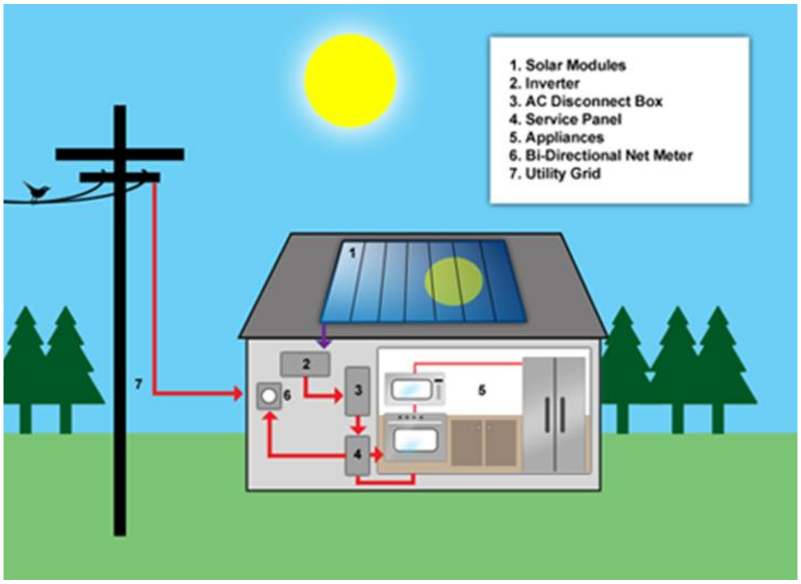
EXERCISE THREE

MICROGRIDS IN A DISASTER



Prepared for Systems Dynamics SYSC 514 (Winter 2016)
Submitted on 3/12/16
Prepared by Lindsay T Mico

The Challenges of Collaboration

An initial goal for this modeling exercise was to (attempt to) collaborate with both other modelers (i.e. fellow class participants) and a subject matter expert (SME) (in this case Mike Hoffman, PNNL). Collaboration was largely unsuccessful unfortunately, and resulted in **very** significant delays in developing a working model framework. As such the author was not able to accomplish some of the outcomes originally anticipated.

Collaborating with a subject matter expert (and in this case also the project proponent or "client") is a key skill for any modeler or analytics consultant. In this case, the primary challenge was that the client did not clearly understand the time and resource constraints associated with the exercise. As such, during an initial kick-off meeting the client was unable to clearly define an achievable set of desired outcomes. It is the author's experience (as a ten+ year consultant) that this is common and in no way reflects negatively on the client. It does, however, emphasize that clear and frank communication about what can be achieved within the constraints of a project is essential to overall success. However as a result of this disconnect the author was not able to engage as meaningfully with the client as originally anticipated. The overall impact on the project as a result of this disconnect was limited to the very early stages, and simply added a layer of complexity to defining the problem space for the project.

In contrast, collaborating with a fellow modeler had a large and substantially negative impact on the quality and timing of the project. The challenges were 1) appropriately dividing tasks, 2) meeting timelines, and 3) integrating feedback from both sides along the way. In this case, the fellow student expressed a desire to play a primary role in developing the initial model framework, and the author agreed to support as needed and requested. At this point, the author agreed in turn to lead calibration and model documentation. In general the author accommodated the expressed desires and intentions of his collaborator. Unfortunately, the quality of work provided to the author was very poor, behind schedule, and lacked sufficient detail to calibrate and run. As such the author was forced to discontinue the collaboration with a week remaining and start from scratch.

It is particularly challenging to model collaboratively in Vensim because of the interdependencies between model components, and the use of a GUI rather than a code based interface. Modeling in a code based environment facilitates independent parallel work on discrete model elements as well as use of version control tools such as Git. There is no intrinsic reason that an SD model cannot be implemented via code, and the author did use GIT internally when preparing the model (.mdl files can be read as text files and uploaded to GitHub). Furthermore, there is an existing Python toolset intended to convert .mdl files into a Python executable script. Although time and resources did not allow experimentation with this tool, it is promising as a way to extend and connect SD models to the broader data science ecosystem. Further info can be found at https://github.com/LTMico/pysd .

More specifically, the author had hoped to address a number of issues itemized below, but was unable to accomplish them due to the aforementioned time limitations. However as the author 1) made a good faith attempt to engage in a productive collaboration outside of his subject matter expertise, and 2) the delays were not the fault of the author, it is hoped that grading and evaluation will take these extenuating circumstances into account.

Key areas/issues originally included in the problem (but scrapped due to lack of time):

- Incorporating budget and equipment cost into the model to identify an optimal use of resources
- Including specific product specifications for household elements such as lighting, appliances, insulation, and the like

Additionally, although the final model accurately reflects the system at a quantitative level, the operationalized model (in SFD form) structure is complex and is more difficult to intuitively understand than desired. Although some of this is due to the limitations of the Vensim package, it is possible that with more time the author could have generated a more elegant modeling framework.

Despite the challenges discussed above, the author remains committed to collaborative work, open sharing of information, ideas, and technology, and views this as a positive learning experience. The primary lessons learned from this effort are to 1) very carefully vet the technical qualifications of a potential collaborator (err on the side of caution here) and 2) build a basic framework **together**, ideally in person.

Problem Formulation

The primary goal of this exercise was to develop and calibrate a model to represent a single residence microgrid system. A microgrid can be defined as '"a localized grouping of electricity sources and loads that normally operates connected to and synchronous with the traditional centralized grid (macrogrid), but can disconnect and function autonomously as physical and/or economic conditions dictate."

The primary goal of this modeling exercise was to simulate the response of a household microgrid to a disaster event, like the subduction zone earthquake, in which the home is cut off from the electrical grid for an indefinite period of time. The main question of interest was how long could a home operate (i.e. produce heat, light, and run appliances) while cut off from the grid? The modeled house contains the following elements:

- Grid connection
- Solar installation (Photovoltaic array + inverter)
- Onsite battery storage
- Onsite gas generator with limited fuel
- Wood stove to be used for heating
- Appliances, light, and electric heat

Due to time and scope limitations (discussed above) these components were modeled at a relatively abstract level without consistent reference to specific products (or their technical specifications). <u>The author explicitly acknowledges that the model structure does not necessarily reflect the mechanistic structure of power generation, storage, and usage.</u> The modeling effort was intentionally focused on addressing the question posed above related to disaster impacts. A non-exclusive list of refinements and improvements to this model are briefly noted at the close of this document. Review and input from a SME are likely to add substantially to that list.

A key methodological requirement was that the model be designed to use and distribute energy in a logical fashion at each time step. Implementing these controls within Vensim was a key methodological challenge for the author and represented a substantial change from the previous course exercises which focused on natural systems (and thus do not have On/Off control systems). These logical requirements (**which are a key part of the reference behavior pattern or RBP**) included the following:

- The gasoline generator is used only when the grid is off **and** the PV array + Battery does not generate sufficient power to meet demand.
- The wood stove is only used as a backup to offset the heat demand when the grid is off
- The batteries only charge when the output of the PV system exceeds the demands on the house.

A second methodological challenge was to identify and apply existing real world data to model calibration. The primary goals of calibration (**another part of the RBP**) were the following:

- Ensure that we get the right amount of power out for a given solar input and PV array size
- Ensure that the heat output is reasonable for a given volume of wood
- Ensure that we get the right amount of power out for a given volume of gas
- Ensure that the total energy usage per household matches real world usage

Model Development

Model development proceeded rapidly once collaboration was terminated. A Stock and Flow diagram (SFD) was developed to represent the system described in the Problem Formulation above. Emphasis was given to including model components and structure needed to realistically answer the question posed above relative to disaster response. As such power generation and storage systems were by necessity substantially simplified in the interest of time as discussed above.

The model was developed using Vensim PLE Plus, with additional data stored in the form of an .XLS spreadsheet which is read into the model at each time step. The final SFD is shown below.

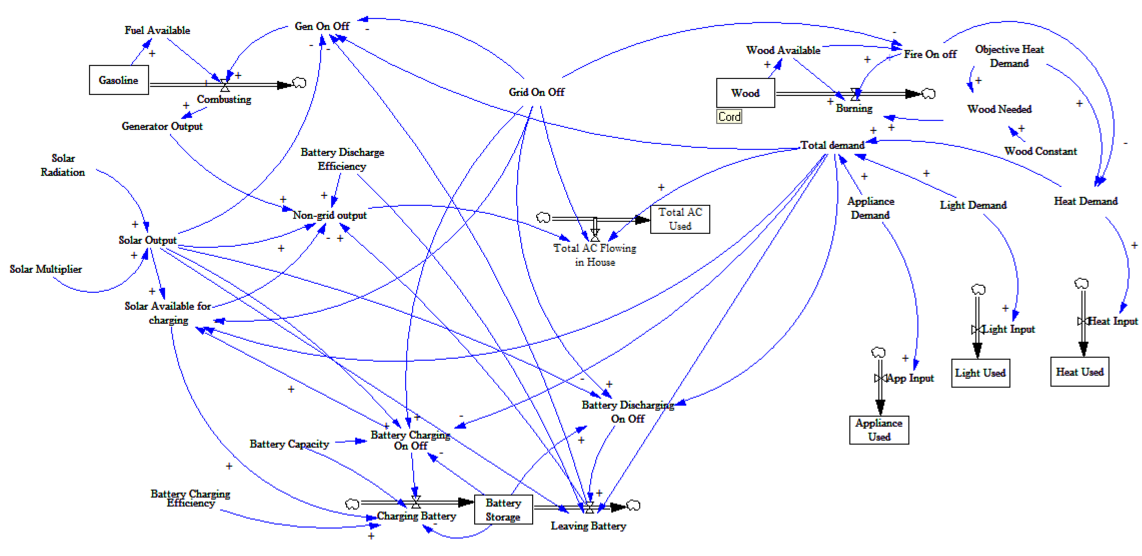


Figure 1. Final SFD of the Home Microgrid

The unit of time was set as one day, with numeric integration occurring every 0.015625 units. This value was chosen primarily to minimize integration errors associated with battery charging. Please note that throughout this document the term ‘time step’ is often used for convenience to refer to a single day, rather than a fraction of it as used by the model. The model was run over 730 days (or two years) to capture the behavior of the system through the full cycle of the seasons. The model begins on the first day of the year (January 1^{st}) and ends on the last (December 31^{st}).

Stock variables include the following:

- Gasoline = INTEG(-Combusting) [*Initial Value = 100 gallons*]
- Wood = INTEG(-Burning) [*Initial Value = 4 cords*)
- Battery Storage = INTEG(Charging Battery-Leaving Battery) [*Initial Value = 0*]
- Total power used = INTEG(Total AC Flowing in House) [*Initial Value = 0*]
- Power used for appliances = INTEG(App input) [*Initial Value* = 0]
- Power used for lighting = INTEG(Light Input) [*Initial Value = 0*]
- Power used for heating = INTEG(Heat Input) [*Initial Value* = 0]

Flow variables include the following:

- Total AC flowing in house = IF THEN ELSE(Grid On Off=1, Total demand , MIN("Non-grid output”, Total demand))
- App Input = Total AC Flowing in House*Appliance Demand/Total demand
- Light Input = Total AC Flowing in House*Light Demand/Total demand
- Heat Input = Total AC Flowing in House*Heat Demand/Total demand
- Burning = Fire On off*Wood Needed*Wood Available
- Combusting = Fuel Available*Gen On Off*3
- Charging Battery = IF THEN ELSE(Battery Storage<Battery Capacity, Solar Available for charging*Battery Charging On Off*Battery Charging Efficiency,0)
- Leaving Battery = Battery Discharging On Off*(Total demand-Solar Output)/Battery Discharge Efficiency

Auxiliary variables include the following:

- Non-grid output = Generator Output+Leaving Battery+Solar Output-Solar Available for charging
- Solar Output = ((Solar Radiation*3.01)+0.65)*Solar Multiplier
- Solar Available for Charging = Battery Charging On Off*(MAX(0,Solar Output-Total demand))
- Fuel Available = IF THEN ELSE(Gasoline>0, 1 , 0)
- Gen On Off = IF THEN ELSE(Grid On Off=0 :AND: (Solar Output+Leaving Battery)<Total demand, 1 , 0)
- Generator Output = Combusting*16
- Battery Charging On Off = IF THEN ELSE(Grid On Off=1 :AND: Battery Storage<=Battery Capacity:OR:(Grid On Off=0 :AND:Solar Output>Total demand) , 1 , 0)
- Battery Discharging On Off = IF THEN ELSE(Grid On Off=0 :AND:Battery Storage>0 :AND:Solar Output<Total demand, 1 , 0)
- Total Demand = Appliance Demand+Heat Demand+Light Demand
- Heat Demand = Objective Heat Demand*(1-Fire On off)

- Wood Available = IF THEN ELSE(Wood>0, 1 , 0)
- Fire On Off = IF THEN ELSE(Grid On Off=1, 0 , 1)
- Wood Needed = Objective Heat Demand*Wood Constant

Parameters include constants (i.e. they do not vary across time steps) as well as data imported from an .XLS file that provided values at each step. Parameters include the following:

- Solar Radiation = GET XLS DATA('InputData.xls' , 'Sheet1' , 'A', 'G2')
- Solar Multiplier = 1
- Grid On Off = 1 or 0
- Wood Constant = 0.00140795 cord
- Objective Heat Demand = GET XLS DATA('InputData.xls' , 'Sheet1' , 'A', 'C2')
- Light Demand = GET XLS DATA('InputData.xls' , 'Sheet1' , 'A', 'D2')
- Appliance Demand = GET XLS DATA('InputData.xls' , 'Sheet1' , 'A', 'E2')
- Battery Capacity = 100
- Battery Storage Efficiency = 0.85
- Battery Discharge Efficiency = 0.85

Model Verification & Calibration

Model testing and calibration was quite challenging for this exercise as the author lacks professional level expertise in microgrid design and power generation. Furthermore the substantial time limitations introduced by attempting to collaborate limited the time available to the author to fully research equipment specifications and design within the context of a working model framework. As such ***the author explicitly acknowledges that 1) he is not in any way a subject matter expert (SME) in microgrid design or power generation and 2) a substantial component of the power generation system (e.g. inverters) have not been explicitly represented in the model***. Prior to real-world application of this model, it is essential that a SME review and refine the assumptions of the power generation process. Put another way, although the model appears to generate qualitatively reasonable behavior, the quantitative output is assumed to be less realistic. With that in mind, a good faith attempt was made to use real world data to accurately calibrate the power generation components of the model.

Verification

As discussed above, defining the appropriate control logic for this model was challenging and complex. Therefore a primary goal of testing was to verify that the right systems engaged in the right order under different test runs. A series of structured model runs (i.e. control tests) were implemented to verify that the model behaved as desired and anticipated. Please note that the figures shown with each one were generated using an uncalibrated version of the model.

1. Testing that wood burning turns on if the grid is off, and with combusting proportional to the actual heat demand (*Grid off at time step 50, heat demand decreases at time step 75*)

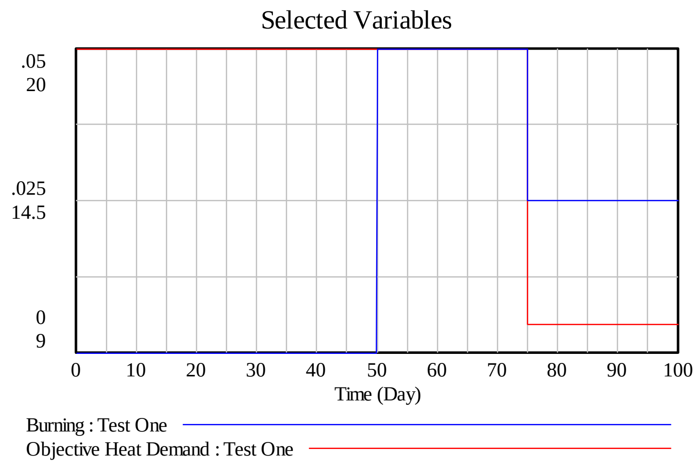


Figure 2. Control test one

2. Testing that the wood stove stops combusting if there is no wood left (*Grid off at time step 50, run model for 1000 steps to use up the wood storage – plot wood and combusting*).

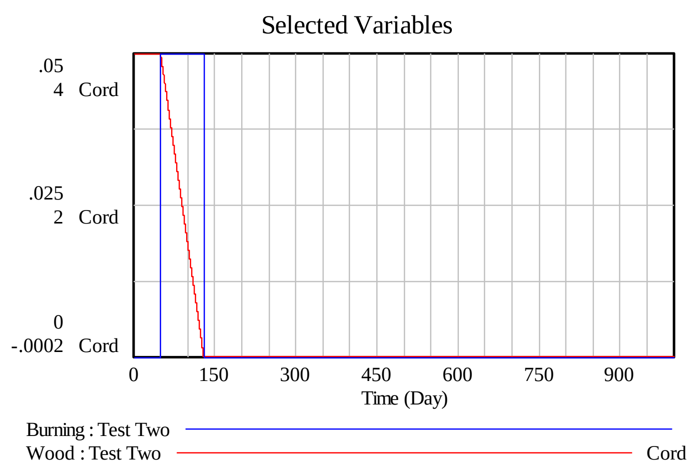


Figure 3. Control test two

3. Testing that the generator only turns on if the grid is off and PV + battery output is insufficient to meet the household demands (*Grid off at 50, PV + Battery Output > Total Demand until 75 step*)

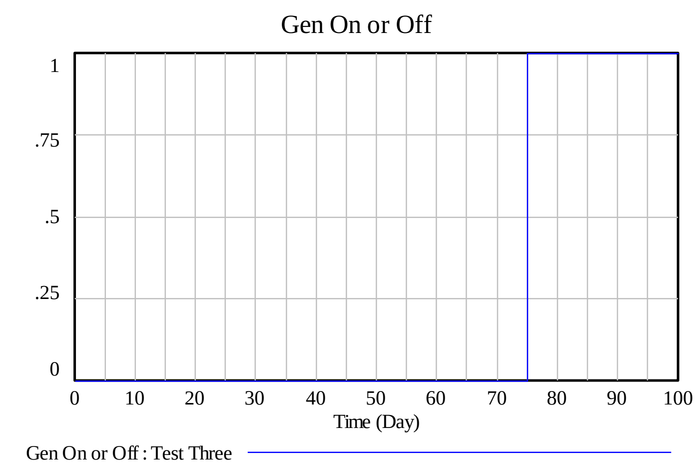


Figure 4. Control test three

4. Testing that the battery only turns on if the grid is off and the PV output is not enough to meet demands (*Grid off at 50, PV Output >Total Demand until 75 step*)

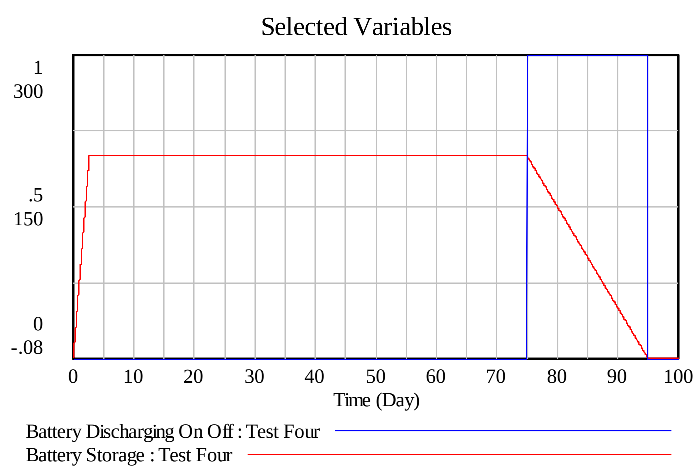


Figure 5. Control test four

5. Testing that the battery only charges to capacity, and only when there is excess PV energy (*Grid off at 50, solar > demand until 75, solar < demand after*)

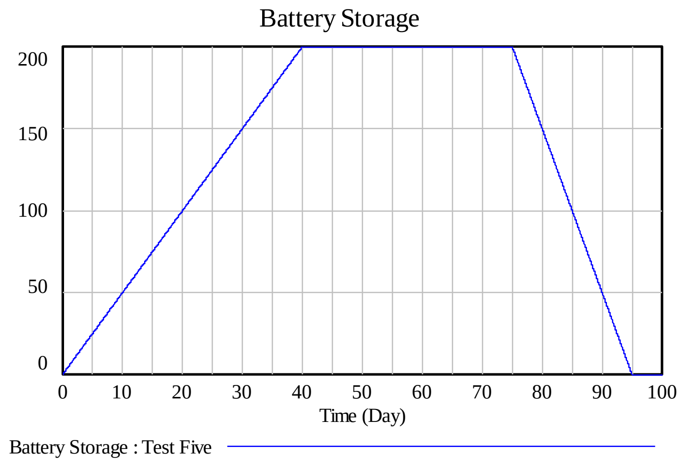


Figure 6. Control test five

6. Testing that solar output is correctly divided between demand and battery charging (*power off at 50*)

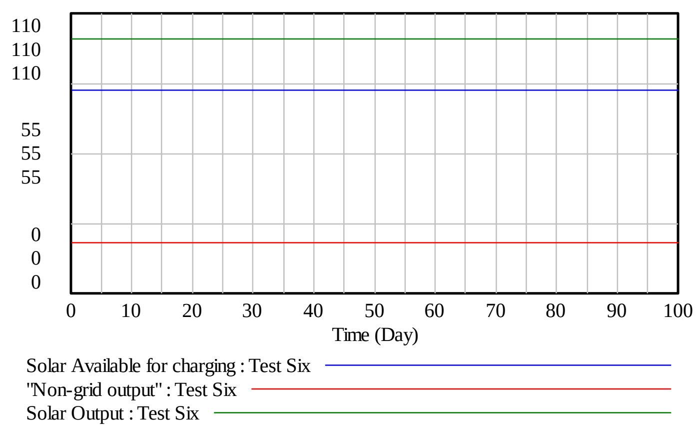


Figure 7. Control test six

Calibration

To restate, the primary goals of calibration were the following:

- Match generator output for a given volume of gas to an actual home model
- Match heat output equivalency for wood to real world experience
- Ensure that the total energy usage per household matches local data
- Ensure that we get the right amount of power out for a given solar input and PV array size

Generator Output

Generator output and storage parameters were estimated by conducting a rapid web search for home generator specifications. The Honda EU2000i was semi-arbitrarily selected (i.e. it seems representative but other models could have just as easily be chosen) as a reasonable generator for home use. This model can run for ~4 hours at rated load (~16 amps) per gallon (equal to 6 gallons per modeled time step), and produces 48 kWh per day (=8 kWh per gallon).

Wood Stove Output

Wood output was specifically formulated as an equivalency to relate the volume of wood burned (in terms of a cord or 4'X4'X8' of dried wood) to heating demand. In this case the author drew on 5+ years of personal experience heating a ~1000 square foot house in western Oregon solely with a wood stove. This experience indicated that 4 cord is sufficient to meet heat demands from October to April. A review of internet resources confirmed this assumption as reasonable. As such the wood equivalency (i.e. Wood Constant) was determined by dividing 4 cord by the sum of Heat Demand (in kWh) from October to April to generate cords/kWh).

Energy Demand

Energy demand per day (Total Demand) was estimated based on yearly data provided by the client for his personal single family residence. Data used in the model was roughly equivalent to that provided by the client, but was rounded (at the least) to an integer value, and was adjusted to account for the timing of his utility bills (i.e. his billing cycle and most of the data runs from the 10^{th} of the month forward). As such is it reasonable to assume that the modeled values are generally appropriate for a single family residence in western Oregon, but are in no way intended to precisely replicate the actual usage for a specific home. Furthermore, a breakdown of energy demand by usage (i.e. light, appliances, heating) was not available. Therefore the total demand was partitioned based on the assumption that 1) heat was not needed in July, 2) appliance demand & lighting was constant throughout the year. Again, these assumptions are intended to create a realistic but non-specific pattern of energy usage. No attempt was made to explicitly model what usage of these sub-demands could produce in a residence (i.e. heat demand was not explicitly related or compared to a given heating system output in terms of BTUs). Although this would be a useful exercise, time was not available within the context of this exercise. The author did note that overall consumption of power for heating seemed somewhat low, whereas the allocation of lighting may be high (and unrealistically does not change by month). However, again time was not available to further refine this input data.

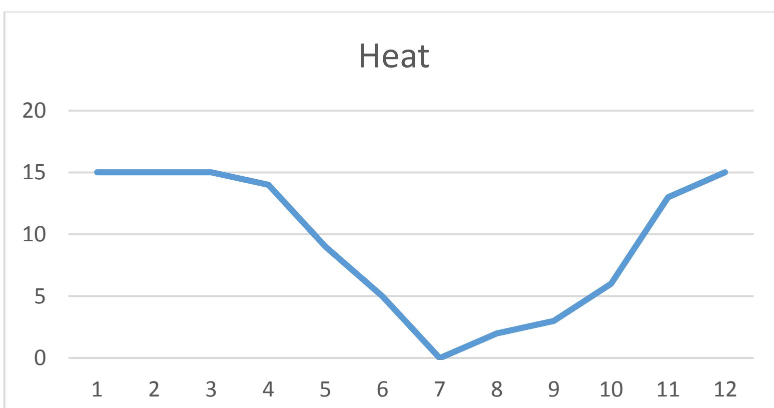


Figure 8. Heat demand in kWh per month

PV Output

Solar input and PV output was determined by using information available from the PVWatts website provided by the National Renewable Energy Laboratory (NREL). PVWatts provides an easy to use calculator for use in microgrid installations such as this one. User defined information on location and (if desired) PV parameters is used to provide estimates of solar radiation and electrical output. A location within the City of Portland near Sylvan Hill (and very near the household used to generate demand estimates) was chosen semi-arbitrarily. System parameters for a rooftop mounted array were set to the default values suggested by PVWatts and are shown below.

PVWatts: PV Specifications	
Lat (deg N):	45.6
Long (deg W):	122.6
Elev (m):	12
DC System Size (kW):	4
Module Type:	Standard
Array Type:	Fixed (roof mount)
Array Tilt (deg):	20
Array Azimuth (deg):	180
System Losses:	14
Invert Efficiency:	96
DC to AC Size Ratio:	1.1

Table 1. Modeled Solar Array specifications used in PVWatts

DC System size was related to PV array areal size using a graphical tool available on PVWatts. The figure below shows (in red outline) the size (27m^2) of the modeled rooftop installation.

Figure 9. Aerial photograph of a house showing the boundaries of the modeled PV array.

Solar Radiation information for that location was extrapolated from nearby weather gauging stations and is shown below.

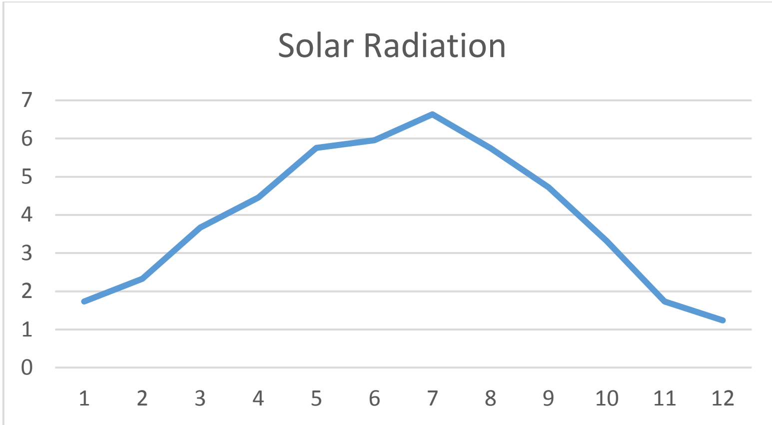


Figure 10. PVWatts generated Solar Radiation as used in the model

In order to calibrate the model, the quantitative relationship between solar input (shown above) and AC electrical output was estimated using a linear regression analysis. Solar input data from PVWatts (January to September - the training set in green below) was used to generate the regression equation. The linear model was then extrapolated to the remaining three months, October to December (the testing set in red below) to test its accuracy. Predicted vs PVWatts data were compared and are shown in the table below. As one can see, the relationship is close to but not perfectly linear. The deviation averages ~2.6% per month, and is largest in February (part of the training set). The error does not substantially increase for the test vs the training data. As such the regression equation appears sufficient to estimate electrical output for this location across the entire calendar year. Application of this regression equation allows the model to generate realistic output for solar input data not specifically included in the PVWatts output. Although this was not strictly necessary for this project, it remains a useful feature and served as a positive learning experience.

Month	Solar Input	PVWatts AC Output/Day	Estimated Output/Day	% Difference
1	1.73	6.06	5.87	3.15%
2	2.33	7.24	7.65	5.68%
3	3.67	12.26	11.69	4.64%
4	4.46	14.30	14.06	1.68%
5	5.75	18.58	17.97	3.29%
6	5.96	18.31	18.59	1.52%
7	6.63	20.55	20.62	0.32%
8	5.75	17.75	17.94	1.09%
9	4.73	14.37	14.88	3.54%
10	3.32	10.86	10.63	2.15%
11	1.74	5.72	5.88	2.76%
12	1.24	4.32	4.37	1.20%

Table 2. PVWatts output vs modeled output. Training set is in green, test set in yellow.

Battery Storage & Output

Modeling battery storage, charging, and discharge is a complex problem in and of itself and could easily consume a model of greater complexity than that described in this document. With this in mind, the battery system has been simplified to assume a 15% loss in energy when charging, a 15% loss when discharging, and an output equal to the difference between total demand and solar output (i.e. it makes up the difference if possible). Finally, battery storage was arbitrarily set at 100 as a starting point for this model.

Model Application

The model as currently implemented is applicable in a qualitative sense to single family residences in western Oregon that are equipped with above described microgrid equipment. However as noted the model would require further review and modification by a SME before it could be used for quantitative purposes, or extended to other building types of areas of the country.

Results & Conclusions

Due to the time constraints discussed above, it was not possible to fully explore and visualize model behavior. ***The author explicitly acknowledges that the experiments, figures, and results below represent only a first pass assessment***.

Feedback Loops

Although the system is heavily interconnected, the number of 'classic' feedback loops is relatively limited compared to the first two exercises completed for this course. Although the defining feature of this model is the activation of various model components based upon the output of other components, these relationships are dominated by On/Off binary switching responses.

System Response to a Grid Outage in Every Season

To test how the system would respond to a power outage at different times of year, four experiments were conducted in the modeled environment. In each case the model was allowed to run through at least nine months uninterrupted to be followed by a permanent grid outage on one of the following four days: October 1st, January 1st, April 1st, and July 1st. The intention was to simulate a power outage during fall, winter, spring, and summer. In each case, a brief analysis of the system electric draw and non-grid generation was conducted. Suggestions for improving the resiliency of the system are also discussed

October 1st Grid Failure

Under this scenario, the system is able to satisfy all of the heating and electrical demands for roughly forty days. The drop off at day 315 is due to the combined effects of running out of fuel at day 315 and the ~50% reduction in solar radiation that occurs from October to November. Note that based on the assumptions laid out in the calibration section, the wood stove continues to be active and supply all needed heat through April of the next year. Although the system is not completely self-sustaining 40 days of self-sufficiency following a disaster event suggest substantial resilience. However the non-grid output only briefly matches the demand during the peak of summer.

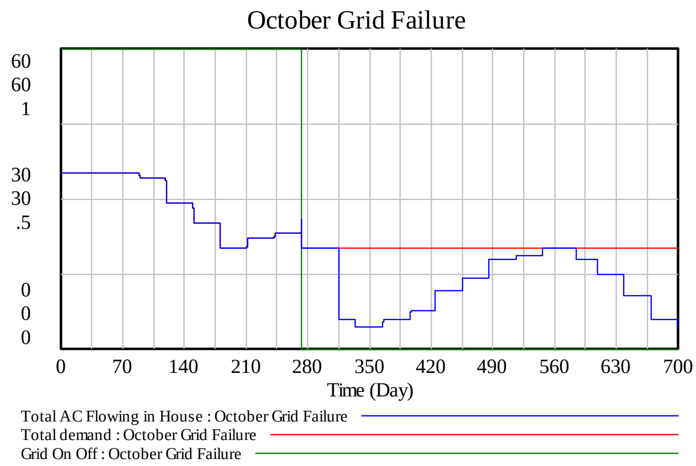


Figure 11. Demand vs output, October grid failure

Doubling the size of the solar array (and thus doubling the output) improves the performance of the system, and extends the time until demand < output up to day 350 (roughly the start of winter), and effectively doubles the time the system is self-sustaining. Power available is below demand for roughly 70 days before solar input is again sufficient to meet demand.

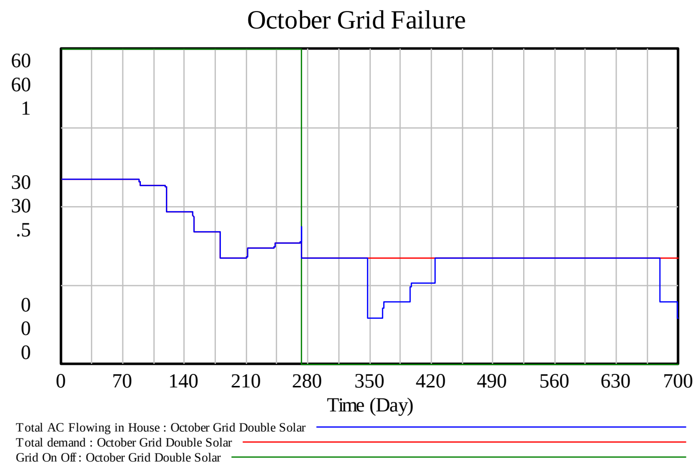


Figure 12. Demand vs output, October grid failure

January 1st Grid Failure

Under this scenario, the system is able to satisfy all of the heating and electrical demands for roughly forty days, essentially the same as the October scenario. However again although not perfectly sustainable, forty days of sufficiency post disaster reflects substantial resilience. However if the grid outage were to persist indefinitely, this configuration would only provide adequate power again for a limited duration at the peak of the summer.

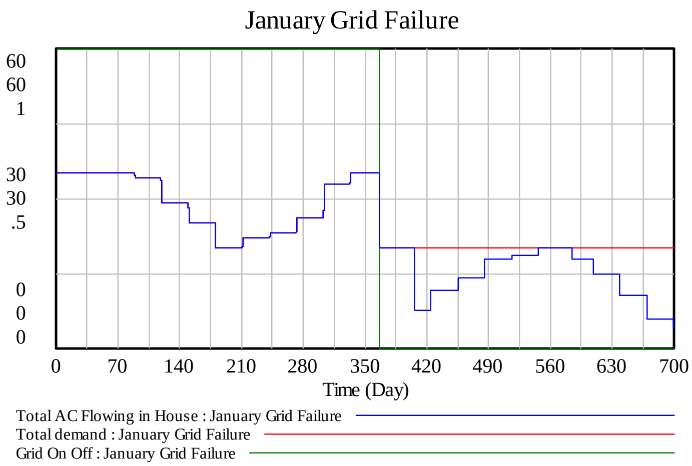


Figure 13. Demand vs output, January grid failure

When the solar output is doubled, the system output still drops below total demand at roughly 40 days, but quickly rebounds as the season progresses.

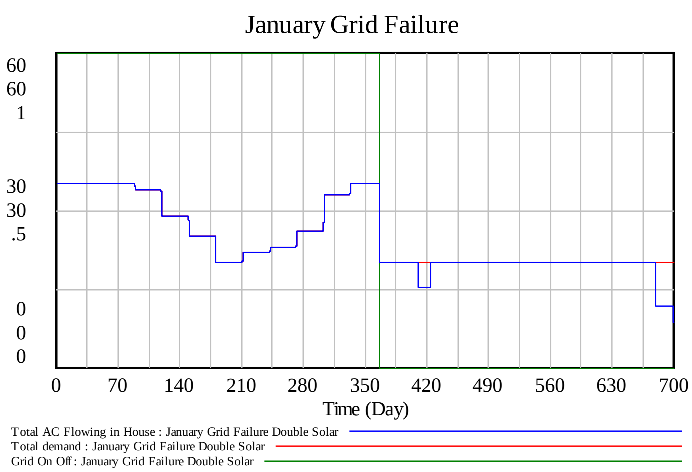


Figure 14. Demand vs output, January grid failure

<u>April 1st Grid Failure</u>

Under this scenario, the system is able to satisfy all of the heating and electrical demands for just over 50 days, again relatively consistent with fall and winter failure. However the output is only barely below demand, and only for a short period suggesting that efficiency options could easily make up for the lack. Overall the system is highly robust to grid outages at this time of year up until solar radiation begins to decrease dramatically in the fall.

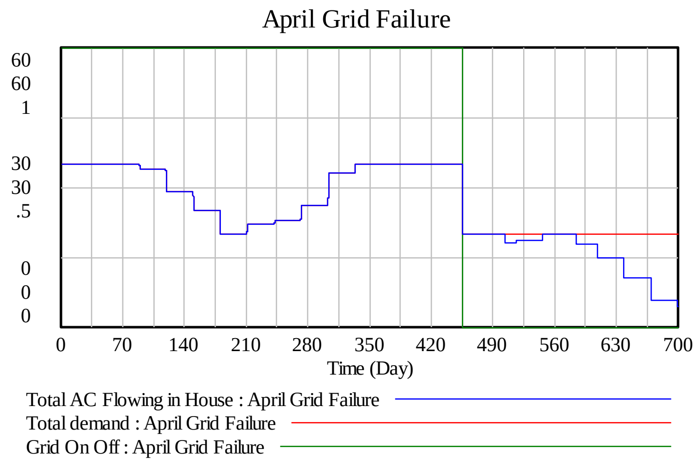


Figure 15. Demand vs output, April grid failure

When solar is doubled, the system becomes even more robust to grid failure and provides sufficient power through November.

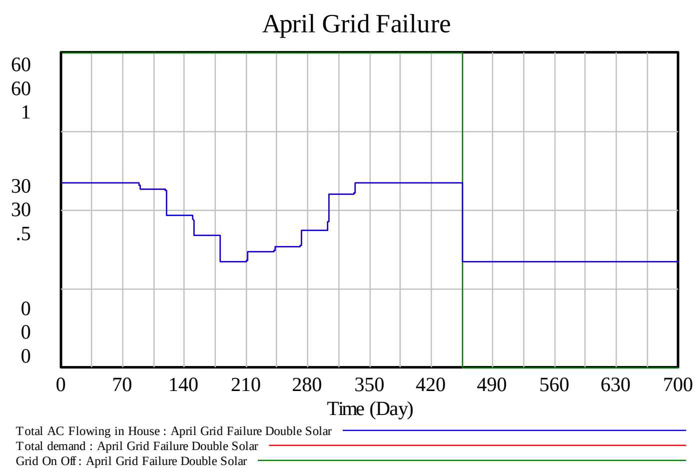


Figure 16. Demand vs output, April grid failure

July 1st Grid Failure

Under this scenario, the system is able to satisfy all of the heating and electrical demands until solar radiance declines in the fall.

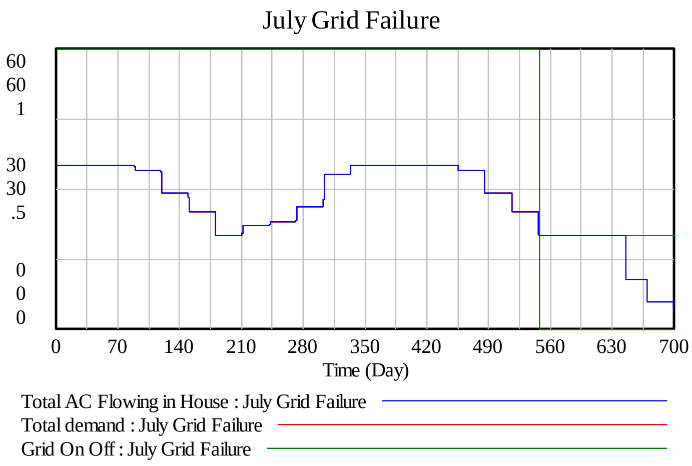


Figure 17. Demand vs output, July grid failure

When solar is doubled, the system is fully robust through the summer season, and behaves effectively as if the grid went off in October (i.e. the generator and wood stove are not needed until this point).

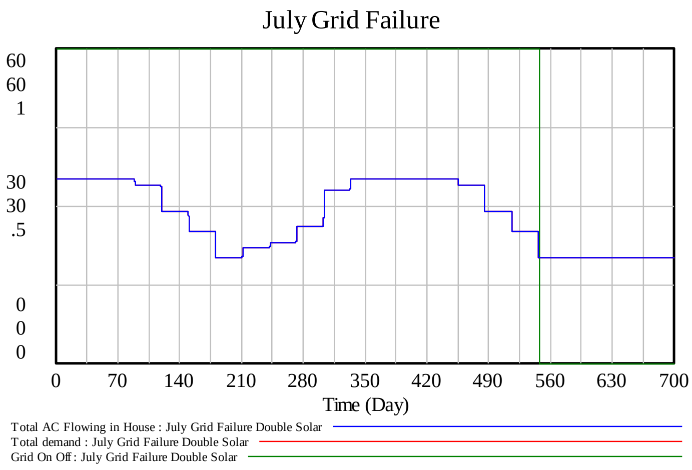


Figure 18. Demand vs output, July grid failure

Summary of Results

The results shown and described above indicate that the modeled system is robust to grid failure at all seasons, not surprisingly most so during the summer months. The most obvious conclusion is that solar power, while very effective during part of the year, is a fundamentally inefficient option during the darker months. Therefore a system intended to persist in perpetuity post grid failure would ideally utilize additional renewable power generation options (e.g. wind power).

Potential Model Improvements

Numerous simplifying assumptions were made in the development of the model. The following non-exclusive list identifies potential improvements and expansions to the model.

- Disaggregate and further calibrate generator specifications, components, and parameters.
- Disaggregate and further calibrate PV specifications, components, and parameters
- Disaggregate and further calibrate battery specifications, components, and parameters
- Express wood stove output directly in terms of BTUs rather than the kWh equivalency used in this model
- Explicitly model household elements that affect energy consumption such as insulation, lighting, appliances, and heaters.
- Include energy efficiency scenarios (e.g. decrease lighting by 50%)
- Incorporate fiscal information to help optimize the most effective configuration of equipment.

Observations on Vensim as a Modeling Tool

Although it was possible to model a microgrid using the Vensim software package, its interface is clearly less efficient than desired. Although a graphical user interface is initially appealing due to its easy to conquer learning curve, it is also inherently limiting. Key issues noted during this exercise include the following:

- The requirement that variables can only be utilized in an equation if they are explicitly connected via an ‘arrow’ results in over-complication of the model diagram, and limits the speed at which equations can be generated.
- The requirement that model runs must be hand implemented and run one at a time over complicates model testing and experimentation.
- Custom graph specification and generation is overly time consuming and tedious
- The lack of basic “For’ and ‘While’ constructs imposes a fundamental limit on the scale of what can be modeled.
- The software is relatively specialized and unknown outside a small community of modelers, limiting its acceptance and use across disciplines.

The author believes that while Vensim (or any GUI based Systems Dynamics package for that matter) may be a useful tool for conceptualizing and beta testing a model framework, it would be strongly preferable to instantiate the final model in a more general purpose language such as Python.

References

- Sterman, J.D. BUSINESS DYNAMICS: Systems Thinking and Modeling for a Complex World. Irwin McGraw-Hill (2000)
- Ventana Systems Inc. Vensim 6.3G PLEPlus. Users Guide http://vensim.com/docs/ (2015)
- Berkeley Labs. About Microgrids. https://building-microgrid.lbl.gov/about-microgrids
- http://www.city-data.com/forum/montana/2100819-how-many-cords-wood-will-i.html
- http://pvwatts.nrel.gov/
- http://powerequipment.honda.com/generators/models/eu2000i
- http://www.eia.gov/consumption/residential/data/2009/
- http://homeguides.sfgate.com/average-electrical-usage-single-family-homes-102002.html
- https://chimneysweeponline.com/howood.htm
- http://modernhomesteading.ca/blog/firewood-basics-five-lessons-for-heating-with-a-wood-stove
- https://www.solaranywhere.com/Public/About.aspx