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

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Distribution is a core idea behind the grid of tomorrow.
What is Distributed Generation?

Homeowners will play a supply role in the future.
Challenge of Uncertainty

Key challenge for the homeowner investing in a DG system will be expensive and uncertainties will impact the costs and benefits of this investment.

Epoch-Era Analysis (EEA) is an approach that allows for the framing and analysis of the impact of short run (epoch) and long run (era) uncertainties on the value of alternative investments.
Guiding 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?

What is problem to be solved? Who are key stakeholders?

What are value criteria used to determine goodness? What are potential alternatives?

What are key uncertainties in terms of potential contexts and needs (epochs)?

How does each alternative perform, and how is it valued, in each epoch?

Within each epoch, how do alternatives compare?

Across the set of epochs, how do alternatives compare?

What are potential sequences of epochs that may be encountered (eras)?

Within each era, how do alternatives compare?
There are many potential stakeholders in the distributed generation system. Simplifying the system diagram allows us to focus on the key relationships.

Chosen focus: the “Homeowner” perspective
Who is the homeowner?

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Cost</td>
<td>0.20</td>
<td>$/kWh</td>
</tr>
<tr>
<td>Yearly Energy Use</td>
<td>6480</td>
<td>kWh/yr</td>
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<tr>
<td>Daily Energy Use</td>
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<td>kWh/day</td>
</tr>
<tr>
<td>DG Percentage</td>
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<td></td>
</tr>
<tr>
<td>DG Daily Operation</td>
<td>2</td>
<td>hours</td>
</tr>
<tr>
<td>DG Capacity</td>
<td>4.44</td>
<td>kW</td>
</tr>
</tbody>
</table>

- What are they looking for?
  - Aesthetic Appeal
  - Maintenance Frequency
  - Product Life
  - Availability
  - Space Required
  - Maintenance Cost
  - Environmental Effect
  - Initial Cost
  - Operating Cost
Value Modeling

Attributes $\rightarrow$ SAE/SAU $\rightarrow$ MAE/MAU

Transforming decision maker criteria into...
levels of satisfaction for each criterion into...
aggregate satisfaction across all criteria

**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 [m²: 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 CO₂/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 [$/yr: 750 to 0$]

$$\text{MAV} = \sum_{i}^{n} k_i SAV_i(X_i), \text{ where } \sum_{i}^{n} k_i = 1$$

for V (value) is E (expense) or U (utility)
Utility and Expense Value Model

Single Attribute Expense (SAE) Curves
- Maintenance Cost
- Environmental Effect
- Initial Cost
- Operating Cost

Single Attribute Utility (SAU) Curves
- Appearance
- Maintenance Frequency
- Product Life
- Availability
- Space Required

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

- None,
- Solar Photovoltaic
- Solar Thermal
- Wind Turbine
- Heat Pump
- Natural Gas Generator
- Diesel Generator
- Propane Generator
- Heating Oil
- Geothermal
Inspecting the system boundary, we see five exogenous factors that pass through:

- **Fuel** (from utility company)
- **Maint** (from maintenance personnel)
- **Opinion** (from neighbor)
- **Product** (from original equipment manufacturer)
- **CO2** (from regulator)

These factors can be used to enumerate potential epochs for the system.

<table>
<thead>
<tr>
<th>Epoch Name</th>
<th>Epoch Descriptor Category</th>
<th>Epoch Descriptor</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price Fossil Fuel</td>
<td>Technology</td>
<td>Fuel</td>
<td>[1.0, 1.5, 2.0]</td>
<td>Multiplier</td>
</tr>
<tr>
<td>Cost of Maintenance</td>
<td>Social</td>
<td>Maint</td>
<td>[0.5, 1.0, 2.0]</td>
<td>Multiplier</td>
</tr>
<tr>
<td>Neighbor Opinion</td>
<td>Social</td>
<td>Opinion</td>
<td>[Disagree, Neutral, Agree]</td>
<td>Level</td>
</tr>
<tr>
<td>Product Available</td>
<td>Technology</td>
<td>Product</td>
<td>[2, 5, 10]</td>
<td>Choices</td>
</tr>
<tr>
<td>CO2 Regulations</td>
<td>Policy</td>
<td>CO2</td>
<td>[None, Cap, Ban]</td>
<td>Level</td>
</tr>
</tbody>
</table>
Evaluating the Alternatives

Data for each of the DG alternatives was collected for each cost and benefit attribute:

<table>
<thead>
<tr>
<th>DG Choice</th>
<th>Description</th>
<th>Maintenance Cost ($/yr)</th>
<th>Environmental Benefit ($/yr)</th>
<th>Initial Cost ($/kW)</th>
<th>Operating Cost ($/kW)</th>
<th>Aesthetic Appeal</th>
<th>Maintenance Frequency (times/yr)</th>
<th>Product Life (yr)</th>
<th>Availability</th>
<th>Space Required (m²/kW)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>Solar Photovoltaic</td>
<td>88.75</td>
<td>0.00</td>
<td>1775.00</td>
<td>33.56</td>
<td>5</td>
<td>1</td>
<td>25</td>
<td>10</td>
<td>57.47</td>
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<tr>
<td>3</td>
<td>Solar Thermal</td>
<td>133.33</td>
<td>0.00</td>
<td>26625.00</td>
<td>97.17</td>
<td>5</td>
<td>2</td>
<td>15</td>
<td>9</td>
<td>17.75</td>
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<tr>
<td>4</td>
<td>Wind Turbine</td>
<td>124.25</td>
<td>0.00</td>
<td>35500.00</td>
<td>38.88</td>
<td>3</td>
<td>8</td>
<td>20</td>
<td>9</td>
<td>210.94</td>
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<td>5</td>
<td>Heat Pump</td>
<td>137.52</td>
<td>770.09</td>
<td>9485.69</td>
<td>91.15</td>
<td>6</td>
<td>1</td>
<td>20</td>
<td>8</td>
<td>0.23</td>
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<tr>
<td>6</td>
<td>Natural Gas Generator</td>
<td>67.55</td>
<td>586.71</td>
<td>2637.85</td>
<td>607.50</td>
<td>4</td>
<td>4</td>
<td>12.5</td>
<td>8</td>
<td>0.19</td>
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<tr>
<td>7</td>
<td>Diesel Generator</td>
<td>117.59</td>
<td>808.86</td>
<td>3439.06</td>
<td>998.05</td>
<td>4</td>
<td>4</td>
<td>12.5</td>
<td>7</td>
<td>0.26</td>
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<tr>
<td>8</td>
<td>Propane Generator</td>
<td>60.79</td>
<td>697.03</td>
<td>2528.75</td>
<td>2044.16</td>
<td>4</td>
<td>4</td>
<td>12.5</td>
<td>8</td>
<td>0.37</td>
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<tr>
<td>9</td>
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<td>37.82</td>
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<td>1371.59</td>
<td>386.13</td>
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<td>20</td>
<td>5</td>
<td>0.08</td>
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<tr>
<td>10</td>
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<td>79.87</td>
<td>770.09</td>
<td>2437.86</td>
<td>173.82</td>
<td>7</td>
<td>3</td>
<td>25</td>
<td>6</td>
<td>117.12</td>
</tr>
</tbody>
</table>

Each exogenous factor level has weight factors that multiply the baseline attribute score, and change the $k_i$ weights in MAE and MAU functions:

- **Assumptions:**
  - Exogenous factors impact attributes independently
  - Exogenous factors will change one at a time

---

**Simple Evalutative Model**

\[
\text{Epoch Scores} = \text{Baseline Attribute Scores} \times \text{Epoch Weighting Factors}
\]

- **Value Model**
- **Utilities and Expenses**
- **Alternatives**

---

**Utility Attribute $k$-Factor**

<table>
<thead>
<tr>
<th>Exogenous Factor</th>
<th>Fuel 0.5X</th>
<th>Fuel 1.0X</th>
<th>Fuel 1.5X</th>
<th>Fuel 2.0X</th>
<th>Maintenance 0.5X</th>
<th>Maintenance 1.0X</th>
<th>Maintenance 1.5X</th>
<th>Maintenance 2.0X</th>
<th>Opinion Agree</th>
<th>Opinion Disagree</th>
<th>Opinion Neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exogenous Factor</td>
<td>0.246</td>
<td>0.196</td>
<td>0.146</td>
<td>0.106</td>
<td>0.093</td>
<td>0.083</td>
<td>0.073</td>
<td>0.066</td>
<td>0.5</td>
<td>0.15</td>
<td>0.10</td>
</tr>
<tr>
<td>Opinion Agree</td>
<td>0.246</td>
<td>0.196</td>
<td>0.146</td>
<td>0.106</td>
<td>0.093</td>
<td>0.083</td>
<td>0.073</td>
<td>0.066</td>
<td>0.5</td>
<td>0.15</td>
<td>0.10</td>
</tr>
<tr>
<td>Opinion Disagree</td>
<td>0.246</td>
<td>0.196</td>
<td>0.146</td>
<td>0.106</td>
<td>0.093</td>
<td>0.083</td>
<td>0.073</td>
<td>0.066</td>
<td>0.5</td>
<td>0.15</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Epoch Benefit-Cost Scatterplots

Within an epoch, what are “best value” solutions?

Use tradespace scatterplot to identify tradeoffs and “good” designs within an epoch.

Epoch: Baseline (N=6)
- None
- Solar Photovoltaic
- Solar Thermal
- Wind Turbine
- Heat Pump
- Natural Gas Generator
- Diesel Generator
- Propane Generator
- Heating Oil
- Geothermal

Epoch: Price Fossil Fuel 1.5X (N=5 out of 10)
- None
- Solar Photovoltaic
- Solar Thermal
- Wind Turbine
- Heat Pump
- Natural Gas Generator
- Diesel Generator
- Propane Generator
- Heating Oil
- Geothermal

Epoch: Price Fossil Fuel 2.0X (N=4 out of 10)
- None
- Solar Photovoltaic
- Solar Thermal
- Wind Turbine
- Heat Pump
- Natural Gas Generator
- Diesel Generator
- Propane Generator
- Heating Oil
- Geothermal

Epoch: Cost of Maintenance 0.5X (N=6 out of 10)
- 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)
- 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)
- 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)
- None
- Solar Photovoltaic
- Solar Thermal
- Wind Turbine
- Heat Pump
- Natural Gas Generator
- Diesel Generator
- Propane Generator
- Heating Oil
- Geothermal

Tradespace Concept
- Benefit
- Cost
- Yield = 100 / 1000 = 10%

Epoch: CSER 2019
Apr 3-4, 2019
An alternative MUST meet minimum acceptability levels in both MAE and MAU in order to be feasible.

### Feasibility Matrix

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Photovoltaic</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
</tr>
<tr>
<td>Solar Thermal</td>
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<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
</tr>
<tr>
<td>Wind Turbine</td>
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<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
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<td>Heat Pump</td>
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<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
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<tr>
<td>Natural Gas Generator</td>
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<td>Feas</td>
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<tr>
<td>Diesel Generator</td>
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<td>Feas</td>
<td>Feas</td>
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<tr>
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<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
</tr>
<tr>
<td>Heating Oil</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
</tr>
<tr>
<td>Geothermal</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
<td>Feas</td>
</tr>
</tbody>
</table>

### All Epoch Cases

Epochs 1-15 are represented with feasible or infeasible status for each alternative. The table highlights the difficulty in achieving feasibility across different alternatives and conditions.
Sensitivity to the Epochs

Across what fraction of epochs is a solution "best value"?

Tradespace Concept

NPT

0.000

0.000

0.000

0.000

0.000

0.000

0.000

0.000

0.000

0.091

0.455

0.636

0.818

None

Solar Photovoltaic

Solar Thermal

Wind Turbine

Heat Pump

Natural Gas Generator

Diesel Generator

Prop Gas Generator

Heating Oil

Geothermal

Fuzzy Normalized Pareto Traces Results

fNPT is the fuzzy Normalized Pareto Trace

Used to find passively value robust alternatives
### Era Descriptions

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

### How do solutions perform across time shifting uncertainties?

![Graphs showing performance over time](image)
It can be useful to summarize trajectory data via an aggregation function

**Pro:** simplify analysis

**Con:** must make assumptions

**Operational value:** time-weighted average MAV, penalizing infeasibility at a point in time with 0 or 1 score for MAU/MAE respectively
Trades Across Homeowners

Interviewed Homeowner Preferences

Homeowner 4

The “Average” Homeowner

Epoch: Baseline (N=6)

Epoch: Baseline (N=6)

Epoch: Baseline (N=6 out of 10)
Average for All?

Homeowner 4

Homeowner 2

The “Average” Homeowner

<table>
<thead>
<tr>
<th>Distributed Generation Selection</th>
<th>Homeowner</th>
<th>Rank</th>
<th>Normalized Pareto Trace</th>
<th>Operational Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Homeowner</td>
<td>1st</td>
<td>Solar PV</td>
<td>Solar PV Solar PV Solar PV Solar PV Solar PV Solar PV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3rd</td>
<td>Heating Oil</td>
<td>Heating Oil Heating Oil Geothermal Heating Oil Geothermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3rd</td>
<td>Heating Oil</td>
<td>Heating Oil Heating Oil Geothermal Geothermal Geothermal</td>
</tr>
<tr>
<td></td>
<td>Homeowner 2</td>
<td>1st</td>
<td>Heating Oil</td>
<td>Geothermal Solar PV Solar PV Geothermal Solar PV Geothermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd</td>
<td>Heating Oil</td>
<td>Heat Pump Geothermal Geothermal Solar PV Geothermal Solar PV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3rd</td>
<td>Solar PV</td>
<td>Heating Oil Heat Pump Solar Thermal Heating Oil Solar Thermal</td>
</tr>
</tbody>
</table>

CSER 2019
Apr 3-4, 2019
Discussion

- EEA approach structured investigation of “robust” decisions across 2 timescales for uncertainty: point futures (epochs) and time-series futures (eras)
  - Different rankings for alternatives for epoch vs era robustness
- The values for decision makers are key in directing “best” solutions
  - Care must be taken in recognizing difference between “average” and custom preferences
  - When possible, decision makers are better off if treated as distinct


Questions?
Era Swing (1 of 3)

The “Average” Homeowner

Homeowner 2

Homeowner 4
Era Swing (2 of 3)

The “Average” Homeowner

Homeowner 2

Homeowner 4
Era Swing (3 of 3)

The “Average” Homeowner

Homeowner 2

Homeowner 4