Applying Epoch-Era Analysis for Homeowner Selection of Distributed Generation Power Systems

By
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S.B. Aerospace Engineering, Massachusetts Institute of Technology, 2009

Submitted to the System Design and Management Program
In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

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ABSTRACT

The current shift from centralized energy generation to a more distributed model has opened a number of choices for homeowners to provide their own power. While there are a number of systems to purchase, there are no tools to help the homeowner determine which system they should select. The research investigates how an Epoch-Era Analysis formulation can be used to select the appropriate distributed generation system for the homeowner. Ten different distributed generation systems were successfully analyzed and resulted in the average homeowner selecting the solar photovoltaic system. Additionally, the research investigated how using an "average" homeowner compared to an individual homeowner might result in a different distributed generation selection. Two randomly selected homeowners were analyzed and there were noticeable differences with the average homeowner results, including one of the homeowners selecting the geothermal system instead. Suggestions for how the research can be expanded – including individual homeowner parameterization, distributed generation systems inclusion, and epoch/era expansion – are covered at the end.

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I would like to thank my girlfriend, Lulu. Being in a relationship with someone who is founding their own company, writing their thesis and planning an energy conference is no easy endeavor but throughout you have maintained your grace and patience. You taught me to enjoy each accomplishment, no matter how small, and continually supported me on this journey without hesitation.

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LIST OF ABBREVIATIONS

CO_2	Carbon Dioxide
DG	Distributed Generation
EEA	Epoch-Era Analysis
fNPT	Fuzzy Normalized Pareto Trace
GHG	Greenhouse Gas
kW	Kilowatt
LCOE	Levelized Cost of Electricity
MAE	Multi-attribute expense
MAU	Multi-attribute utility
NPT	Normalized Pareto Trace
SAE	Single attribute expense
SAU	Single-attribute utility
SEAri	System Engineering Advancement Research Institute
RSC	Responsive Systems Comparison

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Chapter 1 Introduction

1.1 Background and Motivation

Power generation in the United States has largely remained stagnant for a large part of the previous century with the centralized power distribution network. This style of distributed network structure resulted in centralized generation facilities that were connected to consumers with massive transmission and distribution networks. Centralized power structures did not provide the consumer with the ability to generate their own power through renewable and non-traditional generation methods. The Intergovernmental Panel on Climate Change's (IPCC) report indicating the existence of global warming (IPCC Third Assessment Report, 2001) created a shift in public desire to attain energy from renewable resources. When this sentiment shift was coupled with legislation that was restructuring and deregulating the power sector and increasing technological power innovation, a new power generation model became possible – distributed generation.

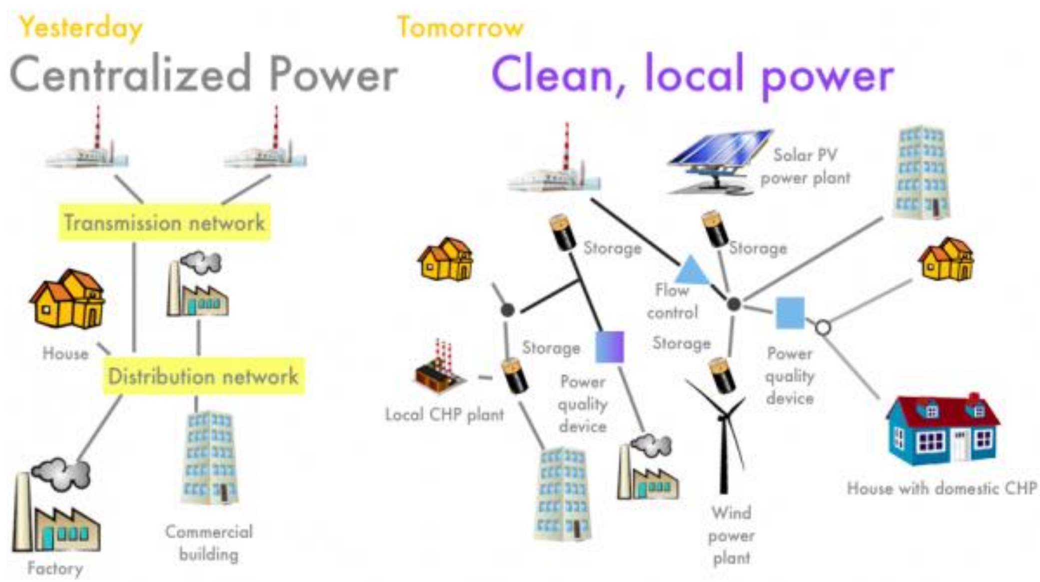

Figure 1-1: Transition from Central to Distributed Generation (Farrell, 2011)

Over the past ten years distributed generation (DG) has started to become economically viable for the average homeowner to install and utilize for their energy needs, due in large part to increased focus placed on finding a solution to curb the increasing global warming trend. As such, there are a number of DG technologies that the homeowner can select, each having their own advantages and disadvantages in certain possible scenarios over the life of the system. This leads to a large degree of uncertainty for the homeowner when trying to determine which DG technologies are most attractive for meeting their needs or even their risk profile, a potentially formidable challenge. Therefore, the homeowner would benefit from a structured approach for comparing the different DG systems across various scenarios, assisting them in determining their most appropriate DG system. This thesis provides an example application of a structured system engineering method for DG system decision. Additionally, two individual homeowner cases are analyzed to determine whether an average of homeowner information can be used or if individual analysis must be performed on each homeowner.

Additional motivation for pursuing this research is from a provider perspective, complementing the homeowner perspective decision problem above. The author has recently started a solar thermal company and is trying to determine the value that the distributed generation system will provide to homeowners in southern California. Since there has not been a widely accepted or publicized method for comparing distributed generation systems, it is difficult to determine where there are unmet homeowner needs. By performing the analysis for all DG systems available to the homeowner, the author will be able to gather insight into where these gaps in the tradespace are and how a new system might be able to provide value to the homeowner.

1.2 Research Scope

Based on the background and motivation aforementioned, the primary focus of the thesis is to create a multi-attributed expense (MAE) and multi-attribute utility (MAU) function – detailed in section 2.2 – that enables the comparison of distributed generation systems using multiple decision making criteria. The variables for the MAU and MAE function will be determined by investigating the preferences of homeowners in Southern California – gathered by in-person interviews – along with collecting data provided by the Department of Energy and other validated resources. These functions will formalize, structure, and make explicit the homeowner preferences on costs and benefits of potential DG systems. This approach enables the researcher to generate homeowner scores for each alternative system and compare them on a common basis.

Since preferences for the homeowner, as well as the performance of DG systems may be impacted by exogenous factors – also referred to as scenarios in this thesis – another component of the research is to evaluate how the score changes for each DG system based on a number of exogenous factors that may occur during the product's lifetime. These changes in the utility value score will provide an indication into which of the DG systems are more robust for each of the given scenarios. A third component of the research will be to evaluate the distributed generation systems across a sequence of the exogenous factors which will represent how the utility value of each system might change over time. By evaluating the change in utility value over time, the homeowner will have a better understanding of which DG system will provide the greatest benefit over the product's life. This approach forms the basis of the Epoch-Era Analysis (EEA) method – described in greater detail during section 2.4 – which provides for visualization and a structured way to think about the temporal system value environment (Ross & Rhodes, 2008).

The final component will be to select a couple of homeowners with vastly different preferences and analyze the best DG system for them based on the previous steps. The results of the analysis will be used to demonstrate that the selection of the average homeowner case may not be the most attractive choice for each homeowner. Therefore, it is more beneficial to find better solutions for each of the individual stakeholders instead of providing a singular solution to all homeowners. To summarize the research, the benefits and limitations will be discussed along with proposed recommendations for future research work.

1.3 Research Objectives

The main objective of the research is to evaluate the different technologies for distributed generation that the Southern California homeowner has available to them and provide the homeowner with a score that can be used to compare the DG systems. The research will incorporate exogenous factors into the resulting scores for each distributed generation system to account for externalities that affect the homeowner's decision making process, but are out of their control. A secondary objective of the research is to provide homeowners with a possible scenario of exogenous factors over the life of the system and capture the utility value created by the system over time. The final objective of the research is to provide evidence – through a few example homeowner cases – whether the "average homeowner" selection matches their individual selection. In summation, these objectives can be described by the following research questions:

- Given an Epoch-Era Analysis formulation, which of the distributed generation power system choices available to the southern California homeowner provides the highest value across the greatest number of epochs and in a select number of potential era scenarios?

- Using the same Epoch-Era Analysis formulation, how does the highest value distributed generation choice for randomly selected homeowners differ from that of the highest value for the homeowner subset average?

1.4 Organization of Thesis

Chapter 2 provides a literature review of distributed generation, methods for tradespace analysis, Multi-Attribute Utility Theory, and Pareto efficiency. Broader discussions will cover the definition of distributed generation and how it is starting to become available to homeowners. This will be followed by a discussion of tradespace analysis methods utilized by the MIT Systems Engineering Advancement Research Initiative (SEAri). Focus will be placed on the methodologies' structure and how they have been previously applied, along with stating how they can be utilized in other technical areas. The author will then proceed to introduce Multi-Attribute Utility Theory, which is a key component of evaluating how differing choices can be compared and analyzed. Lastly, Pareto efficiency – another core concept in the methods – will be explained as it pertains to tradespace analysis and the more specific instruments that are utilized in this thesis.

Chapter 3 will introduce the representative homeowner considered in the study and his available distributed generation system choices. The demographic information that was used to select the homeowners' decision making criteria used for the research will be presented. Following this will be an explanation of the distributed generation systems available to the homeowner and their associated performance metrics of interest to the homeowner, derived from system brochures and government data sources.

Chapter 4 provides the framework that is used in Epoch-Era Analysis when applied to system selection, as opposed to the more traditional system design application. The chapter begins by describing the overarching framework and then decomposes the framework into actionable steps that can be used for the analysis. Each of the steps or processes will include the information that needs to be gathered and produced for providing the desired end result. The author will indicate the modifications to the overarching method for the chosen application and also indicate which of the processes will not be employed.

Chapter 5 utilizes each step in the methodology proposed in Chapter 4 for the average homeowner DG system selection case example. This includes describing the modification to Epoch-Era Analysis methodology and detailing the abstracted system used in the analysis. The steps used to create the model that generates the tradespace analysis and how the utility functions were created to determine the scores for each DG system will be presented. Following the model creation step will be the analysis and results of the epoch periods. Comparison of the epochs to one another will also be displayed in the chapter alongside preliminary determination of trends for each DG system. The author will propose a select number of era scenarios based on research from sources about the likely trend of events over the next period of time – although it will not be an all-inclusive list of possible scenarios.

Chapter 6 evaluates the effect of the individual homeowner attributes on the resulting "best" distributed generation system selection for the aggregate homeowner in Chapter 5. This is done by comparing the best distributed generation resource for the average homeowner to the best DG resource for a couple of randomly selected homeowners. These randomly selected cases will be presented to demonstrate how the average homeowner selection did not match the selection for the individual homeowners and in this case, the interview participants.

Chapter 7 summarizes the answers to the research questions provided by the thesis and indicates areas where future work could strengthen the presented results.

1.5 Data of Thesis

The thesis data for the background information is derived from a literature review of publically available information, while the detailed technical information on the DG systems is summarized from product brochures, interviews with industry experts and government websites. There are a multitude of DG systems available to the homeowner and the systems presented are understood to not be an all-inclusive representation. Information about homeowner preferences is attained from one-on-one interviews with homeowners and their results were anonymized to meet MIT Committee on the Use of Humans as Experimental Subjects (COUHES) standards. Similar to the DG system performance metrics, the number of interviews and information gathered is not intended to represent the entire population of southern California but is intended to be a representative subset. The model and method is still applicable to a larger sample size and the appropriateness of this application is discussed later in the thesis. Some of the data has been inferred by the author, since there are a number of different estimates of possible scenarios of exogenous factors and these inferences are only used to provide examples of how the method could be used to provide results when the data becomes available. Lastly, any of the data presented in this thesis should be independently verified as there are a number of factors that change across the population and over different periods of time as world events continue to shape our responses to different scenarios.

Chapter 2 Literature Review

2.1 Distributed Generation

As mentioned previously in section 1.1, the large majority of residences in the United States receive their power from traditional power systems. These traditional power systems are large generation plants that are geographically isolated from the population where the power is transferred via long distance transmission lines to the end consumer. This type of system requires monitors and system control centers to ensure that the power delivered to the end user meets the required standards (Blaabjerg, et al., 2004).

While the traditional power systems have been successful for a number of years, sentiment has begun to shift about the use of fossil fuels to generate power for the majority of the worldwide economy. Additionally, the traditional power systems are struggling to keep up with the daily increase in demand for energy and the challenges of maintaining the required power standards are manifesting in the form of outages. These two primary factors have driven interest in clean technology development that could be placed closer to the population centers in larger quantities but smaller capacities (Blaabjerg, et al., 2006).

The term for this new concept for power generation systems started out being called *dispersed generation*, but has more recently been called *distributed generation* or simply abbreviated as *DG*. Since DG power systems are much smaller than traditional power systems, they can be placed closer to or within population centers to take advantage of previously untapped renewable and nonconventional energy sources. This ability to generate additional power near the end user has been welcomed into the energy management systems in most countries and has become part of their long term energy solution plans (Guerrero, et al., 2010).

DG systems come in a variety of different forms and technologies to capture previously untapped renewable resources, which include, but are not limited to, solar photovoltaic cells, wind turbines, fuel cells, and combined heat and power turbine (Blaabjerg, et al., 2004). These new technologies have enabled new formations of distribution grids to take place, as seen in Figure 2-1, which capitalize on the different characteristics of the technologies to provide a more efficient and effective power delivery system (Katiraei, et al., 2008).

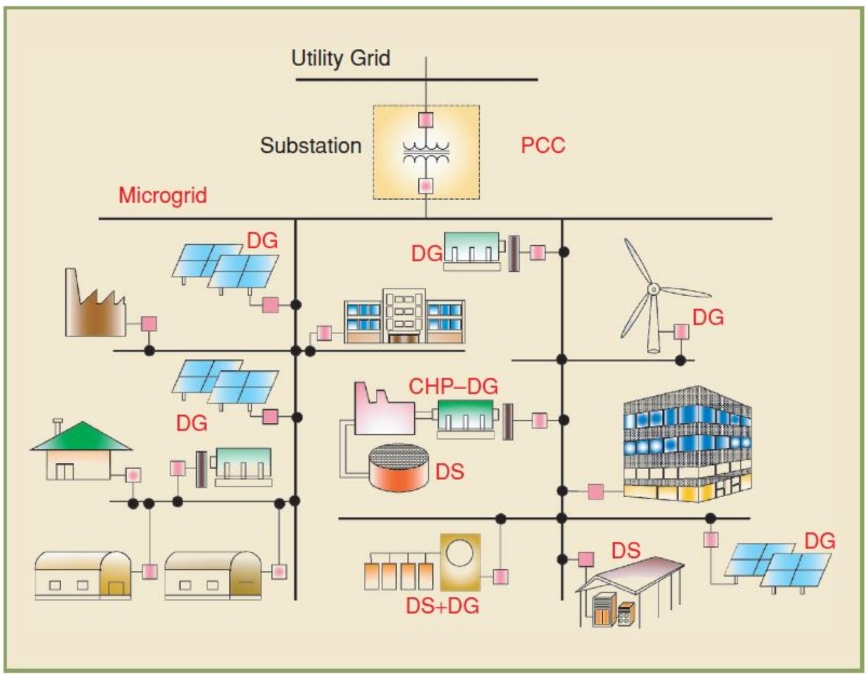

Figure 2-1: A typical microgrid structure including loads and DER units serviced by a distribution system (Katiraei, et al., 2008).

Microgrid is the term typically used for the new formation of the distribution grid that enables the integration of DG technologies due to its ability to be a self-contained grid on a significantly smaller scale than the traditional power grid structure. The arrangement in Figure 2-1 is connected to the traditional power grid, but as described above, it is expected to operate as a standalone entity. This arrangement style enables the DG technologies to work in tandem to deliver reliable power according to the required power standard, something that renewable technologies have had a difficult time meeting in the traditional power systems scale (Katiraei, Iravani, Hatziargyriou, & Dimeas, 2008). As a function of the ability to group renewable resources together in the microgrid model, a number of countries are predicting that there will be much higher percentages of power that will be delivered from a DG resource (Blaabjerg, et al., 2004).

The rise of microgrids and distributed generation as possible solutions to the problems currently experienced by the larger grid creates a new problem about determining which solutions should be incorporated. This problem needs to be addressed beyond selecting the most popular technology at the time and multi-criteria decision making techniques could provide useful in this regard.

2.2 Multi-Attribute Utility Theory (MAUT)

Utility theory was first introduced in 1947 by Von Neumann and Morgenstern (Von Neumann & Morgenstern, 1947) and in its most basic form maps the outcome of an action to a subjective measure of value. According to the theory in the above terms, a rational individual will act in a manner that would maximize their value. In order to generate mathematical equations which could characterize these choices, the authors denoted the action as an attribute and the value as the associated utility. Also, four axioms were generated to characterize rationality through three hypothetical lottery outcomes H, J, and K:

1. For two lotteries H and J, either H is preferred to J, J is preferred to H, or the individual is indifferent between H and J (completeness axiom).
2. If H is preferred to J and J is preferred to K, then H is preferred to K (transitivity axiom).
3. If H is preferred to J and J is preferred to K, then a probability p exists such that an individual is indifferent between ρH + (1-ρ)K and J (continuity axiom).
4. For the three lotteries, H is preferred to J if and only if ρH + (1-ρ)K is preferred to ρJ + (1-ρ)K (independence axiom). (Von Neumann & Morgenstern, 1947)

Based on the work of Von Neumann and Morgenstern, Keeney and Raiffa expanded utility theory to cover instances where there were multiple attributes that concurrently contributed to value. This work became the foundation of Multi-Attribute Utility Theory (MAUT). MAUT enables the classification of user decisions with regards to multiple features of a product or system at the same time, which more closely models the decision making process (Keeney & Raiffa, 1976). Instead of simply having individual scores for each of the product or system attributes – as derived in utility theory – MAUT combines the multiple single attribute utility values across the desired attributes into a single multi-attribute utility value. The single value can then be used to compare multiple products or systems to one another to determine which creates the greatest combined utility for the stakeholder. MAUT can be expressed as the following mathematical equation:

$$U(X) = u(x, k)$$

Equation 2-1: Multi-attribute utility function.

Equation 2-1 can be represented in a number of ways and the simplest is the linear-additive form shown in Equation 2-2 where the desire to represent the decision maker's preferences accurately is balanced by the need to maintain simplicity. Additionally, to utilize this form of the equation the features of the system need to maintain an independent relationship with how they affect the overall utility (Keeney & Raiffa, 1976). For the case that will be presented throughout this body of work, Equation 2-2 will be used to calculate the multi-attribute utility of the proposed DG designs. Shown here is the mathematical representation:

$$U(X) = \sum_{i=1}^{n} k_i \cdot u(x_i)$$

Equation 2-2: Linear-additive form of the multi-attribute utility function.

where *n* values of *k* – acting as a weighting mechanism – sum to one and *u* – representing the single attribute utility value for attribute x_i– ranges from zero (worst) to one (best), resulting in the multi-attribute utility value *U*, ranging from zero (worst) to one (best), for the vector *X* of all attributes.

MAUT is clearly a power approach that creates a single value for multi-criteria decision making situations, but this new information generates a problem when trying to determine how to select a system based on the their respective values. Pareto Optimality is one solution to the problem that could provide useful in selecting the appropriate DG system based upon multi-attribute values.

2.3 Pareto Optimality

Sometimes evaluated design alternatives are compared to one another across more than one factor, such as MAU – the utility metric of the system – and the cost metric of the system. Conceptually this comparison can be considered as the affordability tradeoff (what do you get benefit-wise, for different expenditure of cost?). This comparison across multiple factors without aggregation into a single metric is called a tradespace and different analysis tools for tradespaces will be described in section 2.4. ("Tradespace" is an amalgamation of "trades" and "space" representing that there is a space of tradeoffs where no "best" solution exists without further determining how to evaluate the tradeoffs. This formulation promotes knowledge generation, especially for complex systems where the relationship between costs and benefits may not be obvious a priori.) In the tradespace, multiple designs are compared against each other and a common approach that is used to determine the better designs is the concept of Pareto Optimality, often used in multi-objective analysis. In other words, "Pareto Optimality is achieved when a solution is non-dominated, that is, a solution cannot be improved in a particular objective score without making other objective scores worse" (Ross, et al., 2009).

2.3.1 **Pareto Frontier**

In most tradespaces there is not a single design that is considered the ultimate best as the intention is to provide insight to a decision maker for understanding the result of a design choice (the cost versus benefit tradeoff that may not be well understood in advance). Still, there are designs that can be considered better than the other designs given a certain set of decisions or attributes. For example, there could be a design solution that has the highest utility while having the greatest cost or having the least cost while having the lowest utility.

As described in Ross, Rhodes, and Hastings, the concept of Pareto Optimality can be applied to the tradespaces created by MAUT which results in a number of non-dominated solutions in the tradespace (Ross, et al., 2009). These design solutions result in a boundary in which there are no designs that perform better than the boundary design for that given set of objective metrics. The designs on the frontier represent the most efficient tradeoff of cost and benefit (e.g. MAU) and reduce the tradespace under consideration, providing a simpler subset for comparison by the decision maker.

2.3.2 **Fuzzy Pareto Number**

Although careful analysis is used when creating the values that generate tradespaces, there are instances where uncertainty may exist – especially in cases where the design is highly conceptual or the data tends to vary on uncontrollable factors. One method that can be used to address the uncertainty is to incorporate "fuzziness" into the Pareto Frontier. The fuzzy factor is represented by a fraction or percentage of the Pareto Optimal values, which results in a range of values that are considered part of the non-dominated space (Smaling, 2005). By increasing the acceptable range of values that are non-dominated, the number of designs that a decision maker chooses from may increase to include designs with uncertainty that were near the Pareto Optimal (Ross, et al., 2009). Summarizing the concepts from section 2.3.1and this section, Figure 2-2 presents images that clarify the concept of the Pareto Optimal solution and the effect of including a fuzzy factor to that solution.

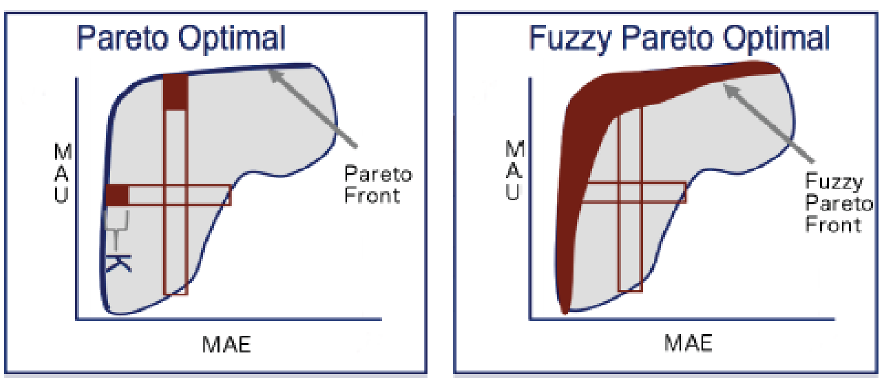

Figure 2-2: A representation of the fuzzy Pareto metric, where K is the level of "fuzziness" applied to the traditional Pareto front (Schaffner, et al., 2014).

2.3.3 **Normalized Pareto Traces**

A method that can be employed by product or system designers is to create multiple tradespaces through the consideration of systems in different short run scenarios, or epochs, to determine how a particular system performs under different circumstances. When multi-tradespace analysis is coupled with standard Pareto Optimality for each design, then the result is called a Pareto Trace. According to Ross, Rhodes, and Hastings, a Pareto Trace is defined as “the number of Pareto Sets containing that design,” (Ross, et al., 2009).

To achieve a Normalized Pareto Trace (NPT), the Pareto Trace must be divided by the total number of Pareto Sets analyzed, which then results in a fractional representation of the number of occurrences where the design is part of the Pareto Set. Normalized Pareto Trace is often used as a metric to determine which of the designs are most passively value robust for the given scenarios investigated (these designs stay utility-cost efficient across a large fraction of considered scenarios) (Ross, et al., 2009).

2.3.4 **Fuzzy NPT**

Similar to how uncertainty may need to be addressed for the Pareto Optimality, there may be the desire to determine the amount of uncertainty in the Normalized Pareto Trace for each design. According to Ross, Rhodes, and Hastings the Fuzzy Pareto Trace is defined as “the number of Fuzzy Pareto Sets containing that design” (Ross, et al., 2009). Typically the amount of fuzziness – represented by the factor K – is varied to determine how often the design is part of the Pareto Set, which defines the band of new Pareto values. To achieve the Fuzzy NPT value, the Fuzzy Pareto Trace number is dived by the number of total number of Pareto Sets analyzed. Fuzzy NPT is another metric that can be used to determine the passive value robustness of a design with uncertain characteristics and over a number of potential scenarios.

2.4 Select System Engineering Methods for Tradespace Analysis

Tradespaces are can be helpful tools when selecting between different design and characterizing the advantages and disadvantages given certain scenarios or desired performance metrics. Research has been performed at MIT to determine how tradespaces can be better utilized by decision makers – where better can be exemplified through either simpler implementation, a more complete representation of the factors involved (Ross, 2006). Ross and Hastings (2005) identified that there were four types of trades that are most common, which are represented in Figure 2-3.

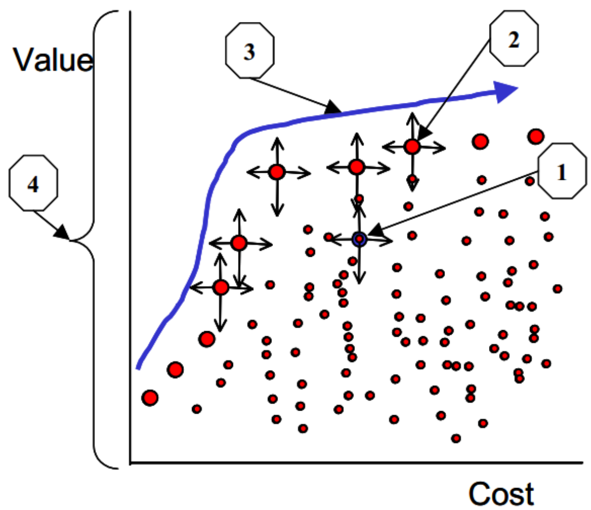

Figure 2-3: Types of trades: 1) local points, 2) frontier points, 3) frontier sets, 4) full tradespace exploration. (Ross & Hastings, 2005)

As one steps through the different types of trades in increasing order, the level of effort that is required to develop a relevant solution also increases – moving from a local point solution to frontier subset to frontier solution set to full tradespace exploration – but the higher effort trades also provide the greatest level of detail, allowing for greater insights into the appropriate design

(Ross & Hastings, 2005). In this research, the full tradespace will be explored with the majority of the analysis focused on the frontier solutions.

Beyond identifying the types of trades that are available for selecting the appropriate design, a number of methodologies can be used to properly set up a tradespace analysis to ensure positive results. In his work from 2006, Ross describes an end-to-end process called Multi-Attribute Tradespace Exploration (MATE) to develop and explore the tradespace that covers the problem identification to generating a utility value. The steps of the process are to:

1. Identify decision-maker needs by eliciting attributes and preferences.
2. Generate attribute utility functions through formal stakeholder interviews.
3. Aggregate utilities into multi-attribute utility function.
4. Propose design solutions to perform well in attributes.
5. Develop models to link solutions to decision-maker value.
6. Apply multi-attribute utility function to evaluated design solutions.
7. Plot utility and other important metric – often a form of cost.
8. Explore the tradespace to generate knowledge of nonobvious trade-offs.

Typically this process utilizes parametric or other numerical computer models that can evaluate a large number of designs while providing the attribute metrics and system costs that are ultimately plotted to create the fully developed tradespace (Ross, 2006).

A weakness of traditional tradespace exploration approaches is that they often assume a static contextual reference for the lifespan of the analysis. This may not be a realistic assumption when scenarios are modeled, leading to inconsistencies and inaccuracies in design selection.

Additionally, this prevents a thorough understanding of the system value across the design's lifespan (Ross & Rhodes, 2008). Building upon the foundation of a strong tradespace analysis, an analysis method to consider the impacts of context changes during the associated timeline called Epoch-Era Analysis (EEA) was developed (Ross, 2006). Considering the impact of context changes enables a more thorough and accurate representation of the desired scenarios (Ross & Rhodes, 2008). Figure 2-4, shown below, illustrates how the context changes, impacting the success of a design, are manifested in the method.

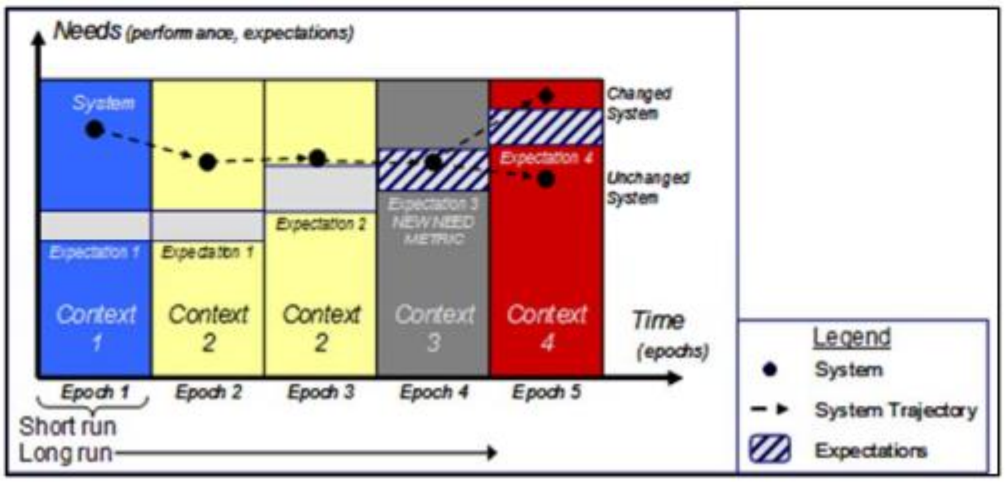

Figure 2-4: System Needs versus Expectations across Epochs of the System Era (Ross & Rhodes, 2008).

An *epoch* is a time period of fixed contexts and needs, sometimes called a "short run scenario." The context and needs may change over time (as represented by exogenous factors). Epochs can also be considered "state scenarios" representing one possible configuration of the exogenous factors (Ross, et al., 2009). An *era* is defined as an ordered sequence of epochs and represents a potential "long run scenario." A collection of epochs form an era and that era varies depending on the composition of the contexts incorporated since each era does not include every context considered in the analysis (Ross & Rhodes, 2008). This form of analysis enables a broad timescale and context understanding of system performance while also using existing tradespace methods including Multi-Attribute Tradespace Exploration (Ross, et al., 2009). The Epoch-Era Analysis formulation used in this research will be addressed in greater detail throughout Chapter 4.

2.5 Summary

Each section of this literature review is meant to build upon each other to provide a base understanding before each of the topics are covered in further depth in the subsequent chapters. The foundation of the research is on distributed generation systems that are available for homeowners. Building on top of this is the need to translate the individual metrics for each system into a value that can be compared across each; therefore, an understanding of Multi-Attribute Utility Theory is needed. Since the systems offer different value for their respective costs, it is important to understand various topics surrounding Pareto Optimality through the concept of a trade-off. Creating a full tradespace analysis enables further investigation into how various contexts may shape an alternative design's value over time. These foundational concepts are necessary to comprehend the Epoch-Era Analysis of distributed generation systems for homeowners.

Chapter 3 Distributed Generation Choices for the Homeowner

Chapter 3 will provide the context for the application of EEA in Chapter 5 and Chapter 6. This chapter will provide the homeowner geographical location and energy use information as well as the homeowner decision criteria. Additionally, the performance metrics of the distributed generation systems used in the analysis will also be provided. These pieces of information are necessary to develop the foundations of the EEA formulation being investigated in the research questions.

3.1 Homeowner Energy Use and DG Selection Criteria

When determining the distributed generation power system choices that are available to the homeowner in this analysis, it is imperative to define the region that the homeowner is from in addition to general power characteristics. The energy use information for a typical San Jose, CA homeowner is found in Table 3-1.

Homeowner (San Jose, CA)		
Description	**Value**	**Units**
Electricity Cost	0.20	$/kWh
Yearly Energy Use	6480	kWh/yr
Daily Energy Use	17.75	kWh/day
DG Percentage	50%	
DG Daily Operation	2	hours
DG Capacity	4.44	kW

Table 3-1: Key description of the example homeowner's energy use and desired DG portfolio.

The location of the homeowner was selected by the author for several reasons. First, the electrical power grid in California is currently undergoing a shift from traditional power generation to distributed power generation. Next, of the states shifting towards distributed generation systems, California provides the greatest number of choices for homeowners pursuing this path. Additionally, the homeowners in this region face higher electricity rates than the majority of the contiguous U.S. while having one of the lowest energy uses per capita, which aligns with the economics of current distributed generation solutions. Lastly, San Jose was selected due to *a priori* knowledge of the city and ease of locating energy use data.

Energy use data and electricity cost data for the homeowner was gathered from the Energy Information Administration website and is based on annual average consumption for the state of California (California State Profile and Energy Estimates, 2014). Although exact usage may vary depending on the homeowner, this approximation is suitable for the analysis presented. In order to achieve a more accurate analysis, a specific homeowner's usage information should replace the more general aggregate data.

In order to determine the data for the distributed generation usage, homeowners were informally polled about the amount of energy they wished to generate from non-grid technologies and how long they wished the system to operate. Again, the numbers provided in Table 3-1 for the DG usage were based on the aggregate, but numbers for a specific homeowner could be incorporated to provide a more accurate analysis. The two previously mentioned numbers resulted in the capacity of the system that would be needed to meet those homeowners' desires.

A fundamental component needed for an Epoch Era Analysis formulation – covered in greater detail in Chapter 4 and Chapter 5 – is the preferences of the primary stakeholder, which in this case is the San Jose homeowner. Using the verbal survey instrument from Appendix A: Survey Instrument, six homeowners were interviewed to determine the criteria that they would use if they were to make a distributed generation purchase. This resulted in the following nine attributes, their definitions that these particular homeowners use during their evaluation process, and the value scales from the least preferred to the most preferred:

- Aesthetic appeal – the system's appearance when considered part of their property having a scale from zero to ten
- Maintenance frequency – the number of maintenance and service events per year that the system requires the homeowner or third party to replace, change, or fix systems or components having a scale from twelve to zero
- Maintenance cost – the total cost in dollars per year required to keep the system operating at full efficiency including parts and labor hours invested by the homeowner or designated third party having a scale from $1000 to $0
- Product life – the minimum numbers of years that the manufacturing or retailing companies specifies that the system is able to operate before replacement having a scale from zero to fifty
- Environmental effect – the pounds of carbon dioxide (lbs. CO_2) that are produced by the system during annual operation having a scale of 2000 to 0
- Availability – how easy is the system to acquire, by the homeowner, as a function of the number of outlets retailing the system for a given region having a scale from zero to ten
- Initial cost – the total cost that the homeowner must pay to acquire the system[1] having a scale from $100,000 to $0

[1] The initial cost will be considered a one-time payment to acquire the system for this research project, but there are other methods that are also considered as the initial cost of the system – financing options, renting, power purchase agreements, etc. – that are not incorporated into this analysis.

- Operating cost – the cost that the homeowner must pay to operate the system with specific focus on fuel or electric usage that is required to produce the homeowners desired amount of energy having a scale from $1000 to $0
- Space required – the number of square meters that are required per kilowatt of generation capacity of the system having a scale from twenty-five to zero.

3.2 DG System Alternative

With the fundamental understanding of the homeowner attributes used when evaluating a distributed generation power system, the alternatives available to the homeowner can now be discussed. The majority of the data provided for each system is from public sources (websites) available through the National Renewable Energy Laboratory (Energy Technology Cost and Performance Data for Distributed Generation, 2013), U.S. Energy Information Administration (Frequently Asked Questions, 2013), and Lawrence Berkeley National Laboratory (Technology data Archive, 2004). The remaining data was gathered directly from informally polling the homeowners in that geographical location.

3.2.1 **Solar Photovoltaic**

Solar photovoltaic, commonly shortened to PV, is the distributed generation technology that converts solar energy directly into electricity using panels of specially manufactured silicon wafers (Solar Photovoltaic Technology Basics, 2012). This type of system has been commercially available to homeowners for the past 30 years, with significant reductions in cost and improvements in performance being realized in the past 10 years. PV panels have become the front runner of DG technologies available to the homeowner for a number of different reasons itemized in Table 3-2.

Solar Photovotaic (PV)		
Attribute	**Value**	**Units**
Aesthetic Appeal	5	
Maintenance Frequency	1	#/year
Maintenance Cost	20.00	$/kW
Product Life	25	years
Environmental Effect	0.00	g CO2/kWh
Availability	10	
Initial Cost	4000.00	$/kW
Operating Cost	0.0104	$/kWh
Space Required	12.95	m^2/kW

Table 3-2: Solar photovoltaic (PV) values considered for this case study.

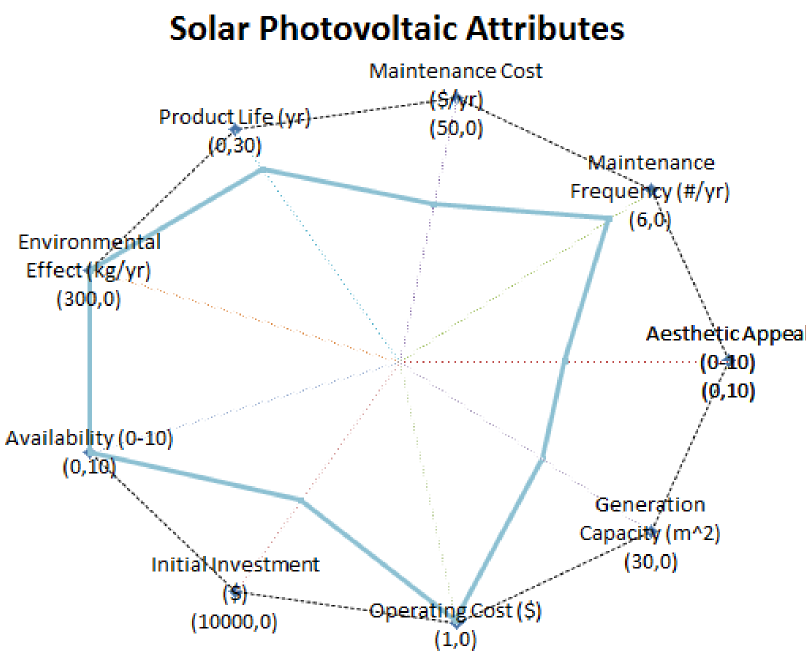

Figure 3-1: Solar photovoltaic performance across all attributes.

Solar PV panels are generally favored by those homeowners looking to reduce their energy generation impact on the environment, but this technology comes with a higher initial cost and one of the larger space requirements of the DG systems that will be analyzed. This DG system is widely available to homeowners in the San Jose area, but it generally negatively affects the aesthetic appeal of the home and therefore acts as another barrier to ownership. These comparisons are illustrated in Figure 3-1, where all the attributes are plotted against a hypothetical maximum and the large area represents a system with high performance. In this case, solar photovoltaic has a very large area and therefore should perform well in the analysis.

3.2.2 **Solar Hot Water**

Solar hot water, or sometimes referred to as solar thermal, is the DG technology that uses solar energy to heat water either directly or indirectly through a heat exchanger and separate fluid. This system typically consists of a solar heated surface where the liquid flows through small tubes and this liquid is then returned to a storage tank to complete the transfer to the homeowner's hot water (Solar Hot Water, 2012). Similar to PV panels, this type of system has been around for 30 years, although solar hot water has not seen the same technical advances or reduction in costs that PV panels have experienced. Therefore, this system is typically not installed in San Jose, CA but there are still a number of vendors the carry the product with the features displayed in Table 3-3.

Solar Hot Water		
Attribute	**Value**	**Units**
Aesthetic Appeal	5	
Maintenance Frequency	2	#/year
Maintenance Cost	30.00	$/kW
Product Life	15	years
Environmental Effect	0.00	g CO2/kWh
Availability	9	
Initial Cost	6000.00	$/kW
Operating Cost	0.0293	$/kWh
Space Required	4	m^2/kW

Table 3-3: Solar hot water values considered for this case study.

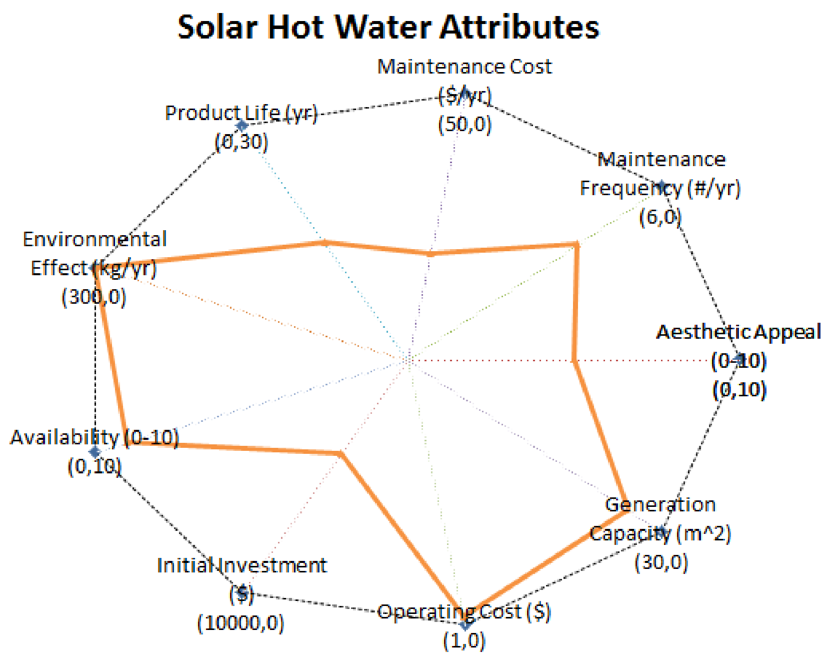

Figure 3-2: Solar hot water performance across all attributes.

Similar to solar PV, solar hot water systems are favored by homeowners that are looking to reduce or eliminate their impact on the environment when product energy but are willing or able to afford the large initial cost that are associated. Since the technology is more efficient than PV panels, a much smaller space is required when installing the DG system but it tends to have a shorter product life due to the use of pumps and other moving mechanisms. These comparisons are illustrated in Figure 3-2, where all the attributes are plotted against a hypothetical. Solar hot water covers a majority of the area and therefore should perform well in the analysis but should perform worse than solar photovoltaic.

3.2.3 **Wind Turbine**

Wind turbines are the distributed generation energy system that utilizes the force of wind to generate electricity. Most commonly this is done using modern aerodynamic principles – developed for aircraft flight – where air motion causes a series of aerodynamic blades to drive a spinning generator which converts the rotational energy into electricity (Wind Energy Basics: How Wind Turbines Work, 2012). Wind turbines have been available on the utility scale since the latter half of the 20th century, but residential scale wind generation has really come to fruition in the most recent 10 years. These systems are relatively rare for home installations, but there are a number of installers that provide turbines with features similar to Table 3-4.

Wind Turbine		
Attribute	**Value**	**Units**
Aesthetic Appeal	3	
Maintenance Frequency	3	#/year
Maintenance Cost	28.00	$/kW
Product Life	20	years
Environmental Effect	0.00	g CO_2/kWh
Availability	9	
Initial Cost	8000.00	$/kW
Operating Cost	0.0120	$/kWh
Space Required	25	m^2/kW

Table 3-4: Wind turbine values considered for this case study.

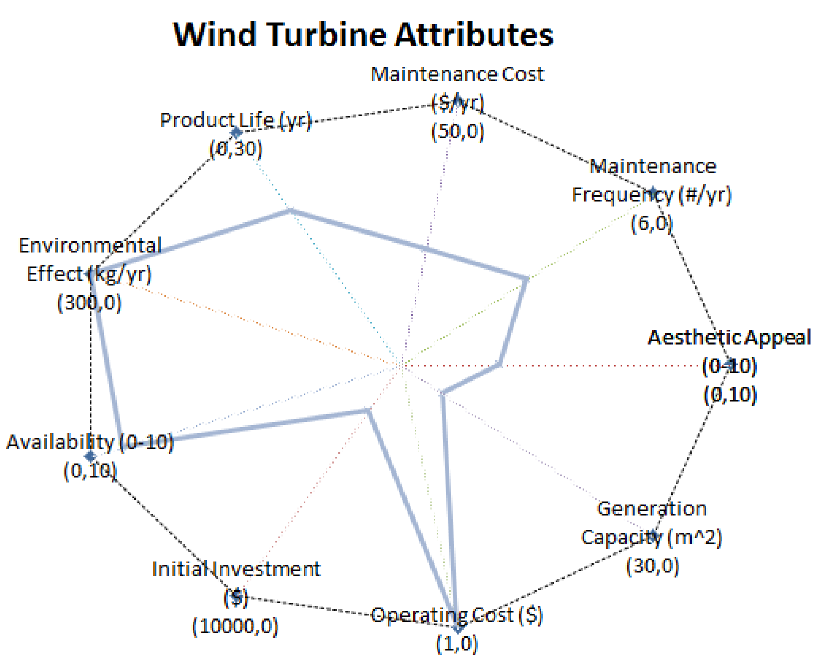

Figure 3-3: Wind turbine performance across all attributes.

As with the previously mentioned solar PV and solar hot water systems, wind turbines are generally favored by homeowners who are attempting to reduce their environmental impact while producing electricity. But, these systems are installed on a limited basis in large part due to their high initial cost, large space requirement, and low aesthetic appeal. These comparisons are illustrated in Figure 3-3, where all the attributes are plotted against a hypothetical maximum. The wind turbine performs well in a few categories, but generally has low values and a small area, which should lead to a poor performance against the other distributed generation systems.

3.2.4 **Heat Pump**

Heat pumps are the distributed generation energy systems that transfer heat between two spaces to efficiently control the temperature of the air. Similar to how a refrigerator functions, the heat pump will transfer heat from a room to the outside air or cool air from the outside to cool a hot room. Since these systems do not actual generate their own energy they are extremely efficient under moderate loading conditions (Heat Pump Systems, 2013). Heat pumps have been widely available for decades but their adoption rates have been low due to geographic constraints to meet idea operating conditions. These DG systems are almost available everywhere in the U.S. with the features found in Table 3-5.

Heat Pump		
Attribute	**Value**	**Units**
Aesthetic Appeal	6	
Maintenance Frequency	1	#/year
Maintenance Cost	30.99	$/kW
Product Life	20	years
Environmental Effect	237.68	g CO2/kWh
Availability	8	
Initial Cost	2137.62	$/kW
Operating Cost	0.0288	$/kWh
Space Required	0.052785795	m^2/kW

Table 3-5: Heat pump values considered for this case study.

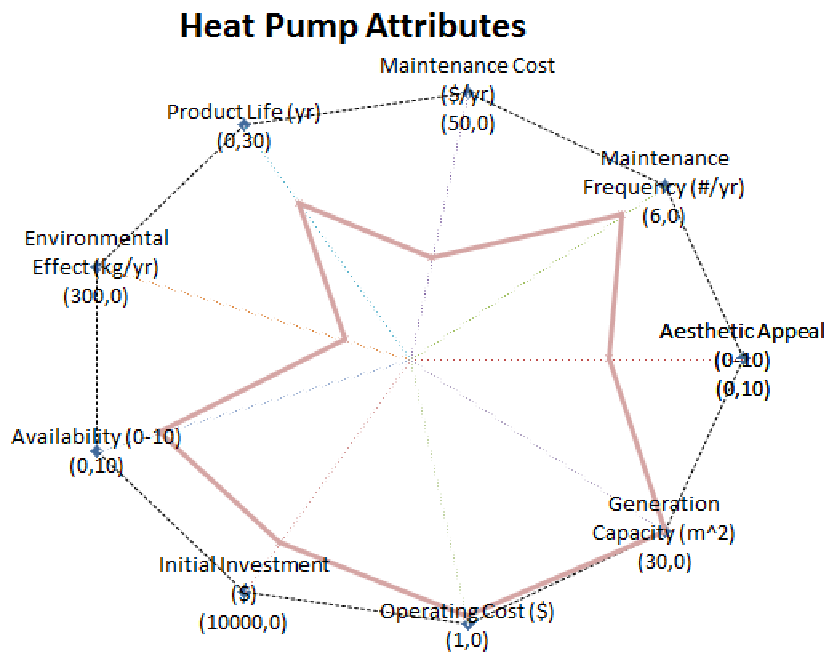

Figure 3-4: Heat pump performance across all attributes.

Heat pumps are near the middle of the systems analyzed in terms of initial and operating costs and because of their large efficiency rating they often pay for themselves very quickly while providing a greater return on investment to the homeowner. As a function of this efficiency, the systems require only a small footprint that eases homeowner concerns about finding adequate mounting space. Although they have high a high efficiency, heat pumps use electricity to operate and thereby produce a fair amount of CO_2 indirectly. These comparisons are illustrated in Figure 3-4, where all the attributes are plotted against a hypothetical maximum. The heat pump has a very large area, similar in size to the solar photovoltaic system, and covers a region different than that of the solar photovoltaic system. Therefore, this system should perform well if there is a split amongst the homeowner preferences.

3.2.5 **Natural Gas Generator**

Natural gas generators are the distributed generation energy system that that utilize an internal combustion engine with an electric generator to produce electrical power for the homeowner. In this application, the fuel is natural gas but the more generic concept can be used with other fossil-fuels – as shown in the following sections. This type of DG system is typically used by homeowners for short durations during emergency situations or in cases where the homeowner does not have access to the electrical grid. These systems are widely available, albeit more prevalent in industrial settings, and there are multiple vendors that provide natural gas generators with features comparable to those listed in Table 3-6.

Natural Gas Generator		
Attribute	**Value**	**Units**
Aesthetic Appeal	4	
Maintenance Frequency	4	#/year
Maintenance Cost	15.22	$/kW
Product Life	12.5	years
Environmental Effect	181.08	g CO2/kWh
Availability	8	
Initial Cost	594.44	$/kW
Operating Cost	0.1875	$/kWh
Space Required	0.042993462	m^2/kW

Table 3-6: Natural gas generator values considered for this case study.

Natural gas generators are one of the cheapest distributed generation technologies that are available for homeowners to purchase and have a very small footprint allowing for easier storage and integration into the home. Since the system generates energy via internal combustion, there is CO_2 that is emitted into the atmosphere, but of all the combustion processes natural gas produces the least CO_2. There are higher operating costs involved with this technology but it is cheaper than the other generator technologies available. These comparisons are illustrated in

Figure 3-5, where all the attributes are plotted against a hypothetical maximum. The natural gas generator almost covers a majority of the space, but it only has one maximum value and it is expected that the performance will be moderate at best.

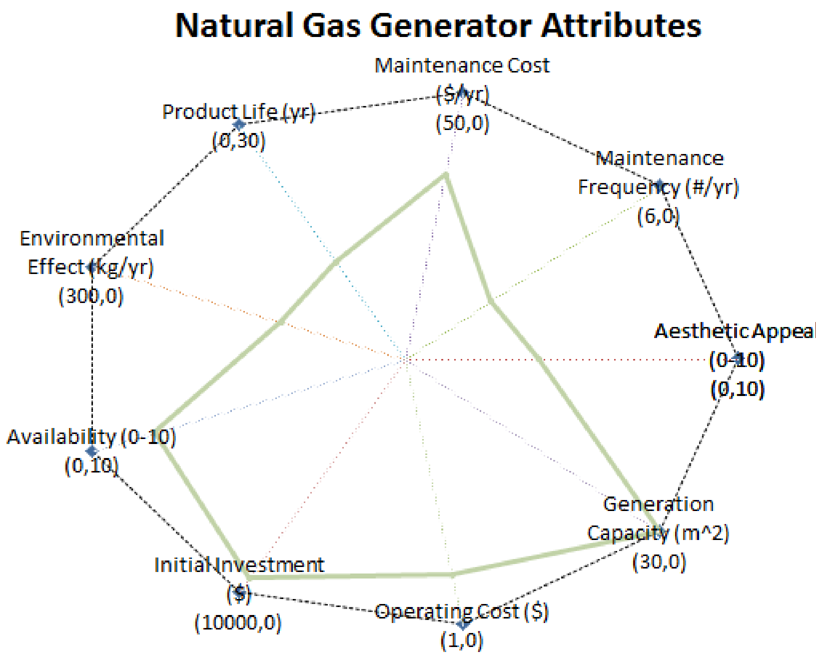

Figure 3-5: Natural gas generator performance across all attributes.

3.2.6 **Diesel Generator**

Diesel generators are a distributed generation technology that utilizes an internal combustion engine along with an electric generator to create electrical power for the homeowner. The difference between the previously mentioned generator and a diesel generator is that this generator uses compression-ignition instead of the spark-ignition – in addition to the different fuel source. This DG system has been in use for a number of years, but is almost exclusively found in commercial applications. While more difficult to acquire, homeowners can purchase systems with the features found in Table 3-7.

Deisel Generator		
Attribute	**Value**	**Units**
Aesthetic Appeal	4	
Maintenance Frequency	4	#/year
Maintenance Cost	26.50	$/kW
Product Life	12.5	years
Environmental Effect	249.65	g CO2/kWh
Availability	7	
Initial Cost	775.00	$/kW
Operating Cost	0.3080	$/kWh
Space Required	0.059626667	m^2/kW

Table 3-7: Diesel generator values considered for this case study.

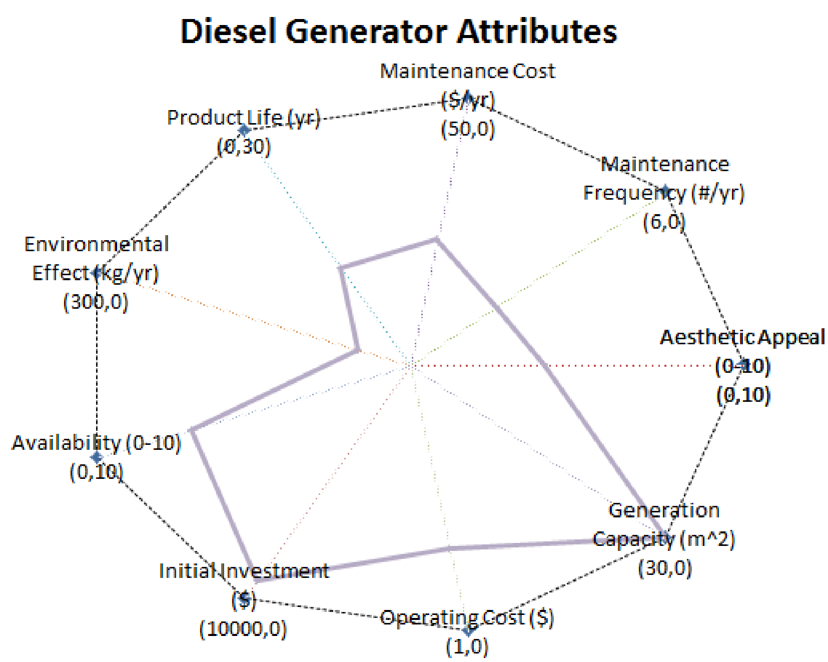

Figure 3-6: Diesel generator performance across all attributes.

A diesel generator is one of the cheaper distributed generation technologies that a homeowner can purchase, in terms of initial cost, but there is an astonishingly high operating cost since the fuel itself is quite expensive. Also, this type of generator has the highest amount of CO2 generated per kilowatt-hour of any of the distributed generation technologies reviewed in this analysis. Beyond the low initial cost, the other benefit of this system is the small space requirement but that is offset by the short product life and frequent maintenance. These comparisons are illustrated in Figure 3-6, where all the attributes are plotted against a hypothetical maximum. The diesel generator has one of the smallest areas of the distributed generation systems and has low scores in a number of attributes, which will results in the system performing poorly in the analysis.

3.2.7 **Propane Generator**

The final type of engine-generator that is considered in the thesis research is the propane generator that utilizes the same spark-ignition internal combustion engine as the natural gas generator with the exception that propane is used as the fossil-fuel. This type of distributed generation is typically only used in locations where there is no natural gas service or in areas that are geographically isolated from the electrical grid. Since propane storage is large an unsightly, the technology is most often used during emergency scenarios. Quite often, the same generator can be used with either natural gas or propane but the energy density of propane is less than natural gas and leads to a reduced electrical output. Propane generators are generally available in the San Jose, CA area and these systems typically have the features presented in Table 3-8.

Propane Generator		
Attribute	**Value**	**Units**
Aesthetic Appeal	4	
Maintenance Frequency	4	#/year
Maintenance Cost	13.70	$/kW
Product Life	12.5	years
Environmental Effect	215.13	g CO2/kWh
Availability	8	
Initial Cost	660.00	$/kW
Operating Cost	0.6340	$/kWh
Space Required	0.038694116	m^2/kW

Table 3-8: Propane generator values considered for this case study.

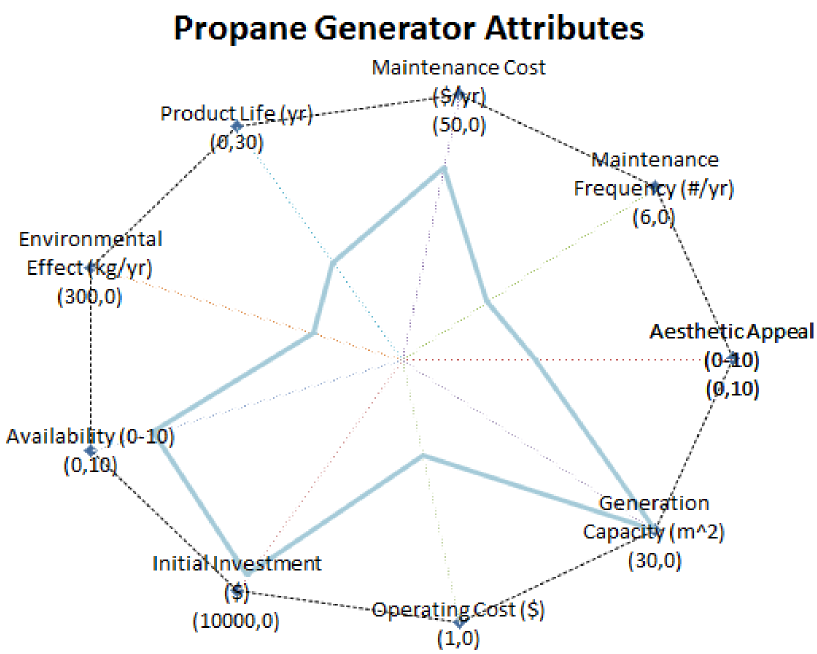

Figure 3-7: Propane generator performance across all attributes.

Similar to the other generator variants, the propane generator is one of the cheapest distributed generation choices available to the homeowner – in terms of initial cost – but this technology has the highest operating cost out of all the technologies considered in the research. When this is combined with its relatively high amount of CO_2 produced per kilowatt-hour, the system is typically not preferred by homeowners, even though it has one of the smallest space requirements. These comparisons are illustrated in Figure 3-7, where all the attributes are plotted against a hypothetical maximum. The propane generator has a similar area to the diesel generator and has similar characteristics, albeit in different attributes, which should result in the system being one of the poorer performers in the research.

3.2.8 **Heating Oil Furnace**

Heating oil furnaces are the distributed generation technology using light oil as the fuel in combustion directly heating a surface that transfers the energy into a fluid, which is typically water for domestic uses. This type of DG is used in regions where other fossil fuels are not easily accessible and it is one of the oldest distributed generation technologies that are currently used (Oil-Fired Boilers and Furnaces, 2013). Although very prevalent in the northeastern U.S., the number of companies that offer the systems in the San Jose, CA area is rather limited and homeowners do not have a large number of choices to choose from. Still, the heating oil furnaces available in the region have features that are similar to the ones listed in Table 3-9.

Heating Oil Furnace		
Attribute	**Value**	**Units**
Aesthetic Appeal	5	
Maintenance Frequency	2	#/year
Maintenance Cost	8.52	$/kW
Product Life	20	years
Environmental Effect	249.65	g CO2/kWh
Availability	5	
Initial Cost	309.09	$/kW
Operating Cost	0.1192	$/kWh
Space Required	0.017741818	m^2/kW

Table 3-9: Heating oil furnace values considered for this case study.

As one would expect due to the maturity of the technology and ubiquitous use, the heating oil furnace is the lowest initial cost distributed generation energy systems available for homeowners. The system also has an extremely compact footprint that enables space constrained homeowners to generate the energy required. Heating oil, unfortunately, is one of the most expensive technologies to operate and also produces the greatest amount of CO_2 per kilowatt-hour of energy generation. This has led to its gradual reduction in use by homeowners in favor of technologies that are significantly cheaper to operate and that result in less impact on the environment. These comparisons are illustrated in Figure 3-8, where all the attributes are plotted against a hypothetical maximum. Heating oil has one of the larger areas of the systems in the research and covers an area that solar photovoltaic and heat pump do not cover, which should lead to a better performance that the majority of the distributed generation choices.

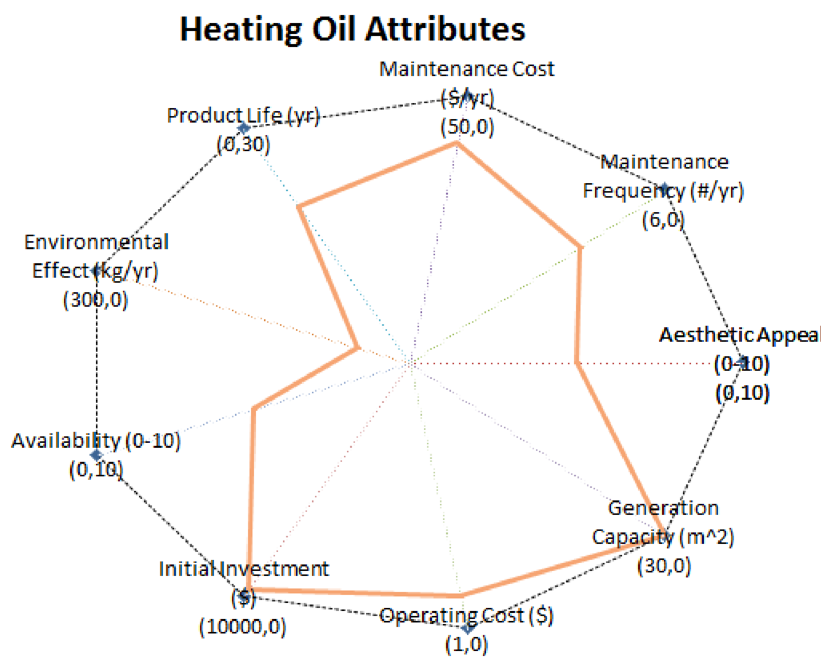

Figure 3-8: Heating oil performance across all attributes.

3.2.9 **Geothermal Heat Pump**

Geothermal heat pumps are the distributed generation energy system that utilizes the ground temperature as the primary transfer source and is similar to the heat pump system described previously. The difference between the systems is that the geothermal heat pump uses a large network of tubes buried in the ground to perform the heat exchange that is used to maintain temperature control over the desired space (Geothermal Heat Pump Basics, 2012). Because they require the homeowner to have property where the tubes can be buried, the systems are primarily installed in suburban or rural areas. Therefore there are only a limited number of companies that will install this DG technology with the features listed in Table 3-10.

Geothermal Heat Pump		
Attribute	**Value**	**Units**
Aesthetic Appeal	7	
Maintenance Frequency	3	#/year
Maintenance Cost	18.00	$/kW
Product Life	25	years
Environmental Effect	237.68	g CO2/kWh
Availability	6	
Initial Cost	1676.14	$/kW
Operating Cost	0.0536	$/kWh
Space Required	26.39289773	m^2/kW

Table 3-10: Geothermal heat pump values considered for this case study.

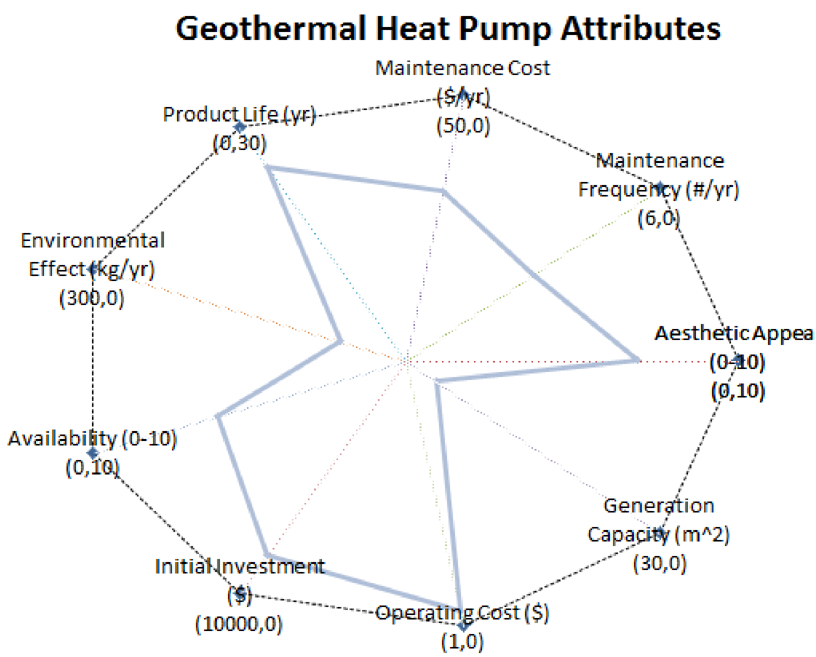

Figure 3-9: Geothermal heat pump performance across all attributes.

Geothermal heat pumps are one of the cheaper DG technologies for the homeowner to install. This is accomplished by installing larger capacity systems to take advantage of the fixed costs – such as transporting equipment to the homeowner. Yet again, these systems are highly efficient and pay for themselves in a short order of time, but they require a pump to be running almost continually which indirectly generates CO_2. One of the largest benefits of this system is that it is mostly “hidden” below the ground and therefore rates highest in aesthetic appeal among homeowners. These comparisons are illustrated in Figure 3-9, where all the attributes are plotted against a hypothetical maximum. Geothermal heat pump has a moderate area and scores generally well in most categories, but it scores very poorly in two categories which will likely affect its overall performance.

3.3 Summary

Although there are a number of different technologies that are available for homeowners to meet their distributed generation needs, – including micro hydro, fuel cells, biodiesel, etc. – they are not considered in this study due to either their technology readiness level or infancy in the consumer market resulting in a lack of reliable data. Still, the nine distributed generation systems accurately portray the landscape of choices available to the San Jose, CA homeowner and provides for an analysis with a sufficient range of alternatives. Although the nine systems will be directly compared across all attributes in Chapter 5, a summary of the performance metrics of all the DG choices available to the homeowner is provided in Table 3-11 where the “best” performing system for each metric is highlighted in green.

DG System	Aesthetic Appeal (0-10)	Maintenance Frequency (#/yr)	Maintenance Cost ($/yr)	Product Life (yr)	Environmental Effect (kg/yr)	Availability (0-10)	Initial Investment ($)	Operating Cost ($)	Generation Capacity (m^2)
Solar Photovoltaic	5	1	20.00	25	0.00	10	4000.00	0.01	12.95
Solar Thermal	5	2	30.00	15	0.00	9	6000.00	0.03	4.00
Wind Turbine	3	3	28.00	20	0.00	9	8000.00	0.01	25.00
Heat Pump	6	1	30.99	20	237.68	8	2137.62	0.03	0.05
Natural Gas Generator	4	4	15.22	12.5	181.08	8	594.44	0.19	0.04
Diesel Generator	4	4	26.50	12.5	249.65	7	775.00	0.31	0.06
Propane Generator	4	4	13.70	12.5	215.13	8	660.00	0.63	0.04
Heating Oil	5	2	8.52	20	249.65	5	309.09	0.12	0.02
Geothermal	7	3	18.00	25	237.68	6	1676.14	0.05	26.39

Table 3-11: Summary of all nine DG systems and their performance across all nine attributes.

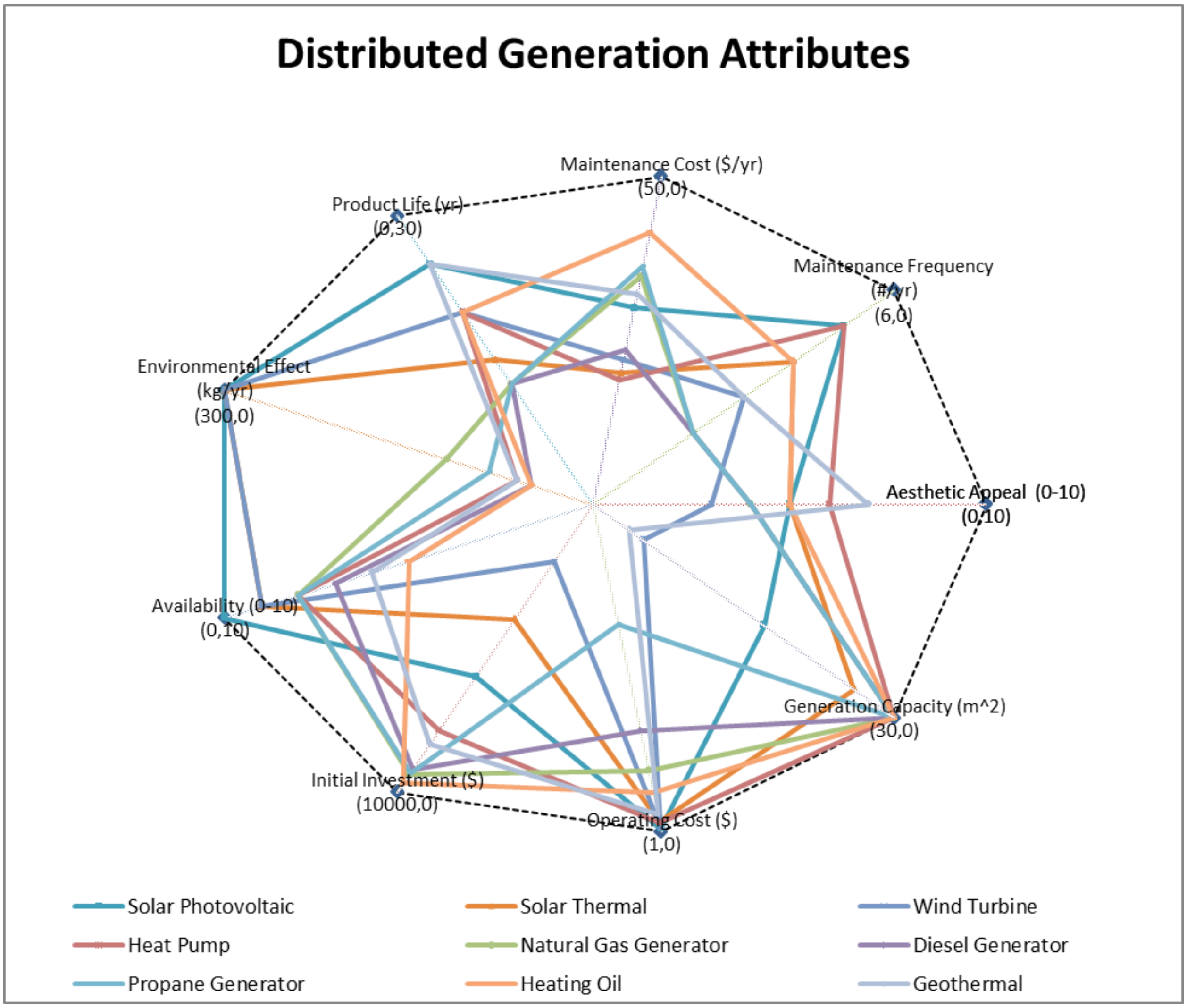

Figure 3-10: Comparison of all the distributed generation system performance attributes with the maximum score on the perimeter.

While Table 3-11 provides an understanding of the best scoring distributed generation system for each attribute, it is difficult to determine the relative rankings of the DG systems across all the attributes. Figure 3-10, a radar plot of all nine homeowner decision-making attributes, presents the comparison between each of the distributed generation system's attribute performance, while also providing insight into how well each system performs across all nine attributes. Similar to Table 3-11, it becomes clear solar photovoltaic performs well amongst the competition, as judged by the area encompasses by the plot, while the diesel generation performs quite poorly, by having the smallest area. With these nine systems and how the homeowner attributes relate to the distributed generation system performance metrics, there is sufficient information to proceed to the case study.

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Chapter 4 Modification of Epoch-Era Analysis for Application to DG System Selection

4.1 Introduction

As mentioned in section 2.4, Multi-Attribute Tradespace Exploration (MATE) and Epoch-Era Analysis (EEA) are two methods that can be used to aid in tradespace analysis of complex problems. These system engineering tools have been operationalized to make their application to the problem straightforward and consistent across all industries. The following sections will demonstrate how an Epoch-Era Analysis formulation can be modified to solve the homeowner distributed generation solution problem posed in the previous chapters. The following is an eight step methodology that was derived from an application of EEA proposed by Ross et al. (2009) and expanded upon by Shaffner et al. (2013).

4.2 Methodology

The structure set forth in Shaffner et al. (2013) consists of the three different phases, each with their own specific processes that when performed in proper sequence will provide the user of the method with a potential solution to the problem they desire to analyze. The three phases and the nine processes that compose the method are shown in Figure 4-1. The first phase is called *Information Gathering* and consists of the value driving context definition, value-driven design formulation, and epoch characterization processes – denoted as processes 1, 2, and 3, respectively, in Figure 4-1. This phase is where the user defines the problem and associated variables that are available to generate a solution along with the problem space boundaries. The second phase is called *Alternatives Evaluation* and consists of the design-epoch tradespace evaluation process – seen in Figure 4-1 as process 4. This phase is where the user generates the tradespace of solutions using models to evaluate the proposed designs in proposed epochs, in most applications using fundamental principles from the MATE methodology, based on the information provided in the previous Alternatives Analysis Phase. The third phase is then *Design Analysis* which consists of single epoch analysis, multi-epoch analysis, era construction, single era analysis, and multi-era analysis –processes 5, 6, 7, 8, and 9, respectively, in Figure 4-1. During this phase the results of MATE are provided through the EEA framework to provide an in-depth analysis about any number of characteristics that have the ability to change over, or be affected by, time (Schaffner, Wu, Ross, & Rhodes, 2013).

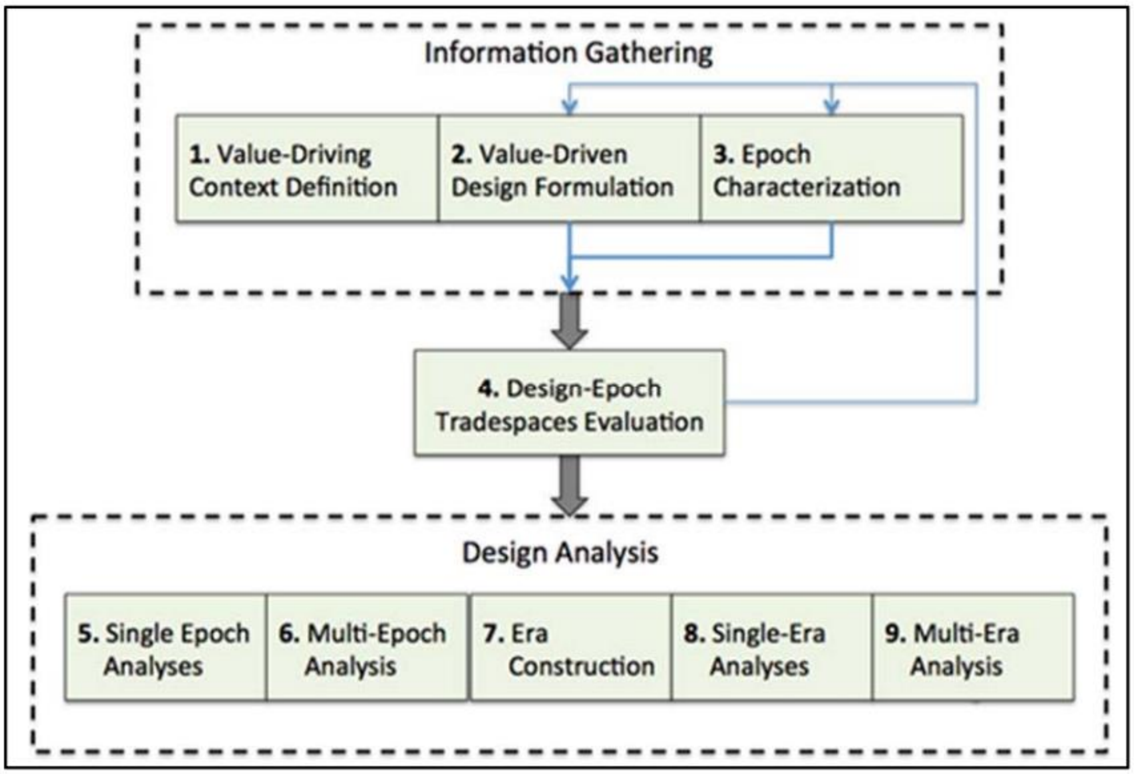


Figure 4-1: A Graphical Overview of the Gather-Evaluate-Analyze Structure of the Method (Schaffner, Wu, Ross, & Rhodes, 2013)

The following sections will describe in-depth what information is required, how that information is utilized to perform the analysis, and potential ways to display the results. After the sections are provided, a user should be able to apply the more general framework to a number of problems that lie outside the industries for which the method has been previously applied.

4.2.1 **Process 1: Value-Driving Context Definition**

The foundation to the method is process 1, where the user defines the system or problem that will be analyzed, which is usually completed by speaking with the various problems' stakeholders. After determining the stakeholders, their objectives and constraints, and their interactions between one another, then the user should create a system diagram as shown in Figure 4-2.

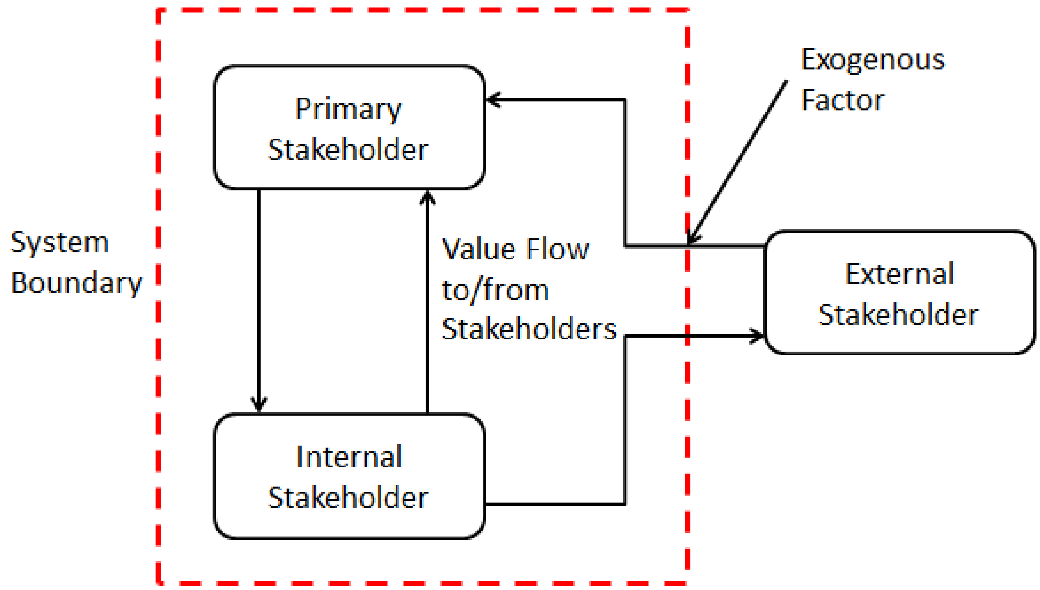


Figure 4-2: Stakeholder System Diagram

The system diagram acts a graphical representation of the problem and allows for the stakeholders to easily identify any interactions that are missing or any objectives that may have been missed. The system boundary defines what aspect of the problem the analysis will investigate and also clarifies which factors are under direct control of the user and which factors are out of their control, or exogenous factors that carry some uncertainty – covered in greater detail in process 3.

4.2.2 **Process 2: Value-Driven Design Formulation**

In Value-Driven Design Formulation Process 2, the user must define what the key stakeholders needs are. These needs, which may have been discovered during process 1, are transferred into attributes and corresponding acceptable performance ranges that can be used to guide the design and analysis of the solutions created later in the method – specifically Process 4. A table similar to Table 4-1 should be used to keep track of and explicitly present which attributes the solution will need to encompass. The attributes that are recorded in Table 4-1 should be noted as either an expense attribute or a utility attribute. An expense attribute is associated with a cost or consequence of the system while the utility attribute is associated with a benefit of the system.

Primary Stakeholder			
Attribute	Units	Range	
		"worst"	"best"
Atrribute 1			
Attribute n			

Table 4-1: Primary Stakeholder Attributes

In conjunction with gathering the information for Table 4-1, the user will elicit expert opinions or previous concepts, if applicable, for the system solution concepts. At this point, no concept should be discredited and any solutions should be recorded to ensure that unexpected results are not suppressed from the analysis. These potential solutions, decomposed as design variables, should then be compared against the expense attributes, as shown in Table 4-2, and utility attributes, as shown in Table 4-3, to determine how each variable affects each attribute. High impact values in the tables are weighted significantly more to ensure that the important interactions are recognized throughout the process and not enveloped by a grouping of less important interactions. The result of the design-value mapping indicates the driving factors and can provide insight for the user with regard to maximizing utility or minimizing expense by selecting the appropriate design variables.

Design-Value Mapping (Notional Values)				
Primary Stakeholder				
Expense Attributes	Design Choices	Option 1	Option n	Total Impact
Attribute 1				
Attribute n				
Total				

Impact Scale: 0-None, 1-Slight, 3-Moderate, 9-High

Table 4-2: A Design-Value Matrix reflecting the notional impact of design variables on expense attributes.

Design-Value Mapping (Notional Values)				
Primary Stakeholder				
Utility Attributes	Design Choices	Option 1	Option n	Total Impact
Attribute 1				
Attribute n				
Total				

Impact Scale: 0-None, 1-Slight, 3-Moderate, 9-High

Table 4-3: A Design-Value Matrix reflecting the notional impact of design variables on utility attributes.

Part of process 2 typically includes a design-variable mapping, but since the research is evaluating already existing designs, instead of generating new designs based on certain design variables, this aspect is not utilized in the distributed generation analysis. The information has been included for completeness and is valuable in explaining a step that should be used if original designs were to be generated.

4.2.3 **Process 3: Epoch Characterization**

One of the key advantages of this analysis is the ability to categorize uncertain factors in the system or design space and incorporate them into the analysis through the use of epoch variables. From the system diagram shown in Figure 4-2 developed as a part of Process 1, there are a number of interactions that affect the primary stakeholder but that are not under their direct control. Examples of these factors would include new regulations or laws, new technology development or a meteor impact. There are a number of different categories that these factors can be categorized as including policy, economy, technology, social, and climate. The categories are useful in ensuring that the system maintains a holistic point of view. These interactions are the epoch factors that are part of the solution space and should be captured in Table 4-4. Since these factors are out of the primary stakeholder's control, the values are typically represented in a range of possible outcomes. The range can then be used to create a set of epochs or short run scenarios and eventual analysis can be performed on each to provide a more in-depth solution space for the trades.

Epoch Descriptions				
Epoch Name	Epoch Descriptor Category	Epoch Descriptor	Range	Units
EN 1		ED 1		
EN n		ED n		

Table 4-4: Epoch Descriptions

Similar to how the design variables were treated in process 2, the epoch factors are evaluated against the expense attributes, as seen in Table 4-5, and the utility attributes, as seen in Table 4-6, to determine whether a certain epoch will affect only a single attribute or multiple attributes concurrently. If the epoch affects multiple attributes, then the simple linear sum of the attributes cannot be used and a more complex function that accounts for interactions between attributes must be utilized.

Epoch Descriptor Impact Matrix				
Expense Attributes	**Epoch Descriptors**	ED 1	ED n	**Total**
EA 1				
EA n				
Total Impact				

Impact Scale: 0-None, 1-Slight, 3-Moderate, 9-High[2]

Table 4-5: A matrix reflecting the notional impact of epoch variables on expense attributes.

Epoch Descriptor Impact Matrix				
Utility Attributes	**Epoch Descriptors**	ED 1	ED n	**Total**
UA 1				
UA n				
Total Impact				

Impact Scale: 0-None, 1-Slight, 3-Moderate, 9-High

Table 4-6: A matrix reflecting the notional impact of epoch variables on utility attributes.

[2] The traditional convention is for the attributes to be listed in the columns and for the epoch descriptors to be listed in the rows, but the convention was changed for this research to emphasize the attributes over the epoch descriptors.

Additionally, large impact sums indicate that the epoch will have a significant effect on that attribute. This impact results in a modification of the decision making behavior of the stakeholder. Therefore, if there are numerous attributes with large totals from the epoch factors then the stakeholder's behavior will fluctuate broadly across the entirety of the epoch space.

After understanding the impact of the epoch factors on the expense and utility attributes, the user is able to translate those impacts into individual weighting factors, as shown in Table 4-7. These epoch weighting factors are derived from the action that occurs as a result of the epoch (i.e. price of fuel doubling) or through expert consultation. The weighting factors directly modify the attribute – or performance value – of the design choices and results in potentially different values for each epoch. The modified epoch values are then to be converted into SAE and SAU values, which will be covered in Process 4.

Epoch Weighting Factor					
Exogenous Factor	Attributes	EA 1	EA n	UA 1	UA n
ED 1					
ED n					

Table 4-7: The epoch weighting factors for both expense and utility attributes.

4.2.4 **Process 4: Design-Epoch Tradespace Evaluation**

The steps that are involved in Design-Epoch Tradespace Evaluation Process 4 are almost identical to those that are prescribed in a standard MATE process and guide the user through the modeling of the tradespace – with the actual simulation of the tradespace occurring in process 5. This is the longest process and is often the most difficult to set up and achieve accurate results. The first step in this process is to generate a value curve that correlates the stakeholder attributes to a value between zero and one – where a low utility value means a worse utility performance and a low expense value means a better expense performance. The most accurate method for determining the value that should be assigned to a specific attribute performance is to conduct interviews with the primary stakeholders, but expert opinions can also be utilized to generate this information.

Single Attribute Expense Values		
Expense Value	EA 1	EA n
0		
0.25		
0.75		
1		

Table 4-8: Single Attribute Expense (SAE) values for the system expense attributes[3].

Single Attribute Utility Values		
Utility Value	UA 1	UA n
0		
0.25		
0.75		
1		

Table 4-9: Single Attribute Utility (SAU) values for the system utilty attributes.

The tables for the expense attributes, shown in Table 4-8, and the utility attributes, shown in Table 4-9, are populated with the responses from the stakeholders or experts. The value column

[3] The standard convention is for the attributes to be in the rows and for the utilities values to be in the columns, but this was changed in this research to simplify the transfer process between the informal interview data and homeowner selection model.

can be divided into any number of rows that the user deems necessary or prudent for the analysis. The data generated in the tables is then used to generate single attribute expense and single attribute utility curves that are shown in Figure 4-3 and Figure 4-4, respectively. These curves are then developed into functions that enable the user to extrapolate a perceived “performance” value for any resulting attribute level from a design in the tradespace.

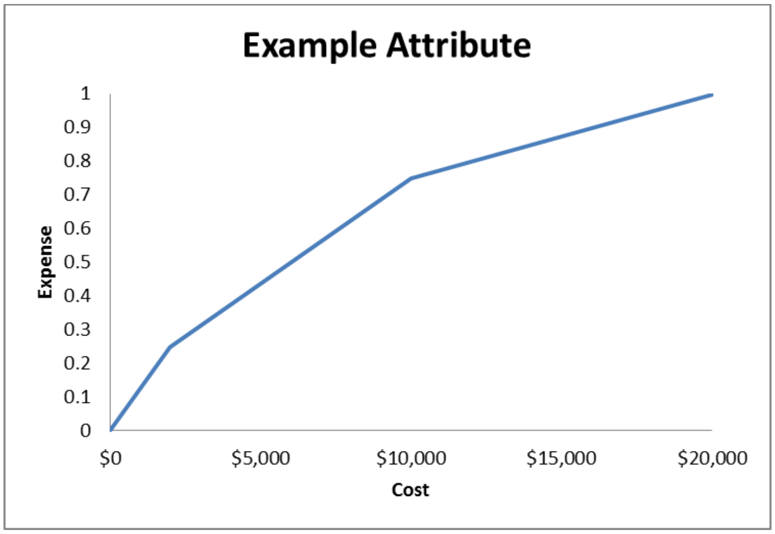


Figure 4-3: Single Attribute Expense (SAE) curve based on an example system attribute.

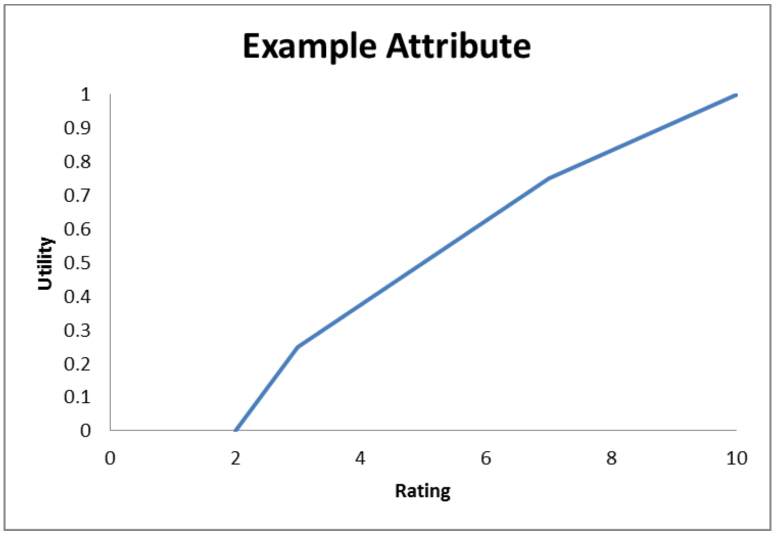


Figure 4-4: Single Attribute Utility (SAU) curve based on an example system attribute.

After creating the curves for all of the expense and utility attributes, then the user is able to start determining how to aggregate the values into a single multi-attribute expense (MAE) value and a single multi-attribute utility (MAU) value. In this scenario a simple weighted sum of the single attribute values will be used and the equation for the MAE value is in Equation 4-1 and the equation for the MAU value is in Equation 4-2. This formulation assumes each attribute contributes independently to the respective multi-attribute function value.

$$\sum_{i}^{n} k_i E_i(X_i)$$

where

$$\sum_{i}^{n} k_i = 1$$

Equation 4-1: Simple weighted sum of the single attribute expenses for calculating MAE

$$\sum_{i}^{N} k_i U_i(X_i)$$

where

$$\sum_{i}^{N} k_i = 1$$

Equation 4-2: Simple weighted sum of the single attribute utilities for calculating MAU

In both of the equations, which were taken from the literature in section 2.2, the weighting value *k* of each attribute is determined by interviewing the stakeholders and asking them to rank the attributes. This ranking for each attribute is then transformed into a weight that is applied to its respective performance value. Although both equations use the same symbol for the weighting factor, it is important to note that each weighting factor is determine for expense and utility attributes individually (i.e. there are always two different weighting sets for the respective attributes). The result of all the steps in Process 4 are shown in Table 4-10 that has all of the expense and utility attribute values for each of the design choices along with the aggregated MAE and MAU values for each design choice.

Epoch: Baseline			
Attributes	Design Choice	DC 1	DC n
EA 1			
SAE 1			
EA n			
SAE n			
MAE			
UA 1			
SAU 1			
UA n			
SAU n			
MAU			

Table 4-10: The evaluated attributes for each design choice with MAE and MAU values.

Summarizing the previous four processes, the user of this modified method will generate the MAE and MAU values for each of the existing distributed generation designs by following these steps:

1. Collect the performance values that align with the stakeholder attributes
2. Utilize a lookup table to select the performance values for each design from step 1.
3. Utilize a lookup table to select the epoch weighting factor for each attribute of the design and apply factors to values from step 2[4].

[4] A lookup table was utilized for steps 2 and 3 since existing design alternatives were available that met the stakeholder needs. Alternatively, models or simulations could be used to generate performance data on hypothetical designs which could then be used for step 4.

4. Apply the SAE and SAU functions to the values from step 3.
5. Apply the MAE and MAU weighting functions to the values from step 4.

The result of these steps will be a tradespace of MAE and MAU values for each of the design choices across all of the different epochs. These values will enable the user to analyze individual epochs as described in Process 5 and perform the multi-epoch analysis described in Process 6.

4.2.5 **Process 5: Single Epoch Analyses**

In Process 4, Table 4-10 was created to represent the baseline epoch case and by following the same process for the remainder of the epoch factors the user generates the values that fill Table 4-11 and Table 4-12. This is accomplished by utilizing the weighting factors from section 4.2.3 where different performance values in each epoch are generated based on the weights.

MAE	Epoch	ED 1	ED n
MAE		1	n
DC 1	1		
DC n	n		

Table 4-11: The MAE values of the design choices for the epoch descriptors.

MAU	Epoch	ED 1	ED n
MAU		1	n
DC 1	1		
DC n	n		

Table 4-12: The MAU values of the design choices for the epoch descriptors.

Additionally, this process is where the merger occurs between the MATE and EEA methodology to generate the deeper analysis for the user. Graphing the values from Table 4-11 and Table 4-12 results in graphs similar to the example in Figure 4-5 where each of the epochs have their own set of design choices plotted according to their MAE and MAU values. These plots allow the user to more easily identify designs that are located on the Pareto Frontier for that specific epoch and visualize the total number of designs that are available as solutions for the stakeholder. Also, the user is able to determine the different expense and utility trades that are available for the epoch to greater understand the passive robust value of the designs. Additional Pareto analysis is performed as part of process 6.

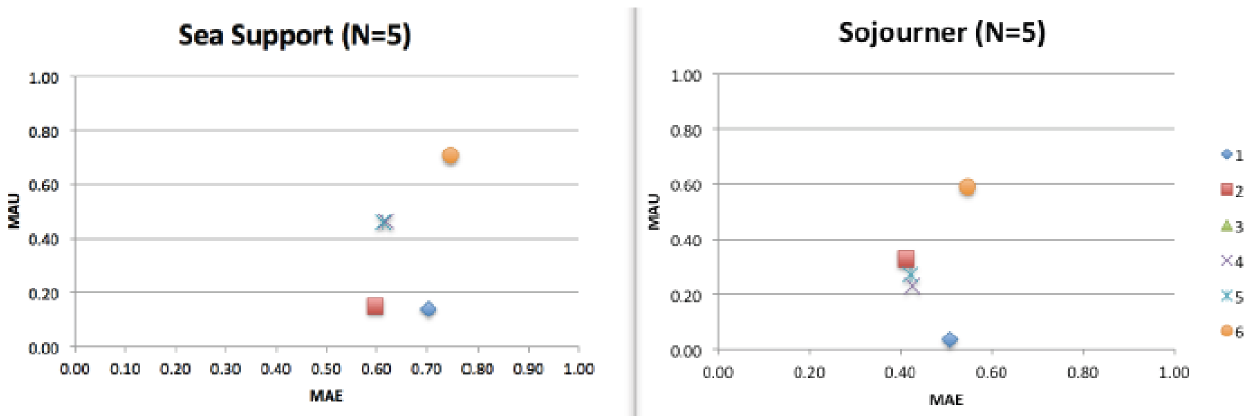


Figure 4-5: Examples of evaluated designs for different epochs. (Schaffner, Ross, & Rhodes, 2014)

4.2.6 **Process 6: Multi-Epoch Analysis**

Depending on the desired metrics for the solution, the user is now able to evaluate the different designs across all the epochs or even simply a subset of the epochs that are deemed to be of greater interest. One of the more helpful metrics for selecting a design is the Pareto Optimal metric that was described throughout section 2.3 and in this case will be the Pareto Frontier, Normalized Pareto Trace, and Fuzzy Normalized Pareto Trace.

The three metrics listed in the previous paragraph build upon one another and can be used collectively or individually to provide additional insight to the user. Since the Pareto optimal for each epoch will have been determined in process 5, the logical progress is to determine how often a design appears as Pareto Optimal across the desired epochs in the analysis. This count is then divided by the total number of epochs in the analysis to create a percentage that the design appears as the Pareto Optimal solution. The results are then placed into a table, similar to Table 4-13, which enables the user to quickly determine the performance of each design compared to the other designs in the tradespace since a higher NPT value signifies a greater number of times being Pareto Optimal and therefore the cost-benefit efficiency of a design.

Design Choices	NPT
DC 1	
DC n	

Table 4-13: The NPT for each design across all epochs.

Building upon the results in Table 4-13, the user is able to then apply a fuzzy factor to the Pareto Optimal used to determine how the NPT changes for each of the designs. This provides insight into whether a design is close to the Pareto Optimal in multiple epochs and is one method for incorporating uncertainty in design performance – as well as aspects in the analysis where there may have been uncertainty. There are multiple methods for selecting the appropriate fuzzy factor for the analysis, but the numbers for this research are chosen to provide clarity into understanding how the fuzzy factor changes the results. After incorporating the fuzzy factor with the calculation utilized to create Table 4-13, the user has a new set of results that is characterized by Table 4-14.

Design Choices	NPT	5% fNPT	10% fNPT	20% fNPT
DC 1				
DC n				

Table 4-14: NPT and fNPT of the design choices.

4.2.7 **Process 7: Era Construction**

As mentioned in section 2.4, an era is an ordered sequence of epochs that demonstrates possible long run scenarios. These scenarios are meant to model how the system will perform over time and are the last tool in the method that the user has to determine the appropriate design for the stakeholders. Unlike the epoch characterization that occurred in process 3, there is no system diagram that can be utilized to inform which of the epochs should be selected or even how they should be ordered to form the individual eras. There are a number of different channels that can provide the user with appropriate information to create the sets including expert opinion, probabilistic modeling, and scenarios of interest to the stakeholders (Schaffner, Ross, & Rhodes, 2014) – quite often the most used method for constructing the era. After these avenues have been investigated, the user will develop the information necessary to fill out Table 4-15 which will guide the analysis that occurs in process 8 and 9.

Era Descriptions				
Era Name	Era Descriptor Category	Era Descriptor	Epoch Sequence	Duration per Epoch
ErN 1		ErD 1		
ErN n		ErD n		

Table 4-15: Construction of Eras including the epoch sequencing and duration.

4.2.8 **Process 8: Single-Era Analyses**

With the information provided in Table 4-15, the user is now ready to start analyzing the eras for the metrics that are most important to the stakeholder as determined by the information collected in Process 1 of this formulation. The first step in the Single-Era Analysis Process is to collect the data from the appropriate epochs and then incorporate any metrics that will modify the MAE or

MAU values over the selected time period. This is represented through the example data provided in Figure 4-6.

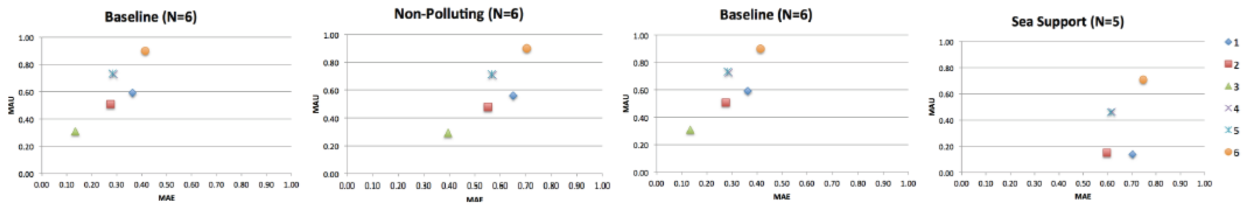


Figure 4-6: Example epoch selection for a single era. (Schaffner, Ross, & Rhodes, 2014)

After the epochs and their interactions over time have been collected and calculated, then the user plots the MAE and MAU values for each epoch and the appropriate duration on separate charts. This is shown through the example provided in Figure 4-7. The user is then able to evaluate the design solutions across the entire era based on the metric and provide the stakeholder with a selection that performs the best under the given scenario. This analysis is performed for each of the eras that are selected in Table 4-15.

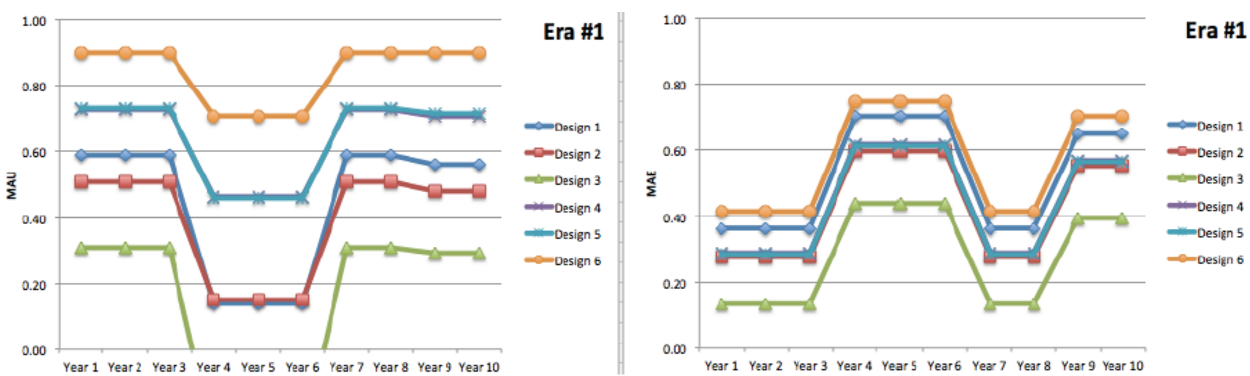


Figure 4-7: Example MAU and MAE values for each design in an era. (Schaffner, Ross, & Rhodes, 2014)

4.2.9 **Process 9: Multi-Era Analysis**

Similar to how process 6 extended the work of process 5 to encapsulate all of the epochs to determine a more comprehensive result of the analysis, Multi-Era Analysis Process 9 extends upon the work in Process 8. The metrics for this process are less defined and allow for the stakeholder to track the "ilities" of a system – including changeability, survivability, durability, etc. – and determine patterns that emerge over longer periods of time which is difficult to quantify through an epoch analysis only. Clearly, the final process in the Epoch-Era Analysis formulation is the most complex process and is currently the subject of research to clarify the metrics that should be utilized as part of the analysis (Wu, 2014) (Schaffner M. A., 2014). Even so, the first eight processes provide valuable information that can aid the user in making a decision about the appropriate system to select. This process is documented in this chapter for completeness but will not be pursued in the following chapters.

4.3 Summary

This chapter presented the Epoch-Era Analysis formulation that will be used to analyze the distributed generation systems described in Chapter 3. This formulation included all of the processes and steps in the different method phases – information gathering, analyzing, and displaying – that are required to provide an analysis about the homeowner selection of distributed generation systems. This chapter also contained all the empty charts that will be filled with results in Chapter 5 and provides the necessary background and information to understand the upcoming results.

Chapter 5 Distributed Generation Case Study

5.1 Introduction

The previous chapter discussed the framework of the Epoch-Era Analysis method in more detail while explaining how the process builds upon the information provided by the previous processes. Since the process was originally designed to generate design concepts and then evaluate those concepts based on the stakeholder needs, the author needed to slightly modify the method allowing its use to evaluate an existing design space as covered by Chapter 4. This chapter demonstrates the application of that method to a specific case, a southern California homeowner's distributed power generation system selection. It will cover the analysis of the distributed generation choices currently available, as described in Chapter 3, and describe the processes needed to generate a solution for the homeowner. A successful application of the Chapter 4 methodology will demonstrate the ability of Epoch-Era Analysis' use in assisting homeowners selecting distributed generation systems.

5.2 Adapted EEA for DG

As mentioned in Chapter 4, the analysis will cover all the processes presented in Figure 4-1 with the exception of Process 9, which is multi-era analysis. While multi-era analysis would add additional insights on the impact of path dependencies on the selection of the distributed generation system for the homeowner, for the purposes of this case study, the required effort and relative immaturity of this process make it unnecessary at this point in time. In this case, the information provided by Processes 6 and 8 is sufficient to select the appropriate distributed generation system. For reference, Figure 5-1 is provided to re-emphasize the processes utilized in the method, their designated phases, and how they build upon the information provided by prior processes.

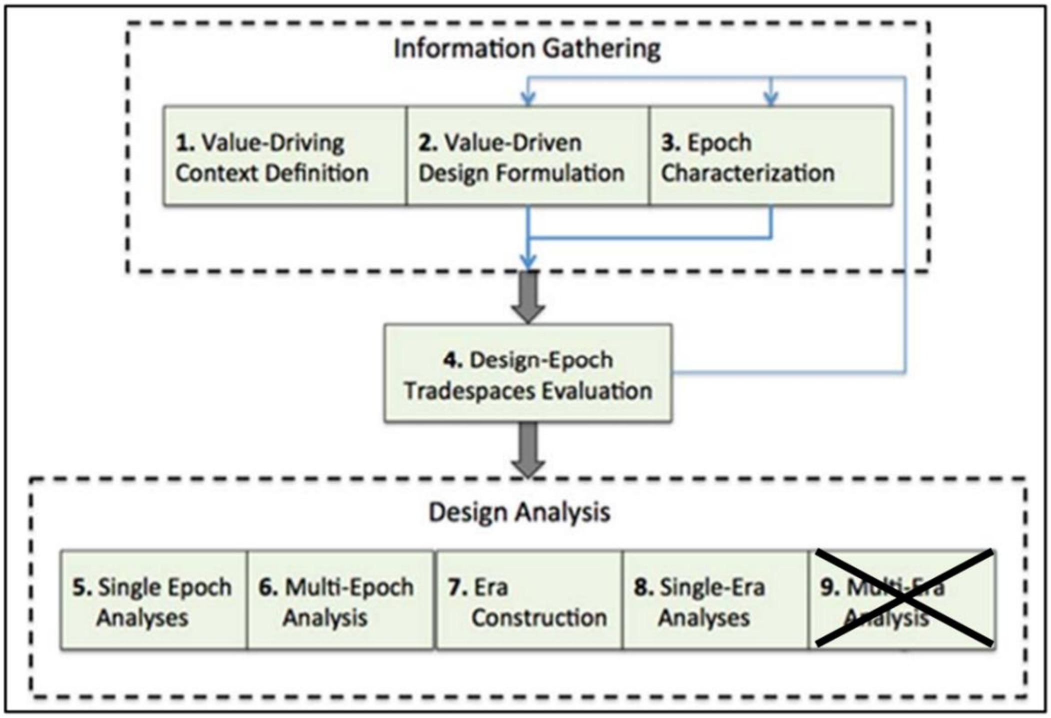


Figure 5-1: A Graphical Overview of the Gather-Evaluate-Analyze Structure without including process 9.

5.2.1 **Process 1: Value-Driving Context Definition**

After speaking with several homeowner in the San Jose, CA region and researching all the interactions that are involved with the homeowner receiving their energy, the system diagram in Figure 5-2 was generated. This system diagram captures the majority of the interactions that occur in order for a homeowner to use and maintain a DG system, but there are interactions outside of the stakeholder shown in the figure that are not represented.

The box surrounding the homeowner and distributed generation blocks, in Figure 5-2, represents factors and interactions the homeowner has control over. Clearly, there are a number of factors beyond that homeowner's control, but not all of these factors interact with the homeowner system. Therefore, the system must be simplified to represent only interactions that directly affect or engage with the homeowner or the distributed generation system. The resulting simplification of the system diagram is found in Figure 5-3, where only the interactions that cross the system boundary are included.

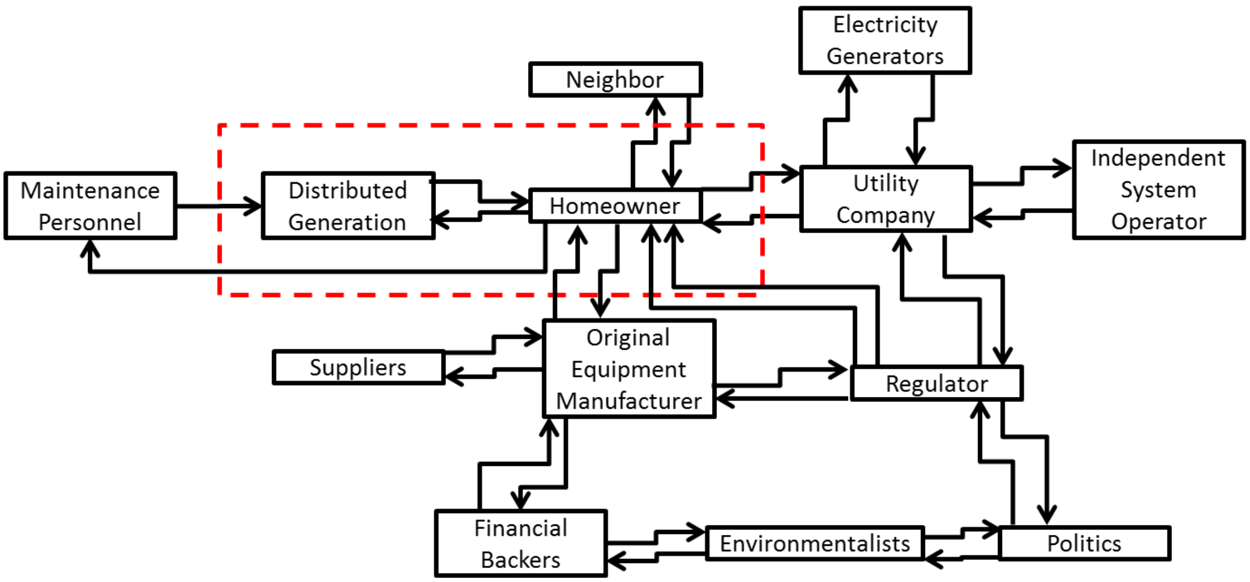


Figure 5-2: Complex system diagram of the homeowner distributed generation network.

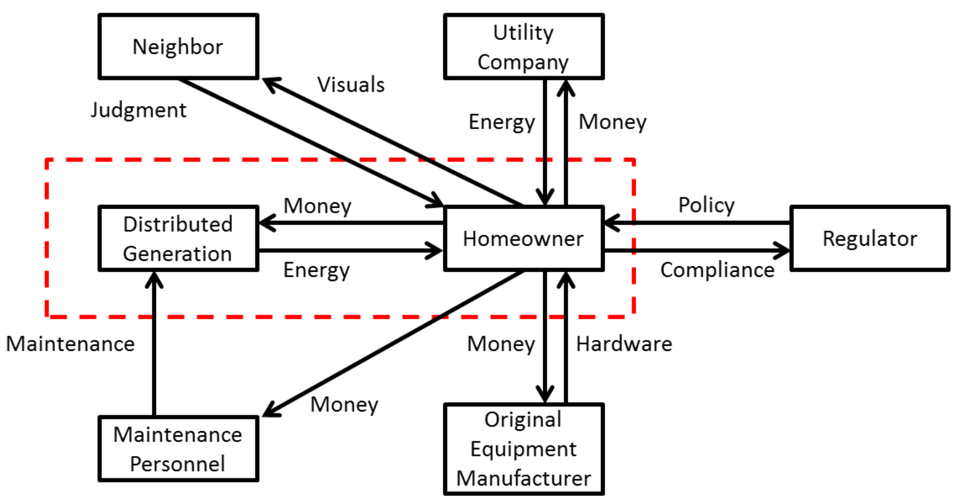


Figure 5-3: Simplified system diagram of the homeowner distributed generation network.

The interactions crossing the boundary, represented by the dashed red line, will become the epoch factors since they are exogenous to the homeowner and potentially carry significant uncertainty (their values will be covered in more detail in section 5.2.3 Process 3: Epoch Characterization). With the system diagram defined, the next process is to translate the stated needs of the homeowner into attributes that will be used to evaluate the various distributed generation designs.

5.2.2 **Process 2: Value-Driven Design Formulation**

Homeowners from the desired homeowner energy use and location in section 0 were interviewed using the survey instrument provided in Appendix A: Survey Instrument. They were presented with the distributed generation choices from section 3.2, along with a list of potential attributes for selecting a DG system, and were asked to select the attributes that they would use when selecting a distributed generation system. The homeowners were also asked to provide any additional criteria that were not presented to them in the survey instrument. From this portion of the survey, the homeowners selected nine attributes they would use when considering the system. The homeowners were then asked to provide the worst and best value they would accept for each of these attributes. While the values varied greatly across the homeowner sample, a general trend of values emerged that was then summarized into Table 5-1.

Primary Stakeholder			
Attribute	Units	Range	
		"worst"	"best"
Aesthetic Appeal		3	7
Maintenance Frequency	#/yr	6	0
Maintenance Cost	$/yr	200	0
Product Life	years	10	30
Environmental Effect	kg CO2/yr	1000	0
Availability		4	10
Initial Cost	$	50000	0
Operating Cost	$/yr	750	0
Space Required	m^2	125.00	0.00

Table 5-1: California homeowner attributes.

It should be noted that the values above are a sample of the homeowner ranges for the nine attributes and the information provided in Table 5-1 does not represent absolute information. Additionally, there may be attributes missing for certain homeowners and attributes never used by other homeowners. One of the many benefits of this analysis method is the information could be customized for each individual homeowner to present a more accurate selection. This was not pursued in the current research but is one of the recommendations for future work.

5.2.3 **Process 3: Epoch Characterization**

The next process is to use the information provided in Figure 5-3 to determine the exogenous factors to the homeowner, and select different values they may have. These exogenous factors and values become the epochs used in process 4 and 5. There are five interactions that cross the system boundary as highlighted in Figure 5-4:

1) Cost of energy from the utility company which is manifested through variation in fuel prices;
2) Amount of maintenance required to keep the distributed generation system operating which is manifested through variation in the maintenance cost;
3) Aesthetic appeal of the system which is manifested through the different neighbor opinions and HOA regulations;
4) Distribution of the system in the homeowner’s region which is manifested through the number of distributed generation products available;
5) Limits on carbon dioxide that can be emitted into the atmosphere which is manifested through the environmental policies from the regulators.

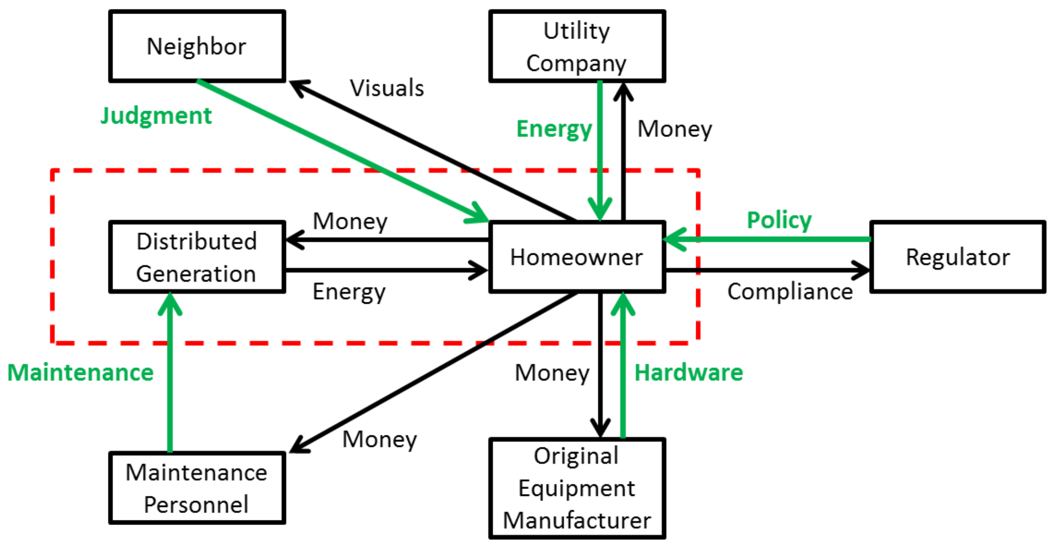


Figure 5-4: The exogenous factors that cross the system boundary and interact with the primary stakeholder system.

Epoch Descriptions				
Epoch Name	**Epoch Descriptor Category**	**Epoch Descriptor**	**Range**	**Units**
Price Fossil Fuel	Economy	Fuel	[1.0, 1.5, 2.0]	Multiplier
Cost of Maintenance	Technology	Maint	[0.5, 1.0, 2.0]	Multiplier
Neighbor Opinion	Social	Opinion	[Disagree, Neutral, Agree]	Level
Product Available	Economy	Product	[2, 5, 10]	Choices
CO2 Regulations	Policy	CO2	[None, Cap, Ban]	Level

Table 5-2: Characterization of epochs that represent exogenous factors from Figure 5-4.

The five interactions then become the epochs shown in Table 5-2. The "Epoch Name" was selected based on the five interactions above, while the "Epoch Descriptor Category" was selected based on the fundamental cause for the interaction (examples of which are provided in section 4.2.3). In this instance, economic factors are driving the fluctuations in the price of fossil fuel and product availability interactions, technological factors are driving how easy the system is to maintenance and therefore resulting in cost changes, social factors are driving how the neighbor perceives the homeowner selection of DG system, and political factors are driving how much CO_2 is allowed to be emitted into the atmosphere. The “Epoch Descriptor” was the shortened abbreviation for the epoch name that was also used to refer to the epoch. The range and units were determined through two different means. The first was through the interviews with homeowners, where the research asked the homeowner about ranges they were concerned about or thought was likely to occur. The second was through the researcher’s previous experience in the field and understanding of the possibilities. These ranges are not meant to be a complete listing of the alternatives, but a representation of a few possibilities.

The next step in the process is to separate the attributes determined through Process 2 into two groups of attributes – expense and utility. As mentioned in Section 4.2.3, the attributes must be categorized as either expense or utility. This leads to the labeling of maintenance costs, environment costs, initial costs, and operating costs as expense attributes and aesthetic appeal, maintenance frequency, product life, availability, and space required as the utility attributes.

Maintenance frequency and space required initially elicit the reaction that they should be categorized as expense attributes, but this research considers them as utility attributes for following reasons. While the number of times that a unit must be maintained is a cost to the homeowner, either through monetary or hourly use of resources, it is also an indicator of the system performance and degradation of said performance over time. Therefore, a system that is maintained fewer times is performing closer to its ideal efficiency between the maintenance periods and thus, maintenance frequency will be used to indicate utility the system is continually providing. The space required of the distributed generation system is considered a utility attribute because of what it means for the expected output of the system. If a system has a smaller space required than another system while delivering the same amount of power, then the smaller system is able to use the space more efficiently. Therefore, the smaller system can deliver more value to the homeowner for a given space.

Now that the attributes have been separated into their respective categories, the next step in the process is to determine the effect of each epoch on homeowner attributes through the use of epoch descriptor impact matrices. Using the impact scale provided in section 4.2.3 to account for the effect of the epochs on the attributes, it becomes clear in Table 5-3 and Table 5-4 that each epoch only greatly impacts a single attribute. This is a modeling assumption and removes the need for a more complicated weighted function or model accounting for emergent properties between attributes and enables use of a direct weighting function for specific attributes based on the corresponding epoch.

Epoch Descriptor Impact Matrix						
Expense Attributes / **Epoch Descriptors**	Fuel	Maint	Opinion	Product	CO2	**Total**
Maintenance Cost	0	9	0	0	0	9
Environmental Effect	1	0	0	0	9	10
Initial Cost	0	0	0	0	1	1
Operating Cost	9	1	0	0	1	11
Total Impact	10	10	0	0	11	

Impact Scale: 0-None, 1-Slight, 3-Moderate, 9-High

Table 5-3: A matrix reflecting the notional impact of the epoch variables on the expense attributes.

Epoch Descriptor Impact Matrix						
Utility Attributes / **Epoch Descriptors**	Fuel	Maint	Opinion	Product	CO2	**Total**
Aesthetic Appeal	0	0	9	0	0	9
Maintenance Frequency	0	1	0	0	0	1
Product Life	0	1	0	0	0	1
Availability	0	0	1	9	3	13
Space Required	0	0	0	0	1	1
Total Impact	0	2	10	9	4	

Impact Scale: 0-None, 1-Slight, 3-Moderate, 9-High

Table 5-4: A matrix reflecting the notional impact of the epoch variables on the utility attributes.

Epoch Weighting Factor									
Exogenous Factor / Attributes	Maintenance Cost ($/year)	Environmental Effect (kg CO2/year)	Initial Cost ($)	Operating Cost ($/year)	Aesthetic Appeal	Maintenance Frequency (#/year)	Product Life (years)	Availability	Space Required (m^2/kW)
Fuel 1.0X	1.0	1.0	1.0	**1.0**	1.0	1.0	1.0	1.0	1.0
Fuel 1.5X	1.0	1.0	1.0	**1.5**	1.0	1.0	1.0	1.0	1.0
Fuel 2.0X	1.0	1.0	1.0	**2.0**	1.0	1.0	1.0	1.0	1.0
Maint 1.0X	**1.0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Maint 0.5X	**0.5**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Maint 2.0X	**2.0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Opinion Neutral	1.0	1.0	1.0	1.0	**1.0**	1.0	1.0	1.0	1.0
Opinion Disagree	1.0	1.0	1.0	1.0	**0.5**	1.0	1.0	1.0	1.0
Opinion Agree	1.0	1.0	1.0	1.0	**2.0**	1.0	1.0	1.0	1.0
Product 10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	**1.0**	1.0
Product 5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	**2.0**	1.0
Product 2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	**5.0**	1.0
CO2 None	1.0	**1.0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CO2 Cap	1.0	**2.0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0
CO2 Ban	1.0	**10.0**	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5-5: The weighting factors of the epochs for both the expense and utility attributes.

From the information presented in Table 5-2, Table 5-3 and Table 5-4, the weighting function for the epoch, or how the epochs modify the attributes, is represented in Table 5-5. The results of this weighting function modify the affected distributed generation system's attribute for the given epoch, which may cause either an increase or decrease in favorability for MAE and MAU values. This will be covered in more detail in Section 5.2.5, where the single era epoch analysis is performed. In Table 5-5, the exogenous factors correspond with the epoch names previously determined in this section and the highlighted cells indicate the weighting factors that are used to modify the attribute performance in the specific epoch. While most of the factors are direct correlations to the name and range provided in Table 5-2, epoch weighting values in Table 5-5 for the CO_2 and neighbor epochs could and should be modified if found to be misaligned with expert opinion.

5.2.4 **Process 4: Design-Epoch Tradespace Evaluation**

Building upon the information provided in Process 3, the application of the EEA methodology can continue with developing the tradespace used to evaluate the distributed generation choices available to homeowners. The first step is to use the information provided by homeowners during the survey to generate single attribute value curves for the expense attributes and utility attributes. Table 5-6 provides the relationship between the distributed generation performance value and the resulting single attribute expense value.

The data from Table 5-6 is then used to generate the performance curves in Figure 5-5, which enable any distributed generation performance metric to be transferred into a single attribute expense value. The worst values from the homeowner in Table 5-1 correspond to a "1" for the expense attribute value while the best values correspond to a "0". These values signify that no homeowner would want the system if the performance value was greater than this and that every homeowner would want the system if the performance value was less than this, respectively. The "0.25" and "0.75" values were determined from investigating consumer reviews about products in the specific distributed generation categories.

Single Attribute Expense				
Expense	Maintenance Cost ($/year)	Environmental Effect (kg CO2/year)	Initial Cost ($)	Operating Cost ($/year)
0	0	0	0	0
0.25	25	100	3000	100
0.75	100	400	20000	450
1	200	1000	50000	750

Table 5-6: Single attribute expense values for distributed generation systems.

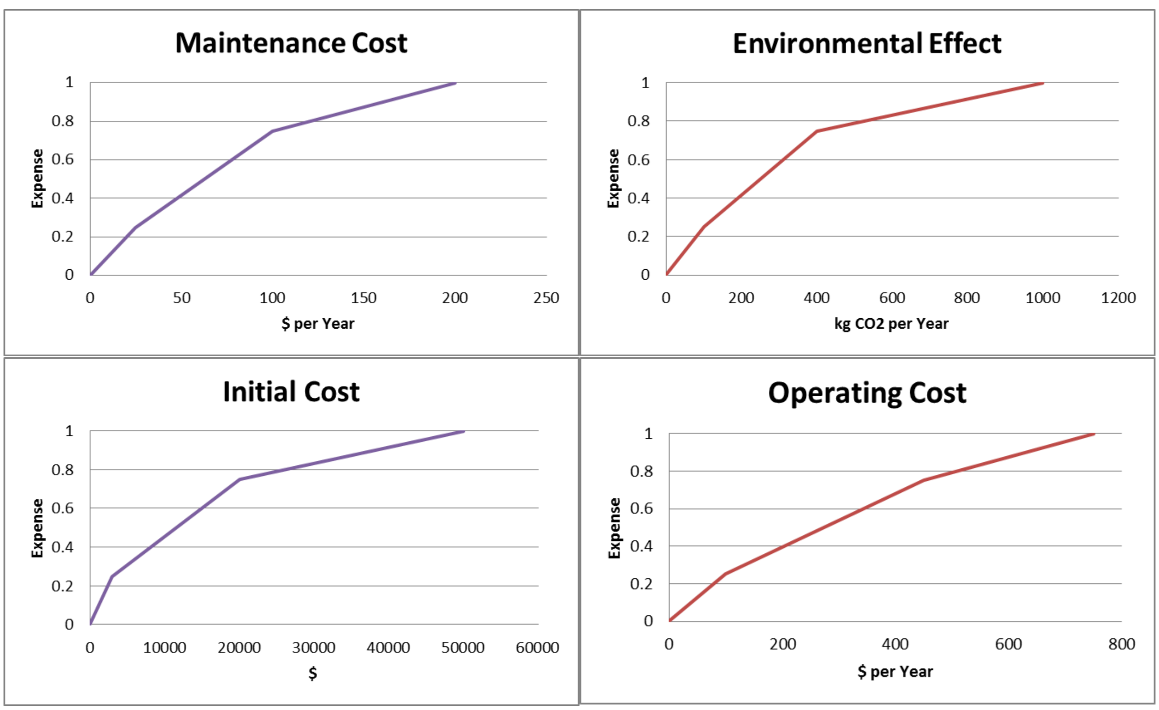


Figure 5-5: Single attribute expense curves based on Table 5-6.

The next step in the process is to aggregate the single attribute expense values into a single multi-attribute expense value which enables the distributed generation systems, all of which have different performance values, to be compared. Using the MAUT theory discussed in the Section 2.2 and information included in Table 5-3, allows for simplified linear weighted sum form represented in Equation 5-1 be used to generate the MAE.

$$\sum_{i}^{n} k_i E_i(X_i)$$

where

$$\sum_{i}^{n} k_i = 1$$

Equation 5-1: Simple weighted sum of the single attribute expenses for calculating MAE

Expense Attribute K Factor						
Exogenous Factor	Expense	Maintenance Cost ($/year)	Environmental Effect (kg CO2/year)	Initial Cost ($)	Operating Cost ($/year)
Fuel 1.0X		0.233	0.086	0.353	0.328
Fuel 1.5X		0.205	0.123	0.311	0.361
Fuel 2.0X		0.193	0.126	0.294	0.387
Maint 1.0X		0.233	0.086	0.353	0.328
Maint 0.5X		0.248	0.103	0.350	0.299
Maint 2.0X		0.299	0.128	0.316	0.256
Opinion Neutral		0.233	0.086	0.353	0.328
Opinion Disagree		0.226	0.165	0.330	0.278
Opinion Agree		0.248	0.111	0.342	0.299
Product 10		0.233	0.086	0.353	0.328
Product 5		0.238	0.148	0.344	0.270
Product 2		0.231	0.162	0.368	0.239
CO2 None		0.233	0.086	0.353	0.328
CO2 Cap		0.174	0.289	0.314	0.223
CO2 Ban		0.198	0.331	0.256	0.215

Table 5-7: MAE k factors for each epoch determined from the homeowner interviews.

The *k* factor for each of the attributes in each epoch was gathered using the survey instrument in Appendix A: Survey Instrument. The homeowner was asked to rank how important each attribute was to them during each epoch case. These rankings for the homeowners were then transformed into a weighted average which represented which factors were the primary concern for the homeowner and is displayed in Table 5-7.

The k factors for the corresponding expense attributes are located in the row for each epoch with each row summing to one. This is a function of how the epoch space was enumerated, where only one exogenous factor is allowed to occur with the other factors remaining at their respective baseline levels. For example, in the "Fuel 2.0X" epoch only the operating cost has been increased while the other factors all remain at the baseline level. It should also be noted that the "Fuel 1.0X", "Maint 1.0X", "Opinion Neutral", "Product 10", and "CO2 None" epochs all equivalently represent the baseline case, but have been included in Table 5-7 for completeness.

As one would expect, the homeowner ranking of attributes changed depending on the epoch that they were under with dramatic shifts occurring in the CO_2 epoch space. During the baseline epoch period the CO_2 attribute was essentially ignored, but once the CO_2 ban was implemented the weight of the CO_2 attributed become the clear cut primary weighted primary. The results of Table 5-7 also correlate with the notional effect of each epoch on the expense attributes from Table 5-3.

The same steps that were used to calculate the SAE and MAE values are also used to determine the SAU and MAU values for the distributed generation systems and the homeowner. There is an exception, though in how the attribute “worst” and “best” values from the homeowner are translated into the SAU value. For three of the attributes, aesthetic appeal; product life; and availability, a higher performance value signifies a greater SAU value, but for the other two attributes, maintenance frequency and space required, a lower performance value signifies a greater SAU value. These changes are captured in Table 5-8.

Single Attribute Utility					
Utility	Aesthetic Appeal	Maintenance Frequency (#/year)	Product Life (years)	Availability	Space Required (m^2/kW)
0	3	6	10	4	125.00
0.25	4	2	15	6	50.00
0.75	5	1	20	8	2.00
1	7	0	30	10	0.00

Table 5-8: Single attribute utility values for distributed generation systems.

Similar to the steps that were used to translate the single attribute expense values from Table 5-6 into the single attribute expense curves in Figure 5-5, the single attribute utility values from Table 5-8 are used to generate the single attribute utility curves in Figure 5-6. As with the SAE values, the SAU values could also be modified based on the input from the individual homeowner to ensure a closer representation of their decision making process. Additionally, the function used to generate the multi-attribute expense value from the SAE values can be used to generate the multi-attribute utility value from the SAU values with a minor modification.

Again based on the Multi-Attribute Utility Theory presented in section 2.2, a simple linear weighted sum can be applied to the SAU values because the attributes are independent and do not affect the one another. Equation 5-2 accounts for the utility attribute values, represented by the *U(X)* term in the sum, and a separate *k* factor that is the homeowner's weighting of the utility attributes across the different epoch periods.

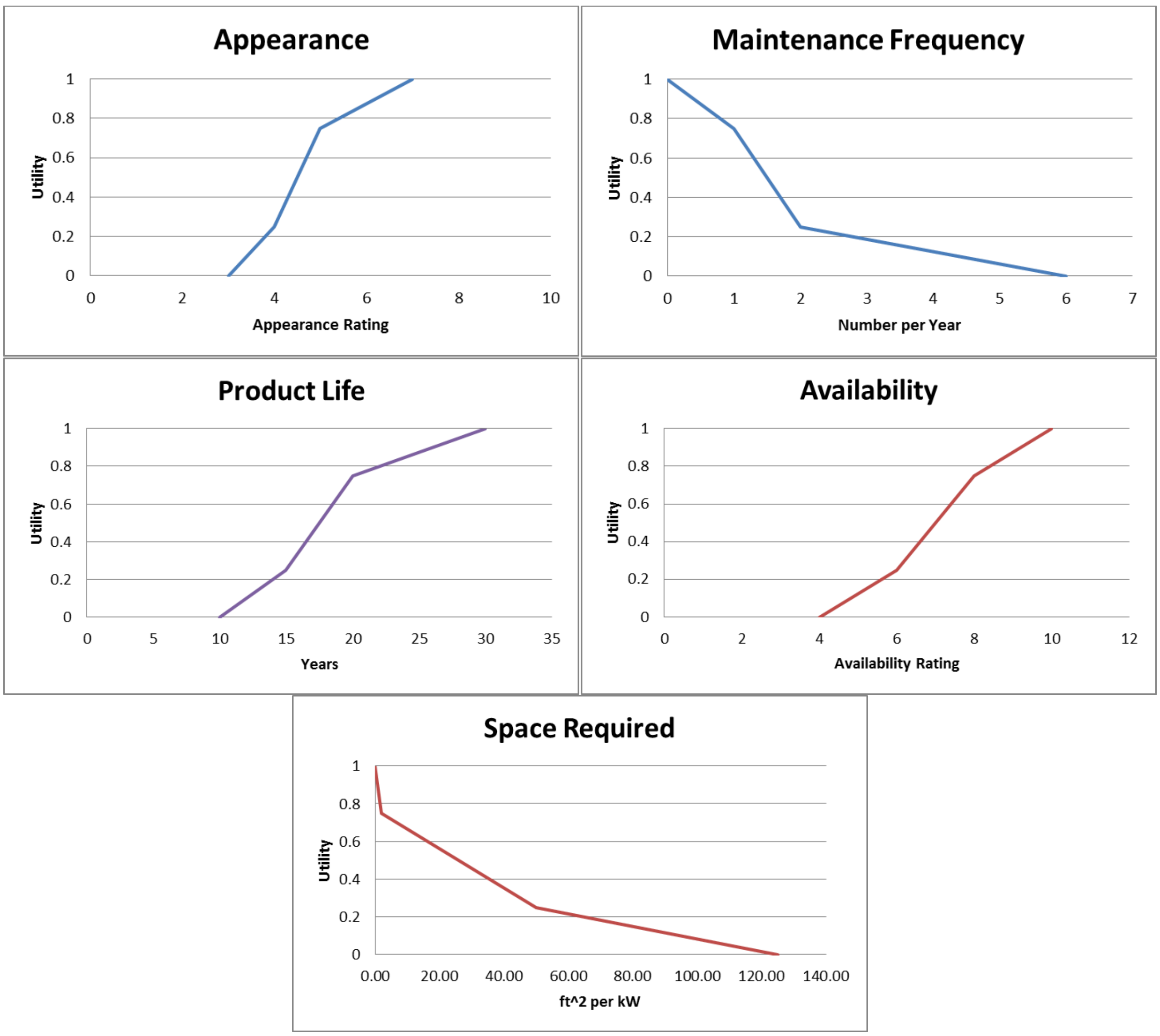


Figure 5-6: Single attribute utility curves based on Table 5-8.

$$\sum_{i}^{N} k_i U_i(X_i)$$

where

$$\sum_{i}^{N} k_i = 1$$

Equation 5-2: Simple weighted sum of the single attribute utilities for calculating MAU.

Utility Attribute K Factor						
Exogenous Factor	Utility	Aesthetic Appeal	Maintenance Frequency (#/year)	Product Life (years)	Availability	Space Required (m^2/kW)
Fuel 1.0X		0.040	0.230	0.240	0.210	0.280
Fuel 1.5X		0.032	0.245	0.245	0.202	0.277
Fuel 2.0X		0.031	0.227	0.247	0.237	0.258
Maint 1.0X		0.040	0.230	0.240	0.210	0.280
Maint 0.5X		0.030	0.253	0.222	0.242	0.253
Maint 2.0X		0.030	0.273	0.263	0.172	0.263
Opinion Neutral		0.040	0.230	0.240	0.210	0.280
Opinion Disagree		0.198	0.208	0.178	0.149	0.267
Opinion Agree		0.061	0.242	0.212	0.182	0.303
Product 10		0.040	0.230	0.240	0.210	0.280
Product 5		0.074	0.181	0.298	0.213	0.234
Product 2		0.051	0.121	0.283	0.232	0.313
CO2 None		0.040	0.230	0.240	0.210	0.280
CO2 Cap		0.053	0.126	0.305	0.168	0.347
CO2 Ban		0.063	0.158	0.295	0.189	0.295

Table 5-9: MAU k factors for each epoch determined from the homeowner interviews.

To determine the *k* factor for the utility attributes the survey instrument in Appendix A: Survey Instrument was used to elicit the ranking of attribute importance according to the homeowner in each epoch period. Similar to the *k* factor that was determined for the SAE values, the ranking was then used to determine a weight that should be applied to each of the attributes to be used in Equation 5-2 to create the MAU value. The k factors for the SAU values are found in Table 5-9.

Just as the weighting factors for the expense attributes changed depending on the epoch, the utility attribute weighting factors in Table 5-9 also change, with the foremost example being the aesthetic appeal attribute. This attribute is far less important than the other utility attributes for the homeowner except when the neighbor disapproves of their system selection. In that epoch the weighting factor nearly becomes the primary attribute that the homeowner would use when deciding on a distributed generation system.

Epoch: Baseline										
Attributes / Design Choice	None	Solar Photovoltaic	Solar Thermal	Wind Turbine	Heat Pump	Natural Gas Generator	Diesel Generator	Propane Generator	Heating Oil	Geothermal
Maintenance Cost	$0.00	$88.75	$133.13	$124.25	$137.52	$67.55	$117.59	$60.79	$37.82	$79.87
SAE	0.00	0.68	0.83	0.81	0.84	0.53	0.79	0.49	0.34	0.62
Environmental Effect	0.000	0.000	0.000	0.000	770.090	586.709	808.856	697.031	808.856	770.090
SAE	0.00	0.00	0.00	0.00	0.90	0.83	0.92	0.87	0.92	0.90
Initial Cost	$0.00	$17,750.00	$26,625.00	$35,500.00	$9,485.69	$2,637.85	$3,439.06	$2,928.75	$1,371.59	$7,437.86
SAE	0.00	0.68	0.81	0.88	0.44	0.22	0.26	0.24	0.11	0.38
Operating Cost	$0.00	$33.56	$94.77	$38.88	$93.15	$607.50	$998.05	$2,054.16	$386.13	$173.82
SAE	0.00	0.08	0.24	0.10	0.23	0.88	infeasible	infeasible	0.66	0.36
MAE	**0.000**	**0.426**	**0.556**	**0.531**	**0.506**	**0.562**	**infeasible**	**infeasible**	**0.414**	**0.472**
Aesthetic Appeal	0.000	5.000	5.000	3.000	6.000	4.000	4.000	4.000	5.000	7.000
SAU	infeasible	0.75	0.75	infeasible	0.88	0.25	0.25	0.25	0.75	1.00
Maintenance Frequency	0.000	1.000	2.000	3.000	1.000	4.000	4.000	4.000	2.000	3.000
SAU	1.00	0.75	0.25	0.19	0.75	0.13	0.13	0.13	0.25	0.19
Product Life	0.000	25.000	15.000	20.000	20.000	12.500	12.500	12.500	20.000	25.000
SAU	0.00	0.88	0.25	0.75	0.75	0.13	0.13	0.13	0.75	0.88
Availability	0.000	10.000	9.000	9.000	8.000	8.000	7.000	8.000	5.000	6.000
SAU	infeasible	1.00	0.88	0.88	0.75	0.75	0.50	0.75	0.13	0.25
Space Required	0.000	57.466	17.750	110.938	0.234	0.191	0.265	0.172	0.079	117.118
SAU	1.00	0.23	0.59	0.05	0.97	0.98	0.97	0.98	0.99	0.03
MAU	**infeasible**	**0.686**	**0.495**	**infeasible**	**0.817**	**0.500**	**0.444**	**0.500**	**0.571**	**0.353**

Table 5-10: The evaluated attributes for each design choice with MAE and MAU values.

The weighting factors for transforming the SAE and SAU values into their respective MAE and MAU values is provided in Table 5-7: MAE k factors for each epoch determined from the homeowner interviews. Table 5-7 and Table 5-9 are then used to calculate the MAE and MAU values for each of the distributed generation solutions during the baseline epoch period. To assist in making comparisons between the systems in non-attribute value metrics, these values are presented in Table 5-10 which also includes the performance values for each of the distributed generation solutions available to the San Jose, CA homeowner. Although the table presents the information, it is difficult to make comparisons between technologies or to even understand which are infeasible designs, designated as having either a "-1" or "infeasible" in the MAE or MAU cell for that design.

Another method for presenting the data is to plot the MAE values, the x-axis, and the MAU value, the y-axis, for each design and then use the Pareto Optimal metrics covered introduced in section 2.3 to determine which design is the "best" choice for the homeowner. The use of these metrics will be covered in greater detail later in the chapter, but by simply looking at the Pareto Frontier in Figure 5-7, it is clear that for the baseline epoch that heating oil, solar photovoltaic, and heat pump distributed generation systems are among solutions that the homeowner should select from. A more general note about the images presented in the remaining body of this research will include the number of feasible distributed generation systems available during the epoch at the top of the figure, signified by "N=", which is shown in Figure 5-7. For every epoch there were a total of ten designs that were analyzed.

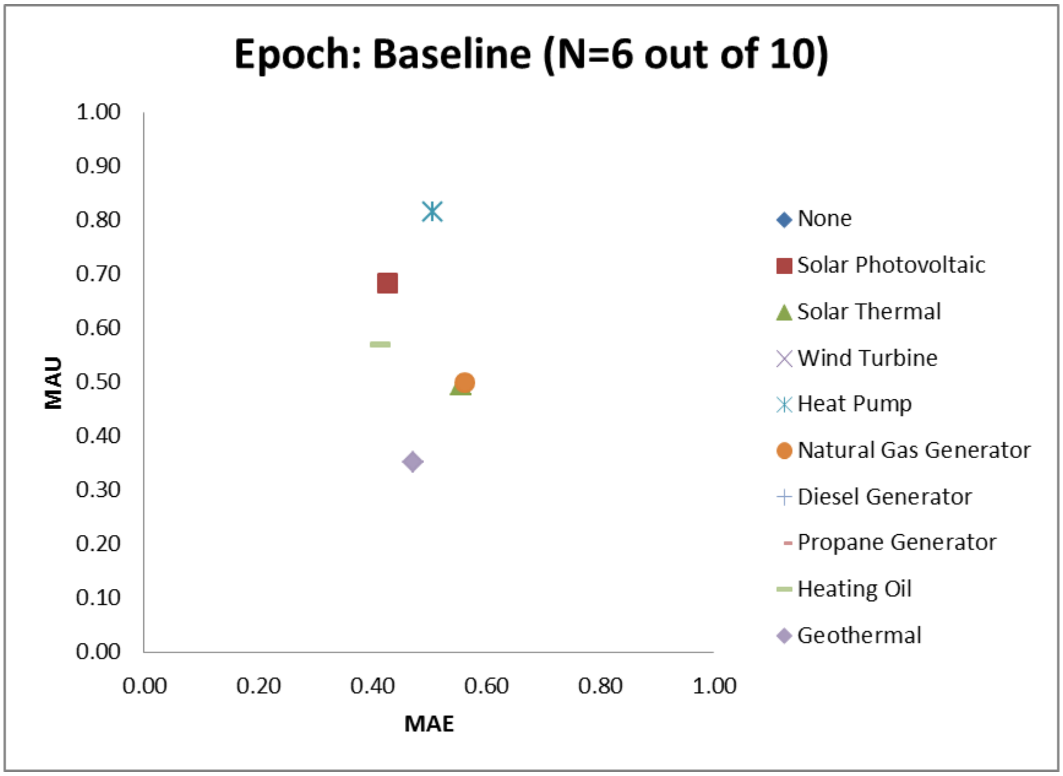


Figure 5-7: Visual tradespace (MAE v. MAU) for the baseline epoch.

5.2.5 **Process 5: Single Epoch Analyses**

The same calculation performed to determine the baseline epoch is now applied to the remaining epochs in the tradespace characterized in Table 5-2, which results in the MAE values produced in Table 5-11, and the MAU values produced in Table 5-12. One of the first noticeable things is the number of infeasible designs that homeowner's have to sort through to determine a system that meets their preferences. For example, the diesel and propane generators never have a positive MAE value and that corresponds to the systems having higher costs than homeowners are willing to bear.

MAE	Price Fossil Fuel 1x	Price Fossil Fuel 1.5x	Price Fossil Fuel 2x	Cost of Maintenance 1x	Cost of Maintenance 0.5x	Cost of Maintenance 2x	Neighbor Opinion - Nuetral	Neighbor Opinion - Disagree	Neighbor Opinion - Agree	Product Available - All	Product Available - Subset	Product Available - Two	Regulation - None	Regulation - CO2 Cap	Regulation - CO2 Ban
None	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Solar Photovoltaic	0.426	0.397	0.396	0.426	0.359	0.520	0.426	0.402	0.426	0.426	0.419	0.427	0.426	0.351	0.327
Solar Thermal	0.556	0.533	0.544	0.556	0.484	-1.000	0.556	0.520	0.553	0.556	0.539	0.545	0.556	0.450	0.422
Wind Turbine	0.531	0.493	0.490	0.531	0.460	-1.000	0.531	0.501	0.531	0.531	0.522	0.533	0.531	0.438	0.407
Heat Pump	0.506	0.532	0.551	0.506	0.451	-1.000	0.506	0.551	0.530	0.506	0.549	0.559	0.506	-1.000	-1.000
Natural Gas Generator	0.562	-1.000	-1.000	0.562	0.502	0.652	0.562	0.575	0.563	0.562	0.563	0.549	0.562	-1.000	-1.000
Diesel Generator	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000
Propane Generator	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000
Heating Oil	0.414	0.527	-1.000	0.414	0.378	0.499	0.414	0.449	0.422	0.414	0.433	0.427	0.414	-1.000	-1.000
Geothermal	0.472	0.529	0.578	0.472	0.419	0.596	0.472	0.513	0.490	0.472	0.507	0.514	0.472	-1.000	-1.000

Table 5-11: The evaluated MAE values for all epochs.

The rationale for all the infeasible designs, represented by "-1.000", in Table 5-11 is because the operating costs of the fossil-fuel distributed generation solutions are already nearing and sometimes exceed the boundary of acceptability to the homeowner. When this is combined with the environmental effect, or CO_2 emissions of the fossil-fuel technology, the result is a large number of technologies that are immediately infeasible – as is the case in the CO_2 cap and ban epoch periods.

The rationale for the infeasible designs in Table 5-12 follows a similar logic to those in Table 5-11. The "none" design, which was included for completeness and to provide a sanity check the analysis performed in an expected and controllable manner, has no utility for the homeowner and violates many of the attributed performance minimums. Immediately noticeable is how the geothermal system is the only feasible solution that meets homeowner's criteria during the epoch where their neighbor disagrees with the selection. Another surprising trend is that the wind turbine is only feasible during the epoch where the neighbor agrees with the selection. The wind turbine generates a large number of infeasible designs because the aesthetic appeal of the system corresponds with the lowest acceptable value from the homeowner. Although it will not be covered in this research, the minimum value acceptable by the homeowner could be modified which would result more designs from the wind turbine that are considered feasible.

MAU	Price Fossil Fuel 1x	Price Fossil Fuel 1.5x	Price Fossil Fuel 2x	Cost of Maintenance 1x	Cost of Maintenance 0.5x	Cost of Maintenance 2x	Neighbor Opinion - Nuetral	Neighbor Opinion - Disagree	Neighbor Opinion - Agree	Product Available - All	Product Available - Subset	Product Available - Two	Regulation - None	Regulation - CO2 Cap	Regulation - CO2 Ban
None	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000
Solar Photovoltaic	0.686	0.686	0.705	0.686	0.706	0.688	0.686	-1.000	0.617	0.686	0.718	0.679	0.686	0.648	0.680
Solar Thermal	0.495	0.485	0.500	0.495	0.501	0.461	0.495	-1.000	0.450	0.495	0.525	0.555	0.495	0.498	0.499
Wind Turbine	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	0.431	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000
Heat Pump	0.817	0.815	0.811	0.817	0.810	0.812	0.817	-1.000	0.771	0.817	0.864	0.884	0.817	0.833	0.823
Natural Gas Generator	0.500	0.491	0.496	0.500	0.495	0.460	0.500	-1.000	0.489	0.500	0.520	0.601	0.500	0.533	0.502
Diesel Generator	0.444	0.438	0.435	0.444	0.432	0.414	0.444	-1.000	0.441	0.444	0.518	0.598	0.444	0.487	0.452
Propane Generator	0.500	0.491	0.497	0.500	0.496	0.460	0.500	-1.000	0.490	0.500	0.520	0.602	0.500	0.533	0.503
Heating Oil	0.571	0.568	0.550	0.571	0.533	0.569	0.571	-1.000	0.542	0.571	0.769	0.823	0.571	0.665	0.623
Geothermal	0.353	0.350	0.356	0.353	0.339	0.361	0.353	0.264	0.284	0.353	0.588	0.561	0.353	0.395	0.406

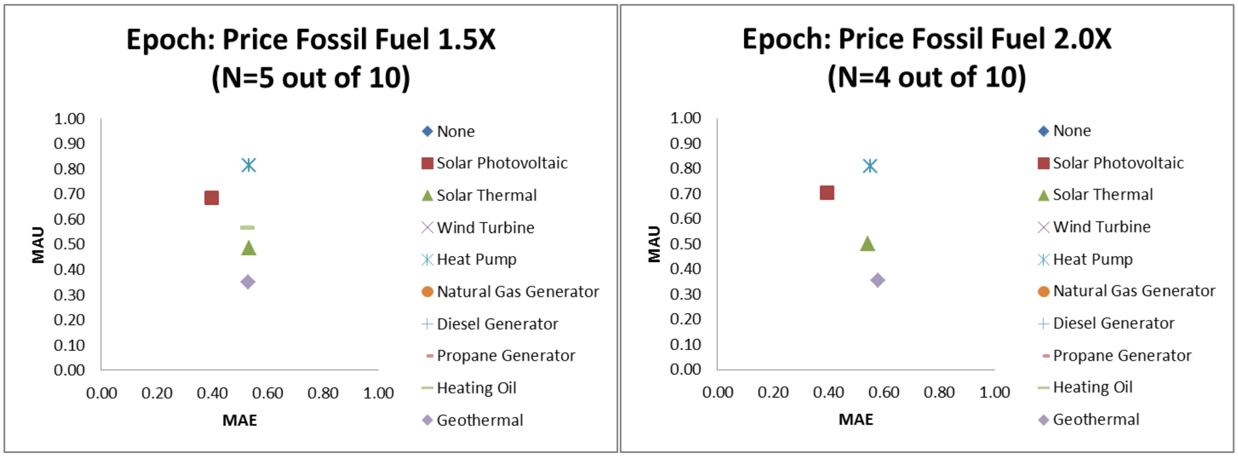
Table 5-12: The evaluated MAU values for all epochs.

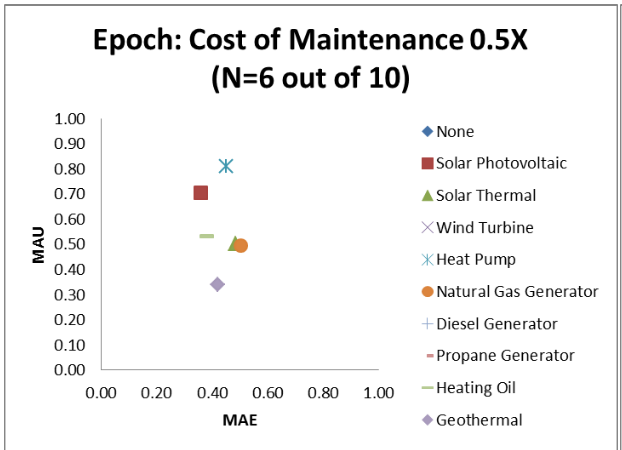
Feasibility Matrix	Epoch	Price Fossil Fuel 1x	Price Fossil Fuel 1.5x	Price Fossil Fuel 2x	Cost of Maintenance 1x	Cost of Maintenance 0.5x	Cost of Maintenance 2x	Neighbor Opinion - Nuetral	Neighbor Opinion - Disagree	Neighbor Opinion - Agree	Product Available - All	Product Available - Subset	Product Available - Two	Regulation - None	Regulation - CO2 Cap	Regulation - CO2 Ban
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
None	1	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas
Solar Photovoltaic	2	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Infeas	Feas	Feas	Feas	Feas	Feas	Feas	Feas
Solar Thermal	3	Feas	Feas	Feas	Feas	Feas	Infeas	Feas	Infeas	Feas	Feas	Feas	Feas	Feas	Feas	Feas
Wind Turbine	4	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Feas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas
Heat Pump	5	Feas	Feas	Feas	Feas	Feas	Infeas	Feas	Infeas	Feas	Feas	Feas	Feas	Feas	Infeas	Infeas
Natural Gas Generator	6	Feas	Infeas	Infeas	Feas	Feas	Feas	Feas	Infeas	Feas	Feas	Feas	Feas	Feas	Infeas	Infeas
Diesel Generator	7	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas
Propane Generator	8	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas	Infeas
Heating Oil	9	Feas	Feas	Infeas	Feas	Feas	Feas	Feas	Infeas	Feas	Feas	Feas	Feas	Feas	Infeas	Infeas
Geothermal	10	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Feas	Infeas	Infeas

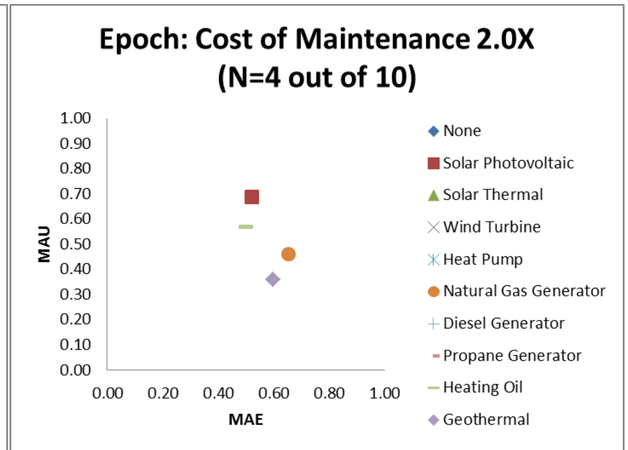
Table 5-13: Joint MAE and MAU feasibility of the distributed generation systems over all epochs.

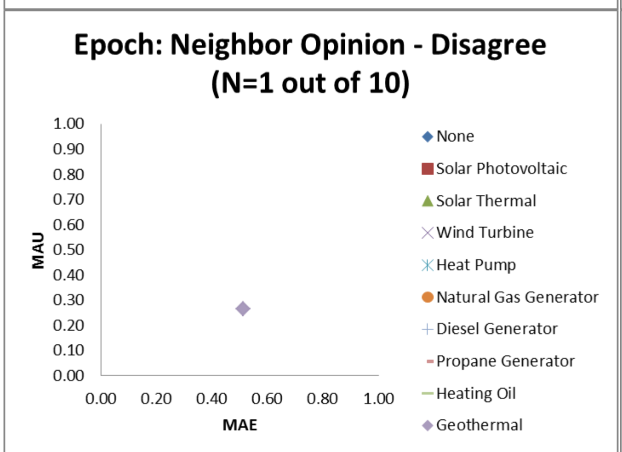
It is difficult to understand which of the design are feasible according to the MAE and MAU values. To alleviate this problem, Table 5-11 and Table 5-12 have been combined into a single table that displays which of the designs are feasible in the tradespace. The green entries in the table are feasible designs for the homeowner selection, while the red entries are infeasible designs. From the information provided in Table 5-13, it is clear that a large portion of designs are never considered because they violate one of the SAE or SAU value minimums. Therefore, the actionable tradespace is much smaller than the complete set of choices offered to the homeowner.

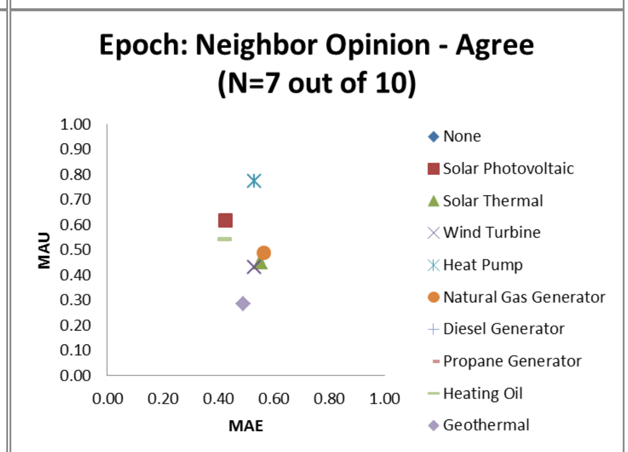
While the aforementioned tables are quite useful in determining which of the designs are available in the tradespace for the homeowner to select, the tables do not enable the homeowner to easily select the best systems. Creating a plot of each epoch enables the homeowner to narrow the selection choices more quickly than parsing through the data in the tables. Accordingly in Figure 5-8, the homeowners is able to glance at each chart for the ten non-baseline epochs and by using the Pareto Frontier metric understand which of the distributed generation choices are best for that scenario.

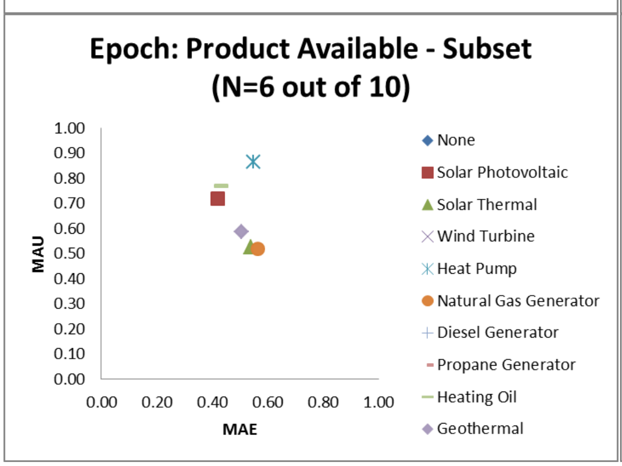


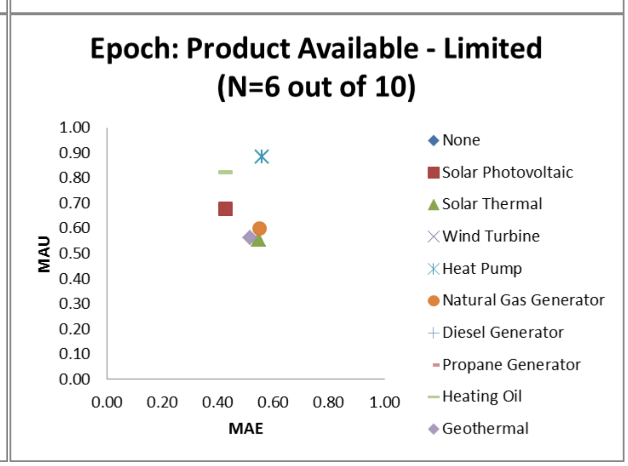

Epoch: Cost of Maintenance 0.5X
(N=6 out of 10)
MAU
1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
0.00 0.20 0.40 0.60 0.80 1.00
MAE
None
Solar Photovoltaic
Solar Thermal
Wind Turbine
Heat Pump
Natural Gas Generator
Diesel Generator
Propane Generator
Heating Oil
Geothermal


Epoch: Cost of Maintenance 2.0X
(N=4 out of 10)
MAU
1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
0.00 0.20 0.40 0.60 0.80 1.00
MAE
None
Solar Photovoltaic
Solar Thermal
Wind Turbine
Heat Pump
Natural Gas Generator
Diesel Generator
Propane Generator
Heating Oil
Geothermal


Epoch: Neighbor Opinion - Disagree
(N=1 out of 10)
MAU
1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
0.00 0.20 0.40 0.60 0.80 1.00
MAE
None
Solar Photovoltaic
Solar Thermal
Wind Turbine
Heat Pump
Natural Gas Generator
Diesel Generator
Propane Generator
Heating Oil
Geothermal


Epoch: Neighbor Opinion - Agree
(N=7 out of 10)
MAU
1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
0.00 0.20 0.40 0.60 0.80 1.00
MAE
None
Solar Photovoltaic
Solar Thermal
Wind Turbine
Heat Pump
Natural Gas Generator
Diesel Generator
Propane Generator
Heating Oil
Geothermal


Epoch: Product Available - Subset
(N=6 out of 10)
MAU
1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
0.00 0.20 0.40 0.60 0.80 1.00
MAE
None
Solar Photovoltaic
Solar Thermal
Wind Turbine
Heat Pump
Natural Gas Generator
Diesel Generator
Propane Generator
Heating Oil
Geothermal


Epoch: Product Available - Limited
(N=6 out of 10)
MAU
1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
0.00 0.20 0.40 0.60 0.80 1.00
MAE
None
Solar Photovoltaic
Solar Thermal
Wind Turbine
Heat Pump
Natural Gas Generator
Diesel Generator
Propane Generator
Heating Oil
Geothermal

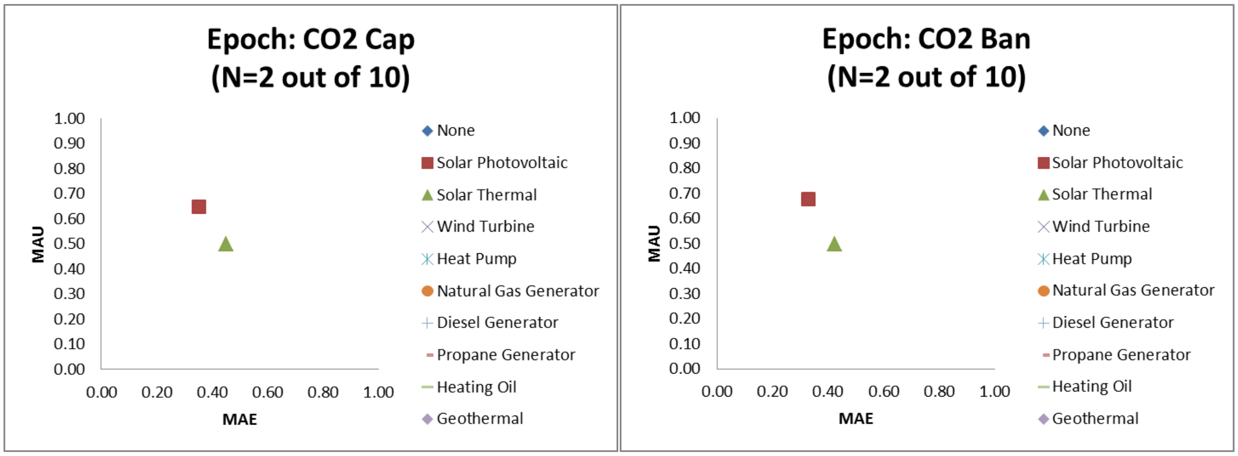


Figure 5-8: The evaluated designs for each of the 10 non-baseline epoch periods.

One of the more surprising conclusions drawn from the charts is that the heating oil distributed generation system is located near the Pareto Frontier most of the time. As one of the more expensive fossil-fuel systems included in this analysis, it was largely written off and anticipated as being an inferior solution in the expected results of the study. Another surprising result is that the heat pump distributed generation system also performs very well according to the Pareto Frontier metric. Although there were surprises in the analysis, the results seem reasonable for a couple of reasons. The cost-benefit performance of the heating oil system aligns with the interviewed homeowner's primary desire to spend the least amount of money initially. It was assumed that the other system attributes, many of which were poor, would counteract this singular positive aspect. Homeowners were generally unfamiliar with heat pump systems and the systems did not rate particularly high in any single attribute and were therefore assumed to perform moderately compared to the other systems. This assumption was incorrect as there are sources that highlight the efficiency and economy of heat pumps (Heat Pump Systems, 2013) and the tradespace results also refute the assumption. . The next process will take a more collective look at the epoch to determine how the systems perform over the range of scenarios that might occur.

5.2.6 **Process 6: Multi-Epoch Analysis**

Section 2.3.3 introduced the Normalized Pareto Trace (NPT), which is the metric to quantify Pareto Optimality that is used determine how a particular design or instance is performance across all epoch periods. For this analysis, the NPT value for each of the distributed generation systems is displayed in Table 5-14 which confirms the results noted in the prior section where there are three designs that appear on the Pareto Frontier frequently.

Design Choices	NPT
None	0.00
Solar Photovoltaic	0.82
Solar Thermal	0.00
Wind Turbine	0.00
Heat Pump	0.64
Natural Gas Generator	0.00
Diesel Generator	0.00
Propane Generator	0.00
Heating Oil	0.45
Geothermal	0.09

Table 5-14: The NPT for each design across all 11 epochs.

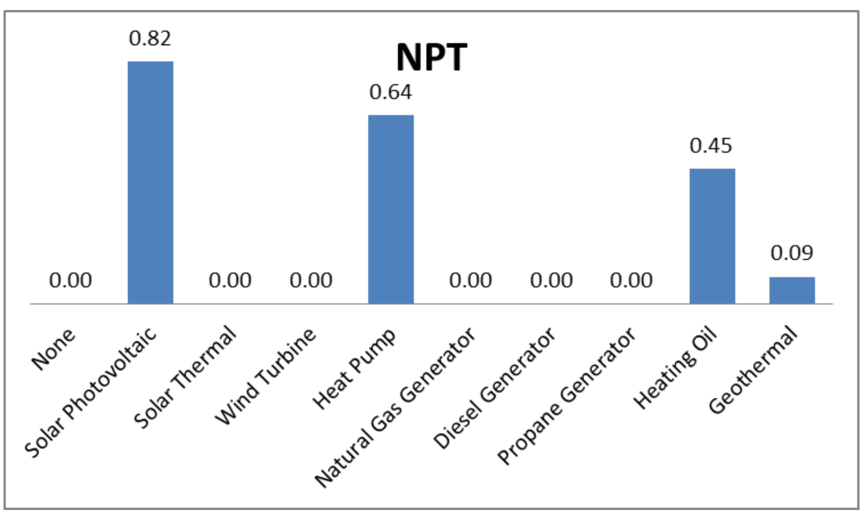


Figure 5-9: Normalized Pareto Trace of the design choices over all 11 epochs.

According to Table 5-14, there are only four of the ten distributed generation systems that are located on the Pareto Frontier for at least one of the 11 epoch periods. It is surprising that so few of the design choices are represented on the frontier and that there is a domination of the tradespace by solar photovoltaic with the heat pump system being close behind. This sentiment is further displayed in Figure 5-9, which plots the data presented in Table 5-14.

This figure does not provide the full tradespace analysis as there could be designs near the Pareto Frontier that are not captured. Since there are varying degrees of uncertainty in the information provided, the current Pareto Frontier may have a thickness or "fuzziness" which would encapsulate additional distributed generation systems. Table 5-15 and Figure 5-10 incorporate varied fuzzy factors into the analysis to determine what level of uncertainty would be required to change the Pareto solution space for the homeowner.

Design Choices	NPT	5% fNPT	10% fNPT	15% fNPT	20% fNPT	25% fNPT	30% fNPT	35% fNPT	40% fNPT
None	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar Photovoltaic	**0.82**	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Solar Thermal	0.00	0.00	0.00	0.00	0.00	0.00	**0.36**	0.73	0.82
Wind Turbine	0.00	0.00	0.00	0.00	0.00	0.00	**0.09**	0.09	0.09
Heat Pump	**0.64**	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
Natural Gas Generator	0.00	0.00	0.00	0.00	0.00	0.00	**0.09**	0.36	0.55
Diesel Generator	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Propane Generator	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heating Oil	**0.45**	0.45	0.55	0.55	0.55	0.55	0.55	0.64	0.64
Geothermal	**0.09**	0.09	0.09	0.18	0.45	0.64	0.64	0.73	0.73

Table 5-15: NPT and fNPT of the distributed generation design choices over all 11 epochs.

Although it is difficult to determine at what level the solution space changes for the homeowner in Table 5-15, it is quite clear in Figure 5-10 how much fuzziness is required for the change to occur. After a fuzzy factor of 20% is included in the Pareto Frontier, the solution space begins to change but there are still marginal gains for the non-dominating distributed generation solutions.

Not until the fuzzy factor is increased to 40% is there a significant change in the choices that the homeowner should select to ensure they their system would perform at a high level in a number of different epoch scenarios. At this stage in the methodology, it appears that the solar photovoltaic, heat pump, and heating oil distributed generation solutions are the best choices for the homeowner.

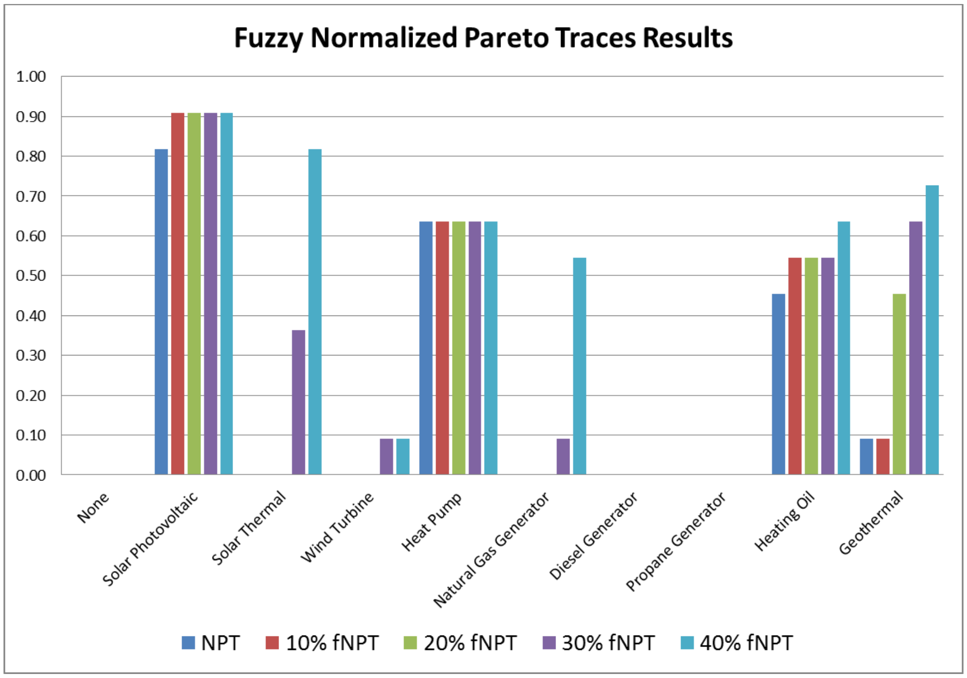


Figure 5-10: Trend of NPT for design choices after inclusion of "fuzzy" boundary.

5.2.7 **Process 7: Era Construction**

The next step in the analysis process is to determine the effect of sequencing epochs into longer duration segments of time, called an era, which enables the analysis to account for the effects of time on the system or an aggregate performance across the usable product life. Utilizing eras helps provide a more accurate representation of how the system might perform over time which enables the homeowner to make a more informed decision about their distributed generation system selection. While there are a number of different sequences that the epoch can be placed into, only three possible eras will be evaluated. These three eras, detailed in Table 5-16, were selected since they are some of the more commonly suggested paths that the future may take. Additionally, there is general interest from the researcher to understand how these situations might alter the competitive landscape for future distributed generation products looking to enter the market.

Era Descriptions				
Era Name	Era Descriptor Category	Era Descriptor	Epoch Sequence	Duration per Epoch
Era1	Policy	Environment	1) Baseline 2) Fossil Fuel 1.5X 3) Neighbor Disagree 4) Regulation - CO2 Ban	3 years
Era2	Economic	Cost	1) Baseline 2) Fossil Fuel 2.0X 3) Maintenance 2.0X 4) Limited Product Available	3 years
Era1	Technology	Hi-Tech	1) Baseline 2) Neighbor Agrees 3) Maintenance 0.5X 4) Regulation - CO2 Cap	3 years

Table 5-16: Era construction of likely scenarios from the represented epochs.

The first era to be explored was the environment era, where the price of fossil-fuel increases by 50%, followed by the neighbor disagreeing with the selection of distributed generation system for not being "green" enough, and lastly capped by a ban on CO_2 emissions. This set of events aligns with "the vision of the masses" that claim climate change needs to be stopped immediately. The second era to be explored was the cost era, where the price of fossil-fuel increased 100%, followed by a labor shortage that increased the cost of maintenance by 100%, and culminated in a limitation of the product being available. This set of events aligns with the "doomsday vision" that is held by some people who preach that the end is near. The final era was the hi-tech era, where the neighbor agrees with your distributed generation selection, the product function improves reducing the cost of maintenance, and there was a CO_2 emissions cap imposed on homeowners. According to the author, this set of events most closely aligns with what homeowners believe will happen over the mid-term. They understand that change will likely occur at some point, but are more focused on the immediate impacts of their distributed generation selection.

The duration per epoch in Table 5-16 was set at three years to match the typical product development life cycle for hardware systems and to represent the long durations that regulations take to be enacted. One could argue that the epoch duration should be longer, but it is important to recall that predictions about events into the future are highly uncertain and would likely cloud results. With all of the eras constructed, the next process of the methodology can commence.

5.2.8 **Process 8: Single-Era Analyses**

Era analysis is an opportunity to research metrics that have not been categorized previously, but still accurately reflect the sentiment of the homeowner during their decision making process. One constant between all the homeowners interviewed was the desire for the system to deliver the "greatest bang for the buck". This mentality can be categorized as wanting to have the highest performing system for the lowest expense possible and a new metric called "operational value" will encompass this though process when applied to era analysis.

Operational value is defined as the time-weighted average MAE and time-weighted average MAU of the distributed generation system while being a feasible design over the era duration. During the period of time when the design is infeasible, zero MAU will be added to the utility aggregate and one MAE will be added to the expense aggregate, which in both cases negatively impact the operational value. A good design will have a high utility average and a low expense average. It should also be noted that this metric does not allow for the homeowner to change their distributed generation system (i.e. the homeowner must select a DG system and use it throughout the era), but this optionality is something that could be researched in the future. This metric is best described through an actual use case and will be detailed greater in the first era analysis.

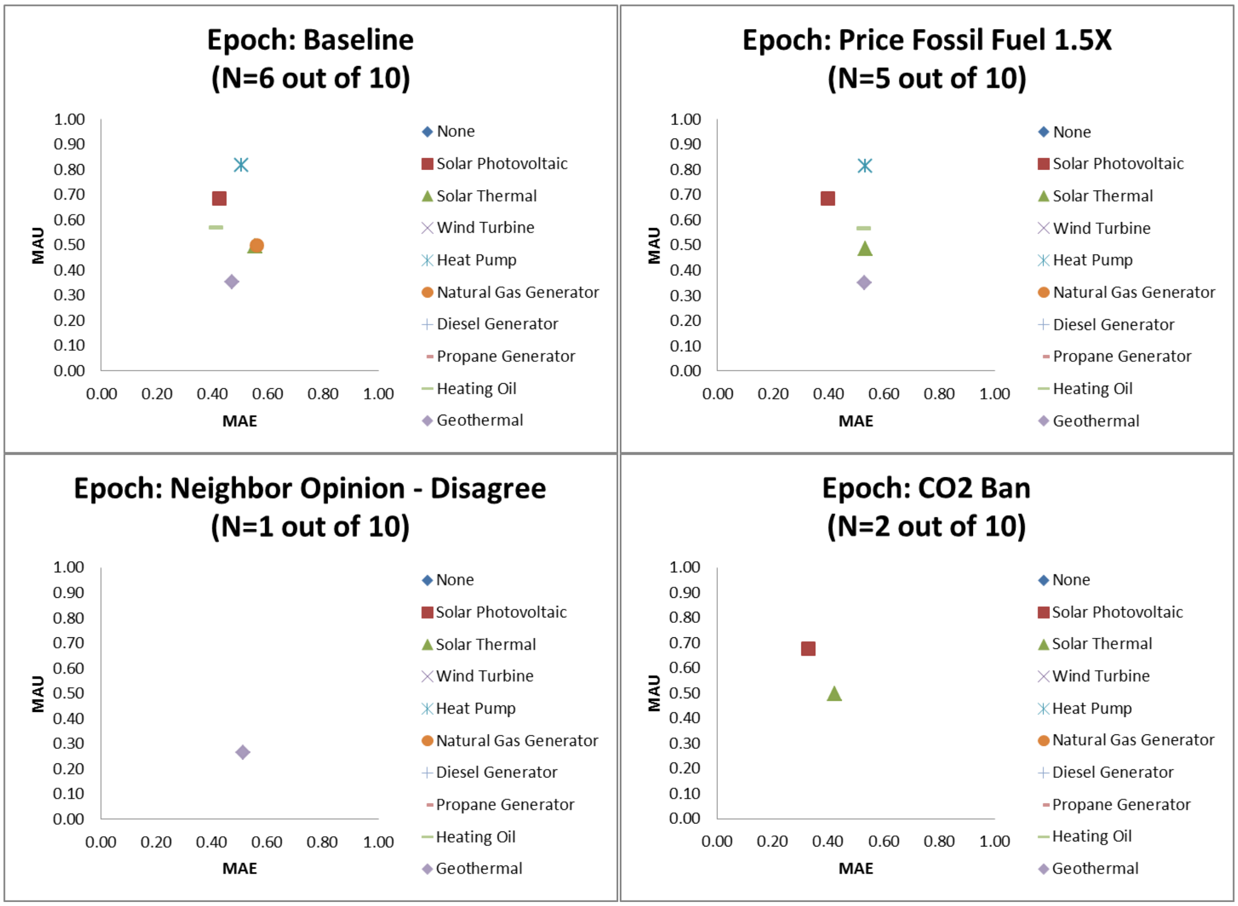
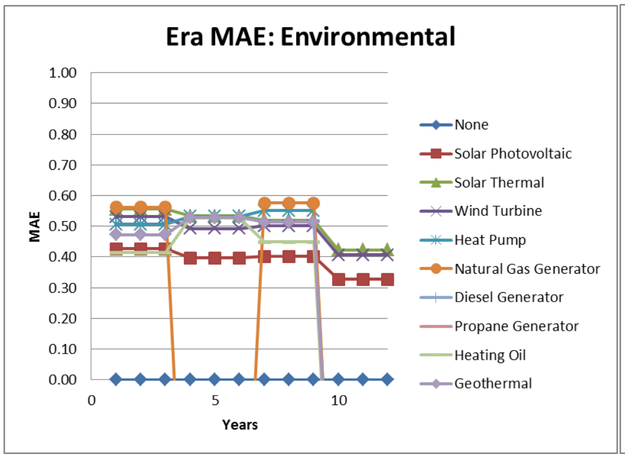


Figure 5-11: Design choice values across each of the epoch in Era1 (Environment) moving from left to right and top to bottom.

The analysis begins with gathering and ordering the epochs for the first era, these epoch tradespaces are shown in Figure 5-11, and then plotting the resulting MAE and MAU values over time for each of the distributed generation designs. The time duration plots for the environment era are shown in Figure 5-12 where it is immediately clear that there are multiple designs that do not provide value during the era. Beyond this initial observation, it is difficult to discern which distributed generation system should be selected by the homeowner. There are a number of different metrics that can be used to determine the right choice, but this research is suggesting the homeowner should evaluate the designs based on their operational value. Since this system will be used on a daily basis for the life of the era, which corresponds with the product life for most choices presented in the research, it is important to select a system that will deliver value through its life.



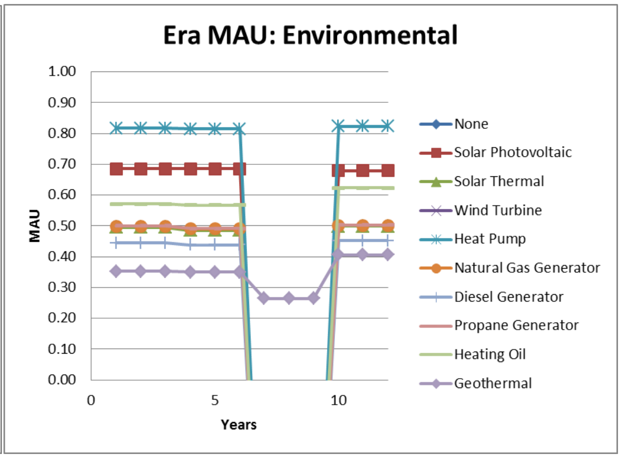


Figure 5-12: Environmental era MAE and MAU values for each design choice over 12 years.

The time-weighted average MAE and MAU values for each of the epochs can be used to combine the plots from Figure 5-12 into a single chart that will enable the homeowner to visualize and quickly select between the distributed generation choices available. The single chart is shown in Figure 5-13 where the homeowner is looking for the design with the greatest MAU value for the lowest MAE value. For this era, it is clear that the homeowner should select the solar photovoltaic distributed generation system and that no other system is able to come close to providing a similar or comparable value. This was an unexpected result since the heat pump scored higher than the solar photovoltaic system in utility and was only slightly more expensive, but after closer inspection of Figure 5-12 the reason becomes apparent. The heat pump is only considered "operational" for six of the twelve years compared to the solar photovoltaic system which is "operational" for nine of the twelve years. These three extra years of value result in the unexpected difference between the two systems.

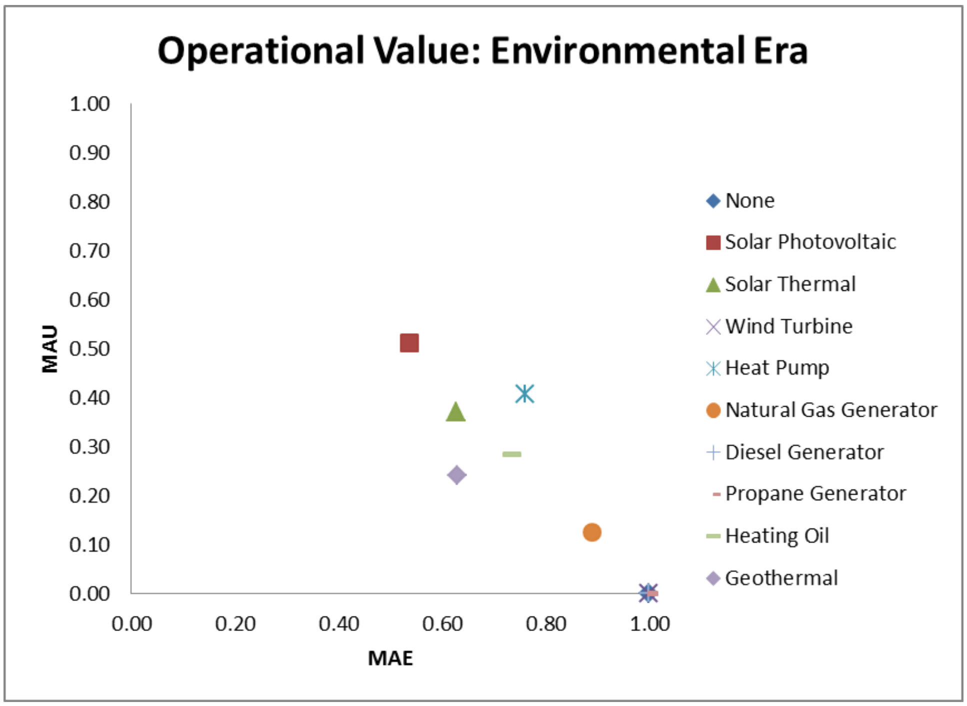


Figure 5-13: Implementation of the operational value metric across the environmental era for all DG systems.

The same method applied to the environmental era can also be applied to the cost era. This second era is comprised of the baseline, price fossil fuel 2.0X, cost of maintenance 2.0X, and limited product availability epochs – tradespace results for the individual epochs are shown in Figure 5-14 – according to the epoch characterization in Table 5-2. Again, the plots help determine the number of systems that meet the homeowner criteria and in this era it is also evident that heating oil, solar photovoltaic, and heat pump systems perform well across each epoch. Plotting the MAE and MAU values from the epochs for the designs, as shown in Figure 5-15, provides additional insight.

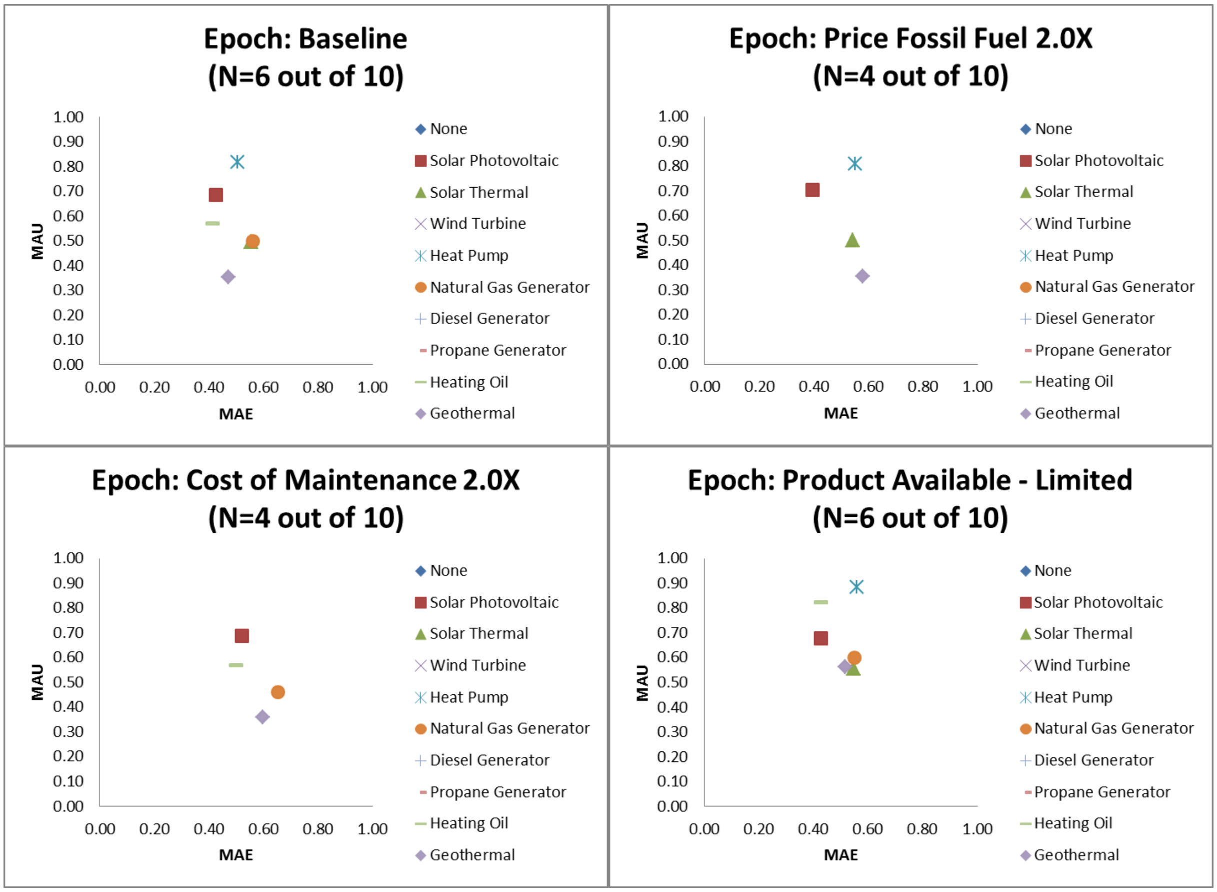


Figure 5-14: Design choice values across each of the epoch in Era2 (Cost) moving from left to right and top to bottom in per English language reading rules.

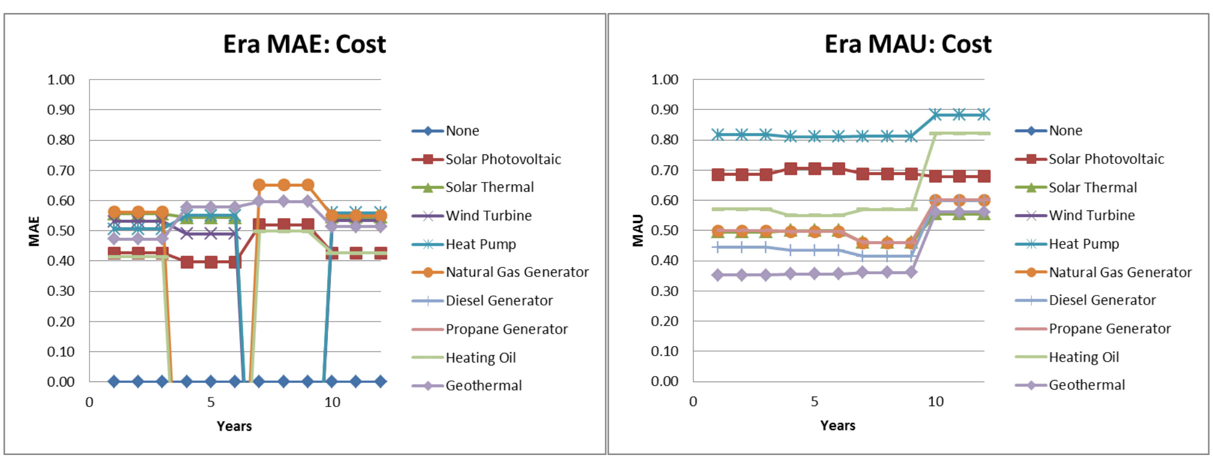


Figure 5-15: Cost era MAE and MAU values for each design choice over 12 years.

Compared with the environmental era, the cost era distributed generation system values change more from epoch to epoch and the dominant solution for the MAE values fluctuates between multiple systems. Still, it is difficult to determine from Figure 5-15 the system the homeowner should select and a second tier analysis is required to clarify the decision.

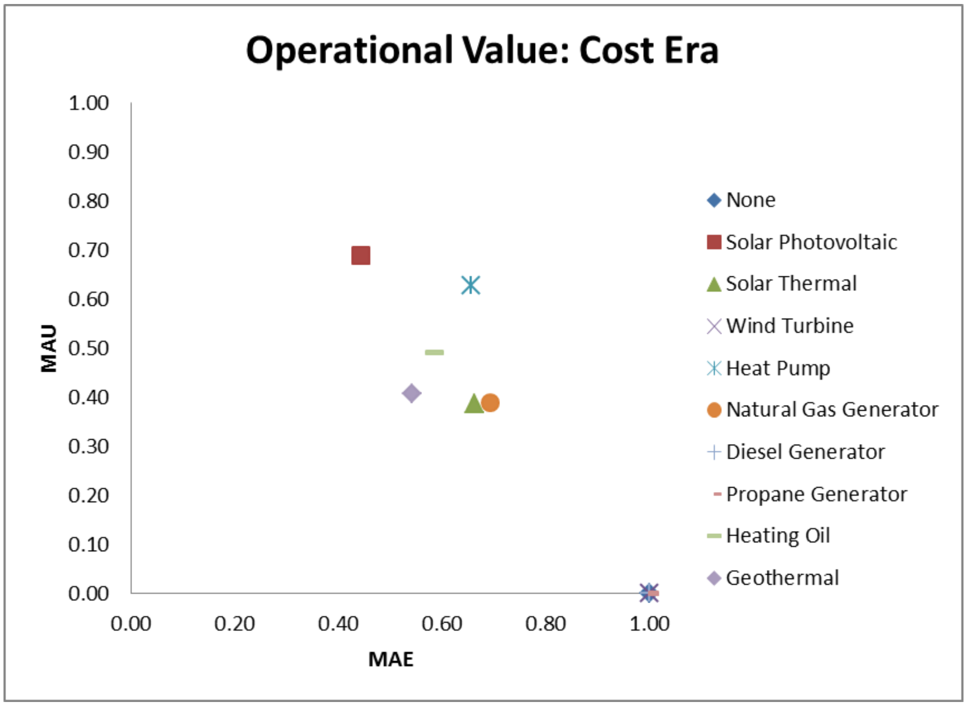


Figure 5-16: Implementation of the operational value metric across the cost era for all DG systems.

Using the operational value metric that was defined in the beginning of this section, the distributed generation systems are plotted in Figure 5-16 and again the obvious choice for the homeowner is the solar photovoltaic system. The reason the heating oil and heat pump systems not being closer to the solar photovoltaic system is each system is below the acceptable criteria for the homeowner, therefore hurting their respective era average MAE and MAU values.

This result is not all that dissimilar from the environmental era, with the exception the solar thermal and heating oil systems have traded relative location to the solar photovoltaic system.

Based solely on the first two single era analyses, the homeowner should select the solar photovoltaic system even though the two eras have included different epochs. One more era will be analyzed to determine whether there is a different system that should be considered as well.

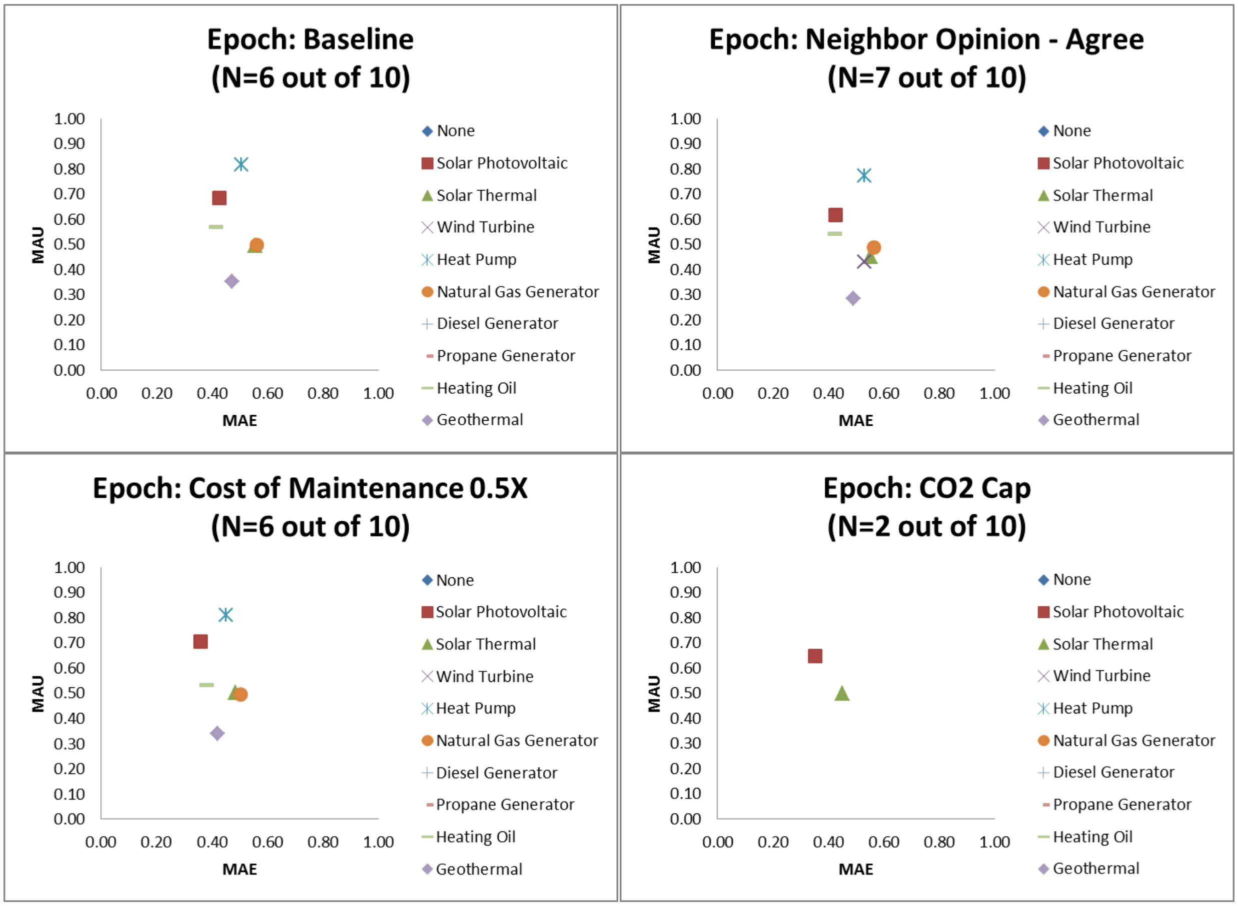


Figure 5-17: Design choice values across each of the epoch in Era3 (Hi-Tech) moving from left to right and top to bottom in per English language reading rules.

The third era consists of a different set of epochs that focus more on the effects of technological change over the period of interest. The hi-tech era consists of the baseline, neighbor opinion agreeing, cost of maintenance reduced by 50%, and there being a cap placed on CO2 emissions epochs that are represented through the tradespaces in Figure 5-17. As with the other eras, there are a number of systems that do not meet the homeowner criteria, but the final epoch in the sequence only has two designs. This will affect the operational values for the era and is discussed later in the section. Otherwise, the top three systems from the multi-epoch analysis are all represented in the era.

Figure 5-18 is produced from the epochs presented in Figure 5-17 and has an interesting pattern different from the other era MAE and MAU plots. In this case, the MAE values are relatively compact and close to one another, while the MAU values are generally widely separated with the heat pump providing a much greater utility. As mentioned previously there are instances where the heat pump does not meet the homeowner criteria and will therefore not perform as well for the operational value metric. An interesting aspect to note about the MAE and MAU plots is that the three sets each have a different shape of distributed generation system performance over time even though a similar pattern is emerging through the operational value metric.

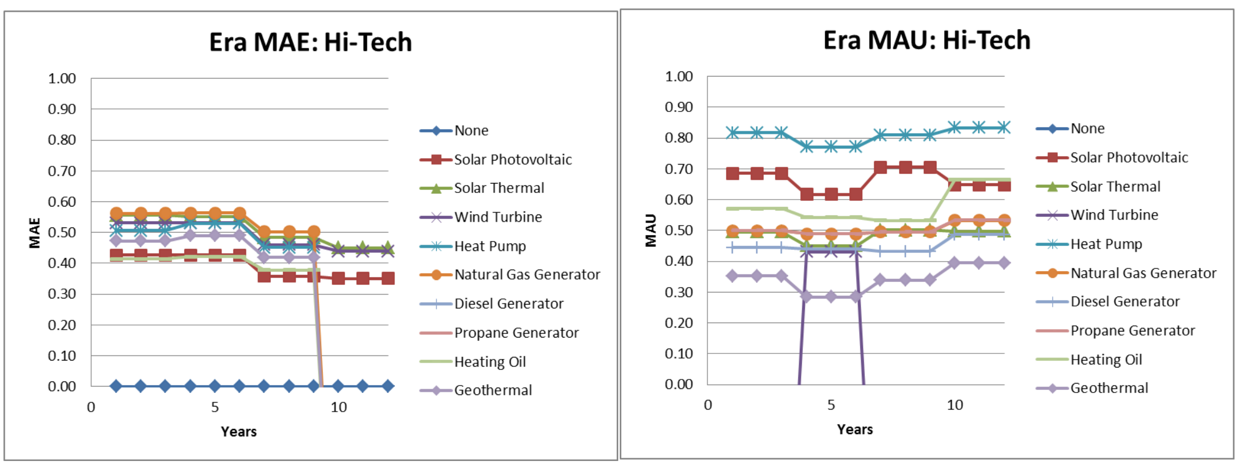


Figure 5-18: Hi-Tech era MAE and MAU values for each design choice over 12 years.

As alluded to in the previous paragraph, the operational value metric plot, seen in Figure 5-19, for the hi-tech era is similar to the previous operation value plots for the other two eras in the homeowner should select the solar photovoltaic distributed generation system. With the heat pump and heating oil systems not providing value during one of the epoch periods, there was no other system that was close to the solar photovoltaic system. Although, it should be noted that the solar thermal system became the next viable system the homeowner should select in this era.

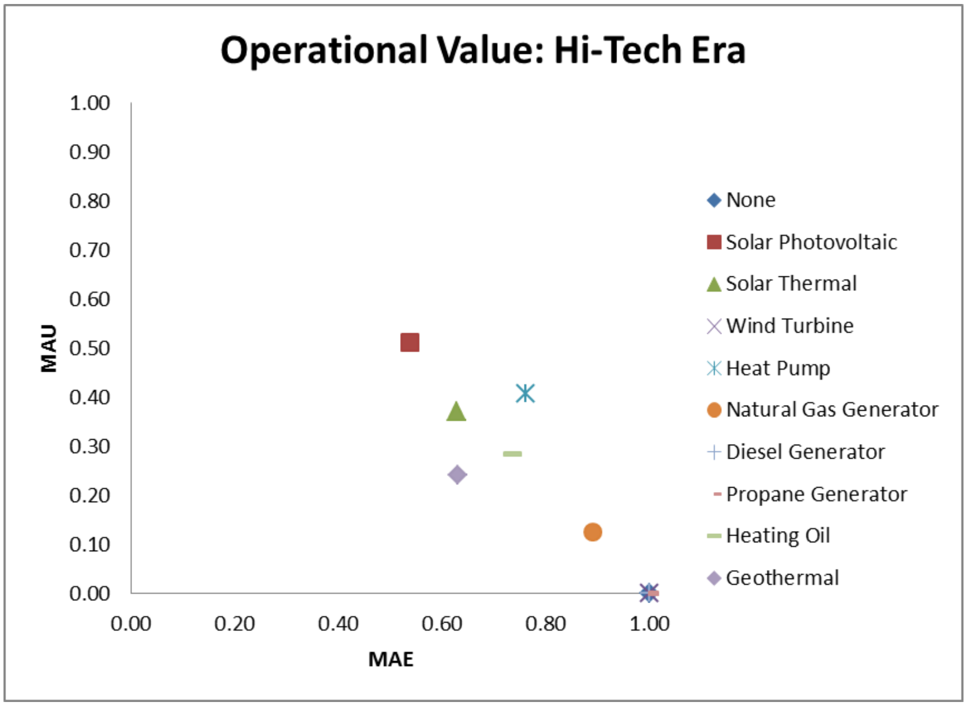


Figure 5-19: Implementation of the operational value metric across the hi-tech era for all DG systems.

5.3 Summary

At almost every step of the Epoch-Era Analysis method, it was apparent the solar photovoltaic distributed generation system most closely met the criteria of the homeowner. Throughout the multi-epoch analysis the system was one of three that separated themselves from the ten possible candidate systems but it was not until the era analysis that the solution became clear. The addition of the second tier analysis in the era investigation process distilled all the information that the homeowner needed to understand into a single chart that encapsulated their decision making criteria from an average perspective. Combining the average homeowner selections from the different analyses culminates the research presented in Chapter 5 and is shown in Table 5-17.

Average Homeowner Selection						
Design Choices	Normalized Pareto Trace			Operational Value		
	0% Fuzzy	10% Fuzzy	20% Fuzzy	Environmental Era	Cost Era	Hi-Tech Era
None						
Solar Photovoltaic	1st	1st	1st	1st	1st	1st
Solar Thermal				2nd		2nd
Wind Turbine						
Heat Pump	2nd	2nd	2nd			
Natural Gas Generator						
Diesel Generator						
Propane Generator						
Heating Oil	3rd	3rd	3rd		3rd	
Geothermal				3rd	2nd	3rd

Table 5-17: Summary of the average homeowner distributed generation system selection through each analysis with 1st in green, 2nd in yellow, and 3rd in orange.

According to the summary table, the analysis indicates that the average homeowner should select the solar photovoltaic system given the choice. The second and third alternative for the homeowner depends largely on their analysis preference. If the homeowner is more concerned with having an alternative that operates in the most epoch periods, then they should select the heat pump system second and select the heating oil system third. If the homeowner is more concerned with an era, they should select the solar thermal system second and the geothermal system third for the environmental and hi-tech era. If they are interested in the cost era, then the homeowner should select the geothermal system second and the heating oil system third. This scenario demonstrates how performing an analysis based on average data might result in a situation where the individual homeowner must still undergo a similar analysis. Therefore, it may be important to perform individual analyses whenever possible to ensure that the selected solution is applicable to a particular homeowner's preferences.

Chapter 6 Homeowner Differentiation

Taking a data set average is one of the most commonly applied statistical methods when trying to determine an optimum solution for multiple data points. This approach is no different in the distributed generation system space where business and policy makers use aggregate homeowner demographics and preference data in an attempt to model the average homeowner, similar to what was done throughout Chapter 5. While this approach simplifies the analysis and allows for the researcher to generate a singular answer for a problem question – for example, what distributed generation should homeowners select? – it does not provide an accurate depiction of what a particular homeowner will select in the “real world”.

In an effort to determine whether this phenomenon is applicable in the homeowner distributed generation system selection case study, two homeowners were randomly selected from the pool of interviewed homeowners used to generate the “average” homeowner decision making process. The following sections will present the analysis for each of these homeowners and detail any differences found in their selection of the distributed generation system. Since there are a number of processes that produce the same results by design, the sections will provide the results for the single epoch, multi-epoch and single era analyses.

6.1 Homeowner 4

As mentioned in the previous section, the individual homeowner will likely have different preferences than the average homeowner preferences and the first case study to determine the effect of those differences on the distributed generation selection will be Homeowner 4. Shown in Figure 6-1 are the nine attributes and their respective ranking for each homeowner where a ranking close to “1” will have the largest weighting factor in the analysis and a ranking close to

“9” will have the smallest weighting factor. The trends between the homeowners are similar, but the major two differences in the rankings occur between the environmental effect and initial investment attributes. Before performing the analysis it would appear that these differences should result in Homeowner 4 favoring distributed generation systems that have a lower initial investment while not heavily penalizing systems with GHG emissions when compared to the average homeowner. There are a number of small differences between the two homeowners and an EEA analysis, exactly like the one performed in Chapter 5, will provide a more complete understanding of how these differences will manifest in the DG selection.

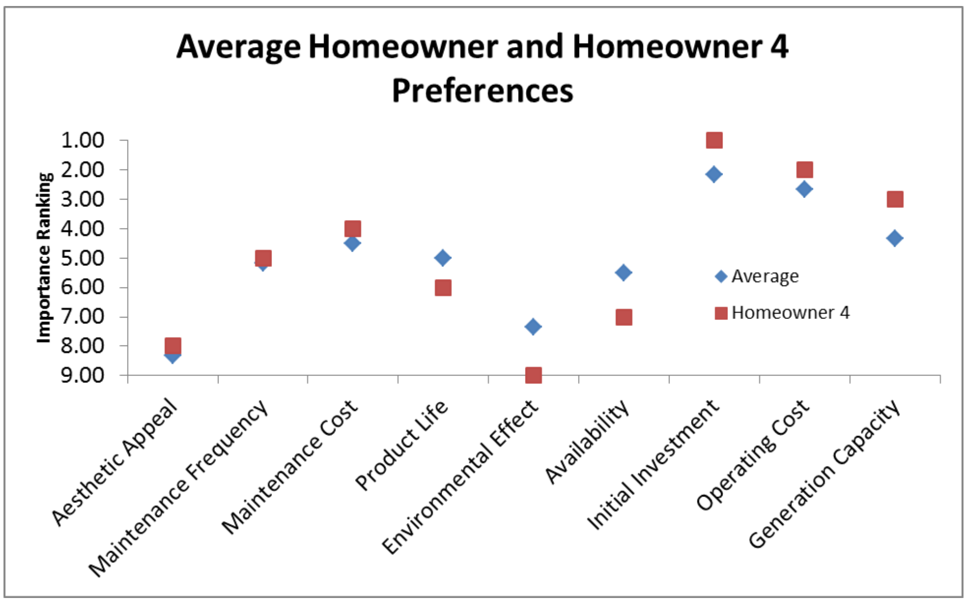


Figure 6-1: Comparison between average homeowner and Homeowner 4 preferences when selecting distributed generation systems.

The resulting tradespace for each of the epoch periods from Homeowner 4 have a similar trend as the average homeowner tradespace, in that heating oil; solar photovoltaic; and heat pump systems are near the Pareto frontier, but there are key differences in how the homeowner values each design. The most drastic difference in the tradespace is illustrated by comparing Figure 6-2 and Figure 6-3. The remaining epoch tradespace plots for Homeowner 4 can be found in Appendix B: Epoch Tradespaces for Homeowner 4 and 2.

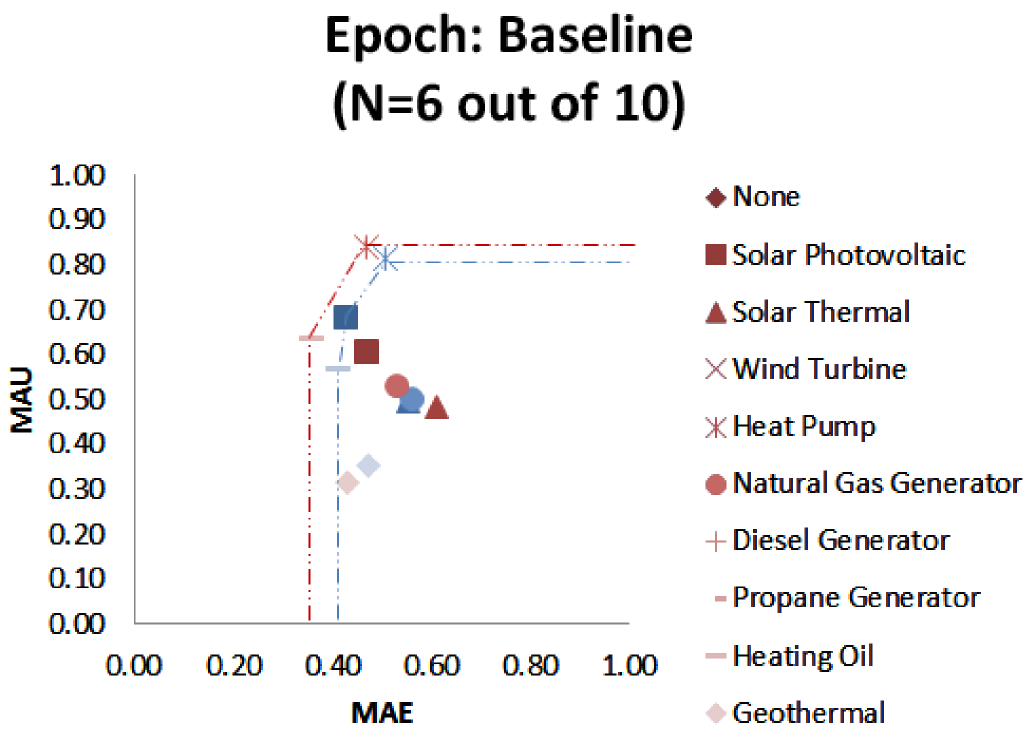


Figure 6-2: The difference in the baseline tradespace between the average homeowner (blue) and Homeowner 4 (red). The Pareto Frontier is represented by the appropriate dotted line.

From Figure 6-2 it is clear that Homeowner 4's criterion for selecting a distributed generation system results in the solar photovoltaic system moving away from the Pareto Frontier of the tradespace. Homeowner 4 would be more interested in non-renewable energy generation systems, as indicated by the increase in MAU value for natural gas, heating oil, and heat pump systems. After exploring one epoch tradespace it would appear that the homeowner is not interested in environmentally friendly solutions when compared to the average homeowner, but the epoch comparison in Figure 6-3 leads to a different conclusion. In this epoch, the decision criteria of Homeowner 4 results in a much higher MAU value for solar photovoltaic, along with an increased MAU value for geothermal systems, and reduced value for heat pump and heating oil systems. This leads to the solar photovoltaic system clearly becoming the solution the homeowner should select to meet their needs. Obviously there are differences between an individual homeowner and the average homeowner when evaluating single epochs, but does the difference continue when performing multi-epoch analysis?

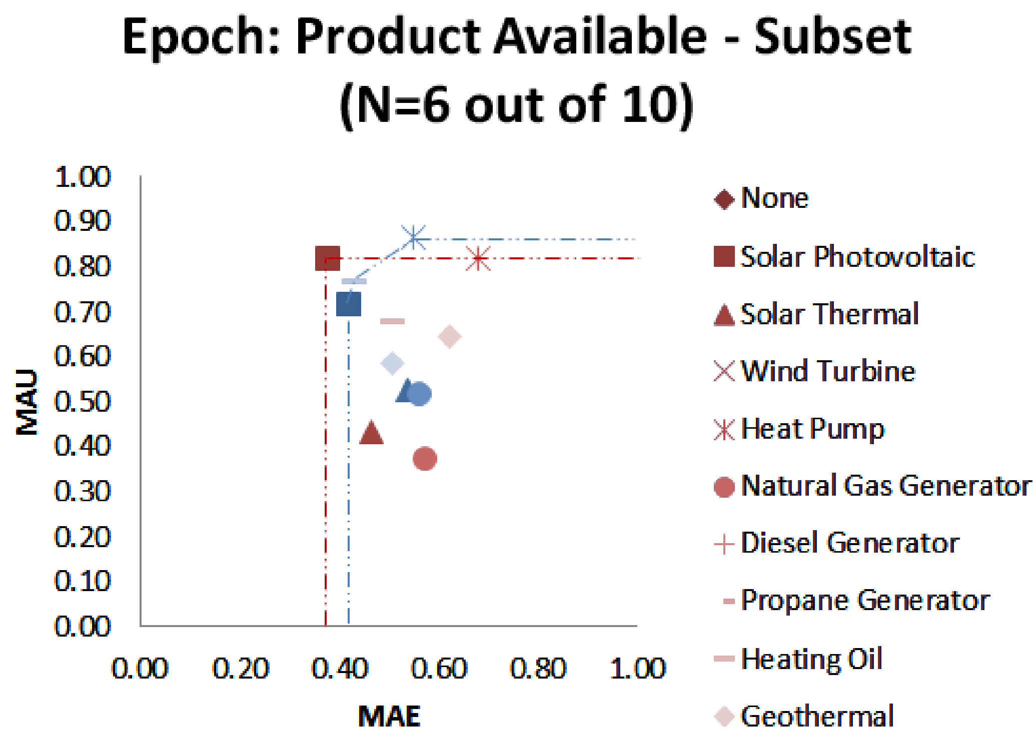


Figure 6-3: The difference in the product available tradespace between the average homeowner (blue) and Homeowner 4 (red). The Pareto Frontier is represented by the appropriate dotted line.

After performing the multi-epoch analysis using the same method utilized in section 5.2.6 – where the Pareto Frontier is calculated, followed by the NPT, and lastly the fNPT values – the complete epoch space is captured in Figure 6-4 where the values for Homeowner 4 are captured in red and compared against the average homeowner values in blue. The same three systems that dominated the tradespace for the average homeowner are present again for Homeowner 4, but the distance between the solar photovoltaic, heat pump, and heating oil systems is much shorter. Also the NPT value for each design does not vary significantly with the increasing fuzzy factor.

This behavior is different than for the average homeowner and the difference between the two sets of fNPT values are enumerated in Table 6-1.

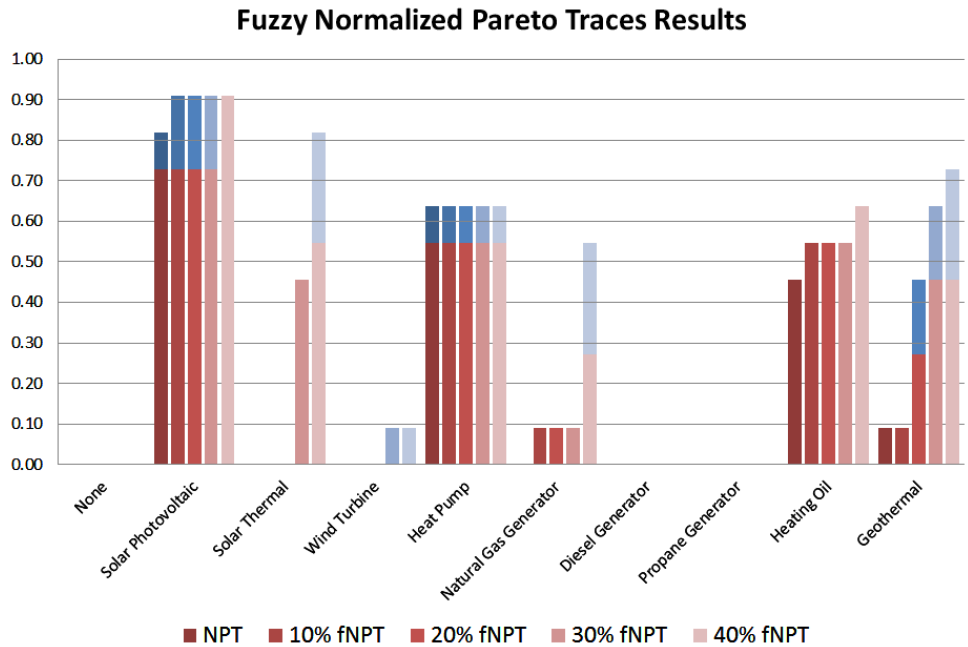


Figure 6-4: Trend of NPT for design choices after inclusion of "fuzzy" boundary for the average homeowner (blue) and Homeowner 4 (red). The results from Homeowner 4 are layered onto the average homeowner results.

The values in Table 6-1 are colored according to the value difference between Homeowner 4 and the average homeowner with blue shading indicating the average homeowner having a larger NPT value, while red shading indicates a larger value for Homeowner 4. A darker blue or red signifies a greater difference between the two homeowners. While this table and the corresponding graph demonstrate the reduction in NPT value separation between the solar photovoltaic system and the heat pump system, the selection of the solar photovoltaic system by the homeowner does not change. Even when the calculated uncertainty in accurately representing the homeowner decision making process is increased, by increasing the fuzzy factor, for the Normalized Pareto Trace, the same result occurs. This is just one of the analyses that Epoch-Era Analysis performs and it is important to evaluate the difference between Homeowner 4 and the average homeowner for the operational value metric used in the three single era analysis – environmental, cost, and hi-tech.

Design Choices	NPT	10% fNPT	20% fNPT	30% fNPT	40% fNPT
None	0.000	0.000	0.000	0.000	0.000
Solar Photovoltaic	-0.091	-0.182	-0.182	-0.182	0.000
Solar Thermal	0.000	0.000	0.000	0.364	-0.273
Wind Turbine	0.000	0.000	0.000	0.000	-0.091
Heat Pump	-0.091	-0.091	-0.091	-0.091	-0.091
Natural Gas Generator	0.000	0.091	0.091	0.091	-0.182
Diesel Generator	0.000	0.000	0.000	0.000	0.000
Propane Generator	0.000	0.000	0.000	0.000	0.000
Heating Oil	0.000	0.000	0.000	0.000	0.000
Geothermal	0.000	0.000	-0.091	-0.364	-0.273

Table 6-1: Difference in the fNPT values between Homeowner 4 and the "average" homeowner.

One of the first noticeable characteristics of the MAE and MAU values for the environmental era analysis of Homeowner 4 is that there is a significant amount of movement amongst the distributed generation systems. This is in contrast to Figure 6-5, only a few of the designs' MAE or MAU values indicate a noticeable changed. Since it was already difficult to discern which system to select based on the era MAE and MAU plots, the additional motion between the designs only complicates the analysis further. The operational value metric will be utilized to help clarify what distributed generation system the homeowner should select.

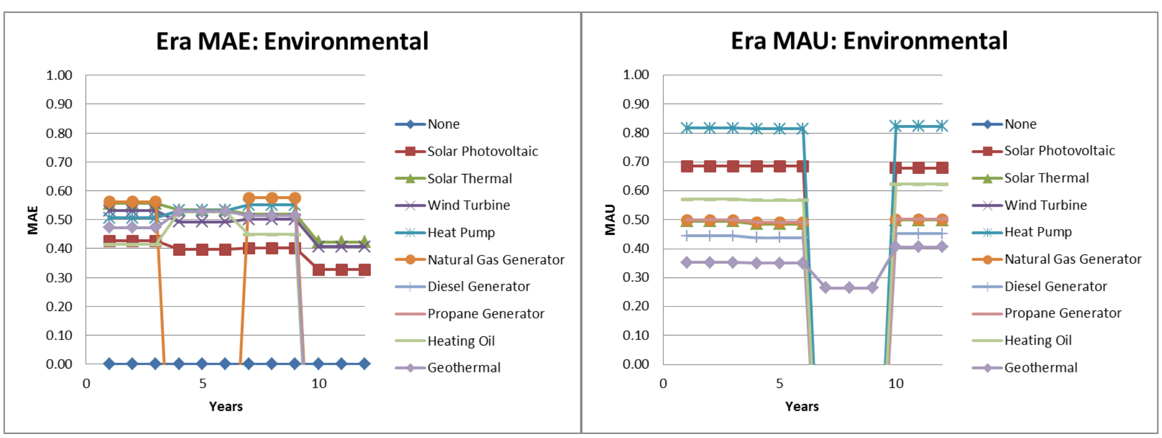


Figure 6-5: Environmental era MAE and MAU values for each design choice over 12 years for the average homeowner.

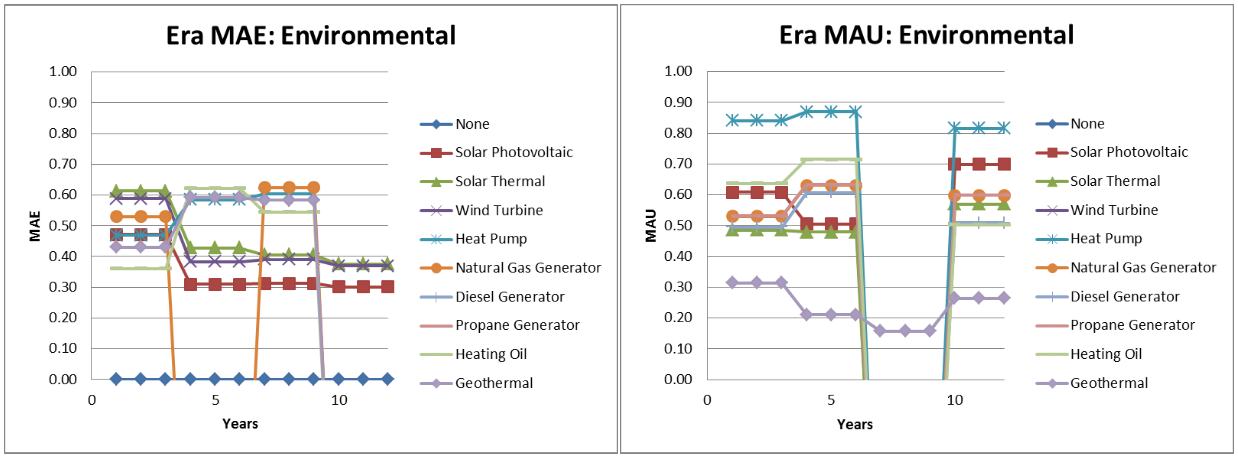


Figure 6-6: Environmental era MAE and MAU values for each design choice over 12 years for Homeowner 4.

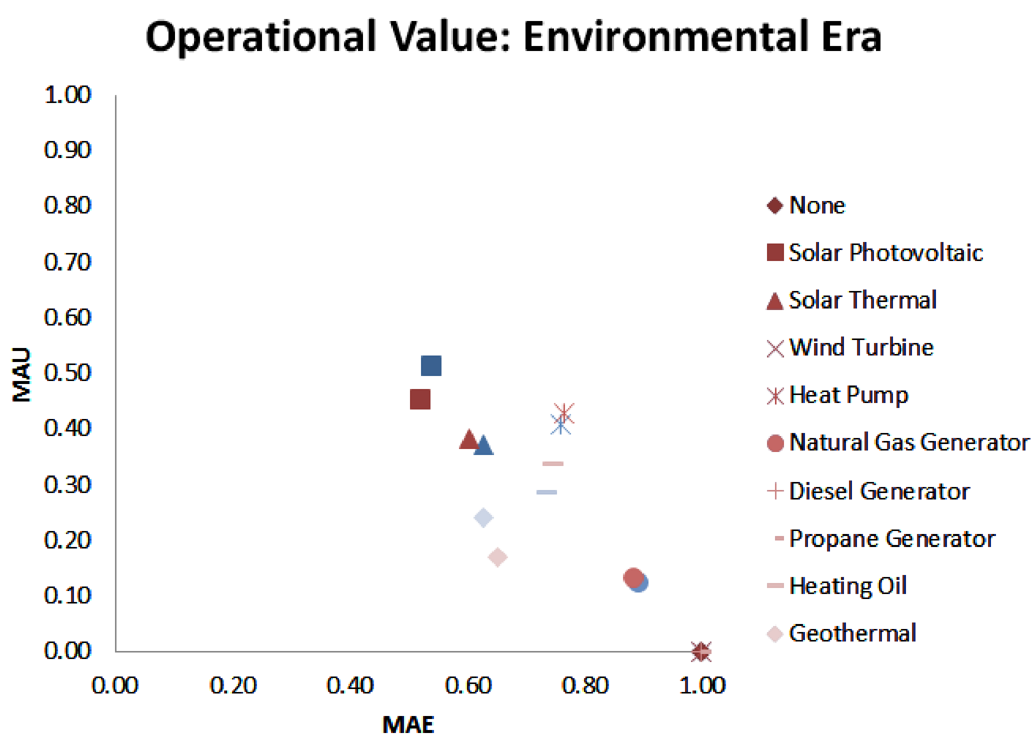


Figure 6-7: Comparison of the operational value metric across the environmental era for the average homeowner (blue) and Homeowner 4 (red).

Based on the method explained in section 5.2.8 for calculating the operational value of the systems, the tradespace that represents Homeowner 4's decision-making process for the environmental era is compared to the average homeowner's process in Figure 6-7. From the plot it is clear that the solar photovoltaic system is still the most likely selection by Homeowner 4. But, just like the multi-epoch analysis the separation between the photovoltaic system and a few distributed generation technologies has decreased. The solar thermal, heating oil and heat pump systems are close enough in MAU value that the uncertainty surrounding homeowner 4's decision-making process becomes a factor that would need to be carefully considered.

Operational Value - Environment Era						
Design Choices	Average Homeowner		Homeowner 4		Homeowner Difference	
	MAE	MAU	MAE	MAU	MAE	MAU
None	1.00	0.00	1.00	0.00	0.00	0.00
Solar Photovoltaic	0.54	0.51	0.52	0.45	-0.02	-0.06
Solar Thermal	0.63	0.37	0.60	0.38	-0.02	0.01
Wind Turbine	1.00	0.00	1.00	0.00	0.00	0.00
Heat Pump	0.76	0.41	0.76	0.43	0.00	0.02
Natural Gas Generator	0.89	0.12	0.88	0.13	-0.01	0.01
Diesel Generator	1.00	0.00	1.00	0.00	0.00	0.00
Propane Generator	1.00	0.00	1.00	0.00	0.00	0.00
Heating Oil	0.74	0.28	0.75	0.34	0.01	0.05
Geothermal	0.63	0.24	0.65	0.17	0.02	-0.07

Table 6-2: Difference in the operational value metric between Homeowner 4 and the "average" homeowner for the environmental era.

Figure 6-7 can also provide insight into how Homeowner 4 differs from the average homeowner when the differences in value between the two are presented in table form. Table 6-2, where no shading indicates little or no change and darker red signifies the largest change, shows that the major difference between the average homeowner and Homeowner 4 is how each value the utility of the distributed generation systems. Therefore, a system that focused on matching the criteria of Homeowner 4 may result in a scenario where the average homeowner does not select the same system for this era.

Keeping in mind the findings from the previous era, the MAE and MAU values for the cost era are calculated and displayed in Figure 6-9. The resulting Homeowner 4 values for the era move around substantial move than in the environmental era and even more so than the values for the average homeowner in Figure 5-15. Again, there are a number of different metrics that could be used to determine which system performs the best during the era and the operational value will be utilized.

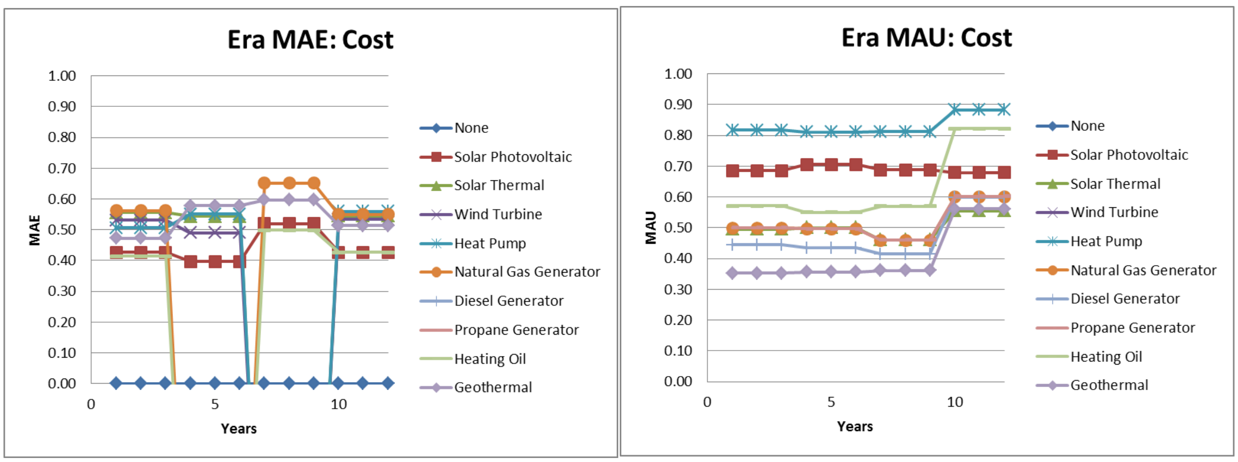


Figure 6-8: Cost era MAE and MAU values for each design choice over 12 years for the average homeowner.

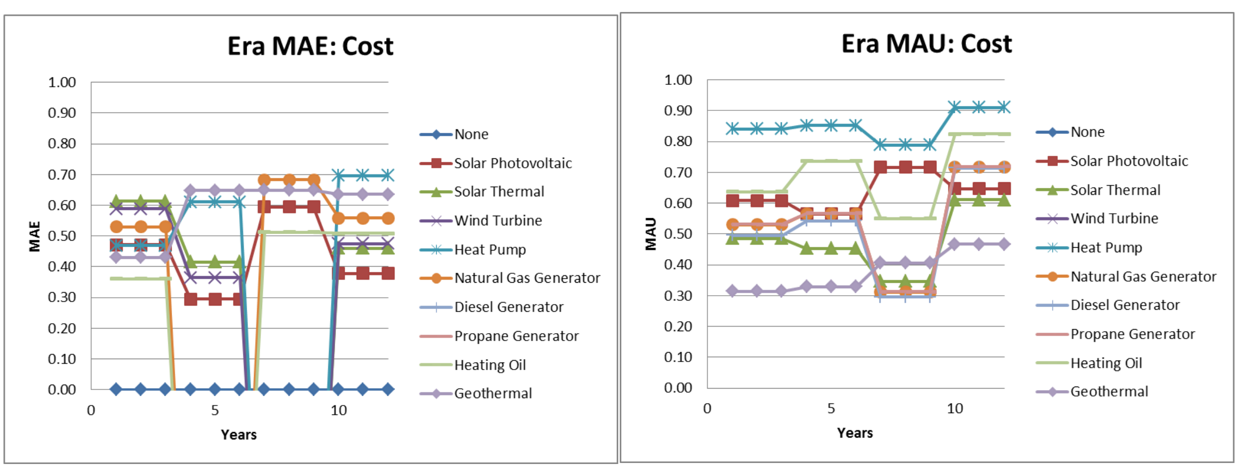


Figure 6-9: Cost era MAE and MAU values for each design choice over 12 years for Homeowner 4.

The operational value for the two homeowners are shown in Figure 6-10 with the most noticeable change being the increased MAU for the heat pump system and the decreased MAU value for the solar photovoltaic system. Additionally, the separation between the solar thermal and geothermal systems decreased to the point where they almost share the same MAE value. Unlike the previous era analysis where it was unclear whether Homeowner 4 may select a different system than the average homeowner, Homeowner 4 may select the heat pump to maximize their MAU value.

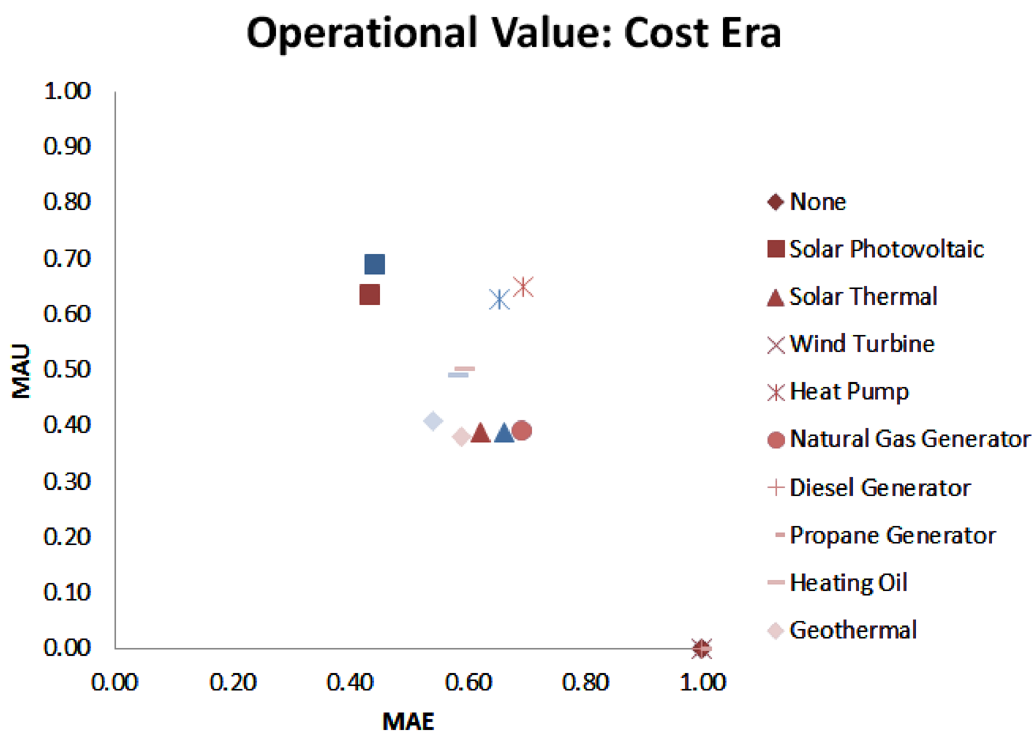


Figure 6-10: Comparison of the operational value metric across the cost era for the average homeowner (blue) and Homeowner 4 (red).

Beyond the visual changes in the plots of the operational value, there are also numerical differences between the two homeowners, which are shown in Table 6-3. In this era, there is no singular aspect that Homeowner 4 is biased toward since there is a shift in similar numbers for both the MAE and MAU values. The rationale for the heat pump now being selected by

Homeowner 4 is the result of the 0.08 value swing that occurred between the solar photovoltaic and heat pump systems. For the cost era, it is plausible that Homeowner 4 selects a different system than the average homeowner when they are focused on the utility of the systems.

Operational Value - Cost Era						
Design Choices	Average Homeowner		Homeowner 4		Homeowner Difference	
	MAE	MAU	MAE	MAU	MAE	MAU
None	1.00	0.00	1.00	0.00	0.00	0.00
Solar Photovoltaic	0.44	0.69	0.44	0.63	-0.01	-0.06
Solar Thermal	0.66	0.39	0.62	0.39	-0.04	0.00
Wind Turbine	1.00	0.00	1.00	0.00	0.00	0.00
Heat Pump	0.65	0.63	0.69	0.65	0.04	0.02
Natural Gas Generator	0.69	0.39	0.69	0.39	0.00	0.00
Diesel Generator	1.00	0.00	1.00	0.00	0.00	0.00
Propane Generator	1.00	0.00	1.00	0.00	0.00	0.00
Heating Oil	0.58	0.49	0.60	0.50	0.01	0.01
Geothermal	0.54	0.41	0.59	0.38	0.05	-0.03

Table 6-3: Difference in the operational value metric between Homeowner 4 and the "average" homeowner for the cost era.

The third and final era analysis is the hi-tech era shown in Figure 6-12 and of the three eras, these plots most closely match the same era plots for the average homeowner in Figure 6-11. Even with matching the majority of the characteristics, there are still recognizable differences. For instance, the MAE value for the heating oil system is much lower than in the average homeowner scenario. Additionally, the MAU value of the solar photovoltaic system is lower during the first two epochs, but has a smaller separation to the heat pump system in the third epoch.

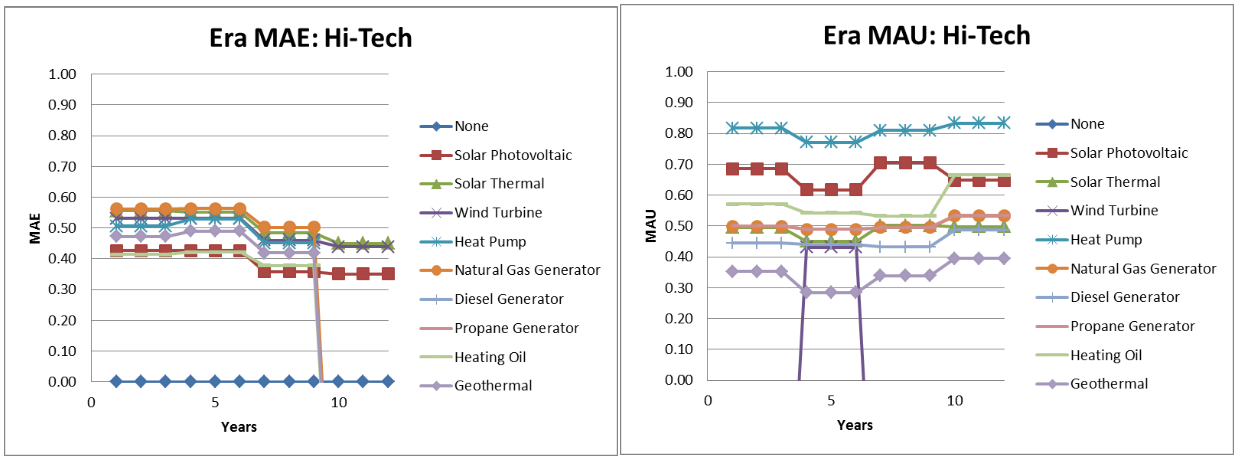


Figure 6-11: Hi-Tech era MAE and MAU values for each design choice over 12 years for the average homeowner.

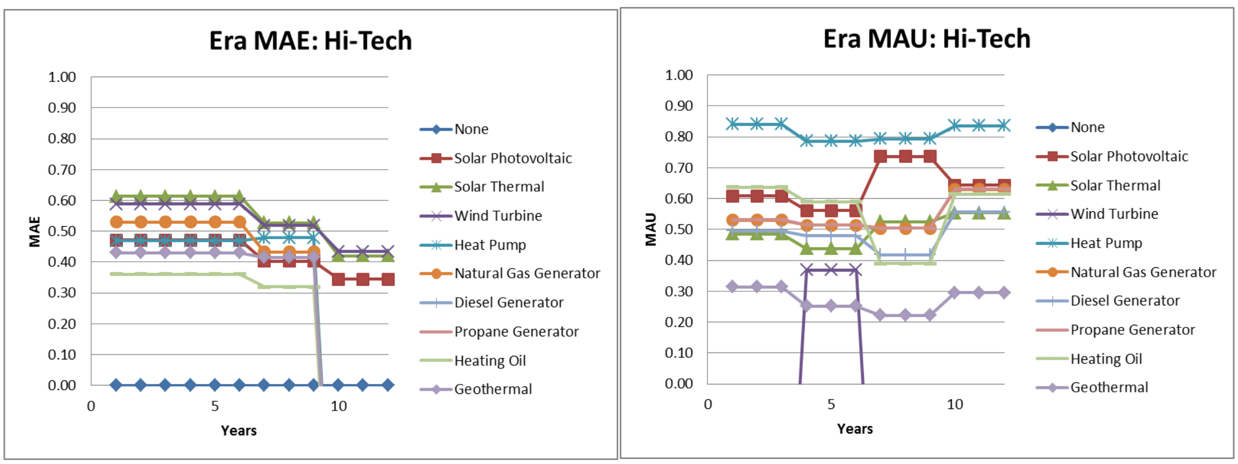


Figure 6-12: Hi-Tech era MAE and MAU values for each design choice over 12 years for Homeowner 4.

The noticeable changes found in Figure 6-12, also manifest in Figure 6-13 where the separation between the solar photovoltaic system and the other systems is reduced to similar levels that the environmental era experienced. Another aspect in the operational value metric that changed was in the MAU value separation between the geothermal system and the solar thermal system, where the separation increased and the geothermal system almost scored as low as the natural gas generation.

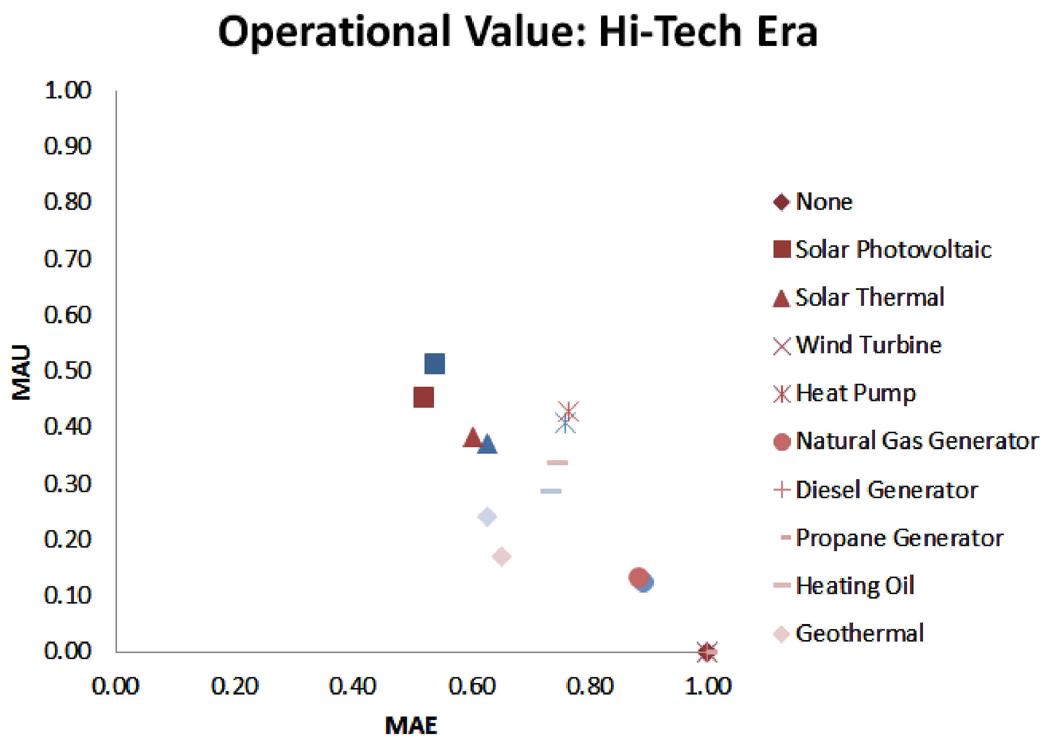


Figure 6-13: Comparison of the operational value metric across the hi-tech era for the average homeowner (blue) and Homeowner 4 (red).

Operational Value - Hi-Tech Era						
Design Choices	Average Homeowner		Homeowner 4		Homeowner Difference	
	MAE	MAU	MAE	MAU	MAE	MAU
None	1.00	0.00	1.00	0.00	0.00	0.00
Solar Photovoltaic	0.39	0.66	0.42	0.64	0.03	-0.03
Solar Thermal	0.51	0.49	0.54	0.50	0.03	0.01
Wind Turbine	0.88	0.11	0.90	0.09	0.01	-0.02
Heat Pump	0.62	0.60	0.60	0.61	-0.02	0.01
Natural Gas Generator	0.66	0.37	0.62	0.39	-0.03	0.02
Diesel Generator	1.00	0.00	1.00	0.00	0.00	0.00
Propane Generator	1.00	0.00	1.00	0.00	0.00	0.00
Heating Oil	0.55	0.41	0.51	0.40	-0.04	-0.01
Geothermal	0.60	0.24	0.57	0.20	-0.03	-0.05

Table 6-4: Difference in the operational value metric between Homeowner 4 and the "average" homeowner for the hi-tech era.

The differences from Figure 6-13 are recorded in Table 6-4 shows Homeowner 4 has a different set of decision-making criteria weighting factors for the MAE value than the average homeowner in the hi-tech era. For the third era Homeowner 4 focuses on a different aspect of the operational value, but there are no scenarios that involve small MAE separation values and would likely resort to the system with the highest utility value. Therefore, similar to the environmental era, if the level of uncertainty were changed then Homeowner 4 might select the heat pump instead of the solar photovoltaic since the MAU values are relatively close.

Homeowner 4 Selection						
Design Choices	Normalized Pareto Trace			Operational Value		
	0% Fuzzy	10% Fuzzy	20% Fuzzy	Environmental Era	Cost Era	Hi-Tech Era
None						
Solar Photovoltaic	1st	1st	1st	1st	1st	1st
Solar Thermal				2nd		2nd
Wind Turbine						
Heat Pump	2nd	2nd	2nd			
Natural Gas Generator						
Diesel Generator						
Propane Generator						
Heating Oil	3rd	2nd	2nd		2nd	
Geothermal				3rd	3rd	3rd

Table 6-5: Summary of Homeowner 4 distributed generation system selection through each analysis with 1st in green, 2nd in yellow, and 3rd in orange.

Combining the Homeowner 4 selections from the different analyses culminates the research presented in section 6.1 and is shown in Table 6-5. Similar to the summary table for the average homeowner, Homeowner 4 should select the solar photovoltaic distributed generation system. The second and third selection for the system are dependent on whether the homeowner prefers a system with a high NPT, in which case they would select the heat pump, or a system with a high operational value, in which case they would select the solar thermal or geothermal. According to this summary, selecting a system based on the average homeowner would result in Homeowner 4 receiving the system they would have selected and demonstrating that an individual analysis would not be prudent. To verify this conclusion, a second individual homeowner analysis will be performed.

6.2 Homeowner 2

The second homeowner case study applied to the EEA formulation from Chapter 5 is Homeowner 2, which will build on the previous case study and help determine whether average or individualized homeowner preferences should be used when selecting a DG system. Visible in Figure 6-14 is a significant difference between the individual attribute ranking of the average homeowner and Homeowner 2.

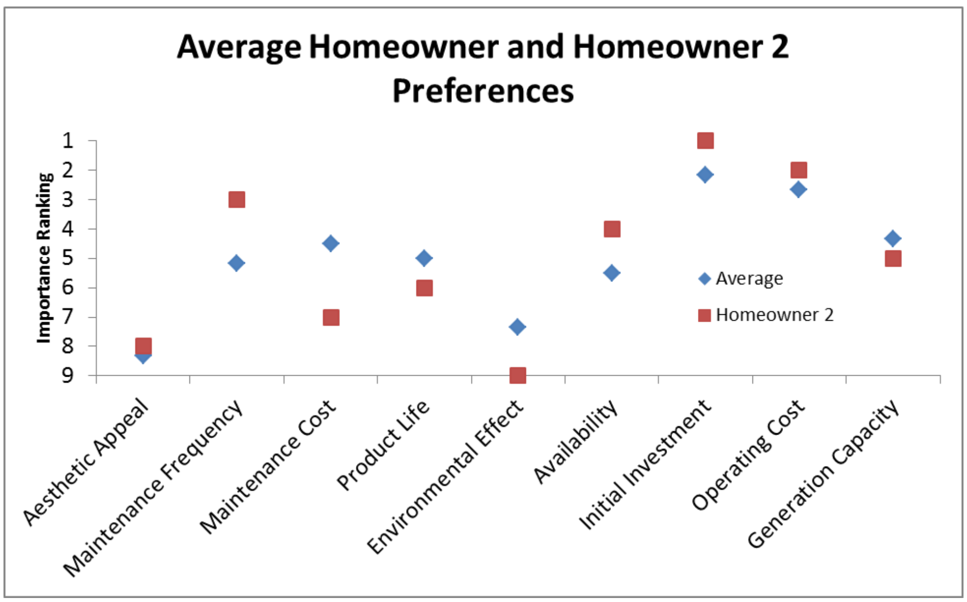


Figure 6-14: Comparison between average homeowner and Homeowner 2 preferences when selecting distributed generation systems.

The largest of the differences occurs in the maintenance frequency and maintenance cost attributes. Unlike the average homeowner, Homeowner 2 shifts the rankings of the two maintenance attributes in opposite directions, with the frequency becoming more heavily weighted than the maintenance cost. Similar to Homeowner 4, Homeowner 2 decreases the weight of the environmental effect and increases the weight of the system initial cost. This should result in the homeowner preferring a system with low maintenance frequency and has low initial costs. Performing the EEA formulation from Chapter 5 will help clarify the resulting difference, if any, between the average homeowner and Homeowner 2 DG system selection.

Unlike the previous homeowner that was described, Homeowner 2 has very few similarities with the average homeowner in the epoch tradespace. This is most clearly exemplified in the 50% cost of maintenance epoch period shown in Figure 6-15, where the solar photovoltaic system is no longer on the Pareto Frontier. Other major changes to the tradespace include the heating oil system moving onto the frontier and the MAE value of the heat pump system decreasing significantly.

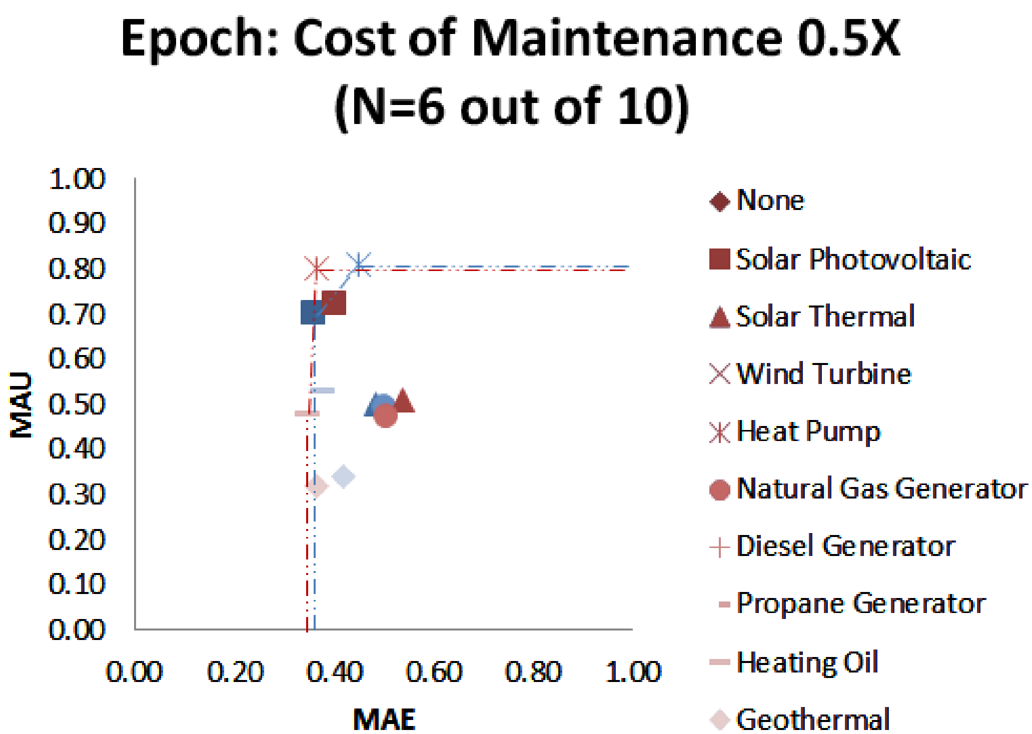


Figure 6-15: The difference in the 50% cost of maintenance tradespace between the average homeowner (blue) and Homeowner 2 (red). The Pareto Frontier is represented by the appropriate dotted line.

While Figure 6-15 is just a singular tradespace from the eleven that were generated, the neighbor agreeing tradespace shown in Figure 6-16 displays similar characteristics. The most prominent move is the heating oil system where the MAU value substantially increased and became a Pareto Optimal choice. Also increasing in MAU value was the heat pump system, although that increase was matched with an increase in MAE value. The final noticeable difference that affects the Pareto Optimal solutions is that the solar photovoltaic system shifted further from the Pareto Frontier. From these two epoch tradespaces, it is clear Homeowner 2 may have a different preference for their distributed generation system and the multi-epoch analysis will help determine whether that is the case or not.

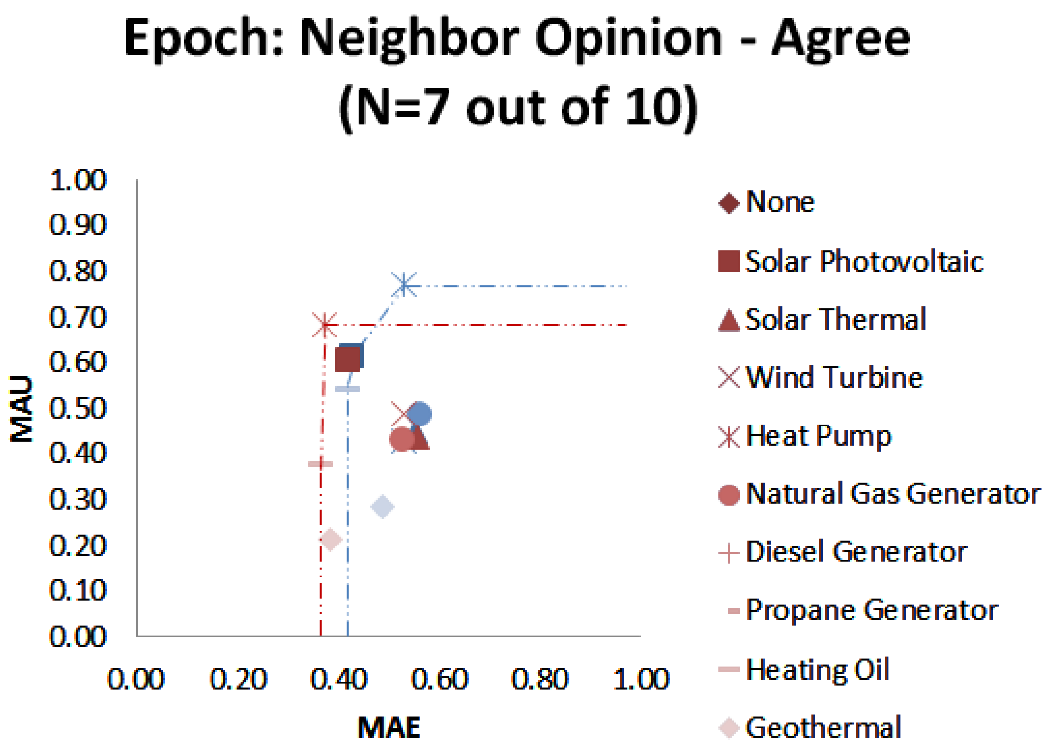


Figure 6-16: The difference in the neighbor agreeing tradespace between the average homeowner (blue) and Homeowner 2 (red). The Pareto Frontier is represented by the appropriate dotted line.

In short, the differences shown in Figure 6-15 and Figure 6-16 continue into the multi-epoch analysis. For the Normalized Prato Trace of Homeowner 2 in Figure 6-17, the solar photovoltaic system is no longer the highest valued choice and has been replaced by the heat pump and heating oil systems as higher ranked choices. Even when the fuzzy factor is increased, the solar photovoltaic system is still dominated until the factor reaches 20%. This could mean a few different things at this point – the homeowner is willing to compromise on value, the model uncertainty is accounted for, or there is an uncertainty of 20% in the MAE or MAU values generated for the homeowner – and future work should be used to determine the root cause. It should also be noted that the geothermal system becomes the primary selection for the homeowner for a 10% fNPT and is a viable secondary choice for the higher fuzzy factors. Clearly, this presents a different landscape of choices for Homeowner 2 than the average homeowner and this difference is captured in Table 6-6.

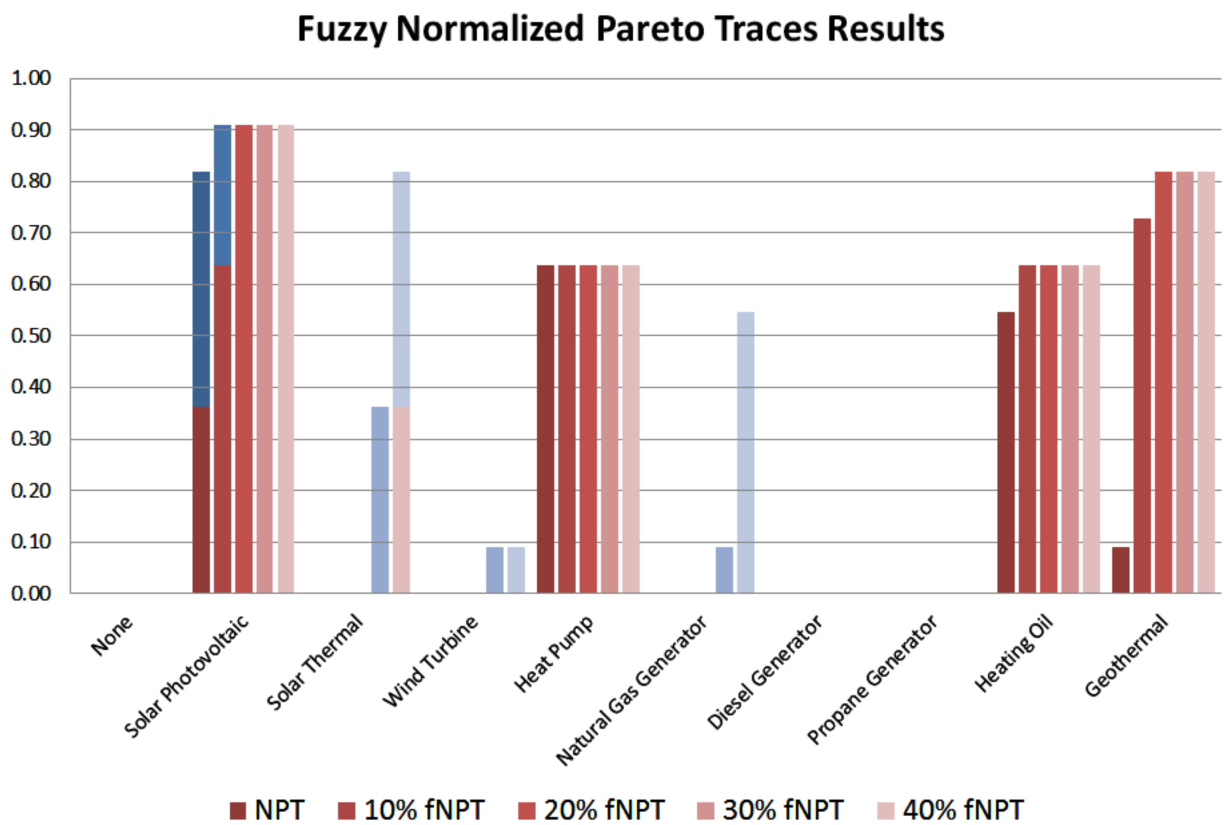


Figure 6-17: Trend of NPT for design choices after inclusion of "fuzzy" boundary for the average homeowner (blue) and Homeowner 2 (red).

Design Choices	NPT	10% fNPT	20% fNPT	30% fNPT	40% fNPT
None	0.000	0.000	0.000	0.000	0.000
Solar Photovoltaic	-0.455	-0.273	-0.182	0.000	0.000
Solar Thermal	0.000	0.000	0.000	0.000	-0.545
Wind Turbine	0.000	0.000	0.000	0.000	-0.091
Heat Pump	0.000	0.000	0.000	0.000	0.000
Natural Gas Generator	0.000	0.000	0.000	0.000	-0.364
Diesel Generator	0.000	0.000	0.000	0.000	0.000
Propane Generator	0.000	0.000	0.000	0.000	0.000
Heating Oil	0.091	0.091	0.091	0.091	0.000
Geothermal	0.000	0.636	0.545	0.182	0.091

Table 6-6: Difference in the fNPT values between Homeowner 2 and the "average" homeowner.

As noted in the previous paragraph, the NPT of the solar photovoltaic system decreased sharply for Homeowner 2 in comparison to the average homeowner while there was a small increase in the NPT of the heating oil system. But the most dramatic change in the multi-epoch analysis is exemplified in the 10% fNPT column where the geothermal system increased its presence on the Pareto Frontier for nearly 64% of the epoch periods while the photovoltaic system saw a decrease of around 27%. Given this information, it would seem that the solar photovoltaic system is would not be selected by Homeowner 2, a difference from the actions of the average homeowner, but the era analysis paints a different image.

Although the multi-epoch analysis demonstrates a difference between the average homeowner and Homeowner 2, the environmental era analysis from Figure 6-19 does not share the same story. There plots are similar in shape and location to the era analysis from Figure 5-12, with the exception of a few systems. For example, the geothermal system has an increased MAU value in the last epoch of the era while also having a decreased MAE value throughout each epoch period. Also, the solar photovoltaic system MAU value increased in for each epoch period but on the whole the other systems appeared to remain similar. These changes can be verified through the operational metric comparison in Figure 6-20.

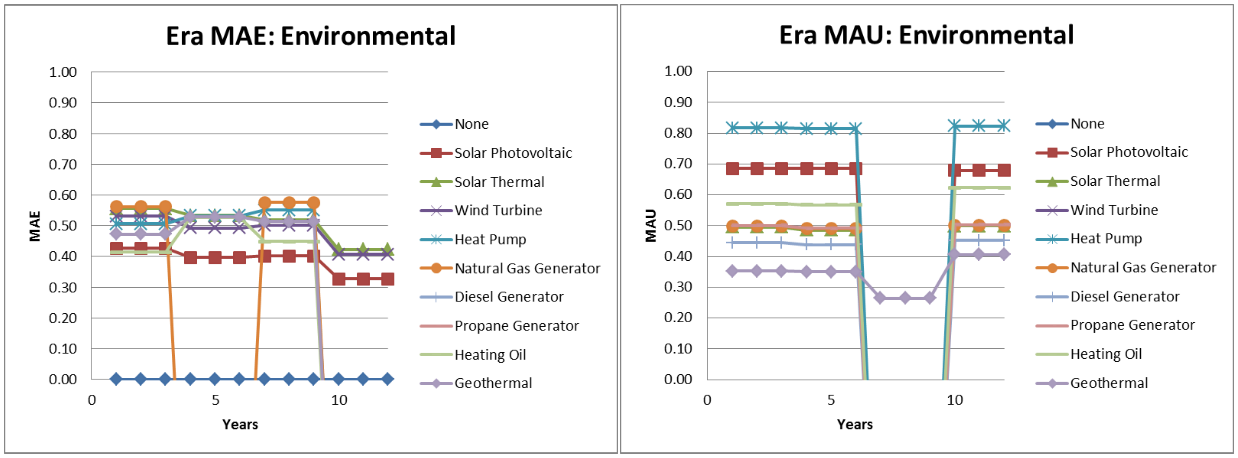


Figure 6-18: Environmental era MAE and MAU values for each design choice over 12 years for the average homeowner.

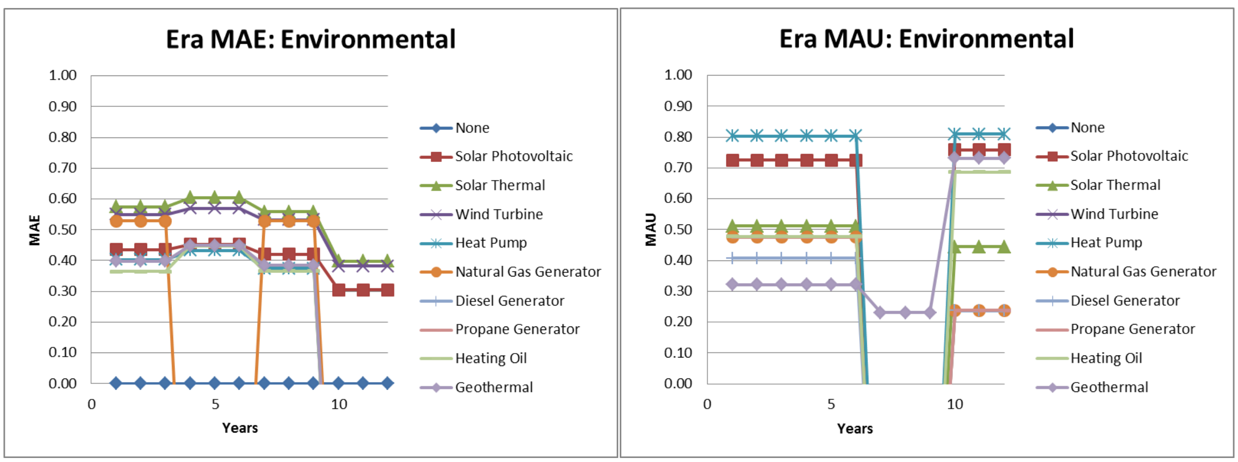


Figure 6-19: Environmental era MAE and MAU values for each design choice over 12 years for Homeowner 2.

As one would suspect, there is little difference between the operational values between the average homeowner and Homeowner 2 in the environmental era analysis. One of the differences is that the geothermal system is much closer to the Pareto Optimal for Homeowner 2, which aligns with the findings from the multi-epoch analysis. The other change that affects which system Homeowner 2 may select is that the separation between the solar photovoltaic system and the other choices increases for Homeowner 2. A more clear visualization of the value changes can be seen in Table 6-7.

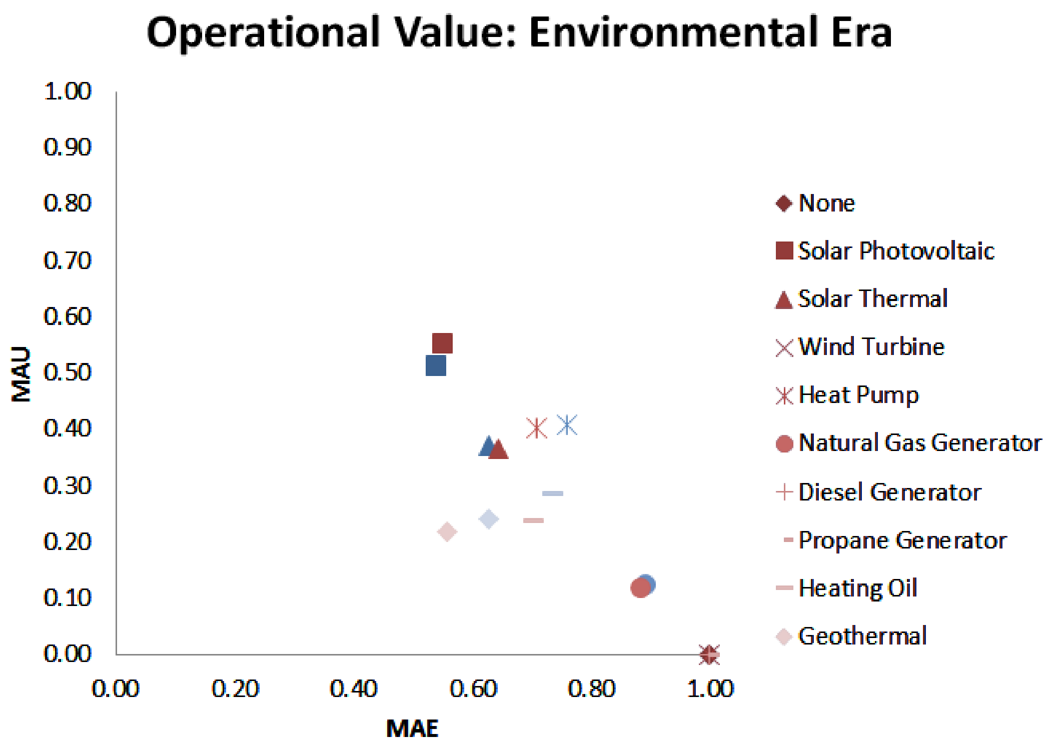


Figure 6-20: Comparison of the operational value metric across the environmental era for the average homeowner (blue) and Homeowner 2 (red).

Operational Value - Environment Era						
Design Choices	Average Homeowner		Homeowner 2		Homeowner Difference	
	MAE	MAU	MAE	MAU	MAE	MAU
None	1.00	0.00	1.00	0.00	0.00	0.00
Solar Photovoltaic	0.54	0.51	0.55	0.55	0.01	0.04
Solar Thermal	0.63	0.37	0.64	0.37	0.02	0.00
Wind Turbine	1.00	0.00	1.00	0.00	0.00	0.00
Heat Pump	0.76	0.41	0.71	0.40	-0.05	-0.01
Natural Gas Generator	0.89	0.12	0.88	0.12	-0.01	-0.01
Diesel Generator	1.00	0.00	1.00	0.00	0.00	0.00
Propane Generator	1.00	0.00	1.00	0.00	0.00	0.00
Heating Oil	0.74	0.28	0.70	0.24	-0.03	-0.05
Geothermal	0.63	0.24	0.56	0.22	-0.07	-0.02

Table 6-7: Difference in the operational value metric between Homeowner 2 and the "average" homeowner for the environmental era.

As previously discussed the biggest mover is the geothermal system with its reduction in the MAE value. Also clear in the table is the increase in MAU value for the solar photovoltaic system that results in the growing separation from the other designs. When these changes are coupled with the multi-epoch analysis, it would seem to indicate Homeowner 2 might select the geothermal system instead of the average homeowner selection of the solar photovoltaic system. Before coming to a conclusion, that other two eras need to be analyzed, the results of the cost era analysis are provided in Figure 6-22.

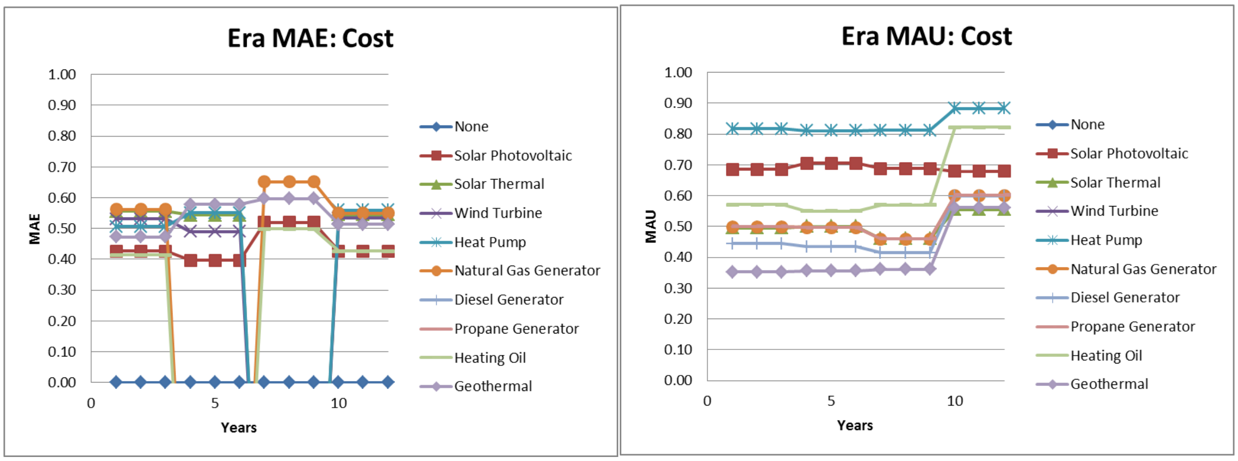


Figure 6-21: Cost era MAE and MAU values for each design choice over 12 years for the average homeowner.

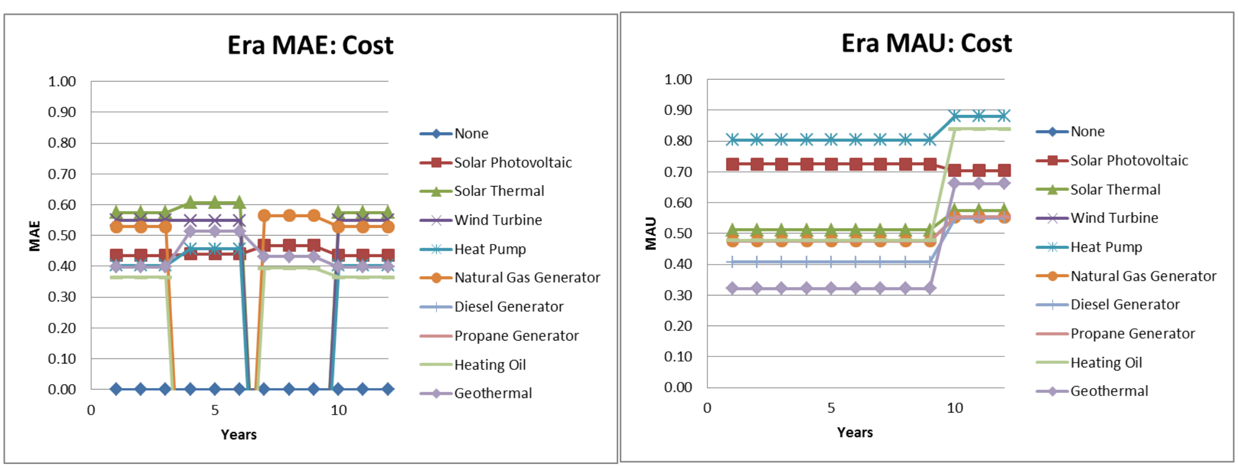


Figure 6-22: Cost era MAE and MAU values for each design choice over 12 years for Homeowner 2.

The most noticeable finding from the era analysis is that the system MAE values are more closely packed than previously and there is not a system that dominates the lowest MAE value through the era. Another interesting trend in the plot is that there is a significant rise in geothermal and heating oil system MAU values during the last epoch, while the MAU value of the solar photovoltaic system decreases slightly. These noticeable trends in the era analysis also manifest themselves in the operational value metric for the distributed generation systems in Figure 6-23.

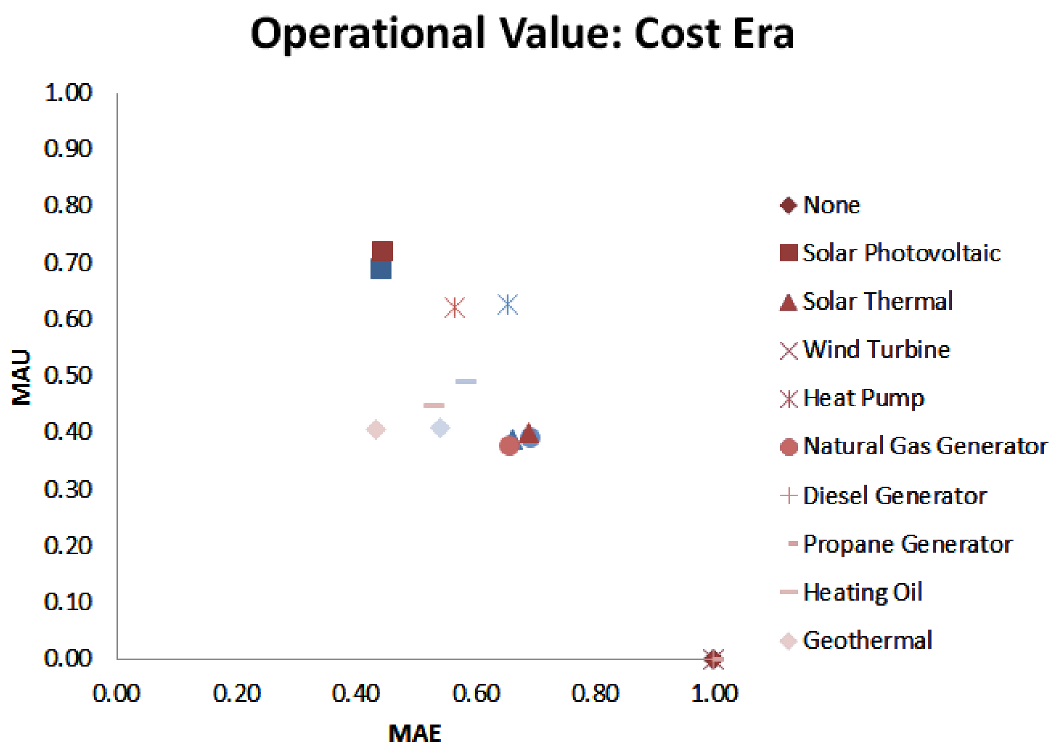


Figure 6-23: Comparison of the operational value metric across the cost era for the average homeowner (blue) and Homeowner 2 (red).

Compared to the average homeowner, the geothermal system has a reduced MAE value for Homeowner 2 and the solar photovoltaic system has an increased MAU value, which aligns with trends noticed in Figure 6-22. While there are other changes in the operational value metric – including the switching in relative position between the natural gas and solar thermal systems –

the geothermal and solar photovoltaic system competition to be selected by Homeowner 2 is the most important. These changes are detailed in Table 6-8

Operational Value - Cost Era						
Design Choices	Average Homeowner		Homeowner 2		Homeowner Difference	
	MAE	MAU	MAE	MAU	MAE	MAU
None	1.00	0.00	1.00	0.00	0.00	0.00
Solar Photovoltaic	0.44	0.69	0.44	0.72	0.00	0.03
Solar Thermal	0.66	0.39	0.69	0.40	0.03	0.01
Wind Turbine	1.00	0.00	1.00	0.00	0.00	0.00
Heat Pump	0.65	0.63	0.57	0.62	-0.09	-0.01
Natural Gas Generator	0.69	0.39	0.66	0.38	-0.04	-0.01
Diesel Generator	1.00	0.00	1.00	0.00	0.00	0.00
Propane Generator	1.00	0.00	1.00	0.00	0.00	0.00
Heating Oil	0.58	0.49	0.53	0.45	-0.05	-0.04
Geothermal	0.54	0.41	0.44	0.41	-0.11	0.00

Table 6-8: Difference in the operational value metric between Homeowner 2 and the "average" homeowner for the cost era.

As was in the case in the environmental era analysis, the geothermal system MAE value change is the largest between the average homeowner and Homeowner 2 for the cost era operational value metric. It should be noted that the heat pump also has a significant reduction in its MAE value, but it still is not located on the Pareto Frontier of the operational value metric. In this era, the geothermal system has a lower MAE than the solar photovoltaic system, which may lead a more expense conscience homeowner to select that system, even though the solar photovoltaic system has a significantly higher MAU value.

The final era analysis for Homeowner 2 is the hi-tech era. The hi-tech era, shown in Figure 6-25, has a number of instances where the relative position of the distributed generation MAU value changes across the epoch space. Similar to the last epoch in the cost era, the separation between the geothermal and solar photovoltaic system is much smaller for Homeowner 2 than the average homeowner plot in Figure 5-18. On the other hand, the absolute MAE values for the systems do not change across the epochs and the geothermal system has the lowest MAE value, for the first time in the research. This analysis results in the operational value plots in Figure 6-26.

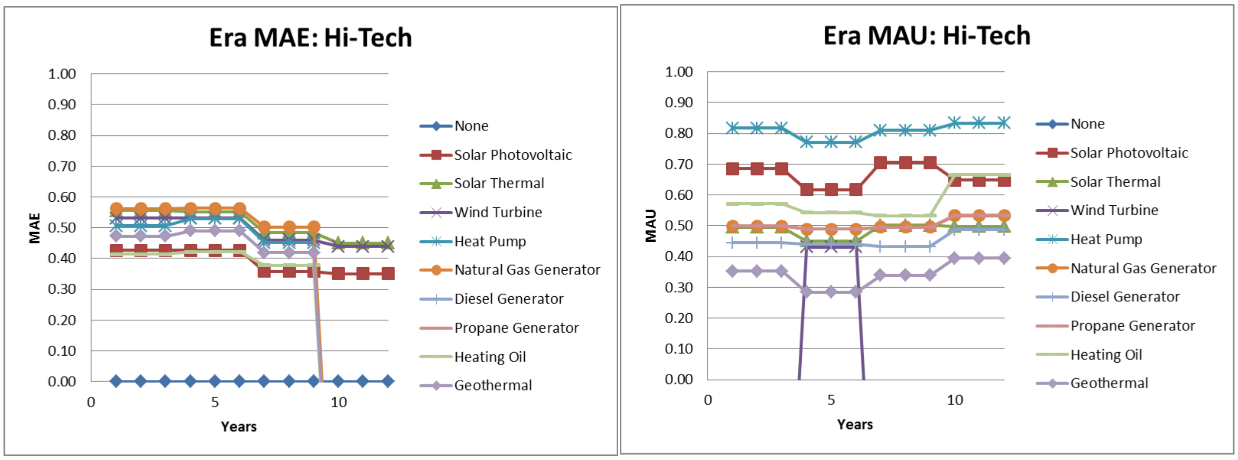


Figure 6-24: Hi-Tech era MAE and MAU values for each design choice over 12 years for the average homeowner.

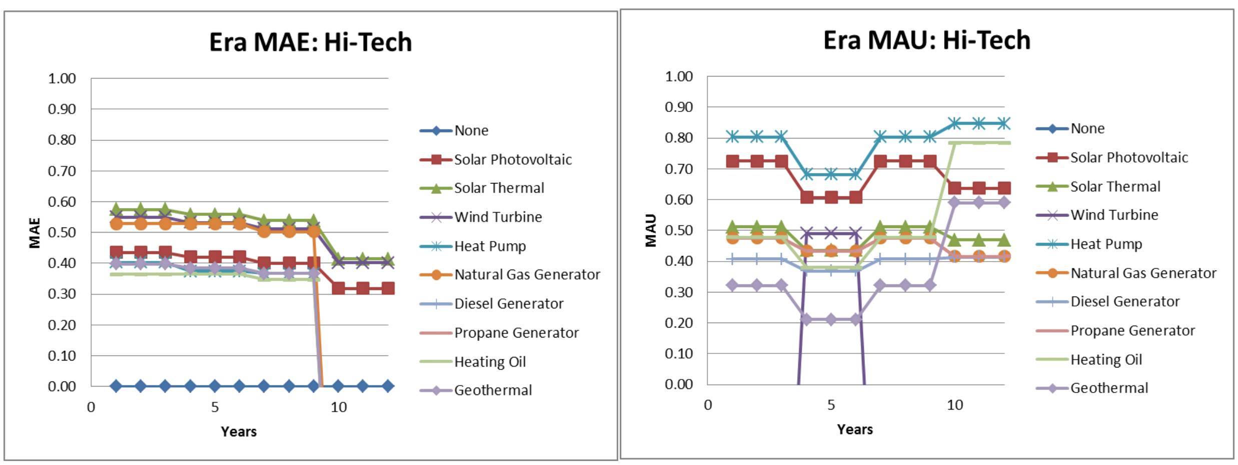


Figure 6-25: Hi-Tech era MAE and MAU values for each design choice over 12 years for Homeowner 2.

As was the case in the other two era analysis comparisons between the average homeowner and Homeowner 2, the hi-tech era analysis shows the geothermal systems is very close to having the same MAE value as the solar photovoltaic system and the solar photovoltaic system's MAU value increased. Additionally, the MAE value for the heat pump system decreased, but it is still dominated by the solar photovoltaic and geothermal systems. The numerical changes for all the systems are presented in Table 6-9.

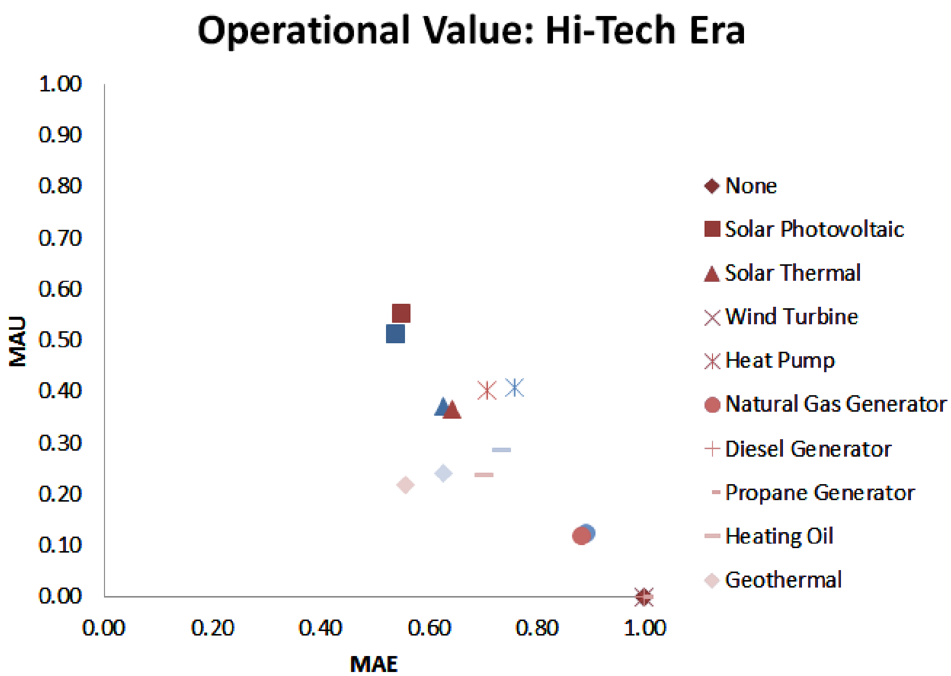


Figure 6-26: Comparison of the operational value metric across the hi-tech era for the average homeowner (blue) and Homeowner 2 (red).

Operational Value - Hi-Tech Era						
Design Choices	Average Homeowner		Homeowner 2		Homeowner Difference	
	MAE	MAU	MAE	MAU	MAE	MAU
None	1.00	0.00	1.00	0.00	0.00	0.00
Solar Photovoltaic	0.39	0.66	0.39	0.67	0.00	0.01
Solar Thermal	0.51	0.49	0.52	0.48	0.01	0.00
Wind Turbine	0.88	0.11	0.88	0.12	0.00	0.01
Heat Pump	0.62	0.60	0.54	0.57	-0.09	-0.03
Natural Gas Generator	0.66	0.37	0.64	0.35	-0.02	-0.03
Diesel Generator	1.00	0.00	1.00	0.00	0.00	0.00
Propane Generator	1.00	0.00	1.00	0.00	0.00	0.00
Heating Oil	0.55	0.41	0.52	0.33	-0.03	-0.08
Geothermal	0.60	0.24	0.54	0.21	-0.06	-0.03

Table 6-9: Difference in the operational value metric between Homeowner 2 and the "average" homeowner for the hi-tech era.

The largest change in value for a system was the heat pump MAE value and the geothermal system had the second largest MAE change – as noted in the previous paragraph – which resulted in the geothermal system competing with the solar photovoltaic system for the Homeowner 2 distributed generation system selection. This battle between the two systems is a far cry from the average homeowner selection of the solar photovoltaic system without hesitation and persisted over the three era analyses. Therefore, it would appear that Homeowner 2 might make a different selection than the average homeowner and choose to install geothermal.

Homeowner 2 Selection						
	Normalized Pareto Trace			Operational Value		
Design Choices	0% Fuzzy	10% Fuzzy	20% Fuzzy	Environmental Era	Cost Era	Hi-Tech Era
None						
Solar Photovoltaic	3rd	2nd	1st	1st	2nd	1st
Solar Thermal				3rd		3rd
Wind Turbine						
Heat Pump	1st	2nd	3rd			
Natural Gas Generator						
Diesel Generator						
Propane Generator						
Heating Oil	2nd	2nd	3rd		3rd	
Geothermal		1st	2nd	2nd	1st	2nd

Table 6-10: Summary of Homeowner 2 distributed generation system selection through each analysis with 1st in green, 2nd in yellow, and 3rd in orange.

Combining the Homeowner 2 selections from the different analyses culminates the research presented in section 6.2 and is shown in Table 6-10. Unlike the summary table for the average homeowner and Homeowner 4 where the homeowner should select the solar photovoltaic DG system, it is not immediately clear what distributed generation system Homeowner 2 should select. The summary table does provide the homeowner with a guide that can help them select the correct system to match their concerns about the future. For instance, if they are most concerned with the Cost Era, then they should select the geothermal system and likewise for the other scenarios. Therefore, this individual analysis for the homeowner would likely result in individualized guides to help homeowners understand the different possible scenarios and help them sort through the numerous DG systems available to them.

6.3 Summary

After performing the two individual homeowner analyses and comparing the results to the average homeowner result from the Epoch-Era Analysis formulation, it became clear from the average of the group's selection criteria may not match the selection that the individual homeowner would have made. Shown in Figure 6-27 is the attribute rankings for all interviewed homeowners, with the average homeowner illustrated by the black marker.

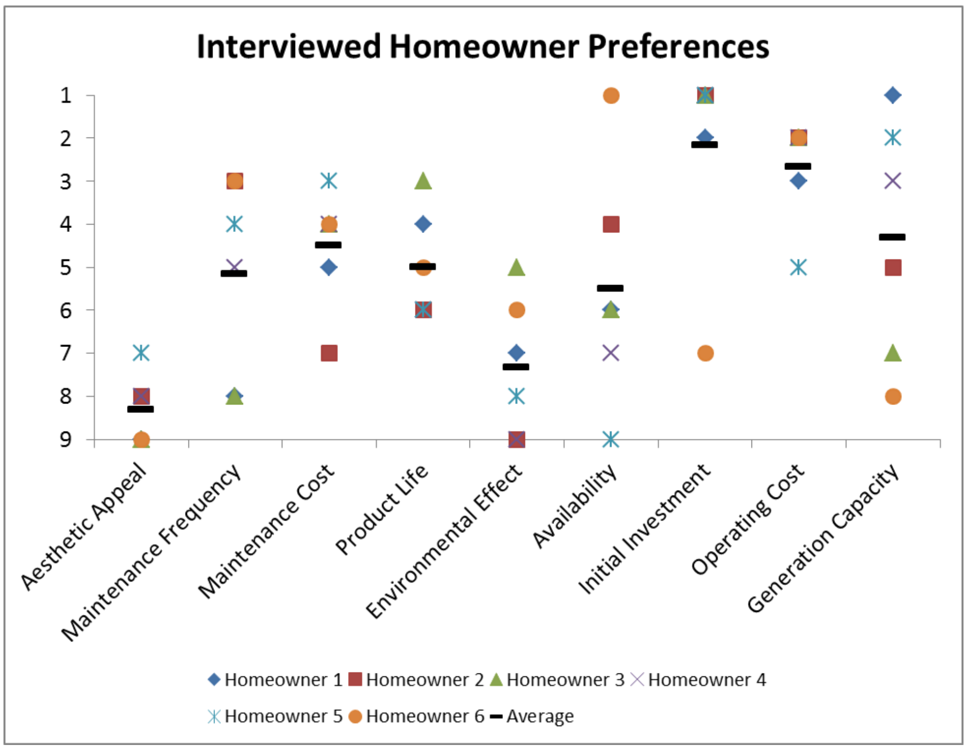


Figure 6-27: All interviewed homeowner preferences when selecting distributed generation systems compared to the average "homeowner".

According to the figure, there are multiple homeowners that have even larger differences from the average homeowner attribute ranking than the two homeowners that were analyzed in this chapter (i.e. Homeowner 5). These differences would have likely resulted in a number of instances where the analysis for the individual homeowner would have likely pointed to a different distributed generation system than the average homeowner selection did. Based on the attribute rankings of the homeowners that were analyzed, the analysis should be performed on an individualized basis, but the overall of the analysis should be considered as well.

Dsitrubted Generation Selection							
Homeowner	Rank	Normalized Pareto Trace			Operational Value		
		0% Fuzzy	10% Fuzzy	20% Fuzzy	Environmental Era	Cost Era	Hi-Tech Era
Average Homeowner	1st	Solar PV	Solar PV	Solar PV	Solar PV	Solar PV	Solar PV
	2nd	Heat Pump	Heat Pump	Heat Pump	Solar Thermal	Geothermal	Solar Thermal
	3rd	Heating Oil	Heating Oil	Heating Oil	Geothermal	Heating Oil	Geothermal
Homeowner 4	1st	Solar PV	Solar PV	Solar PV	Solar PV	Solar PV	Solar PV
	2nd	Heat Pump	Heat Pump	Heat Pump	Solar Thermal	Heating Oil	Solar Thermal
	3rd	Heating Oil	Heating Oil	Heating Oil	Geothermal	Geothermal	Geothermal
Homeowner 2	1st	Heat Pump	Geothermal	Solar PV	Solar PV	Geothermal	Solar PV
	2nd	Heating Oil	Heat Pump	Geothermal	Geothermal	Solar PV	Geothermal
	3rd	Solar PV	Heating Oil	Heat Pump	Solar Thermal	Heating Oil	Solar Thermal

Table 6-11: Summary of the top three selections for the average homeowner, Homeowner 2, and Homeowner 4 across the different analyses with 1st in green, 2nd in yellow, and 3rd in orange.

Table 6-11 combines the overall results of the average homeowner, Homeowner 4, and Homeowner 2 epoch-era analysis. This table clearly demonstrates the difference in system DG system selection among the homeowners, even in the case of homeowner 4 who had one of the most similar attribute rankings to the average of homeowners interviewed. The best example of the difference between the homeowners is from the Cost Era, where each homeowner has a different ordering for their DG selection. Therefore, according to this research the analysis output should be an individualized guide for the homeowner. This individualized guide would provide the homeowner with the information necessary to make the best selection for them instead of the selection that the average homeowner for their area might select.

It should be noted, the sample size of homeowners was not large enough to provide a completely accurate representation of the demographic, but larger samples sizes might exacerbate the differences between the average and individual homeowner. This would likely be the case since the difference between the systems in the tradespaces is small and a change in the homeowner criteria results in a rather dramatic shift in the MAE and MAU values of the systems. Still, this analysis indicates that an individual homeowner analysis may be necessary when the homeowner is determining which distributed generation systems to select.

Chapter 7 Conclusions, Additional Thoughts, and Future Work

After performing the research into using an Epoch-Era Analysis formulation to assist the homeowner in deciding which distributed generation system, there was a wealth of information generated. This ranged from how to apply a method typically used for space and satellite-based applications and utilize it in different industries to determining the value of aggregate and individualized analysis. Moreover, there were a number of surprises and additional questions raised by the research which enables a conversation about the work and how it may be developed in the future. Lastly, there were a number of opportunities for the research to be continued to further enhance the results provided herein and these areas are discussed.

7.1 Conclusions

The beginning of the energy grid's shift from a traditional transmission/distribution grid to a more local/distributed approach presents homeowners with a number of choices for generating their own power. These choices have different advantages and disadvantages that are often difficult to compare to one another. This situation has left the homeowner without a clear understanding of which distributed generation system is best suited to match their needs. Ultimately, homeowners are looking for a tool or method for comparing the different systems that will provide them an answer regarding which system they should select.

From this homeowner need, two primary thesis questions were generation that guided the research and results provided in the previous sections. The answers to the thesis questions, shown below, will be summarized in sections 7.1.1 and 7.1.2.

- Given an Epoch-Era Analysis formulation, which of the distributed generation power system choices available to the southern California homeowner provides the highest value across the greatest number of epochs and in a select number of potential era scenarios?

- Using the same Epoch-Era Analysis formulation, how does the highest value distributed generation choice for randomly selected homeowners differ from that of the highest value for the homeowner subset average?

7.1.1 **EEA Formulation for DG Selection**

Epoch-Era Analysis (EEA) formulations have been used for a number of years on satellite and space based applications and there are a number of similarities between those problems and the one of the homeowner. Essentially, both have to determine the best solution from a group of alternatives when considering the stakeholder needs and how the situation that the system operates in changes over time. With some slight modification to the EEA formulation, it appeared that the method would work with the homeowner distributed generation system selection problem.

San Jose, CA homeowners were interviewed to determine their selection criteria when evaluation distributed generation system. They were also consulted to select the potential distributed generation systems they were considering and this information was later supplemented with data from federal websites. With the basic inputs into the methodology gathered, the method was applied to the “average” homeowner. This average homeowner was meant to act a representative homeowner for the entire sample and was calculated by averaging all the responses to the interviews with homeowners in the region.

The results from the analysis were that all homeowners should select the solar photovoltaic system because it performed the best in the multi-epoch and single era analyses that were considered as part of the method. Solar photovoltaic is currently the system prescribed to all homeowners and partially validates the results of the analysis. This result demonstrates that an EEA formulation could be applied to a non-space based problem and still assist the key stakeholder, in this case the homeowner, in finding a solution to a complex and time varying problem.

7.1.2 **Benefit of Individual Homeowner Analysis**

Since all homeowners do not act the same and each have a wide range of criteria they use when selecting a distributed generation system, the analysis was re-run for two randomly selected homeowners to determine how those different views affected the outcome of the analysis. The first homeowner selected provided similar results to the average homeowner analysis with a number of small differences in the ranking of certain distributed generation systems. The second homeowner provided different results than the average homeowner and may have ended up selecting a different distributed generation solution, the geothermal heat pump system.

Even though a larger number of homeowners should be evaluated, the initial conclusion of this research is that the analysis should be performed for the individual homeowner to provide them with a guide in selecting the system that matches the scenarios they are most concerned about. This is because there was a shift in how the second homeowner rated the distributed generation systems and cascaded through the analysis. It is likely that with a larger sample size an increasing number of individual homeowners would experience a shift similar to the second homeowner, albeit not in the same direction or magnitude.

This conclusion should be investigated further by performing a number of statistical analyses, including Spearman's rho, to determine the variation between the different homeowner selection processes. This variation can be used to calculate the benefit to the homeowner for personalizing the system guide against the cost of performing individualized analysis. Given the correct application, the EEA formulation for an individual homeowner can be a tool to help a homeowner attempting to capitalize on new energy generation opportunities.

7.2 Additional Thoughts

Before performing this analysis the researcher had some presumptions about how specific distributed generation technologies would perform, but there were a few surprises throughout the analysis. The first surprise was that the heating oil and heat pump systems performed surprisingly well among the homeowners and actually were near the Pareto Optimal in a number of the epochs. After reviewing section 3.2.4 and 3.2.8 for the performance characteristics of the DG systems, there should not have been surprise since each of the systems had larger areas in the radar style plots – where a large area represents better system performance – which indicated that each system would perform well against the homeowner needs. This shows the power of using a structured method such as the one demonstrated in this thesis research, for reducing surprises due to cognitive limitations (i.e. how much one can think about simultaneously) and surprises due to lack of understanding or unpredictability in the problem at hand.

On the opposite side of the spectrum, it was surprising to see how poorly solar hot water performed since they utilize the same primary resource as solar photovoltaic systems for generating energy the homeowner can use. There a couple different explanations for why this difference occurred. The first of which are the numerous differences between the performance characteristics between the two systems. In general, the solar hot water system performance is worse across the different attributes, with the exception of generation capacity, and therefore would likely result in the worse performance seen through the analysis. The second reason for the large difference in performance between the two is each affects homeowner energy use differently. The solar photovoltaic system generates electricity the homeowner can use whereas the solar hot water system reduces the homeowners use of energy. The analysis considered the absolute effect on the energy available to the homeowner but this may not align with how the homeowner views energy use. How this should be accounted for is covered in the future work section of the thesis.

An area where the analysis could have been performed differently was the enumeration of the epoch space generated from the system diagram. While the exogenous factors identified have appropriate ranges, the single factor enumeration generated an overly simplified epoch space. A more thorough analysis of this space would include multi-factor enumeration (i.e. the price of fuel increasing while the neighbor disagrees with the homeowner selection) and this would enable pairs or groups of exogenous factor to be analyzed simultaneously, which is a possibility. Beyond increasing the epochs that could be analyzed, this would also increase the variations in single era creation and enable more realistic scenarios. Although, a downside to the number of epochs increasing is that the computation resources required to perform the analysis will grow which may result in the analysis becoming too costly to generate. A cost-benefit analysis should be run to determine whether this increase realism increases the accuracy of the results enough to offset the costs associated with the additional complexity.

One of the weakest areas in the analysis, beyond the sample size of the homeowners, is the disconnect between the physical distributed generation choices available to the interviewed homeowners and the "choices" generated from homeowner demographic and average product performance in those categories. Since the homeowner requirements are created from a homeowner demographic based on average data, it is possible the product with those performance metrics does not exist in any given distributed generation category. Therefore, it would have been a better analysis to select products for every distributed generation choice available to the homeowner. This would have ensured the results created in the research could have been used immediately by the homeowner and would have ensured the analysis only used a viable dataset to generate a more realistic result for the homeowner.

7.3 Future Work

Although the research effort was able to provide an answer to the questions posed in the beginning of this thesis, there are still a number of items that could be done to continue solving the problem for the homeowner of choosing between the various distributed generation systems available. This research should be viewed as a building block that has opened the door for more detailed and precise work to develop a tool to aid the homeowner, having successfully proven that Epoch-Era Analysis formulations can be extremely useful for judging distributed generation systems.

The primary focus of the follow on work should center around parameterization of the model to enable analyses based on the entire situation of the individual homeowner. The result would be an interactive tool where the homeowner would simply answer a few questions about their energy use and geographical location. Additionally, the homeowner would need to provide their selection criteria and the weighting for those criteria to ensure that the analysis is completely personalized for that homeowner. From there the EEA formulation would run in the background and present the homeowner with the type of distributed generation system they should select given their situation.

A similar area that needs focus for the next body of work is a larger database of distributed generation systems a homeowner might select. Currently the research only provides average performance data for a category of distributed generation systems, but the analysis would be more helpful to the homeowner if a specific model could be recommended by the analysis. This could be done by having the homeowner enter the systems there were evaluating or by creating a database of products that are available to the homeowner which they may have not heard about previously.

Another area of the research that could be expanded is the performance characteristics of the distributed generation technologies. The current analysis focuses on the aspects that are closely associated with the generation of energy, but the economic performance of the system was largely underutilized in the analysis. For instance, one criterion that could have been added would be the return on investment of the system or include different payment structures that are currently available. In addition to the economic aspects, the analysis did not fully incorporate the geographical characteristics of the homeowner's location. This would be more critical for the renewable technologies, since it would provide the amount of wind energy available or whether the home is facing the right direction to capture the sunlight.

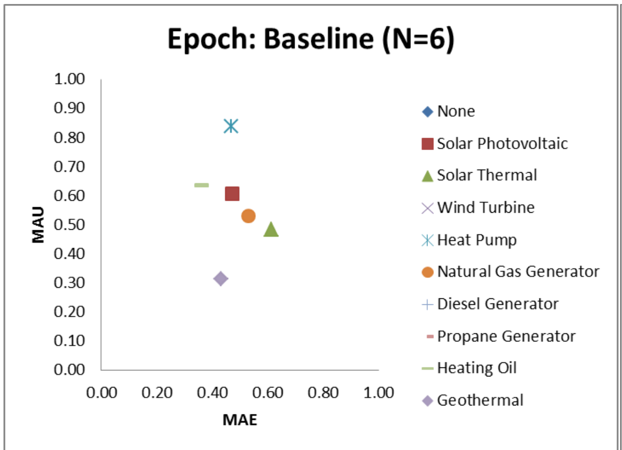
Beyond the future work on this topic related to the input of the model, the model itself could be modified to include multiple different metrics for the era analysis to determine the correct selection for the homeowner. While the operational value metric was useful in parsing the data in the single era analysis, there are a number of different metrics the homeowner may be interested in or may provide more insight into the appropriate system to select. These metrics could also include different weighting schemes for the epochs, since there are some epochs which are more likely to occur than others and this should be reflected in the analysis. Ultimately, there are multiple directions that the research can move in after this study and the author looks forward to seeing those developments occur.

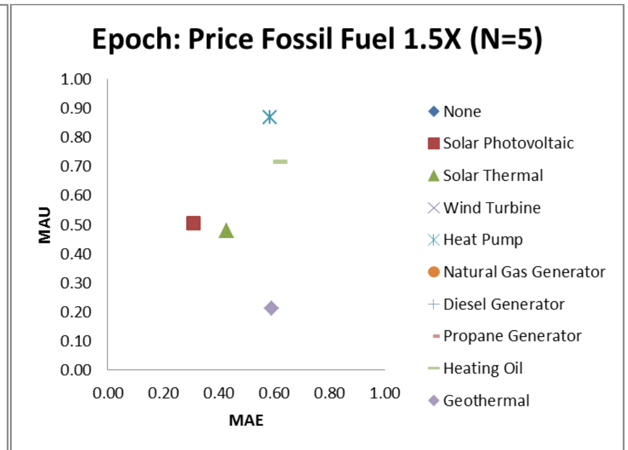
Appendix A: Survey Instrument

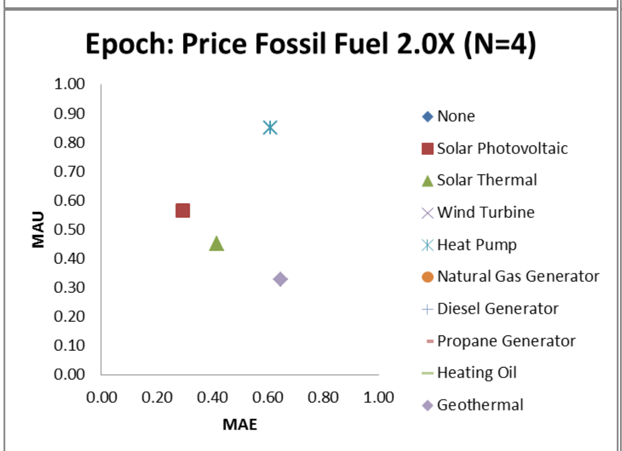
1. Do you own a home? Y (proceed) / N (stop interview)
2. Are you considering additional energy generation for your home? Y (proceed) / N (stop interview)
3. Which of the following energy generation resources are considering? Add additional resources that are not listed.
    a. None
    b. Solar Photovoltaic
    c. Solar Thermal
    d. Wind
    e. Heat Pump
    f. Natural Gas Generator
    g. Diesel Generator
    h. Propane Generator
    i. Heating Oil
    j.
4. When evaluating one energy generation resource against another, what are the criteria that you use to determine which is better?
    a.
    b.
    c.
    d.
    e.
    f.
5. Amongst the criteria that you have listed and the list below, please rank them from most important to least important with the number one being the most important.
    a. Overall Price of Energy
    b. Maintenance Frequency
    c. Maintenance Cost
    d. Product Life
    e. Environmental Effect
    f. Availability/Ease of Access
    g. Initial Investment
    h. Operating Cost (Fuel or Electricity)
    i.
6. How would the ranking in question 5 change if the price of fossil fuel increased 50%? If the price doubled?
    a. Overall Price of Energy
    b. Maintenance Frequency
    c. Maintenance Cost
    d. Product Life
    e. Environmental Effect
    f. Availability/Ease of Access
    g. Initial Investment
    h. Operating Cost (Fuel or Electricity)
    i.

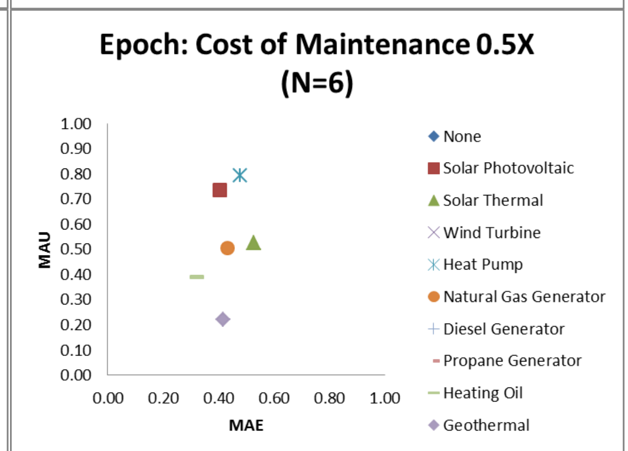
7. How would the ranking in question 5 change if the cost of maintenance was low? If the cost was high?
    a. Overall Price of Energy
    b. Maintenance Frequency
    c. Maintenance Cost
    d. Product Life
    e. Environmental Effect
    f. Availability/Ease of Access
    g. Initial Investment
    h. Operating Cost (Fuel or Electricity)
    i.
8. How would the ranking in question 5 change if your neighbor disapproved of your generation resource selection? Approved of your selection?
    a. Overall Price of Energy
    b. Maintenance Frequency
    c. Maintenance Cost
    d. Product Life
    e. Environmental Effect
    f. Availability/Ease of Access
    g. Initial Investment
    h. Operating Cost (Fuel or Electricity)
    i.
9. How would the ranking in question 5 change if there was a limitation in the generation resources available to select from? If you could only select from two options?
    a. Overall Price of Energy
    b. Maintenance Frequency
    c. Maintenance Cost
    d. Product Life
    e. Environmental Effect
    f. Availability/Ease of Access
    g. Initial Investment
    h. Operating Cost (Fuel or Electricity)
    i.
10. How would the ranking in question 5 change if regulations limiting the amount of CO2 produced were introduced? If you could not produce any CO2?
    a. Overall Price of Energy
    b. Maintenance Frequency
    c. Maintenance Cost
    d. Product Life
    e. Environmental Effect
    f. Availability/Ease of Access
    g. Initial Investment
    h. Operating Cost (Fuel or Electricity)
    i.
11. What factors, out of your control, are you worried that might change which would affect your decision in the generation resource selection or the ranking of the criteria?

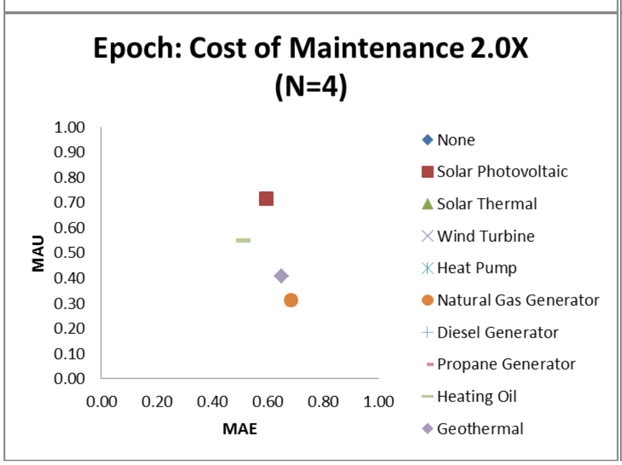
Appendix B: Epoch Tradespaces for Homeowner 4 and 2

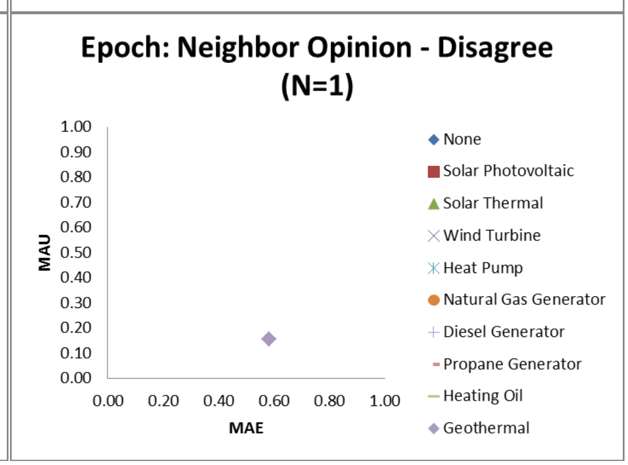












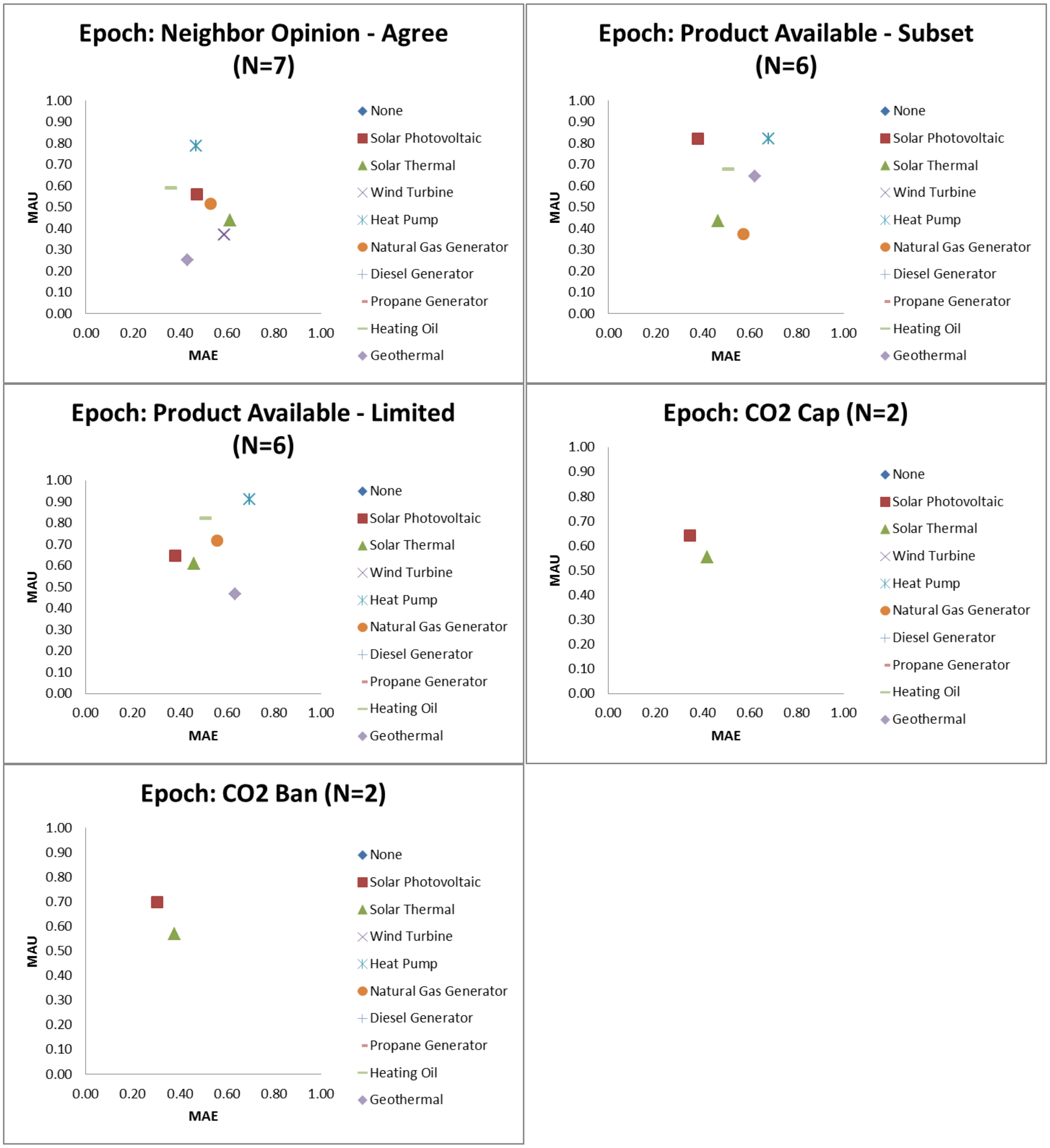
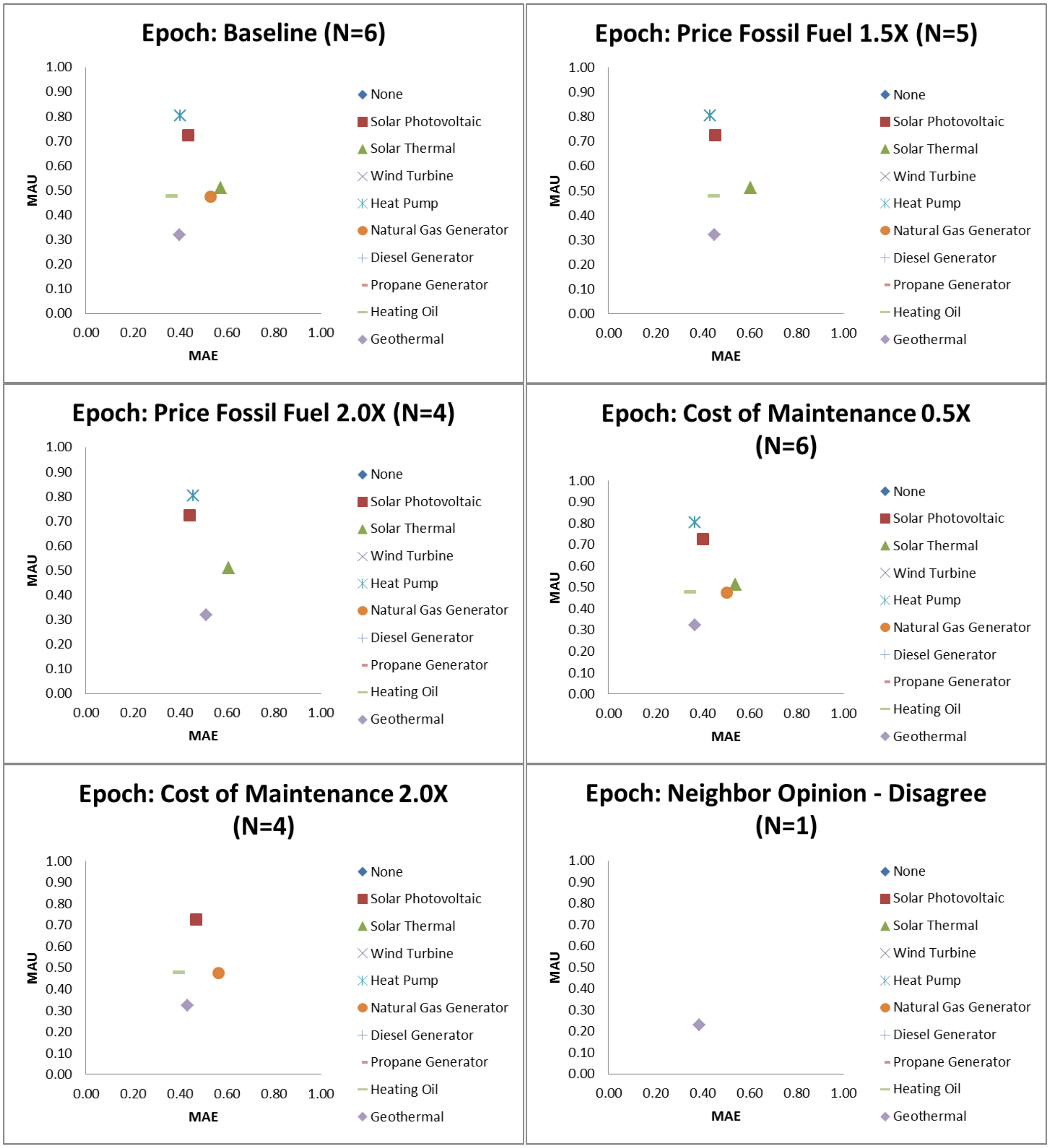


Figure B-1: The evaluated designs for each of the 11 epoch periods for Homeowner 4.


Epoch: Baseline (N=6)
Epoch: Price Fossil Fuel 1.5X (N=5)
Epoch: Price Fossil Fuel 2.0X (N=4)
Epoch: Cost of Maintenance 0.5X (N=6)
Epoch: Cost of Maintenance 2.0X (N=4)
Epoch: Neighbor Opinion - Disagree (N=1)
MAU
MAE
None
Solar Photovoltaic
Solar Thermal
Wind Turbine
Heat Pump
Natural Gas Generator
Diesel Generator
Propane Generator
Heating Oil
Geothermal

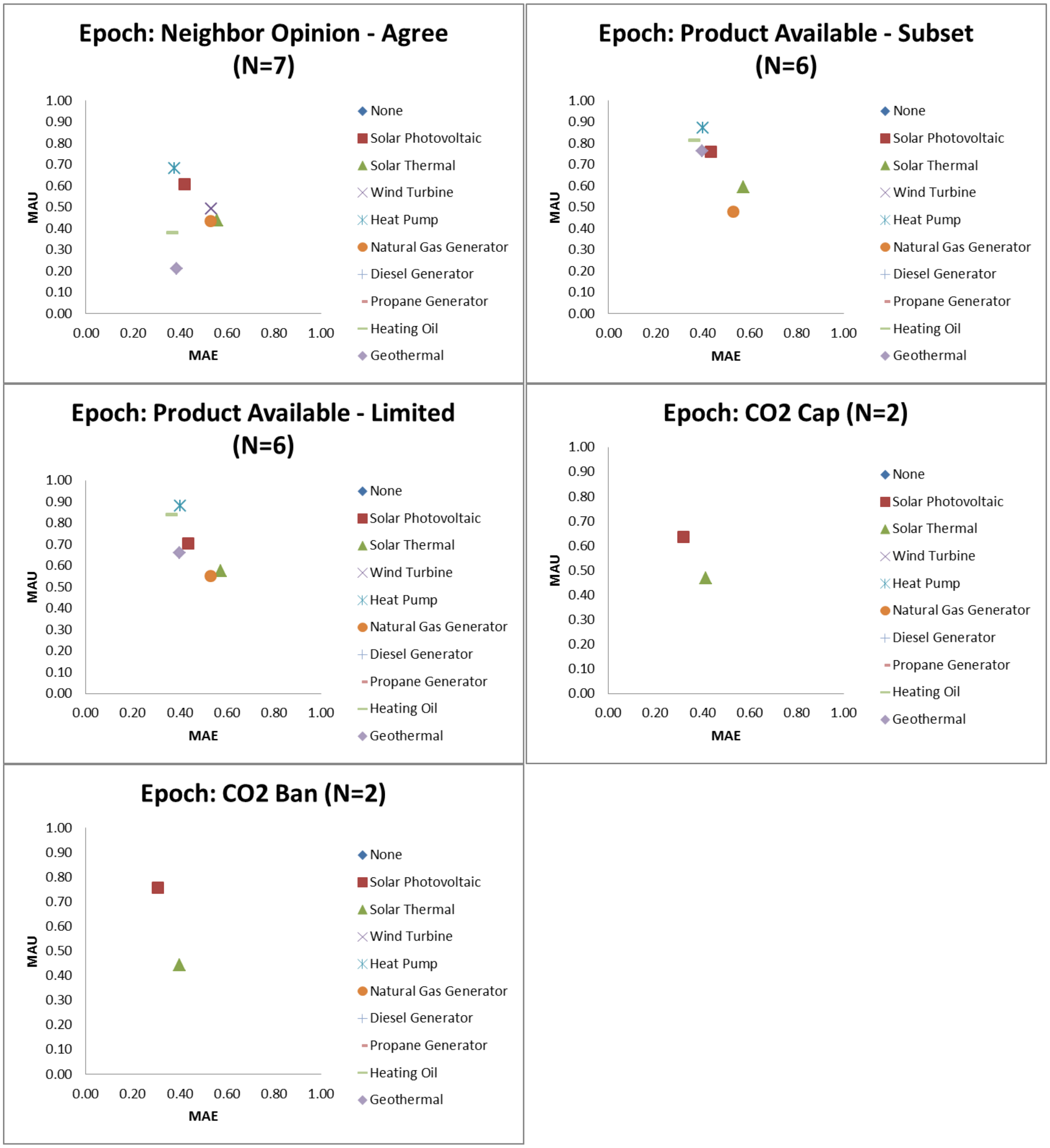


Figure B-2: The evaluated design for each of the 11 epoch periods for Homeowner 2.

Appendix C: Homeowner Survey Results

Homeowner 1									
Description	Aesthetic Appeal	Maintenance Frequency	Maintenance Cost	Product Life	Environmental Effect	Availability	Initial Investment	Operating Cost	Generation Capacity
Price Fossil Fuel 1x	9	8	5	4	7	6	2	3	1
Price Fossil Fuel 1.5x	9	6	5	4	8	7	1	2	3
Price Fossil Fuel 2x	9	6	5	4	8	7	2	1	3
Cost of Maintenance 1x	9	8	5	4	7	6	2	3	1
Cost of Maintenance 0.5x	9	8	5	4	7	6	2	3	1
Cost of Maintenance 2x	9	8	5	4	7	6	2	3	1
Neighbor Opinion - Nuetral	9	8	5	4	7	6	2	3	1
Neighbor Opinion - Disagree	9	8	5	4	7	6	2	3	1
Neighbor Opinion - Agree	9	8	5	4	7	6	2	3	1
Product Available - All	9	8	5	4	7	6	2	3	1
Product Available - Subset	9	8	5	4	7	6	2	3	1
Product Available - Two	9	8	5	4	7	6	2	3	1
Regulation - None	9	8	5	4	7	6	2	3	1
Regulation - CO2 Cap	9	8	6	5	4	7	2	3	1
Regulation - CO2 Ban	9	8	6	5	1	7	3	4	2

Homeowner 2									
Description	Aesthetic Appeal	Maintenance Frequency	Maintenance Cost	Product Life	Environmental Effect	Availability	Initial Investment	Operating Cost	Generation Capacity
Price Fossil Fuel 1x	8	3	7	6	9	4	1	2	5
Price Fossil Fuel 1.5x	8	3	7	6	9	4	1	2	5
Price Fossil Fuel 2x	8	3	7	6	9	4	2	1	5
Cost of Maintenance 1x	8	3	7	6	9	4	1	2	5
Cost of Maintenance 0.5x	8	3	7	6	9	4	1	2	5
Cost of Maintenance 2x	8	3	7	6	9	4	1	2	5
Neighbor Opinion - Nuetral	8	3	7	6	9	4	1	2	5
Neighbor Opinion - Disagree	6	3	8	7	9	4	1	2	5
Neighbor Opinion - Agree	6	3	8	7	9	4	1	2	5
Product Available - All	8	3	7	6	9	4	1	2	5
Product Available - Subset	4	8	7	3	9	5	1	2	6
Product Available - Two	6	8	7	3	9	5	1	2	4
Regulation - None	8	3	7	6	9	4	1	2	5
Regulation - CO2 Cap	6	8	7	4	2	9	1	3	5
Regulation - CO2 Ban	5	7	6	4	1	9	2	3	8

Homeowner 3									
Description	Aesthetic Appeal	Maintenance Frequency	Maintenance Cost	Product Life	Environmental Effect	Availability	Initial Investment	Operating Cost	Generation Capacity
Price Fossil Fuel 1x	9	8	4	3	5	6	1	2	7
Price Fossil Fuel 1.5x	9	8	4	3	5	6	1	2	7
Price Fossil Fuel 2x	9	8	5	4	6	1	2	3	7
Cost of Maintenance 1x	9	8	4	3	5	6	1	2	7
Cost of Maintenance 0.5x	9	8	4	3	5	6	1	2	7
Cost of Maintenance 2x	9	8	2	4	5	6	1	3	7
Neighbor Opinion - Nuetral	9	8	4	3	5	6	1	2	7
Neighbor Opinion - Disagree	2	9	5	4	6	7	1	3	8
Neighbor Opinion - Agree	9	8	4	3	5	6	1	2	7
Product Available - All	9	8	4	3	5	6	1	2	7
Product Available - Subset	9	8	4	3	5	6	1	2	7
Product Available - Two	9	8	4	3	5	6	1	2	7
Regulation - None	9	8	4	3	5	6	1	2	7
Regulation - CO2 Cap	9	8	5	4	2	6	1	3	7
Regulation - CO2 Ban	9	8	5	4	1	6	2	3	7

Homeowner 4									
Description	Aesthetic Appeal	Maintenance Frequency	Maintenance Cost	Product Life	Environmental Effect	Availability	Initial Investment	Operating Cost	Generation Capacity
Price Fossil Fuel 1x	8	5	4	6	9	7	1	2	3
Price Fossil Fuel 1.5x	9	6	5	7	3	8	4	1	2
Price Fossil Fuel 2x	9	7	6	5	2	8	4	1	3
Cost of Maintenance 1x	8	5	4	6	9	7	1	2	3
Cost of Maintenance 0.5x	9	3	2	8	7	4	1	5	6
Cost of Maintenance 2x	9	2	1	3	7	8	4	5	6
Neighbor Opinion - Nuetral	8	5	4	6	9	7	1	2	3
Neighbor Opinion - Disagree	1	7	6	8	2	9	3	4	5
Neighbor Opinion - Agree	8	5	4	6	9	7	1	2	3
Product Available - All	8	5	4	6	9	7	1	2	3
Product Available - Subset	9	5	4	3	1	6	2	7	8
Product Available - Two	9	6	5	7	1	4	2	8	3
Regulation - None	8	5	4	6	9	7	1	2	3
Regulation - CO2 Cap	9	7	6	5	1	4	3	8	2
Regulation - CO2 Ban	9	5	4	6	1	2	7	8	3

Homeowner 5									
Description	Aesthetic Appeal	Maintenance Frequency	Maintenance Cost	Product Life	Environmental Effect	Availability	Initial Investment	Operating Cost	Generation Capacity
Price Fossil Fuel 1x	7	4	3	6	8	9	1	5	2
Price Fossil Fuel 1.5x	7	5	4	6	8	9	2	1	3
Price Fossil Fuel 2x	7	5	4	6	8	9	2	1	3
Cost of Maintenance 1x	7	4	3	6	8	9	1	5	2
Cost of Maintenance 0.5x	7	4	3	6	8	9	1	5	2
Cost of Maintenance 2x	7	4	3	6	8	9	1	5	2
Neighbor Opinion - Nuetral	7	4	3	6	8	9	1	5	2
Neighbor Opinion - Disagree	7	4	3	6	8	9	1	5	2
Neighbor Opinion - Agree	7	4	3	6	8	9	1	5	2
Product Available - All	7	4	3	6	8	9	1	5	2
Product Available - Subset	7	5	4	6	8	9	1	3	2
Product Available - Two	7	5	4	6	8	9	1	3	2
Regulation - None	7	4	3	6	8	9	1	5	2
Regulation - CO2 Cap	7	4	3	6	8	9	1	5	2
Regulation - CO2 Ban	7	4	3	6	8	9	1	5	2

Homeowner 6									
Description	Aesthetic Appeal	Maintenance Frequency	Maintenance Cost	Product Life	Environmental Effect	Availability	Initial Investment	Operating Cost	Generation Capacity
Price Fossil Fuel 1x	9	3	4	5	6	1	7	2	8
Price Fossil Fuel 1.5x	9	3	4	5	6	1	7	2	8
Price Fossil Fuel 2x	9	3	4	5	6	2	7	1	8
Cost of Maintenance 1x	9	3	4	5	6	1	7	2	8
Cost of Maintenance 0.5x	9	3	4	5	6	1	7	2	8
Cost of Maintenance 2x	9	2	1	5	3	4	8	6	7
Neighbor Opinion - Nuetral	9	3	4	5	6	1	7	2	8
Neighbor Opinion - Disagree	9	2	1	7	3	4	8	5	6
Neighbor Opinion - Agree	9	2	1	7	3	4	8	5	6
Product Available - All	9	3	4	5	6	1	7	2	8
Product Available - Subset	9	3	1	7	6	2	5	4	8
Product Available - Two	9	7	2	3	5	1	4	8	6
Regulation - None	9	3	4	5	6	1	7	2	8
Regulation - CO2 Cap	9	7	6	1	2	3	8	5	4
Regulation - CO2 Ban	9	7	6	1	2	3	8	5	4

Figure C-1: The interviewed homeowner ranking of selection criteria across all epochs.

BIBLIOGRAPHY

Blaabjerg, F., Chen, Z., & Kjaer, S. B. (2004). Power Electronics as Efficient Interface in Dispersed Power Generation Systems. *IEEE Transactionis on Power Electronics*, *19*(5), 1184-1194.

Blaabjerg, F., Teodorescu, R., Liserre, M., & Timbus, A. V. (2006). Overview of Control and Grid Synchronization for Distributed Power Generation Systems. *IEEE Transactions of Industrial Electronics*, *53*(5), 1398-1409.

California State Profile and Energy Estimates. (2014). Retrieved from U.S. Energy Information Administration: http://www.eia.gov/state/?sid=ca

Energy Technology Cost and Performance Data for Distributed Generation. (2013). Retrieved from NREL Energy Analysis: http://www.nrel.gov/analysis/tech_cost_dg.html

Farrell, J. (2011, October 17). *The Challenge of Reconciling a Centralized v. Decentralized Electricity System*. Retrieved from Institute for Local Self-Reliance: http://www.ilsr.org/challenge-reconciling-centralized-v-decentralized-electricity-system/

Frequently Asked Questions. (2013). Retrieved from U.S. Energy Information Administration: http://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11

Geothermal Heat Pump Basics. (2012). Retrieved from National Renewable Energy Laboratory: http://www.nrel.gov/learning/re_geo_heat_pumps.html

Gerst, K. J. (2011). Evaluating the Impact of Government Energy R&D Investments through a Multi-Attribute Utility-based Decision Tool. *(Master's thesis, Massachusetts Institute of Technology)*. Retrieved from http://seari.mit.edu/publications.php

Guerrero, J. M., Blaabjerg, F., Zhelev, T., Hemmes, K., Monmasson, E., Jemei, S., . . . Frau, J. I. (2010). Distributed Generation: Toward a New Energy Paradigm. *IEEE Industrial Electronics Magazine, March*, 52-64.

Heat Pump Systems. (2013). Retrieved from U.S. Department of Energy: http://energy.gov/energysaver/articles/heat-pump-systems

IPCC Third Assessment Report. (2001). Retrieved from GRID Arendal: http://www.grida.no/publications/other/ipcc_tar/

Katiraei, F., Iravani, R., Hatziargyriou, N., & Dimeas, A. (2008). Microgrids Management: Controls and Operation Aspects of Microgrids. *IEEE Power and Energy Magazine, May/June*, 54-65.

Keeney, R. L., & Raiffa, H. (1976). *Decisions with Multiple Objectives: Preferences and Valu Tradeoffs.* New York: Wiley.

Koo, K. C. (2010). Investigating Army Systems and Systems of Systems for Value Robustness. *(Master's thesis, Massachusetts Institute of Technology)*. Retrieved from http://seari.mit.edu/publications.php

Manfren, M., Caputo, P., & Costa, G. (2011). Paradigm shift in urban energy systems through distributed generation: Methods and models. *Applied Energy, 88*, 1032-1048.

Nickel, J. (2010). Using Multi-Attribute Tradespace Exploration for the Architecting and Design of Transportation Systems. *(Master's thesis, Massachusetts Institute of Technology).* Retrieved from http://seari.mit.edu/publications.php

Oil-Fired Boilers and Furnaces. (2013). Retrieved from U.S. Department of Energy: http://energy.gov/energysaver/articles/oil-fired-boilers-and-furnaces

Roberts, C. J., Richards, M. G., Ross, A. M., Rhodes, D. H., & Hastings, D. E. (2009). Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration. *3rd Annual IEEE Systems Conference 2009* (pp. 366-371). Vancouver: IEEE.

Ross, A. M. (2006). Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration. *Doctor of Philosophy Dissertation.* Cambridge: Engineering Systems Division, MIT.

Ross, A. M., & Hastings, D. E. (2005). The Tradespace Exploration Paradigm. *INCOSE international Symposium.* Rochester, NY.

Ross, A. M., & Rhodes, D. H. (2008). Using natural value-centric time scales for conceptualizing system timelines through epoch-era analysis. *INCOSE International Symposium 2008.* Utrecht, the Netherlands.

Ross, A. M., Rhodes, D. H., & Hastings, D. E. (2009). Using Pareto Trace to Determine System Passive Value Robustness. *3rd Annual IEEE Systems Conference.* Vancouver: IEEE.

Schaffner, M. A. (2014). Designing Systems for Many Possible Futures: The RSC-based Method for Affordable Concept Selection (RMACS), with Multi-Era Analysis. *Master of Science Thesis.* Cambridge: Aeronautics and Astronuatics Department, MIT.

Schaffner, M. A., Ross, A. M., & Rhodes, D. H. (2014). A Method for Selecting Affordable System Concepts: A Case Application to Naval Ship Design. *Conference on Systems Engineering Research (CSER 2014),* (pp. 1-10). Redondo Beach, CA.

Schaffner, M., Wu, M. S., Ross, A. M., & Rhodes, D. H. (2013). Enabling Design for Affordability: An Epoch-Era Analysis Approach. *Tenth Annual Acquisition Research Symposium Acquisition Management* (pp. 262-279). Monterey: Naval Postgraduate School.

Schofield, D. M. (2010). A Framework and Methodology for Enhancing Operaitonal Requirements Development: United States Coast Guard Cutter Project Case Study. *(Master's thesis, Massachusetts Institute of Technology)*. Retrieved from http://seari.mit.edu/publications.php

Smaling, R. (2005). System Architecture Analysis and Selection Under Uncertainty. *Doctor of Philosophy Dissertation.* Cambridge: Engineering Systems Division, MIT.

Solar Hot Water. (2012). Retrieved from National Renewable Energy Laboratory: http://www.nrel.gov/learning/re_solar_hot_water.html

Solar Photovoltaic Technology Basics. (2012). Retrieved from National Renewable Energy Laboratory: http://www.nrel.gov/learning/re_photovoltaics.html

Technology data Archive. (2004). Retrieved from Microgrids at Berkeley Lab: http://der.lbl.gov/der-cam/technology-data-archive

Von Neumann, J. A., & Morgenstern, O. (1947). *Theory of Games and Economic Behavior.* Princeton: Princeton University Press.

Wind Energy Basics: How Wind Turbines Work. (2012). Retrieved from National Renwable Energy Laboratory: http://www.nrel.gov/learning/re_wind.html

Wu, M. S. (2014). Design for Affordability in Defense and Aerospace Systems Using Tradespace-based Methods. *Master of Science Thesis.* Cambrdige: Engineering Systems Division, MIT.