Taking our daily insolation value to be 4.52 kWh/m^2/day (NREL 2008), we multiply by the area of the selected array, the panel efficiency, and 365 days/yr to arrive at the expected AC power production. Multiplying this by a standard AC to DC conversion derating factor of 0.77 (NREL 2008) yields the total kilowatt-hours of usable electricity generated by the array.

5.2.2 Daylighting

As discussed in the HC tool section of this paper, daylighting represents the use of windows and light sensing controls to increase the amount of natural light used in illuminating a space, consequentially decreasing the amount of electrical lighting required. We treat daylighting in a more complex manner in the PVSN tool. As we are considering modifications to existing buildings, we will consider daylighting as the addition of skylights (as opposed to the reconfiguration of existing windows to improve lighting).

In gathering cost data, we took the cost of a skylight to be $500, and the labor to install it to be $300 (Velux USA 2008). The cost of electric lighting controls was found to be $0.70/ft2, with an additional $0.90/ft2 labor cost (Rubinstein, Neils et al. 2001).

Electricity savings estimation was performed using the steps outlined by Ander (2002). We ask the user to provide the number of skylights to install, as well as the area of the space to be daylit, allowing us to calculate the skylight to floor ratio. We define Well Factor (WF) as the ratio of the amount of light leaving a skylight to the amount of light entering through the skylight. Visible transmittance (VT) is defined as the percentage of visible light that passes through a glazing system. We take Ander's assumed values of WF = 0.9 and VT = 0.5 for a skylight, and used these to calculate the Effective Aperture (EA) of the skylighting system as:

EA = (skylight to floor ratio)*(WF)*(VT)

The effective aperture represents the potential for a skylight system to admit light. We use the effective aperture to estimate the number of footcandles of illuminance captured from daylight at each hour of the day for each month for our given region, using Ander's table of regional footcandle values. Following Figure 12, we can then estimate the fraction of electrical energy saved through use of daylighting and dimming controls for each hour of the day for each month.

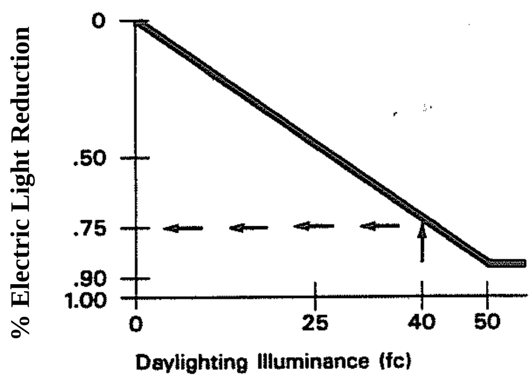


Figure 12 - Footcandles admitted vs. Percent Electric Lighting reduction

For instance, suppose we wish to take a 400 ft^2 space and add two 12 ft^2 skylights to it. Based on our assumptions above, we then have:

Skylight to floor area ratio = (24/400) = 0.06

WF = 0.9

VT = 0.5

EA = 0.06 * 0.9 * 0.5 = 0.027

Ander provides hourly regional footcandle data for an EA of 0.01. For our example, we'll look at the tenth hour of the day for January. Ander gives us the fact that an EA of

0.01 will yield 12 fc of illuminance for this hour of this particular month. We find the illuminance for our EA simply by multiplying by the ratio of the EAs:

12 fc * (0.027 / 0.01) = 32.4 fc.

So we see that given our EA, illuminance in the space from daylighting will be 32.4 fc. To calculate the percent of electric lighting reduction from this level of illuminance, we use the graph in Figure 12 to find that the illuminance combined with lighting controls will result in a 61% reduction in electric light use.

An important consideration in the calculation of energy savings is the type of facility under inspection. Daylighting will be of greater impact in commercial building, which is highly utilized during daylight hours, as opposed to a residence, which may not use much electric lighting during the day. Again we follow Ander's example to estimate the percent of lights in use for commercial and residential structures for each hour of the day for each month, differentiating between weekends and weekdays. Using an assumed lighting value of 1.8 W/ft^2, we can then calculate the total energy savings for the year as:

(1.8 W/ft2) * (daylit area)*(percent lights in use)*(percent energy saved).

This assumed value of 1.8 W/ft2 remains static, regardless of whether or not the user is selecting CFLs for lighting. In reality, use of more CFLs will reduce the wattage per square foot. Thus, our model will overestimate the benefit to the user should they select both daylighting and CFLs. This presents a point of improvement for future work.

5.2.3 Space Heating Technologies

We include the same space heating technologies in the PVSN tool that were found in the HC tool: geothermal, biomass, and biodiesel. While we had initially intended to include CHP, the development of CHP technology for small residential and commercial applications has only recently begun (EPA 2008). Thus, it makes sense to leave the addition of this technology to the tool to future development.

As with solar PV and daylighting, the calculations used for these technologies are less simplistic than in the HC tool. One added complexity stems from the fact that a given green technology may not be able to completely satisfy the heating needs of a building, and thus a backup system may be required. We handle this in the following manner. Using a contractors rule of thumb for sizing heating systems (Vonwentzel.net 2007), we take:

- Total Btus required (calculated from user inputs & selections)
- Average Annual Heating Degree Days for Pioneer Valley: 6175 (NOAA 2009)
- Largest Expected indoor/outdoor temperature difference: 75 deg F (Weather Underground 2009)

To find the annual heat output by any system requiring a backup, we take:

(System Size (Btus/hour) * 24 hr/day * 6175 day–degF) / (75 degF) = Total Btus.

If the total heat requirement of the building exceeds the Total Btus produced by the system in a year, the auxiliary system will be used to satisfy the remainder of the heat requirement. The auxiliary system is assumed to be the heating system currently in place.

At the input screen, the user is asked to specify the annual maintenance cost, remaining life, and replacement cost for their current heating unit. The assumptions used in the model to calculate costs associated with heating are as follows. If a user does not specify a renewable heating option, it is assumed that they will continue using their current system. Thus, the O&M costs and future replacement cost they specify will be factored into the cost calculation. If geothermal or biomass is selected, the user pays the installation and annual maintenance costs for these systems, and retains the current heating system as a backup. The annual maintenance cost for the backup heat is reduced to zero in this case, as we assume auxiliary heating will be used infrequently. Fuel costs for auxiliary heat are still paid. In the event that the user selects biodiesel and currently uses oil, the initially specified O&M and future replacement costs are used. If the user selects biodiesel and does not currently use oil, the installation and O&M costs associated with a new oil burner are used.

5.2.3.1 Geothermal

Geothermal heating systems use the relatively constant temperature of the earth to provide the heating needs of a building. Geothermal systems require a well to be dug, and pipes to be installed deep into the earth. Fluid is circulated through these pipes, warmed by the heat within the earth, and passed through a heat exchanger to provide useable heat to a building. Geothermal systems generally require a backup heating system.

We allow users to select a 3 ton or 4 ton geothermal heating unit, sizes typical for residential or small commercial applications. Cost data gathered for these systems is shown below:

Size (ton)	3 Ton	4 Ton
System Cost	$7,500	$10,000
Well Cost	$8,000	$8,000
Installation Cost	$3,000	$3,000
Maint (per 2 yrs)	$200	$200
Life (yrs)	25	25
Federal Tax Credit	30%	30%
Tax Credit Max	$2,000	$2,000
Installed Cost	$18,500	$21,000
Tax Credit Refund	-$2,000	-$2,000
Installed Cost w/ Tax Credit	$16,500	$19,000

Table 13 - Geothermal Cost data

System costs were derived from technology guides (NAHB Research Center 2008), and well, installation, and maintenance costs came from conversations with installers (Advanced Energy Concepts 2008). It is worth noting that users can adjust the expected well costs based on their own knowledge of their property. We also include a residential renewable energy tax credit offered by the federal government, which covers 30% of installed costs up to a maximum of $2,000 (NCSU 2008).

Geothermal heat pumps burn no fuel to produce heat, but do require electrical input to operate. Technical characteristics of the geothermal systems we model are as follows (Econar 2008):

Size (ton)	3 Ton	4 Ton
Output (Btu/hr)	32,800	45,700
COP	3.3	3.3
Electrical Input (Btu/hr)	9939.39	13848.48
Electrical Input (kW)	2.91	4.06

Table 14 - Geothermal Output data

We must calculate the amount of electricity used by the geothermal system to produce the amount of heat required of the renewable system. As shown above, we use the coefficient of performance (COP) rating of the system to find the amount of electrical input require for the maximum heat output. We calculate the number of hours the system must run at its maximum setting to meet the required number of MMBtus for the building, and multiply by the kW of electrical input to arrive at the total electrical power requirement of the geothermal system.

5.2.3.2 Biomass

Biomass heating systems produce heat through the combustion of biofuels. The biomass heating systems currently modeled in the PVSN tool are wood fired boilers, which burn either pellets or cordwood. We include three system sizes for selection in the PVSN tool, with the following characteristics (Tarm USA 2008):

	Small Boiler	Medium Boiler	Large Boiler
Max Output Wood (Btu/hr)	100,000	140,000	198,000
System Efficiency	0.75	0.75	0.75
Price	$7,200	$7,850	$8,600
Annual Maintenance	$300	$300	$300
Installation	$550	$550	$550

Table 15 - Biomass data

To meet the renewable system heat requirement, the appropriate amount of wood must be fed to the biomass system. We assume burning of seasoned hardwood, with an average heat content of 22 MMBtu/cord (The Chimney Sweep 2008) and an average price of $385/cord. The total number of cords required is calculated as:

(Renewable Heat Output) / (System Efficiency * 22 MMBtu/cord)

It is worth noting that biomass has a high annual maintenance cost in comparison with other technologies, due to the extra labor required to keep the system stocked with fuel.

5.2.3.3 Biodiesel

Biodiesel fuel is derived from vegetable oil or fat, and has lower emissions content than traditional fossil fuels. Biodiesel can be burned by a regular oil burner, and thus requires no significant initial investment to someone already in possession of an oil burner. It is generally sold in three varieties: B5 (5% biodiesel, 95% fuel oil), B20 (20% biodiesel, 80% fuel oil) and B100 (100% biodiesel). We offer each of these three blends as options for use as a heating fuel in the PVSN model.

In modeling biodiesel, we first check whether the user currently has oil heat. If so, no initial expense is incurred. Otherwise, an installed cost of $6,000 is incurred for the installation of a new oil burning heating system, with maintenance costs of $100 every two years. We assume an efficiency of 90% for a new heating system, and use the user entered efficiency if the existing system is to be used. We calculate the number of gallons of biodiesel required to satisfy the heating requirement, as well as the fuel cost, using the following data (EPA 2002):

	B5	B20	B100
Price ($/gal)	$3.89	$3.92	$5.02
Btu/gal	136,973	133,894	117,468

Table 16 - Biodiesel data

It is worth noting that B100 is not frequently used to heat commercially, as it can corrode rubber seals that are part of the heating system. However, it is occasionally used, and is included here for the sake of completeness. Future versions of the tool may include a higher annual maintenance cost associated with using B100, due to this potential for corrosion.

5.2.4 Solar Hot Water

Solar hot water (SHW) systems capture heat from the sun to provide a portion of required hot water to a home or building. SHW systems are generally comprised of roof mounted solar collectors, through which an antifreeze solution is pumped. The antifreeze circulates through the collectors as well as through a heat exchanger, which transfers the heat to the hot water in a storage tank.

In our modeling of SHW, we provide users with the binary option of either installing or not installing an SHW system. If the SHW system is selected, we then choose the appropriate sized system based on the number of occupants of the building as indicated by the user at input. The data we use for systems is displayed below (FSEC 2009).

#Occ	1	2	3	4	5	6	7	8
Gal/day	40	50	60	70	80	90	100	110
Collector	ICS 32sf	ICS 32sf	ICS 40sf	ICS 40sf	ICS 40sf	2@32	2@40 sf	2@40 sf
Storage	66	66	80	80	80	120	120	120
SEF Fuel	0.9	0.9	1.2	1.2	1.2	1.2	1.4	1.4
SEF Elec	2.1	2.1	2.6	2.6	2.6	2.6	3.4	3.4
Cost	$3,600	$3,600	$4,800	$4,800	$4,800	$5,800	$6,400	$6,400

Table 17 - Solar Hot Water system data

In addition to the installed costs represented in the table above, each system has a maintenance cost of $425 every ten years to replace the pump and the tank. We also include a residential renewable energy tax credit offered by the federal government, which covers 30% of installed costs up to a maximum of $2,000 (NCSU 2008).

The SEF, or Solar Energy Factor, is a rating given by the Solar Rating and Certification Corporation (SRCC). It is defined as the energy delivered to the system divided by the energy from fuel or electrical input. The SEF of a SHW system varies based on whether the auxiliary heating system is electric or nonelectric, due to the different efficiencies and standby losses of each system type (SRCC 2008).

To calculate the hot water supplied by the SHW system, we must first determine the total hot water load for the structure. Following the example of the FSEC calculations, we find:

GPD: gallons hot water used per day, equal to 30 +10*(# occupants)

D: water density, 8.3 lbs/gal

SH: specific heat of water, 1 cal/g-degC

T_{set}: set point of hot water heater, assumed to be 120 degF

T_{mains}: temperature of water coming in from water main, calculated for Pioneer Valley to be 54.2 degF (Hendron 2008)

We can calculate the hot water load as:

H_{day} = GPD * D * SH * ($T_{set} - T_{mains}$), measured in Btu/day

$H_{yr} = H_{day}$ * 365, measured in Btu/yr

We can now calculate the solar fraction, which represents the fraction of the total load to be provided by the solar hot water system. Each SHW system is rated with a Solar Energy Factor (SEF), which varies based on the system type and the fuel used for water heating. We calculate the solar fraction (SF) of a system as:

SF = 1-(Auxiliary Heating Efficiency/SEF)

Thus, if we calculate SF = 0.5, the model will provide half of the hot water load (H_{yr}) from the SHW system and half of the load from the auxiliary (existing) water heating system.

5.2.5 Efficiency Measures

In addition to the renewable energy technologies discussed above, we will allow users to select from a number of energy efficient technologies to implement in their buildings. These technologies serve to reduce the amount of energy required by a structure to maintain a given level of performance. We include the use of compact fluorescent lights (CFLs) and energy efficient refrigeration as means to reduce electrical energy use, and the replacement of insulation and windows as means of reducing heat use.

5.2.5.1 Compact Fluorescent Lights

Replacing incandescent bulbs with compact fluorescent bulbs is a simple and effective way to reduce electricity use. CFLs require less electricity and last much longer than normal bulbs. In our modeling of CFLs, we allow the user to replace 40, 60, 75, and 100 Watt incandescent bulbs with the equivalent CFL bulb. We ask the user to specify the number of bulbs of each wattage to be replaced, as well as the frequency of use of these bulbs. Following the calculations used for the Database for Energy Efficiency Resources (Itron Inc. 2005), we define frequency of use as follows.

Bulb Use	Hours/Day
Frequent	6
Moderate	2.5
Infrequent	0.5

Table 18 - CFL frequency of use

The following data were used in our calculation of energy savings (Itron Inc. 2005).

Incandescent (W)	CFL Replacement (W)	ΔW	Cost($/bulb)	Life (yr)
40	9	31	1.72	9
60	14	46	1.72	9
75	20	55	6.97	9
100	27	73	6.97	9

Table 19 - CFL data

The grid electricity use reduction is then simple.

ΔElectric Use = (ΔW) * (# bulbs to replace) * (frequency of use) * 365

Performing this calculation for each wattage of bulb to be replaced, and summing over all bulbs, yields the total annual electricity savings.

5.2.5.2 Efficient Refrigeration

In general, refrigerators run constantly throughout the day and night. Thus, upgrading to a refrigerator that uses less energy to provide the same amount of refrigeration is an effective means of reducing electricity consumption. We allow users to choose select their own refrigerator size opt to replace it with an efficient refrigerator of the same size. The data used for refrigerators is as follows (EnergyStar 2008).

Size	**Brand**	**Volume (Ft3)**	**kWh/year**	**Federal Std (kWh/year)**	**Price**	**Life (yr)**
Small	GE	15.54	363	454	$759	13
Medium	Amana	18.51	448	560	$1015	13
Large	Amana	25.41	577	726	$1190	13

Table 20 - Efficient Refrigerator data

The calculation for energy savings from the purchase of an energy efficient refrigerator is straightforward. We assume that the user's current refrigerator operates at the federal standard level of electricity consumption. If the user selects an efficient refrigerator, we simply take the difference between the federal standard consumption and the efficient refrigerator consumption to be the annual electricity savings from the upgrade.

5.2.5.3 Insulation

Insulation is used to fill cavities in the walls, ceilings, and roofs of buildings to prevent heat loss. The effectiveness of insulation is given by its R-value, a measure of thermal resistance. In the PVSN tool, we consider the impacts of improving existing insulation in a building. We consider walls and roof/ceiling separately. Re-insulation of the ceiling or roof is generally straightforward, as these areas are easily accessible. Re-insulation of walls, however, is a more complex process, generally must be done by a professional, and incurs a higher expense.

We require the user to specify the square footage of the area to re-insulate, as well as their current level of insulation and the degree to which they wish to improve this insulation. We elicit this information from the user through drop-down menus, and display the corresponding R-value of their selections for their information. The levels of insulation we allow are found in

Table 21 (Fissette 2009). While other building components (studs, siding, etc) contribute to the overall R value of a wall, we simply use the R value of insulation in our calculations. This is reasonable, as our tool is meant to be used for comparative purposes. To calculate the total heat savings in Btus from a change in insulation, we compute the following:

Heat savings = $((1/R_{new}) – (1/R_{current}))$ * (HDD) * (24 hrs/day) * (area)

where area corresponds to the reinsulation area specified by the user, and HDD corresponds to the average number of heating degree days for the region (6,175 for the Pioneer Valley).

We calculate the cost of a re-insulating project using the following data (Home Depot 2009). We allow the user to select only “Well Insulated” as the level to reinsulated walls, and “Moderately Insulated” and “Well Insulated” as the levels to which the roof/ceiling may be reinsulated.

Wall	Wall R-Val	Labor & Materials ($/ft2)
No Insulation	2	n/a
Moderately Insulated	11	n/a
Well Insulated	19	3.50

Roof/Ceiling	Roof/Ceiling - R-Value	Labor & Materials ($/ft2)
No Insulation	2	n/a
Poorly Insulated	13	n/a
Moderately Insulated	40	1.60
Well Insulated	60	1.75

Table 21 - Wall and Ceiling Insulation data

We also provide the user with the ability to include the residential energy efficiency tax credit offered by the federal government. This credit covers 10% of installed costs of efficiency improvements, with a cap of $500 (NCSU 2008).

5.2.5.4 Windows

Window replacement is another means of improving a building envelope and reducing heat loss. Many types of windows exist, each with different insulating properties. We consider three types of windows in our tool: single pane, double pane, and double pane low-e. Double pane windows are composed of two panes of glass with a layer of air sandwiched between them, for extra insulation. Double pane low-e windows are similar, but have an added low emissivity coating. Thermal resistance of windows is measured by a U-factor, which is equivalent to the inverse of the R-value discussed above.

We perform heat savings calculations for windows very similarly to our insulation calculations. We require the user to select the type of window that best represents their current windows, the type of windows to which they'd like to upgrade, and the number of windows to replace. We use the following data for our calculations (Andersen Windows 2009).

	U-Factor (Btu/hr-ft2-F)	Area (ft2)	Price ($/window)	Installation ($/window)
Single Pane	1	12.43	-	-
Double Pane	0.5	12.43	248	300
Double Pane Low-e	0.31	12.35	487	300

Table 22 - Replacement window data

The calculation of total cost of materials and labor is straightforward. The energy efficiency tax credit mentioned regarding insulation can also be applied to the installation of new windows. The heat savings from window replacement can be calculated similarly to that for insulation. Specifically, we take:

Heat savings = $(U_{new} - U_{current})$ * (HDD) * (24 hrs/day) * (area)

where area represents the total area of the windows to be replaced, and HDD corresponds to the average number of heating degree days for the region (6,175 for the Pioneer Valley).

5.3 Emissions

One major issue with conventional methods of energy generation is the emissions they produce. We have mentioned the many negative impacts that stem from the emission of CO_2, SO_2, and NO_x, including climate change, acid rain, and health effects. It is import to quantify the emissions of the building under consideration by the tool in order to be able to demonstrate to the user how changes in technology use can impact their own emissions.

We consider emissions from two sources in the PVSN tool: electricity generation and heating fuel use. Table 23 shows the emissions data for electricity generation in Massachusetts (ISO-NE 2002).

CO_2 (lb/kWh)	**NO_x (lb/kWh)**	**SO_2 (lb/kWh)**
1.293	0.00021	0.005557

Table 23 - Electricity generation emission data for MA

To find the level of emissions for the user, we simply take the kilowatt-hours of grid electricity used in a year, and multiply by the appropriate factor from the table above.

Fuel emissions are similarly calculated, though they will vary based on the fuel used.

Table 24 displays the emissions data we use in our computations (EPA 2002; EPA 2003; British Columbia Ministry of Environment 2005).

	Natural Gas (lb/MMbtu)	Propane (lb/MMbtu)	Oil (lb/MMbtu)	B100 (lb/MMbtu)	B20 (lb/MMbtu)	B5 (lb/MMbtu)	Biomass (lb/ton)
CO_2	117.08	139.18	159.23	49.94	137.372	153.7655	n/a
NO_x	0.15	0.149	0.129	0.146028	0.13158	0.129	0.5761
SO_2	0.0006	0.00106	2.028	0	1.6224	1.9266	0.0823

Table 24 - Fuel emissions profiles

We multiply the amount of any fuel used by the appropriate factors to determine the emissions level from fuel use. Wood boilers are assumed to have neutral CO_2 emissions, as the emissions released through combustion had previously been absorbed from the atmosphere by the tree. It is also important to note that these figures represent direct emissions from biodiesel; life cycle effects could cause these to be lower or higher.

Costs associated with emissions are based on current allowance prices for emitting pollutants. CO2 allowances are based on the EU allowance price, as currently there is no allowance price in the US.

Table 25 shows these costs (Argus Air Daily 2008; Point Carbon 2008).

	$/ton
SO_2	$548
NO_x	$2,950
CO_2	$32

Table 25 - Emission costs

5.4 Human Health Impacts

SO_2 and NO_x are polluting emissions which have numerous negative impacts on human health. These impacts are wide ranging, and include lost work days, asthma attacks, and premature mortality. We wish to use the PVSN tool to inform users as to how their own emissions are impacting the health of those around them, and how they can mitigate these impacts through technological investment. In order to quantify these health impacts, we utilize EPA estimates of the direct costs and societal values placed associated with each type of impact. The impacts and associated costs are displayed in Table 26 (Healthcare Clean Energy Exchange 2008).

	Incidence/ton emitted SO_2	NO_x	Societal Value/ Incident	Direct Cost/ Incident
Premature Mortality	0.00273	0.00171	$6,480,334.56	$273,117.86
Chronic Bronchitis	0.00174	0.00108	$353,232.43	$110,292.69
Hospital + ER Visits	0.00246	0.00159	$2,677.90	$9,562.95
Asthma Attacks	0.05604	0.03507	$2.81	$52.28
Respiratory Symptoms	2.69316	1.58298	$0.00	$33.15
Work Loss Days	0.49323	0.30855	$12.75	$154.28

Table 26 - Health impact data

We represent the health impacts to the user in the form of a single number: the annual worth of the total societal value of health impacts over the 22 year period of consideration. To calculate this, we first find the total incidence of each type of impact based on the tons of SO_2 and NO_x emitted. We then calculate the direct cost (DC) by:

DC = Incidence * Direct Cost per Incident * NERC Region Medical Multiplier

where the medical multiplier for our region is 1.399. We then find the total Societal Value (SV) as :

SV = Incidence * (SV per Incident) + DC.

Summing the societal value across all types of impacts provides a total societal value. Thus we can present the user with a monetarily quantifiable representation of the direct costs and externalities associated with health damages from emissions.

5.5 Uncertainty

There exists a great deal of uncertainty around the issue of climate change. While scientists have drawn a strong connection between human behavior and the rising global temperature (IPCC 2008), it is uncertain what the true cost of damages from climate change may be. Some feel that damages will be very severe indeed, while others believe that measures taken to fight climate change will be more costly than climate change itself. We address this issue in our tool through inclusion of probabilistic simulation. This functionality will allow users to visualize their own exposure to climate related costs, and make investment decisions with these costs in mind.

To effectively communicate uncertainty, Savage et al (2006) recommend the use of "coherent modeling." This type modeling involves the use of interactive simulation to provide users with interactive visual feedback regarding uncertainty of a parameter, thus providing an experiential understanding of uncertainty and associated risk. This method is superior to the more common method of using a single average value to represent a random variable. In the PVSN Tool, the random variable that we will be modeling is the total annualized cost, which incorporates financial, environmental, and health impact costs. The randomness of this total cost comes from uncertainty regarding the cost of damages associated with emissions.

In order to quantify the uncertainty regarding the cost of damages related to CO_2 emissions, we look to the work of Tol (2005). Tol peformed a survey of 28 studies done on this subject, and created probability density functions over the marginal cost of damages from CO_2 emissions. A subset of these PDFs is displayed in Figure 13.

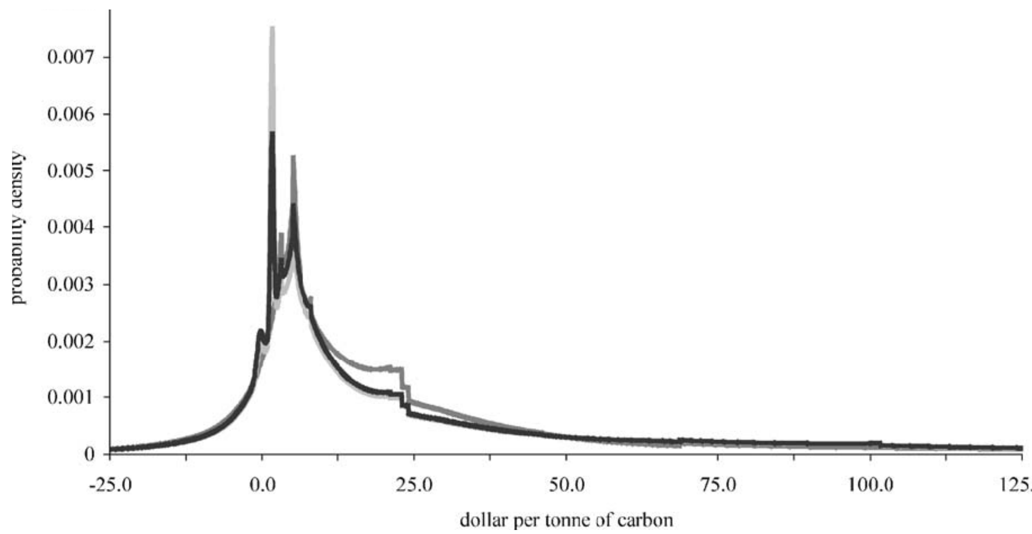


Figure 13 - Tol's PDF over the marginal cost of damages of carbon emissions

We will use Tol's distribution that includes quality weighted, peer reviewed studies to provide random values for the cost of damages from CO_2 emissions.

We base our modeling of uncertainty on the assumption that the true cost of CO_2 damages will be discovered ten years into the future. Until that point, we model the cost per ton CO_2 as $32, the current European allowance price. After that point, we pull a value from Tol's PDF to represent the "true" cost of damages from emissions from that time onward. The mean cost per ton of carbon from Tol's distribution is $54/ton, higher than what we use for the current trading value. To capture the risk associated with emissions, we include the ability to run Monte Carlo simulations on the total annualized cost. The user can simply click a button in the tool, and 1000 trials of a Monte Carlo simulation will be run. Each simulation run pulls a new value for the cost of damages from emissions from Tol's PDF, and uses this value to calculate the total annualized cost. The values resulting from these simulations are stored in memory.

We provide the user with two visual representations of emissions damages uncertainty. The first is a column chart which displays the probability density functions over total cost for the Status Quo (the building as it is currently), and the Proposed Changes (the building including currently selected green technologies). These PDFs are generated from the most recent Monte Carlo simulation. Figure 14 provides an example.

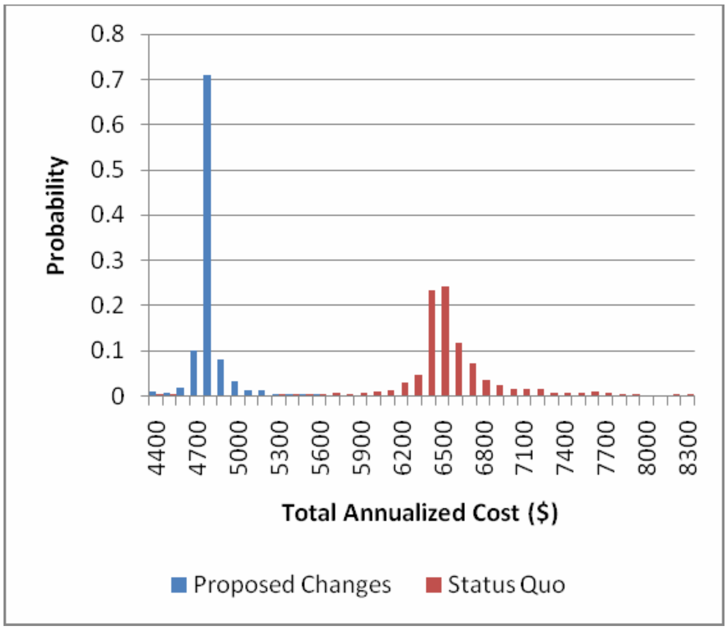


Figure 14 - PVSN tool display of PDFs of total cost

The proposed changes in this case consists of the use of a wood boiler combined with a small solar photovoltaic array. The user can see that the Status Quo has a higher average cost, and has a wider, and therefore riskier, distribution than the Current Selection. Because of the carbon neutrality assumption for biomass, the proposed changes produce very low levels of CO_2, and are therefore less risky.

We also give the user a means of visualizing costs as a time series. Figure 15 allows the user to compare the Proposed Changes with the Status Quo over time, by showing the 10th, 50th, and 90th percentiles for the total cost after the change to the "true" cost of damages from emissions.

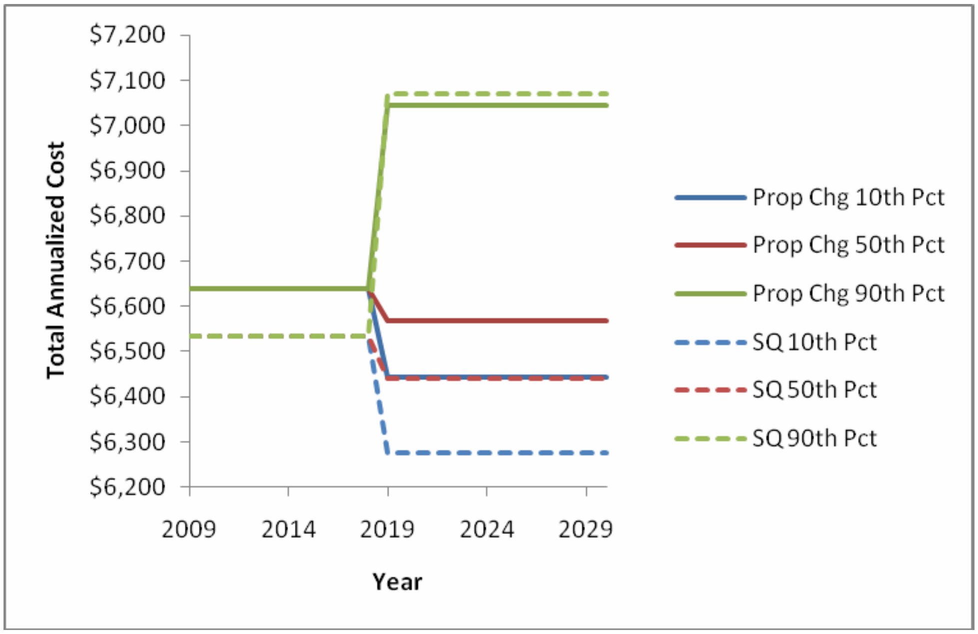


Figure 15 - PVSN tool time series uncertainty display

The proposed changes here include 15 200W solar panels. It may be useful for a user interested in solar panels to see that over time the 10th, 50th, and 90th percentile costs of using solar are below the 90th percentile cost of maintaining the status quo. We also see that the 90th percentile of total cost with solar panels falls below the 90th percentile of total cost without solar panels. This implies that using solar panels may be less risky than not. However, we also see that there is a very high up front cost associated with a very small level of risk protection.

5.6 PVSN Tool Results and Analysis

We use two sample buildings to test our model and provide some results and analysis from the PVSN tool. We examine different technology investment scenarios and view the PVSN tool's output for these examples under current assumptions. We also test the sensitivity of our results to changes in some of our base assumptions to get an idea of the robustness of the tool's results.

The two sample buildings under inspection in this section are both residential homes. They differ in their age, size, number of occupants, and energy usage. Full details of these buildings can be found in

Table 27.

	Home A	Home B
Electricity	5840 kWh	3497 kWh
Heating Fuel	Oil	Natural Gas
Annual Fuel Use	750 gal	1457 therm
Efficiency Heating Unit	0.8	0.85
Annual Maint Cost	$100	$75
Remaining Life	18 yrs	15 yrs
Replacement cost	$4,000	$4,500
Water Heating Method	Oil	Natural Gas
Square Footage	2200	2000
Building Type	Residential	Residential
Occupants	4	2
Discount Rate	0.05	0.05
Ceiling Insulation	Well Insulated	Poorly Insulated
Wall Insulation	Well Insulated	Moderately Insulated
Windows	Double Pane	Double Pane Low-e
CFLs	Many	Some
Ann Financial Cost	$3,699.36	$3,146.03
Ann Total Cost	$6,532.38	$3,852.77

Table 27 - Sample home specifications

One interesting point of note regarding these two homes is the large difference in their annualized total cost. Recall that total cost includes environmental and health impact costs, which are dependent on emissions of CO2, SO_2, and NO_x. Because Home A uses oil, which has a higher emissions profile than natural gas, it incurs greater environmental and health impact costs, and thus has a significantly higher total cost.

5.6.1 Home A Analysis

Home A is a modular home, construction on which was completed in 2003. As a result, many efficiency standards not found in older homes are found in Home A. For instance, we see from

Table 27 that Home A is well insulated in both walls and ceiling, has double pane windows, and uses mainly compact fluorescent bulbs for lighting. Thus we will focus our analysis of Home A on green energy options that might be installed, as opposed to efficiency options.

We examine technology selections in two ways. We can first compare the annualized financial cost of proposed technology additions to the current financial cost of providing energy to the building. This is the typical way building owners make decisions regarding investments. We can also look at what we will refer to as the "total cost," which includes the financial cost as well as costs associated with emissions damages and human health impacts. Total cost will allow users to think beyond their own financial costs, and compare the impacts of their status quo energy use on others, and see how these external impacts might change through investment in green technologies.

Using the tool, we add the various technologies to Home A.

Table 28 displays results for technologies that appear favorable.

	Financial Cost	Total Cost
Status Quo	$3,699.36	$6,532.38
Geothermal (3 ton system)	$3,667.27	$5,101.17
Biomass (small boiler)	$3,743.26	$4,642.61
Biodiesel (B20)	$3,816.36	$6,018.30
Biodiesel (B5)	$3,740.86	$6,169.44
Solar Hot Water (40 sq ft collector)	$3,761.42	$6,394.73

Table 28 - Favorable technologies for Home A

The Status Quo, highlighted in blue, is presented for comparison purposes. The 3 ton geothermal system is the only technological option to appear favorable in terms of both financial and total costs, and is highlighted in pink. The biomass, B5 biodiesel, B20 biodiesel, and solar hot water options are all favorable in terms of total cost, but not financial cost. These are highlighted in green. The higher financial cost for biomass and solar hot water stem from additional capital expenditures required to purchase and install these new systems. The higher financial cost for biodiesel (which requires no new equipment) stems from the higher price and lower Btu content of the fuel. All these technologies, however, reduce emissions of CO_2, SO_2, and NO_X. This consequently reduces costs associated with emissions and health impacts, lowering the total cost. The other technologies available in the PVSN tool were not found to be either viable for either financial cost or total cost.

It is important to note that those technologies highlighted in green above represent investments that are not financially viable for the homeowner, but are economically beneficial to society. The implication is that there is value to the government to provide incentives for people to invest in these technologies. In particular we see that biomass has a significantly lower total cost than the status quo. Thus, based on our results, biomass would be a particularly good candidate for subsidization. However, it is worth noting that our model doesn't incorporate all concerns regarding biomass, such as emission of particulate matter.

We can also examine the risk inherent in the technological options that appear favorable, to get a better understanding of how different scenarios might play out under different costs from carbon damages. Running the simulation for the 3 ton geothermal system yields the following results.

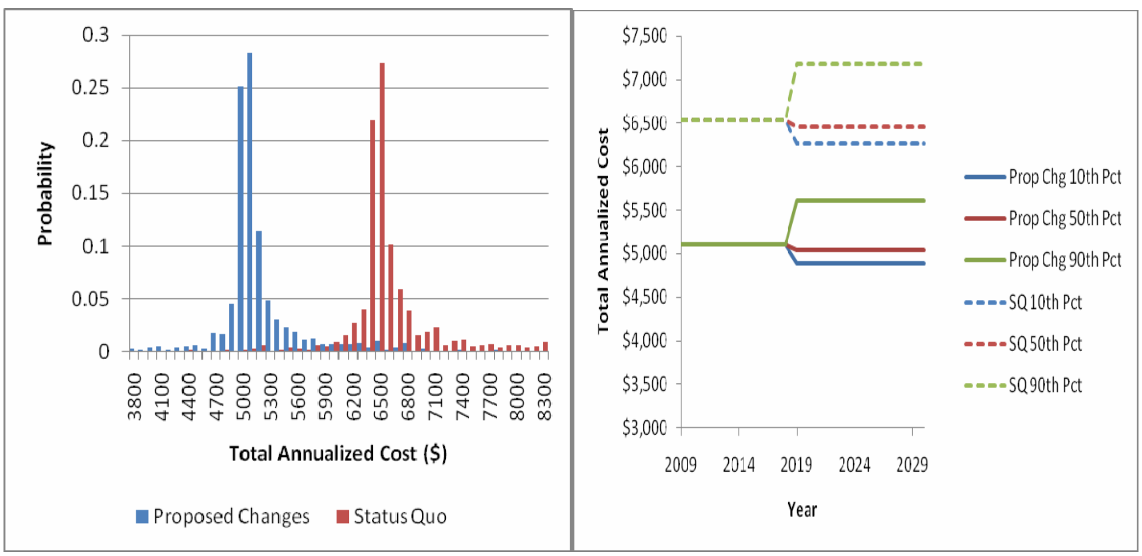


Figure 16 - 3 Ton Geothermal simulation results

These results indicate that use of the geothermal system provides an effective hedge against uncertain carbon costs. The probability distribution function over total cost shows a very high probability that the costs associated with the geothermal system will be lower than those associated with the status quo. We can also compare cost percentiles over time, seeing that even the 90th percentile of costs for the geothermal system is below the 10th percentil for the status quo.

A similar analysis of B5 biodiesel heating is shown in Figure 17 below.

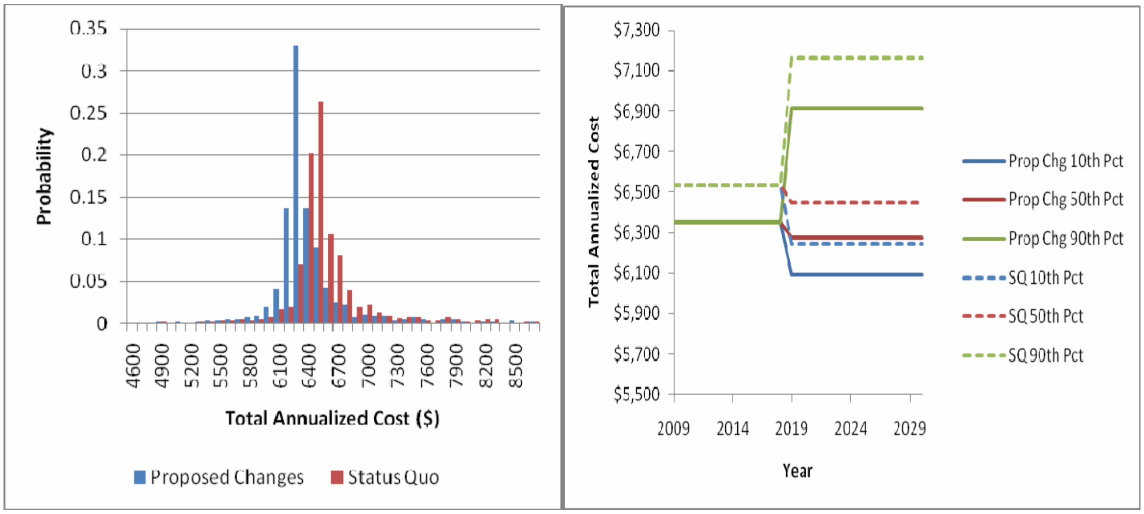


Figure 17 - B5 biodiesel simulation results

These results show B5 biodiesel as a less effective hedge against risk associated with costs due to carbon damages. The PDFs displayed have significantly more overlap, with the centers of the distributions located much closer together. We see similar results in the time series display, where the 90th percentile of costs with biodiesel is much higher than the 50th percentile of costs for the status quo.

5.6.2 Home A Sensitivity

5.6.2.1 Geothermal

Clearly sensitivity analysis is warranted in the case of geothermal heating, as the tool implies that a new geothermal heating system would be more cost effective to install and operate than the existing oil system. To examine the robustness of this result, we analyze key assumptions of our geothermal heating model. We should examine the sensitivity to oil prices, the fuel providing heat for the status quo case. We also vary the percentage of heat deliverable by the geothermal system, as the current results show the geothermal system providing the majority of the required heat. Finally, we vary the cost to excavate a well to provide the system with access to subterranean heat. The base assumption is a well cost of $8,000, but this can be highly variable based on how easy or difficult it is to dig in a certain location.

Varying the cost to dig a well from $3,000 to $20,000, we see the following results.

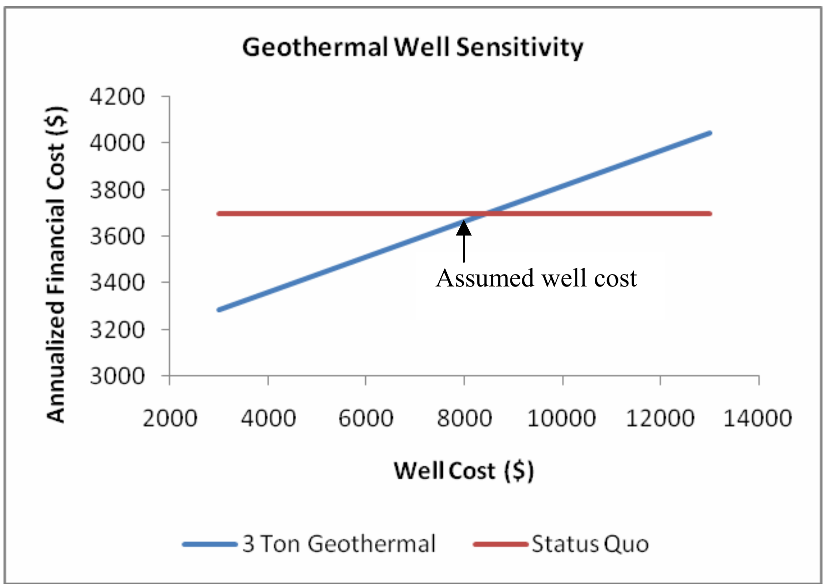


Figure 18 - Geothermal Well cost sensitivity

We only examine financial cost, as changes in well cost will have identical effects on total cost. We see that the tool's result favoring geothermal is not robust. In fact, the $8,000 default well cost lies nearly exactly at the point where geothermal ceases to be preferable. Thus, we see that Home A's financial cost will exceed that of their current heating system if well digging costs exceed $8,000.

Currently, the model predicts that the 3 ton geothermal system will be able to provide 94% of the heat needed by Home A, with the remaining 6% coming from the backup oil system. This division of heat supply may vary, however, from year to year with variations in temperature. We now examine the sensitivity of our results to the amount of heat supplied by geothermal.

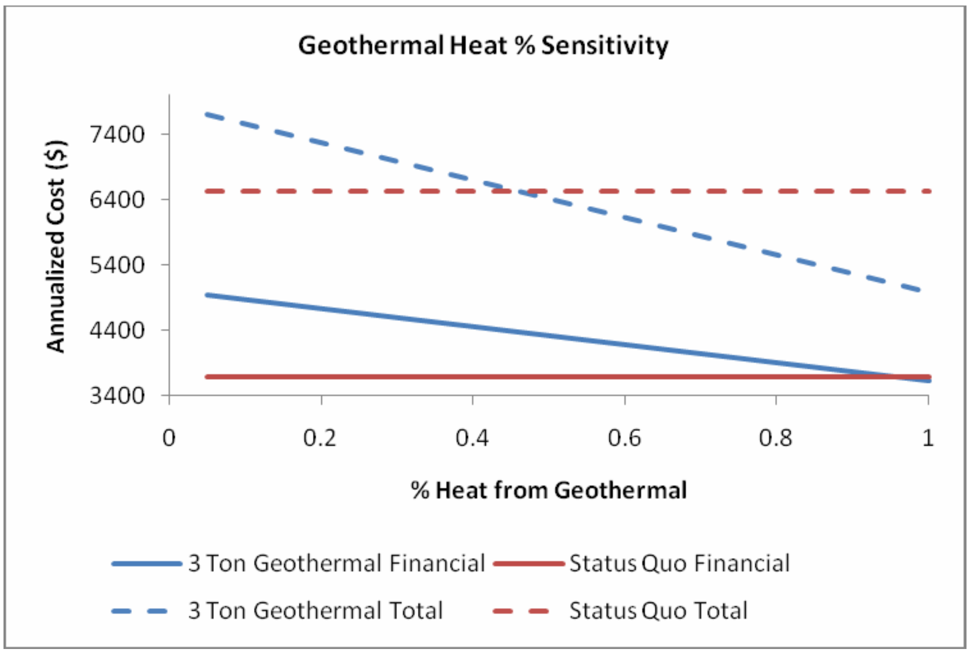


Figure 19 - Sensitivity to percentage of heat supplied by geothermal system

We see that in terms of financial cost alone, we once again are right at the break point between geothermal and the status quo. If the geothermal system provides much less than 94% of the required heat, it will cease to be financially preferable. However, in terms of total cost, we see that geothermal is preferable when providing 45% or more of the required heat. This is due to reductions in emissions and human health costs associated with reducing fuel use from geothermal.

Finally, we vary the oil prices. We deviate from the EIA oil projections, which vary over time, for this analysis, instead using a single value for oil price for all years. It is also important to note that changing this oil price does not impact electricity prices in our model, which would most likely not be the case in reality.

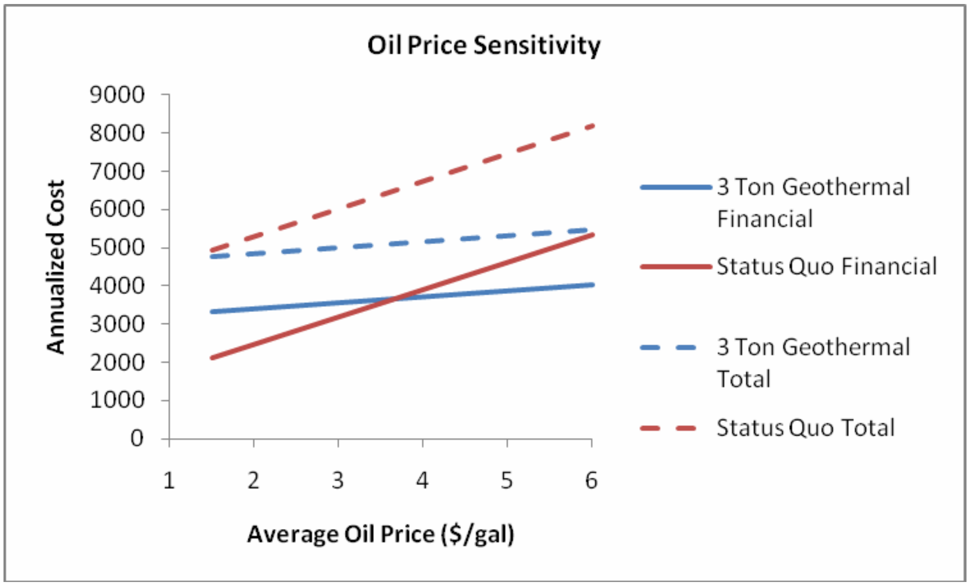


Figure 20 - Geothermal sensitivity to oil price

Holding all other assumptions the same, we see that the geothermal system is financially preferable given the average oil price exceeds $3.65/gal. The total cost, however, is insensitive to oil price. Given that our assumptions about well cost and heating supply discussed above hold true, the environmental and health benefits from the geothermal system are greater than the financial benefits of cheap oil.

The results of this sensitivity analysis show that the owner of Home A should do further research before investing in a geothermal heating system. If they can install a well for $8,000 or less and guarantee that the geothermal system can cover at least 95% of their heat requirement, it will be a financially sound investment. We have shown that there is more flexibility to these numbers should Home A's owner choose to think beyond financial considerations, and include environmental and health considerations in their decision.

5.6.2.2 Solar Hot Water

Use of a solar hot water system is shown to be preferable based on total cost, but not based on financial cost. The PVSN tool shows that a solar hot water system would be able to provide approximately half of the total hot water needs of the home. We will examine the sensitivity of these results to changes the solar fraction (% of hot water from SHW system), as well as oil price, as this is the fuel used to heat water.

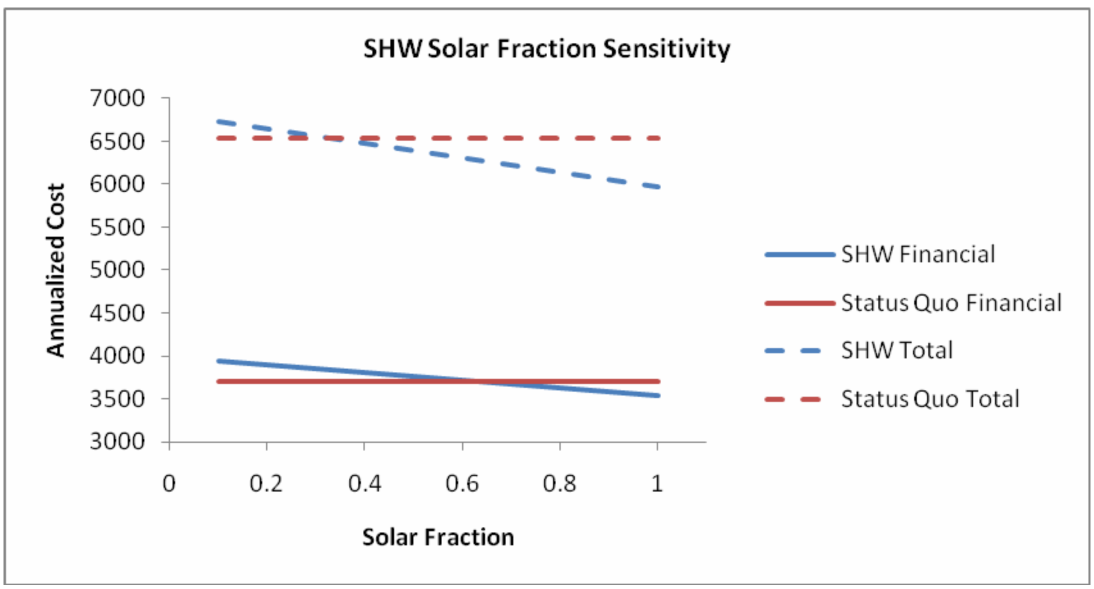


Figure 21 - Solar Hot Water sensitivity to solar fraction

Sensitivity of results to solar fraction are shown in Figure 21. We see that the percentage of hot water provided by the solar hot water system would need to increase to about 0.63 in order for the SHW system to be considered financially viable. However, the solar fraction is currently well above the point (0.3) for the SHW system to be considered preferable based on total cost.

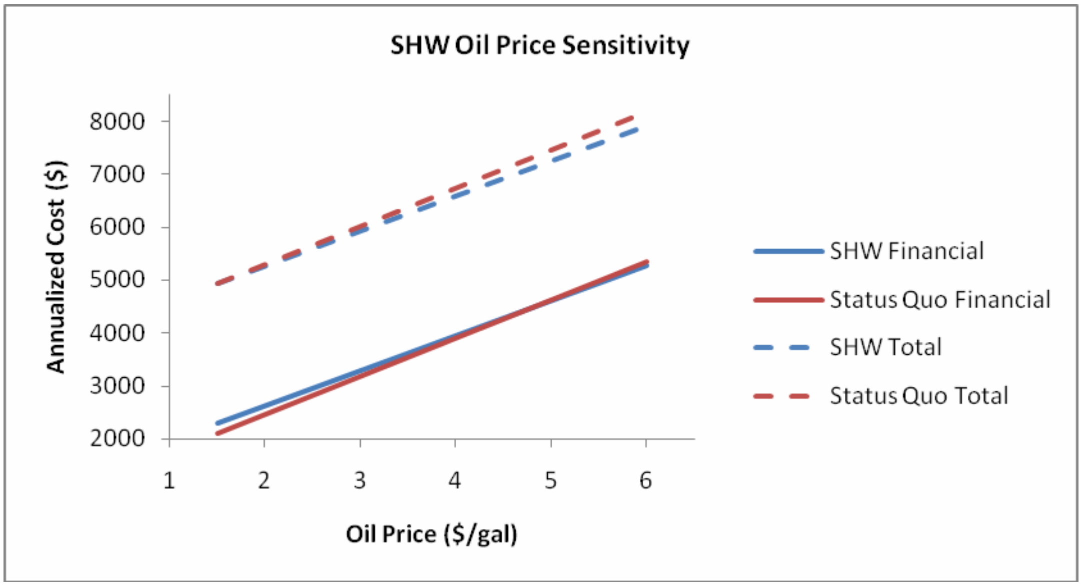


Figure 22 - Solar Hot Water sensitivity to oil price

Figure 22 shows the sensitivity of costs to the price of oil. We see that oil would need to reach a price of about $4.70/gallon for SHW to be financially viable, and is always seen to be viable in terms of total cost. However, the similarity in the slopes of the lines displayed in Figure 22 implies that costs are relatively insensitive to oil price. This makes sense, as the amount of heat provided by the SHW system is relatively small compared to the total heat used by the Home A.

The owner of Home A should consider SHW if thinking from a total cost perspective, or if they feel that they can provide greater than 63% of their hot water from a solar system. Also, if they believe oil prices will be very high on average in the future, an investment in SHW would be advisable.

5.6.2.3 Photovoltaics

Photovoltaics were not recommended as an option for Home A. It may be interesting, however, to examine the rebates and incentives for PV and see at what point it may become a more realistic option. The default rebates are set at $1.00/W installed (MTC Commonwealth Solar Program), and a federal tax credit of 30% of total costs. For this analysis, we use a 2 kW system comprised of ten 200 W photovoltaic panels, which should generate enough electricity to cover close to half of the annual electric load for Home A.

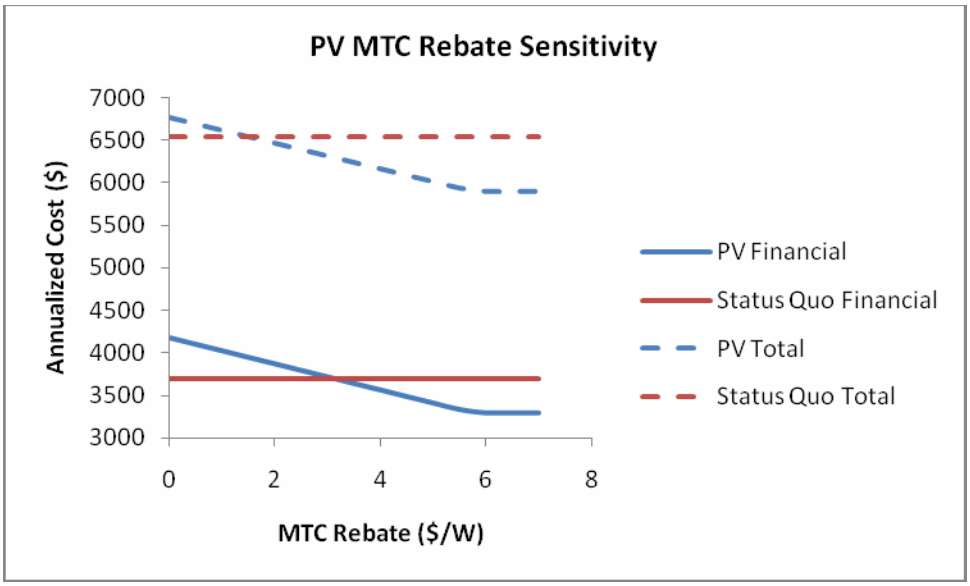


Figure 23 - Photovoltaic sensitivity to MTC rebates

The MTC rebate analysis is interesting, as it shows that the current rebate level of $1/W is very close to the breakpoint for total cost. In fact, if the rebate were increased up to $1.75/W, the solar array would be preferred from a total cost perspective. A much more significant increase (up to $3/W) would be needed to make solar financially preferable. However, this too is important, as rebates available from the MTC can increase significantly from the initial $1/W level, given certain conditions (use of components made in MA, addition of array to a public building or space, etc.). Thus, based on the users qualifications, it is entirely possible that a solar array could be both financially and totally preferred.

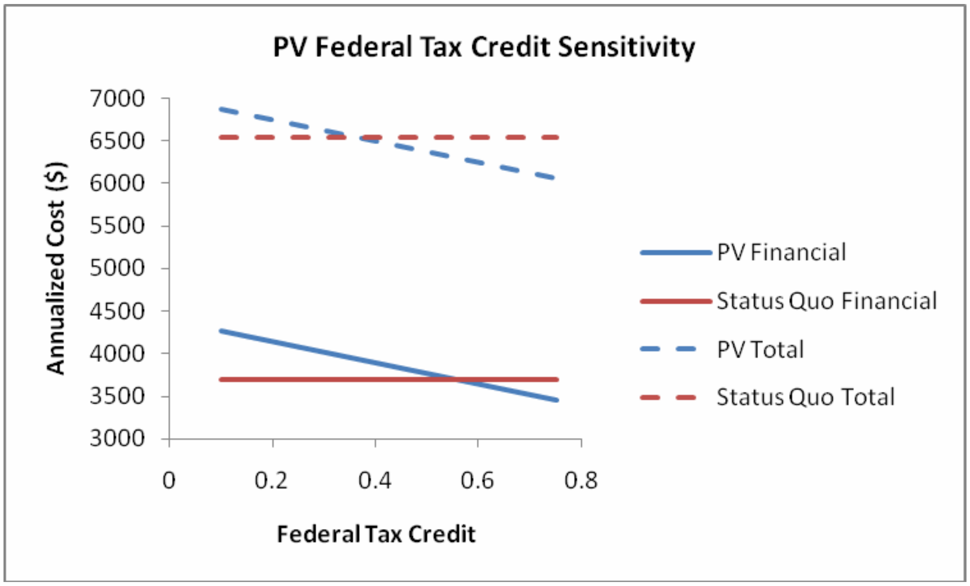


Figure 24 - Photovoltaic sensitivity to federal tax credit percentage

Examining changes to the percentage of installed costs that can be claimed as a federal tax credit is also useful. From a total cost perspective, the rebate would need to be at 38%, very close to the current 30%, for solar to be preferred. A more dramatic increase up to 55% would be needed for financial preference.

We see from this analysis that solar is quite close to being viable, particularly from a total cost perspective. Relatively small increases in state rebates and federal tax incentives would go a long way toward making a solar array viable for Home A.

5.6.3 Home B Analysis

Home B was constructed in 1925. The age of this home leaves much more room for efficiency improvements than in Home A. For example, Home B's owner had some small construction work done recently, and was told that they should consider replacing ceiling and wall insulation. Home B differs from Home A in its heating fuel use (natural gas as opposed to oil), and its fewer number of occupants. This leads to a smaller requirement for electricity, as well as less hot water usage. Home B also has a few CFLs installed, but produces a majority of its electric lighting with incandescent light bulbs.

As before, we use the PVSN tool to evaluate the implementation of various technologies in Home B.

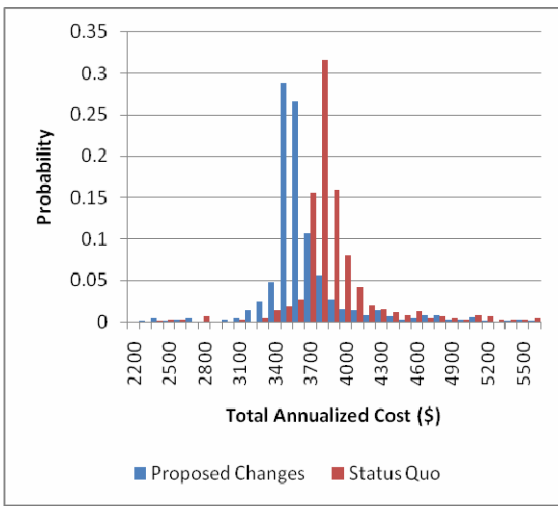
Table 29 displays those which are recommended.

	Financial Cost	Total Cost
Status Quo	$3,146.03	$3,852.77
20 (60W Moderate) CFL	$3,036.20	$3,676.40
Ceiling Insulation (R13 --> R60)	$3,096.44	$3,775.30
Ceiling Ins & CFLs	$2,986.61	$3,598.93
Daylighting (2 skylights)	$3,205.14	$3,847.43

Table 29 - Favorable technologies for Home B

We see a distinct difference here in the recommendations of the PVSN tool in comparison with Home A. First of all, the majority of the recommendations are efficiency technologies, as opposed to renewable energy technologies. We also see that these efficiency oriented technologies appear favorable in terms of both financial and total cost. Daylighting is also recommended, though only in terms of total cost, and even then the annualized total cost is only slightly less than that of the status quo. Home A had a number of heating technologies recommended from the total cost perspective, while Home B has none. This is a direct result of the fact that Home B uses natural gas for its heating fuel, while Home A uses oil. Natural gas has a significantly lower SO_2 content than oil, and SO_2 plays a large role in the costs of both environmental and health impacts. Thus, a home heating with oil will incur higher environmental and health impact costs than one heating with natural gas, and will have greater opportunity to reduce its total cost through reduced oil consumption.

Simulation provides us with a clearer perspective on risks relating to carbon emissions costs. Simulating carbon costs for the combination of attic insulation and CFLs, which provides the lowest financial and total costs, provides the following output.



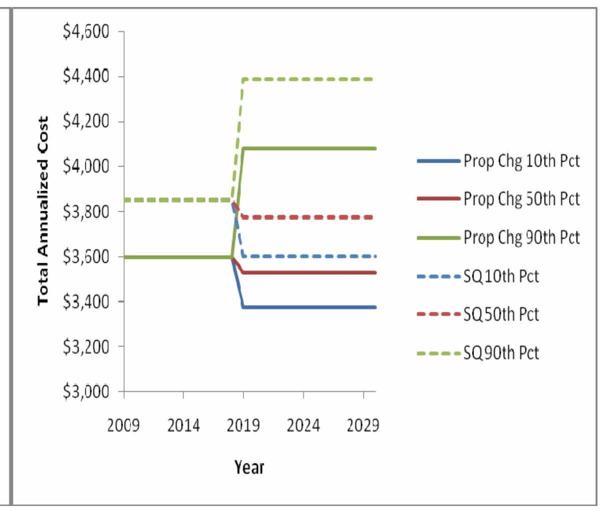


Figure 25 - Attic insulation & CFL simulation results

We see the efficiency improvements provide a moderate hedge against potential future costs of CO_2 emissions. The PDF for these proposed changes is shifted to the left of the status quo, though there does exist a bit of overlap. This is further clarified by the time series display, showing that the 10^{th}, 50^{th}, and 90^{th} percentiles of total cost for the proposed changes fall below those of the status quo. However, we see that the 90^{th}

percentile of the proposed changes exceeds the 50th percentile for the status quo, implying that costs with the status quo could potentially be lower than with the proposed changes.

It is also interesting to examine simulation of technologies that did not initially appear favorable, as high future carbon costs could make these technologies cost effective in the long run. Below we simulate Home B with the addtion of a 3 kW photovoltaic array.

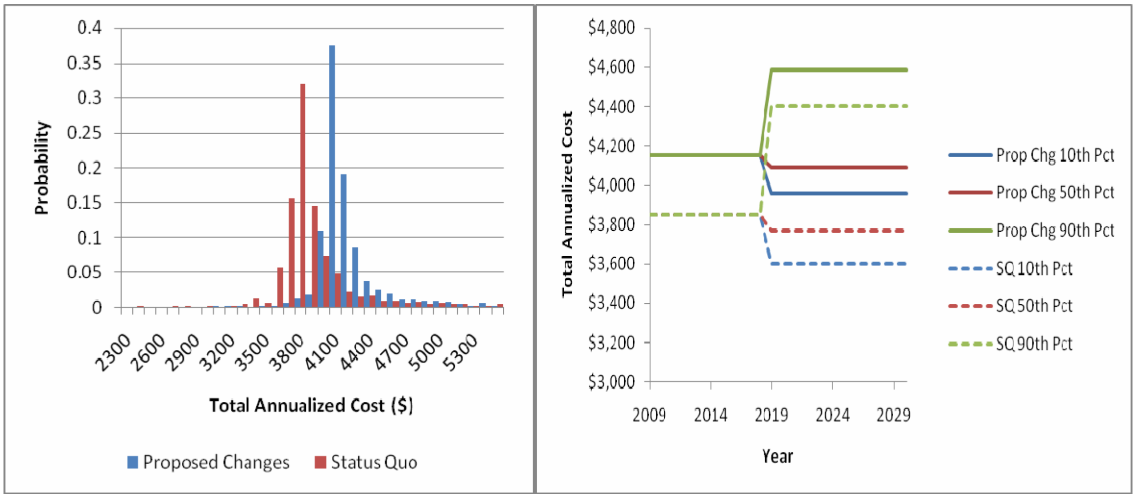


Figure 26 – 3 kW array simulation results

We see that the probability does exist that the total cost with solar panels could be lower than the total cost of the status quo. Thus, they may feel that photovoltaics are a worthwhile investment.

5.6.4 Home B Sensitivity

5.6.4.1 Daylighting

The use of daylighting in Home B warrants some sensitivity analysis, as our initial results showed it to be slightly favorable to the status quo from a total cost perspective. With our initial assumptions, the PVSN tool indicates that at an installed cost of $2,240, two skylights with lighting controls can save the homeowner 813 kWh per year. We vary each of these values in Figure 27 to see where changes in the decision might occur.

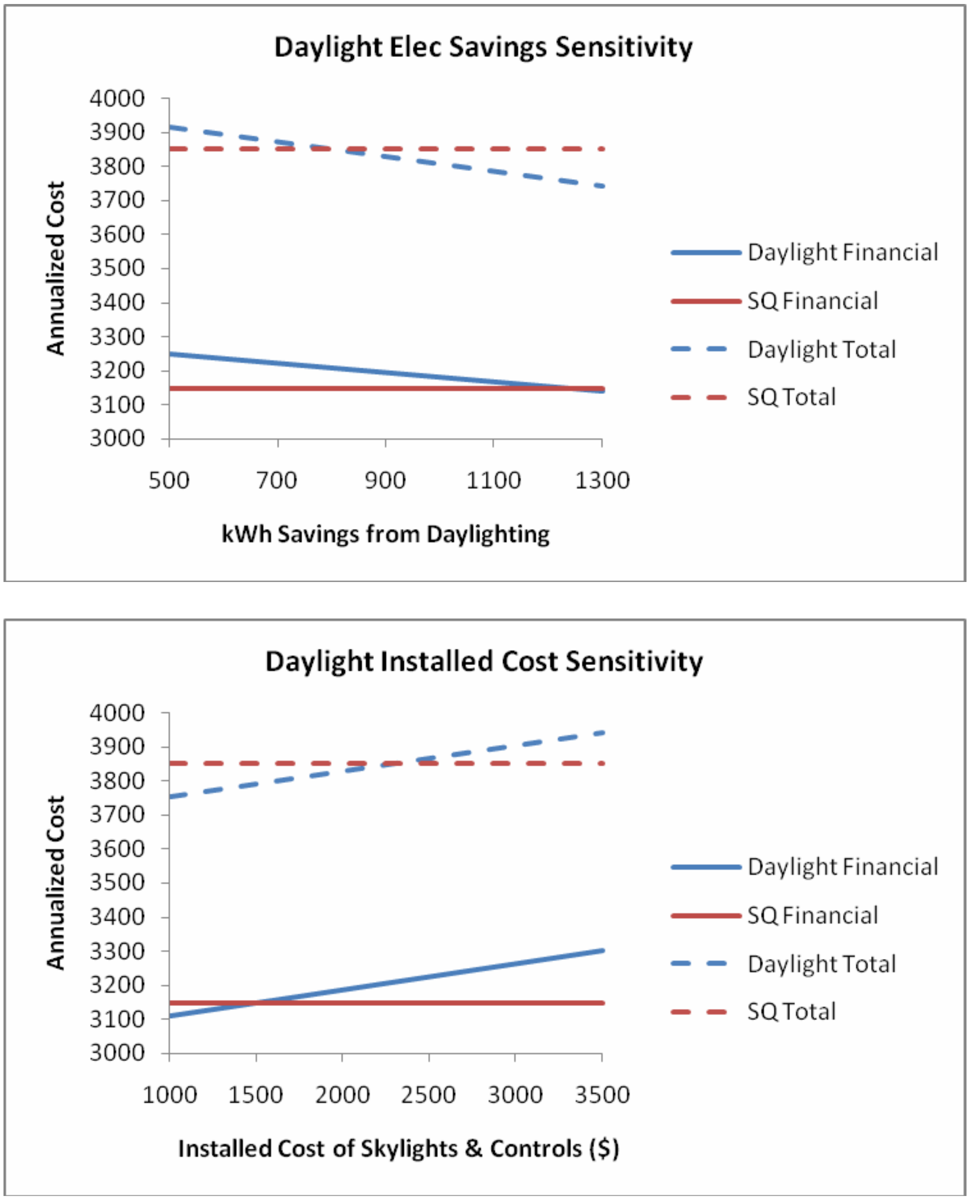


Figure 27 - Daylighting sensitivity graphs

The results of our analysis indicate that to be financially preferable about 1250 kWh/yr would have to be saved by daylighting, and to be totally preferable about 800 kWh/yr would have to be saved. In terms of installed costs, a $1500 installed cost is the breakpoint for financial preference, while a $2,300 installed cost is the breakpoint for total preference.

This analysis provides the user with some guidance regarding the installation of a 2 skylight daylighting system. If they find a contractor offering a low installed cost, for instance, they may wish to pursue the installation. Likewise, if they feel that siting specifics will allow them to achieve a significantly higher electrical savings than that generated by the model, they may wish to install daylighting. Its also worth noting that many people install skylighting systems not for energy saving reasons, but simply because they enjoy exposure to natural light. This externality is not measured by the PVSN tool, and when taken into account may make daylighting appear even more favorable.

5.6.4.2 Wall Insulation

Despite the fact that updating the insulation of a home is considered to be one of the most cost effective means of improving a building's performance, our model did not indicate the addition of wall insulation from R11 up to R19 as favorable. This result stems from the high cost of drilling, blowing, and sealing insulation into existing walls compared to the relatively low heat savings that can be gained from the change. We perform sensitivity on two parameters to further evaluate this option: the cost of labor and materials to re-insulate (currently set at $\$3.50/ft^2$), as well as the true initial R-value of the wall, which may not fit precisely within the categories allowed by the PVSN tool.

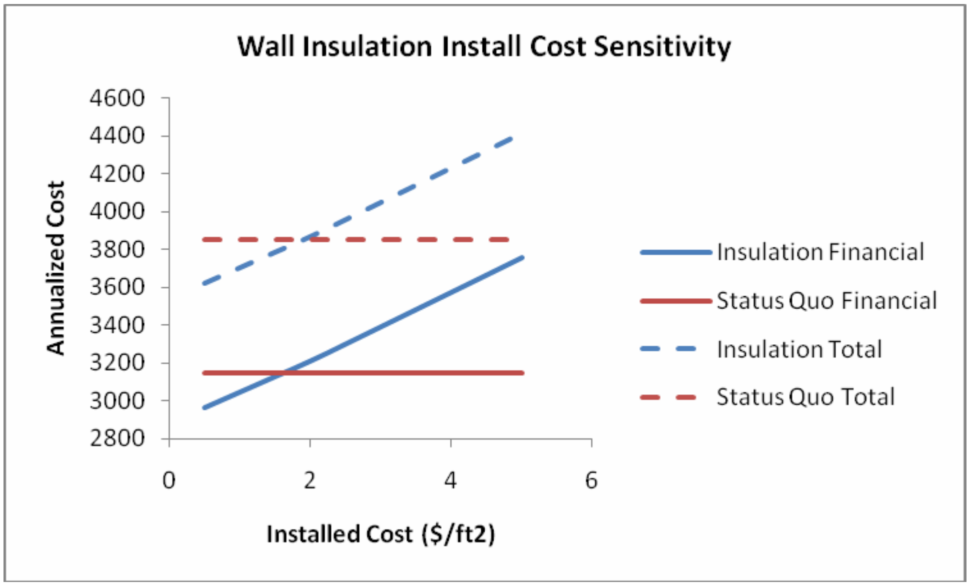


Figure 28 - Sensitivity to wall insulation costs

We see above that given that the current wall insulation level is R11, a drop in the cost of labor and materials to $1.75/ft^2$ will make wall insulation financially favorable. We also see that wall insulation is totally preferable if installation price drops below $2/ft^2$.

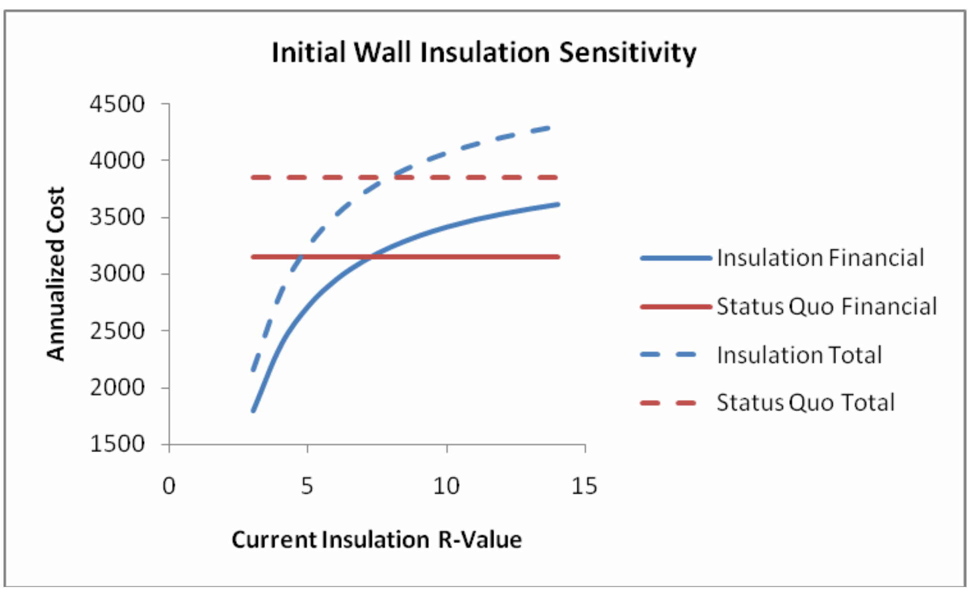


Figure 29 - Sensitivity to true initial R-value of walls

The more interesting parameter is the current insulation level of the walls. Because wall insulation is generally quite difficult to access, it may be hard for the homeowner to determine to what level their walls are insulated. Given a consistent materials and labor cost of $3.50/ft2, we see that wall insulation will be financially preferable given an initial R-value of 7, and totally preferable given an R-value of 8. This provides useful information to the user, as performing an accurate check of their wall insulation's R-value could lead them to decide that re-insulating is a good strategy for them at current prices.

5.6.4.3 Biomass

One key difference between the tool's results for Home A and Home B is the lack of heating technology recommendations for Home B. As mentioned, this stems from Home B's use of natural gas for heating, which causes fewer emissions and therefore fewer impacts than oil heat. One renewable technology that has relatively low emissions is biomass, which is considered to be carbon neutral. Biomass was not initially shown as favorable by our tool, mainly due to high fuel, capital, and installation costs. However, the fuel used for biomass heating is cordwood, which is the only fuel in the tool which the users have the ability to harvest for themselves. Depending on how the user values their time, acquiring wood instead of purchasing it could make biomass appear more favorable. Thus, we perform a sensitivity analysis on the cost per cord of wood.

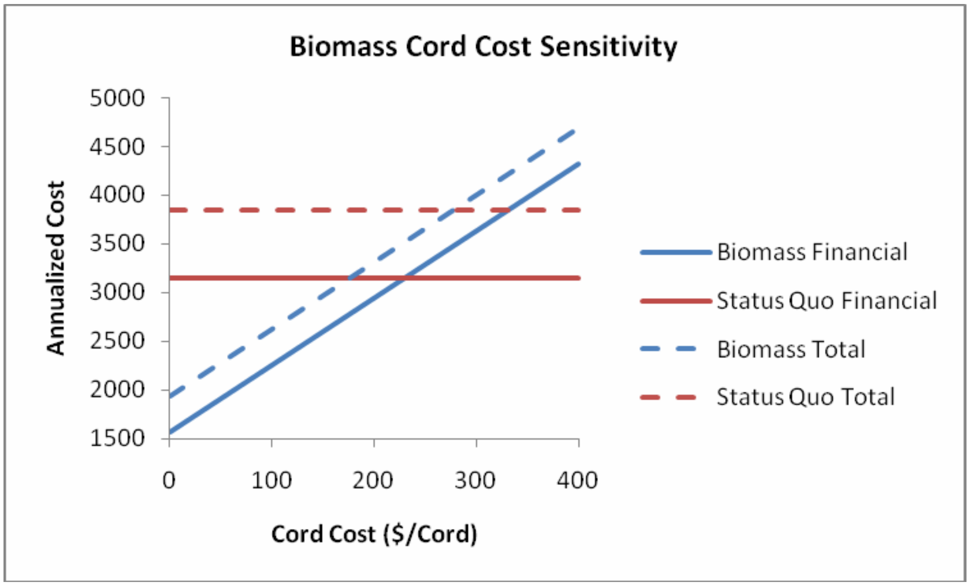


Figure 30 - Sensitivity to the cost of a cord of wood for biomass

Our base value of cost per cord is $385, based on calls to local dealers. We see that if this cost dropped to about $225, biomass would be financially viable for Home B. Thus, if the user values the time and energy it takes to collect a cord of wood at $225 or less, they may consider biomass to be a good option. This will likely depend on their living situation; if woods are easily accessible and plentiful, they will likely be more willing to gather wood themselves. We also see that a cost of $270 will make biomass totally preferable.

5.7 Future Work

The PVSN tool can be used to help people evaluate potential green energy investments; however, it can certainly be improved upon to model technologies and buildings more realistically. Some improvements to be considered for the future are:

1. Represent emissions and health impacts not only in dollar terms, but in a manner that allows users to easily grasp the significance of the impact (i.e., trees needed to absorb carbon emissions, total lives lost from emissions, etc).
2. The current model does not account for cooling loads in a home. To be more accurate, summertime cooling loads should be considered.
3. The efficiency measure of sealing air leaks in a building should be included.
4. Wood burning stoves, a common heating method in our region, should be included.
5. Our treatment of uncertainty should be extended to include more of the uncertain variables in the tool. For example, including probability distributions over energy prices or heating degree days would lead to a more complete analysis of a given scenario.
6. Some user friendly sensitivity analysis would be useful. While the tool does facilitate the sensitivity analysis of results, in its current form it requires a skilled user to do so. Updating the tool to make sensitivity analysis easy for all users would certainly improve upon the tool's utility.
7. Detail could be added to our display of results. Tufte (1980) recommends revealing data to users at several layers of detail. In its current form, the PVSN tool displays mainly high level data associated with overall costs, emission, and health impacts. The tool could include the ability to drill down and see the contribution of each selected technology to the overall results.

5.8 Conclusion

In this chapter, we have discussed in detail the creation and implementation of the Pioneer Valley Sustainability Network decision-aid tool. This tool allows home or business owners to enter information about their structure, and then view the financial, environmental, and health impacts that could result from the implementation of “green” technologies. The tool also allows users to simulate potential future carbon costs, providing them with an idea of the uncertainty of the total costs associated with a given technology selection. We present data and calculations used for the renewable energy and energy efficiency technologies present in the tool, as well as relevant emissions and human health impact calculations. We present two homes, which serve as test cases for our tool, along with a number of future improvements that could be made to enhance the tool’s functionality.

The results derived from using the PVSN tool to analyze Homes A and B are quite interesting. We see that the differences in the existing efficiency and fuel use of these structures have a direct impact on the recommendations of the tool. In the case of Home A, which is a more efficient structure but uses emission rich oil for heat and hot water, the tool showed a number of renewable heating technologies to be preferred to the status quo. For Home B, which uses cleaner natural gas for heat and hot water, the tool did not show any of the green heating technologies to be preferred. Instead, Home B’s recommendations focused heavily on the implementation of efficiency improvements like insulation and lighting. Through sensitivity analysis, we further analyzed interesting recommended scenarios, to provide the user with more information on conditions under which the scenarios remain favorable. We were able to provide more information as to when undesirable scenarios, like photovoltaics in the case of Home A and wall insulation and biomass in the case of Home B, become favorable. We also used the Monte Carlo simulation functionality to view the level of uncertainty of the total cost of different technology selections associated with carbon emissions.

6 CONCLUSION

This thesis presents the development of three tools to be used in the area of renewable energy investment decision making. The demand for such tools is a result of mounting concerns about human impacts on the natural environment, and a resulting desire to take steps to mitigate these negative impacts. We lay a foundation for our work by presenting relevant literature in the form of existing environmental decision tools, as well as methods for handling interface design and uncertainty. We then explore two prototype tools. Chapter 3 discusses the HC tool, which allows users to directly compare a variety of green energy alternatives based on the metrics of financial cost, environmental cost, and educational value. The optimization model based tool described in Chapter 4 focuses more deeply on two specific technologies (CHP and solar), and also delves more deeply into non-technological aspects of the investment decision, like fuel costs and federal rebates. Finally, in Chapter 5 we discuss the PVSN tool, which is the culmination of the work done on the previous two tools. In the PVSN tool we generalize our user interface, expand the technologies available for selection, refine our data and calculations, include federal and state incentives for renewable, use time variable fuel prices, and implement probabilistic modeling of uncertainty associated with costs of carbon emissions. The PVSN tool will be placed on the web for use by members of the community, to serve as an easy-to-use means of evaluating potential renewable or efficient technologies. Our hope is that through use of the PVSN tool, people will consider including externalities like emissions damages or human health impacts in their decision making process.

APPENDIX A

This table shows the default, minimum, and maximum values for parameters used in the construction of tornado diagrams in Section 3.4.1.

General	**Current**	**Min**	**Max**
Price Electricity ($/kWh)	0.14	0.05	0.3
Price Propane ($/gallon)	1.98	1	8
Yearly Electricity Use (kWh)	12432	5000	20000
Yearly Propane Use (gal)	933.7	700	1500
Env Cost/ton CO2 emitted	183	10	1000
Discount Rate (%)	0.03	0.01	0.15
Alternative specific			
Daylighting			
Reconstruction ($/ft^2)	5	0	100
Electricity Savings (curent building)	0.1	0	0.6
Electricity Savings (new building)	0.15	0	0.6
Double-Pane Clear heat savings	0.01	-0.3	0.1
Double-Pane Tinted heat savings	0.02	-0.3	0.1
Double-Pane Low e heat savings	0.03	-0.3	0.1
Solar			
Triple-Junction 24 cost	18799.95	16000	20000
Mono-crystalline 28 cost	31358.50	27000	34000
Mono-crystalline 42 cost	47091.75	43000	50000
Triple-Junction 48 cost	37599.95	33000	41000
Triple-Junction 72 cost	56399.85	53000	59000
Triple-Junction 96 cost	75199.80	71000	79000
Mono Useful Hrs per day	4.9	2	9
Triple J Useful Hrs per day	5.3	2	9
Mono kW/Panel	0.17	0.05	0.4
Triple J kW/Panel	0.124	0.05	0.4
Water			
BTU Reduction From GH (Living Machine)	0.23	-0.1	0.75
Heat			
Propane BTU/gal	92000	80000	120000
Biodiesel BTU/gal	121000	100000	150000
Corn (BTU/lb)	6133.33	4000	10000
Biodiesel $/gal	3	1	10
Corn ($/ton)	108.6	50	200

APPENDIX B

CHP dataset, as discussed in Section 4.1

Technology	**Steam Turbine**		**Reciprocating Engine**		
Type	**Sys 1**	**Sys 2**	**Sys 1**	**Sys 2**	**Sys 3**
Electricity Rating (kW)	500	3000	100	300	800
Heat (MMBtu/hr)	19.6	107	0.57	1.51	3.5
Install Cost ($/kW)	918	385	1515	1200	1000
O&M Cost ($/kWh)	0.004	0.004	0.0184	0.0128	0.0097
Fuel Type	all	all	natural gas propane oil	natural gas propane oil	natural gas propane oil
Fuel Input (MMBtu/hr)	26.7	147.4	1.11	3.29	8.2
Useful Life (hrs)	50 yrs	50 yrs	100000	100000	100000
Availability	99.9%	99.9%	95%	95%	95%

Technology	**Gas Turbine**		
Type	**Sys 1**	**Sys 2**	**Sys 3**
Electricity Rating (kW)	1000	5000	10000
Heat (MMBtu/hr)	7.1	26.6	49.6
Install Cost ($/kW)	1780	1010	970
O&M Cost ($/kWh)	0.0096	0.0059	0.0055
Fuel Type	natural gas propane oil	natural gas propane oil	natural gas propane oil
Fuel Input (MMBtu/hr)	15.6	62.9	117.7
Useful Life (hrs)	50000	50000	50000
Availability	95%	95%	95%

Technology	Microturbine			Fuel Cell	
Type	Sys 1	Sys 2	Sys 3	PAFC	MCFC
Electricity Rating (kW)	70	100	350	200	2000
Heat (MMBtu/hr)	0.369	0.555	1.987	0.37	1.89
Install Cost ($/kW)	2031	1561	1339	3000	2800
O&M Cost ($/kWh)	0.01	0.01	0.01	0.029	0.033
Fuel Type	natural gas	natural gas	natural gas	hydrocarbons	hydrocarbons
	propane	propane	propane	natural gas	natural gas
	oil	oil	oil	coal gas	coal gas
Fuel Input (MMBtu/hr)	0.948	1.264	4.118	1.9	14.8
Useful Life (hrs)	70000	70000	70000	70000	70000
Availability	99%	99%	99%	90%	not available

APPENDIX C

Photovoltaic dataset, as discussed in section 4.2

	Crystalline Silicon		Crystallline based Silicon	
	Mono crystalline Silicon	Multi crystalline Silicon	Ribbon sheet silicon	Concentrators Silicon cell
Installation Cost ($/W)	3.75	3.55	3.35	5
Balance of the system ($/W)	1.6	1.6	1.3	1.2
O and M Cost ($/W)	0.006	0.006	0.007	0.01
O and M Cost ($/W)	$0.07	$0.12	$0.14	$0.20
Total Cost ($/W)	$5.42	$5.27	$4.79	$6.40
Efficiency	0.15	0.12	0.14	0.25

	Non Crystalline Silicon	Non Silicon	
	Amorphous silicon	Copper Indium Diselendie	Cadium Telliride
Installation Cost ($/W)	2.5	2.5	2.5
Balance of the system ($/W)	2.5	1.6	1.6
O and M Cost ($/W)	0.001	0.001	0.001
O and M Cost ($/W) PV	$0.02	$0.02	$0.02
Total Cost ($/W)	$5.02	$4.12	$4.12
Efficiency	0.07	0.11	0.07

APPENDIX D

Solar rebates & Incentives, as discussed in Section 4.4.2

Utility/State/Federal	Program	Type of Consumer	Amount	Max
Chicopee Electric Light	Solar Rebate Program	Residential	$2.50/W	$5,000
Mass Energy	Renewable Energy Certificate Incentive	All	$0.03/kWh (sell surplus)	-
Mass Techonology Collaborative	Clean Energy Pre-development Financing Initiative	Commercial, Industrial	-	$150,000
Mass Techonology Collaborative	Commonwealth Solar Rebate	All	$2-$5.5/W	$1,200,000
Mass Techonology Collaborative	Massachusetts Green Communities Grant	All	50%	$580,000
Mass Techonology Collaborative	Sustainable Energy Economic Development (SEED) Initiative	Commercial, Industrial	-	$500,000
Federal	Business Energy Tax Credit	Commercial, Industrial	30% of expenditures	-
Federal	Residential Solar and Fuel Cell Tax Credit	Residential	-	$2,000
Federal	USDA Renewable Energy Systems and Energy Efficiency Improvements Program	Commercial Agriculture	-	500,000

APPENDIX E

Emission Factors, as discussed in Sections 4.5

Emission Factors for Electricity (lb/kWh)

	CO_2	NO_x	SO_2
Massachusetts	1.105	0.00064	0.00265

Emission Factors for Fossil Fuels (lb/MMBtu)

	Natural Gas	Propane	Butane	No. 2 Oil	No.4 Oil	No. 6 Oil
CO_2	117.08	139.18	152.13	159.23	178.57	178.57
NO_x	0.150	0.149	0.160	0.129	0.143	0.393
SO_2*	0.00060	0.00106S	0.00096S	1.014S	1.071S	1.121S

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