Development of a Green Building Decision Support Tool: A Collaborative Process

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Abstract

In this paper, 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. 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.

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 2 of this paper 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 our 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.

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.

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.

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.

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 obstructions by shadow casting objects) 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.

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.

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.

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 90th percentile value from an analysis of 28 studies on the subject by Tol. We present the range of values in Table 1. 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.

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.

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). 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. <u>Decision Tool Description</u>

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.

3.1. 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.

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.

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.

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. 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.

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.

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.

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.

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.

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.

4.2. <u>One Dimensional Analysis</u>

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 uses 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 (as labeled in legends), and the Status Quo. We will vary the marginal cost from a low of $10/ton to a high of $1000/ton.

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.

4.3. 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 the 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.

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.

5. 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.

Appendix A: This table shows the default, minimum, and maximum values for parameters used in the construction of tornado diagrams in Section 4.

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
Yearly Water Use (gal)	40050	20000	100000
Utility Cost/1000 gal H2O	3	1	5
Env Cost/1000 gal H2O	3	1	10
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

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Table 1 - Valuations of damages from CO2 emissions

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 (90^{th} percentile value)	385

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

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 3 – Costs associated with solar technologies

	Solar					
	Mono-crystalline		Triple-Junction			
Number of Panels	28	42	24	48	72	96
Initial System Price	$31,358.50	$47,091.75	$18,799.95	$37,599.95	$56,399.85	$75,199.80
Installation	$840.00	$1,260.00	$720.00	$1,440.00	$2,160.00	$2,880.00
O&M Cost (per year)	$746.67	$1,120.00	$640.00	$1,280.00	$1,920.00	$2,560.00
Inverter Cost	$2,220.99	$2,220.99	$1,897.50	$1,897.50	$1,897.50	$1,897.50
Disposal Cost	$200.59	$300.89	$171.94	$343.88	$515.81	$687.75

Table 4 - Costs associated with daylighting technologies

		Double Pane Clear	Daylighting 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 building	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 5 - Costs associated with water use technologies

	Town Water	Water Free Urinal	Water Composting Toilet	Living Machine
Initial Cost	$0.00	$377.94	$2,753.00	$10,814.89
Maintenance Cost (per year)	$0.00	$75.82	$53.33	$300.00
Disposal Cost	$5.54	$5.54	$6.42	$205.40

Table 6 - Costs associated with heating technologies in the new building

	Heating			
	Propane	**Biodiesel**	**Biomass**	**Geothermal**
Initial Cost	$1000.00	$3,500.00	$3,500.00	$18,500.00
O&M Cost (per year)	$0.00	$0.00	$1,000.00	$0.00
Disposal Cost	$55.37	$55.37	$55.37	$2,768.38

Table 7 – Example of electricity and heat requirement calculation

Electricity	
Total Electricity Needed (kWh/yr):	12432
Need reduced by Daylighting (10% svgs):	-1243.2
Electricity provided by Solar Selection (kWh):	-5751.6
Remaining electricity provided by grid (kWh):	5437.2
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 8 - Numerical output of decision tool

	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 9 - Alternative sets

	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 10 - EVPI for several parameters (present value)

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

Figure 1 - US Freshwater valuation by region

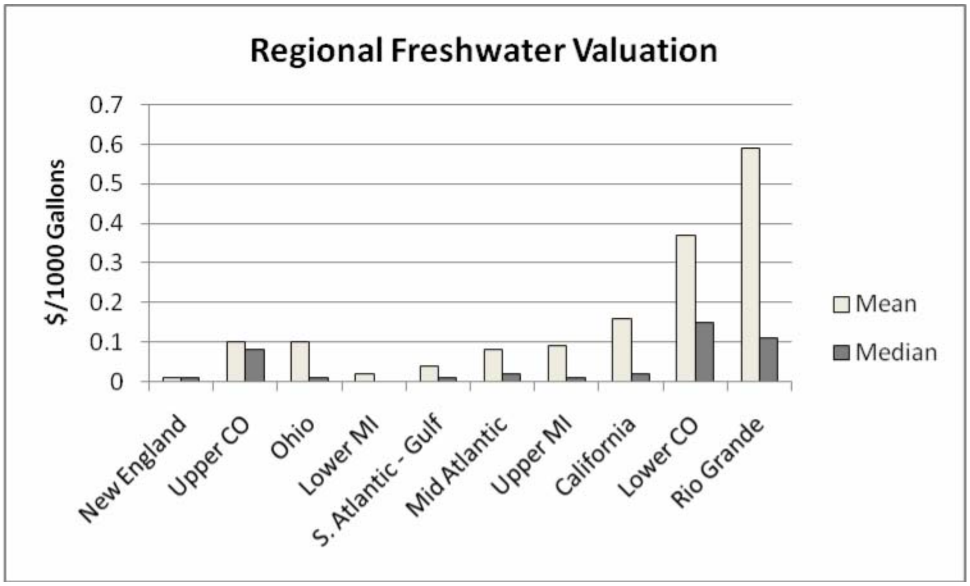

Figure 2 - Selection menus and parameters

Selection Menus:

- Current Building
- New Building

Daylighting

- None
- Double Pane Clear
- Double Pane Tinted
- Double Pane Low e

Solar

- None
- Triple Junction 24 Panel
- Monocrystalline 28 Panel
- Monocrystalline 42 Panel
- Triple Junction 48 Panel
- Triple Junction 72 Panel
- Triple Junction 96 Panel

- Full Buyback
- No Buyback

Water

- No Change
- Waterless Urinal
- Composting Toilet
- Living Machine

Heating

- Propane
- Biodiesel
- Biomass
- Geothermal

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 3 - Sample of graphical model output

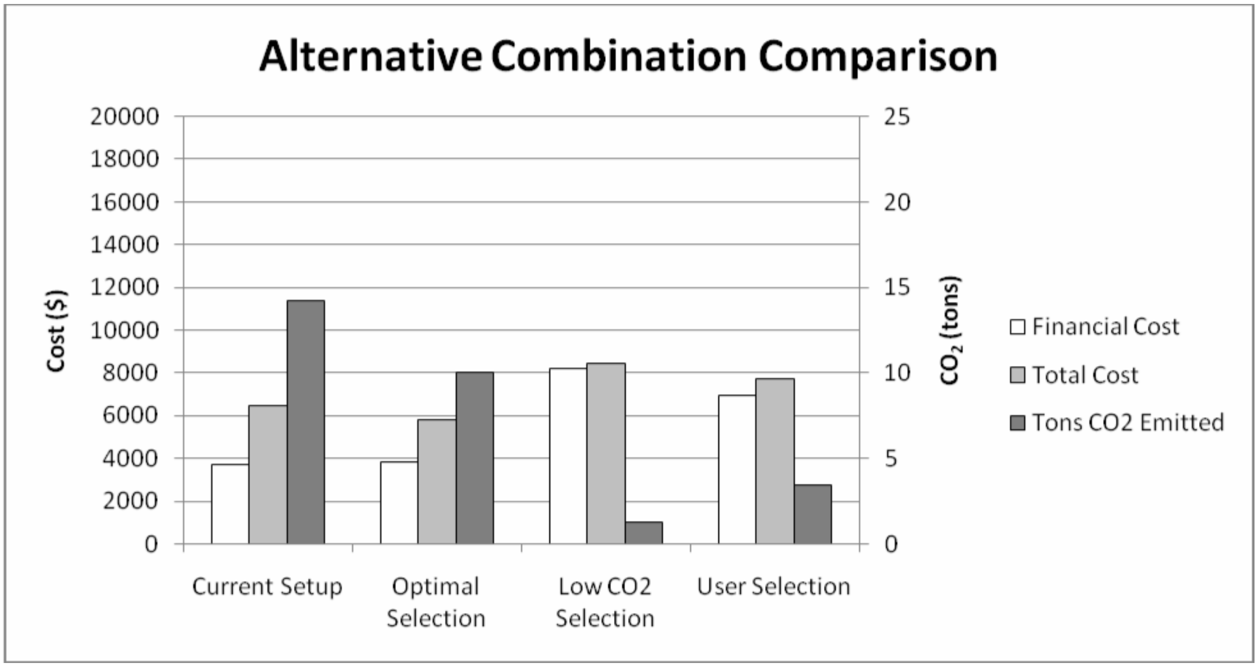

Figure 4 - Tornado diagrams for the Low Carbon and Optimal sets

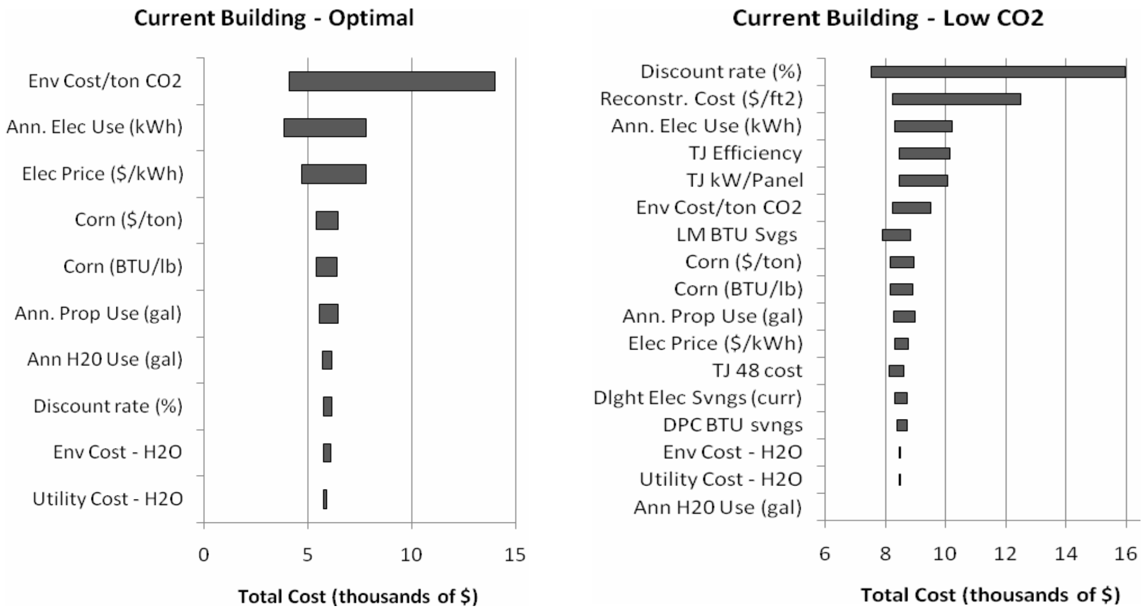

Figure 5 - Marginal cost of carbon damages sensitivity analysis