Flexibility for the Design of a Residential Heat Pump System

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Executive Summary

This paper examines the value of flexibility in home heat pump systems. A number of flexible design options are identified including upgrading to ground source technology, improving component efficiency, providing switching of fuel types, and system improvements by increasing the number of heating and cooling zones. Several possible uncertainties affecting the operation of the system are identified against which a flexible design might provide value. These include energy prices, technology improvement, government policy, and future weather conditions. The flexibility easily incorporate future efficiency improvements at a cost lower than system replacement is chosen for more detailed analysis against the uncertainty of future prices for electricity.

Analysis is done using a 2 stage decision analysis where the possibility to install an inflexible or flexible system is the stage 1 decision, and the ability to upgrade the flexible system is the stage 2 decision. Uncertainties in electricity prices are considered and evaluated after each decision. A lattice analysis was also performed considering 6 price periods of 3 years each for future electricity prices with options to upgrade the flexible system starting in the 2nd 3 year period with declining upgrade costs in each subsequent period.

Both analyses predict that the value of the flexible system is in protecting against significant increased costs in the case of high future electricity prices. The benefits of the flexible system are significant in a relatively small number of cases. The option to choose a fixed or flexible system are considered in terms of several common decision making criteria including maximizing Expected Net Present Value, maximizing Value at Risk, and minimizing initial capital expenditure. The flexible system is determined to be a better choice in terms of Expected Net Present Value and Value at Risk, while the fixed system is a better choice in terms of initial capital expenditure. The results of the analysis lead to a conclusion that a more thorough evaluation of the flexibility concept presented are valuable.

Chapter 1: System Description and Motivation

The system considered in the Application Portfolio is a home heating and cooling system. This system will include the heating and cooling equipment as well as any equipment required to distribute or capture heat from within the building.

The recent concerns over energy security have led to increased research and development efforts in home energy efficiency. One of the main consumers of energy is the home's heating and cooling system. These systems have lifetimes between 10 and 20 years. Systems installed today may not be able to take advantage of improvements that become commercially available over the next several years. In addition, energy prices fluctuate, and the relative costs of different fuels change over time.

Today's cost effective heating and cooling system may rely natural gas for heating and electricity for cooling, but advancements in technology and changes in energy prices may provide future opportunity for system upgrades which improve cost effectiveness, particularly if market signals for carbon emission reduction through carbon taxes or carbon cap and trade policies are enacted.

1-1 Design Variables

There are several design options that can be considered in the design of a home heating and cooling system. For purposes of this exercise, we will limit the analysis to include an air source or ground source heat pump system. Some of the design decisions currently considered include:

Air source or ground source (geothermal). Ground source heat pumps take advantage of the constant temperatures available several feet below ground to operate heat pumps across a more efficient temperature gradient. However, ground source heat exchangers are very expensive to install and often not worth the initial cost under today's conditions.

Backup fuel source (for cold weather operations) of electricity, oil, or natural gas. Natural gas currently offers the most economic het content for providing backup heat when outside temperatures make an air source heat pump inefficient or inoperable. Future energy prices could change and oil or electricity may be more efficient in the future.

Number of Zones of operation. Installing multiple heating and cooling zones in a house reduces the percentage of the house that needs to be heated or cooled to comfortable level. The equipment to control multiple zones is expensive and often not worth the initial expense. This option may be difficult to model and considering this flexibility may be beyond the scope of the exercise.

System Efficiency. Higher efficiency systems are available and have higher initial cost but lower operation costs as they use less energy. This is the main design decision that is faced when installing a new system. The capability of current systems will be extened in the analysis by incorporating the flexibility to upgrade efficiency in the future.

System Model

Analysis of available standard designs will be used to establish a baseline NPV or net lifecycle cost against future fixed energy prices as anticipated by the Energy Information Agency or a similar forecast. A model for uncertain and variable future costs in energy related to possible changes in commodity prices and government policy will be also be considered.

The flexible design will incorporate the option to start with an economic set of features that may be upgraded in response to future improvements in technology or changes in technology. (air source heat pump with natural gas backup, 1 zone of operation) The flexible design will include an increased cost that will allow future improvements to be implemented at substantially lower cost in the future. Most, if not all, current designs on the market must be replaced to achieve substantial performance improvement.

There are many models for calculating home energy use. We will use a simple model based on weather conditions using the predicted number of heating and cooling degree days for a specific location. We will use a simple model which calculates energy costs as a function of system efficiency, the number of heating and cooling degree days, an assumption about building performance, and a model for predicting energy prices.

Incorporating Flexible Design

We can estimate what the added initial cost of a flexible system would be. These would be costs associated with making the various upgrades to be considered easier to implement. Since it is difficult to know what this cost is, we will assume an increase amount and attempt to justify it in a future exercise. Design Options will include:

Switching from Air Source to Ground Source. A model for the future cost of this transition may be considered.

Switching fuel types. All heat pumps will use electricity, but in some areas switching between oil and natural gas as a backup fuel may be an attractive option.

Improving efficiency. Upgrades to improve efficiency may be attractive if energy prices rise or if technology advances reduce the cost of high efficiency components. A simulation model that determines the benefit and cost of utilizing technology improvements throughout the product lifecycle will need to be considered.

Changing the number of heating and cooling zones. Although this may be beyond scope, including this option will be considered.

Chapter 2: Uncertainties

There are several factors which may make it desirable to improve the performance of the flexible system over its life cycle. Those include:

2.1 Uncertainties

Weather. Average annual weather conditions for a location may vary year to year. To simplify the analysis, average weather conditions will be chosen, since variability in the weather should not affect our design options and decisions. With the possible exception of new insight from climate change research, it is unlikely that the weather conditions over the next several years will cause a significant change in future predictions of weather conditions.

Energy Prices. Energy prices have been extremely volatile in recent years. Technological improvements may lower long term energy prices and the scarcity of resources may increase prices. Government policy may increase prices. Political and economic forces may impact the marketplace.

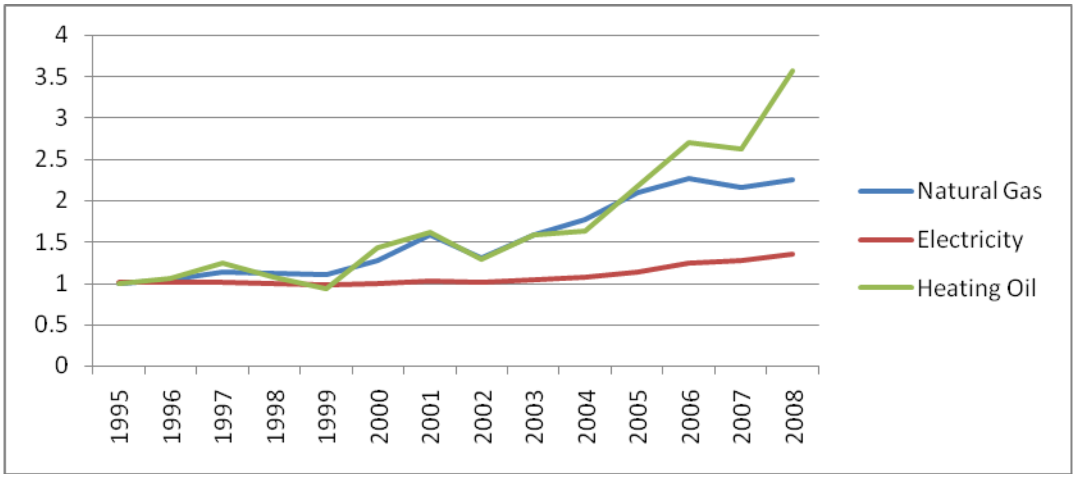

Figure 1-1: Growth in Annual Average Fuel Prices Since 1995, Source: Energy Information Administration

Technology. Improved component efficiency and reduced costs of existing technologies may result from Research and Development efforts. Describing the advantages of a system which can economically take advantage of improved technology is the motivation for a flexible design.

Government Incentives. State and Federal government agencies may offer rebates for the installation of energy efficient measures. Other policies such as renewable portfolio standards may enable the homeowner to sell renewable energy credits from efficiency improvements to utilities held to meeting these standards. A model may need to be developed to simulate changing government incentives, or this may be determined to be beyond the scope of the exercise.

With regards to home a home heating system, the 2 uncertainties that will be considered in more detail are the future costs of energy and the future performance and costs of new technology.

2.1.1 Uncertainty in Energy (Electricity) Prices

For the future costs of energy, we can look at historical data to gain an understanding about the volatility of future prices. The US Department of Energy’s Energy Information Administration (EIA) supplies historical and forecast data for many sources of energy. We will use these forecasts and develop a probability distribution to develop the forecast into a range of prices.

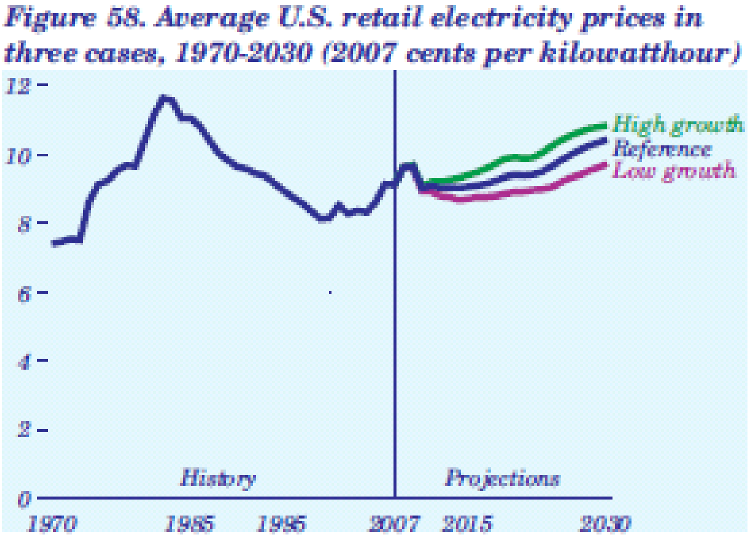

Figure 2-1: EIA Forecast of Retail Electricity Prices (http://www.eia.doe.gov/)

Figure 2-1 is the most recent residential retail electricity price forecast form the EIA. It uses real cost of electricity in 2007 to predict growth over the next 20 years. Note that the future predictions include a range that is relatively narrow given the historical variation in energy prices. The EIA itself notes several uncertainties in the future price of electricity including fuel costs, capital costs for new power plants, greenhouse gas emissions costs, and the future costs of renewable energy sources.

The EIA reference case predicts an increase from 9 cents/kWh in 2010 to 10.4 cents/kWh in 2030. Their high range is based only on variability in economic growth and is 10.8 cents/kWh in 2030 and their low range is 9.7 cents/kwH in 2030. However, the current average rate is 11.6 cents/kWh. We can see the price has already moved outside this relatively recent forecast.

Since using the EIA forecast seems unreasonable given its relative stability to historical trends, a fit of electricity prices to historical data back to 1960 was done. This data was fit to an exponential curve and the results appear in Figure 2-2 and Figure 2-3.

It is found using this data that the average growth rate for electricity prices is 3.7%/year. The variance in the growth rate is almost 20%/year. Note also that trends tend to last for periods of over 10 years. In the above graph, growth is flat for 12 years (1960 to the early 1970s), then grows rapidly for 10 years (to the early 1980s), grows more slowly for 15 years (into the late 1990s), flattens out for several years (into the early 2000s), and then grows significantly for the last several years.

This suggests that we can use a scenario approach for prices over long periods of time. The average scenario would be the average growth rate of 3.7%/year. The high growth rate scenario would be double the historical average for a total of 7.4%/year. The low growth rate scenario would be no growth in pricing. It seems reasonable to make the average approach slightly more likely than the two extreme approaches. So we can assume a 40% chance of average growth, with 30% chance of high growth, and a 30% chance of no growth in electricity prices.

For a probabilistic approach, we can use the growth rate of 3.7% and the variance of 20% to generate forecasts for future prices.

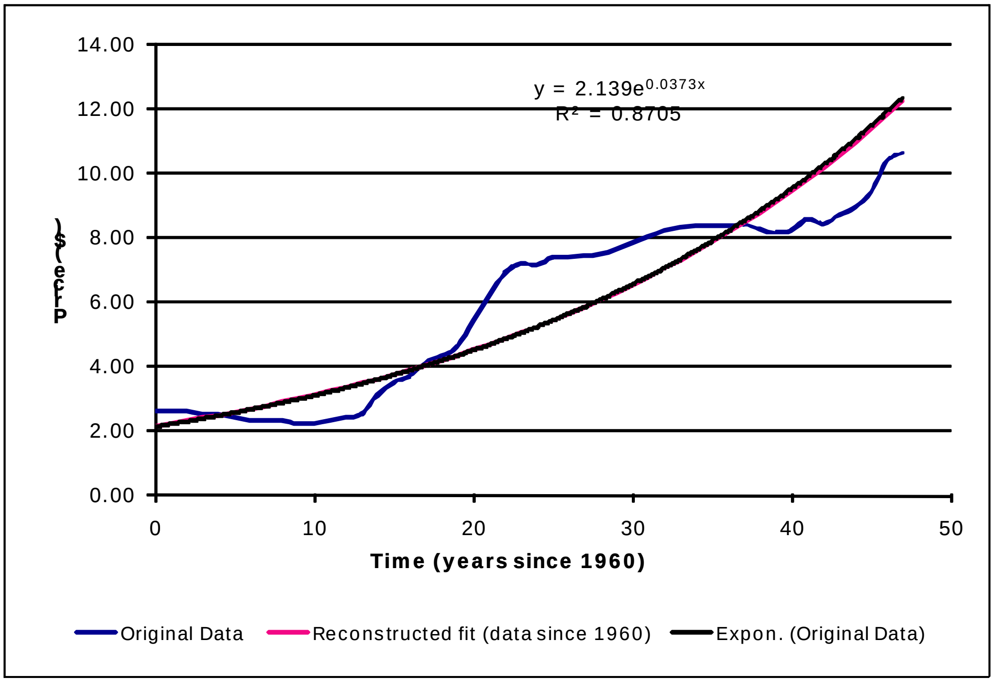

Figure 2-2: Fit of historical electricity prices from 1960 to 2008 to an exponential growth curve.

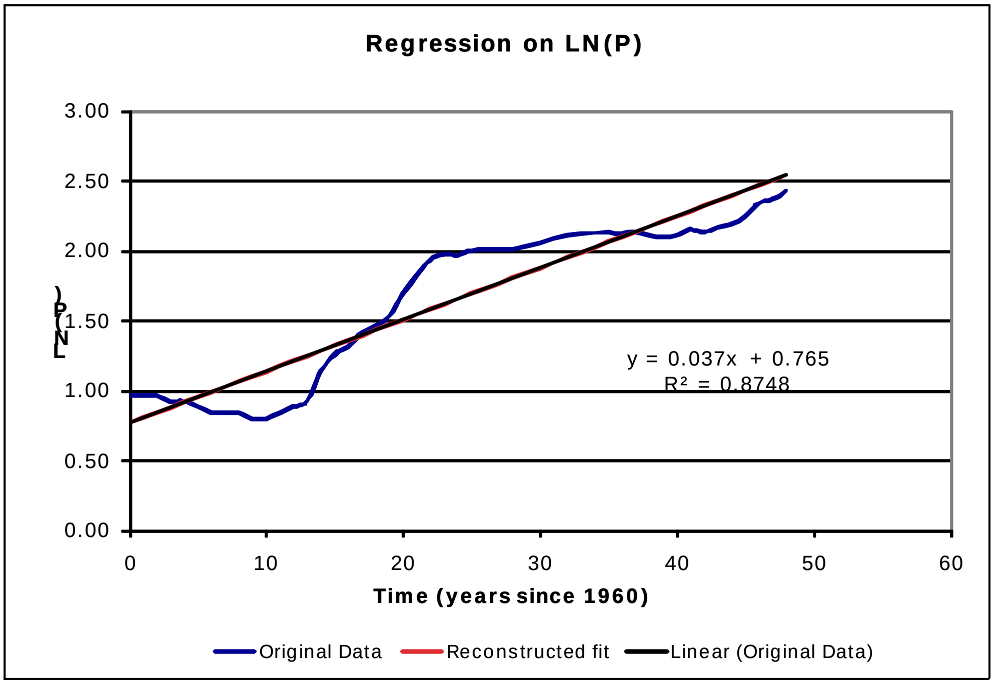

Figure 2-3: Linear fit of Natural Log of Residential Electricity Price Data from 1960-2008

2.1.2 Uncertainty in Technology Developments

The potential developments of future technologies can be drawn from two sources. First, historical data relating to Appliance standards can be reviewed to identify trends in the improvement of environmental heat pumps. Second, the goals of research programs can be used as starting points to develop benchmarks for future technology improvements.

Since research and development programs have uncertain outcomes, we can assume a normal distribution of outcomes of future research programs in terms of technology and price. There are several options for how to represent the output of this uncertainty. We could identify a single point with a specific level of efficiency and a specific price that we can implement or we can develop a range of improvements where the marginal cost for a unit improvement in efficiency increases with efficiency.

Prices for 2 Ton Gas and Electric backup heated heat pumps are shown in Figure 2-3. While an overall view of the data makes it difficult to differentiate price for gas vs. electric, comparable units from a single manufacturer GOODMAN indicate a roughly $500 premium for gas over electric backup heat.

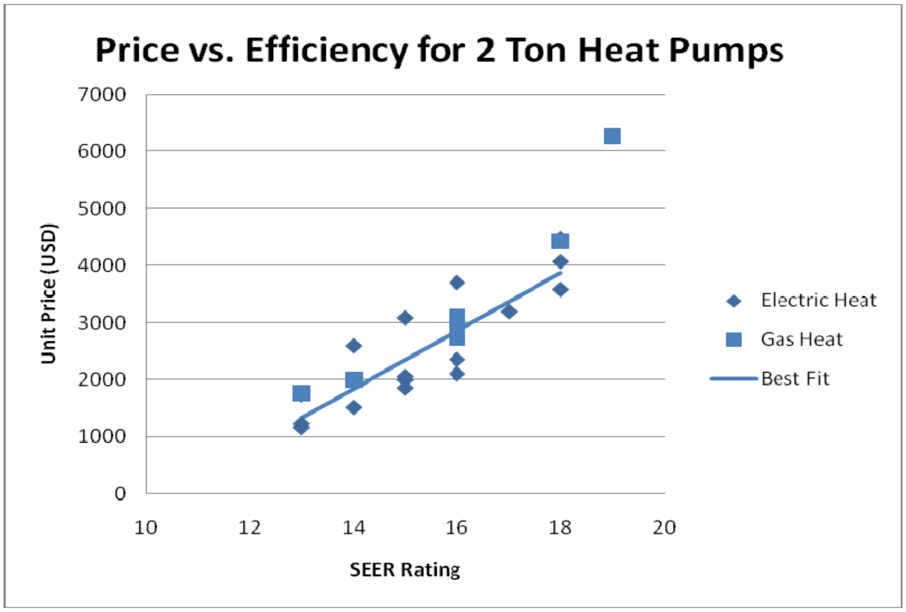

Figure 2-3: Price and Efficiency for 2 Ton Heat Pumps with Gas and Electric Backup Heat (Data Source http://www.theacoutlet.com 5 October 2009)

According to the Department of Energy's Buildings Technologies Program 2008 Mulit-year plan (MYP) (http://www1.eere.energy.gov/buildings/mypp.html pg. 2-42), their goal is to develop a 24 SEER rated heat pump by 2020. We can assume there will be some cost premium to this development over the existing 18 SEER units which represent the top of the market. We will assume the goal is to reach about a $1000 premium over the current cost of units with an 18 SEER rating.

Since R&D targets are often ambitious, we can assume there is less than a 50% chance of meeting this target. A reasonable assumption for a normal distribution might be to assume the target values are one standard deviation above the mean results of such a program (indicating they are only met one-third of the time). We would like to model the improvement of technology with a distribution containing a lower bound and a long tail on the high end. This will allow us to easily model improvement from a starting point of current technology.

For a scenario based approach, we could assume a 25% chance that the research target or 24 SEER is met, a 50% chance that they reach a SEER rating of 22, and a 25% chance they reach a SEER rating of 20.

For a probabilistic based approach, a good distribution to accomplish this model would be a lognormal distribution. To model in such a way that we can represent random improvement year by year, we note that over ten years we expect to see improvement of about 0.6 SEER/year. We want to have a roughly 25% chance of seeing a cumulative improvement of 6 SEER over ten years. An expected increase in SEER over ten years to about 22 or 23 is reasonable. Using lognormal distribution with a mean of -1.1 and a standard deviation of 0.9 gives reasonable results for future SEER rating.

Results for 1000 simulations showing the resulting simulated PDF and CDF for final SEER value are shown in Figure 2-4. The mean final SEER rating was 22.8 and the standard deviation was 1.46. About 23% of the simulations reached the target SEER value of 24. The maximum SEER obtained was 27.5. The minimum was 20.

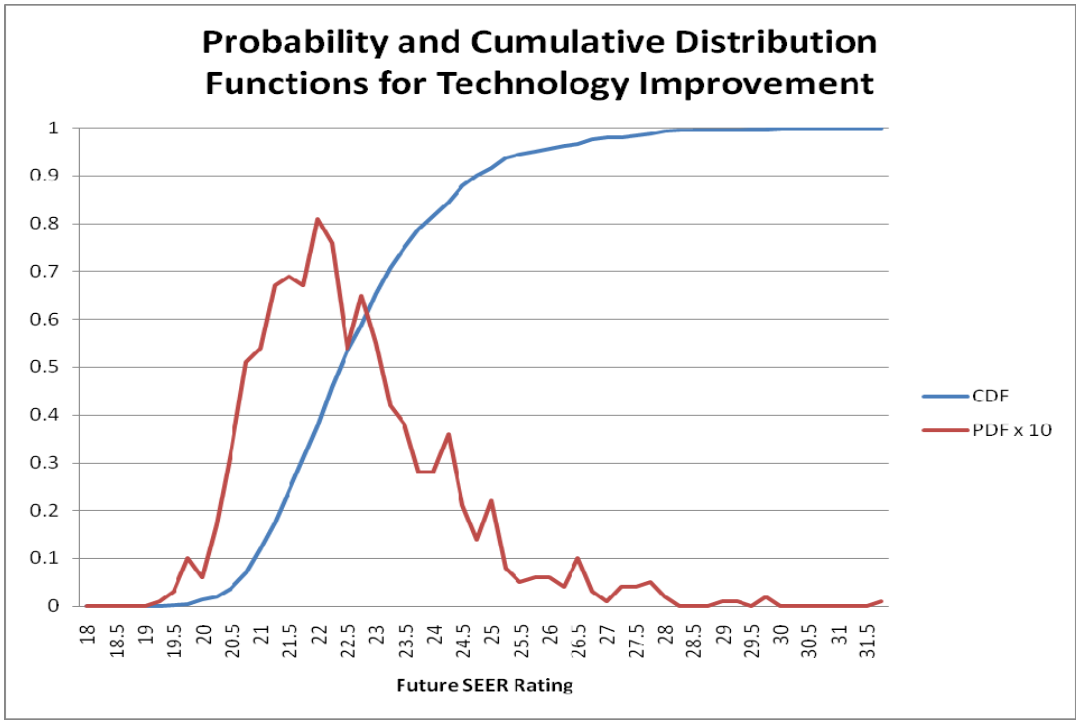

Figure 2-4: Results of Simulation for Technology Improvement Uncertainty Model

To incorporate into a decision model, we would need to assume a price for the improved technology at comparable levels to the most efficient models available today, around $4500 to $5000 (excluding the 19 SEER model) and then fit a cost versus efficiency curve over the new range. Improvements in energy efficiency are realized when more efficient technology can be used to replace existing technology and the lower operating costs of the equipment are sufficient to recoup the capital cost of equipment replacement. We will again consider the NPV of installing, operating, and potentially upgrading the heat pump system as the basis for measuring the impact of this uncertainty on the system.

Chapter 3: System Models

3.1 Fixed System Model

The fixed system model consists of a standard system utilizing today's technology at today's prices. Various options based on the best fit line in Figure 2-3 will be available for use in the system. We will assume that installation costs are fixed regardless of the level of performance selected. An installation cost of $1,000 will be used. Upgrades to the fixed system result in the need to pay full system price plus installation costs. Used systems generally do not have resale value so no residual cost for the discarded system is considered.

The benefit of the fixed system is that the equipment and installation costs occur once when the original equipment is installed and it will be less expensive than a flexible system. The risk of the fixed system is that the system performance cannot be improved in response to increased energy costs or easily take advantage of technology improvements if they become available. If a high performance system is selected initially, energy costs may not increase as much as anticipated or the performance may become available at a lower cost later.

3.2 Flexible System Model

The flexible system model will consist of a standard system with an incremental cost over the fixed system. The increased cost reflects the addition of product features that allow easy system upgrades for future technologies. Since such systems are not available on the market, we will assume a cost increase of 10% for this design flexibility. Installation costs for the initial system will be the same as for the fixed system, $1000.

We also need to define the upgrade cost and performance of the system based on the technology improvements in the previous section. In the previous section, we developed a model for pricing future technology improvements on a yearly basis. The price for a future upgrade from a low efficiency unit to a higher efficiency unit will be more than the future price difference between those two units. Again, since this price premium is difficult to estimate, a 10% premium over the price difference will be assumed. We will assume that an upgrade will cost half as much as a new installation, or $500.

The flexible system has increased cost initially, but is able to be upgraded at relatively low cost in response to increased energy costs or technology improvements that make more efficient operation desirable. If energy prices increase quickly, the flexible system will be upgraded sooner before technology costs fall significantly. Technology costs may not fall as forecast and energy prices may not rise significantly, so the additional initial cost may not result in added value later.

3.3 Example

A heat pump unit with a 13 SEER rating costs about $1200. A flexible unit will cost an additional 10% or $1,320.

In 10 years, if technology improvements have made available a heat pump unit with a SEER value of 20 and a price of $5,000, while the 13 SEER heat pump still costs $1,000. A new unit to replace a fixed system would cost $5,000 plus $1,000 for a total cost of $6,000. For the flexible system, the upgrade would cost $4,400 plus the $500 for upgrade installation. Therefore, to achieve the same performance level under these conditions, the flexible system would save $1,100 compared to the fixed system in year 10. Assuming a discount rate of 15%, the NPV of the flexible system would be $151 higher than the fixed system.

3.4 Model of System Performance

The main goal of the system model is to determine the operating costs of the system based on the efficiency level selected. It is assumed that the heat pump equipment will run at relatively constant efficiency determined from its SEER rating. The amount of energy required to be moved to heat or cool a building over the course of a year will be determined from the average number of degree days for a particular location and the performance characteristics of the building being considered.

3.4.1 Heat Pump Modeling

The performance of a heat pump in cooling mode is determined by:

Energy Use (kWh) = Cumulative Energy Flow (BTU) / [(1000 (Wh/kWh) * SEER (BTU/wH)]

For simplicity, we will assume equal performance for heating. This is not an accurate representation of the heating performance for all conditions since performance is reduced significantly for heating in colder climates. And in extremely cold conditions, backup heat sources are used instead of drawing heat from outside air using the heat pump. However, the model is a reasonable assumption for the scope of this paper.

3.4.2 Weather Models

For weather, we will use the average number of Heating Degree Days and Cooling Degree Days (DD) per year for specific regions of the country. Examples for selected regions of the US based on data from 2001-2008 are shown in Table 3-1

Table 3-1: Average Yearly Heating and Cooling Degree Day Data for Selected US Regions 2001-2008 (National Climactic Data Center, http://www.ncdc.noaa.gov/oa/ncdc.html)

US Region	**Cooling Degree Days**	**Heating Degree Days**
Northeast	508	6358
Central	792	6122
West North Central	1019	6314
Southwest	2600	2088
Northwest	1523	4865

3.4.3 Building Models

For purposes of this paper, we looked for existing data on single family residences with adequate information to use in the model described above. A more sophisiticated model using building energy modeling tools is beyond the scope of this paper.

Most importantly, we want data for a typical average new home, a typical high efficiency home, and a typical older home that has poor performance. Home Energy Magazine (http://www.homeenergy.org/consumerinfo/benchmarking-energy-usage.php) has published a range of values for benchmarking home energy use by providing example performance values for Energy Use/HDD/Sq. Ft. We can assume values of 5 BTUs/HDD/ft^2, 10 , and 15 for our high efficiency, average, and older home based on this data. We can assume a home size of about 1,500 square feet, typical for a 2 ton Heat Pump Unit. Thus, we get the following performance:

Energy Efficient Home: 7,500 BTU/HDD

Average Home: 15,000 BTU/DD

Poor Performing Home: 22,500 BTU/DD

3.4.4 Operating Cost Models

Since we know building performance in terms of Energy Moved by the heat pump per DD, the average number of degree days, the efficiency of the heat pumps, and the cost of electricity, we can determine system operating costs.

Total Cost/Year = Electricity Cost (cents/kWh)* Building Performance Factor (BTU/DD) * Degree Days (DD/year) / [1000 (wH/kWh) * SEER (BTU/wH)]

Chapter 4: Decision Tree Analysis

The value of a flexible design is evaluated through a decision tree analysis. The analysis will focus on the potential of incorporating new technology in the future using a flexible design. The decision tree will consist of an initial decision which is or not to install a fixed design or a flexible design. Then we will have a chance node that sets the initial price trajectory for electricity prices for 10 years. Then, for the flexible design, the decision on whether or not to upgrade will be made. After the decision, another uncertain price trajectory will be determined based on chance nodes.

We will consider the costs incurred to install and operate the system over a 20 year period. One opportunity to upgrade the system will be considered after 10 years.

We use the price trajectories provided by the EIA for future electricity prices. We considered equal possibility of total increases of 0.0 cents, 1.6 cents, and 3.0 cents over a 20 year period. For the analysis we will consider a home in the Central US region with an average of 6912 degree days/year. We consider a decision point at 8 years of the lifetime of the system where it may be upgraded to 20 SEER which will cost $3300 including installation costs we considered above.

For the fixed system, the SEER level from figure 2-3 that is most economical was found. For this conditions stated above, the most economical fixed system was the 13 SEER unit. Therefore, a 13 SEER initial unit will also be used for the flexible system. The conditions are shown in table 4-1.

The uncertainty for electricity prices is summarized in Table 4-2. The set of parameters for the initial time period is from the analysis in Chapter 2. The probabilities for the second set of chance nodes are made dependent on the result of the initial chance node. It was chosen to make the initial trend at the first chance node increase the probability of the same result at the second chance node. Also, if the initial change was low or high, we made it more likely to switch to the average value than to the opposite low or high value.

Table 4-1: Conditions used for Decision Tree Analysis considering Fixed vs. Flexible System Performance

Fixed System Cost	$ 1,300.00	
Flexible System Cost	$ 1,430.00	
Initial System Installation Cost	$1000	
Initial SEER Value	13	SEER
Upgrade SEER Value	22	SEER
Upgrade SEER Cost	$3,000.00	
Upgrade Installation Cost	$500.00	
Building Performance Factor	15,000	BTU/DD
Climate Degree Days	6,912	DD/Year
Decision Year	10	
Discount Rate	0.12	%
Initial Electricity Price	11.6	cents/kWh

Table 4-2: Probabilities for Low, Average, or High Price trends for the initial and Subsequent Time Periods

	Change/Year (%)	Initial Probability	Second Probability given Initial P is Low	Second Probability given Initial P is Average	Second Probability given Initial P is High
Low Price	0	0.3	0.5	0.25	0.2
Average Price	3.7	0.4	0.3	0.5	0.3
High Price	7.4	0.3	0.2	0.25	0.5

The decision tree is shown in figure 4-1. The decision tree shows that the optimal strategy is to install the flexible system initially, and then upgrade if prices in the initial period increase at an average or above average rate.

The fixed system is about $89 more expensive than the flexible design over the system's lifecycle. Note that the initial price premium for the flexible design was $130 dollars, so the flexible system could cost up to about $200 more than the fixed design and still be cost effective.

Figure 4-2 shows the Value at Risk and Gain for both the flexible and inflexible systems. It is clear from the graph that the value of the flexible system is to protect against worst case scenarios for electricity prices where the flexible system performs much better than the inflexible system.

Table 4-3 shows several typical decision making criteria and the resulting decision that would be made using each criteria. The flexible system is preferred if we consider Expected Net Present Value or the Value at risk measure using P10. If we consider initial capital cost, CAPEX, the inflexible system is preferred.

Table 4-3: Different Decision Making Criteria Using Decision Analysis Results

Criteria	**Inflexible System**	**Flexible System**	**Choice**
ENPV	($11,520)	($11,609)	Flexible
VAR, P10	($14,564)	($13,831)	Flexible
CAPEX	($2,300)	($2,430)	Inflexible

The decision tree analysis is subject to the specific assumptions and decisions that we have allowed. The only uncertainty considered is in electricity prices, ignoring uncertainty in technology development and other areas. Also, there is only one opportunity to upgrade system performance rather than opportunities every year. The work in other sections will look into models that address these shortcomings.

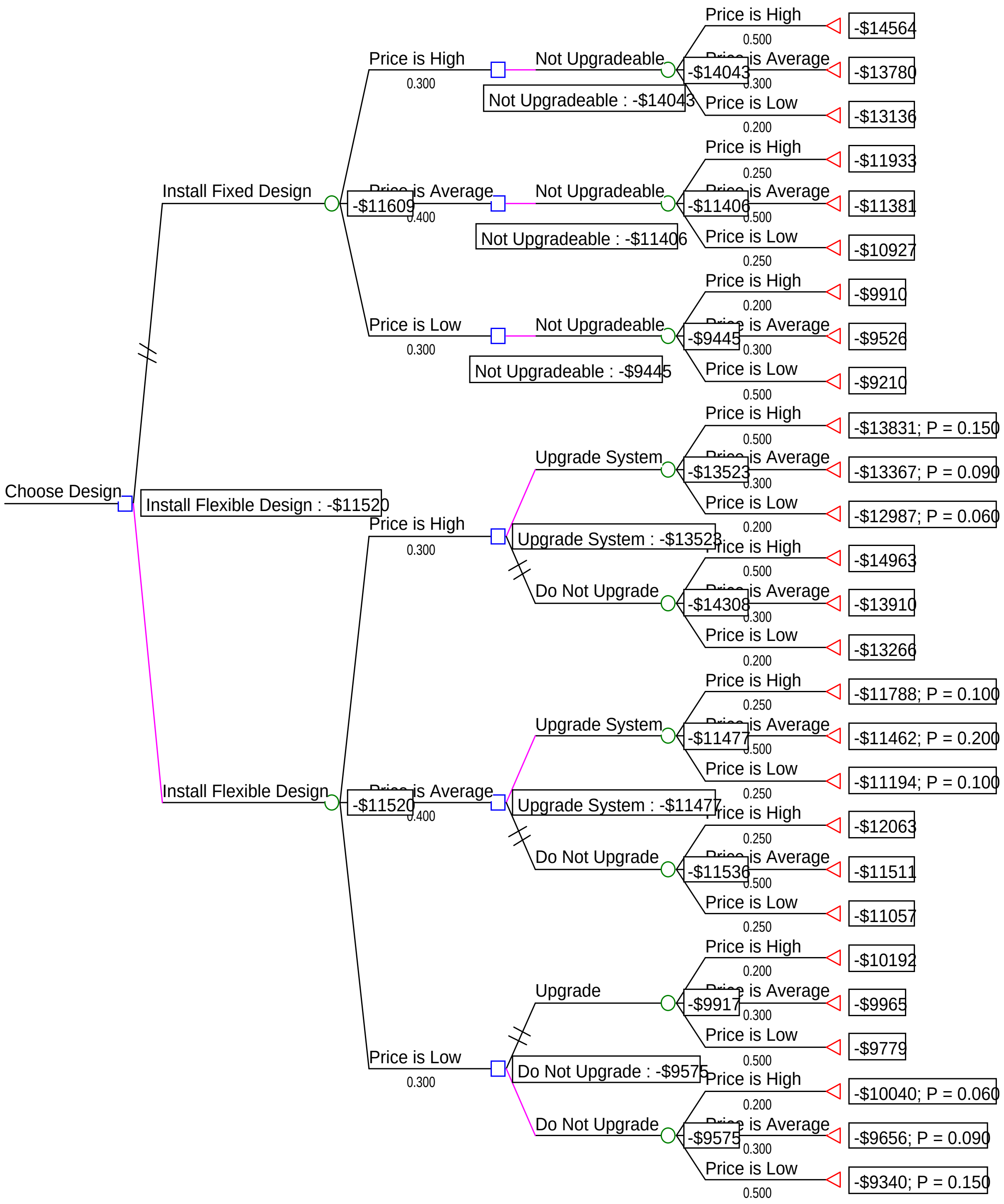

Figure 4-1: Decision Tree for Fixed vs. Flexible System Design (Values are NPV of Total Cost)

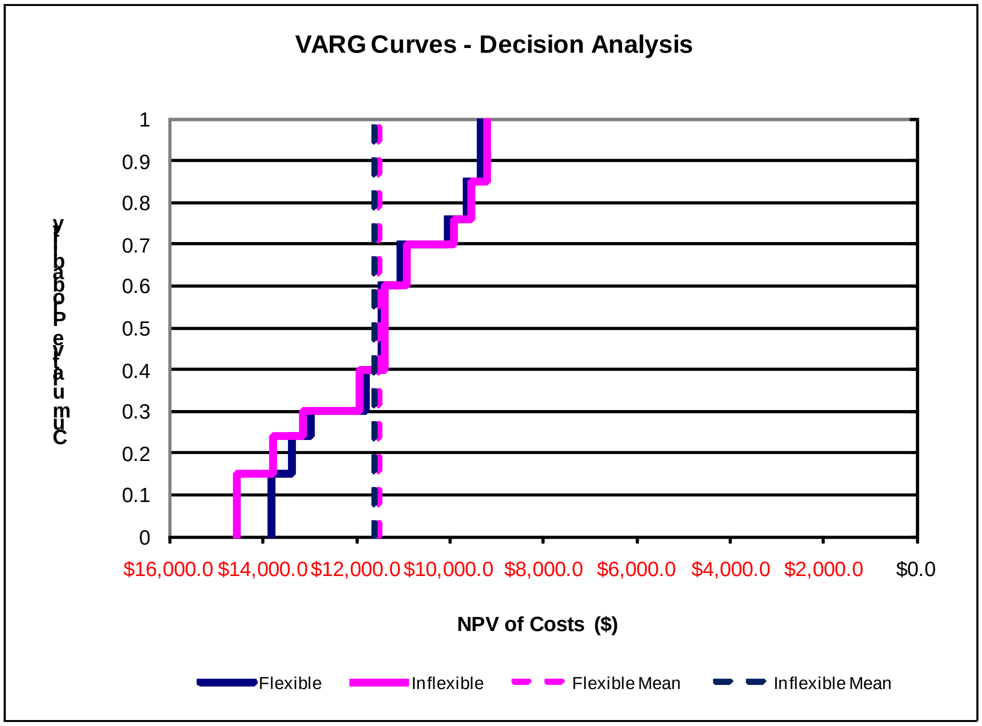

Figure 4-2: Value at Risk and Gain for Decision Analysis of both the Fixed and Flexible Systems

Chapter 5: Lattice Analysis

A more detailed analysis will be done by using a binomial lattice approach for modeling the uncertainty in future electricity prices. We will use the resulting price distributions to evaluate the NPV of the fixed and flexible system designs from AP3.

To generate the parameters u, p, and d for the binomial lattice the year end residential retail electricity prices from 1960 to 2009 were used. The exponential fit for this data was developed in Chapter 2.

For the lattice analysis, it is desirable to look over a 20 year period. So a lattice model using the parameters derived from the best fit data were used to develop a lattice for future electricity prices. We used the v value of 3.7% increase per year, the variance of 20 % per year, and a time interval of 3 years for each stage of the lattice. This resulted in the following lattice parameters

Up Probability = 66 %
Down Probability = 34%
Up Factor = 1.41
Down Factor = 0.71

The resulting distribution for prices is shown in Figure 5-1.

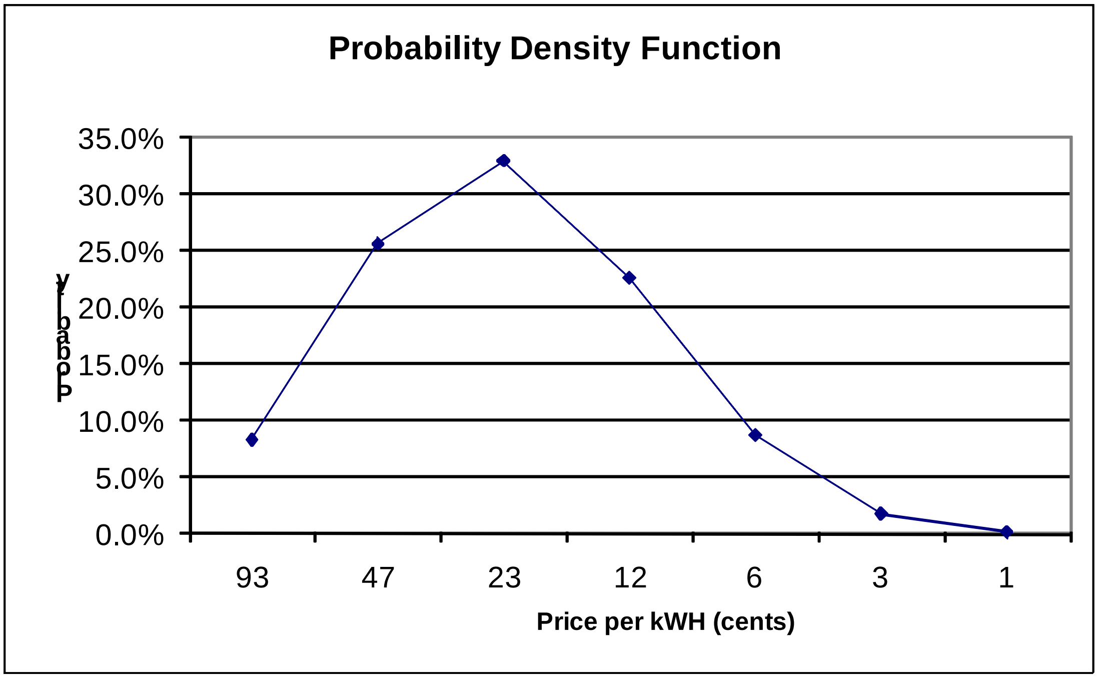

Figure 5-1: Initial Price PDF for Exponential Data Fit and Binomial Lattice Analysis

These results seem to generate electricity prices significantly more expensive then we anticipate. The mean price in 20 years is over 30 cents/kWh. Average growth of 3.7% would give us a price of about 22 cents/kWh in 18 years. Therefore, the Up Factor and Down Factors are reduced significantly to:

Up Factor = 1.28
Down Factor = 0.78

This resulted in a price distribution in 18 years shown in figure 5-2. Note the mean electricity price is now around 21.7 cents/kWh, in line with what an average growth rate would predict.

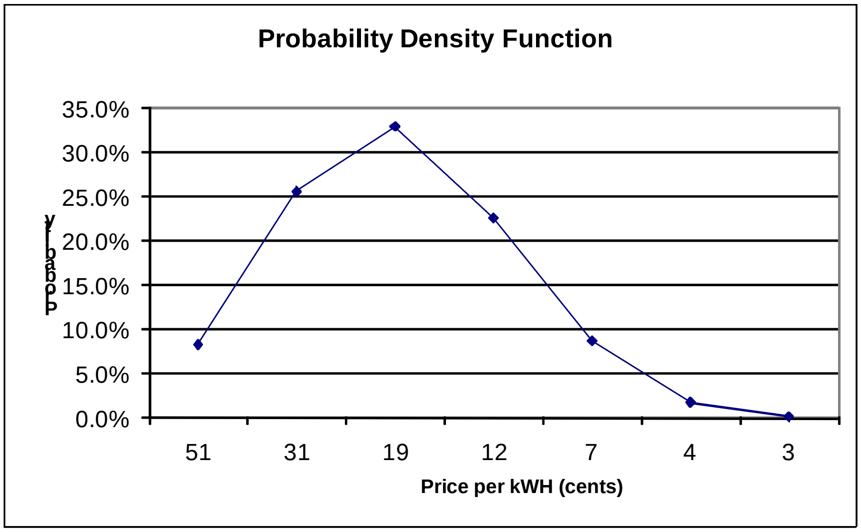

Figure 5-2: Final Price PDF for Exponential Data Fit and Binomial Lattice Analysis

The data for price and probability using the final binomial lattice parameters are shown in Table 5-1 and Table 5-2.

Table 5-1: Lattice Model Analysis of Future Electricity Prices

Period	**0**	**3**	**6**	**9**	**12**	**15**	**18**
Price	11.65	14.88	19.01	24.29	**31.03**	39.65	50.65
		9.12	11.65	14.88	19.01	24.29	31.03
			7.14	9.12	11.65	14.88	19.01
				5.59	7.14	9.12	11.65
					4.37	5.59	7.14
						3.42	4.37
							2.68

Table 5-2: Lattice Model Probabilities for Each Price in Table 5-1

Period	**0**	**3**	**6**	**9**	**12**	**15**	**18**
Probabilities:	1.00	0.66	0.44	0.288	0.190	0.126	0.083
		0.34	0.45	0.444	0.391	0.323	0.256
			0.12	0.229	0.302	0.332	0.329
				0.039	0.104	0.171	0.226
					0.013	0.044	0.087
						0.005	0.018
							0.002

Now that we have established the model for the future price distributions for electricity, the operating cost model from AP3 was used to determine the operating costs for each design (fixed at initial 13 SEER and upgraded to 24 SEER) over each period. The period 0 costs represent the capital and installation costs for fixed system in the 13 SEER table and the flexible system in the 24 SEER table. The single year operating cost was multiplied by $[(1+R)^2+(1+R)+1]/(1+R)^2]$ to adjust for the 3 year period and to include discounting for the 2nd and 3rd years of operation. All of the three year cash flows are discounted to the first year of each period of operation (i.e. the value for years 1 to 3 is discounted to be equivalent to all costs in year 1 by using a formula Yearly Cost * $[1 + [1+r] + [1+r]^2]/[1+r]^2)$

Table 5-3: Period Cash Flows for 13 SEER Heat Pump System (Period 0 Costs Reflect Fixed System Installation Costs

Period	**0**	**3**	**6**	**9**	**12**	**15**	**18**
Cash Flow:	$ (2,300)	$ (3,234)	$ (4,131)	$ (5,278)	$ (6,743)	$ (8,615)	$ (11,006)
13 SEER System		$ (1,981)	$ (2,531)	$ (3,234)	$ (4,131)	$ (5,278)	$ (6,743)
			$ (1,551)	$ (1,981)	$ (2,531)	$ (3,234)	$ (4,131)
				$ (1,214)	$ (1,551)	$ (1,981)	$ (2,531)
					$ (950)	$ (1,214)	$ (1,551)
						$ (744)	$ (950)
							$ (582)

Table 5-4: Period Cash Flows for an upgraded 24 SEER Heat Pump System (Period 0 Costs Reflect Flexible System Installation Cost)

Period	**0**	**3**	**6**	**9**	**12**	**15**	**18**
Cash Flow	$ (2,430)	$ (1,752)	$ (2,238)	$ (2,859)	$ (3,652)	$ (4,666)	$ (5,961)
24 SEER System		$ (1,073)	$ (1,371)	$ (1,752)	$ (2,238)	$ (2,859)	$ (3,652)
			$ (840)	$ (1,073)	$ (1,371)	$ (1,752)	$ (2,238)
				$ (658)	$ (840)	$ (1,073)	$ (1,371)
					$ (515)	$ (658)	$ (840)
						$ (403)	$ (515)
							$ (315)

Next, the price for technology improvement was modeled to decrease in subsequent 3 year periods. In 3 years, it is assumed that the upgrade cost to go from 13 SEER to 24 SEER would be $6,000, and decline by 15 % every 3 year period. Note that the table indicates the first opportunity to upgrade is in the period ending in year 6. If the upgrade is done, it assumed to happen at the beginning of the period and operating costs for that period are for the upgraded system.

Table 5-5: Model For Upgrade Cost of System by Period

Period Ending Year	**0**	**3**	**6**	**9**	**12**	**15**	**18**
Discounted Option Cost			3,813	2,307	1,396	844	511
Option Cost			6,000	5,100	4,335	3,685	3,132

Next, the present values for all cash flows for the fixed system were considered. In addition to the operating costs above, the initial cost of $1300 and installation of $1000 were added in period 0. The discount rate was 12%. Table 5-6 is calculated using the values in table 5-3, starting at the right side of the table and moving left such that each cell represents the ENPV for that period and all future periods for that node of the lattice. The total ENPV of costs for the fixed system is -$11,332. The results of this analysis are shown in Table 5-6.

Table 5-6: ENPV of Cash Flows for a 13 SEER system at each node in the binomial lattice (Period 0 Costs for Fixed System Installation).

Period	**0**	**3**	**6**	**9**	**12**	**15**	**18**
ENPV (Cash Flow)	$ (11,332)	$ (11,648)	$ (13,612)	$ (15,337)	$ (16,273)	$ (15,417)	$ (11,006)
Orignial System		$ (7,136)	$ (8,340)	$ (9,397)	$ (9,970)	$ (9,446)	$ (6,743)
			$ (5,110)	$ (5,757)	$ (6,109)	$ (5,788)	$ (4,131)
				$ (3,527)	$ (3,743)	$ (3,546)	$ (2,531)
					$ (2,293)	$ (2,173)	$ (1,551)
						$ (1,331)	$ (950)
							$ (582)

The present value for all cash flows that result after the system has been upgraded system are calculated using the same approach that was used for the original system using the cash flows in table 5-4. This table provides data that allows in later analysis to determine if we should upgrade at any specific point in time. This is shown in Table 5-7.

Table 5-7: ENPV of Cash Flows for a 24 SEER System (Period 0 Costs are for Flexible System Installation)

Period	**0**	**3**	**6**	**9**	**12**	**15**	**18**
ENPV (Cash Flow)	$ (7,322)	$ (6,309)	$ (7,373)	$ (8,308)	$ (8,815)	$ (8,351)	$ (5,961)
Upgraded System		$ (3,866)	$ (4,517)	$ (5,090)	$ (5,401)	$ (5,117)	$ (3,652)
			$ (2,768)	$ (3,119)	$ (3,309)	$ (3,135)	$ (2,238)
				$ (1,911)	$ (2,027)	$ (1,921)	$ (1,371)
					$ (1,242)	$ (1,177)	$ (840)
						$ (721)	$ (515)
							$ (315)

To determine the costs of the flexible system, a dynamic programming approach was used on top of the lattice model. The decision rule was:

> If Current Upgrade Cost (From Table 5-5) plus ENPV of Current and Future Operating Costs (24 SEER, Table 5-7) is greater than (since costs are negative values) the ENPV of Future Operating Costs (from the DP model, Table 5-9) plus the Current Operating Costs (13 SEER, Table 5-6) then Upgrade the system at the beginning of this period.

Since the system is installed in year 0, and upgrades are assumed to occur at the beginning of a period, no upgrade is allowed in the first period for years 1 through 3.

A dynamic programming approach starting from the last period and working backwards in time to period 0 is considered. For each node the probability weighted present value of optimal future costs plus costs for a non upgraded system for the current period are compared to upgrading now and using the present value for operating costs for an upgraded system for all future costs.

Table 5-8 indicates when we upgrade according to the current model assumptions according to the decision rule described above. Table 5-9e shows the ENPV for the selected option for each node in the lattice analysis.

Table 5-8: Results of Decision Rule for When to Upgrade Flexible Heat Pump System to 24 SEER System

Period Ending Year	**0**	**3**	**6**	**9**	**12**	**15**	**18**
Discounted Option Cost			**3,813**	**2,307**	**1,396**	**844**	**511**
Option Cost			**6,000**	**5,100**	**4,335**	**3,685**	**3,132**
Excercise CALL	NO	NO	NO	**YES**	**YES**	**YES**	**YES**
OPTION ?		NO	NO	NO	NO	**YES**	NO
			NO	NO	NO	NO	NO
				NO	NO	NO	NO
					NO	NO	NO
						NO	NO
							NO

Table 5-9: ENPV for Each Node in the Binomial Lattice for a Flexible System after Applying Dynamic Programming

Period Ending Year	**0**	**3**	**6**	**9**	**12**	**15**	**18**
PV Flexible System	$ (11,182)	$ (11,189)	$ (12,670)	$ (13,408)	$ (13,150)	$ (12,036)	$ (9,093)
		$ (7,105)	$ (8,273)	$ (9,254)	$ (9,667)	$ (8,801)	$ (6,743)
			$ (5,110)	$ (5,757)	$ (6,109)	$ (5,788)	$ (4,131)
				$ (3,527)	$ (3,743)	$ (3,546)	$ (2,531)
					$ (2,293)	$ (2,173)	$ (1,551)
						$ (1,331)	$ (950)
							$ (582)

Finally, for each path the probability and NPV of all costs is calculated and presented in the form of a cumulative distribution function or a value at risk and gain plot. This is shown in figure 5-7. From the curves, we can see that if electricity prices remain low, the costs will be relatively low and the fixed system will cost less than the flexible system. However, if electricity prices increase, the flexible system will be upgraded and costs will be reduced. At the high end of the VARG curves, the flexible system results in significantly lower costs over the system's lifetime. However, the fixed system still has a lower Expected NPV for the assumptions considered.

For the current analysis, the flexible system does not appear to be a cost effective alternative to a fixed system unless the costs for implementing flexibility can be minimized. Because a fixed system can always be replaced in response to future changes in technology and energy prices, the flexible system is not able to be built smaller initially and upgraded later under the assumptions for energy prices used. In order for a flexible design to be successful, it must minimize the up front costs and offer significant price advantages for upgrading later, especially since the upgrade costs are discounted significantly in NPV analysis for upgrades later in the product's life cycle.

The same decision making criteria that were considered in Chapter 4 are again considered for the results of the lattice analysis in table 5-10. The results for the lattice analysis are the same as for the decision analysis. The flexible system would be chosen if Expected Net Present Value or Value at Risk, P10, were the criteria. If initial capital expenditure, CAPEX, were the criteria, then the Inflexible system would be chosen.

Table 5-10: Different Decision Making Criteria Using Decision Analysis Results

Criteria	**Inflexible System**	**Flexible System**	**Choice**
ENPV	($11,332)	($11,182)	Flexible
P10	($15,446)	($14,384)	Flexible
CAPEX	($2,300)	($2,430)	Inflexible

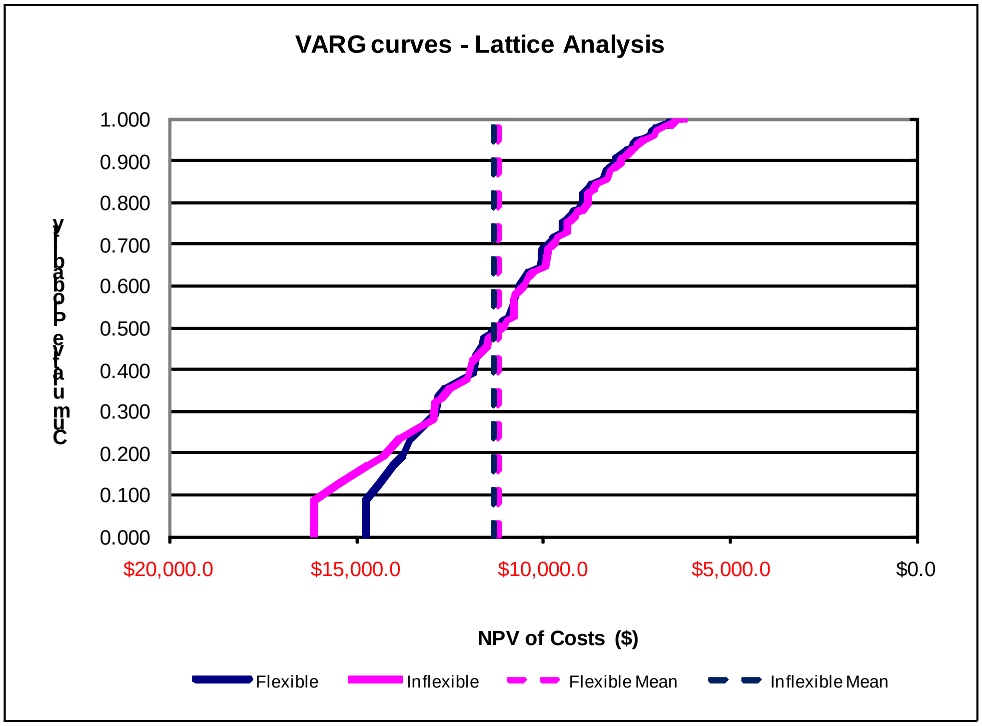

Figure 5-5: VARG Curve for Fixed and Flexible System using Lattice Analysis

Chapter 6: Conclusion

Through this analysis, it is clear that flexibility is only desirable if it can be done meeting both of the following criteria:

1. There is a minimum of additional initial cost required to allow for future flexibility.
2. Future flexibility can be implemented at a significant discount to replacing the entire system.

There may be other ways to implement the flexibility, and an important factor may be to consider flexibility which takes advantage of several potential future improvements.

In this case, both the decision analysis and lattice analysis produced very similar results. Because of this, the decision analysis is probably a preferred approach. Decision analysis can be more easily adapted to reflect additional uncertainties such as the rate and cost of technology improvements with only moderate additional complexity. The modeling of a roughly 20 year time horizon using the lattice analysis is difficult, and the use of historical prices to generate the future prices used in the lattice was not straightforward.

The approach used here demonstrated the difficulty in choosing how to incorporate and model flexibility into a system. In this system a number of ways to incorporate flexibility were identified. Further analysis to incorporate other possible flexible designs might demonstrate that other flexibilities are more valuable than the efficiency flexibilities we considered. The importance of having a useful model to evaluate these flexibilities with relatively little effort is important in selecting options for further analysis and possible implementation.

In addition to potential cost savings, flexibility may offer other advantages that should be considered. First, having flexible systems in the field provides a potential upgrade market to existing equipment when more efficient technology is developed. This might be desirable in an industry where installed equipment is often not replaced until it is no longer serviceable. Also, since heat pumps are often replaced only when an already installed unit breaks down, often in the midst of extremely warm or cold weather, the owners of these systems are often most interested in the speed at which the unit can be replaced, not the performance of the system or the lifecycle costs. Promoting flexible systems allows those purchasing these systems to install a basic system when needed, with the option to upgrade to a higher performing one when economic or other conditions make this desirable.