A Systems Analysis of Consumer Energy Decisions

by

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ABSTRACT

American consumers make a number of decisions that significantly impact their energy use. Some of the most important of these decisions were identified and analyzed for the purpose of including them in a Consumer Energy Decisions Model (CEDM). These decisions included housing choices that affect space heating, water heating, solar photovoltaic and transportation. The CEDM was used to calculate values of recurring and capital cost for all permutations of all the decision components for New York City, Minneapolis and Seattle. These results were analyzed using Pareto plots of recurring versus capital cost. There was a wide range of costs associated with the different solutions, indicating that there is tremendous value in making good energy decisions. The type of vehicle showed the most notable effect on return on investment. Four vehicles were analyzed, a Toyota Camry, Camry Hybrid, Jetta Turbo Diesel (TDI) and an electric Nissan Leaf. The hybrid showed the worst return on investment relative to the Camry with a payback rate of about 9 years, while the TDI and Leaf had payback rates of 1-2 and 6-10 years relative to the Camry, with the added benefits of using less energy and emitting less CO_2. Housing choices were the next most favorable investments, with payback rates around 10 years for the most economical choices. They showed good returns at some points but showed diminishing returns as continued improvements were made. Finally, the solar PV and solar hot water options are bad investments for the sites analyzed, which receive much less sunlight than other parts of the country. The effects of incentives and tax credits were not analyzed in this study.

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Chapter 1: Consumer Energy Decisions

1.1 Motivation and Objective

The impending threat of climate change due to greenhouse gas emissions and the increasing cost of fossil fuels have motivated efforts to reduce energy use and shift energy generation to alternative sources (UNFCCC, 2007). Efforts to reduce energy use are focused primarily on improving the efficiency of products (i.e. cars, houses, appliances) (McKinsey & Co., 2009) while efforts to shift generation are focused on clean, renewable energy sources (i.e. wind and solar) (Ayres & Ayres). Consumers wishing to reduce their energy use now face a barrage of options ranging from buying a hybrid car to installing solar panels on their roof. This wide range of options makes it difficult for each consumer, with their unique set of circumstances, to make the right choices for them (MacKay, 2009).

The goal of this research is to build and analyze a model which better advises these decisions. This model will be named the Consumer Energy Decision Model (CEDM) and will only consider energy decisions deemed to be *major* – those that have the potential to make significant reductions in energy use. The CEDM will also assume the lifestyle of its users is static. It will not make recommendations to drive less, use less electricity or live in smaller houses. It will simply advise decisions within the framework of a given lifestyle that will not alter that lifestyle.

1.2 Consumer Energy Use in the US

The energy use by sector in the United States is presented in Figure 1 below (EIA, 2009). Consumers directly consume all the energy of the residential sector and a significant portion of the energy used by the transportation sector. This represents a significant portion of all the energy consumption in the US. The other sectors are also indirectly affected by consumers as companies and the government must shift their production with shifting consumer demand. This is an indication that consumers have a tremendous potential to reduce overall energy use and greenhouse gas emissions.

2009 US Energy Use by Sector

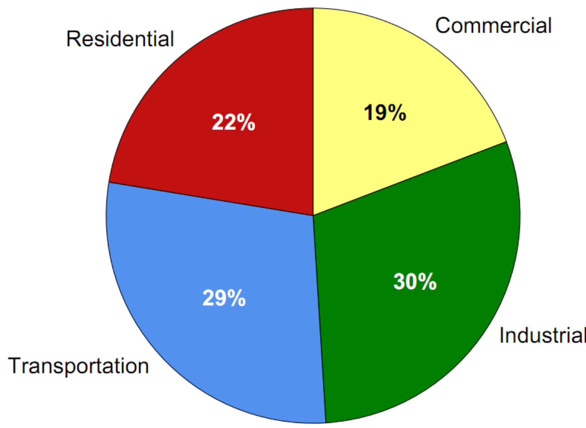

Figure 1. US Energy use by sector. Consumer energy decisions directly impact the residential and transportation sectors or approximately half of total energy use.

The residential and transportation sectors that consumers most impact are the focus of this research. Residential energy consumption is comprised of the components shown in Figure 2 (DOE). The end uses which consume the most energy in the residential sector are space and water heating. The third largest consumer, space cooling, will be neglected in the CEDM, which will focus on northern locations where air conditioning is not as prevalent. Finally, the majority of the end uses remaining (lighting, electronics, refrigeration, etc.) run on electricity. The CEDM will include an analysis of residential solar photovoltaic (PV) installations that reduce a residence's electricity demand and emissions.

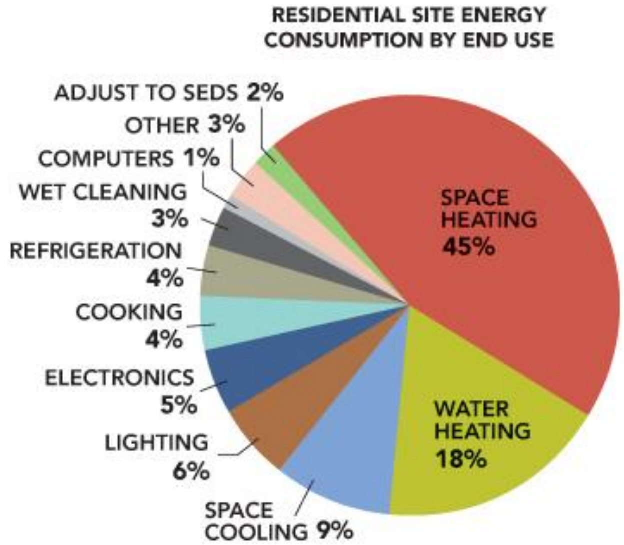

Figure 2. Residential energy consumption by end use.

Transportation consumption by end use is presented in Figure 3 below (DOE, 2008). The largest single consumer of transportation energy is light vehicle traffic at 61%, which is primarily used by consumers. An analysis of some light vehicle options will be analyzed in the CEDM and presented in this report.

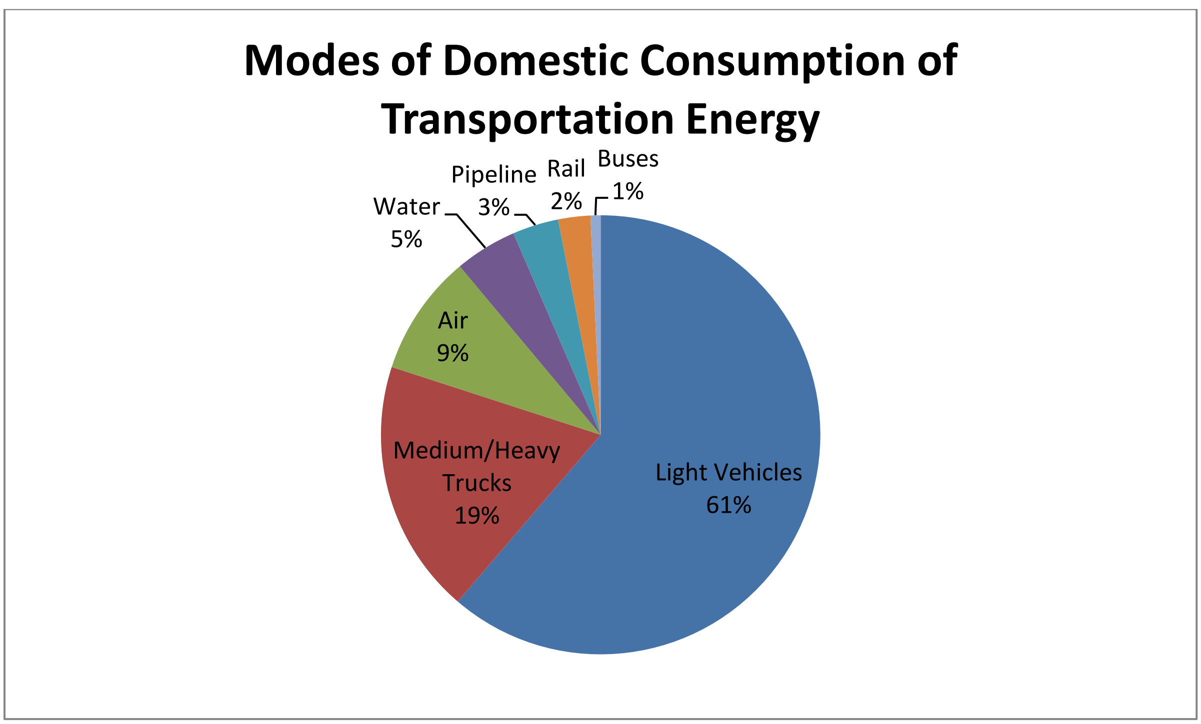

Figure 3. 2008 US domestic consumption of energy in the transportation sector by end use.

A number of studies have cited the importance and cost-effectiveness of improving energy efficiency. In *Crossing the Energy Divide*, Edward and Robert Ayres cite energy efficiency as an important step to cutting carbon emissions and economic growth. They also cite that the overall efficiency of all energy uses in the United States is a mere 13% (compared with 20% in Japan), so there is significant room for improvement (Ayres & Ayres). The central conclusion of McKinsey's 2009 report *Unlocking Energy Efficiency in the U.S. Economy* was that 'energy efficiency offers a vast, low-cost energy resource for the US economy – but only if the nation can craft a comprehensive and innovative approach to unlock it' (McKinsey & Co., 2009). The CEDM will hope to offer one of the components of this comprehensive and innovative approach by informing consumers of the most cost-effective methods of improving their personal energy efficiency.

There are currently plenty of popular products which provide advice for individual components of consumer energy use. There are tools that perform energy analysis of houses (see: Resnet, Home Energy Advisor), tools that advise car choices (Edmunds.com, autotrader.com), and even tools which advise solar energy decisions (System Adviser Model). Yet, a tool which accurately compares a consumer's entire energy portfolio is not widely used. Without this comparison consumers can not accurately unlock that low-cost resource called energy efficiency. They will not know how to best spend their money to improve their energy efficiency and reduce their carbon footprint.

1.3 Specific Objective

The objective of this research is to develop a model which compares all the major energy decisions that consumers make which will be called the Consumer Energy Decision Model (CEDM). These decisions will include the components of a home that contribute to space heating (insulation, windows, furnace, etc.), water heating, solar PV as a means of reducing electricity demand and transportation. A few different options for each component will be included, but the objective of the CEDM is not to make specific product recommendations, but to examine representative values of the components and begin to determine which components make the biggest difference in cost and energy use. These options will be analyzed on a like basis using a systems approach which will calculate all possible permutations and compare them by initial and recurring cost, emissions and net present value.

The thesis will begin with an analysis of each decision component along with a description of how they will be modeled within the framework of the CEDM in Chapter 2. Chapter 3 will present the results and some analysis of the CEDM and Chapter 4 will present the conclusions of this research along with some recommendations for future work.

Chapter 2: Development of Model

This chapter describes the overall methodology used in developing the CEDM and presents and provides some analysis of each component analyzed in the CEDM. Section 2.1 describes the methodology used to develop the model. Section 2.2 presents and analyzes the components which affect home space heating. Section 2.3 discusses domestic hot water heating options. Section 2.4 presents some optional rooftop solar phovoltaic installations. Finally, section 2.5 discusses and analyzes the transportation options used in the CEDM.

2.1 Method

A Consumer Energy Decision Model (CEDM) will be developed to compare major energy decisions made by consumers. It will analyze home space heating, water heating, solar photovoltaics and transportation. It will be capable of analyzing all types of different consumers by allowing variable locations, house sizes and configurations, and transportation habits to be input. All tax credits and incentives will be neglected in the CEDM, although it is important to note that those do play a significant role in influencing consumer decisions. Finally, this analysis neglects changeover and sunk costs. It assumes that consumers are making their initial energy decisions (buying a new car, building a new house, etc.).

A systems model will be prepared using MATLAB to compute all the permutations of components and compare those using calculated results of capital cost, recurring cost, emissions, and net present value. A series of nested for loops will be used to calculate every permutation of component options. The goal of this model is not to make specific recommendations but to find representative values for components to see which components are the most important.

The CEDM will take as inputs house floor area, volume (if known), number of floors, height of each floor, basement depth, window area, desired inside temperature, US zip code, typical electricity usage, and annual miles driven. In order to do some analysis of the CEDM some typical values will be used for these inputs for the cities of New York, Minneapolis and Seattle. The results and analysis of the CEDM will be presented in Chapter 3.

2.2 Home Space Heating

This section will present the overall method and development behind the specific home heating model. Section 2.2.1 describes the development of the thermal heat loss model used to determine home space heating requirements in the CEDM. Section 2.2.2 presents how that model was validated. Section 2.2.3 presents a heat loss analysis performed on five sample houses using the thermal heat loss model. Sections 2.2.4 to 2.2.8 describe each component which contributes to heat loss (walls, basement, windows, roof, and infiltration respectively). Section 2.2.9 describes the home heating options analyzed in the CEDM.

2.2.1 Thermal Heat Loss Model

A thermal model of a home will be created for the CEDM which will predict the heat loss of a house and how much energy and money will be required to heat it. This model will be simplistic. It will not include heat gain from solar radiation or heat loss due to doors. The types of heat loss that will be analyzed are shown in Figure 4 below along with typical relative magnitudes (Ha).

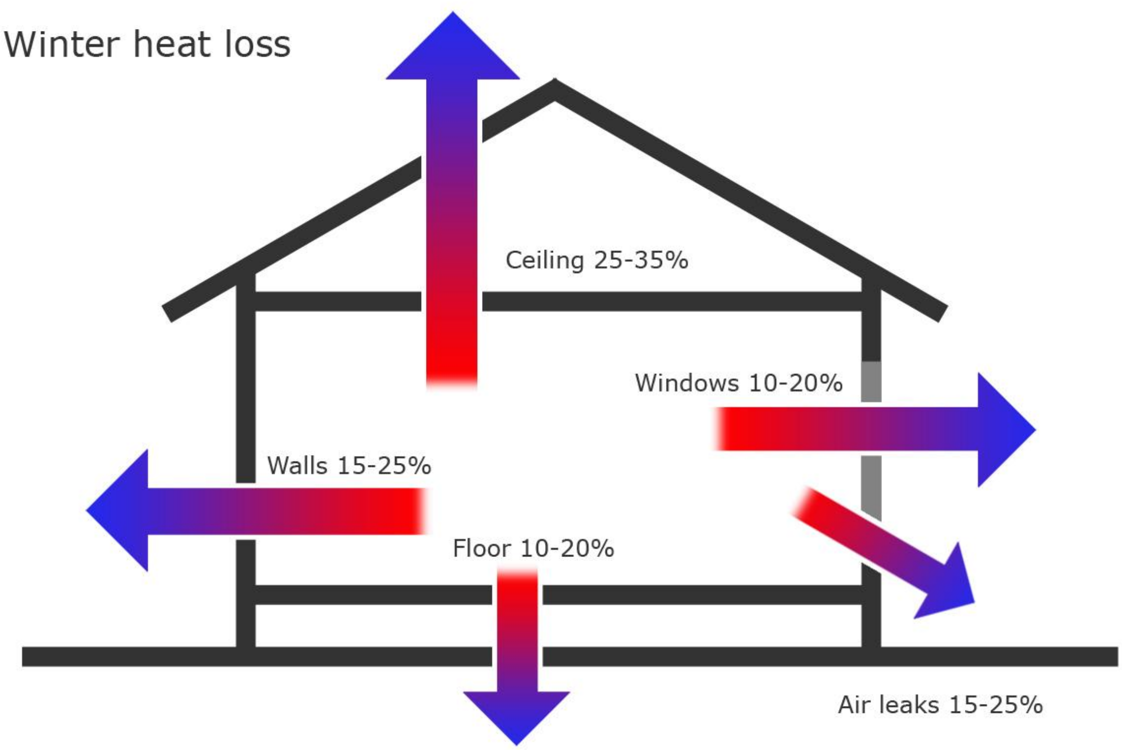

Figure 4. Major types of home heat loss with typical relative magnitudes.

All types of heat loss except air leaks will be calculated using variations of the basic heat loss equation shown in equation 1:

$$\dot{Q} = UA\Delta T \qquad (1)$$

Where $\dot{Q}$ is the heat loss over time, U is a constant which depends on the thermal resistance of the material that the heat is passing through (i.e. walls or windows of a house), A is the surface area, and ΔT is the temperature difference between the inside and outside. Equation 1 ignores heat loss due to radiation, which will be ignored in this model as it depends on temperature difference to the fourth power, which, at these small temperature differences is small relative to the losses due to conduction and convection (SOURCE). Windows are rated by their U value, while wall, basement and roof insulation is rated in R-values which relate to the inverse of U above to give the equation:

$$\dot{Q} = \frac{A\Delta T}{R} \qquad (2)$$

To calculate a value for annual heat loss using equations 1 and 2, heating degree days will be used. Heating degree days are a measure of how much (in degrees) and for how long (in days) the exterior temperature is lower than the interior (BizEE). Degree days for New York City for the last 10 years assuming a 68F interior temperature are shown in Figure 5 (EnergyCAP, 2011).

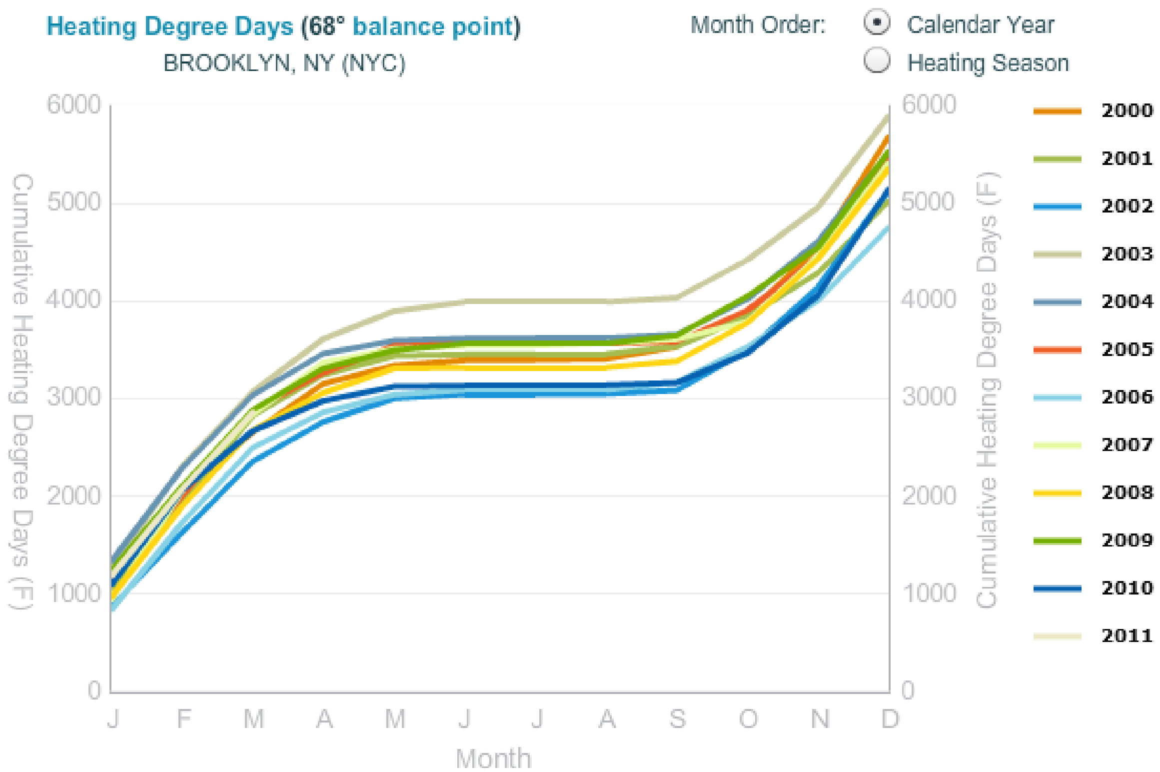

Figure 5. Heating Degree Days by month in New York City for 2000-2011 with a 68F interior temperature. The plot begins with the degree days from January and cumulatively sums them until December. The important metric that will be used is the final annual degree days.

The CEDM will use an average value of annual degree days for the three cities analyzed. These average values are shown in Table 1 below (EnergyCAP, 2011).

Table 1: Annual Average Degree Days of Cities Analyzed

New York City	Minneapolis	Seattle
5,500	8,200	5,700

Annual values for heat loss will be calculated by multiplying degree days (*D*) by surface are and the heat loss coefficient as shown in equations 3 and 4:

$$Q_{annual,\ windows} = AUD \qquad (3)$$

$$Q_{annual,\ walls\ and\ roof} = \frac{AD}{R} \qquad (4)$$

These equations will be used to model the heat loss at the windows, walls and roof, but the heat loss of the basement must be modeled differently because it has the added thermal resistance of ground to prevent heat loss. Additionally, the thermal resistance depends on the depth of the basement. Heat loss from the basement will be modeled using the approximations shown in the equations below. Equation 5 is for wall depths of less than 2 feet, 6 is for depths between 2 and 5 feet, 7 is for depths greater than 5 feet, 8 is for basement slabs at ground level (which depends on perimeter, *P*, rather than area), and 9 is for basement slabs below ground level (NAHB Research Center, 1997).

$$Q_{<2} = \frac{AD}{1.35+R} \quad (5)$$

$$Q_{2-5} = \frac{AD}{7.9+1.12R} \quad (6)$$

$$Q_{>5} = \frac{AD}{11.3+1.13R} \quad (7)$$

$$Q_{slab\ on\ grade} = \frac{P\Delta T}{1.21+0.214R+0.0103R^2} \quad (8)$$

$$Q_{slab\ under\ grade} = \frac{AD}{41.7+R} \quad (9)$$

A final method of heat loss is infiltration due to cracks or holes in the house. Every house has some infiltration that is typically determined using what is known as a blower door test. From these blower door tests, energy analysts can determine the natural infiltration of the house in air changes per hour (ACH, number of times the entire air volume changes per hour). Some typical values of air changes per hour for different building sizes are shown in Table 2 (Rutkowski, 2004).

Table 2: Typical Air Changes per Hour

	Building Size (Square feet)			
Quality	< 900	900-1500	1500-2100	2100+
Best	0.4	0.4	0.3	0.3
Average	1.2	1	0.8	0.7
Poor	2.2	1.6	1.2	1

From air changes per hour, an expected value of annual heat loss due to infiltration can be calculated by multiplying air changes, *ACH*, by the mass of the air in the house, m_{air}, the specific heat capacity of that air, $c_{p,air}$, degree days, *D*, and by 24 hours/day.

$$Q_{infiltration,annual} = ACH * m_{air} * c_{p,air} * \frac{24hrs}{day} * D \quad (10)$$

The next section will present the validation of the thermal heat loss model described in this section.

2.2.2 Validation

The equations outlined in the previous section were combined to form a preliminary home energy simulation model in Microsoft Excel. This model was then validated using the Home Energy Rating System Building Energy Simulation Test (HERS BESTEST), provided by the National Renewable Energy Laboratory (NREL). HERS BESTEST is used to validate the accuracy of Building Simulation models. The HERS BESTEST provides a series of test cases for a house along with predicted results for heat loss. The test cases are designed to test all the components that contribute to heat loss. These same tests are used to validate Home Energy Simulation Programs that are seeking HERS certification (Judkoff & Neymark, 1995).

The first five test cases, which test different window, wall and infiltration components, were run with the preliminary CEDM heat loss model and compared with the HERS BESTEST required upper and lower bounds for certification. The results were favorable, indicating that the CEDM was quite accurate, not enough to be certified, but sufficient for the purposes of the overall CEDM analysis. The results of the test cases are shown along with the upper and lower bounds in Figure 6 below (Judkoff & Neymark, 1995).

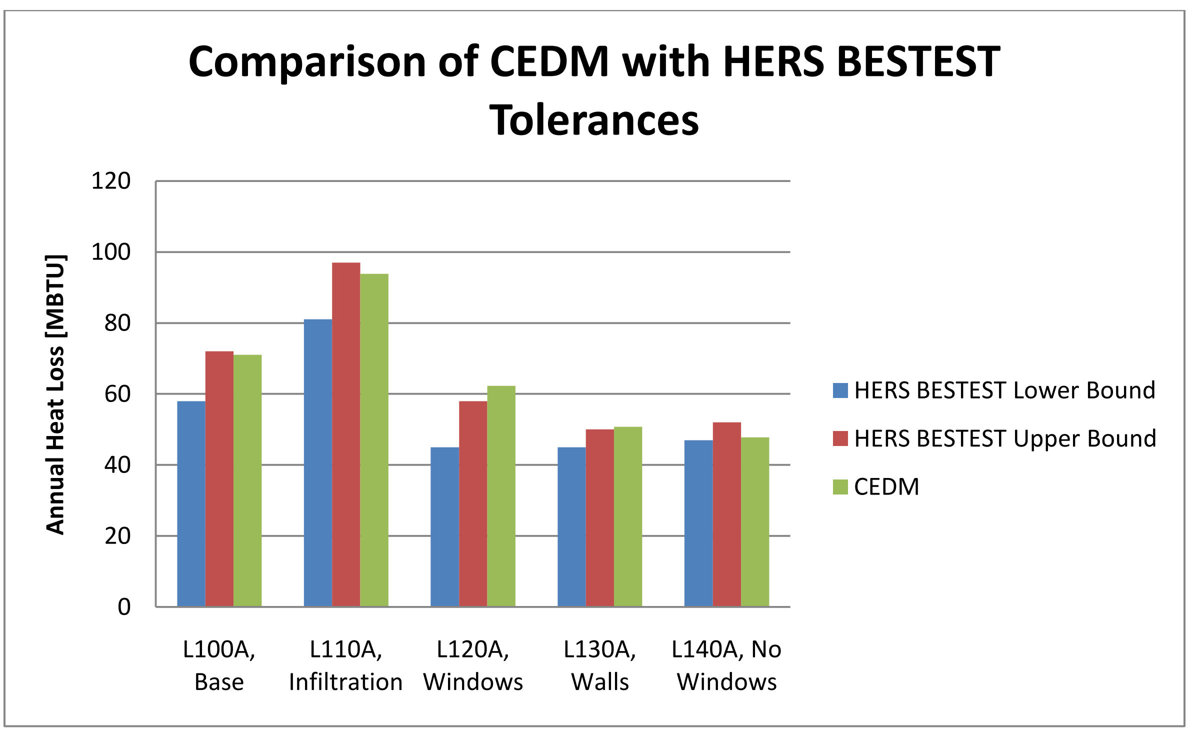

Figure 6. Comparison of the specified upper and lower bounds of the HERS BESTEST results with the results of the CEDM.

The next section will present an analysis of five sample houses using the thermal heat loss model that was validated in this section.

2.2.3 Sample Houses

The thermal heat loss model described in section 2.2.1 and validated in section 2.2.2 was used to analyze energy audits of real houses received courtesy of Sisler Builders of Stowe, VT (D'Muhala & Sisler, 2011). Sisler Builders reported the dimensions of five houses (floor area, window area, basement depth, etc.), the insulation R-values of the different parts of the house, window U-values, the results of a blower door test, the average interior temperature, and the amount of propane or wood used to heat the house annually. The expected annual heat loss of the CEDM model was compared with the reported annual heating energy. There was significant variation in the results: for one house, the results were accurate to within 1% while another was only within 50%. This variation is indicative of the difficulty of collecting accurate data for the various house components and for energy usage. The comparison of expected heat loss using the thermal heat loss model with the reported heating energy used for all five houses is shown in Figure 7 in millions of BTUs (MBTU).

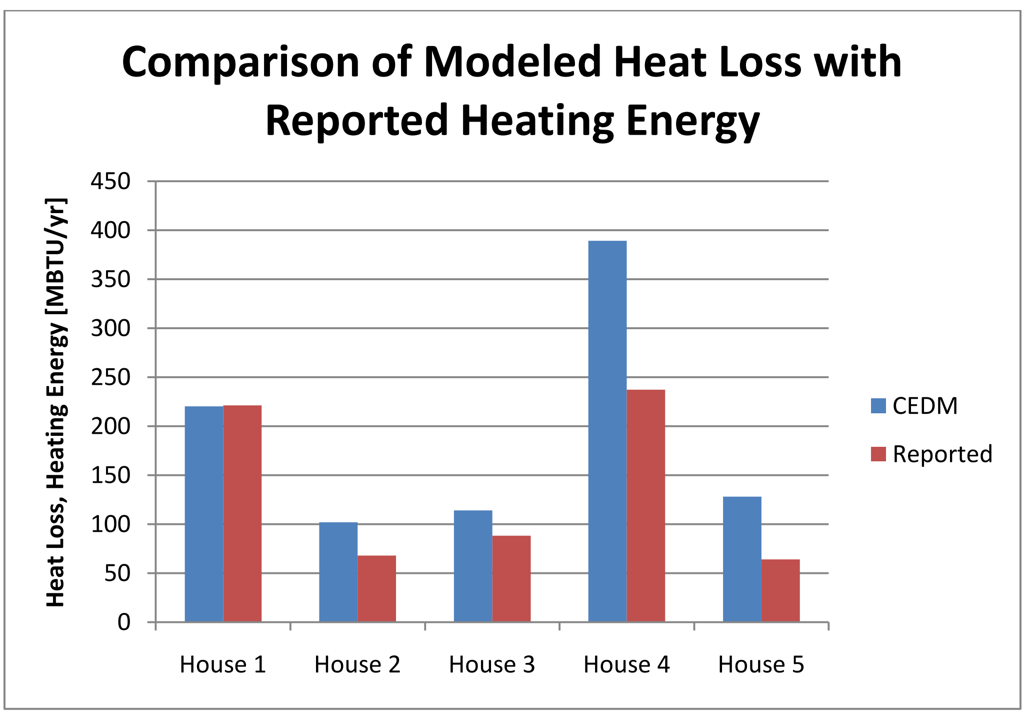

Figure 7. Comparison of expected heat loss from the CEDM with reported heating energy consumption for five Sisler Builders' energy audits.

From these sample houses, an analysis of the types of heat loss was performed to see which contribute most to the total. Figure 8 shows a plot of the relative contributions of each heat loss type for each of the five houses as calculated by the thermal heat loss model. The walls, windows and infiltration generally contribute the most to the heat loss, while roof and basement contribute the least. Sisler Builders does a number of energy-motivated renovations and they have found that reducing infiltration is generally the most cost effective method of improving house efficiency. This is because reducing infiltration is generally only a matter of plugging holes and can make a significant difference in energy consumption, while improving the walls or windows includes a significant materials and reconstruction cost (Sisler, 2011).

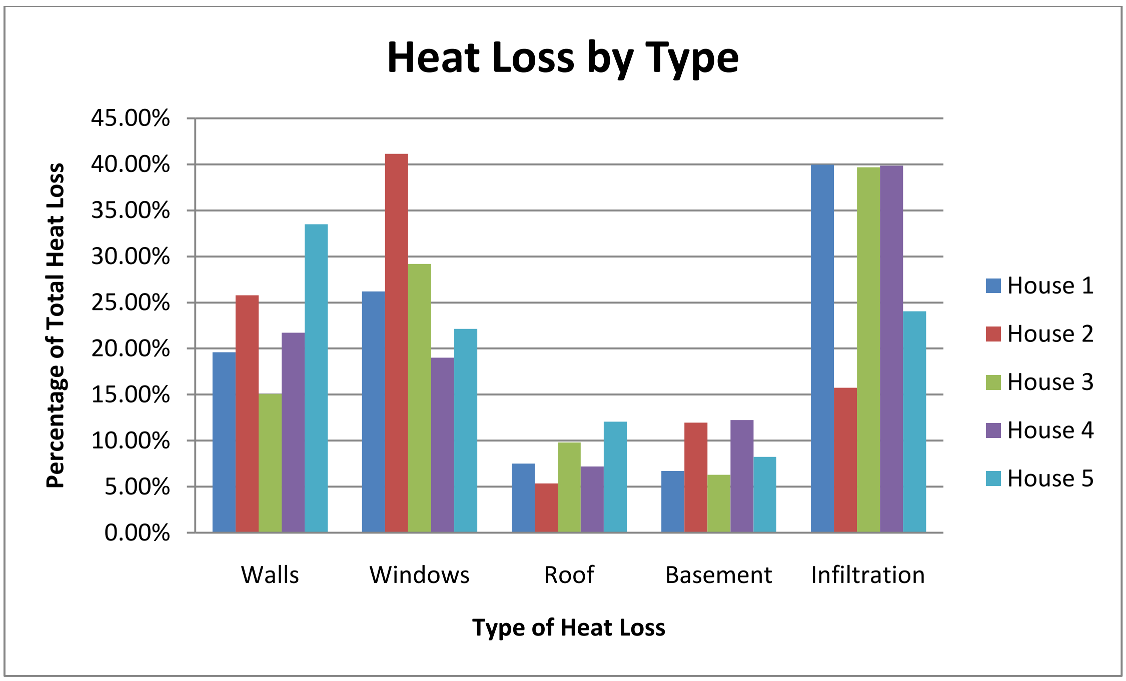

Figure 8. Relative heat loss consumption by type for the five Sisler Builders energy audits.

Now that the thermal heat loss model has been described, validated and used to analyze some sample homes, the specifics of how it will be used within the framework of the larger CEDM. Each housing component that will be analyzed in the CEDM will be described in the following sections, beginning with walls in the next section.

2.2.4 Walls

The wall area is calculated, assuming a square floor-plan house, by taking the square root of floor area (*FA*) divided by the number of floors (*floors*), multiplying by the four walls, and then multiplying by the wall height of the building (h_{wall}) as shown in equation 11:

$$A = 4 * \sqrt{\frac{FA}{floors}} * h_{wall} \quad (11)$$

Next, a price matrix must be created for wall constructions of varying insulation values. Wall constructions vary significantly in cost depending on variables such as wall design, materials used and the cost of labor. Analysis of these variables is beyond the scope of this thesis. This research is only concerned with how the cost of walls varies with the insulation R-value. Carrie Brown, a graduate student at MIT, has simulated the costs of a number of different wall assemblies using the building cost simulation software RSMeans. Some representative values from her work will be used as the price matrix for insulation of wall assemblies. One of Ms. Brown's plots of cost per square foot vs. insulation R-Value is shown in Figure 9 below (Brown, 2010).

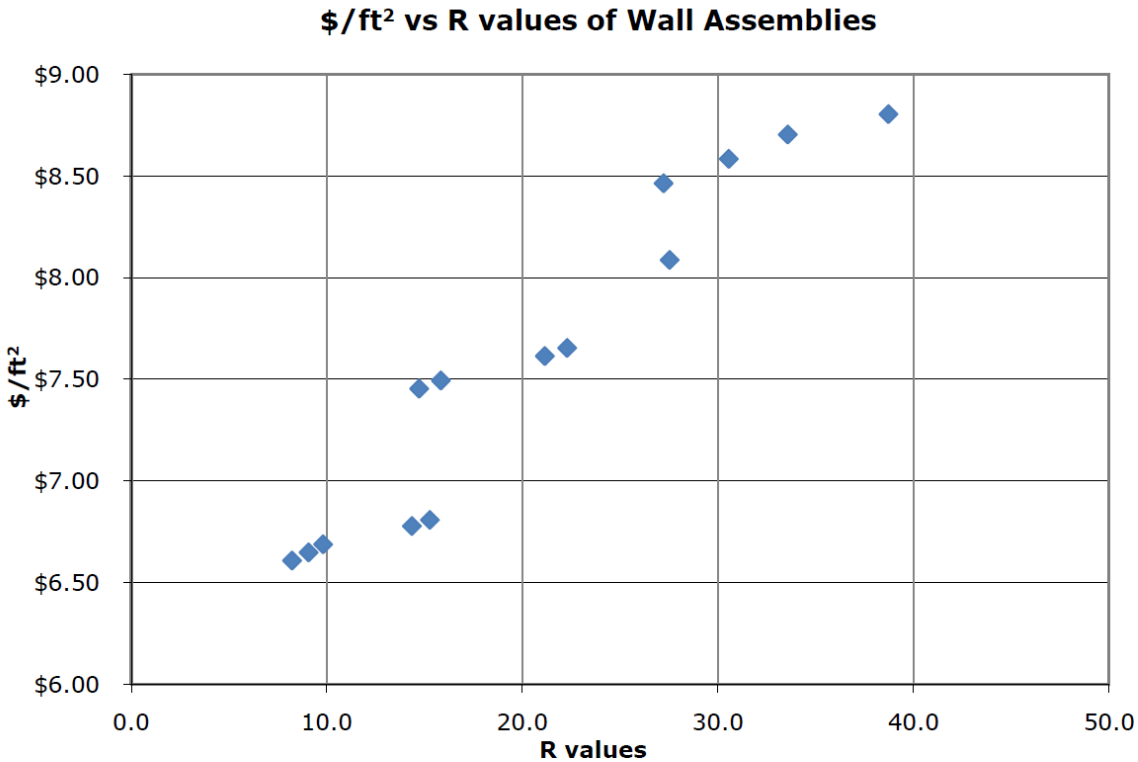

Figure 9. Cost/ft2 vs. R-values of various wall assemblies. Courtesy of Carrie Brown, graduate student at MIT, who calculated them using the building simulation software RSMeans.

From Ms. Brown's plot, some rough, representative points will be selected to create a price matrix at R-values of 10, 20, 30, and 40. The price matrix that will be used in the CEDM is shown in Table 3:

Table 3: Price Matrix of Wall Assemblies

R-value [hr*ft^2*°F/BTU]	10	20	30	40
Specific Cost [$/ft^2]	$6.70	$7.50	$8.25	$9.00

The capital cost of each wall assembly is calculated by multiplying the specific cost by wall area. The annual heat loss of each wall assembly is calculated according to equation 4.

The next section will describe the basement options analyzed in the CEDM.

2.2.5 Basement

The cost of insulation values in basement assemblies will sometimes be greater than the cost of wall assemblies and sometimes be less depending on the type of basement (Oak Ridge National Laboratory, 2008). For simplicity, this model uses the same price matrix for basement insulation as for wall insulation. The capital cost of each basement assembly is calculated by multiplying the below ground wall area and the specific cost of the assembly. The below ground wall area is calculated by replacing the wall height with basement depth in equation 11. Because a below grade basement floor already has significant natural thermal resistance, the option of adding extra insulation to the basement floor is neglected in the CEDM. Since this is not a design option presented for the consumer, the heat loss associated with the basement floor is not calculated in the CEDM. Therefore, the annual heat loss of the basement is calculated using only equations 5-7 above. The basement wall area at each depth specified by equations 5-7 is calculated. Then the heat loss at each of these depths is calculated and summed to determine the total basement heat loss.

The window options analyzed in the CEDM are presented in the next section.

2.2.6 Windows

The price matrix for windows was built by dividing the cost by the area of a few Andersen windows. The price matrix used for the model is shown in table 4 below (Andersen Windows).

Table 4: Price Matrix of Windows

U-value [BTU/(hr*ft^2*°F)]	0.45	0.33	0.28
Specific Cost [$/ft^2]	$19.00	$25.00	$43.00

The window capital cost is calculated by multiplying the window area and the specific cost of each window. The annual heat loss is calculated for each window according to equation 3.

The roof options used in the CEDM are described in the following section.

2.2.7 Roof

The price matrix for roof assemblies was compiled from the recommendations of Steve Sisler of Sisler Builders and is shown in table 5 below (Sisler, 2011).

Table 5: Price Matrix of Roofs

R-value [hr*ft^2*°F/BTU]	38	50	80
Specific Cost [$/ft^2]	$2.65	$3.49	$7.68

The roof area is calculated by simply dividing the floor area by the number of floors. The roof capital cost is then calculated by multiplying the roof area by the specific cost. The annual heat loss of each roof option is calculated according to equation 4 above.

A discussion of infiltration follows in the next section.

2.2.8 Infiltration

Infiltration is neglected in the CEDM because there is tremendous variation in the cost associated with reducing infiltration. It would require a tremendous amount of analysis beyond the scope of this thesis to determine the costs of reducing infiltration and personalizing it for various consumers and it would be virtually impossible to assign representative costs for infiltration levels in the manner done for the other components. However, it is important to note that infiltration improvements are often where the easiest gains in overall house efficiency can be made, especially in retrofit scenarios. Improving infiltration often only requires easy fixes like resealing windows and doors and filling in holes from vents. Reducing the heat loss due to windows and walls, on the other hand, are much more expensive because they require new materials and, in the case of retrofits, renovation. That said, infiltration reductions must always be made while keeping moisture issues in mind as reducing the natural ventilation of the house may trap more moisture in the house and cause mold. A forced air ventilation system is required if the natural ventilation is below a certain level (Sisler, Steve; 2011).

A description of the heating options used in the CEDM is presented in the next section.

2.2.9 Heating

The furnace price matrix was also compiled at the recommendation of Steve Sisler of Sisler Builders and is shown in table 6 below (Sisler, Steve; 2011).

Table 6: Price Matrix of Furnaces

Furnace Efficiency	85%	90%	93%
Furnace Cost	$2,000	$3,700	$7,300

The annual energy required for the furnace is calculated by summing the heat loss of all the components described above and dividing by the efficiency. The boiler is assumed to run on natural gas. The annual heating cost is calculated by multiplying the natural gas required by the price of natural gas. The prices of residential natural gas are shown in Table 7 (US Energy Information Administration (EIA), 2011):

Table 7: Natural Gas Prices [$/mmBTU][1]

New York City	Minneapolis	Seattle
$11.66	$8.26	$11.47

[1]Natural Gas prices are reported in thousand cubic feet so a conversion factor of 1.029 MBTU/thousand cubic feet was used to calculate price per MBTU (Energy Star).

The annual CO_2 emissions are calculated by multiplying the amount of natural gas used by the furnace by the CO_2 emission factor for natural gas, 117.1 lb/MBTU (Supple, 2007).

This section completes the description of how home space heating is analyzed in the CEDM. The next section previews the domestic hot water heating options that will be analyzed in the CEDM.

2.3 Domestic Hot Water

This section describes the domestic hot water options analyzed in the CEDM. This analysis will focus on a comparison between solar and conventional hot water heating. Section 2.3.1 presents some background information on solar water heaters. Section 2.3.2 discusses the performance, energy requirements and cost of solar water heaters in the US. In section 2.3.3 the annual emissions of each of the hot water heating systems is calculated.

2.3.1 Solar Hot Water Heaters

A number of different domestic hot water heaters will be analyzed within the framework of the CEDM, including those with solar collectors, which are generally used in rooftop installations and use the sun's energy to heat the water. Hot water systems that include solar collectors generally must also include a boiler that uses an on-demand fuel such as electricity or natural gas. Otherwise during the winter or cloudy days, homeowners with only solar hot water heating would have to greatly limit their consumption. Hot water heating systems are generally designed as shown in Figure 10 below, with the solar collector feeding hot water to a storage tank with a back up electric or natural gas boiler used to heat the water any additional amount required.

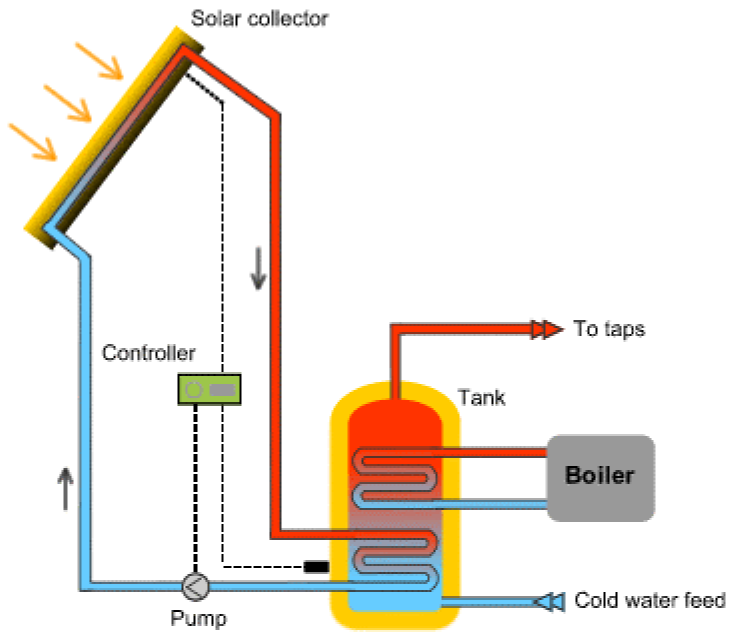

Figure 10. Typical design of a residential solar hot water heating system (Arredemo).

The CEDM will analyze flat-plate solar collectors (FPSCs) in addition to conventional hot water heating systems. FPSCs are the perhaps the most popular solar water heating system in the US (Gil & Parker, 2009). They are essentially metal boxes with glass or plastic covers, dark absorber plate bottoms and insulated sides to minimize heat loss. Sunlight passes through the transparent cover, heats up the absorber plate, which heats up liquid passing through pipes attached to the absorber plate. A simple schematic diagram of a flat plate solar collector is shown in Figure 11 below (FLA Solar).

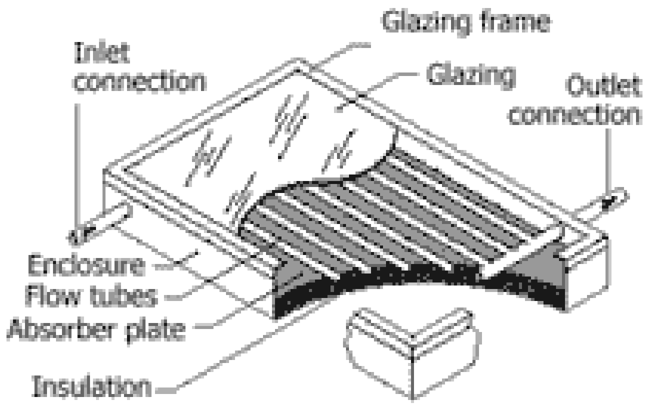

Figure 11. Diagram of a flat-plate solar collector. Sunlight passes through the glazing, heats up the absorber plate, which heats up the liquid flowing through pipes attached to the absorber plate.

This concludes a background description of solar hot water heaters. The next section will present some analysis of the performance of solar hot water heaters in different geographical locations.

2.3.2 Performance, Energy Requirements and Costs

Much of this analysis comes from the Gil and Parker paper, which presents the results of simulations of a number of different hot water heating options. Their study simulates the energy requirements of typical electric and natural gas boilers, used as the sole form of heating, and in conjunction with 40 and 64 ft^2 FPSCs. The natural gas boiler used in the simulation has an efficiency of 59%, while the electric boiler is 90% efficient (Gil & Parker, 2009). The simulation assumes that 60 gallons of hot water is used each day.

Performance of solar collectors depends on the amount of sunlight they receive, which varies by geography and climate. To illustrate this fact, Figure 12 shows a map displaying annual fractional savings of a solar hot water heating system in different locations in the US. The southern locations, which enjoy the most sun, are also those which receive the highest portion of their water heating from the solar collector.

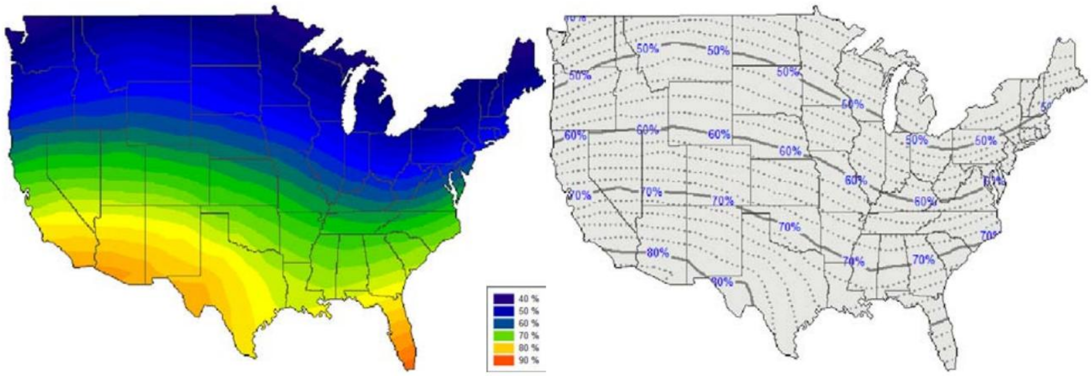

Figure 12. Annual fractional energy savings (%) for a household using 60 gallons of hot water a day, with a standard 40 gallon electric water heater combined with a 40 ft^2 flat plate closed loop solar water heater.

The energy required for water heating also varies geographically because the temperature of water flowing into a hot water heating system from the water mains will vary significantly with the location, weather and time of year. The annual energy required for water heating can vary by as much 2:1 due to varying inlet temperatures in extreme locations of the US (Gil & Parker, 2009). An equation has been developed which estimates water main temperatures depending on location, weather data and time of year and is shown below as equation 12 (Hendron R, 2004).

$$T_{mains} = (T_{amb,avg} + offset) + ratio * \left(\frac{\Delta T_{amb,max}}{2}\right) * \sin\left(0.986 * (day\# - 15 - lag) - 90\right) \quad (12)$$

Where: T_{mains} = mains (supply) temperature to domestic hot water tank (°F)

$T_{amb,avg}$ = annual average ambient air temperature (°F)

$\Delta T_{amb,\ max}$ = maximum difference between monthly average ambient temperatures (e.g., $T_{amb,avg,july} - T_{amb,\ avg,\ 27anuary}$) (°F)

0.986 = degrees / day (360 / 365)

day# = Julian day of the year (1 – 365)

offset = 6 °F

ratio = 0.4 + 0.01 · (Tamb,avg – 44)

lag = 35 – 1.0 · (Tamb,avg – 44) (°F)

A monthly temperature profile of water mains in Chicago is shown in Figure 13 to illustrate the magnitude and lag time with which water main temperature varies relative to ambient temperature (Gil & Parker, 2009).

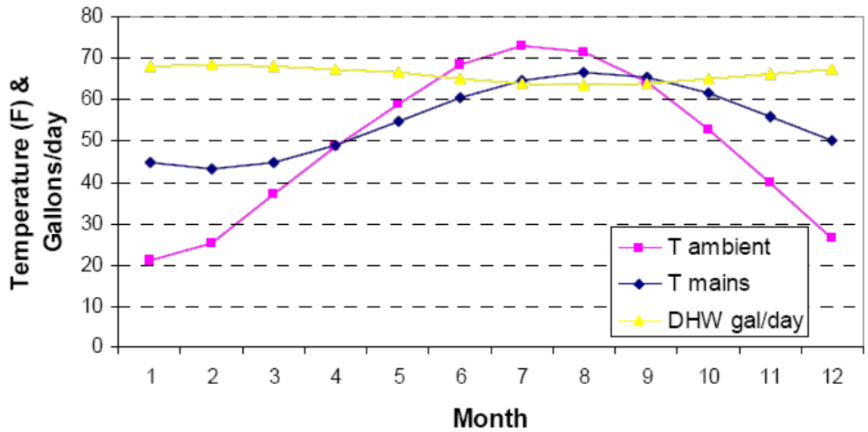

Figure 13. Water main temperature profile for Chicago.

Since water main temperatures are lower in colder, more northern locations, more energy is required to heat that water for domestic use. So even though southern locations will experience the highest relative energy savings with a solar water heater, they do not have the highest absolute savings. The highest absolute savings of solar water heaters occur in states like Colorado and Utah, which are very sunny, but are colder than more southern states and require more energy for water heating. A map of absolute energy savings is shown in Figure 14 for the same system that was shown in Figure 12 (Gil & Parker, 2009).

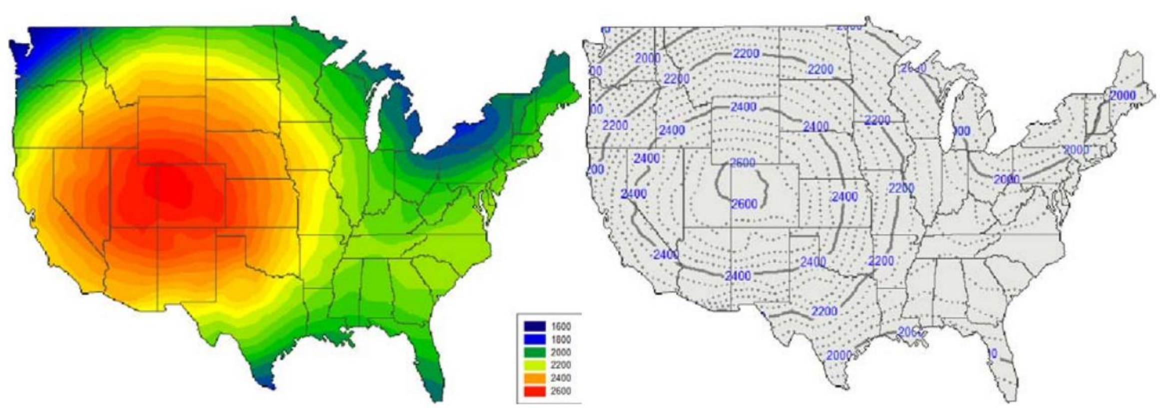

Figure 14. Annual absolute energy savings in kWh for a standard 40 gallons electric water heater combined with a 40 ft2 flat plate closed loop solar water heater.

The Gil and Parker report provides annual expected energy requirements for the electric and natural gas boilers for cities across the US along with the expected absolute savings for the two solar collectors. From this data, expected energy required of the electric or gas boiler was calculated for each system. These data are shown for New York City, Minneapolis and Seattle, the three sites analyzed by the CEDM in Table 8.

Table 8: Annual Expected Energy Requirements of Water Heating Systems

Water Heater Type	New York City	Minneapolis	Seattle
Electric [kWh]	3776	4438	3965
Electric w/ 40 ft^2 FPSC [kWh]	1748	2344	2289
Electric w/ 64 ft^2 FPSC [kWh]	1253	1723	1818
Natural Gas [therms]	209	243	218
Gas w/ 40 ft^2 FPSC [therms]	132	166	155
Gas w/ 64 ft^2 FPSC [therms]	106	136	132

Using the data from Table 8, an annual cost of each of the systems can be calculated by multiplying the energy requirement of the boiler by the cost of electricity or natural gas in the region. The costs of electricity and natural gas for the three sites are shown in table 9 (US Energy Information Administration (EIA), 2011).

Table 9: Electricity and Natural Gas Prices

	New York City	Minneapolis	Seattle
Electricity [$/kwh]	$0.174	$0.1035	$0.0802
Natural Gas [$/therm][1]	$1.166	$0.826	$1.147

[1]Natural Gas prices are reported in thousand cubic feet so a conversion factor of 10.29 therms/thousand cubic feet was used to calculate price per therm (Energy Star).

From the data presented in Tables 8 and 9, a recurring energy cost can be calculated. However, for a full cost comparison, the capital cost of each system must be estimated. An electric water heater with the same specifications as the one used in the Gil and Parker study costs approximately $240, while a natural gas heater costs approximately $300 (Sears). Another half of that cost is added as an approximate installation cost. This results in final estimated costs of $360 and $450 for the electric and gas boilers respectively. A 40 ft^2 flat-plate solar collector costs approximately $1,000, but has a total installed system cost, including the boiler, of approximately $5,000 (Sun Source Energy Products). The 64 ft^2 flat-plate collector will be estimated at a 50% increase from the 40 ft^2 at $1,500, and assuming an increase in the component and installation requirements will be estimated to have a total installed cost of

$6,000. Table 10 presents the estimated total installed cost of each system along with the estimated annual heating costs in each geographic location.

Table 10: Initial Installed and Annual Heating Costs of Water Heater Systems

Water Heater Type	Installed Cost	NYC	Minneapolis	Seattle
Electric	$360	$657	$459	$318
Electric w/ 40 ft^2 FPSC	$5,000	$304	$243	$184
Electric w/ 64 ft^2 FPSC	$6,000	$218	$178	$146
Conventional Gas	$450	$244	$201	$250
Gas w/ 40 ft^2 FPSC	$5,000	$154	$137	$178
Electric w/ 64 ft^2 FPSC	$6,000	$124	$112	$151

In order to better visualize and compare the recurring costs displayed in Table 10, Figure 15 below presents the annual water heating cost of the various systems and geographic locations.

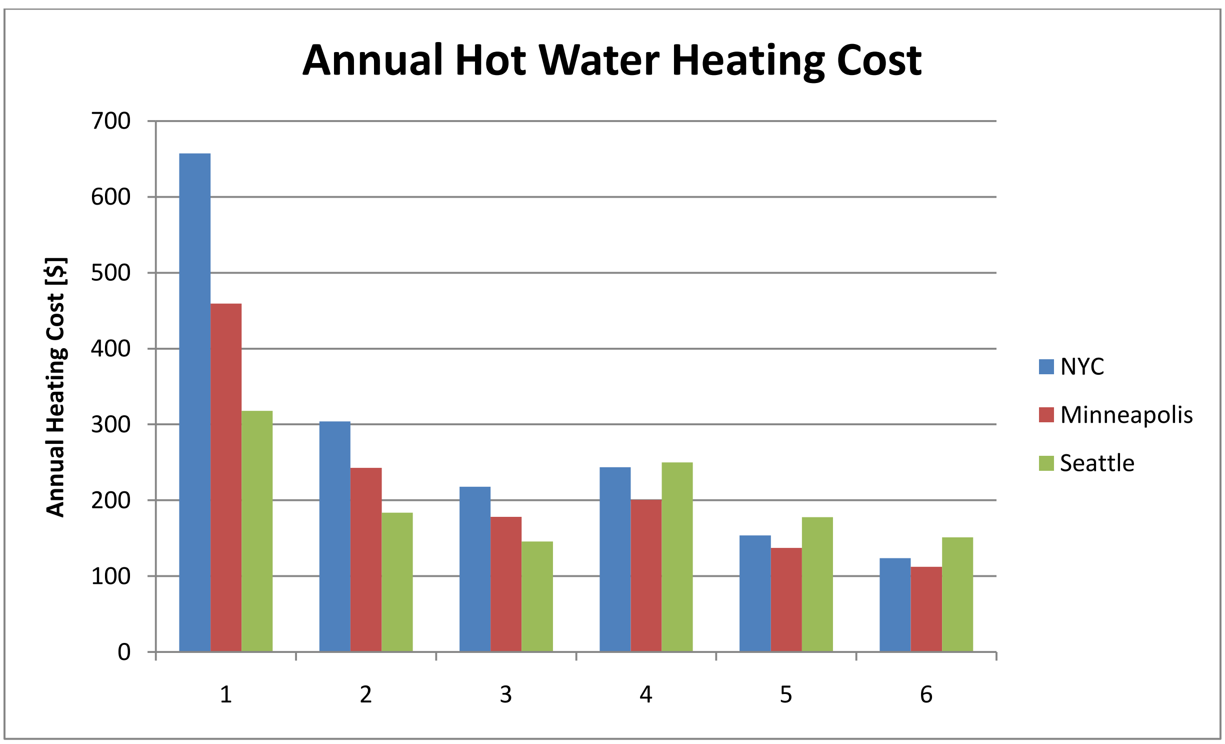

Figure 15. Annual Hot Water Heating Cost. 1: Electric, 2: Electric w/ 40 ft2FPSC, 3: Electric w/ 64 ft2 FPSC, 4: Natural Gas, 5: Gas w/ 40 ft2 FPSC, 6: Gas w/ 64 ft2 FPSC.

In the next section, the annual emissions of the hot water heating systems are calculated.

2.3.3 Emissions

The electric water heaters in all three geographic locations will be assumed to use average grid electricity which has CO_2 emissions of 1.34 lb/kWh. Natural gas has a CO_2 emission rate of 117.1 lb/MBTU (equivalent to 11.71 lb/therm) (Supple, 2007). Figure 16 presents the expected annual CO_2 emissions for the various hot water heaters and geographic locations. A table of these results is also presented in Table 1A of the appendix.

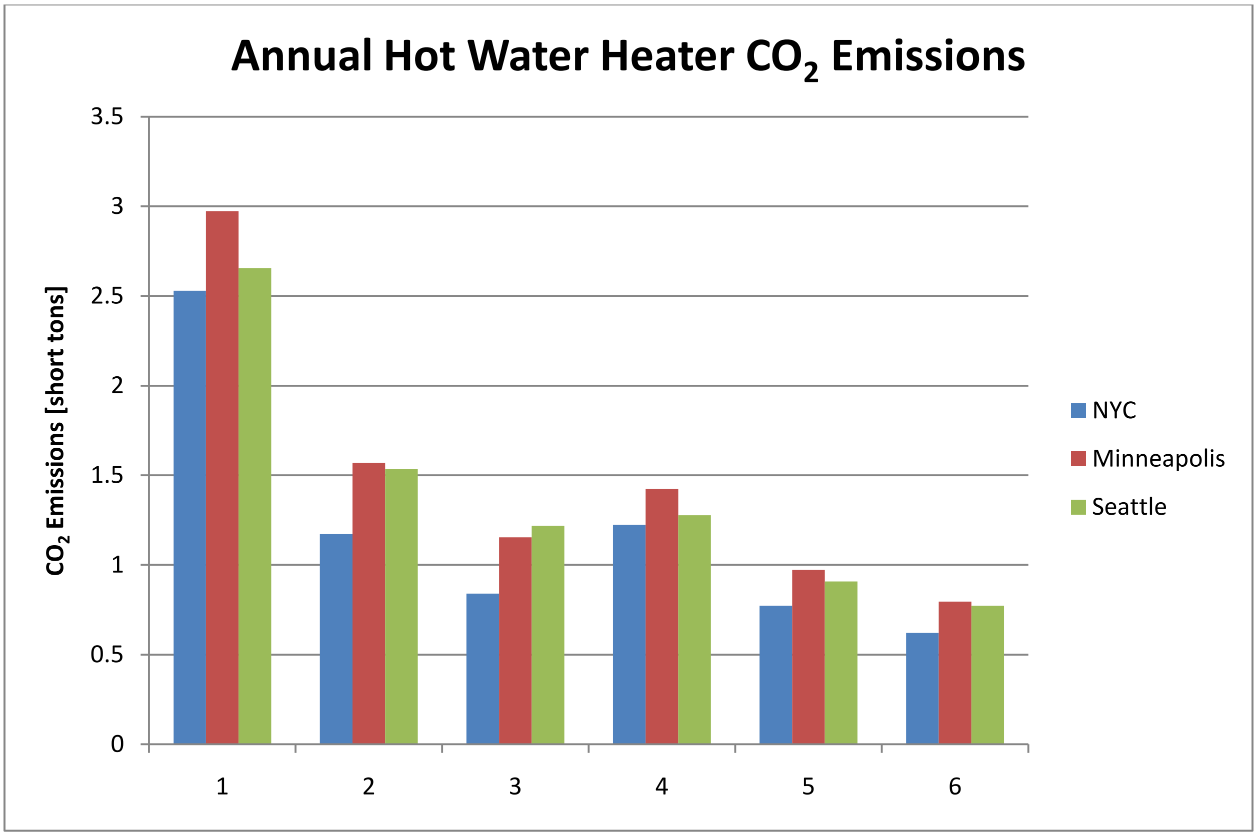

Figure 16. Annual hot water heater CO2 emissions. 1: Electric, 2: Electric w/ 40 ft2FPSC, 3: Electric w/ 64 ft2 FPSC, 4: Natural Gas, 5: Gas w/ 40 ft2 FPSC, 6: Gas w/ 64 ft2 FPSC.

From both a cost and emissions perspective, natural gas is clearly a superior fuel for water heating than electricity in all three locations. However, the analysis of the value of the solar water heater is much more subtle, and is one component where the systems analysis approach used in the CEDM will prove valuable.

This concludes the analysis of domestic hot water heating. The next section will present a discussion of solar PV options analyzed in the CEDM.

2.4 Solar Photovoltaic

With a power reaching the earth's surface of $3.6*10^4$ TW, the sun is the greatest renewable energy resource available and dwarfs the current human energy use of approximately 50 TW (Buonassissi, 2010). This immense magnitude of renewable, clean energy is the impetus behind what has thus far been an exponential growth of solar photovoltaic installations. Figure 17 presents a plot of total installed solar photovoltaic capacity by year (Renewable Energy, 2009).

Installed Solar Photovoltaic Capacity

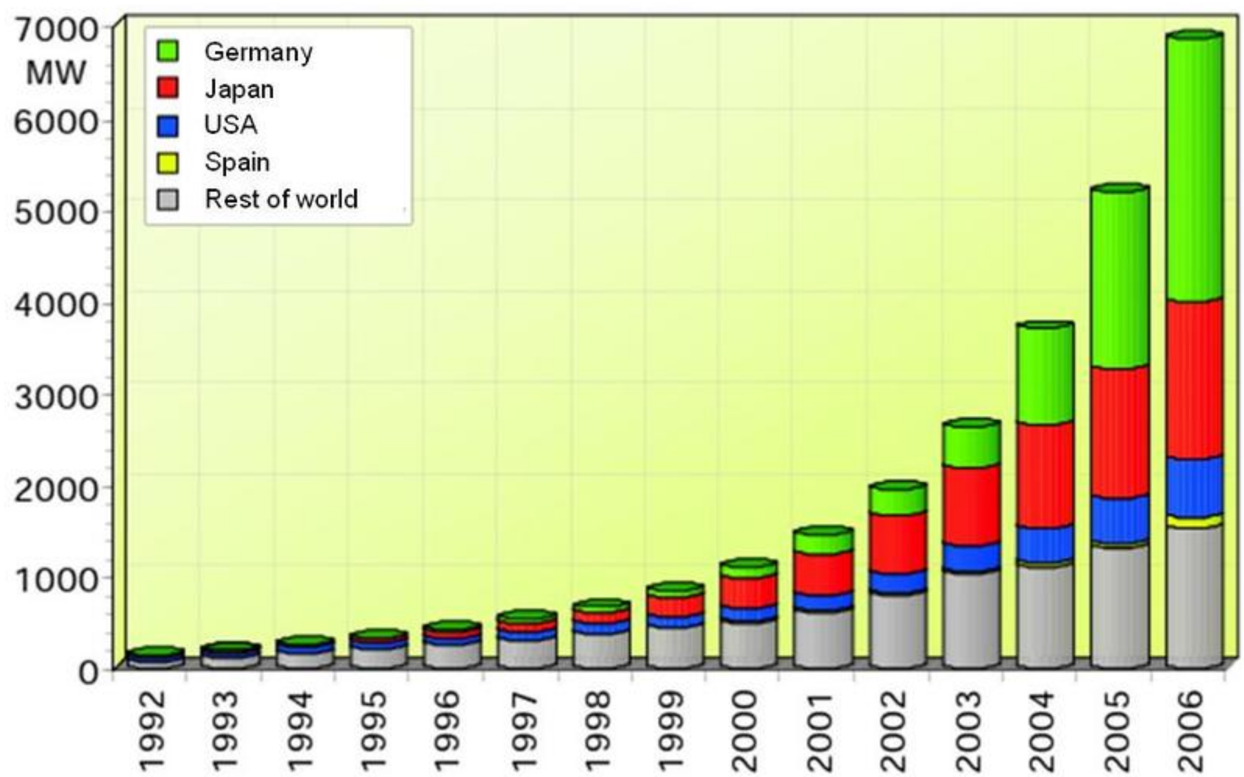

Figure 17. Global installed photovoltaic capacity by year.

A consumer can choose to install a rooftop solar photovoltaic (PV) array to reduce their electricity use and carbon emissions. Electricity use is an input of the CEDM, but for the analysis presented in Chapter 3, a monthly usage of 800 kwh and annual usage of 9600 kwh is assumed. The CEDM includes optional 2, 4, and 6 kW rooftop arrays as part of its analysis. NREL's System Advisor Model (SAM) is used to calculate the installation costs and expected electricity returns of each system in each site. SAM predicts that the arrays will have the capital costs shown in table 11, regardless of location (National Renewable Energy Laboratory (NREL), 2011).

Table 11: Expected Installed Costs of PV

Rated Power [kw]	Installed Cost
2	$11,868.80
4	$22,337.60
6	$32,806.40

SAM is also used to calculate the expected annual electricity generated in each of the cities. The expected annual electricity generated by each of the arrays in each of the cities is shown in Figure 18 below (National Renewable Energy Laboratory (NREL), 2011).

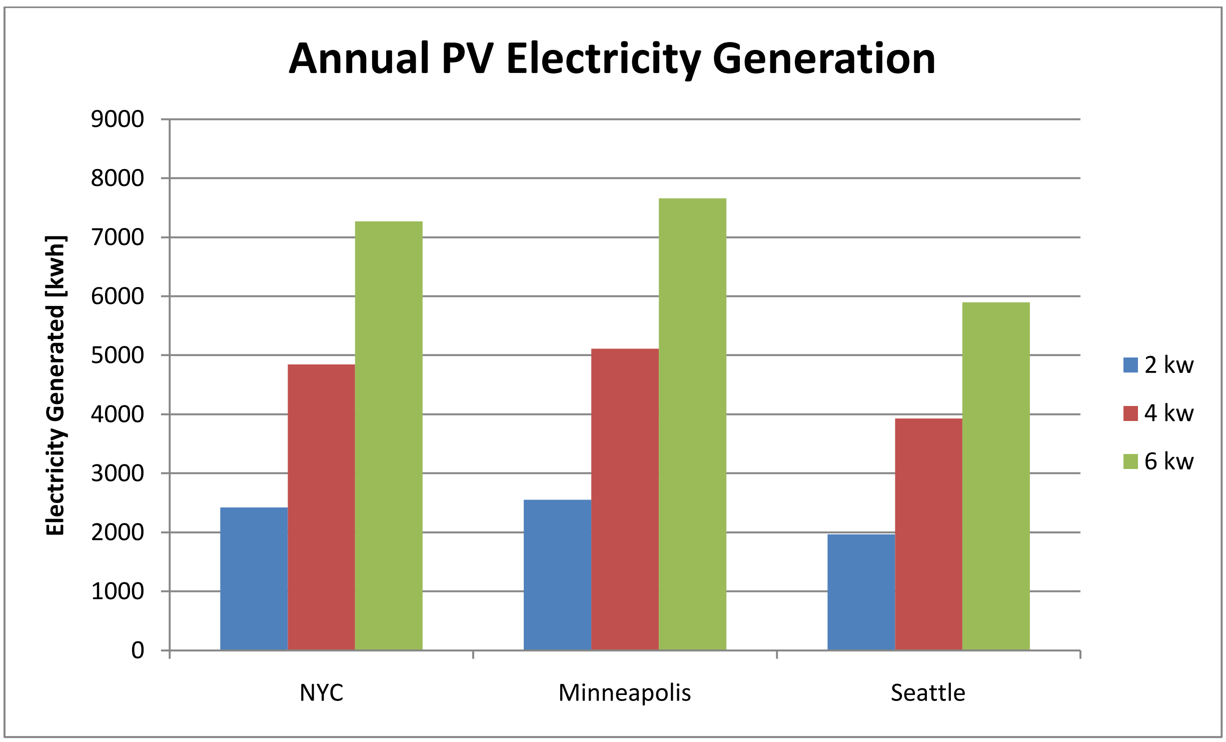

Figure 18. Expected annual PV electricity generation.

In the CEDM, the electricity generated by the PV system will be subtracted from the electricity used by the consumer before multiplying by the electricity price.

This concludes the analysis of solar PV and the analysis of home energy options as a whole. The next section will cover the transportation options analyzed in the CEDM.

2.5 Transportation

The primary method of daily passenger transportation in the US, and the largest consumer of energy in the transportation energy sector, is light vehicle traffic (US Department of Energy (DOE), 2008). Also, people who own their own houses and can make choices about their home energy use typically also drive cars and have the ability to make choices about what car they drive. So, the CEDM will only analyze automobile transportation. The CEDM will analyze four vehicle options: conventional gasoline-powered, hybrid-electric, turbo-diesel and electric-powered. This analysis of automobiles will make the assumption that an electric car is equivalent to an internal combustion car (IC) in its usability. This is not the case. The infrastructure is not properly setup for electric cars to be used in the same way as ICs. Electric cars can, however, replace ICs for the bulk of automobile travel, which occurs in short trips within the range of most electric vehicles. In the United States, where many families of four own more than one automobile, owning a single electric car would be easily manageable, because when taking longer trips outside of the range of the electric car, the other vehicle could be used.

A car comparison web site, Edmunds.com, was used to select four cars of similar size and features. The Toyota Camry, Camry Hybrid, Volkswagen Jetta TDI and Nissan Leaf were selected and are displayed in Table 12 with their respective costs and fuel economies (Edmunds). A screenshot of the comparison from Edmunds is shown in the Appendix.

Table 12: Car Options

	Camry	**Camry Hybrid**	**Jetta TDI**	**Leaf**
Cost	$21,464	$24,540	$22,075	$31,394
Fuel Economy (city/hwy)	22/32 mpg	31/35 mpg	30/42 mpg	3.15/2.73 mile/kwh[1]

[1]This value has been converted from miles per gallon equivalent (MPGe), a measurement of fuel economy developed by the EPA to compare fuel economies of internal combustion and alternative vehicles. 1 gallon equivalent (Ge) is 33.7 kwh, but the conversion has already been made in the table (Seredynski, 2010).

For this analysis an average of the city and highway fuel economies will be used as a lumped fuel economy. The miles driven by the consumer is an input of the CEDM, but for this analysis will be assumed to be 12,500 miles per year. The number of gallons of gasoline, diesel or kilowatt-hours is calculated by dividing miles driven by the lumped fuel economy of each vehicle. The annual energy use of each car is presented in Figure 19. It is calculated by multiplying the fuel consumption by the energy content (lower heating values) of each fuel. For electricity, the electricity consumption is divided by the average overall efficiency of the US electric grid of 33% to determine overall energy use (Ayres & Ayres). The lower heating values of gasoline and diesel are 121.3 and 135.5 MJ/gal respectively (Supple, 2007).

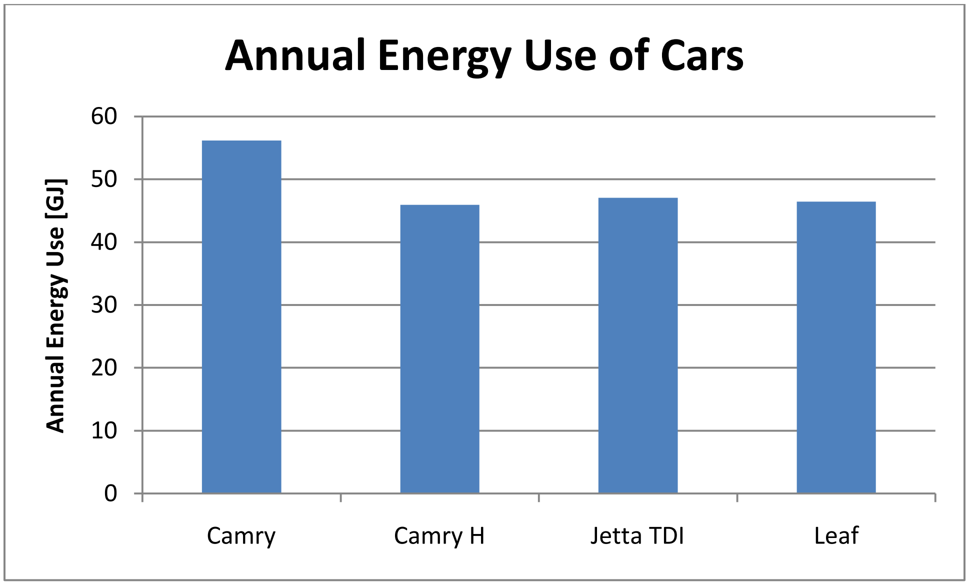

Figure 19. Annual Energy Use of Cars assuming 12,500 miles driven per year.

The annual cost is calculated by multiplying the fuel consumption of each vehicle by the cost of the fuel it uses. The costs of gasoline, diesel, and electricity in each region are shown in Table 13 below (EIA, 2011).

Table 13: Gasoline, Diesel and Electricity Prices (5/2/11)

Region	Gasoline [$/gal]	Diesel [$/gal]	Electricity [$/kwh][1]
East Coast (New York)	3.93	4.13	0.174
Midwest (Minnesota)	4.01	4.09	0.1035
West Coast (Washington)	4.14	4.33	0.0802

[1]Gas and diesel prices are for regions, while electricity prices are for states indicated.

The annual fuel costs of driving each of the automobiles at a rate of 12,500 miles/yr are shown in Figure 20 below. These costs will obviously vary with the costs of their respective fuels, but it is interesting to note that the Leaf costs a fraction of the cost of the others to operate and is run using a fuel that can come from many different sources.

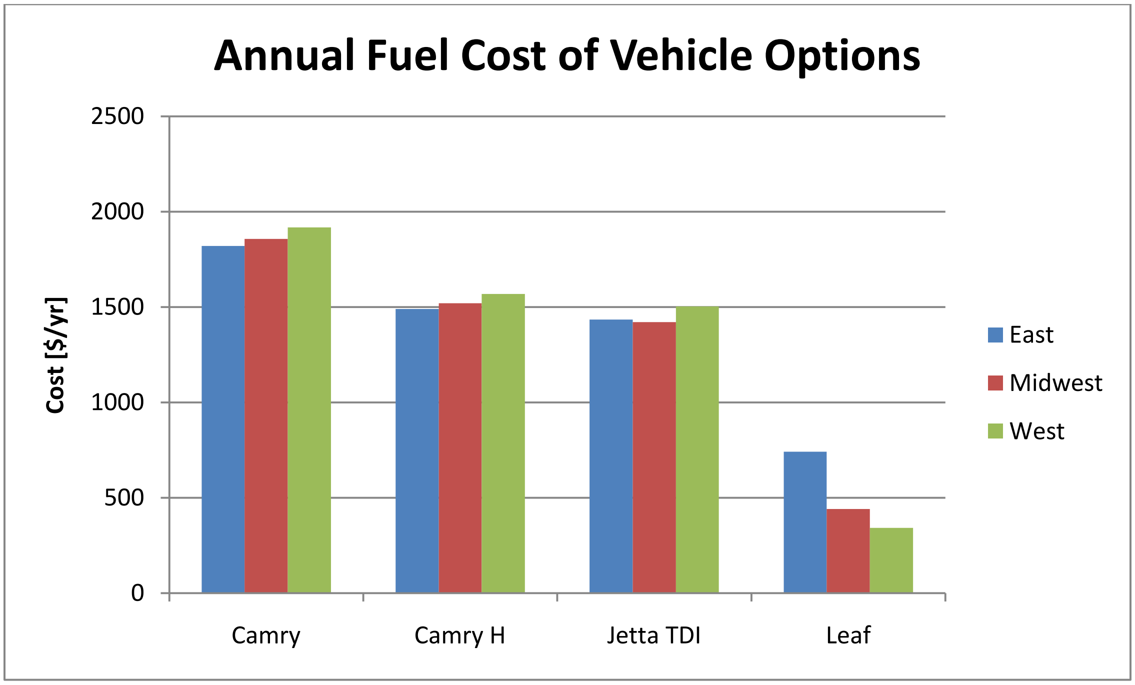

Figure 20. Annual cost of fuel of the four different automobiles.

The simple payback periods of each of the more expensive vehicles (the Camry Hybrid, Jetta and Leaf) when compared with the Camry were calculated and are presented in Figure 21.

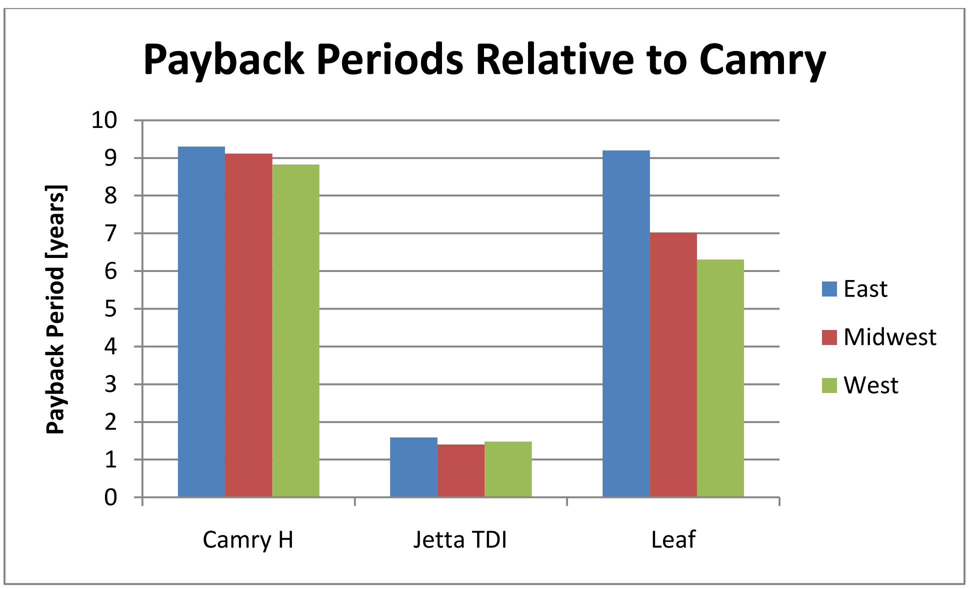

Figure 21. Simple Payback Periods for the more expensive vehicles relative to the Toyota Camry.

The average length of light vehicle ownership for new cars in the US is between 4 and 5 years (DOE Energy Efficiency and Renewable Energy, 2010). So, typical consumers who buy the Jetta TDI, with a payback period of about a year and a half, will easily recover their extra investment before they sell their car. However, consumers who choose to buy the Hybrid or the Leaf will have to wait a lot longer to recover their investment.

The emissions are calculated by multiplying the amount of energy used (in gallons or kwh) by the specific emissions of each fuel. Gasoline has an average CO_2 emission factor of 19.56 lb/gal, diesel has an average emission factor of 22.38 lb/gal and US grid electricity has an average emission factor of 1.34 lb/kwh (Supple, 2007). The annual emissions of each automobile are presented in Figure 22.

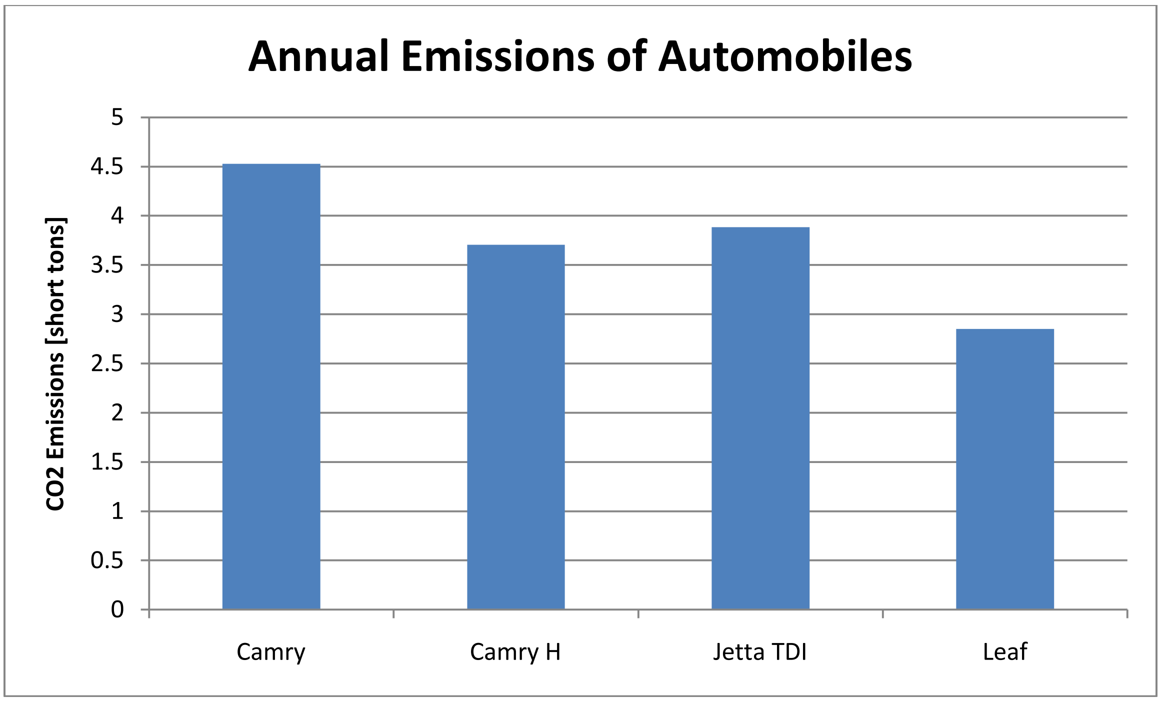

Figure 22. Annual emissions of automobile options.

After comparing these four cars it appears that for most consumers in the US, the Jetta TDI, with a short payback period and reduced energy use and emissions relative to the Camry is an excellent investment. For consumers who wish to make a larger reduction in their emissions, are willing to wait longer to recover their investment and aren't worried about the range issues associated with an electric car, the Leaf is a good option. The Camry Hybrid however, does not look like a good investment. It costs more and has a much slower payback than the Jetta and only has slightly lower emissions. It also has about the same payback rate as the Leaf, which emits much less.

This concludes chapter 2. Chapter 3 will present the results from the CEDM.

Chapter 3: Results

This chapter presents the analysis performed on the CEDM. One of the goals for the CEDM is to be easily customizable for many different consumers. In order to analyze begin to analyze the consumer energy decisions with a systems approach, some test cases must be run using the CEDM. This chapter presents the results of those test cases along with some discussion. Section 3.1 provides a short description of the test cases and Pareto cost analysis. Section 3.2 focuses on an analysis of just the housing components. In section 3.3, PV and domestic hot water options are introduced. Finally, in section 3.4 the car options are introduced and all the components of the CEDM are analyzed at once.

3.1 Pareto Cost Analysis

The three locations analyzed were the Northern cities New York City, Minneapolis and Seattle. The consumers are assumed to be families of 4 living in a 3-story (basement and two above-ground floors), 2,000 ft^2 house, with 300 ft^2 of windows, using 60 gallons of hot water a day, 800 kwh of electricity every month and driving one car 12,500 miles per year. The test cases are analyzed in a Pareto cost analysis, which compares capital and recurring cost.

A series of Pareto plots of recurring and capital cost were made using the CEDM for various groups of components of the three test cases analyzed. Section 3.2 focuses just on the housing components which affect space heating.

3.2 Housing Components

The CEDM calculates values of annual recurring cost and initial capital cost for all the permutations (solutions) of the price matrices of all the components outlined above. First the solutions that just include house components will be analyzed. The solutions will be analyzed using what is known as a Pareto chart. A Pareto chart is a useful tool to compare a number of options when more than one variable is of concern. The variables that will be examined in this study are recurring and capital cost. A Pareto plot of recurring vs. capital cost for the New York City housing components is shown in Figure 21 below. The points that fall to the lower left portion of the plot are the most desirable solutions because they minimize both capital and recurring cost, and any point that lies diagonally up and to the right of those points is inherently undesirable, or dominated, because it is more expensive on both axes. The points that lie on the lower left portion of the plot make up a curve that is known as the Pareto front.

The plot includes reference lines that show what a simple 10 year (line on the left) and 20 year (right) payback look like. The lines are drawn from the point with the lowest capital and highest recurring cost. Any point that falls to the left of the blue line will have less than a 10 year payback time when compared with that initial point with the lowest capital cost. When comparing with other points, the line would need to be redrawn with the same slope starting from the other point of comparison (or just visualized in the new location). In the Pareto front in Figure 21, only one point has less than a 10 year payback over the initial reference point. The only upgrade for that point is upgrading the wall insulation from R-10 to R-20. As the Pareto front moves left the rates of return of investment to house components clearly diminish. Initially, there are some points which have around a 10-year payback (circled in green), then a significant number of solutions which have less than a 20 year payback (circled in red), and then many more points that would have longer than 20 year payback periods (circled in purple).

There is not any indication from this plot of one component of the house being a significantly better investment than the others. This is due to the diminishing returns of improving a single house component. The plot shown in Figure 8 showed that heat loss in houses comes from a number of different sources. If a single component (i.e. windows or walls) is improved significantly it can only reduce the entire heating cost by at most the portion that that type of heat loss contributes (say 30%). So what makes the most economic sense is not to improve a single component significantly, but to improve all of them together.

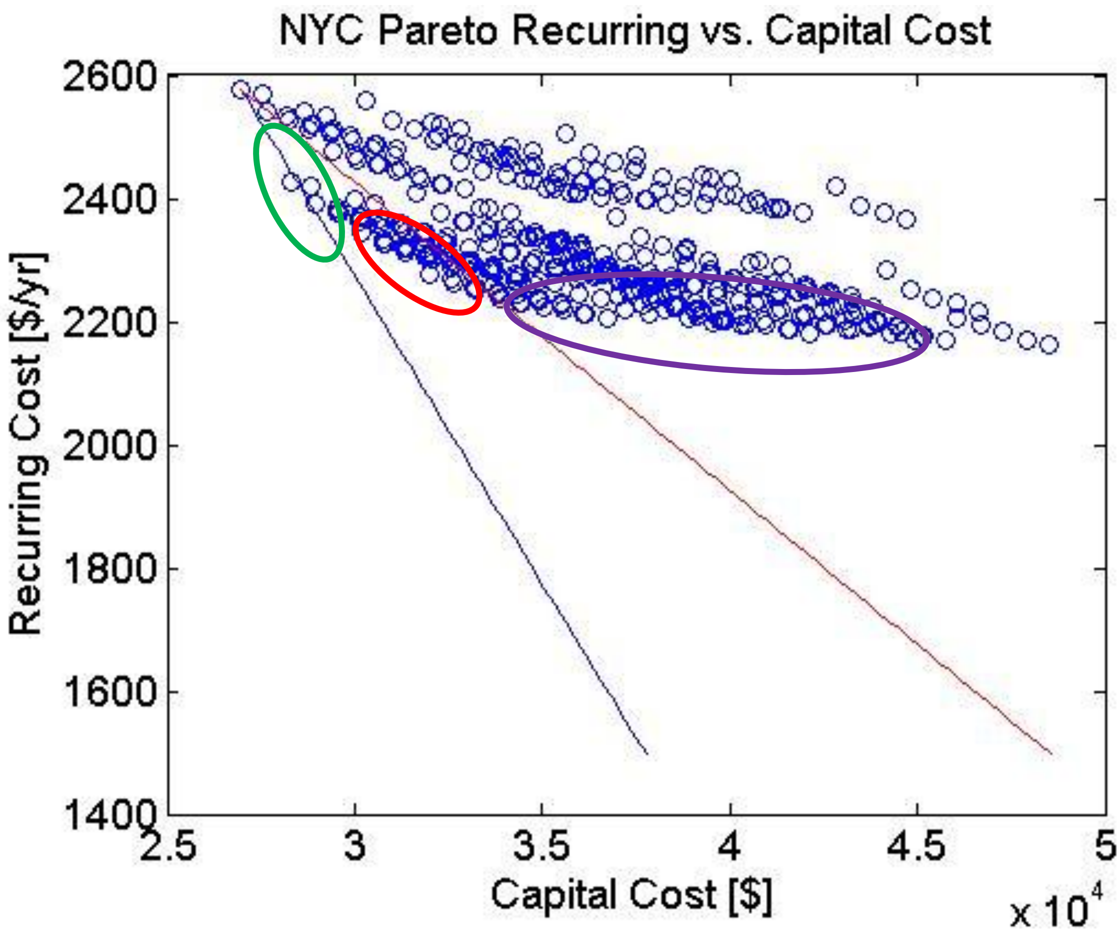

Figure 23. New York City Pareto Recurring vs. Capital Cost for house components.

Table 14 presents some of the most economical solution on the Pareto front. The capital cost is calculated from the cost of housing components and the recurring cost just includes the cost of heating and electricity. The reference point (lowest capital, highest recurring cost) appears first and payback periods of the following solutions are calculated relative to the reference. 10 year life cycle costs are calculated from the recurring and capital costs. Annual emissions are calculated for the heating and electricity. Within the price matrices of components analyzed it appears that marginal improvements to wall and basement insulation have the best return on investment with windows next, while roof and furnace improvements do not seem to be very economical. Table 14 also presents the calculated 10 year life cycle costs and annual CO_2 emissions of each solution. These results indicate a clear inverse relationship between payback period and emissions.

Table 14: Characteristics of Some of the Most Economical Solutions for Housing Options in New York

Wall [R]	Basement [R]	Window [U]	Roof [R]	Furnace Efficiency	Payback Period [yr]	10 yr life cycle ($)	Annual Emissions (t)
10	10	0.45	38	0.85	0	49,404	9.76
20	10	0.45	38	0.85	8.8	49,226	9.01
20	20	0.45	38	0.85	10.8	49,547	8.83
30	20	0.45	38	0.85	13.8	50,286	8.58
30	20	0.33	38	0.85	16.8	51,436	8.26
30	30	0.33	38	0.85	18.0	51,906	8.18

The same Pareto plot as shown in Figure 23 for New York is presented for Minneapolis in Figure 24. Despite Minneapolis being significantly colder (approximately 3000 more heating degree days) than New York, the shape of the Pareto front looks nearly the same. This is likely because natural gas is significantly cheaper in Minneapolis than New York, so the increase in required heating is offset by the reduction in natural gas prices.

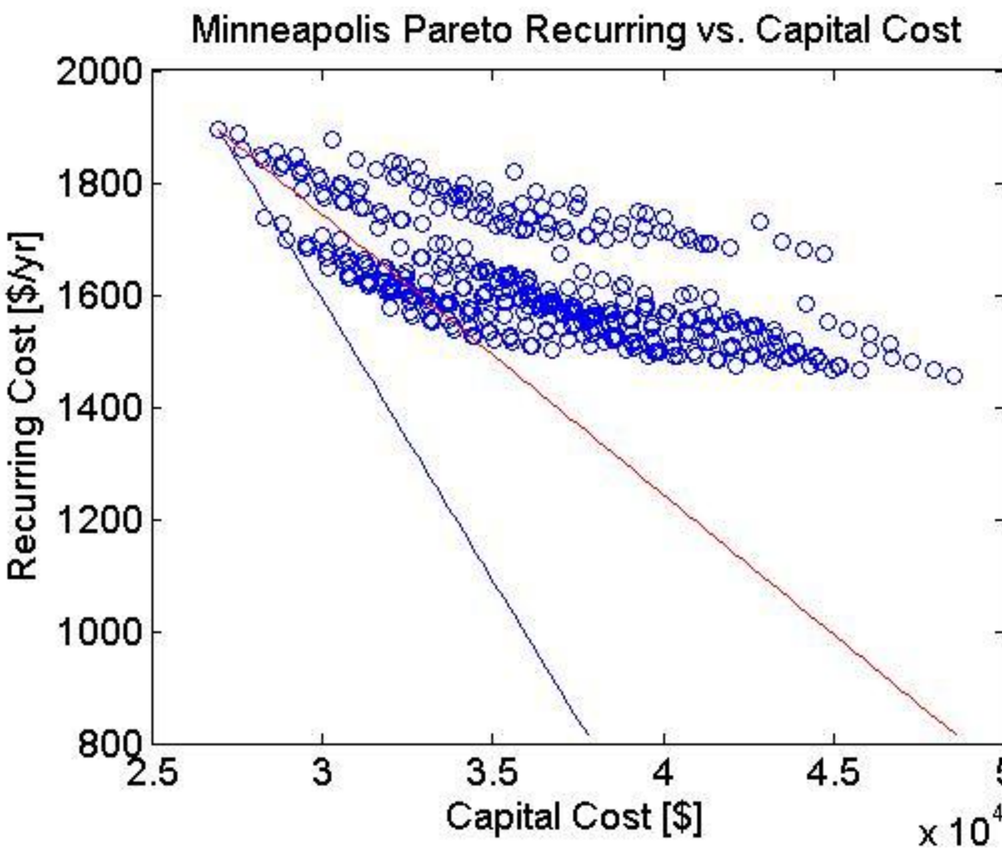

Figure 24. Pareto Cost Analysis of Housing Options in Minneapolis.

Seattle has a similar Pareto front for housing components as the other two cities and its plot is shown in the appendix. This concludes the specific analysis of housing components. In the next section domestic hot water will be introduced for analysis.

3.3 Adding Domestic Hot Water

Introducing domestic hot water options to the Pareto analysis does not change the analysis significantly. A Pareto cost analysis of housing components with domestic hot water is shown for New York in Figure 25. The Pareto plots for Minneapolis and Seattle are similar and are shown in the appendix. The only noticeable effect adding domestic hot water has on the Pareto plot is an increased density of solutions where the oval is drawn on Figure 25. This is where solutions which include solar hot water collectors show up. None of the solutions with solar hot water heating have payback periods less than 20 years.

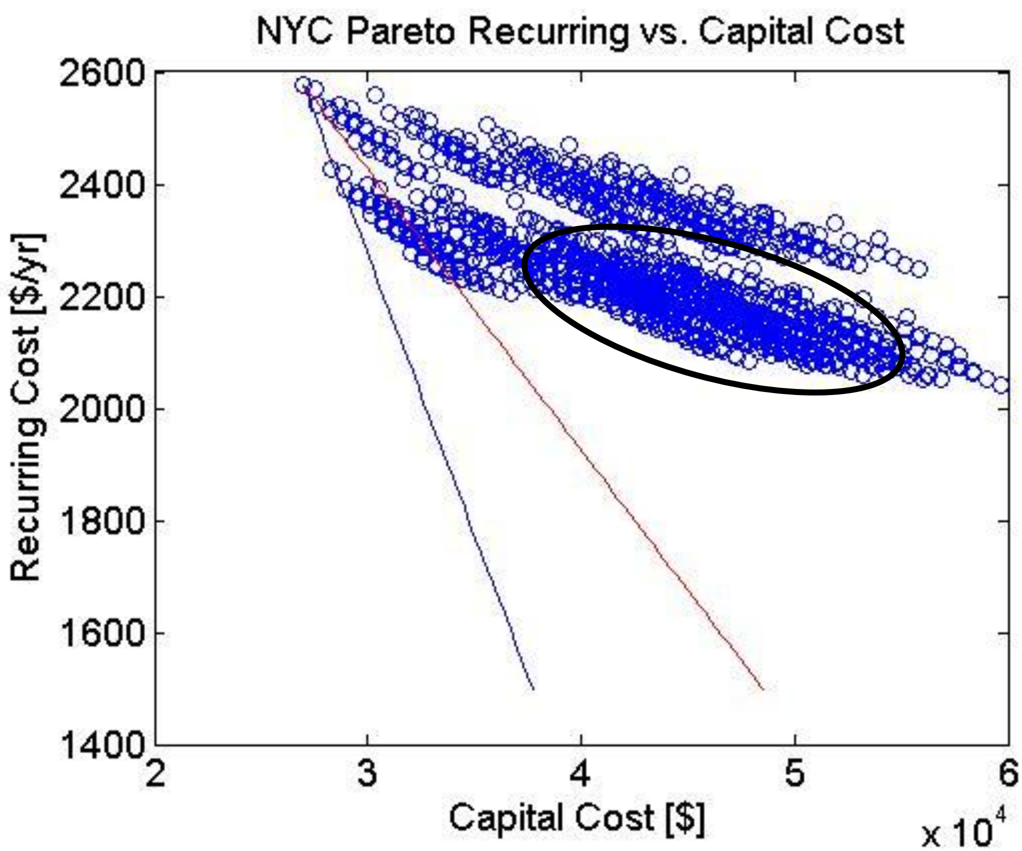

Figure 25. Pareto cost analysis for housing components and hot water heaters in New York.

Solar hot water heating does not appear to be a good investment for consumers in the locations analyzed. The most economical solutions after adding the domestic hot water component are essentially the same as those shown in Table 14 with the natural gas hot water heater included. In the next section, solar PV will be added and analyzed.

3.4 Solar PV

In this section solar PV is added to the components analyzed. A plot of the Pareto cost analysis for New York of these components is shown in Figure 26. Because PV is so expensive, it dominates the pattern of the Pareto front. To illustrate this ovals are drawn around all the solutions which include the different PV options. The purple oval surrounds solutions with no PV, the yellow oval surrounds those with a 2 kw PV installation, the green oval surrounds solutions with 4 kw PV and the red surrounds solutions with 6 kw PV. Adding PV in New York appears to have a little more than a 20 year payback, so it is easy to imagine that PV in a sunnier region like the Southwest would be a good investment. Also, this analysis ignores tax credits and incentives, but there is a 30% federal tax credit for PV in the US and additional tax credits in many states that would also make a PV installation more economically favorable (National Renewable Energy Laboratory (NREL), 2011).

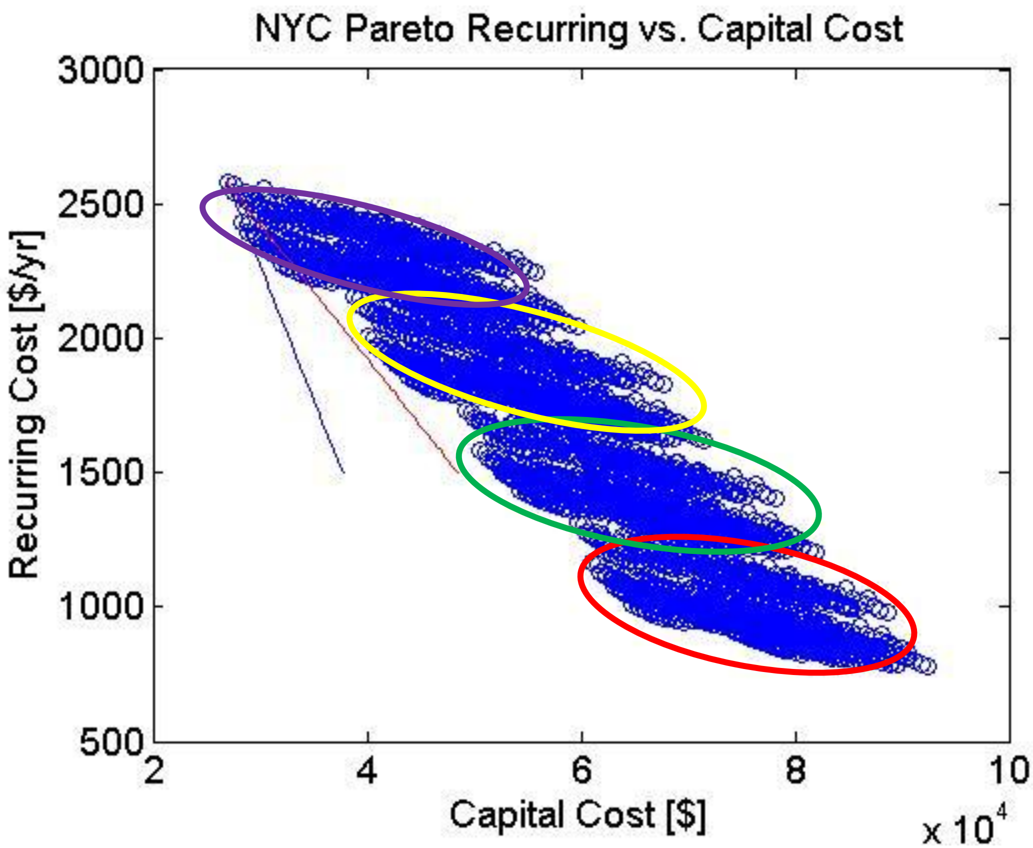

Figure 26. Pareto Cost Analysis of House, PV and Hot Water Heating Options. Purple oval surrounds solutions with no PV, yellow oval surrounds solutions with 2 kw PV, green oval surrounds solutions with 4 kw PV and red oval surrounds solutions with 6 kw.

Minneapolis and New York get similar amounts of sun, so they have similar Pareto fronts for this analysis, but cloudy Seattle gets much less sun and has a much different Pareto front. This is shown in Figure 27. Figure 27 indicates that PV in Seattle has a much slower payback than in New York or Minneapolis and is not an intelligent investment.

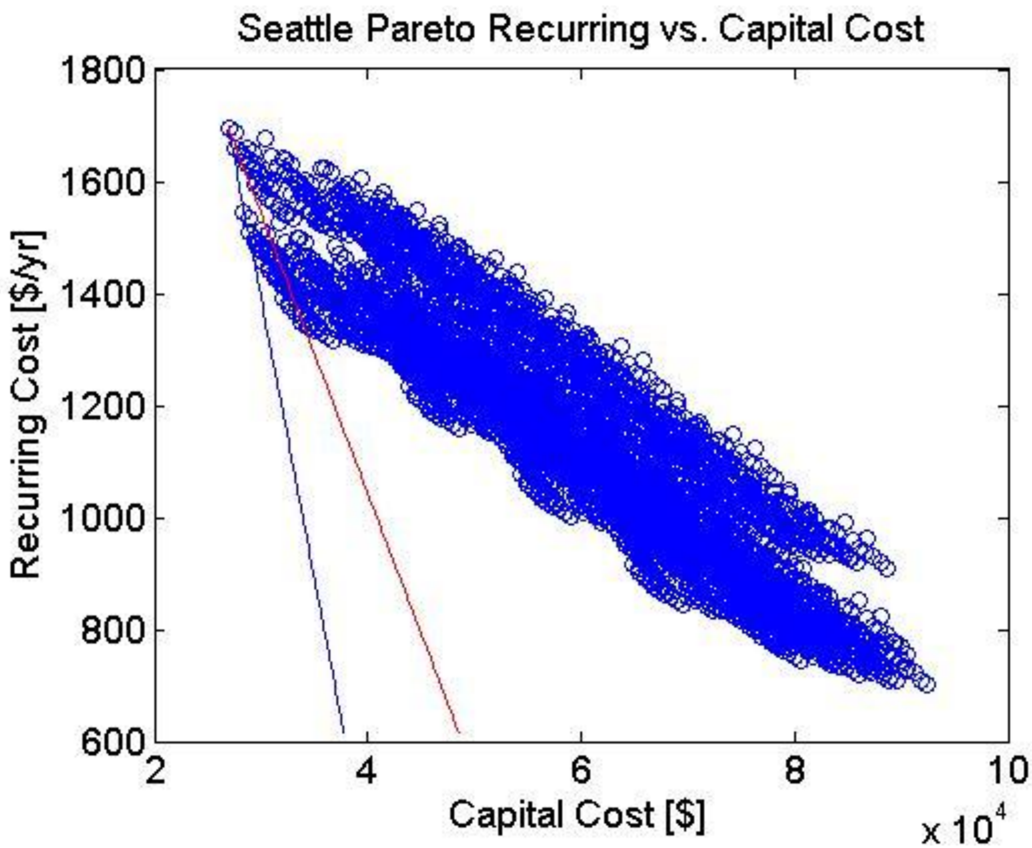

Figure 27. Pareto cost analysis of house, PV and water heating options for Seattle.

The most economical solutions after including the PV component are the same as shown in Table 14 because PV is not an especially good investment in any of the sites analyzed. Finally, in the next section, the transportation component will be added to the analysis and the full CEDM will be analyzed.

3.5 Transportation

In this section, the transportation component is added to complete the Pareto analysis. The entire Pareto cost analysis for New York is shown in Figure 28. Of all the components analyzed where the consumer actually has to choose one of them, car choice has the largest impact on capital and recurring cost (choosing a PV array has a similar level of capital cost, but the consumer has the option of not choosing to use PV). This can be seen simply in the shift of pattern of the Pareto front. Previously the Pareto front had been essentially in the same pattern as with just housing components and then repeated a couple times with the PV. But the car component causes a completely new pattern to the front.

Since car choice has such a significant impact on costs, it has a dominant impact on where the solutions lie on the Pareto front. To illustrate this, ovals have been drawn in Figure 28 around where solutions with certain car types are located. The purple oval in Figure 28 surrounds solutions which include the Toyota Camry, the orange oval surrounds solutions which include the Jetta TDI, the green oval surrounds solutions which include the Nissan Leaf, and the red curve surrounds solutions that include the very high capital cost items like PV and solar hot water collectors. Virtually no solutions which included the Camry Hybrid were on the lower left of the Pareto front, indicating that it is a dominated, undesirable decision.

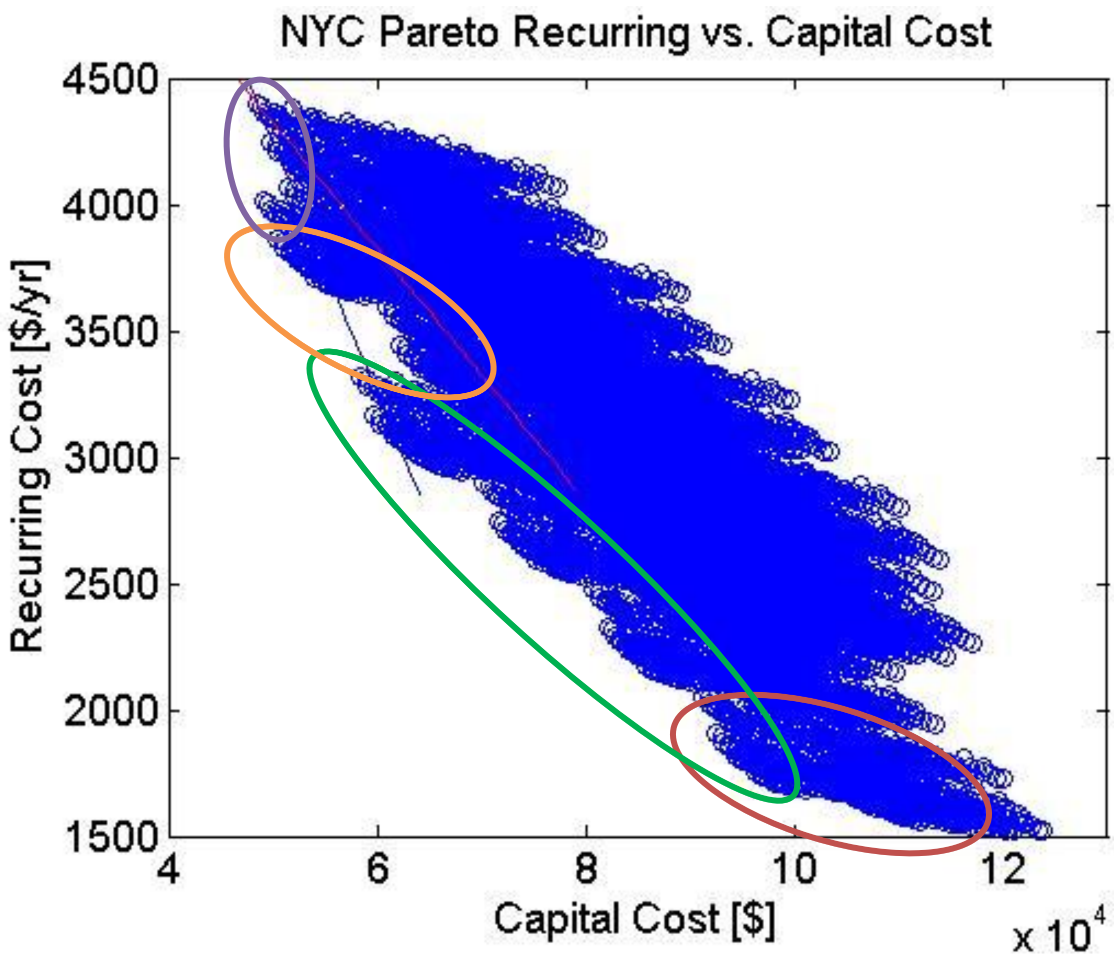

Figure 28. New York City Pareto Recurring vs. Capitsl Cost. A 10 year simple payback line is shown in blue and a 20 year payback line is shown in red. Purple oval surrounds solutions which include the Toyota Camry, orange oval surrounds solutions which include the Jetta TDI, the green oval surrounds solutions which include the Nissan Leaf, and the red oval surrounds solutions which include high capital cost options like PV and solar hot water heaters.

Table 15 presents some of the best overall solutions. Domestic hot water and PV are neglected in the table because only one hot water heater option was a good investment in the locations analyzed and PV was not a good investment either. Capital cost is calculated of the car and housing components and recurring cost is calculated of the electricity, heating and transportation fuel costs. Payback periods are calculated relative to the first reference point and 10 year life cycle costs are calculated. Annual emissions are calculated by summing the emissions from heating, electricity and transportation. Of the housing components, only the wall insulation R-value varied in this set of solutions so the other components are left out of the Table. All the cheapest options for those components were used (10-R basement, 0.45-U windows, 38-R roof, and 0.85-efficient furnace).

Table 15: Characteristics of Some of the Most Economical Housing and Car Solutions in New York

Wall [R]	Car	Payback Period [yr]	10 yr Lifecycle Cost [$]	CO_2 Emissions [tons]
10	Camry	0	89,058	14.29
10	Jetta TDI	1.59	85,819	13.64
20	Jetta TDI	3.61	85,641	12.89
10	Leaf	9.20	88,198	12.61
20	Leaf	9.16	88,030	11.86

The entire Pareto plots for Minneapolis and Seattle are shown in Figures 29 and 30 respectively. These show an even more pronounced difference between the electric car and the other car options. The solutions which include the Nissan Leaf are not even connected to the rest of the solutions. This is because electricity prices are much cheaper in Minneapolis and Seattle than in New York, while gas and diesel prices are approximately the same. Many of the electric car solutions in both cases have significantly less than a 10 year payback period.

Finally, it is interesting how thick the Pareto plot is. In some cases the difference between a good and bad solution is about $1,000 in recurring cost with no change in capital cost. From a capital cost perspective, the difference is as much as $20,000 in capital cost with no change in recurring cost. There is a lot of money to be saved by making the right energy decisions. Also, a lower recurring cost is an indication of less energy used and less CO_2 emissions. Pareto plots of emissions vs. NPV are presented in the appendix.

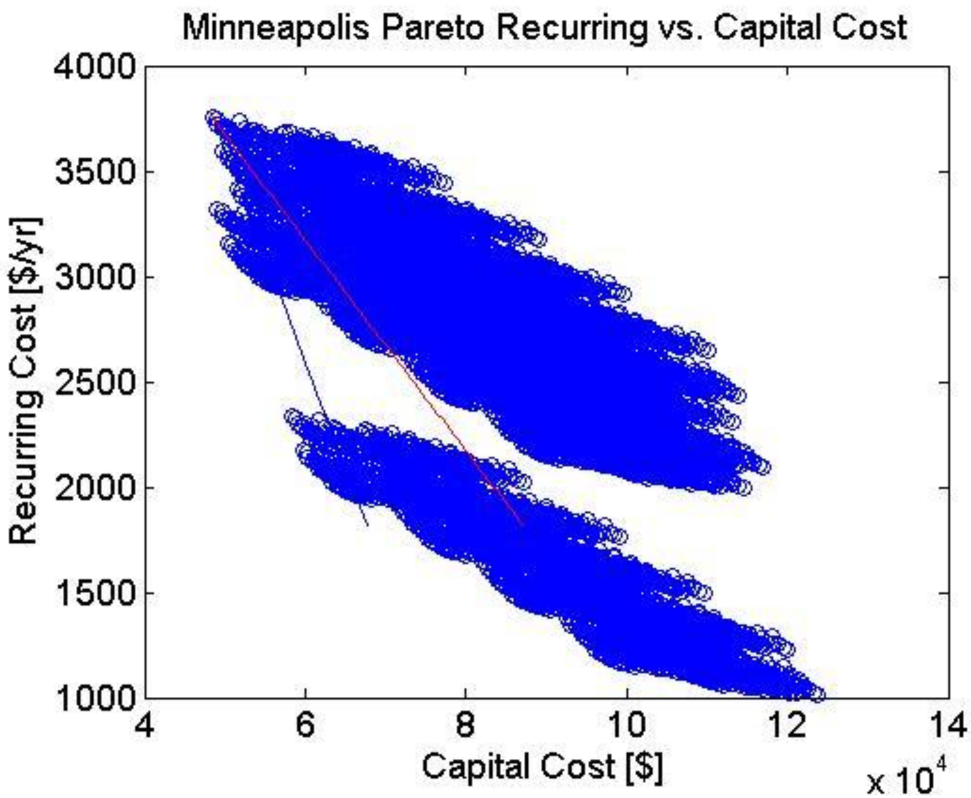

Figure 29. Minneapolis Pareto Recurring vs. Capital Cost.

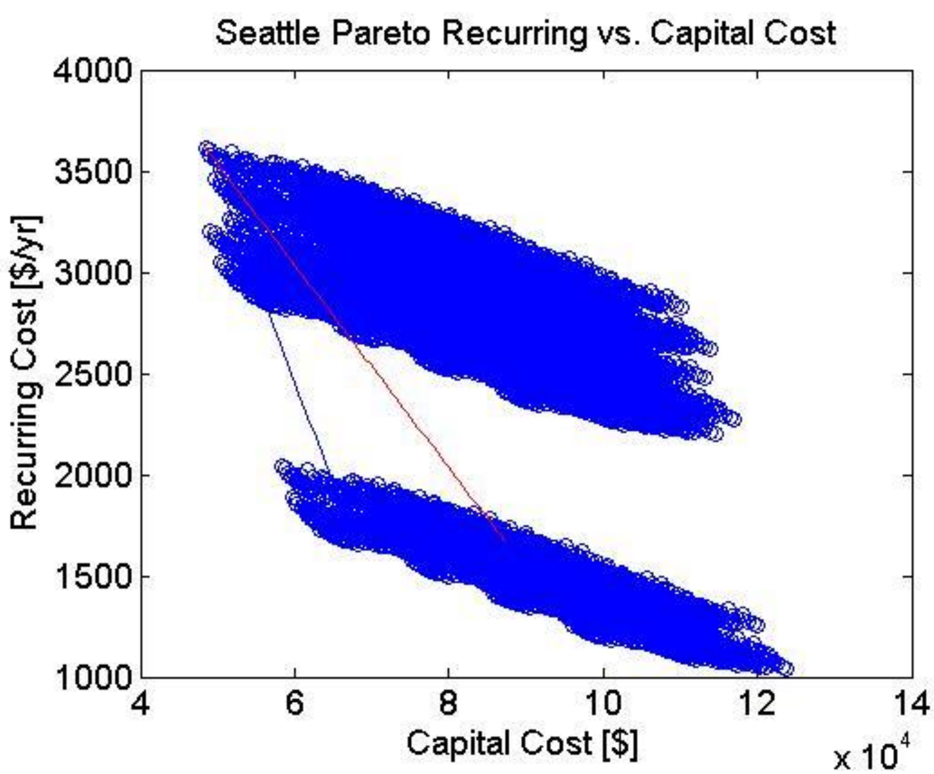

Figure 30. Seattle Pareto Recurring vs. Capital Cost.

3.6 Pareto NPV vs. Emissions

In addition to the Pareto capital and recurring cost analysis, some Pareto analysis of CO_2 emissions was performed, but will not be discussed in detail in this report. Net present value (NPV) of each solution was calculated assuming an interest rate of 8% and used as a metric to compare with emissions. This allows for an effective comparison of environmental and economic tradeoffs. A Pareto plot of emissions vs. NPV for all the components of the CEDM in New York is presented in Figure 31. In the Figure, solutions with higher NPV (farther right on the plot) are more economically favorable while solutions that are lower on the plot produce fewer emissions and are more environmentally favorable. In this analysis the best solutions fall to the lower right of the plot. The plot indicates that there are many dominated cases where a reduction in CO_2 emissions could be made without any added economic costs.

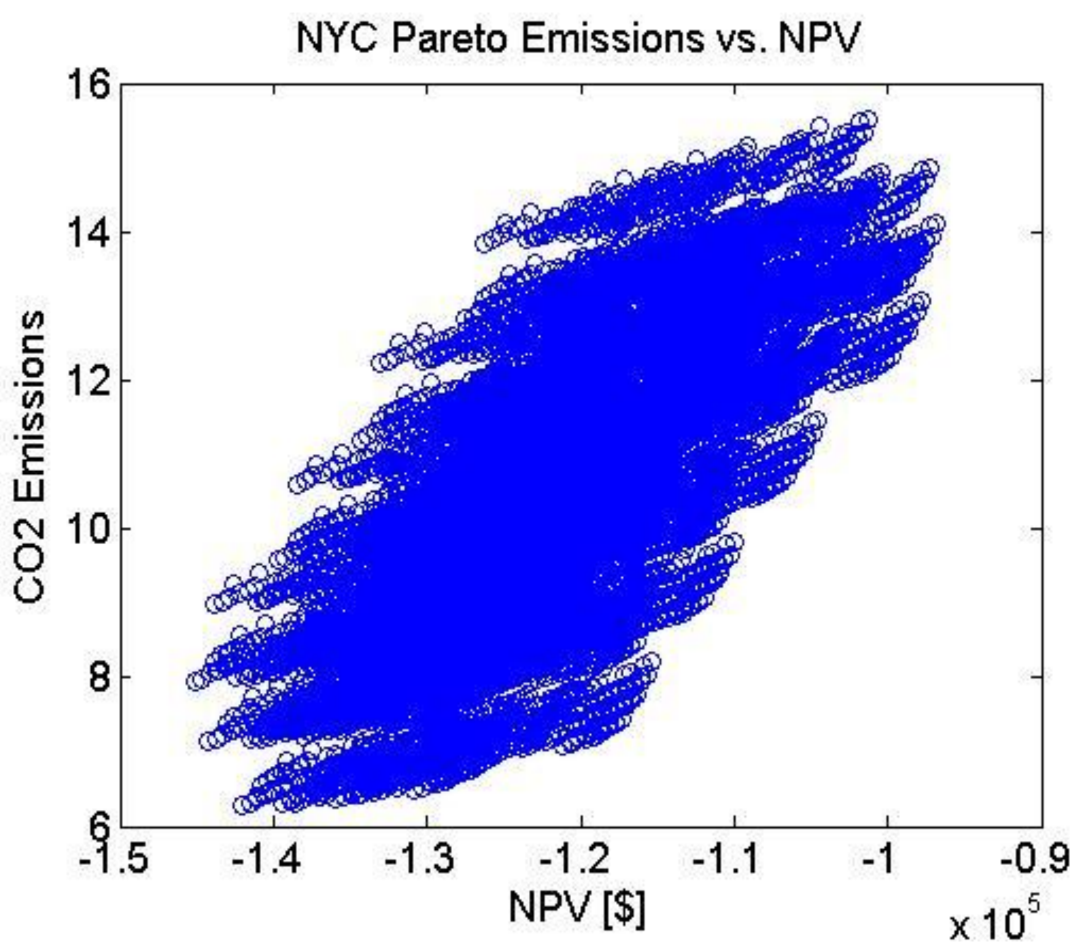

Figure 31. New York City Pareto Emissions vs. Net Present Value (NPV).

Pareto plots of NPV vs. emissions for Minneapolis and Seattle are presented in the appendix.

While a detailed analysis of the emissions vs. NPV Pareto comparison is not presented in this thesis, it can be a very valuable comparison for consumers who are concerned with their environmental impact. This concludes the results chapter of this thesis. The next chapter will discuss some of the major conclusions of this research.

Chapter 4: Conclusion and Future Work

Perhaps the most important conclusion of this research is that there are thousands of dominated consumer energy decisions that consumers undoubtedly choose without realizing there are better options. The results of this research also indicate that making the wrong decisions can be costly. The difference between a good and bad solution could cause a difference of $1,000 in annual recurring cost or $20,000 in capital cost. A tool such as the CEDM could be tremendously valuable in helping consumers make the right choices initially, save a lot of money and reduce their individual emissions.

4.1 Cars

Another interesting conclusion is the remarkably low-cost associated with driving an electric car. The annual fuel cost to power an electric car is a fraction of what it is for similar internal combustion vehicles. Also, if the electric car is using average US electric grid power, it will produce far less CO_2 than its hydro-carbon powered counterparts. The problem facing the widespread adoption of electric cars is a lack of infrastructure to support them. Contemporary electric vehicles have a range on the order of 100 miles and take hours to recharge, which is very limited when compared with internal combustion engines that have many times the range of an electric car and can be refueled in minutes. However, the vast majority car travel is done in trips within the range of an electric car. The average American drives approximately 30 miles/day (Ride to Work). Also, there are approximately 0.84 cars/person in the US (US Department of Energy (DOE), 2008), so a family of four would have, on average, at least two cars. If one of those cars were electric it could be used along with a second conventional car for daily commuting while on the occasions when the family goes on longer distance trips, the conventional vehicle could be used.

4.2 Housing Options

For the northern climates analyzed, the medium levels of housing components (medium R-value insulation, U-value windows, etc.) showed fairly good returns on investment with simple payback rates around 10-20 years, while the higher level components showed slower returns on investment with payback periods on the order of 40 to 50 years. Also, it tends to make the most sense to improve the components as a group, not to improve one component significantly by itself.[1]

4.3 Solar Options

In the northern locations of New York and Minneapolis, rooftop solar photovoltaic installations showed modest returns on investment, with simple payback periods of a bit more than 20 years. In Seattle, which gets a lot less sun, PV showed much worse returns on investment. However, in sunnier regions like the Southwest and with tax credits and incentives factored in, PV would be a much better investment. With natural gas prices fairly low, solar hot water heaters did not appear to be good investments in any of the cases analyzed.

4.4 Future Work

A number of simplifications were made in the development of the CEDM that if it is to be implemented into an adjustable, useable model for consumers would have to be improved upon. For example, the model requires all information that varies with location (solar insolation, energy prices, heating degree days, etc.) to be manually entered into the model. This would need to be automated. More importantly, a simpler method of communicating the results to consumers needs to be developed. Consumers should not have to navigate thousands of solutions, they should have a few of the best options presented to them to choose between. Finally, the model should incorporate items the consumer already owns into the economic analysis.

[1] The wording here is misleading: this is assuming the user is choosing which components to improve during the design phase of a new house not during a renovation. Improving components when they are already there will have additional costs that were not analyzed.

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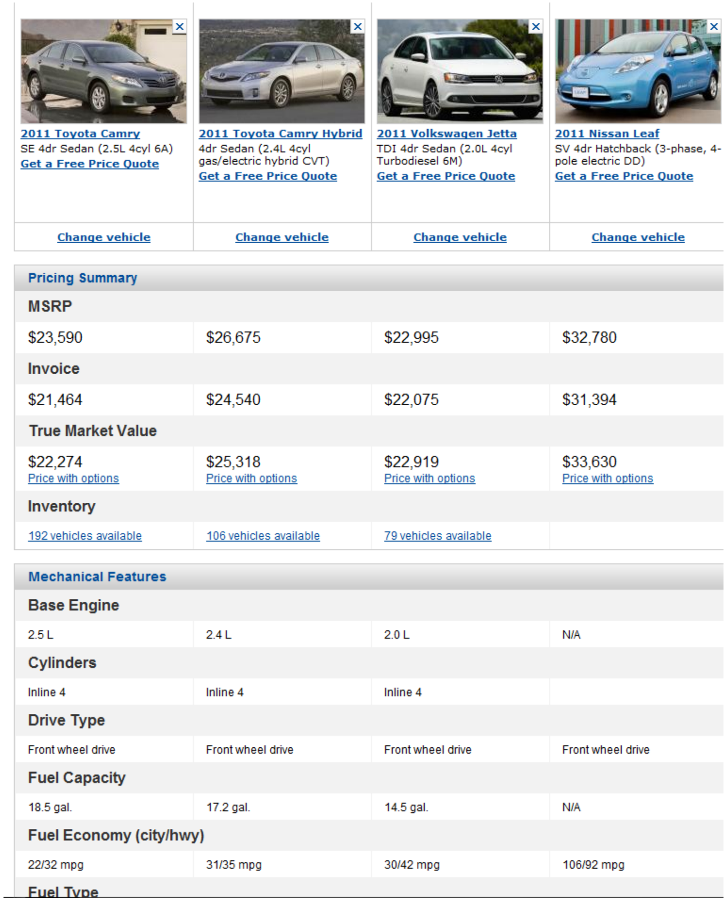
Appendix

Table 1A: Annual CO_2 Emissions [short tons] due to Water Heater

Water Heater Type	New York City	Minneapolis	Seattle
Electric	2.53	2.97	2.66
Electric w/ 40 ft^2 FPSSC	1.17	1.57	1.53
Electric w/ 64 ft^2 FPSSC	0.84	1.15	1.22
Natural Gas	1.22	1.42	1.28
Gas w/ 40 ft^2 FPSSC	0.77	0.97	0.91
Gas w/ 64 ft^2 FPSSC	0.62	0.80	0.77



2011 Toyota Camry	2011 Toyota Camry Hybrid	2011 Volkswagen Jetta	2011 Nissan Leaf
SE 4dr Sedan (2.5L 4cyl 6A)	4dr Sedan (2.4L 4cyl gas/electric hybrid CVT)	TDI 4dr Sedan (2.0L 4cyl Turbodiesel 6M)	SV 4dr Hatchback (3-phase, 4-pole electric DD)
Get a Free Price Quote	Get a Free Price Quote	Get a Free Price Quote	Get a Free Price Quote
Change vehicle	Change vehicle	Change vehicle	Change vehicle
Pricing Summary			
MSRP			
$23,590	$26,675	$22,995	$32,780
Invoice			
$21,464	$24,540	$22,075	$31,394
True Market Value			
$22,274 Price with options	$25,318 Price with options	$22,919 Price with options	$33,630 Price with options
Inventory			
192 vehicles available	106 vehicles available	79 vehicles available	
Mechanical Features			
Base Engine			
2.5 L	2.4 L	2.0 L	N/A
Cylinders			
Inline 4	Inline 4	Inline 4	
Drive Type			
Front wheel drive	Front wheel drive	Front wheel drive	Front wheel drive
Fuel Capacity			
18.5 gal.	17.2 gal.	14.5 gal.	N/A
Fuel Economy (city/hwy)			
22/32 mpg	31/35 mpg	30/42 mpg	106/92 mpg
Fuel Type			

Figure 32. Automobile Comparison from Edmunds.com

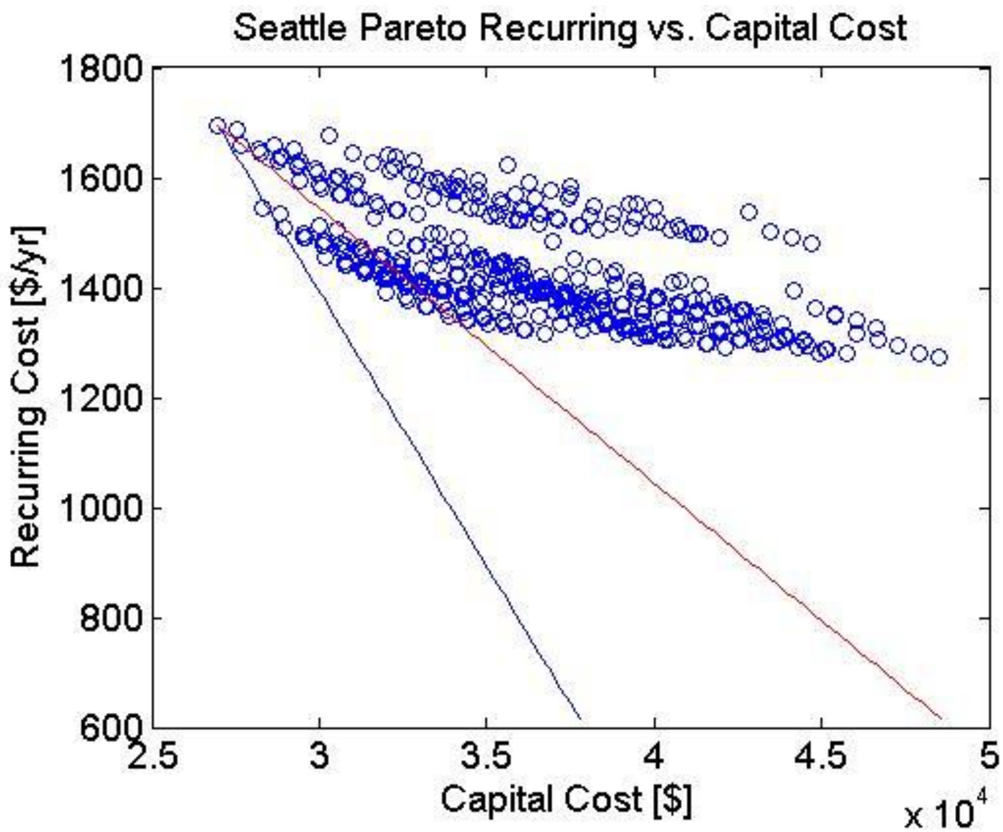


Figure 33. Seattle Pareto Cost Analysis of Housing Options

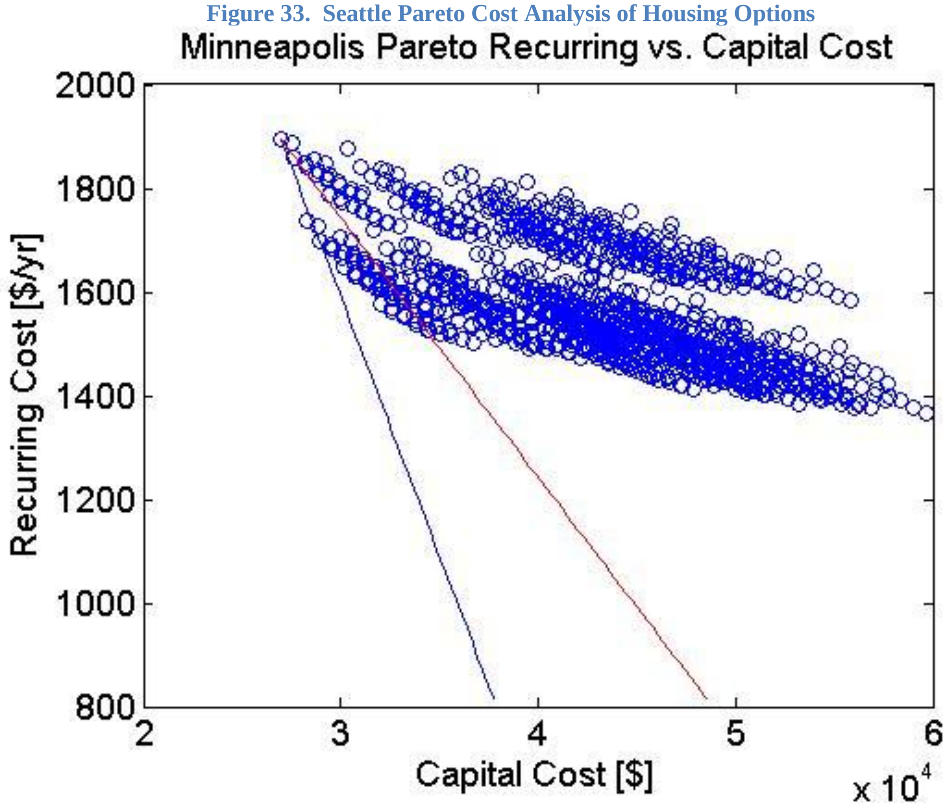


Figure 34. Minneapolis Pareto Cost Analysis of Housing Options.

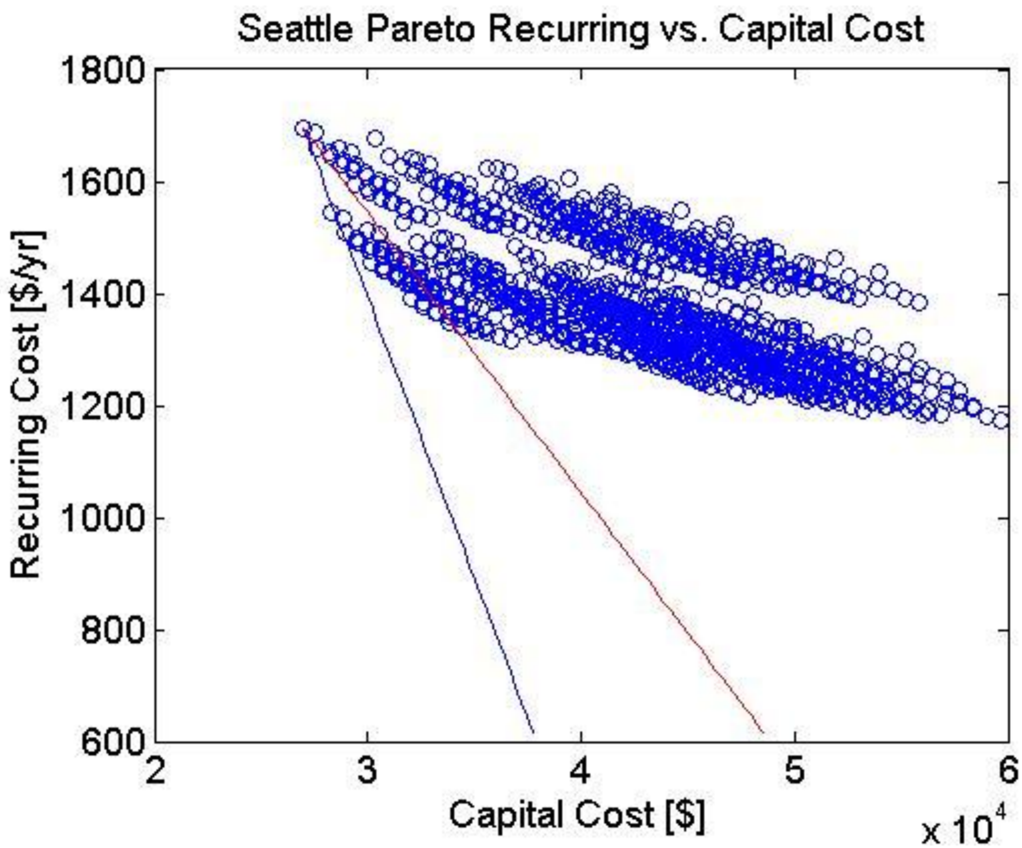


Figure 35. Seattle Pareto cost analysis for housing components and domestic hot water.

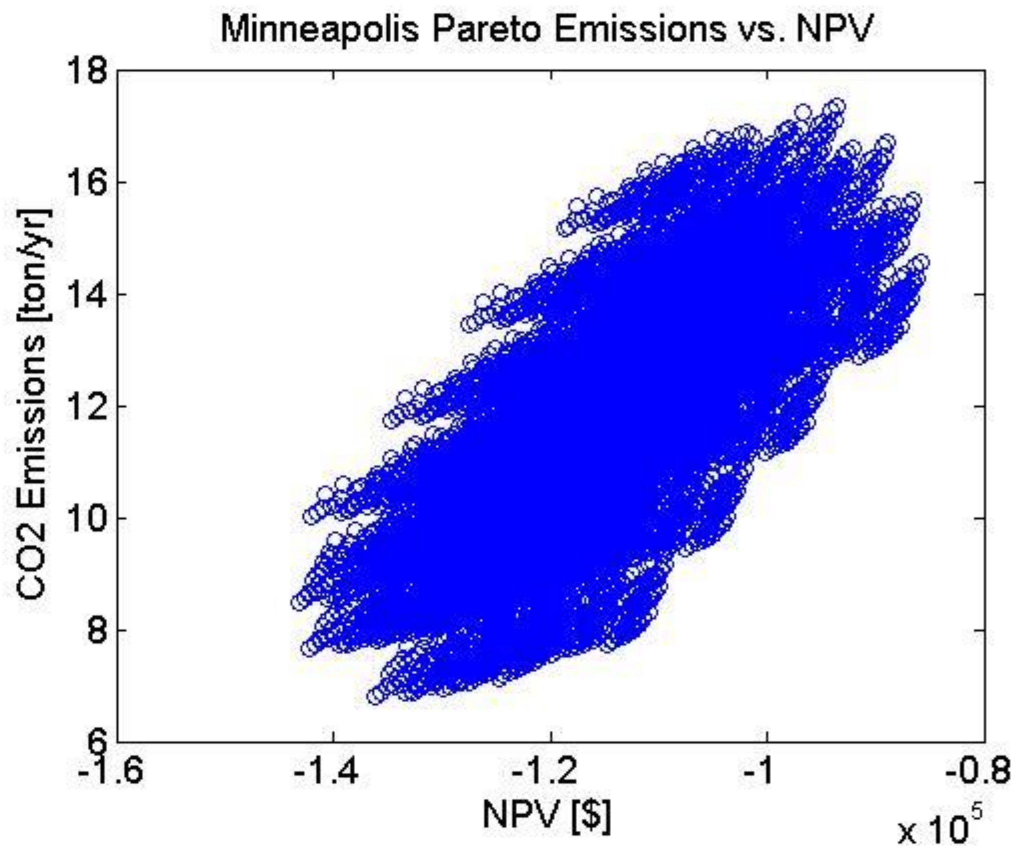


Figure 36. Minneapolis Pareto Emissions vs. NPV.

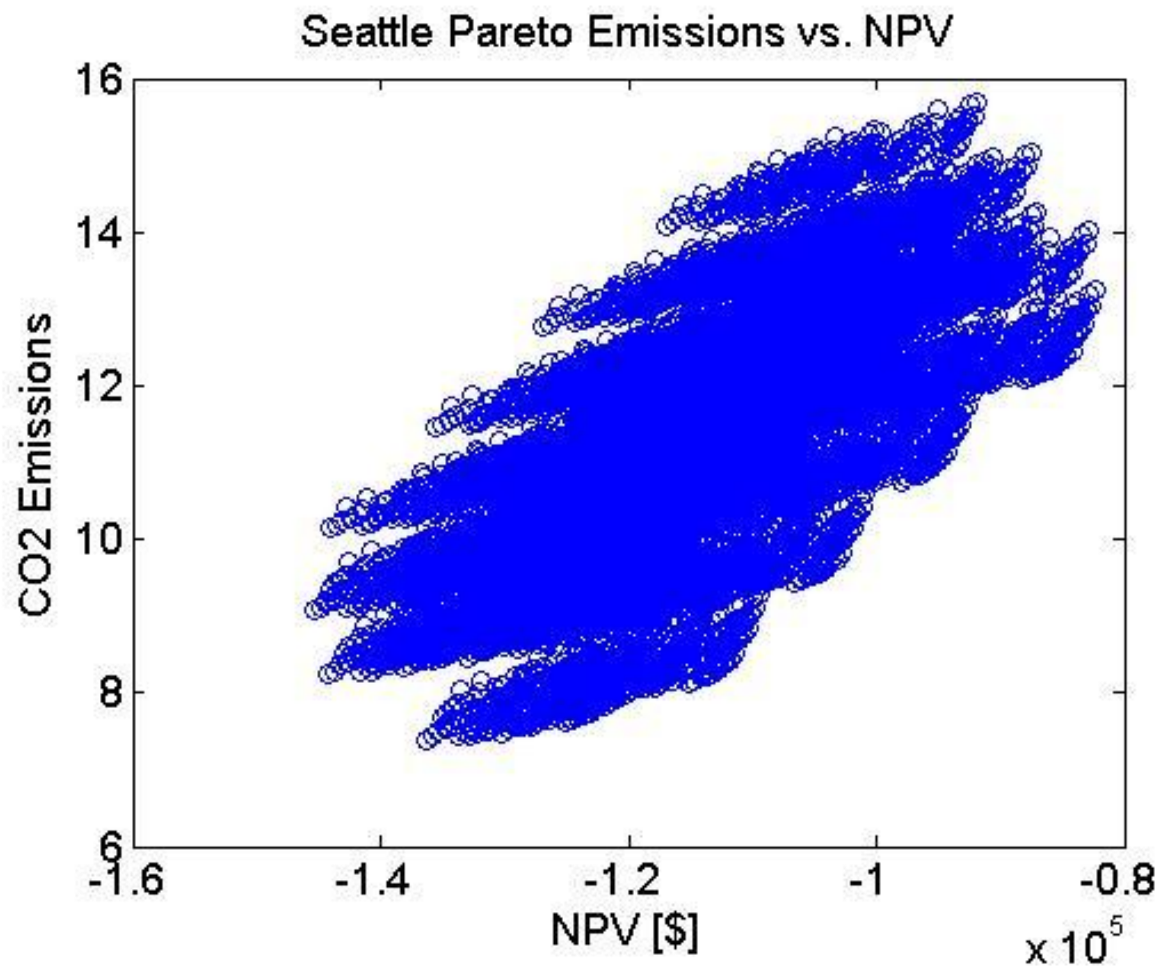


Figure 37. Seattle Pareto Emissions vs. NPV.

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