Final Application Portfolio

Community Level Solar Energy System

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ESD.71
Fall 2010
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Abstract

The engineering system under analysis is a single home within a community-level solar energy system. The goal was to effectively model the home's electricity consumption across an entire 20-year system life span. The simulation included solar arrays for power generation, a flywheel for energy storage as well as uncertain inputs for grid provided electricity price growth rates. Decision rules were established to determine whether or not to increase the size of the solar array based that were dependent on potential year to year increases in electricity prices.

Even with government subsidies included, the system was not profitable in any scenario tested. This is largely due to the high capital expenses combined with energy savings totaling under $1,000/year per home. With a discount rate of 10%, these savings were insufficient to turn the enterprise profitable.

Modeling more than one home may allow economies of scale to be realized through the use of demand response load leveling. However, significant financial savings are realistic only if electricity prices increase significantly or capital costs, especially for the flywheel energy storage system, decrease considerably.

Another aspect often considered when exploring the utility of such a system is the benefit it provides to the environment. In this case, use of the system would result in a reduction of approximately 6.8 metric tons of carbon dioxide emitted into the atmosphere per home per year.

Acknowledgements

Special thanks to Howard Yue for his advice on mechanizing my model. His advice was instrumental in handling a system with so many data points.

Contents

1.0 System Definition

The engineering system being explored is a community-level solar energy system. Rather than each individual home in a community or housing development attempting to employ alternative energy source such as solar panels individually, I am curious if there are economies of scale for a system designed to operate at the community level.

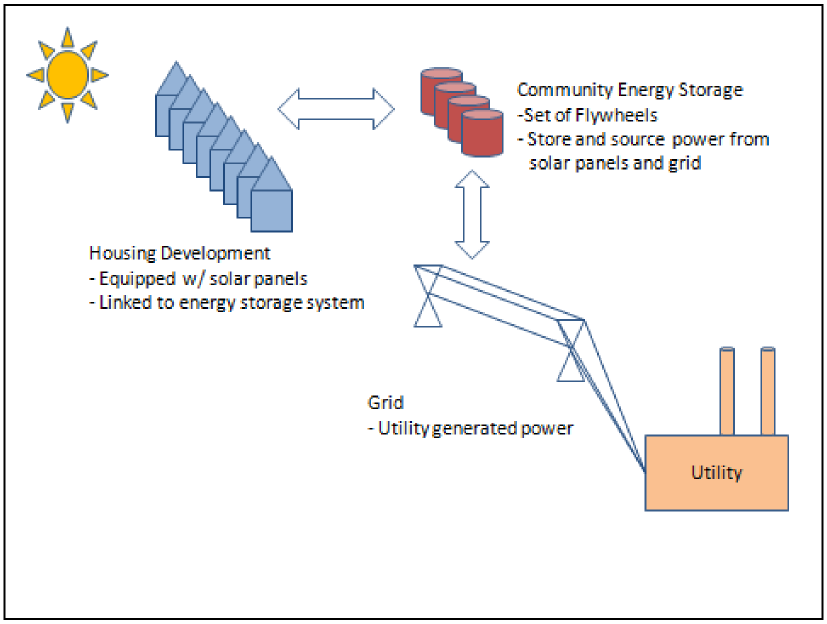

Figure 1 System Overview Graphic

Figure 1 shows a top-level overview of the complete system. The system's operation is best described over the course of a 24-hour cycle:

- ***12 am midnight (0000 hrs)***

The cycle begins at midnight when lower cost, off-peak power from the grid is used to recharge the community energy storage bank. This bank is envisioned to be a set of flywheels which would "spin up" converting electrical power into rotational kinetic energy.

- **6am-5pm (0600-1700 hrs)**

Beginning between 6 and 9am when people start to begin the day through the morning "rush hour" period, power is sourced from the energy storage bank to the houses avoiding the need for more expensive, peak power from the grid. This is done by converting rotational kinetic energy back into electrical power. Simultaneously, as the sun rises, electricity is generated by the community's solar arrays. Solar power is generated throughout the day which is then used to provide power to the houses with any excess going first to the energy storage bank and secondly back to the grid for a credit.

- **5pm-12am (1700-0000 hrs)**

In the late afternoon when solar energy available starts to decline and people return home from the day's activities, energy usage peaks. Power is again pulled from the energy storage bank as well as the grid as necessary to cover the energy needs of the community during the evening's peak activities. The cycle then repeats again late in the night when charging of the energy storage bank is repeated.

The potential advantages of this system over independent systems installed by homeowners include the ability to spread the costs of power generation and storage equipment across many homes. Another advantage is the homes in the development may share the aggregate power generated increasing efficiency of the overall system. At any given time, some homes may be in surplus while others may be consuming. This would allow one set of solar panels to drive HVAC units across multiple homes if those units were sequentially cycled on and off in an intelligent manner so all were not drawing power at the same time. Along the same lines, the system also enables participation in the "demand response" market where power use is shifted in time to avoid peak use times. Utilities often pay for this service if the offset in demand is sufficiently large in magnitude.

1.1 Scope of Study

As shown in Figure 2, the scope of this study was to build a simulation of a single home's operation within a community level system. This simulation could then be used to explore design and operational options and flexibilities. While outside the scope of this effort, variants of this model can subsequently be aggregated together in order to create a working model of an entire development. Another option for further study would be to use the high fidelity model of an individual home's behavior to create a screening mid-fidelity model with which to explore community level operation and design flexibilities.

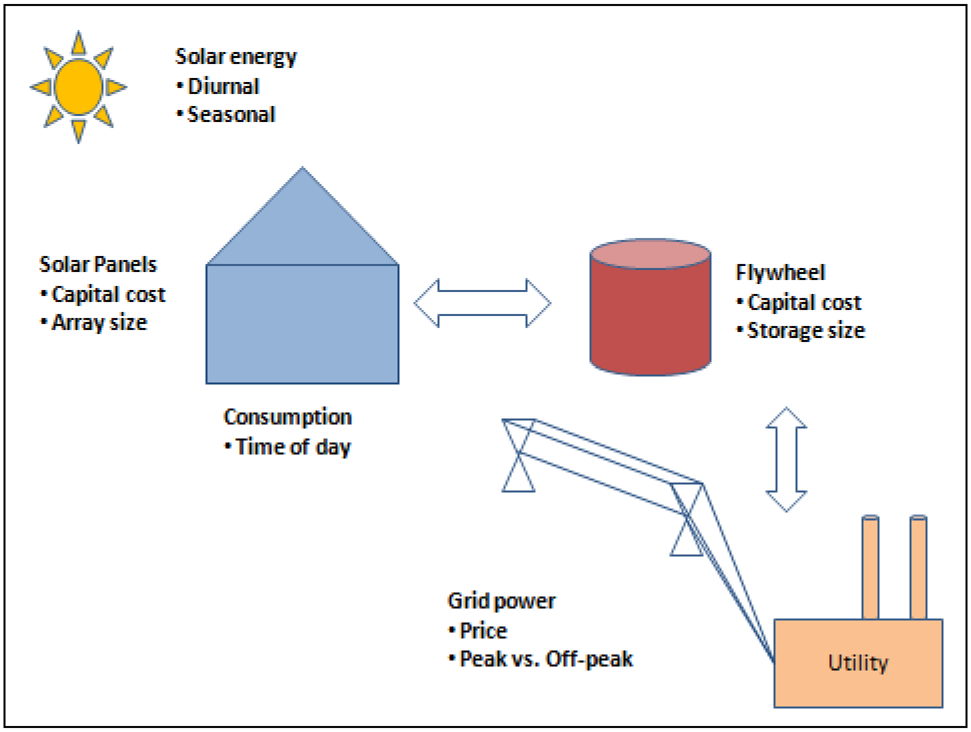

Figure 2 Model Scope

2.0 Model Structure

The model was structured to capture performance on a hourly basis across an entire year (8,760 hours). This performance was then replicated across 20 years of operation (175,200 hours) in order to allow for flexibilities to be incorporated from one year to the next based on decision rules discussed in section 2.6. This section describes how each component shown in Figure 2 above was modeled.

2.1 Solar Energy / Solar Panel Output

The hourly energy output of a solar panel array is largely dependent upon three factors: The size of the array, the solar insolation incident on the panel and the efficiency of the conversion from DC to AC power. The National Renewable Energy Laboratory provides an on-line utility known as PVWATTS that generates representative hourly AC electricity output across a full year given the location, orientation and size of the array. (National Renewable Energy Laboratory, 2010). This utility was used to generate power output data for differing sizes of solar array. The first was a 5.5kWh installation consisting of 24 230-watt panels. This array is the size initially installed on the home. The second was a 0.92 kWh installation consisting of 4 panels. This array was the increment of additional panels that would be added in later years of operation if decision rule criteria were met. Table 1 provides the parameters used by PV Watts to generate hourly data.

Paramenter	5.5 kWh Array	920 Wh Array
City:	TUCSON	TUCSON
State:	Arizona	Arizona
Lat (deg N):	32.12	32.12
Long (deg W):	110.93	110.93
Elev (m):	779	779
Array Type:	Fixed Tilt	Fixed Tilt
Array Tilt (deg):	32.1	32.1
Array Azimuth (deg):	180	180
DC Rating (kW):	5.5	0.9
DC to AC Derate Factor:	0.77	0.77
AC Rating (kW):	4.3	0.7
Cost	$17,139	$2,500
yearly output (kWh)	9178.20	1529.67

Table 1 Parameters for Model Solar Array

The costs of the arrays were obtained from a wholesale seller of solar power systems. The price for the 5.5kWh array was the complete system price including the inverter necessary to convert DC electricity to AC power suitable for home use. The 0.92 kWh system cost included only the panels since it is expected that these would just be added to the existing system and utilize the same supporting electronics. (Wholesale Solar, Inc., 2010) Figure 3 provides a snapshot of the data output from the PV Watts tool that was used in the simulation. Two days worth of hourly data are shown for the 5.5 kWh array. The table shows there is are distinct differences in output from hour to hour and day to day. Therefore in order to get a picture of true system performance, it was important to model the system throughout the entire year on an hourly basis.

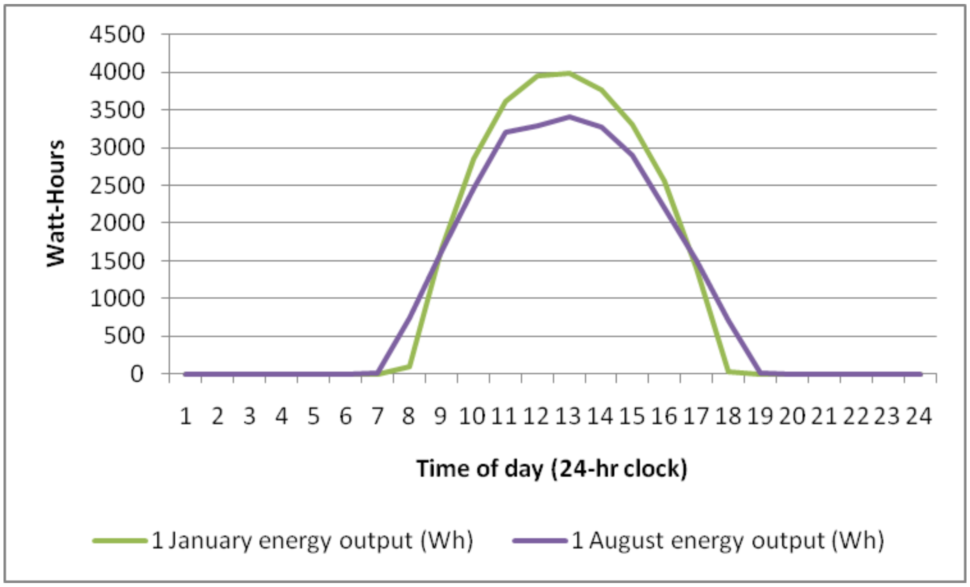

Figure 3: Hourly Solar Energy Output (5.5 kWh Array)

2.2 Consumption Profile

The next step in building the model was to create a profile for the home's energy consumption across each 24 hour period. Residential energy use can be viewed as consisting of two components. A variable load tied to the amount of heating or cooling required plus a base load that includes all other electricity uses (lighting, appliances, etc). The variable component was calculated using monthly heating and cooling degree days for Tucson (NOAA, 2010). As a simplification, the degree days per month were allocated equally across each day in the month. The next step was to determine an appropriate way to allocate a day's worth of consumption across each of the 24 hours in the day. Research revealed two applicable load profiles, one for week days and one for weekend days. (LaCommare, 2002) Based on the research, load profiles were created and are shown in Figure 4. These profiles were then used as multipliers to allocate consumption across each 24 hour period. On average, annual residential consumption in Arizona totals 1,095 kWh per home. (US Energy Information Administration, 2008)

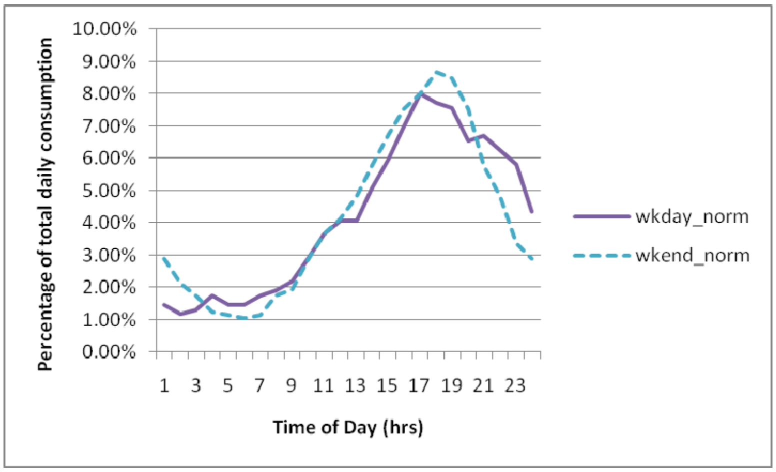

Figure 4 Home Power Consumption Load Profiles

2.3 Energy Storage

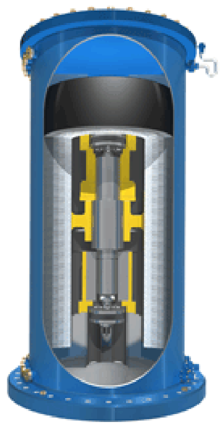

Figure 5: Flywheel (http://www.beaconpower.com)

The community level system utilizes flywheels for energy storage. They have the ability to spool up and down as required to either store or source energy and are not cycle limited. One maker of fly wheels, Beacon Power of Tyngsboro Massachusetts, indicated that they have fabricated flywheels with 3 kWh or 25 kWh capacities. A rough estimate of price for the 3 kWh system was $60,000 while the 25 KwH system was roughly $120,000. The price did not rise at the same rate as energy storage since a large part of the cost is the controlling electronics and motor/generator which remains fairly constant in price regardless of the flywheel's capacity. (Polimeno, 2010)

As an initial approach to determining the best size flywheel for the model, flywheel size was varied and the effect on yearly operational savings was observed. The "Solver" function within Excel was used to find the flywheel size that would yield the maximum yearly operational savings in the no-uncertainty model. For this static base case, the best size flywheel was one with a 12.67 kWh capacity. This capacity is fortuitously within the bounds of Beacon Power's production ability. In a more complex model (ie one incorporating HVAC unit use scheduling), the optimum size would likely change since hourly power consumption would be altered. As shown in Figure 6 below, within the confines of the current model, savings are fairly stable at flywheel sizes between 5 and 15 kWh. Therefore in order to minimize capital costs, a 5 kWh flywheel was chosen with an assumed capital cost of $60,000.

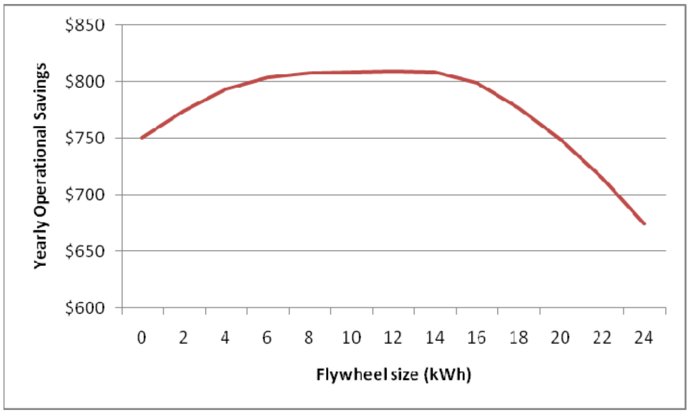

Figure 6 Flywheel Size vs. Operational Savings

2.4 Grid Power

The US Energy Information Administration forecasts average residential electricity prices annually as part of its Annual Energy Outlook (AEO) report. The report also includes historical actual prices dating back to 1970. Figure 7 is a graph of the historical prices as well as predicted prices from each of the AEO reports from 2000 to 2009.

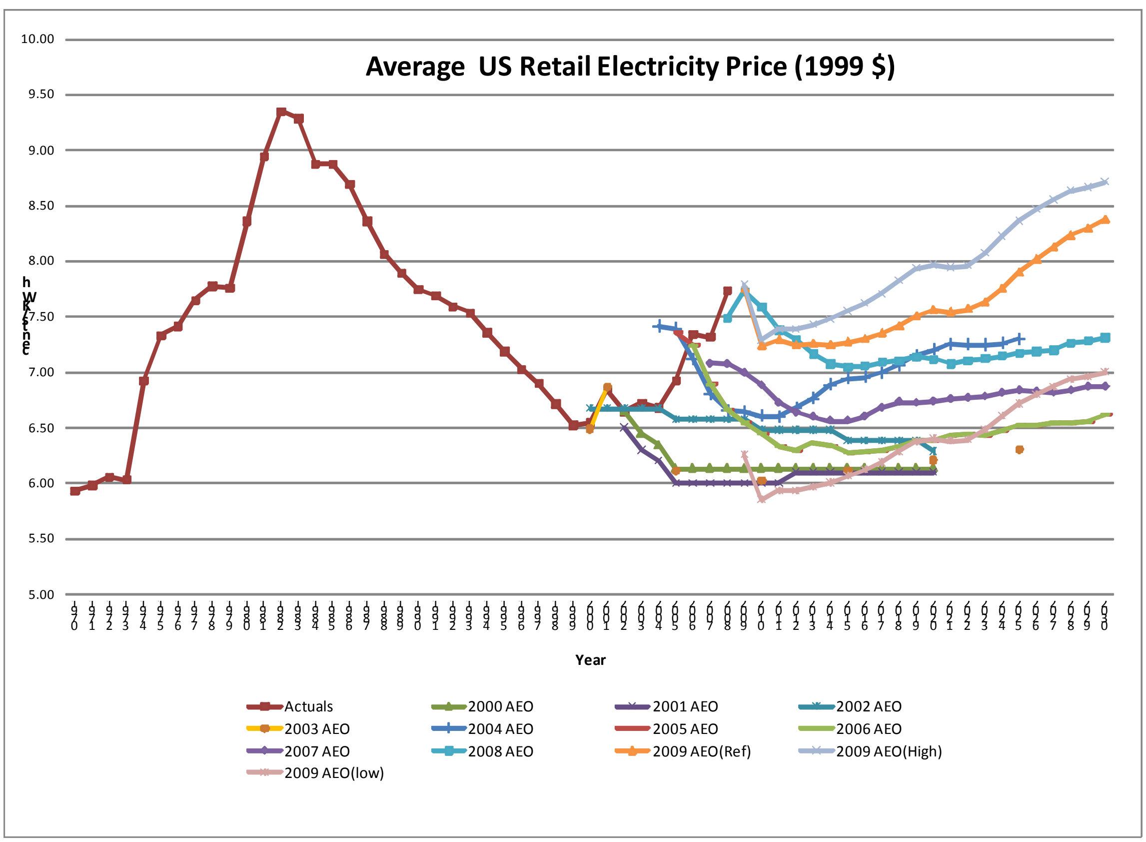

Figure 7 Historical and Predicted Electricity Prices

As briefly discussed in the ESD.70 excel primer, a series like electricity prices over time can be considered a stochastic process. Some of the earlier predictions appear to be based on a mean-reversion model with 6 cents/KWh being the mean. However, actual behavior appears to be better modeled by a random walk type model.

Within the model, grid provided electricity was priced in one of two ways depending if it was being consumed during peak hours (1200-1800 hrs) or off-peak hours. At the start of the simulation, the peak power price was set to the current average in Arizona, $0.103/kWh. Off-peak power was set throughout the simulation as two-thirds the price of peak power. Regardless of time of day, it was assumed that any power sold back to the utility would be priced the same as off-peak power. For subsequent years, The peak power price was based on the previous year's price plus a growth trend of 1%-5% of the previous year's price plus a normally distributed random component with a standard deviation equal to plus or minus 10% of last year's peak power price.

2.5 Government Subsidies

Upon reviewing the results of initial simulations, Mr. Howard Yue mentioned the possibility of subsidies. Additional research was conducted and it appears that combined federal and state subsidies for solar system installation result in rebates of roughly $2.70 per Watt DC rating of installed solar power panels. (Tucson Electric Power Inc., 2010) These subsidies were added to the simulation and greatly reduced the CAPEX of the project.

2.6 Simulation Decision Rules

Following execution of the simulation in a static mode, decision rules were implemented allowing flexibility to be incorporated at the end of each year. The first set of decision rules involved whether to expand the solar array at the end of each simulated year. The rule is currently mechanized as follows:

If the current year's grid provided electricity price is 10% or more above last year's price, add an additional 4 panels to each home's array.

This rule was chosen in order to increasingly reduce reliance on grid-provided power if it became significantly more expensive as time progressed. At some grid-power price, (albeit not a currently realistic one), it is expected that the capital costs incurred due to expansion will be offset by the operational savings generated by the larger array.

The decision rule was implemented using two different thresholds for increasing the size of the solar array. The first threshold used was a 10% year-to-year increase in the price of grid power as described above. A second threshold of 5% was also modeled along with a higher trend growth rate of 2% for grid electricity price.

3.0 Deterministic Design Results

The simulation was first run across 20 years of operation without the above decision rule in place. Regardless of the price of electricity, the solar array size remained fixed at the 24 panels (5.52 kWh).

Figure 7 shows the interplay between the solar panels, flywheel and net consumption over the course of two days. At the start of day 1 (hour 1) , the flywheel is fully charged with off-peak power from the grid. As the night goes on, the slow rate of consumption is sourced from the energy stored in the flywheel. Between 0700-0900 hrs (hour 7-9), the sun rises which results in more power being generated that consumed. The surplus power is used to spool back up the flywheel to its maximum capacity of 5 kWh where it remains until 1700 hrs (hour 17). Without any more solar power being generated, the energy in the flywheel is rapidly depleted and power is again drawn from the grid. The cycle begins again and similar results occur over the course of the second day (hours 24-48). The shape of the curves is different due to differences in the the solar power generated between the two days.

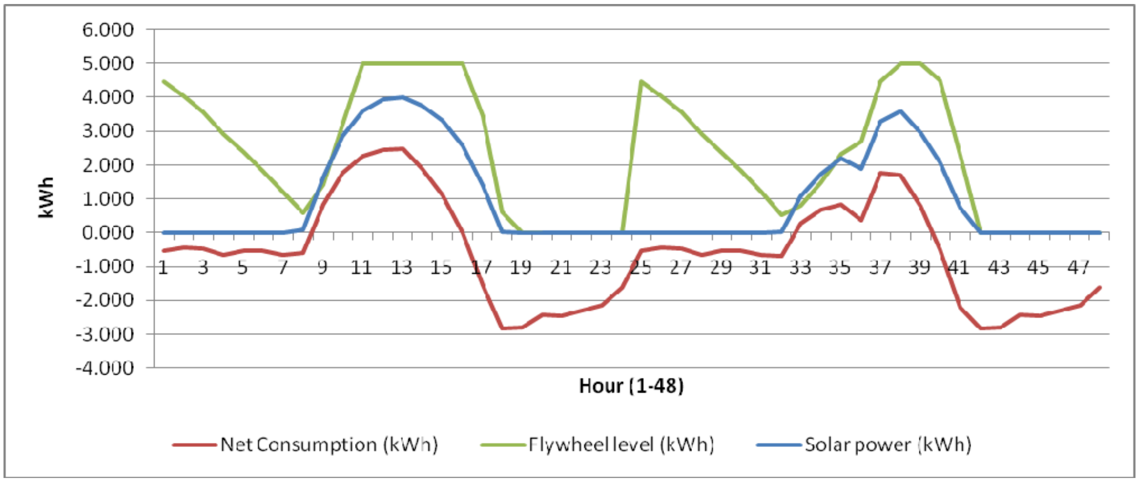

Figure 8 Energy Flow Over 2 Days

The following provides very top level information on the financial outcome of the simulation. Although in each year, between $700 and $1,500 is saved in electricity costs, when discounted at 10% they are insufficient to overcome the large capital expense of the system. This holds true even with a generous subsidy of $2.70/Watt DC installed.

Summary of Results	
CAPEX	$14,235.00
Project NPV	($6,086.38) Loss

Table 2 Static Case Results

4.0 Results with Flexibility Incorporated

The next step was to conduct monte carlo simulationof the system using @Risk. Electricity price variability was introduced and the decision rule on expansion was put into place. With the decision rule requiring a 10% growth in electricity price from one year to the next, a simulation of 500 runs did not result in a single case of expansion. The mean NPV of the project was a negative $6,087 as shown in CDF below (Figure 9). This result indicates that for realistically slow growth rates in grid electricity price, there will be no expansion of the solar array over the 20-year life of the project.

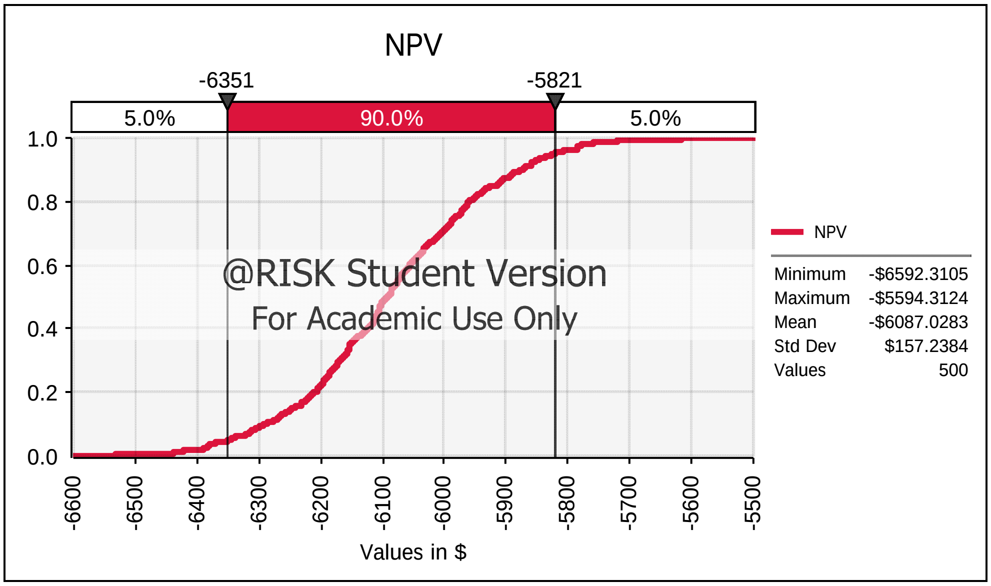

Figure 9 Flexible Case CDF (10% expansion rule)

As discussed previously, a second Monte Carlo simulation was run with the decision rule changed to result in solar array expansion if the electricity price from year to year grew by 5%. This changed the CDF that shown in Figure 9 above to the CDF shown as Figure 10 below.

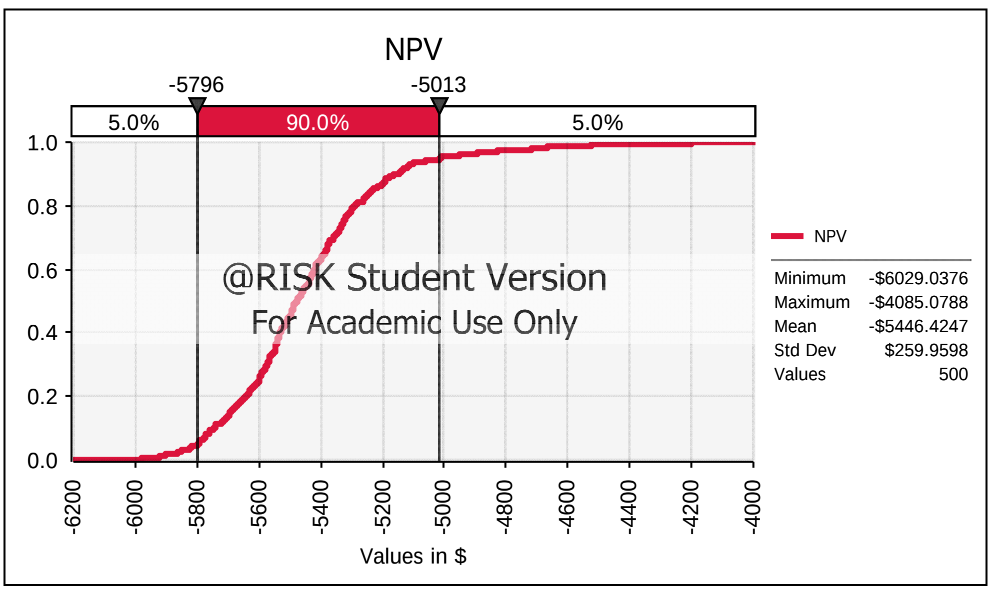

Figure 10 Flexible Case CDF (5% expansion rule w/ 2% grid price growth rate)

It appears that introducing flexibility improved the upside of the system with the 90% point moving from -$5,821 to -$5,013.

One additional case was modeled in order to examine system behavior if the price of grid-provided electricity grew with a faster trend rate of 3%. The decision rule was kept at expansion if the price of electricity grew 5% from one year to the next. The resulting CDF is shown below as Figure 11. As the electricity price trend growth rate increases, system financial losses decrease. Expansion of the array always led to an increase in the NPV (albeit still negative in total). This indicated that there were no "false alarm" expansions which would have occurred if the price of electricity had plunged after expansion had occurred. Such a large movement in electricity price could be forced by altering the way price is modeled (increasing the variable component of the price).

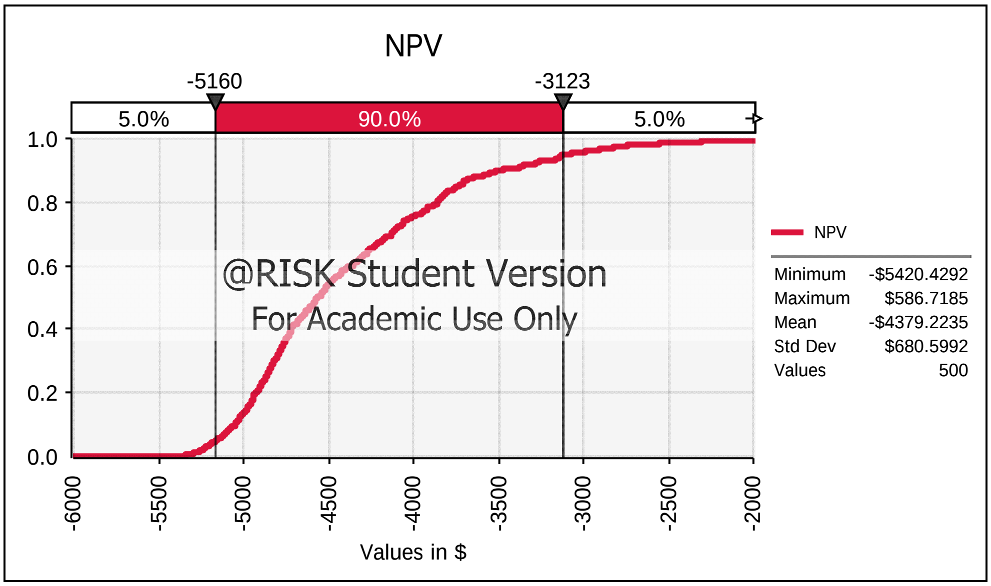

Figure 11: Flexible Case CDF (5% expansion rule w/ 3% grid price growth rate)

Threshold	Mean	P90	P05	Std Dev
10% w/ 1% trend	($6,087)	($5,821)	($6,351)	$157
5% w/ 2% trend	($5,446)	($5,013)	($5,796)	$260
5% w/ 3% trend	($4,379)	($3,123)	($5,160)	$681

Table 3 Summary of Results

5.0 Conclusions

In the case of this simulation, a better decision rule set would be one that maximized the savings generated by the solar power system. At current prices and assuming that not constructing the system is not an option, the best decision rule would be one that produced the lowest loss over the duration of the system's operation.

As shown above, the decision rules initially chosen for this simulation are not very effective in generating varied outcomes. While the results improve as the rate of electricity price growth was increased, each simulation resulted in a net negative NPV. This was the case even with a generous upfront subsidy. This is due to the large capital expense of the system in comparison with savings under $1,300 in each year of operation.

Since all Net Present Values are negative, from a strictly financial perspective this project should not be undertaken unless capital expenses decrease considerably or the price of electricity grows much more rapidly than it has in the past. However, the project may still be feasible if the system was viewed as providing social value to its customers in the form of less reliance on fossil fuel based grid power and hence a "greener" environment. Operation of the system avoids the generation of over 11,500 kWh per year. On average, electricity generation across the United States produces 1.3 pounds of carbon dioxide per kWh generated. Thus operation of this system avoids the release of over 6.8 metric tons of carbon dioxide per year per home.

6.0 Reflections

This exercise drove home the realization that modeling real world systems is a complex endeavor that relies on numerous underlying assumptions and calculations. It is extremely important to understand the assumptions being made in order to determine if they are realistic and if they would be better represented using uncertainty rather than a discrete point value. Just as important is the conducting of a rigorous review of all algorithms used in the simulation. Throughout this project, coding errors were discovered that distorted the results until they were found and corrected.

Flexible design is most useful in the face of the large uncertainties. If the future is very predictable, flexibility in design does not return as much value as it does when the future is unknown. Flexibility provides the ability to minimize losses in the face of a negative future while also maximizing returns in the face of positive outcomes.

This application has clearly demonstrated to me how complex a system model can become and how important it is to understand the sources of uncertainty and the places where management decisions can have the greatest effect. This application would be perfect for the use of a screening model approach where once the behavior of one home was characterized during 20 years of hourly operation, the results could be used to create a less detailed model at the community level in order to further explore sharing of resources across the community and the expected benefits in doing so.

7.0 Next Step

If this project was continued after the conclusion of ESD.71, the next step would be to create a screening model that could be used to create a model where interactions between multiple houses could be explored. Making this project feasible from a financial perspective depends on how much additional savings can be generated through the intelligent cycling of appliances and HVAC units across multiple homes to reduce, spread and shift the instantaneous demand for power in order to maximize use of solar and off-peak power.

8.0 References

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