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Procedia Computer Science 00 (2019) 000–000

Procedia Computer Science

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17th Annual Conference on Systems Engineering Research (CSER)

Application of epoch-era analysis to the selection of a distributed power generation system

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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 many potential systems to purchase, there are few good tools to help the homeowner determine which system they should select, given practical uncertainties typically faced. This research investigates how an Epoch-Era Analysis analytic approach can be used to select the appropriate distributed generation system for the homeowner. Ten different distributed generation alternatives were analyzed with the results suggesting that the average homeowner should select a solar photovoltaic system. Additionally, the research investigated how the use of an average composite homeowner profile, as compared to an individualized homeowner profile, might result in a different distributed generation selection. Two individual homeowners were randomly selected from the pool of homeowners from which the composite was constructed. There were noticeable differences between the individualized profile and that of the average profile, including one of the homeowners selecting the geothermal system instead of the solar photovoltaic. The research suggests that use of average preferences may lead to misleading results when aggregating groups of heterogeneous individuals, potentially creating missed market opportunities for firms making product offering decisions to satisfy diverse customer needs.

Keywords: multi-attribute; tradespace exploration; epoch-era analysis; distributed generation; utility; expense; technology asessment

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1. Introduction

One of the principal strengths of systems engineering (SE) approaches is their broad applicability and usefulness across a range of domains, even if the original motivation of such approaches stem from one domain in particular. The research described in this paper is one such example, demonstrating the application of a set of SE methods, motivated by the aerospace domain, to the energy domain [1].

Power generation in the United States has largely remained stagnant for a large part of the previous century with a centralized power distribution network. This 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 created a shift in public desire to attain energy from renewable resources [2]. 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 (DG). (Power storage, while complementary, was scoped out of this study for pedagogical and resource-constraint reasons.)

Over the past fifteen years, 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 several DG technologies that a homeowner can select, each having its own advantages and disadvantages over the life of the system, potentially decades. This leads to a large degree of uncertainty for a homeowner when trying to determine which DG technologies are most attractive for meeting their needs over time. Therefore, a homeowner would benefit from a structured approach for comparing different DG systems across various scenarios, assisting them in determining the most appropriate DG system. This paper provides an example application of a structured SE method for a DG system selection decision. Additionally, two individual homeowner cases are analyzed to determine whether an average of homeowner information is sufficient for recommending a DG system, or if individualized analysis should be performed for each homeowner.

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

2. Approach

Since preferences for the homeowner, as well as the performance of DG systems, may be impacted by exogenous factors (i.e., scenarios) another component of the approach is to evaluate how the value scores for each DG system might be impacted as a function of several exogenous factors that may change during a system's lifetime. These changes in the value scores will provide an indication of the robustness of DG systems across the given scenarios. A third component of the research will be to evaluate the DG systems across a sequence of the exogenous factors, which will represent how the value of each system might change over time. By evaluating the change in value over time, the homeowner will have a better understanding of which DG system will provide the greatest value over the system's life. This approach is derived from Epoch-Era Analysis (EEA), which provides for visualization and a structured way to think about the temporal system value environment [3].

The final component will be to select a couple of homeowners with different preferences and analyze the best DG system for them using similar analyses. 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. Here, it may be more beneficial to find better solutions for each individual stakeholder instead of providing a single solution for all.

Multi-Attribute Tradespace Exploration (MATE) and Epoch-Era Analysis (EEA) are two SE-based methods with associated frameworks that can be used to aid in tradespace analysis of complex problems. They have been operationalized to make their application to a problem straightforward and consistent across industries. The following sections will demonstrate how an EEA formulation can be modified to address the homeowner DG solution problem.

This study was conducted using an eight-step approach derived from prior applications of EEA [4, 5]. The structure consists of three different phases, each with their own specific processes that, when performed in proper sequence, will provide the method user 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 Fig. 1.

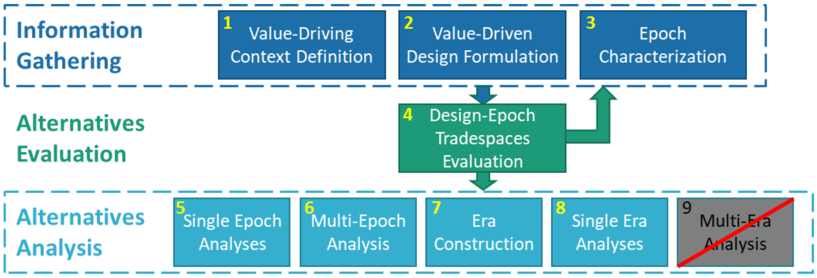


Fig. 1. Modified EEA approach

The first phase is called Information Gathering and consists of (1) value-driving context definition, (2) value-driven design formulation, and (3) epoch characterization processes. 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 (process 4). This phase is where the user generates the tradespace of solutions using models to evaluate the proposed designs in proposed epochs (often using fundamental principles from the MATE methodology) based on the information provided in the previous phase. The third phase is Alternatives 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. During this phase the evaluation data is structured through the EEA framework to provide an in-depth analysis about any number of characteristics that could change over, or be affected by, time [6].

3. Case demonstration

This section demonstrates the application of modified EEA to a specific case, a southern California homeowner's DG system selection. It will cover the analysis of the DG choices currently available, and describe the processes needed to generate a solution for the homeowner. A successful application of the method will demonstrate the ability of EEA in assisting homeowners selecting DG systems.

3.1. Phase 1: information gathering (processes 1, 2, and 3)

The goals of the information gathering phase are to frame the decision opportunity, including identification of system boundary and exogenous factors, elicit value metrics used by homeowners for differentiating and selecting potential DG systems, develop a set of DG alternatives, and characterize the exogenous factors into potential epochs.

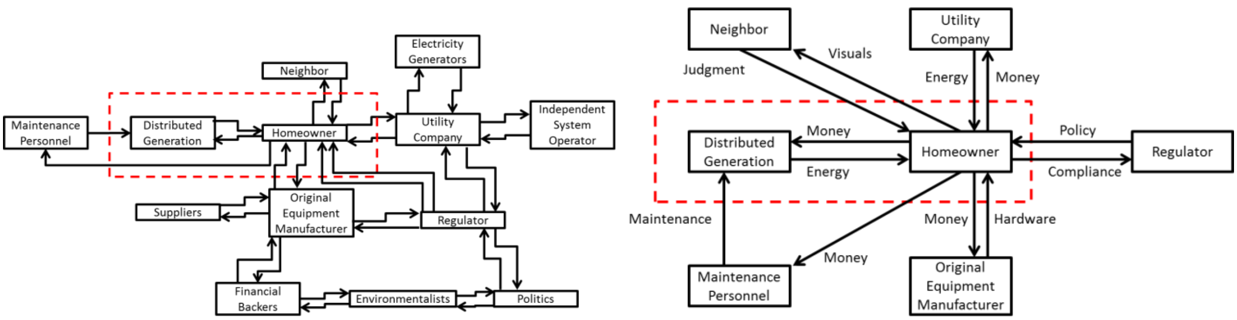


Fig. 2. System diagram of the homeowner distributed power generation network full (left), simplified (right)

After speaking with several homeowners in the San Jose, CA region and researching all the interactions that are involved with the homeowner receiving their energy, the system diagram in Fig. 2 was generated. This system diagram captures many of the interactions that occur for a homeowner to use and maintain a DG system. Elements within the dashed box surrounding the homeowner and DG blocks represents factors and interactions the homeowner has control over. Given that elements beyond the control of the homeowner can be abstracted away as uncertainties, a simplified version of the diagram can be constructed. The simplified version is shown on the right in the figure, where only the interactions that cross the system boundary are included. The interactions crossing the boundary (dashed red line) will become the epoch factors; they are exogenous to the homeowner and potentially carry significant uncertainty.

Six representative homeowners were interviewed to determine the criteria that they would use to make a DG purchase. This resulted in the following nine attributes, the definitions these homeowners used during their evaluation process, and the potential attribute ranges considered [from least preferred to most preferred]:

Benefit attributes (i.e., contributing to utility)

- Aesthetic appeal – the system's appearance when considered part of their property [ordinal: 3 to 7]
- 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 [#/yr: 6 to 0]
- Product life – minimum number of years that the manufacturing or retailing companies specifies that the system is able to operate before replacement [yrs: 10 to 30]
- 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 [ordinal: 4 to 10]
- Space required – number of square meters required per kilowatt of system generation capacity [m^2: 125 to 0]

Cost attributes (i.e., contributing to expense)

- 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 [$/yr: 200 to 0]
- Environmental effect – mass of carbon dioxide that is produced by the system during annual operation [kg CO_2/yr: 1000 to 0]
- Initial cost – total cost that the homeowner must pay to acquire the system [$: 50,000 to 0]
- Operating cost – 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 [$/yr: 750 to 0]

Single attribute value functions were determined (single attribute utilities (SAU) for benefit attributes, and single attribute expenses (SAE) for cost attributes) for each attribute X_i in each set (utility or expense). Details on curves and weights can be found in Ref [1].

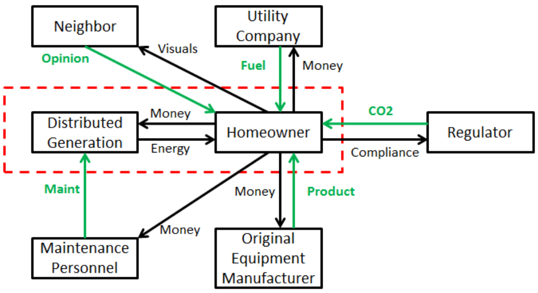
$$\text{MAV} = \sum_i^n k_i SAV_i(X_i), \text{ where } \sum_i^n k_i = 1 \text{ for V (value) is E (expense) or U (utility)}$$

Each of these were then aggregated using a linear weighted sum model: either a multi-attribute utility (MAU) or multi-attribute expense (MAE), which assumes each attribute contributes independently to overall value. This is key: the value model (i.e., the mathematical formulation for MAE and MAU) was fixed, but the parameters (k_i) and single attribute scores (X_i) for a given evaluation will be dependent on the particular epoch experienced by a DG, which will be detailed in the next section.

The set of DG alternatives considered in this study includes: None, Solar Photovoltaic, Solar Thermal, Wind Turbine, Heat Pump, Natural Gas Generator, Diesel Generator, Propane Generator, Heating Oil, and Geothermal. Although there are a number of different technologies that are available for homeowners to meet their DG 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 unreliable data). Still, the nine DG 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. Alternatives that are not practical (e.g., no available wind) could be removed from a particular analysis prior to evaluation. In this case, all alternatives were kept as potentially practical.

Given the uncertainty factors crossing the system boundary, the next step is to name the key exogenous factors and different levels they might display. These exogenous factors and levels become the epochs used in Alternatives Evaluation and Analysis. There are five interactions that cross the system boundary as highlighted in Fig. 3:

- Fuel: Cost of energy from the utility company, manifested as variation in fuel prices;
- Maint: Amount of maintenance required for DG system operations, manifested as variation in maintenance cost;
- Opinion: Aesthetic appeal of system, manifested through different neighbor opinions and HOA regulations;
- Product: Distribution of system in the homeowner’s region, manifested as the number of DG products available;
- CO2: Limits on carbon dioxide that can be emitted into the atmosphere, manifested as environmental policies.



Epoch Descriptions				
Epoch Name	**Epoch Descriptor Category**	**Epoch Descriptor**	**Range**	**Units**
Price Fossil Fuel	Economic	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	Economic	Product	[2, 5, 10]	Choices
CO2 Regulations	Policy	CO2	[None, Cap, Ban]	Level

Fig. 3. Exogenous factors impacting the primary stakeholder system and characterization of epochs that represent the exogenous factors

The five interactions then become the epochs shown in Fig. 3. 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 interviews with homeowners, where the researcher asked about ranges homeowners may be concerned about or thought likely to occur. The second was through the researcher’s previous experience in the field. These ranges are not meant to be a complete listing, but rather representative of possibilities.

The next step is to determine the effect of each epoch on homeowner attributes using epoch descriptor impact matrices. This matrix uses a qualitative screening metric to determine how strongly changes in an epoch factor might impact the attributes. For this study it became clear that each epoch factor only greatly impacts a single attribute. As a modeling assumption, this removes the need for a more complicated model to account for emergent properties between attributes, enabling the use of a direct weighting function for calculating the impact on specific attributes.

As epochs change the attribute scores X_i assigned to each DG alternative changes, and so too does the k_i weighting factors in the value model. This means that the contribution to overall value from each attribute changes as a function of epoch (e.g., as CO2 regulations change from none to cap to ban, the weight on environmental effect increases since the homeowner cares more and more about that effect for their overall considered value).

3.2. Phase 2: alternatives evaluation (process 4)

The baseline performance model is a lookup table generated through specifications, interviews, and SME on the nine representative alternative DG systems. The performance for each of these nine alternatives (plus “none”) is listed in Fig. 4. For each epoch considered, the “epoch weighting factor” is multiplied by baseline attribute scores.

DG Choice	Description	Maintenance Cost ($/yr)	Environmental Effect (kg/yr)	Initial Cost ($)	Operating Cost ($/yr)	Aesthetic Appeal (0-10)	Maintenance Frequency (#/yr)	Product Life (yr)	Availability (0-10)	Space Required (m^2/kW)
1	None	0.00	0.00	0.00	0.00	0	0	0	0	0.00
2	Solar Photovoltaic	88.75	0.00	17750.00	33.56	5	1	25	10	57.47
3	Solar Thermal	133.13	0.00	26625.00	94.77	5	2	15	9	17.75
4	Wind Turbine	124.25	0.00	35500.00	38.88	3	3	20	9	110.94
5	Heat Pump	137.52	770.09	9485.69	93.15	6	1	20	8	0.23
6	Natural Gas Generator	67.55	586.71	2637.85	607.50	4	4	12.5	8	0.19
7	Diesel Generator	117.59	808.86	3439.06	998.05	4	4	12.5	7	0.26
8	Propane Generator	60.79	697.03	2928.75	2054.16	4	4	12.5	8	0.17
9	Heating Oil	37.82	808.86	1371.59	386.13	5	2	20	5	0.08
10	Geothermal	79.87	770.09	7437.86	173.82	7	3	25	6	117.12

Fig. 4. Summary of all nine DG systems and per unit baseline performance across attributes

Using the epoch weighting factors in Fig. 5, each DG alternative now has attribute scores, SAU, SAE, MAU, and MAE calculated for every potential epoch. This dataset then becomes the basis for analyses in the next phase.

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

Fig. 5. Epoch weighting factors that multiply baseline attribute scores

3.3. Phase 3: alternatives analysis (processes 5, 6, 7, and 8)

The most common initial look at a tradespace dataset is via a MAE vs. MAU scatterplot, depicting the cost vs benefit tradeoffs of alternatives (the baseline epoch is shown in Fig. 6). A key feature to investigate is the Pareto Set, which is the set of alternatives with the highest benefit for a given cost. One of the more surprising conclusions drawn from the DG scatterplots is that the heating oil DG 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 DG system also performs very well according to the Pareto Set metric.

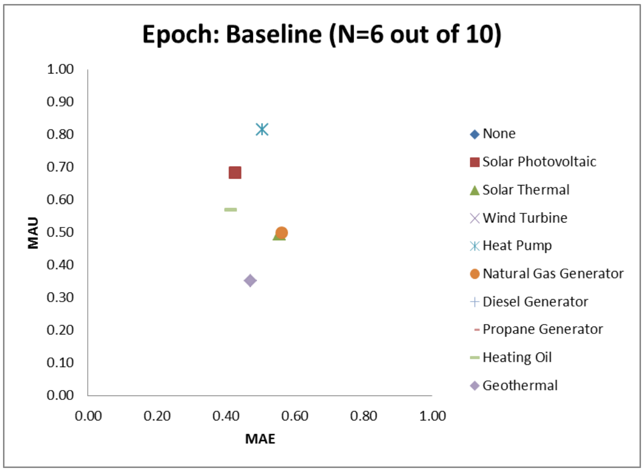


Fig. 6. Baseline epoch tradespace MAU vs. MAE scatterplot showing 6 out of 10 feasible DG alternatives

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. Another key feature in the results is that at least one alternative is infeasible in each epoch (the baseline has four infeasible alternatives). Fig. 7 shows the feasibility of the alternative DG systems across the 15 epochs. An alternative is infeasible if it violates one (or more) minimum acceptable attribute levels.

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

Fig. 7. Feasibility matrix for the DG alternatives across the 15 epochs (infeasible = violate minimum acceptable levels for an attribute)

Looking across the epochs, there are only four DG systems located on the Pareto Frontier in at least one of the epochs. 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. The Normalized Pareto Trace (NPT) metric scores the fraction of the epoch space a given alternative is in the Pareto Set (Fig. 8, NPT), which is a measure of robustness across the uncertainties represented by changing epochs. This metric does not capture alternatives that might be "near" the Pareto Front. If we allow for uncertainty in both the value and evaluation model, we might be interested in some "fuzzy" distance from the Pareto Front that might be acceptable. Fuzzy NPT (fNPT) counts alternatives within f% of the Pareto Front across the epoch space (Fig. 8, fNPT). Increasing the fuzziness increases the number of alternatives that might be considered robust. In this case, the top four remain.

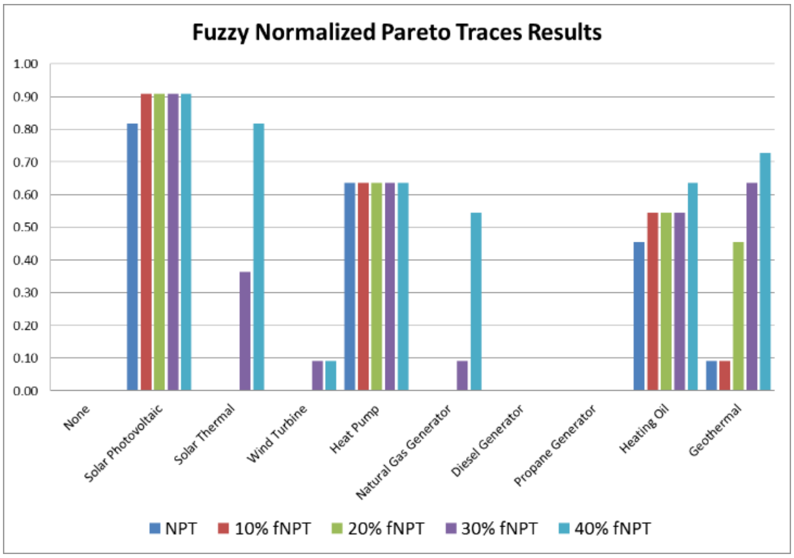


Fig. 8. Fuzzy normalized pareto trace of the DG choices across all epochs

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
Era3	Technology	Hi-Tech	1) Baseline	2) Neighbor Agrees	3) Maintenance 0.5X	4) Regulation - CO2 Cap	3 years

Fig. 9. Narratively constructed example set of three eras

At this point in the study, it appears that the solar photovoltaic, heat pump, and heating oil DG solutions are the best choices for the homeowner (most robust to the epoch space variations). Will time-dependence change this result?

Error! Reference source not found. shows a set of three narratively constructed eras of four epochs each. Given these eras, how do the DG alternatives perform? Operational value is defined as the time-weighted average MAE and time-weighted average MAU of the DG system while being feasible over the era duration. During any time an alternative is infeasible (either due to unacceptable MAU or MAE), 0 will be added to the utility aggregate and 1 will be added to the expense aggregate, which in both cases negatively impact operational value. A good alternative will have a high utility average and a low expense average. This metric does not allow for the homeowner to change their DG system (i.e., the homeowner must select a DG system and stick with it), but optionality is something that could be researched.

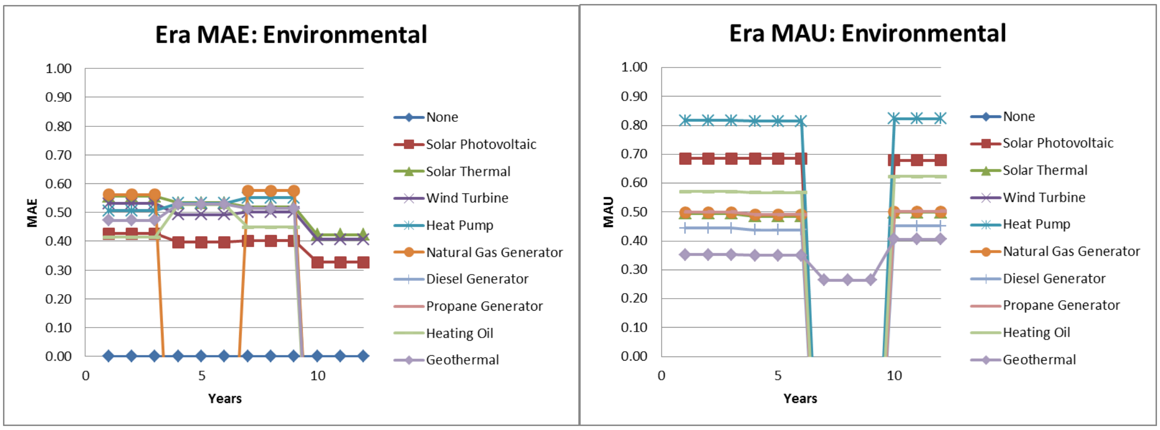


Fig. 10. Environmental era MAE and MAU values for each DG choice over 12 years

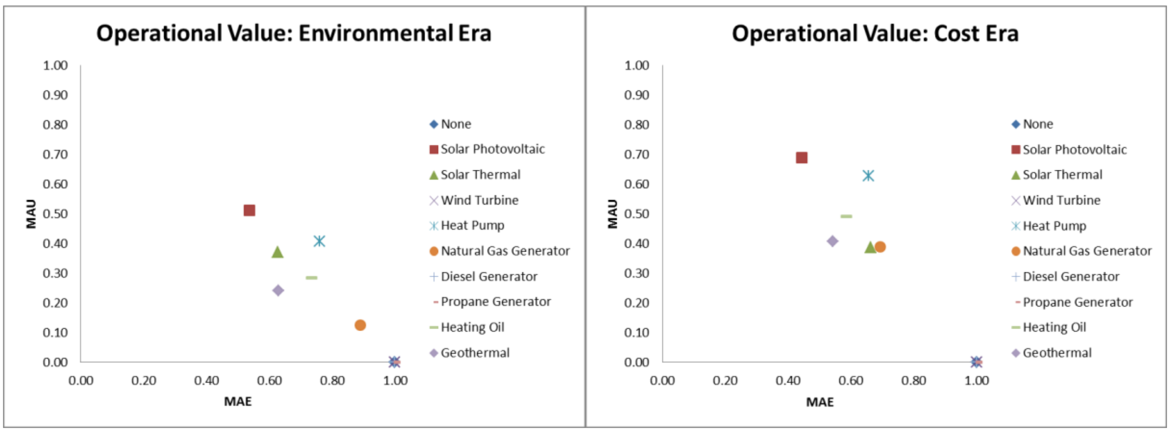


Fig. 11. Scatterplot of operational value for both the environmental and cost eras

The MAE and MAU trajectories of the DG systems in the Environmental era are illustrated in Fig. 10. Points in time when a DG alternative becomes infeasible is illustrated where the trajectory drops below the x-axis. Notice that high MAU DGs (e.g., heat pump) can become unacceptable around year 7. Scatterplots of the roll up of these trajectories into operational value scores are shown in Fig. 11 (the Cost era is also shown to contrast against the Environmental era). Even considering time-dependence (i.e., era-level analysis), the solar photovoltaic DG system appears to dominate. Here the heat pump, even though its MAU trajectory looks to be better than solar photovoltaic, is rolled up to a lower net MAU because it has unacceptable MAE from year 10 to 12.

4. Discussion

At almost every step of this case it was apparent the solar photovoltaic DG 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. 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 performs well in the most epochs, then they should select the heat pump second and the heating oil third. If the homeowner is more concerned with an era, they should select the solar thermal second and the geothermal third for the environmental and hi-tech era. If they are interested in the cost era, then select the geothermal second and the heating oil third.

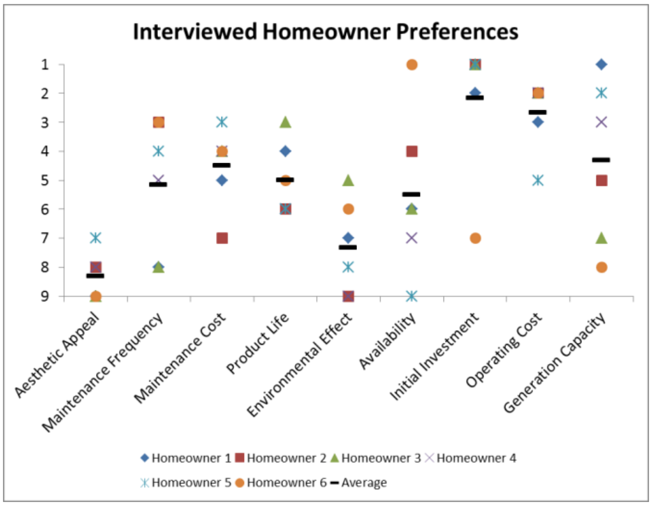


Fig. 12. Summary of attribute rankings across individual and average homeowners

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 DG system space where business and policy makers use aggregate homeowner demographics and preference data to model the average homeowner, similar to what was done throughout this study. While this approach simplifies the analysis and allows for the researcher to generate a singular answer for a problem question – for example, what DG should homeowners select? – it does not provide an accurate depiction of what a particular homeowner will select in the "real world." Given the potential variance between homeowner rankings of attribute importance (Fig. 12), two homeowners were randomly selected from the pool of interviewed homeowners used to generate the "average" homeowner to see whether the use of an average, rather than the particular, significantly impacts the insights from the analysis. (The averaging of utility curves, likewise obfuscates individual risk tolerances, but is excluded from this paper for sake of brevity.) The study was repeated for each of the individual homeowner preference profiles instead of the “average” homeowner preference profile. The resulting DG rankings from each of these studies are summarized in Fig. 13.

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

Fig. 13. Summary of average homeowner, homeowner 4, and homeowner 2 DG rankings across analysis type

This figure clearly demonstrates the difference in DG system rankings among the homeowners, even in the case of homeowner 4 who had one of the most similar preferences to the homeowner average. 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 case, 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 what 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 sample 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 of the systems. Still, this analysis indicates that an individual homeowner analysis may be necessary when the homeowner is determining which DG systems to select.

Before performing this analysis, the researcher had some presumptions about how specific DG technologies would perform, but there were a few surprises throughout the analysis. For example, the heating oil and heat pump systems performed surprisingly well among the homeowners and were near the Pareto Frontier in a number of the epochs. This shows the power of using a generalized and structured SE-derived method, 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.

References

[1] Pina AL, Applying Epoch-Era Analysis for Homeowner Selection of Distributed Generation Power Systems, Master of Science in Engineering and Management, System Design and Management Program, MIT, June 2014.

[2] IPCC Third Assessment Report, Retrieved from GRID Arendal: http://www.grida.no/publications/other/ipcc_tar/, 2001.

[3] Ross AM, and Rhodes DH. Using natural value-centric time scales for conceptualizing system timelines through epoch-era analysis. INCOSE Int’l Symp. (INCOSE08). Utrecht, the Netherlands, 2008.

[4] Ross AM, Rhodes DH, and Hastings DE. Using Pareto Trace to Determine System Passive Value Robustness. 3rd IEEE Sys Conf. (SysCon09), Vancouver, 2009.

[5] Schaffner M, Wu MS, Ross AM, and Rhodes DH. Enabling Design for Affordability: An Epoch-Era Analysis Approach. 10th Acquisition Research Symposium Acquisition Management. Monterey: Naval Postgraduate School. 2013. pp. 262-279.

[6] Schaffner, MA, Ross AM, and Rhodes DH. A Method for Selecting Affordable System Concepts: A Case Application to Naval Ship Design. Conf on Sys Eng Research (CSER14). Redondo Beach, CA. 2014.