

Spring 1-1-2013

# Dynamic Modeling of Hybrid Renewable Energy Systems for Off-Grid Applications

Mark David Hasemeyer

University of Colorado at Boulder, [mark.hasemeyer@colorado.edu](mailto:mark.hasemeyer@colorado.edu)

Follow this and additional works at: [https://scholar.colorado.edu/cven\\_gradetds](https://scholar.colorado.edu/cven_gradetds)



Part of the [Energy Systems Commons](#), and the [Sustainability Commons](#)

---

## Recommended Citation

Hasemeyer, Mark David, "Dynamic Modeling of Hybrid Renewable Energy Systems for Off-Grid Applications" (2013). *Civil Engineering Graduate Theses & Dissertations*. 264.  
[https://scholar.colorado.edu/cven\\_gradetds/264](https://scholar.colorado.edu/cven_gradetds/264)

This Thesis is brought to you for free and open access by Civil, Environmental, and Architectural Engineering at CU Scholar. It has been accepted for inclusion in Civil Engineering Graduate Theses & Dissertations by an authorized administrator of CU Scholar. For more information, please contact [cuscholaradmin@colorado.edu](mailto:cuscholaradmin@colorado.edu).

DYNAMIC MODELING OF HYBRID RENEWABLE ENERGY SYSTEMS

FOR OFF-GRID APPLICATIONS

by

MARK DAVID HASEMEYER

B.S. University of Colorado, 2010

---

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Master of Engineering

Department of Civil, Environmental, and Architectural Engineering

2013

This thesis entitled:

Dynamic Modeling of Hybrid Renewable Energy Systems for Off-grid Applications

Written by Mark David Hasemeyer

Has been approved for the Department of Civil, Environmental, and Architectural Engineering

---

Paul Chinowsky, Ph.D.

---

Bernard Amadei, Ph.D.

---

Michael Hannigan, Ph.D.

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline

## **Abstract**

The volatile prices of fossil fuels and their contribution to global warming have caused many people to turn to renewable energy systems. Many developing communities are forced to use these systems as they are too far from electrical distribution. As a result, numerous software models have been developed to simulate hybrid renewable energy systems. However almost, if not all, implementations are static in design. A static design limits the ability of the model to account for changes over time. Dynamic modeling can be used to fill the gaps where other modeling techniques fall short. This modeling practice allows the user to account for the effects of technological and economic factors over time. These factors can include changes in energy demand, energy production, and income level. Dynamic modeling can be particularly useful for developing communities who are off-grid and developing at rapid rates. In this study, a dynamic model was used to evaluate a real world system. A non-governmental organization interested in improving their current infrastructure was selected. Five different scenarios were analyzed and compared in order to discover which factors the model is most sensitive to. In four of the scenarios, a new energy system was purchased in order to account for the opening of a restaurant that would be used as a source of local income generation. These scenarios were then compared to a base case in which a new system was not purchased, and the restaurant was not opened. Finally, the results were used to determine which variables had the greatest impact on the various outputs of the simulation.

## **Dedication**

To my incredible wife for dedicating countless hours editing my horrible grammar.

## **Acknowledgments**

I would like to thank the NEGES Foundation for sparking my research interest and for being such a wonderful host in Haiti.

I would also like to thank the Mortenson Center in Engineering for Developing Communities for funding my trip to Léogâne.

## Table of Contents

Abstract .....	iii
Dedication .....	iv
Acknowledgments .....	v
List of Tables .....	ix
List of Figures.....	x
Summary .....	1
Introduction.....	2
Homer Energy Software .....	4
The problem .....	5
The objective .....	7
Layout .....	8
Target Group .....	9
Personal Motivation .....	9
Research Method .....	9
Literature Review .....	10
Methodology .....	16
High Level Overview .....	17
Model Details .....	19
User Input .....	19
Energy Calculations .....	28
Economic Projections .....	47
Overall and Monthly Results .....	57
Model Assumptions.....	62

Energy Related.....	62
Economic Related .....	63
Flowchart.....	63
Analysis and Results .....	64
Background Information.....	65
The NEGES Foundation.....	65
A Developing Community .....	66
Current Situation .....	67
Common Setup Between Cases.....	71
Base Case.....	73
Realistic Scenarios .....	76
Scenario Two .....	76
Scenario Three.....	79
Worst-Case Scenarios.....	81
Scenario Four.....	81
Scenario Five.....	84
Discussion of Findings .....	87
Timing of Purchase .....	87
Income Sensitivity .....	88
Suggestions for Improvement .....	90
Energy Related.....	90
Economic Related .....	90
General .....	91
Conclusion .....	91



Bibliography.....93

Appendix A: Costs of the Initial System.....95

Appendix B: Costs of New System (Realistic) .....96

Appendix C: Costs of New System (Worst-Case) .....97

## List of Tables

Table 1: System Characteristics Variables .....	25
Table 2: Economic variables .....	27
Table 3: Overall results per system .....	60
Table 4: Overall results over simulation timeframe .....	60
Table 5: SWOC Analysis .....	67
Table 6: Constant variables across each scenario .....	73
Table 7: Base case - volatile variables .....	74
Table 8: Scenario four - volatile variables .....	81

## List of Figures

Figure 1: Sensitivity Output from <i>HOMER</i> .....	4
Figure 2: Power tracking performance of the hybrid topology (Tsao) .....	13
Figure 3: Sensitivity analysis by component (Chun-Hua Li) .....	14
Figure 4: Traditional PV based system .....	17
Figure 5: High level block diagram of model functionality .....	18
Figure 6: HOMER's GHR and System Load - Data Set Generators .....	21
Figure 7: Kinetic Battery Model .....	41
Figure 8: Sample spreadsheet output .....	54
Figure 10: Example cash flow by system component.....	55
Figure 9: Example cash flow by expense type .....	55
Figure 11: Example balance over simulation.....	57
Figure 12: Example monthly output .....	60
Figure 13: Flowchart of model logic .....	64
Figure 14: NEGES' current PV array .....	66
Figure 15: Base case - cash flow .....	74
Figure 16: Base case - balance.....	75
Figure 17: Scenario two - volatile variables.....	76
Figure 18: Scenario two - cash flow.....	77
Figure 19: Scenario two - balance .....	78
Figure 20: Scenario three - cash flow .....	79
Figure 21: Scenario three – balance .....	80

Figure 22: Scenario four - cash flow .....	82
Figure 23: Scenario four – balance .....	83
Figure 24: Scenario four - balance with smaller profit margin .....	84
Figure 25: Scenario five - cash flow .....	85
Figure 26: Scenario five -balance.....	85
Figure 27: Scenario five - balance with smaller profit margin .....	86
Figure 28: Scenario two - no profit increase .....	89
Figure 29: Scenario three - no profit increase .....	89

## Summary

The study and development of renewable energy systems is a constantly growing area. This growth can be attributed to a few factors. The volatility of market prices of fossil fuels has caused energy costs to grow dramatically, making them increasingly difficult to rely on. In addition, the green house gasses they create are likely contributing to global warming. Last, others are forced to use renewable energy systems, as they are too far from any sort of electrical distribution network. For these reasons many organizations have turned to renewable energy systems. As a result, numerous efforts have been made to develop modeling software to help people realize the benefits of renewable energy systems.

Some models will take into account both technological and economic aspects of the system. With these models, a user defines numerous systemic and economic variables that the model uses to simulate over an arbitrary timeframe. However, all known implementations are static in design, meaning that they cannot account for changes overtime. Dynamic modeling can be used as a tool to answer this problem. My model was developed to provide a new way to simulate hybrid renewable energy systems and to account for changes over time. It is able to account for increases in energy demand over time, and allows for the purchasing of new energy systems mid-simulation. It is also capable of simulating a loan if the organization lacks sufficient funds when a new system is purchased. This is especially useful for developing communities, where changes to infrastructure can happen very quickly and micro-loans are known to be extremely effective.

The model's energy and economic related calculations, as well as its algorithms, are discussed in detail. Then, a real word problem is evaluated using the newly developed model. A non-governmental organization's energy demand, energy production, and economic factors are all taken into account. Five different scenarios are analyzed and compared over a twenty-five year time frame. The scenarios can be divided up into three categories: a base case, realistic scenarios, and worst-case scenarios. From this analysis, various findings can be concluded. A few variables were found to have significant influence on the model. These variables are the time at which a new system is purchased, and changes in the user's income level. Both have significant effect on the end result of the simulation.

## **Introduction**

The analysis of energy systems has been a highly studied field, and will likely continue to grow due to the controversial issues of global warming and fossil fuel consumption. In response to these issues, scholars have evaluated various types of renewable energy systems and their implementation feasibility in different environments. Many studies have attempted to optimize them for maximum energy efficiency at a minimal cost. System dynamics modeling has been widely adopted to help solve and optimize many of these large and complex system problems.

System dynamics is a modeling technique used for understanding, discussing, developing, and analyzing boundary conditions for intricate issues and problems. This type of modeling process can help one understand the behavior of complex systems over time. It addresses internal feedback loops and time delays that influence the behavior of the entire system. Each of these

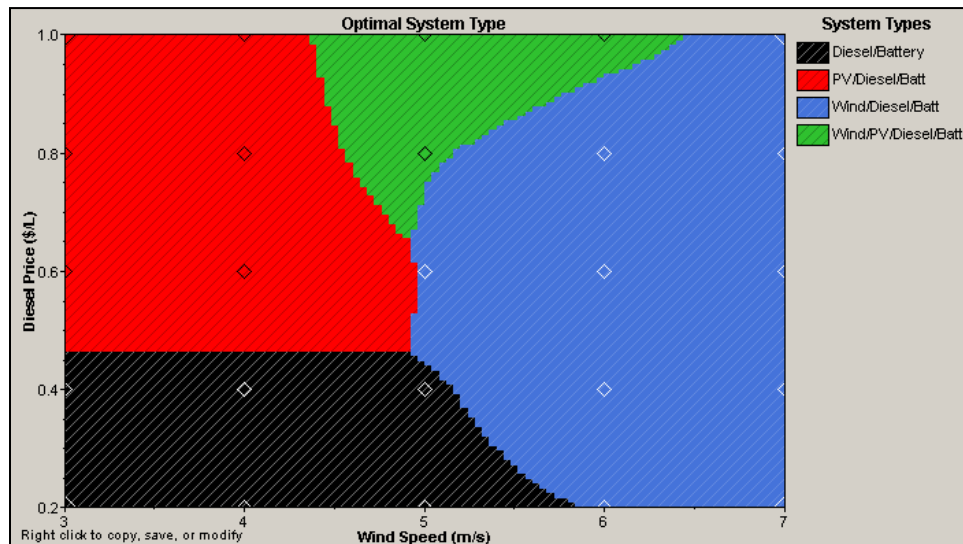
essential pieces help to describe and understand the complexity and non-linearity of what can appear to be the simplest of systems.

Current energy system modeling is focused on analyzing the feasibility and efficiency of various systems in different environments. If feasible, researchers often analyze how they can optimize current technologies to be more energy efficient and effectively meet the demands of the environment they are placed in. However, in most cases, system analysis stops here. Economic impact is sometimes overlooked, even though it is a driving factor in the decision making process when purchasing renewable energy systems. When going through the decision process, it is important to consider the full life cycle analysis of energy systems, and also to include those results in conjunction with system energy capacity, efficiency and economic impact.

Even though it is often overlooked, some research has begun to take economics into account. Models have been developed that provide algorithms to calculate the best system for a particular application with the highest energy production to cost ratio. Models have also been developed on the commercial level to provide companies, government agencies, universities, individuals, and non-governmental organizations (NGOs) with modeling tools to easily optimize a renewable energy system in order to meet their demands. In some cases, economic projections can be generated based on a chosen system that help the user understand what sort of budget would be required to operate and maintain such a system. However, these projections are static and cannot account for changes in energy demand or energy production over time.

## Homer Energy Software

*HOMER Energy*, a small company out of Boulder, Colorado, has done a great job developing a mature software suite called *HOMER*. This software helps users to model, analyze, and optimize various renewable energy systems to meet their specific needs. The early stages of the modeling software were developed by the National Renewable Energy Laboratory (NREL) before being passed on to *HOMER Energy* as a commercial outlet. It is a very thorough piece of software that is capable of handling many complex modeling problems. Through *HOMER*, it is possible to review different economic projections, sensitivity analysis, and system optimizations based upon a variable set entered by the user. Figure 1 shows an example output of a sensitivity analysis conducted by *HOMER*.



**Figure 1: Sensitivity Output from *HOMER***

By looking at the sensitivity analysis, one can determine the optimal system type for their project based on the price of diesel fuel and wind speed in the area. By looking at Figure 1, one can see that the program is capable of handling a variety of renewable energy sources such as



photovoltaic panels, wind turbines, hydropower, and fuel cells. Overall, *HOMER* is one of the best modeling tools for hybrid renewable energy systems on the market today, and is also the basis for the development of my dynamic model.

## **The problem**

Although the *HOMER* software and many other related studies are very thorough when it comes to system feasibility, optimization, and economic projection, they fail to appropriately consider an entire area of energy application: hybrid renewable energy systems for developing communities. Developing communities and the non-governmental organizations that work in them face consistently changing environments. Developing areas like these often have high potential for growth and expansion. There are limited laws when it comes to restricting development, and construction permits rarely have to be applied for. Additionally, many areas have minimal to no access to the local electrical grid, requiring the use gasoline or diesel generators to power any needed loads. This can be problematic for many reasons. First and most importantly, it subjects the community or NGO to the volatile and expensive prices of fossil fuels. If prices were to rise, the community would be forced to slow development, and may be required to decrease their quality of life. The use of gasoline or diesel generators is also destructive to the environment on both a local, and global scale. The exhaust from generators reduces the air quality of the area and emits green house gases that contribute to global warming. Generators are also inefficient; much of the chemical energy provided by fuel is lost to friction and heat. It can be argued that renewable energy systems are not much better at converting energy than generators. However, if renewable energy sources such as solar radiation, wind, and hydro are not utilized, their energy potential is wasted. The sun will shine,

wind will blow, and water will flow regardless if we use the energy or not. From this, one can deduce that any amount of energy utilization is better than none.

Software such as *HOMER* is very useful for many applications, but it is not dynamic enough to model changes in a system. Once the model is initialized, it is left to run. *HOMER* is static in the sense that it cannot change the modeled system's capabilities over time. It is also not capable of accounting for energy demand increases as a community, company, or NGO develops.

*HOMER* is great at optimizing systems and conducting sensitivity analysis, but does not effectively project a community's energy supply and demand changes over time. As a community grows, so does its energy demand. In order to meet the growing demand, energy production must be increased. This usually involves purchasing more solar panels, wind turbines, or a better hydropower system. As a worst-case scenario, the community may need to run the generator more often, resulting in more fuel consumption. Projecting energy and economic changes over time is where most research studies and software tools such as *HOMER* fall short. Because of this, it is the area that I decided to focus my thesis research. The model is currently intended for use as a supplementary tool alongside the *HOMER* software suite. This is because the model requires a large amount of technical information to be input by its user, and *HOMER* is a great tool to generate the information needed by my model. Using *HOMER* together with the dynamic model developed in this thesis creates a powerful tool combination for analyzing hybrid renewable energy systems and the changes that occur within them over time.

## **The objective**

How can a developing community, NGO, or other rapidly changing organization determine their energy requirements and model them to find an efficient and economic solution? Dynamic modeling is a useful method for addressing the problem at hand. I wanted to develop a dynamic model that is able to account for changes over time as well as analyze a system's feasibility according to economic and power constraints. Not only did I want it be flexible over time, but to also allow for a sensitivity analysis based on the fluctuation of various input variables. The end goal would be for the user to see what set of renewable energy system changes could be made over time to in order to meet their increasing energy demands, while minimizing cost. It would also allow the NGO or community to start with a small system if their income is not sufficient enough for their ideal energy system, and increase in size when funds allow.

This is a worthwhile area of study because it is realistic, useful, and novel. Although the model developed is only a proof of concept and could be greatly improved upon, it is useful in current, real world scenarios. As a test, the model is used to simulate an existing hybrid renewable energy system owned by an NGO located in Haiti. Various outcomes are taken into account as the NGO grows and the community nearby develops. The end goal of this thesis research is to develop a dynamic energy systems model that helps developing communities determine the most economic and energy efficient system that meets their requirements and changes with them as they grow. It should allow the user to model various potential scenarios in order to determine the best time to upgrade their system, develop their infrastructure, and minimize costs related to capital purchases, operation, and maintenance.

## Layout

The first section of this study is an introduction to the research. Its purpose is to introduce the reader to the area of research that this paper covers: dynamic modeling of energy systems.

The introduction addresses research that has already been conducted within the field and findings that have been made. It then presents the research problem at hand and why it is worthwhile to study. Last, it discusses the research objective of this paper and why it is useful.

The next section conducts a literature review of four different articles that relate to dynamic modeling of energy systems. It summarizes and analyzes each study and explains how they relate to each other and my research. It then discusses how the studies fall short, and why the research I've conducted is unique. All research was grounded in these previous studies that have provided the basis for my research objective.

After the literature review, the details of the model are discussed in the methodology section. This section provides a high level overview of the algorithms used to run a simulation. It also defines the various energy and economic related equations the model uses to calculate its outputs and results.

The last section tests the model by conducting an analysis on a real world example problem. Five different scenarios are evaluated and compared in order to find an optimal solution. The scenarios are divided into three categories: a base case, realistic scenarios, and worst-case scenarios. From the results, observations and conclusions are made, and a sensitivity analysis is conducted. A best-case scenario is then determined.

## **Target Group**

This research is mainly intended for NGOs and developing communities, but could be of interest to other students and researchers interested in global development, dynamic modeling, or energy systems. It is beneficial if the reader has a background in or is involved with any of the above listed fields, but it is not necessary.

## **Personal Motivation**

I have studied and received a certificate in Engineering for Developing Communities at the University of Colorado. This has been one the motivating factors for my research. The engineering profession is a valuable resource that can be used to help improve the quality of life for people in the developed and developing world. Because I live a privileged life in a developed country, I feel morally responsible to help people that lack the necessary resources and/or skill sets to improve their own quality of life.

## **Research Method**

The research model was developed in Microsoft Excel, as it is efficient at handling large data sets and supports Visual Basic for Applications (VBA), a Microsoft based scripting language. VBA helped me implement the dynamic features desired in the model. The model is tested used to create numerous scenarios so that a set of useful results can be generated. Multiple simulation iterations are compared to each other in order to determine the optimal setup. Examples can be found in the analysis section of this paper.

## Literature Review

I looked at four publications that use or address the benefits of system dynamics techniques to model complex systems. Three of the articles looked at the optimization of hybrid renewable energy systems, and the fourth analyzed the benefits of dynamic modeling with respect to large projects. A few major themes can be drawn from the publications: system feasibility, optimization and efficiency, and the ability to solve complex problems using dynamic modeling techniques.

In his article, "System Dynamics Modeling for Project Management," Mr. Sterman talks about the benefits of dynamic computer models for management of large, complex engineering projects. These types of systems are difficult to work with because they are extremely complex and highly dynamic. They involve multiple feedback processes, nonlinear relationships, and work with both, qualitative and quantitative data sets. He points out the disadvantages to mental models and their ability to solve dynamic system problems stating that, "...people do a poor job of interpreting the assumptions of their own mental models" (Sterman). Although flexible, the human mind is limited in its reasoning and processing capabilities. Even experts can have a difficult time inferring the behavior of complex dynamic systems. He argues that computer models can overcome many of the limitations of mental models because they are explicit, and any assumptions are made public for assessment. This can also be seen in each of the other publications that utilize dynamic modeling to optimize and analyze various renewable energy systems. If model assumptions are not clearly stated, they can be inferred by studying the model and its behavior based on the conditions and inputs provided. Sterman also describes dynamic computer modeling as infallible in its ability to

compute the logical consequences of the modeler's assumptions. This means that the model will catch all poorly made logical decisions. The system's behavior will not behave as expected, causing the modeler to re-assess his or her logic. In the context of energy modeling, if a system's energy capacity is not capable of meeting demand, it is clear that the system is insufficient and the modeler must re-think his or her approach to find the correct solution.

Sherman also argues that computer models are more capable than the human mind at interrelating a large number of factors simultaneously. It is extremely difficult to process all of the factors that affect energy systems. System optimization and efficiency must be tied to social, economic, and political factors, all of which have a weight on the decision process of selecting a favorable system. The human mind can only grasp a basic understanding of how these factors interrelate. Quantifying the results would be near impossible without the aid of computer modeling. Finally, Sherman says that dynamic computer modeling can be simulated under controlled conditions. This allows "...analysts to conduct experiments which are not feasible or ethical in the real system." In the case of energy systems, dynamic computer modeling provides a simplified way to conduct sensitivity analysis. This allows for better optimization of the system according to certain variables of interest. It is for these reasons the other studies I looked at used dynamic modeling as their preferred tool for undertaking the research questions at hand.

The other three publications use dynamic modeling techniques to explore the feasibility of various hybrid renewable energy system implementations. If feasible, some studies conducted sensitivity analysis in order to test the system's capabilities under different conditions. In the

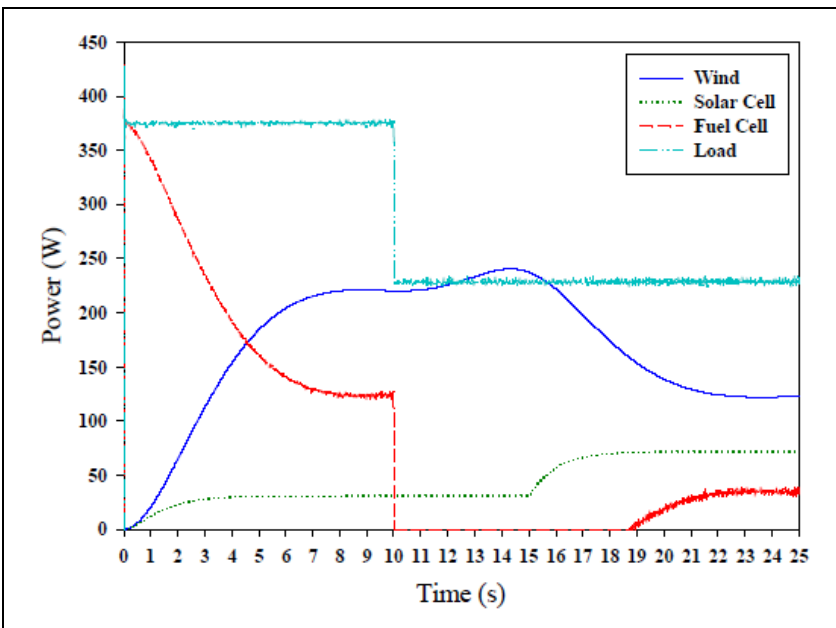
last case, optimization was performed for energy efficiency in conjunction with economics. In their study, "Dynamic modeling and simulation of a small wind–fuel cell hybrid energy system," M.J. Khan and M.T. Iqbal describe dynamic modeling and simulation results of a small wind-fuel cell hybrid energy system. The system consists of a small wind turbine, a fuel cell, ultracapacitors, an electrolyzer, and a power converter. Each component is modeled separately and then connected, creating a highly nonlinear system. The research group chose SIMULINK™ as their computer modeling software tool. With this software they looked at the voltage variation and transient responses throughout the system as wind speed and power demand fluctuated. System optimization was not performed, as this study was more a demonstration of concept. The end results proved the feasibility of the system, however, the authors have suggested further analysis in order to better optimize the system.

In their publication, "Dynamic Modeling and Simulation of Hybrid Power Systems Based on Renewable Energy," Mr. Tsao and his colleagues use dynamic modeling to simulate a more complex renewable energy system. This is accomplished by adding photovoltaic panels to a system similar to the one used in Khan and Iqbal's study. As wind speed and solar radiance vary, ultracapacitors are integrated to regulate the voltage fluctuation and ensure that the system performs well under all conditions. Excess wind and solar energy are converted to hydrogen for use in the fuel cell during peak energy production times. A number of variables are altered in order to analyze their affect on the system's components. These include changes in energy demand, ambient temperature, and wind speed. SIMULINK™ was also used as the dynamic modeling software for these tests. Figure 2 provides for a good example of the various components used, their outputs, and how they are interrelated.



As in the previously mentioned study, the system was not optimized. However, the feasibility of the system was evaluated using a sensitivity analysis of different environmental conditions.

In the final journal publication titled, "Dynamic modeling and sizing optimization of stand-alone photovoltaic power systems using hybrid energy storage technology," Mr. Li and his affiliates



**Figure 2: Power tracking performance of the hybrid topology (Tsao)**

take their study a step further than the others. Three stand-alone photovoltaic power systems are analyzed, optimized, and compared.

Each system uses a different energy storage

technique: battery bank, fuel cell system, and

battery bank/fuel cell hybrid. System optimization and decision analysis is performed considering both system performance and cost. According to their abstract, "the obtained results indicate that maximizing the system efficiency while minimizing system cost is a multi-objective optimization problem" (Chun-Hua Li). Several metrics are used to assess the technical and economic efficiency of the hybrid power systems. These include but are not limited to component size, electric usage, replacement and operation and maintenance costs, component lifetime, and initial purchase price. The sensitivity of these metrics are compared and analyzed

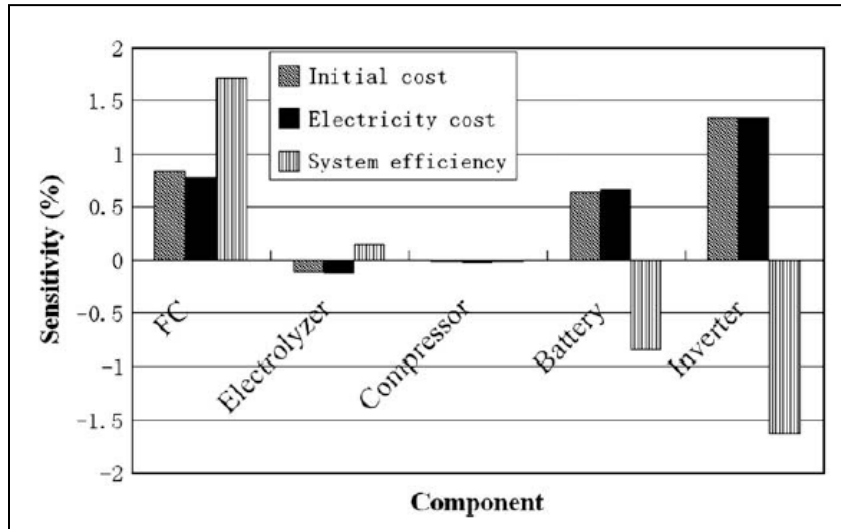
to see how they are affected by changes in various environmental variables such as energy demand and solar radiance. Figure 3 shows the results of the sensitivity analysis. From their

analysis, Mr. Li and his affiliates conclude that a photovoltaic/battery bank/fuel cell hybrid system provided for the most efficient system.

Although the battery bank is the most efficient form of energy storage at 73.1%

efficient (Chun-Hua Li), it is very costly to replace the bank. Also, a battery's lifetime is short compared to that of a fuel cell. The fuel cell is only 29.84% efficient, but its minimal cost and longer lifespan are attractive. The study ultimately proves that the high efficiency of batteries in combination with the lower cost of fuel cells yields an efficient system with lower system cost.

Each study successfully uses or addresses dynamic modeling techniques in order to analyze highly complex, nonlinear systems. The feasibility of each respective system was evaluated and, in some cases, optimization and sensitivity analyses were conducted in order properly choose the best system for the situation. Mr. Li's group of colleagues also took into account the economic impact of each system possibility in conjunction with its energy capacity and



**Figure 3: Sensitivity analysis by component (Chun-Hua Li)**

efficiency in order to conduct a proper decision analysis. These studies prove that dynamic modeling is useful for analyzing complex problems, especially in the context of hybrid renewable energy systems.

My research was driven by the same characteristics as the other system modeling studies. Each modeled system was intended for use in off grid applications where utility companies have not expanded. This is why various energy storage techniques were modeled, but the electrical grid was never taken into account. These studies were also interested in the use of green energy to combat fossil fuel consumption and its effects on global warming. Although the reduction of green house gases is not the primary reason for using renewable energy system in off-grid applications, it is certainly a benefit that should not be disregarded. Finally, each study was interested in the same set (or subset) of model outputs when analyzing their results: Feasibility, optimization, and economics. This is the same set of outputs that I focused on while analyzing the results of my model.

Although each study was comprehensive, I hoped to take my dynamic model a step further. My model was developed with the intent of analyzing the feasibility, optimization, and economic impact of multiple hybrid renewable energy systems at a certain location over a twenty-five year time period. The goal is for an organization or community who live outside the range of utility services use the model to recognize their energy options while taking into account economic and geographic status, as well as energy requirements. Variables can be adjusted to see how a community's energy systems will perform under different conditions and, in turn, how it will impact their budget. This model is innovative, dynamic, and useful. It covers an area

of renewable energy modeling that has not been carefully explored, and also builds off the studies explored in this literature review.

## **Methodology**

The methodology of the model is discussed in this section. It introduces the dynamic model and the details of how it was developed. There are many software tools available to create dynamic models. Examples include *Stella* developed by *isee systems*, and *Simile* by *Simulistics*. After testing numerous types of dynamic modeling software, I was unable to find any that were efficient at handling large data sets. Simulation speeds were very slow, if possible. This drove me to use Microsoft Excel because of its efficiency at working with large data sets. It also has support for a programming backend (Visual Basic for Applications) that allows for the addition of dynamic features desired for the model.

## High Level Overview

The model is traditional in the sense that it simulates conventional renewable energy system

components. Each

system must consist of

five major parts:

photovoltaic array,

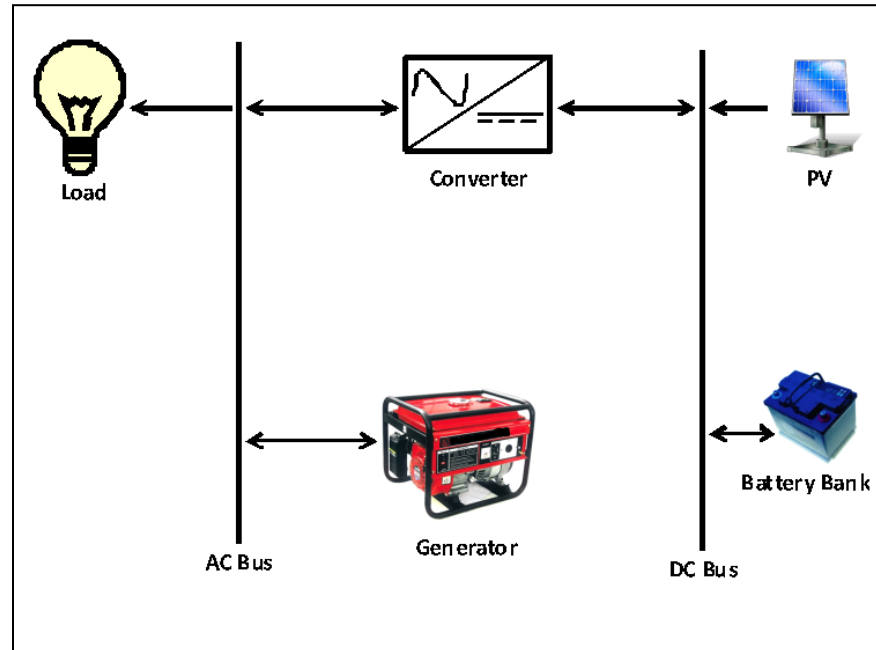
battery bank, AC-DC

converter, load, and

generator (if needed).

Currently the model is

only able to simulate a



**Figure 4: Traditional PV based system**

PV array as the

renewable energy source, but new sources could be added in the future. Figure 4 displays the

layout of a traditional photovoltaic-based renewable energy system.

Each component is simulated separately and the flow of energy between them is calculated on

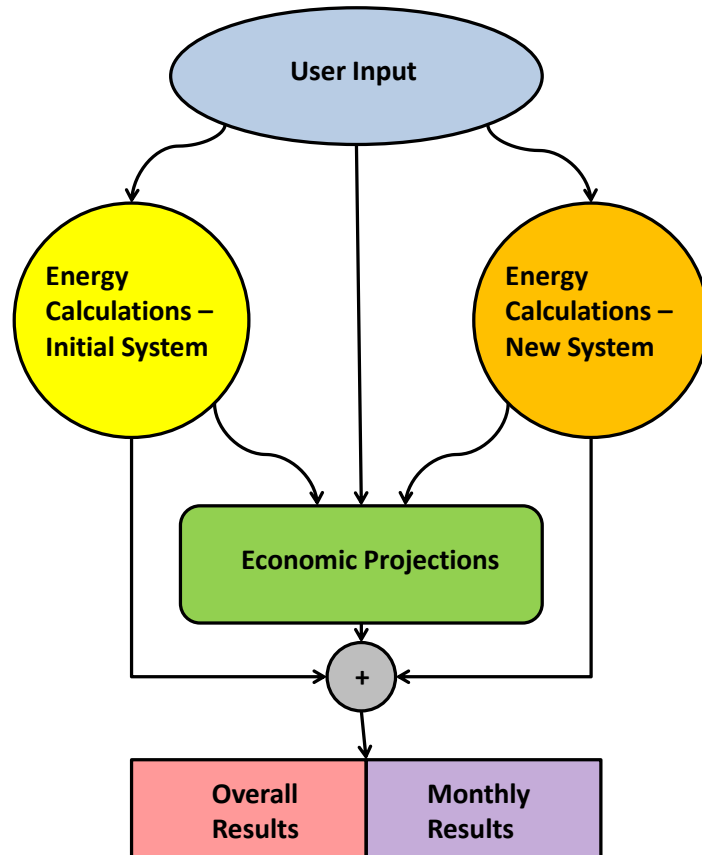
an hourly basis. The algorithm can be divided up into five sections: user input, energy

calculations, economic projections, monthly results, and overall results. Each section is

developed on a separate worksheet within the Excel workbook, but all five sections are inter-

related. Figure 5 shows a high-level block diagram of the model and the connections between

each section.



**Figure 5: High level block diagram of model functionality**

The user begins by entering information about the energy system(s) that they are using and/or wish to purchase. The energy related characteristics are then calculated for each system so that the model can determine the system's capacity. The result is then compared to the user's energy demand to see if the amount of energy production would be sufficient. If there is not enough production to meet demand, a warning message is triggered to tell the user that there is an energy deficit with their current setup. Once the feasibility of the system is determined the energy related calculations are passed onto the economic projections section. From here, the amount of money spent on capital, operation and maintenance, fuel, and other areas can be calculated. If the user does not have sufficient income stream to maintain the system,

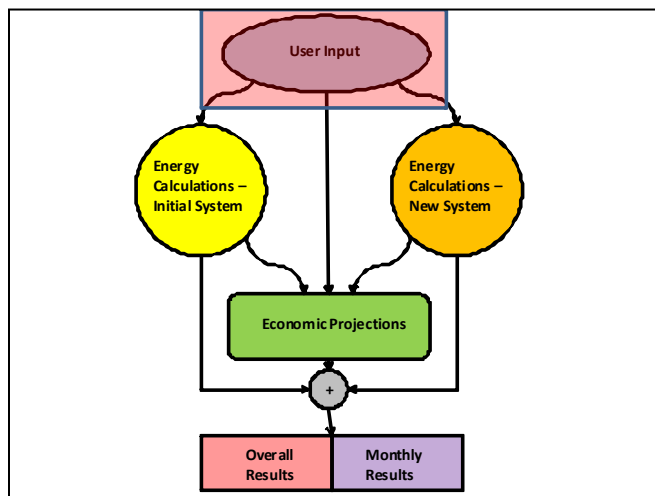
another warning message is triggered to let them know that the system will put them into debt. Finally, all of the information is aggregated together to display a table of results. The results are shown in various formats, depending on the variable of interest. Some information is given as a monthly output, some variables are yearly, and others involve the entire twenty-five year simulation period. It is up to the user to interpret the information and choose the best set of systems for their application and budget.

## Model Details

The functionality of each section of the model is broken down in detail. The variables and formulas that are used to calculate the results are discussed.

## User Input

The user inputs section is the initial worksheet the user sees when the model is opened. It is



where each model variable is specified for use in calculations. The user input worksheet can be divided up into five sections: global radiation and demand, geographic location, initial system characteristics, future system characteristics, and economics. It is

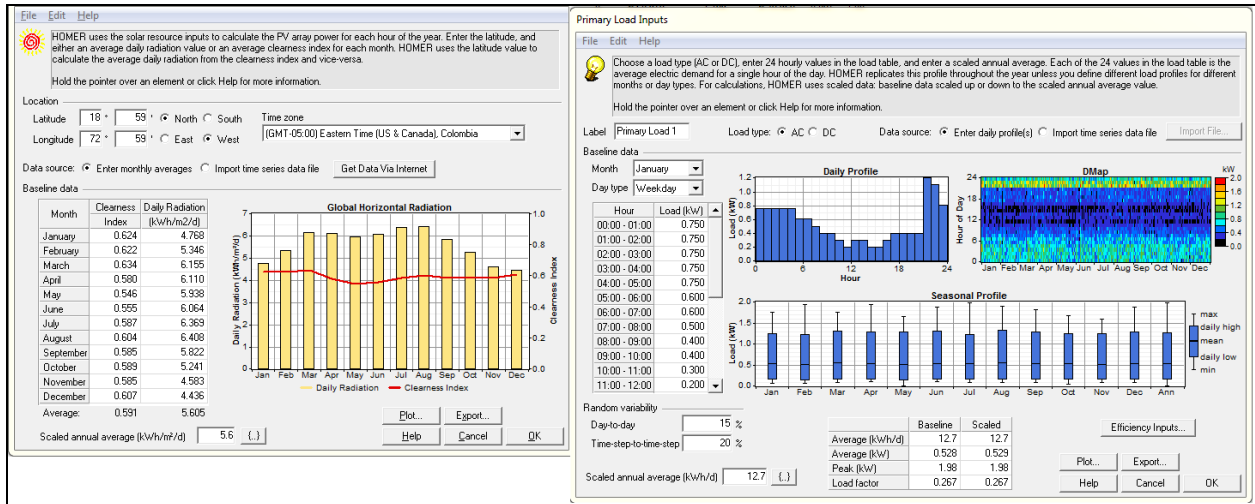
helpful for the user to initially build their system in *HOMER*, as it provides most of the technical information that is required by the model. By using *HOMER*, most of the input variables can be

"copy-pasted" without the user needing to have a significant amount of technical knowledge about renewable energy systems.

### ***Global Horizontal Radiation and Demand***

The global radiation and demand section provides the foundation for the rest of the calculations used in the model. First, the user needs to specify the Global Horizontal Radiation (GHR) data set for the geographic location of where the system(s) are, or will be located. The GHR is defined as the sum of the direct and diffused radiation components as measured on a flat horizontal plane. The GHR data set can be obtained by data collection from the field or by using an existing database. NREL has data sets available for most of the world, and *HOMER* can conveniently access NREL's database for you. The user only needs to enter the geographic coordinates of the system's location. For this model, the GHR needs to be entered as an hourly data set over a one year time period. The GHR should be entered in kilowatts per square meter. Next, the load on the system needs to be specified. This also needs to be entered as an hourly data set over a one year time period. Conveniently, *HOMER* is also capable of generating a randomized load data set based on user specifications. The system load information must be entered in kilowatt-hours. Figure 6 shows *HOMER*'s global horizontal radiation and system load data set generators.





**Figure 6: HOMER's GHR and System Load - Data Set Generators**

The load on the system is considered to be constant through each hourly time step. Although hourly time steps are not ideal, the model would quickly become overly complex if it were run with a smaller time step resolution. This simplification step is considered to have negligible effects on the overall outcome after running the simulation over a twenty-five year time period. This is because when modeling the system's lifecycle, one becomes more concerned with the overall system throughput than the variation of demand between hourly time steps. The model currently only accounts for the overall system load. This means that the user must aggregate the energy demands of every item that will be connected to the system. As a suggestion for further development, the user could be allowed to enter the requirements of each load separately and let the model perform the aggregating.

### **Geographic Information**

The next section of the user input worksheet is the geographic location section. The model requires the longitude and latitude, as well as time zone of the system(s) location relative to

Greenwich Mean Time. These variables are needed to perform proper energy calculations. This information allows the model to calculate where the sun will be at each hour of the day throughout the year. In turn, it is possible to predict how much solar radiation will be in contact with the photovoltaic panels.

### ***Initial and Future System Characteristics***

The system characteristics section is likely the most technically complicated section for the user. Fortunately *HOMER* can be used to help generate some of the information required for the input cells. The model is able to calculate some of the variables based on user input, but most of the information must be hand-entered. Table 1 describes the system variables and a description of each of them.

<b><u>Variable [units]</u></b>	<b><u>Method of Input</u></b>	<b><u>Details</u></b>
<b>Photovoltaic Array</b>		
<b>Rated STD Output [kW]</b>	User defined	Ideal solar output at 1kW/m <sup>2</sup>
<b>Derating Factor [%]</b>	User defined	Scaling factor for real world operating conditions
<b>Slope of PV Panels [°]</b>	User defined	Relate to horizontal ground
<b>Azimuth [°]</b>	User defined	Direction panels are facing
<b>Ground reflectance [%]</b>	User defined	Amount of reflected solar radiation
<b>Lifetime [yrs]</b>	User defined	Operating lifetime of photovoltaic array
<b>Battery Characteristics</b>		
<b>Nominal capacity [Ah]</b>	User defined	Battery capacity at a 20 hour discharge

		rate
<b>Maximum capacity [Ah]</b>	Calculated by model	Theoretical maximum charge
<b>Lifetime throughput [kWh]</b>	HOMER	Amount of energy that can be cycled through the battery
<b>Nominal Voltage [V]</b>	User defined	Battery voltage
<b>Round trip efficiency [%]</b>	User defined	Energy in to energy out conversion efficiency
<b>Minimum state of charge [%]</b>	User defined	Minimum charge percentage allowed until turning on the backup generator
<b>Setpoint stage of charge [%]</b>	User defined	Charge percentage to charge batteries to when generator is on
<b>Float life [yrs]</b>	User defined	Lifecycle of unused battery
<b>Maximum charge rate [A/Ah]</b>	User defined	Maximum charge rate proportional to unfilled capacity
<b>Maximum charge current [A]</b>	User defined	Maximum amount of current into battery regardless of charge state
<b>Capacity Ratio</b>	HOMER	Ratio of available energy to total energy
<b>Rate Constant</b>	HOMER	Measure of how quickly energy can move between "available" and "bound" sections of the battery

<b>Battery Bank Arrangement</b>		
<b>Batteries per string</b>	User defined	Amount of batteries connected in series
<b>Number of strings</b>	User defined	Number of strings connected in parallel
<b>Batteries in bank</b>	Calculated by model	Total number of batteries in bank
<b>Bank voltage [V]</b>	Calculated by model	Voltage of battery bank
<b>Bank capacity [Ah]</b>	Calculated by model	Total capacity of battery bank
<b>Maximum Bank Energy [kWh]</b>	Calculated by model	Total amount of energy in fully charged battery bank
<b>Converter Characteristics</b>		
<b>Maximum throughput [kW]</b>	User defined	Maximum amount of power that can go through converter at any one time
<b>Inverter Efficiency [%]</b>	User defined	Efficiency at converting DC to AC
<b>Rectifier Efficiency [%]</b>	User defined	Efficiency at converting AC to DC
<b>Lifetime [yrs]</b>	User defined	Operating lifetime of converter
<b>Generator Characteristics (if applicable)</b>		
<b>Maximum output power [kW]</b>	User defined	Maximum power output of generator
<b>Lifetime [yrs]</b>	User defined	Operating lifetime of generator

<b>Fuel curve intercept coefficient [L/hr/kW]</b>	HOMER	Used to calculate generator's fuel consumption
<b>Fuel curve slope [L/hr/kW]</b>	HOMER	Used to calculate generator's fuel consumption

**Table 1: System Characteristics Variables**

An instance of the variable set listed in Table 1 exists for both the initial system and the future system (if applicable). From Table 1, one can see that there are three possible methods of input: user defined, HOMER, and calculated by model. "User defined" variables must be determined by the user and hand-entered into the model. "HOMER" variables must also be hand-entered, but the appropriate values can be obtained with the help of the *HOMER* software. Last, "calculated by model" variables do not require any intervention from the user and are automatically calculated by the model. These variables could be considered technically overwhelming and further development could be done in order to abstract these variables from the user and simplify the user interface.

### ***Economics***

The economics section of the user input worksheet encompasses the costs of purchasing, maintaining and operating the system(s). The model also allows for the entry of non-system related income and expenses. Other variables may include starting income, loan interest rates, payback period, and when to make future investments. These variables give the model enough information to determine whether or not the chosen system(s) are economically feasible over

the twenty-five year simulation period. Table 2 provides a detailed overview of the economic variables used in the model.

<u>Variable</u>	<u>Details</u>
<b>General</b>	
<b>Initial balance</b>	Starting balance at before initial system is purchase
<b>Non-system related income (pre-investment)</b>	Annual non-system related income with initial system
<b>Non-system related expenses (pre-investment)</b>	Annual non-system related expenses with initial system
<b>Non-system related income (post-investment)</b>	Annual non-system related income with new system
<b>Non-system related expenses (post-investment)</b>	Annual non-system related expenses with new system
<b>Loan interest rate</b>	Interest rate of loan to purchase new system (if needed)
<b>Loan payback period</b>	Payback period for the loan (in years)
<b>Extra loan amount</b>	Extra money borrowed beyond the amount needed to buy the new system
<b>System Economics</b>	
<b>Fuel cost [\$/L]</b>	Cost of fuel for the generator in dollars per liter
<b>PV cost [\$/kW]</b>	Cost of photovoltaic panels in dollars per kilowatt
<b>Individual battery cost</b>	Capital cost of an individual battery in the battery bank

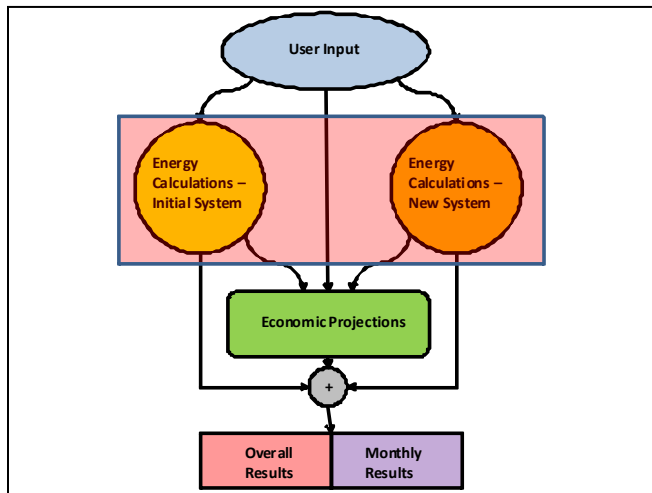
<b>PV Array</b>	Capital, Replacement, and O&M of PV array for each system
<b>Battery Bank</b>	Capital, Replacement, and O&M of battery bank for each system
<b>Converter</b>	Capital, Replacement, and O&M of converter for each system
<b>Generator</b>	Capital, Replacement, and O&M of generator for each system (if needed)
<b>New System</b>	
<b>Make future investment?</b>	Have the model attempt to purchase a new system later in time
<b>Invest by year?</b>	Purchase a new system at a certain year number, or when a certain amount of money is available
<b>Investment year</b>	Year to purchase new system (if invest by year = TRUE)
<b>Minimum investment balance</b>	Minimum amount of money needed before purchasing new system (if invest by year = FALSE)
<b>Take out a loan if needed?</b>	Borrow money if the model wishes to purchase a new system when there are insufficient funds

**Table 2: Economic variables**

An instance of the economic variables listed in Table 2 exists for both the initial system and new system (if purchased). This allows for a sensitivity analysis to be conducted on economic changes over time such as rises in fuel costs, the availability of cheaper photovoltaic panels, and fluctuation in battery prices.

## Energy Calculations

The energy calculations of the model are completed over two iterations, first for the initial system and then for the potential future system. These calculations provide the model with a large amount of information related to system feasibility and cost. This information includes outputs such as system capacity, battery bank life expectancy, fuel consumption, energy



throughput, and average daily load. These values are then passed on for use in the economic projections and results sections of the model. The simulation follows many of *HOMER's* algorithms related to energy calculations, which are documented and available with the software suite download (*HOMER ENERGY*). Calculations are performed on an hourly basis for one year, yielding 8,760 hourly time steps. From the simulation the model determines whether or not the current configuration is feasible from an electrical standpoint. If the configuration is feasible, it then uses the hourly-based simulation to predict the behavior of the initial (and new) system over a twenty-five year time period. Each hour the model compares electrical production versus demand and calculates the flow of energy to and from each component in the system(s). If there is not enough energy available from the PV array and battery bank, the model turns the generator on (assuming the generator's output is capable of meeting the



demand). The extra energy from the generator is used to supply the load demand, as well as to charge the battery bank. A sensitivity analysis can be conducted by changing various input variables to see how they affect the capabilities and efficiency of the system.

The energy calculations can be divided up into three broad sections: solar radiation, energy output and control, and battery bank modeling.

### ***Solar Radiation***

When modeling a photovoltaic array's energy output, it is important to determine the amount of global radiation incident that is in contact with the panels. To do this, the orientation of the panels must be calculated along with other relevant geometric variables such as the time of day, day of the year, and latitude.

The day of the year can be used to determine the solar declination ( $\delta$ ), which is the latitude at which the incoming solar radiance is orthogonal to the surface of the earth at solar noon. This can be calculated by equation 1:

$$(1) \quad \delta = 23.45^\circ \sin\left(360^\circ \frac{284 + n}{365}\right)$$

Where:

$$n = \text{day of year (integer 1 - 365)}$$

The location of the sun in the sky is also affected by the time of day. This can be modeled by calculating the hour angle ( $\omega$ ). The hour angle is considered to be zero at the time of day when the sun is its highest point in the sky, also known as solar noon. Any hour angle measurements

made before solar noon are negative, and measurements made after solar noon are positive.

The hour angle is calculated by equation 2:

$$(2) \quad \omega = (t_s - 12\text{hr}) * 15^\circ/\text{hr}$$

Where:

$$t_s = \text{solar time [hr]}$$

The hour angle is derived from the fact that the sun moves across the sky at approximately 15 degrees per hour. In the above equation, the solar time is considered to be twelve at solar noon, 10.5 an hour and half before, 13.5 an hour and half after, etc.

The model is not able to calculate all time dependent information in solar time. Instead it computes everything in civil time, also known as local standard time. For this reason, solar time must be derived from civil time. Equation 3 relates solar time to civil time.

$$(3) \quad t_s = t_c + \frac{\lambda}{15^\circ/\text{hr}} - Z_c + E$$

Where:

$$t_c = \text{civil time at the midpoint of the simulation time step [hr]}$$

$$\lambda = \text{longitude } [^\circ]$$

$$Z_c = \text{time zone offset east of Greenwich Mean Time [hr]}$$

$$E = \text{equation of time [hr]}$$

In the above equation, west longitudes are negative. Time zones west of Greenwich Mean Time (GMT) are also considered to be negative.

The equation of time ( $E$ ) is used to simulate the tilt of the Earth's rotational axis, known as obliquity. It is also used to account for the eccentricity of the Earth's orbit. The equation of time is given in equation 4:

$$(4) \quad E = 3.82(0.000075 + 0.001868 * \cos \beta - 0.032077 * \sin \beta \\ - 0.014615 * \cos 2\beta - 0.04089 * \sin 2\beta)$$

Where:

$$\beta = 360^\circ \frac{(n - 1)}{365}$$

The variable  $n$  is an integer between one and three hundred and sixty-five that represents the day of the year. The number one would represent January 1st.

By using the previous equations it is possible to define the angle of incidence for a PV panel with any orientation. The angle of incidence can be defined as the angle between the sun's direct radiation and a line normal to the PV surface. Equation 5 shows how to calculate the angle of incidence.

$$(5) \quad \cos \theta = \sin \delta \sin \varphi \cos \beta - \sin \delta \cos \varphi \sin \beta \cos \gamma + \cos \delta \cos \varphi \cos \beta \cos \omega \\ + \cos \delta \sin \varphi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega$$

Where:

$\theta = \text{angle of incidence } [^\circ]$

$\beta = \text{slope of the PV panel } [^\circ]$

$\gamma = \text{azimuth of the PV panel } [^\circ]$

$\varphi = \text{latitude } [^\circ]$

$\delta = \text{solar declination } [^\circ]$

$\omega = \text{hour angle } [^\circ]$

The azimuth angle represents the direction that the PV panel is facing. An azimuth of zero would correspond to straight south, 90° would represent west, -90° would be east, etc.

A particularly important angle of incident is the zenith angle ( $\theta_z$ ). It represents the angle between the sun and an imaginary line perpendicular to a flat surface. The zenith angle would be 90° when the sun is on the horizon, and 0° when the sun is directly overhead. We can set  $\beta$  equal to zero in this previous equation to find the zenith angle. This is because a horizontal surface has a slope of zero. Setting  $\beta$  equal to zero yields equation 6:

$$(6) \quad \cos \theta_z = \cos \varphi \cos \delta \cos \omega + \sin \varphi \sin \delta$$

Where:

$\theta_z = \text{zenith angle } [^\circ]$

The previous equation completes the angle calculations needed in order to ascertain the hourly solar incidence radiation. However, the amount of radiation penetrating the atmosphere must also be determined. This can be done by determining the amount of extraterrestrial normal

radiation ( $G_{on}$ ) for each day of the year. Extraterrestrial normal radiation can be defined as the amount of solar radiation striking a surface normal to the top of the Earth's atmosphere. This can be calculated using equation 7:

$$(7) \quad G_{on} = G_{sc} \left( 1 + 0.033 * \cos \frac{360n}{365} \right)$$

Where:

$$G_{on} = \text{extraterrestrial normal radiation} \left[ \frac{kW}{m^2} \right]$$

$$G_{sc} = \text{solar constant} = 1.367 \frac{kW}{m^2}$$

$$n = \text{day of the year [integer between 1 - 365]}$$

From here, the extraterrestrial horizontal radiation ( $G_o$ ) is calculated.  $G_o$  is the amount of solar radiation striking a surface horizontal to the top of the Earth's atmosphere and can be calculated using equation 8:

$$(8) \quad G_o = G_{on} \cos \theta_z$$

Where:

$$G_o = \text{extraterrestrial horizontal radiation} \left[ \frac{kW}{m^2} \right]$$

$$G_{on} = \text{extraterrestrial normal radiation} \left[ \frac{kW}{m^2} \right]$$

$$\theta_z = \text{zenith angle } [^\circ]$$

Because the simulation runs in hourly increments, the above equation is integrated over one time step in order to find the average extraterrestrial horizontal radiation for each hour. This can be done using equation 9:

$$(9) \quad \bar{G}_o = \frac{12}{\pi} G_{on} [\cos \varphi \cos \delta (\sin \omega_2 - \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180^\circ} \sin \varphi \sin \delta]$$

Where:

$$\bar{G}_o = \text{average extraterrestrial horizontal radiation over one time step} \left[ \frac{kW}{m^2} \right]$$

$$G_{on} = \text{extraterrestrial normal radiation} \left[ \frac{kW}{m^2} \right]$$

$$\omega_1 = \text{hour angle at the beginning of the time step} [^\circ]$$

$$\omega_2 = \text{hour angle at the end of the time step} [^\circ]$$

The average amount of solar radiation striking the top of the Earth's atmosphere is given in the previous equation. The amount of solar radiation in contact with the Earth's surface is obtained from the Global Horizontal Radiation data set mentioned earlier. The ratio between these two variables is called the clearness index, and is defined in equation 10:

$$(10) \quad k_T = \frac{\bar{G}}{\bar{G}_o}$$

Where:

$$\bar{G} = \text{Global Horizontal Radiation} \left[ \frac{kW}{m^2} \right]$$

$$\overline{G}_o = \text{average extraterrestrial horizontal radiation over one time step} \left[ \frac{kW}{m^2} \right]$$

Global solar radiation that reaches the Earth's surface can be divided into two types: beam radiation and diffuse radiation. Beam radiation, the type that one normally thinks of, is direct radiation from the sun. Diffuse radiation is radiation that has been deflected and dispersed by the Earth's atmosphere, and can come from any direction in the sky. Therefore, GHR can be expressed by equation 11:

$$(11) \overline{G} = \overline{G}_b + \overline{G}_d$$

Where:

$$\overline{G}_b = \text{beam radiation} \left[ \frac{kW}{m^2} \right]$$

$$\overline{G}_d = \text{diffuse radiation} \left[ \frac{kW}{m^2} \right]$$

It is necessary to distinguish between the two types of solar radiation because each one has a different amount of influence on the PV array. The orientation of the PV array is much more sensitive to beam radiation than diffuse radiation. However, in this case, the diffuse component is not available. Only the sum of the two components added together is given as the GHR. The model is capable of splitting the GHR into its two components by using a correlation factor found in the Solar Energy journal (Erbs 1982). The correlation is listed below in equation 12.

$$(12) \frac{\overline{G_d}}{\overline{G}} = \begin{cases} 1.0 - 0.09 * k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & \text{for } 0.22 < k_T \leq 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases}$$

At each time step, the model uses the above equation to determine the amount of diffuse radiation from the total global horizontal radiation. It can then calculate the beam radiation component by using equation 11. Once the GHR is split up into its two components, the diffuse radiation must be further split into its three components: isotropic, circumsolar, and horizontal brightening. Splitting the diffuse component can be done by following the HDKR model, which is described in Solar Engineering of Thermal Processes (Duffie 1991). The isotropic component ( $R_b$ ) describes the ratio of beam radiation on the PV array to beam radiation on a horizontal surface:

$$(13) \quad R_b = \frac{\cos \theta}{\cos \theta_z}$$

The circumsolar component, also known as forward scattered radiation, is given by the anisotropy index ( $A_i$ ). This index defines the atmospheric transmittance of beam radiation.

$$(14) \quad A_i = \frac{\overline{G_b}}{\overline{G_o}}$$

The final component of the diffuse radiation takes into account horizontal brightening ( $f$ ). Horizontal brightening is a component used to describe the fact that most diffuse radiation comes from the horizon rather than above. Horizontal brightening is mainly affected by cloud obstruction and is defined as:



$$(15) \quad f = \sqrt{\frac{\overline{G}_b}{\overline{G}}}$$

Finally, the global radiation incident on the photovoltaic array can be calculated by using the HDKR model using equation 16:

$$(16) \quad \overline{G}_T = (\overline{G}_b + \overline{G}_d A_i) R_b + \overline{G}_d (1 - A_i) \left( \frac{1 + \cos \beta}{2} \right) \left[ 1 + f \sin^3 \left( \frac{\beta}{2} \right) \right] + \overline{G} \rho_g \left( \frac{1 - \cos \beta}{2} \right)$$

Where:

$$\beta = \text{slove of the PV array } [^\circ]$$

$$\rho_g = \text{ground reflectance (albedo)} [^\circ]$$

The model uses the global radiation incident ( $\overline{G}_T$ ) in order to calculate the power output of the PV array at each hour.

### ***Energy Output and Control***

The energy output and control section of the model handles the connections between the PV array, generator, and battery bank components, and allows them to work together simultaneously. It gives priority to the PV array and tries to power all system loads from it first.

The output power of the photovoltaic array is dependent on the global incident radiation, derating factor, and the rated capacity of the panels. The model uses equation 17 to calculate the PV array power output ( $P_{PV}$ ). For simplification purposes, the effects of PV cell temperature on the array output power are ignored in this equation.

$$(17) P_{PV} = Y_{PV} f_{PV} \left( \frac{\bar{G}_T}{\bar{G}_{T,STC}} \right)$$

Where:

$Y_{PV}$  = PV array's power output under standard test conditions [kW]

$f_{PV}$  = PV derating factor [%]

$\bar{G}_T$  = solar incident radiation on array at current timestep  $\left[ \frac{kW}{m^2} \right]$

$\bar{G}_{T,STC}$  = incident radiation at standard test conditions  $\left[ 1 \frac{kW}{m^2} \right]$

The de-rating factor is used to account for real world conditions that diminish the ideal power output of the PV array. This can include conditions such as dirty panels, age degradation, distribution losses, shading, and temperature effects. The incident radiation at standard conditions ( $\bar{G}_{T,STC}$ ) is a constant equal to 1 kW/m<sup>2</sup>. All newly designed PV panels are rated under standard test conditions. This means that they are exposed to an incident radiation of 1 kW/m<sup>2</sup>, maintain a cell temperature of 25°C, and do not experience wind.  $Y_{PV}$  represents the array's output power under these standardized test conditions.

Extra energy is drawn from the battery bank if the load demand for the current time step is greater than the power output of the PV array. This usually happens at night when the output power of the panels is zero, or during peak usage times such as when people are cooking or running fans/air-conditioning units. The details of the calculations related to charging and discharging the battery bank is covered in the next section.

As a last resort, the generator is turned on if the combined output power of the battery bank and PV array cannot keep up with demand. The generator will re-charge the battery bank and provide power to the current load. The control methods for generator operation are defined in the user input section of the model. These methods are defined by setting the minimum state of charge, and setpoint state of charge variables listed under the battery characteristics section. The minimum state of charge variable tells the generator when to turn on. If the battery bank's state of charge falls below this value, the generator turns on protecting the bank from total discharge. Total discharge can severely diminish battery life and therefore increase battery bank replacement costs. The setpoint state of charge variable controls when the generator is switched off. While running, the generator charges the battery bank up to the setpoint state of charge. Then it is powered down. It is assumed that the generator runs at full power for the entire time that it is on. It is also assumed that the generator does not have variable control. Using a single-speed generator prevents the model from becoming overcomplicated. It is also realistic considering many of the generators in developing areas do not have variable control. Because of this assumption, output power and fuel consumption from the generator is considered to be constant. The output power is set to the generator's maximum rated output ( $Y_{gen}$ ), which is specified by the user on the input worksheet of the model. Its fuel consumption ( $F$ ) can be calculated using equation 18:

$$(18) \quad F = F_0 * y_{gen} + F_1 * P_{gen}$$

Where:

$$F = \text{fuel consumption at current timestep [L]}$$

$F_0 = \text{generator fuel curve intercept coefficient } [(L/hr)/kW_{rated}]$

$F_1 = \text{generator fuel curve slope } [(L/hr)/kW]$

$Y_{gen} = \text{rated capacity of the generator } [kW]$

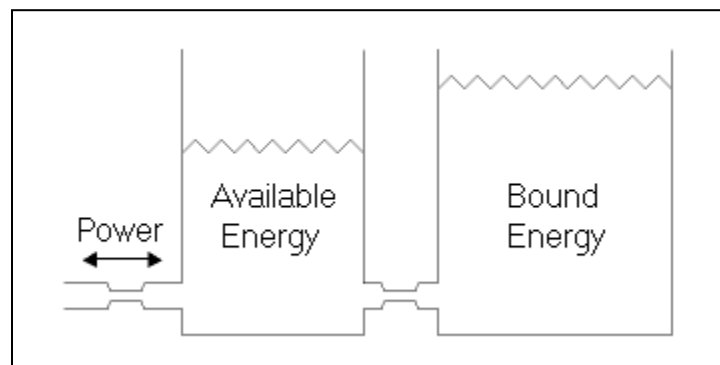
$P_{gen} = \text{generator output power at current timestep } [kW]$

The fuel consumption is calculated at each time step. The generator fuel curve coefficient and fuel slope variables ( $F_0$  and  $F_1$ ) can be obtained with the help of *HOMER* by using its built-in fuel curve calculator. The amount of fuel consumed is then multiplied by the cost of fuel in order to calculate the total fuel cost of the system.

In summary, the model prioritizes its energy sources. Energy is first drawn from the photovoltaic array, then from the battery bank, and from the generator as a last resort. It is important to note that each source can be used in conjunction with one another. If the generator is turned on while the PV array is providing power, the renewable energy component is still utilized, as the total output power of the system gets added together. The simulation will warn the user if the system's total output power at any time step is not sufficient to meet the current demand. It will also warn the user if any one component is not capable of handling the energy throughput. For example, if the system's inverter is rated for 3.5 kW, but the load is drawing 5 kW, it will warn the user that the inverter's capacity is not adequate for the simulation.

## **Battery Bank Modeling**

The last area of energy-related calculations involves the battery bank. The model follows *HOMER's* technique by using the Kinetic Battery Model developed by Manwell and McGowan in their *Solar Energy* journal entry, "Lead Acid Battery Storage Model for Hybrid Energy Systems." The Kinetic Battery Model was adopted because it provides a way to determine how much energy can be absorbed or withdrawn from the battery bank at any one time step. The algorithm is based off of electrochemical kinetics and models the batteries as a two-tank system. The first tank represents the amount of "available energy" in the battery, while the second type represents the amount of "bound energy." The available energy tank contains the amount of energy available for conversion from chemical to electrical energy (direct current electricity). The bound energy tank holds the chemically bound energy that is not yet available for withdrawal. However, the two tanks are connected and energy is allowed to flow between the two tanks. Figure 7 illustrates the Kinetic Battery Model:



**Figure 7: Kinetic Battery Model**

Various parameters are used to effectively calculate the flow of energy between the two tanks. The first parameter is the theoretical maximum battery capacity ( $Q_{max}$ ). It is used to represent

the total amount of energy that the two tanks can hold together. Next, the capacity ratio ( $c$ ) describes the ratio of the amount of available energy relative to the combined size of both tanks. Last, the rate constant ( $k$ ) is used to describe how quickly energy can flow between the two tanks. This is also known as the tank conductance. The rate at which energy flows between the two tanks is affected by the tank conductance and the charge difference between the two tanks.

$Q_{max}$  can be calculated by using equation 19:

$$(19) \quad Q_{max} = \frac{Q_{T=20} * [(1 - e^{-k20})(1 - c) + kc20]}{kc20}$$

Where:

$$Q_{T=20} = \text{standard capacity (20 hour rate)} [Ah]$$

$$c = \text{battery capacity ratio}$$

$$k = \text{battery rate constant } [h^{-1}]$$

The above equation is dependent on the previously mentioned parameters as well as the battery's 20-hour discharge rate capacity. The model automatically calculates the theoretical maximum battery capacity. However, the capacity ratio and rate constant are not automatically calculated. *HOMER* can be utilized to help the user determine these values so that they can be copied into the model.

It is important to distinguish the difference between the theoretical maximum ( $Q_{max}$ ) and the amount of total energy currently in the battery bank ( $Q$ ). The total amount of energy in the battery bank is calculated at each time step and is the sum of the available and bound energies.

$$(20) \quad Q = Q_1 + Q_2$$

Where:

$$Q_1 = \text{available energy}$$

$$Q_2 = \text{bound energy}$$

In order to find the total amount of energy in the battery bank, the available and bound energies must be calculated at each time step. Equations 21 and 22 show how these values are found:

$$(21) Q_{1,end} = Q_1 e^{-kt} + \frac{(Qkc - P)(1 - e^{-kt})}{k} + \frac{Pc(kt - 1 + e^{-kt})}{k}$$

$$(22) Q_{2,end} = Q_2 e^{-kt} + Q(1 - c)(1 - e^{-kt}) + \frac{P(1 - c)(kt - 1 + e^{-kt})}{k}$$

Where:

$$Q_1 = \text{available energy at the beginning of the time step [kWh]}$$

$$Q_2 = \text{bound energy at the beginning of the time step [kWh]}$$

$$Q_{1,end} = \text{available energy at the end of the time step [kWh]}$$

$$Q_{2,end} = \text{bound energy at the end of the time step [kWh]}$$

$P = \text{power provided to or withdrawn from the battery bank}$

$t = \text{length of the time step [hr]}$

The length of the time step ( $t$ ) is always considered to be one hour in the model. However, calculating the amount of power provided to, or withdrawn from, the battery bank is more complicated. The battery bank is not 100% efficient at converting electrical energy to chemical energy and vice versa. Compared to an ideal battery bank, a real battery bank takes more energy to charge the batteries, and less energy is available for extraction. The battery bank efficiency is set by the "round trip efficiency" variable in the user input section. A typical value is approximately 85% efficient. In order to account for this efficiency loss, the power into or out of the battery bank must be multiplied by the round trip efficiency. It is this value that is used as " $P$ " in equations 21 and 22.

The battery bank is limited by the amount of power that it can absorb or release over a particular time period. At each time step, the model makes sure that the amount of power going into or out of the battery bank does not exceed the bank's maximum charge and discharge capabilities. The battery bank's maximum charge and discharge rates are recalculated at each time step. They are dependent on the amount of available and total energies stored in the battery bank. In order to calculate the maximum battery charge power, the model uses the minimum value from three separate equations (equation 26). The first limitation is derived from the Kinetic Battery Model and represents the maximum amount of power that can be absorbed by the two-tank system:



$$(23) \quad P_{batt, cmax, kbm} = \frac{kQ_1 e^{-kt} + Qkc(1 - e^{-kt})}{1 - e^{-kt} + c(kt - 1 + e^{-kt})}$$

The second limitation is related to the maximum charge rate of the battery bank. This limit is inversely proportional to the current charge state of the batteries. As the battery bank's state of charge increases, the allowable amount of charge current decreases.

$$(24) \quad P_{batt, cmax, mcr} = \frac{(1 - e^{-\alpha_c t})(Q_{max} - Q)}{t}$$

Where:

$$\alpha_c = \text{maximum charge rate of battery bank } \left[ \frac{A}{Ah} \right]$$

The final limitation takes into account a maximum absolute charge rate. This is represented in equation 25:

$$(25) \quad P_{batt, cmax, mcc} = \frac{N_{batt} I_{max} V_{nom}}{1000}$$

Where:

$$N_{batt} = \text{number of batteries in the battery bank}$$

$$I_{max} = \text{battery's maximum charge current [A]}$$

$$V_{nom} = \text{battery's nominal voltage [V]}$$

The maximum charge rate ( $\alpha_c$ ), maximum charge current ( $I_{max}$ ) and nominal voltage ( $V_{nom}$ ) must be defined by the user. This information can be obtained from the battery manufacturer's

datasheet. The maximum charge rate is then calculated by taking the minimum value from the above equations and dividing it by the battery charge efficiency ( $\eta_{batt,c}$ ):

$$(26) P_{batt,cmax} = \frac{MIN(P_{batt,cmax,kbm}, P_{batt,cmax,mcr}, P_{batt,cmax,mcc})}{\eta_{batt,c}}$$

Where:

$$\eta_{batt,c} = \sqrt{\text{round trip efficiency}}$$

Similar to its maximum charge rate power limitation, the battery bank is also limited by the amount of power it can discharge over any one time step. The maximum battery discharge power is limitation is also derived from the Kinetic Battery Model. This maximum discharge rate can be described by equation 27:

$$(27) P_{batt,dmax,kbm} = \frac{-kcQ_{max} + kQ_1e^{-kt} + Qkc(1 - e^{-kt})}{1 - e^{-kt} + c(kt - 1 + e^{-kt})}$$

Like the maximum charge calculation in equation 26, the model takes into account discharging losses as energy is extracted from the battery bank. Because of this, the bank's maximum discharge power is given by:

$$(28) P_{batt,dmax} = \eta_{batt,d} P_{batt,dmax,kbm}$$

Where:

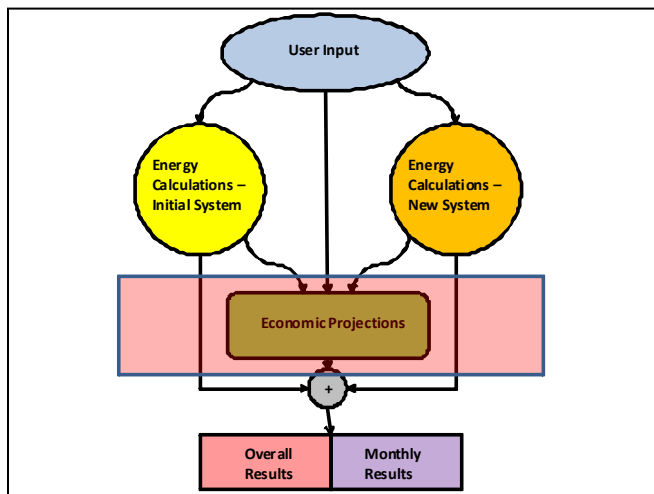
$$\eta_{batt,d} = \sqrt{\text{round trip efficiency}}$$

Once the maximum charge and discharge rates are calculated, they are compared to the actual charge or discharge rates for the current time step. If the current charge or discharge rate is larger than the maximum calculated rate, the maximum values are used for "P." The variable "P" is then used to determine the amount of available and bound energies for the current time step (equations 21 and 22).

Although the Kinetic Battery Model may not perfectly model a battery bank, it provides a fairly accurate, yet simplified algorithm that the model can use to simulate energy flow into and out of the battery bank.

### Economic Projections

The economic projections section of the model provides numerous functions and outputs for



the simulation. These include model features such as economic feasibility studies, loan simulations, system costs, and system changes over time. Outputs from the energy calculations section are passed as inputs to the economic projections section. Examples of these

energy calculations include component lifetimes and fuel costs. In addition, other variables are taken from the user input section such as system costs, loan rates, and purchasing requirements. All of the information is then aggregated together to provide the user with a breakdown of the various costs and revenues that will occur over a twenty-five year period.

### *System Related Cash Flows*

Each component from the initial and new system has a capital, operation and maintenance (O&M), replacement, and salvage value associated with it. The user enters these values before beginning the simulation. The capital cost is considered to be the purchase price if the component if it were bought new. Throughout a projection, capital related costs should only occur once per component, per system. For example, a PV array for the initial system will be purchased at a specified price, and another capital expense will not be seen from the PV component until a new system is purchased (if applicable). At that point, another PV array will be purchased for the new system, yielding an additional capital cost.

Replacement costs account for components failing as they reach the end of their lifetime, and the cost associated with replacing them. This is mainly a concern with the battery bank, as batteries tend to have a shorter lifetime than other components. The model is designed to automatically replace system components when they reach the end of their lifetime. For example, if the battery bank's lifetime is 2.5 years, the model will automatically purchase new batteries at their replacement cost value every two and a half years. Replacement costs are usually less than capital costs, as certain equipment associated with the components can be re-used. These costs could include items such as distribution wiring, charge controllers, and joint boxes. It is up to the user to define the replacement costs.

Depending on the component, its lifetime is either manually entered, or calculated by the model. The model calculates the generator and battery bank's lifetimes. They are dependent on how heavily each item is used. The user manually enters the lifetimes of the other

components. The lifetime of the battery bank is determined by two independent factors: lifetime throughput ( $Q_{lifetime}$ ) and float life ( $R_{batt,f}$ ). In summary, the batteries will either die from use or old age. The model will use whichever one comes first. The following equation describes a battery bank's lifetime expectancy ( $R_{batt}$ ):

$$(29) R_{batt} = MIN \left( \frac{N_{batt} Q_{lifetime}}{Q_{thrpt}}, R_{batt,f} \right)$$

Where:

$$R_{batt} = \text{battery bank life [yrs]}$$

$$Q_{lifetime} = \text{lifetime throughput of a single battery [kWh]}$$

$$Q_{thrpt} = \text{annual throughput of battery} \left[ \frac{\text{kWh}}{\text{yr}} \right]$$

$$R_{batt,f} = \text{battery float life}$$

The lifetime throughput of each battery must be manually entered by the user, but can be easily calculated with the help of *HOMER*. The model then calculates the annual throughput. The energy calculations are completed first because the battery bank's annual throughput is dependent on the energy related calculations.

The generator's estimated lifetime is simpler to determine. Its lifetime is calculated by taking at its rated lifetime ( $R_{gen,h}$ ), and dividing that value by how frequently it is ran. Equation 30 shows how the model determines the generator's operational life:

$$(30)R_{gen} = \frac{R_{gen,h}}{N_{gen}}$$

Where:

$R_{gen,h}$  = *rated lifetime of generator [hr]*

$N_{gen}$  = *number of hours the generator is operated per year [hr/yr]*

Note that a generator's rated lifetime is usually listed in hours of operation rather than years. The rated lifetime can usually be obtained from the manufacturer's datasheet. Typical values for a gasoline-powered generator are between 250-1,000 hours, while a diesel generator's typical lifetime can be between 6,000-10,000 hours.

Operation and maintenance related costs are less complex than replacement costs. The user enters the cost to operate and maintain each component on an annual basis. Then the model deducts this value from a running balance each year. Examples of operation and maintenance costs can include purchasing oil for the generator, battery fluid for the battery bank, and technician fees to ensure the system is functioning properly. O&M costs do not include purchasing fuel for the generator, as this is treated as a separate expense. O&M fees should be thought of as a consistent annuity rather than a one-time expenditure.

Each component has a salvage value, which is treated as revenue, rather than an expense. It can be defined as the component's remaining value at the end of the system's lifetime. The model assumes that the value of each system component depreciates linearly over time. This means that that a components salvage value is directly proportional to its remaining life. The

model also assumes that the salvage value is based off of the components replacement cost rather than its capital cost. According to this algorithm, the model uses the following equations to calculate the salvage value of each component:

$$(31) \quad S = C_{rep} * \frac{R_{rem}}{R_{comp}}$$

$R_{rem}$  represents the remaining life of a component at the end of a system's lifetime. It can be calculated by:

$$(32) \quad R_{rem} = R_{comp} - (R_{sys} - R_{rep})$$

$R_{rep}$  is the replacement cost duration, which represents the last time the component was replaced:

$$(33) \quad R_{rep} = R_{comp} * INT\left(\frac{R_{sys}}{R_{comp}}\right)$$

Where:

$$C_{rep} = \text{component replacement cost [\$]}$$

$$R_{comp} = \text{component lifetime [yrs]}$$

$$R_{sys} = \text{system lifetime [yrs]}$$

The system lifetime is treated differently depending whether or not the model is working with the initial system, or the new system. When working with the initial system, the system's lifetime is set equal to the purchase year of the new system. It is assumed that the initial system is then sold for its salvage value and the new system is purchased. If the model is

working with the new system, the system's lifetime is equal to the simulation length minus the purchase year of the new system. For example, if the new system were purchased at year nine, the result would be calculated by subtracting nine from twenty-five, yielding a sixteen-year system lifetime. This is because the simulation length is always twenty-five years.

### ***Purchases and Loans***

Various settings can be specified by the user to reflect his or her economic strategies. This includes defining variables such as loan interest rates, payback periods, and new system purchasing options. The model gives the user three options to choose how the new energy system is purchased. The first option is defined by the "make future investment" variable. This can be set to true or false, allowing the user to specify whether he or she wants to purchase a new system or not. If it is set to false, the model will only purchase the initial system and run the economic projection solely off of the initial system's characteristics. If it is set to true, the model will purchase a new system at a user specified point in time. However, this point in time can be set via two algorithms, and is defined by the "invest by year" variable. If set to true, the model will purchase the new energy system at a particular year number specified by the user, regardless of budget. This can be beneficial if one knows when their energy budget will need to be increased. Examples could be the opening of a restaurant, installation of air conditioning units, or general population growth. If it is set to false, the model will purchase a new system when the user's balance has reached a specified amount. This allows the purchase to occur independent of year number. The minimum amount of funds needed can be specified in the user input section of the model.



It is important to note that a new system can be purchased even if sufficient funds are not available. However, this is only possible if the "take out loan" variable is set to true. If enabled, and there are not sufficient funds to purchase the new system, the model will take out a loan with an interest rate and payback period specified by the user. These variables are defined on the user input worksheet. The loan will automatically be set to the exact amount needed to purchase the new system. For example, if the new system cost \$25,000 and the user had \$16,000, the loan amount would automatically be set for \$9,000. The model will then deduct annuitized loan payments from the user's budget each year. The annuitized rate is affected by the total loan amount, interest rate, and payback period. If loan payments are still being paid by the end of the twenty-five year simulation period, the rest of the loan balance is automatically paid off.

On the other hand, if the "take out loan" variable is set to false, the model will not take out a loan, even if the user goes into debt. However, if the user does go into debt, the model will warn the user that they do not have sufficient funds to purchase and/or sustain their desired setup. The simulation will only take out a loan if two conditions are met: the "take out loan" variable is set to true, and there are insufficient funds to purchase the new system. The model will not take out a loan if the projected balance becomes negative due to operation, maintenance, fuel, or replacement costs. Instead it will warn the user that there is insufficient income to sustain their desired setup. The model was designed like this on purpose in order to prevent an unrealistic scenario where loans are continuously being compounded. This would only put the user further and further into debt. It can be economically beneficial to take out a

loan in order to expand capital. However, it is unsustainable to rely on loans in order to operate and maintain existing equipment.

Other economic variables to consider are the user's income, and non-system related expenses. This allows for system integration into the user's budget. The model also allows for these variables to change over time. It is realistic that income and non-system related expenses could change over time, especially after a new energy system is purchased. For this reason, the user input section of the model allows the user to enter different income and expense values for both the initial and new systems. An example of this economic dynamic could be the construction of a new restaurant. A new energy system would need to be purchased in order to meet the increased energy demand from the cooking equipment. However, the new restaurant would also increase the user's income and non-system related expenses. The model allows the user to account for such scenarios.

The outputs of the economic projection are comprehensive. They let the user analyze all economic factors by breaking them down on a spreadsheet. It also graphs the spreadsheet in various formats, depending what the user is interested in. An example subsection of the spreadsheet can be seen in Figure 8.

		Year	1	2	3	4
		System	Initial	Initial	New	New
Component		Category				
System Economics	PV	Capital	-\$4,884.10	\$0.00	-\$12,000.00	\$0.00
		Replacement	\$0.00	\$0.00	\$0.00	\$0.00
		O&M	-\$5.00	-\$5.00	-\$10.00	-\$10.00
		Salvage	\$0.00	\$0.00	\$3,495.69	\$0.00
		Total	-\$4,889.10	-\$5.00	-\$8,514.31	-\$10.00
	Generator	Capital	-\$1,000.00	\$0.00	\$0.00	\$0.00
		Replacement	\$0.00	\$0.00	\$0.00	\$0.00
		O&M	-\$50.00	-\$50.00	-\$60.00	-\$60.00
		Fuel	-\$1,850.43	-\$1,850.43	-\$638.55	-\$638.55
		Salvage	\$0.00	\$0.00	\$815.48	\$0.00
		Total	-\$2,900.43	-\$1,900.43	-\$698.55	-\$698.55
	Battery Bank	Capital	-\$3,600.00	\$0.00	-\$8,000.00	\$0.00
		Replacement	\$0.00	\$0.00	\$0.00	\$0.00
		O&M	-\$7.00	-\$7.00	-\$6.00	-\$6.00
		Salvage	\$0.00	\$0.00	\$278.35	\$0.00
		Total	-\$3,607.00	-\$7.00	-\$7,727.65	-\$6.00
	Converter	Capital	-\$2,500.00	\$0.00	-\$3,000.00	\$0.00
		Replacement	\$0.00	\$0.00	\$0.00	\$0.00
		O&M	-\$3.00	-\$3.00	-\$4.00	-\$4.00
		Salvage	\$0.00	\$0.00	\$2,070.00	\$0.00
Total		-\$2,503.00	-\$3.00	-\$934.00	-\$4.00	
Entire System	Capital	-\$11,984.10	\$0.00	-\$23,000.00	\$0.00	
	Replacement	\$0.00	\$0.00	\$0.00	\$0.00	
	O&M	-\$65.00	-\$65.00	-\$80.00	-\$80.00	
	Fuel	-\$1,850.43	-\$1,850.43	-\$638.55	-\$638.55	
	Salvage	\$0.00	\$0.00	\$6,659.52	\$0.00	
	Total	-\$13,899.53	-\$1,915.43	-\$17,059.03	-\$718.55	
Organization Budget	Non-system related income	\$10,000.00	\$10,000.00	\$15,000.00	\$15,000.00	
	Non-system related expenses	-\$5,000.00	-\$5,000.00	-\$7,000.00	-\$7,000.00	
	Non-system related Net	\$5,000.00	\$5,000.00	\$8,000.00	\$8,000.00	
Loans	Money Borrowed	\$0.00	\$0.00	\$2,889.89	\$0.00	
	Loan Payments	\$0.00	\$0.00	\$0.00	-\$686.05	
Totals	Total Net	-\$8,899.53	\$3,084.57	-\$6,169.14	\$6,595.40	
	Total Balance	\$11,984.10	\$3,084.57	\$6,169.14	\$0.00	\$6,595.40

**Figure 8: Sample spreadsheet output**

In addition, two types of cash flow charts can be generated: cash flow by expense type (Figure 10) or cash flow by system component (Figure 9).

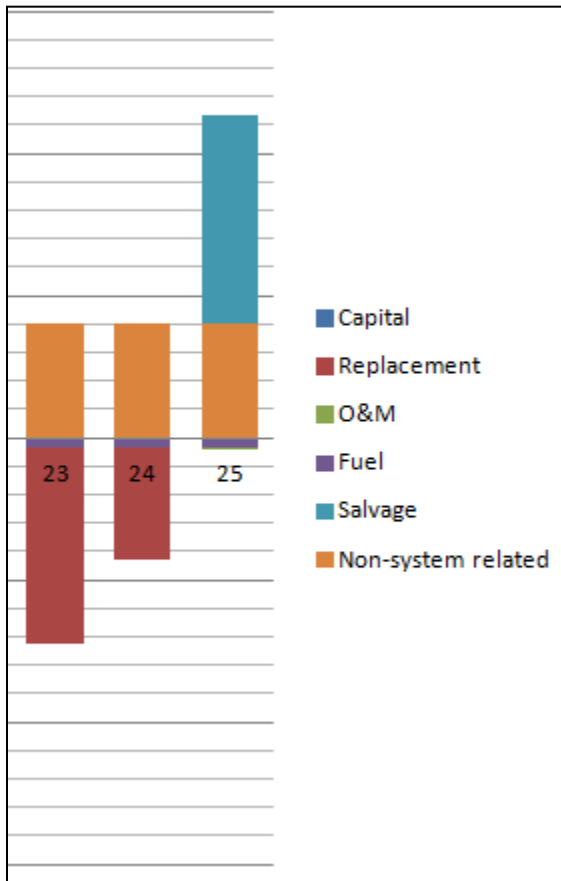


Figure 10: Example cash flow by expense

type

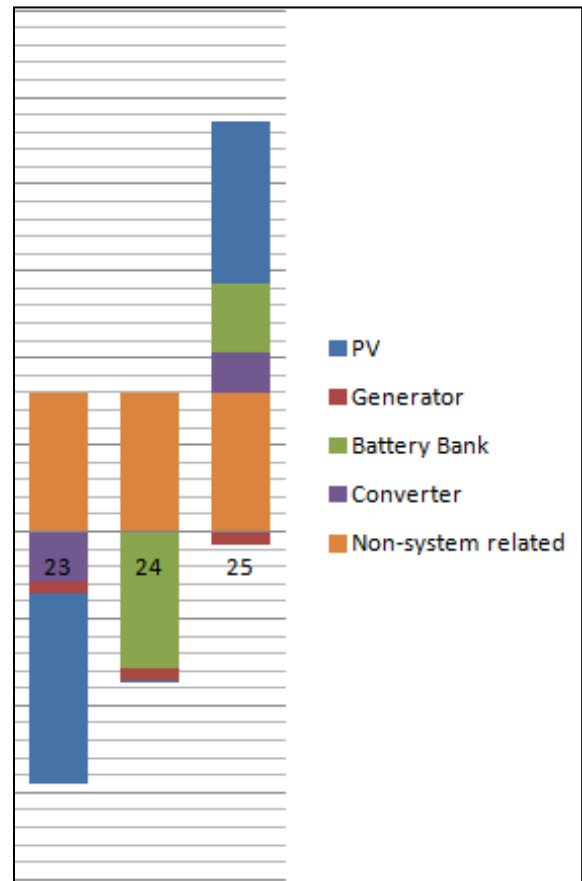
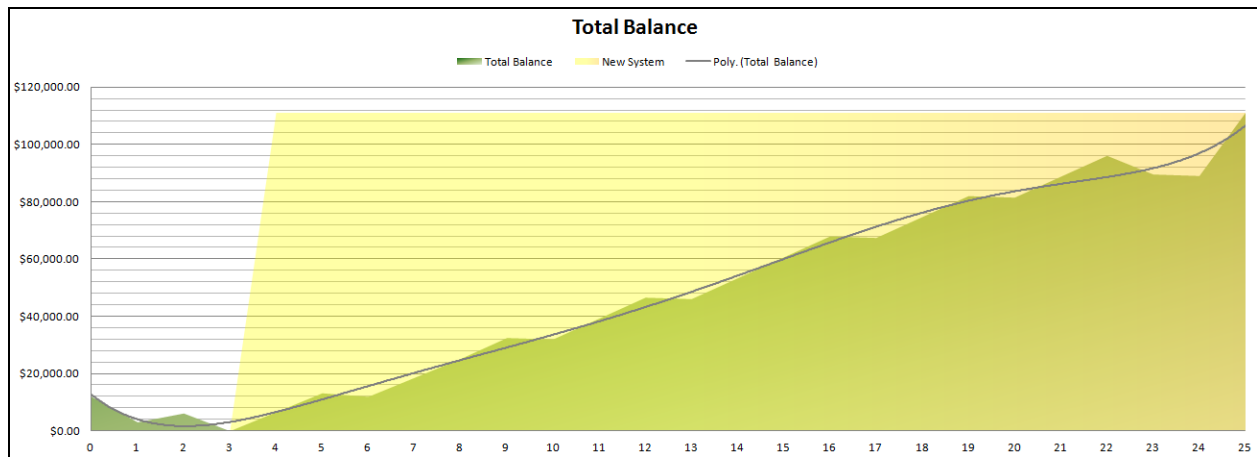


Figure 9: Example cash flow by system

component

The last economic output allows the user to see his or her balance over a twenty-five year simulation period. See Figure 11.

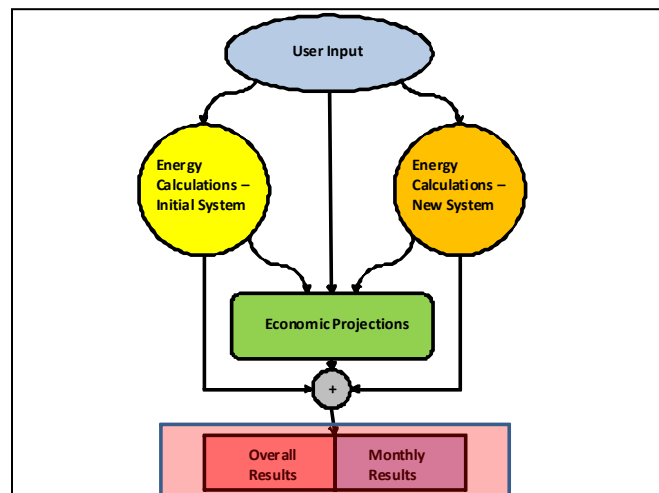


**Figure 11: Example balance over simulation**

The yellow area represents the time that the new system was used. In this particular example, one can see that a new system was purchased at year three. The gray line is a polynomial-based trend line intended to help the user better visualize the changes in his or her balance over the simulation time frame.

### Overall and Monthly Results

The last section of the model includes both monthly and overall results of the simulation. This includes all of the energy outputs, as well as economic results not covered in the economic projections section. The two results sections are generated on separate worksheets in the model. Each worksheet displays information on a different level of detail.



## Overall Results

The overall results section of the model covers yearly and overall outputs. It is divided up by system, and then by component. Examples of some the overall results include generator and battery bank life expectancy, electrical production, fuel consumption, fuel cost, and total monetary gain or loss. Table 3 provides a table of the overall results.

<u>Variable</u>	<u>Description</u>
<b>PV Array</b>	
<b>Rated capacity [kW]</b>	Rated capacity of panels under standard test conditions
<b>Maximum output [kW]</b>	Maximum production at any point over the course of a year
<b>Mean output [kW]</b>	Average load over the course of a year
<b>Mean output [kWh/day]</b>	Average energy consumed each day
<b>Total average production [kWh/yr]</b>	Average energy production per year
<b>Hours of operation [hrs/yr]</b>	Average hours of operation each year
<b>Battery Bank</b>	
<b>String size</b>	Number of batteries wired in series
<b>Strings in parallel</b>	Number of battery strings wired in parallel
<b>Batteries in bank</b>	Total number of batteries in the battery bank
<b>Bus voltage</b>	Operating DC voltage of the battery bank
<b>Lifetime throughput</b>	Amount of energy the battery bank can absorb and

	discharge before needing to be replaced
<b>Annual throughput</b>	The average amount of energy cycling through the battery bank each year
<b>Expected life (yrs)</b>	Life expectancy of battery bank
<b>Autonomy</b>	Ratio of battery bank size to electrical load
<b>Generator (if applicable)</b>	
<b>Electrical production [kWh/yr]</b>	Average electrical production per year
<b>Hours of operation [hrs/yr]</b>	Average hours of operation each year
<b>Fuel consumption [L/yr]</b>	Average fuel consumption per year
<b>Fuel cost [\$ /yr]</b>	Average cost of fuel per year
<b>Expected life [yrs]</b>	Life expectancy of generator
<b>General</b>	
<b>Energy shortage [kWh]</b>	Average amount of energy demand that cannot be met each year
<b>Maximum power consumption [kW]</b>	Maximum load draw at any point over the course of a year
<b>Average load [kWh/day]</b>	Average load demand each day
<b>Economics</b>	
<b>Cost over lifespan</b>	Cost of the system over its lifespan (capital, replacement, O&M, etc.)
<b>Net over system lifespan</b>	Total net change in balance over system lifespan

<b>Average annual net</b>	Average net change each year over system lifespan
---------------------------	---

**Table 3: Overall results per system**

Note that the above outputs are system specific. This means that an instance of the output set listed in Table 3 exists for both the initial system and the new system (if applicable). Another set of overall outputs can be seen for the entire simulation. These outputs can be seen in Table 4.

<u>Variable</u>	<u>Description</u>
<b>Overall Results</b>	
<b>New system purchased?</b>	Displays true or false, depending whether or not a new system was purchased or not
<b>Purchase year (if applicable)</b>	Displays what year the new system was purchased in
<b>Total system cost</b>	Total cost to purchase, operate and maintain the system(s) over the simulation period
<b>Total net</b>	Total net change in balance over simulation timeframe
<b>Total average annual net</b>	Average net change each year over simulation timeframe

**Table 4: Overall results over simulation timeframe**

Additional outputs could be generated in this section if the user wishes to see a more detailed analysis of the simulation. However, the current list is fairly comprehensive, and it can quickly become overwhelming if too many results are displayed at once.



### Monthly Results

The monthly results section of the model is used to display detailed energy outputs over one

year. The monthly results include tables and graphs of the following outputs broken down by month: global horizontal radiation, energy

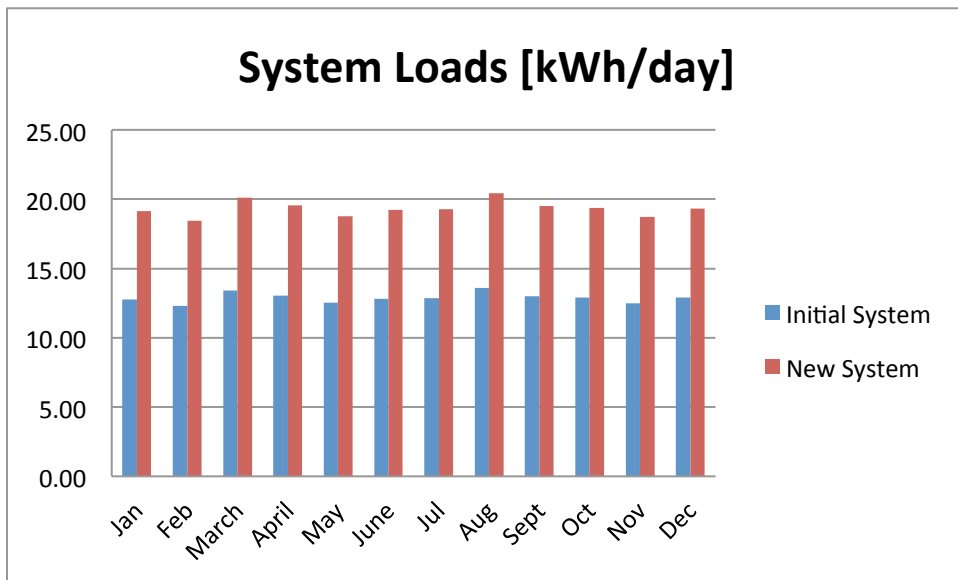


Figure 12: Example monthly output

demand, solar output, and generator operation. Currently only a few energy related outputs are generated, but the model can be easily expanded upon to include energy and economic related variables. Figure 12 shows an example of the electrical load on both systems.

## **Model Assumptions**

Numerous assumptions were made when developing the model. This section intends to list the majority of them.

### **Energy Related**

The following is a list of energy related assumptions:

- Energy demand is constant throughout each hourly time step
- Energy is consumed from various sources on the following priority levels:
  1. PV system
  2. Battery bank
  3. Generator
- The generator is turned on when the battery bank reaches the "minimum state of charge," and is left on until the battery bank reaches the "setpoint state of charge"
- The generator lacks variable speed functionality. It is assumed that it will run at full capacity while running
- Global horizontal radiation is assumed to be the same each year
- Energy demand behavioral patterns are assumed to be the same throughout the life of a system

## **Economic Related**

The following is a list of economic related assumptions:

- The salvage value of each component depreciates linearly on a yearly basis
- Components are sold at salvage value on two occasions:
  1. A new system is purchased
  2. The model has reached the end of the simulation timeframe
- If a loan balance remains at the end of the simulation, it is paid off completely
- System components are automatically replaced at the end of their lifetime
- All dollar amounts are given in present value. Any rise in component prices are assumed to follow natural inflation rates, unless specified by the user
- If enabled (and needed), a loan is taken out when purchasing a new system

## **Flowchart**

Figure 13 shows a high level view of the algorithm that the model uses to generate its outputs and economic projections.

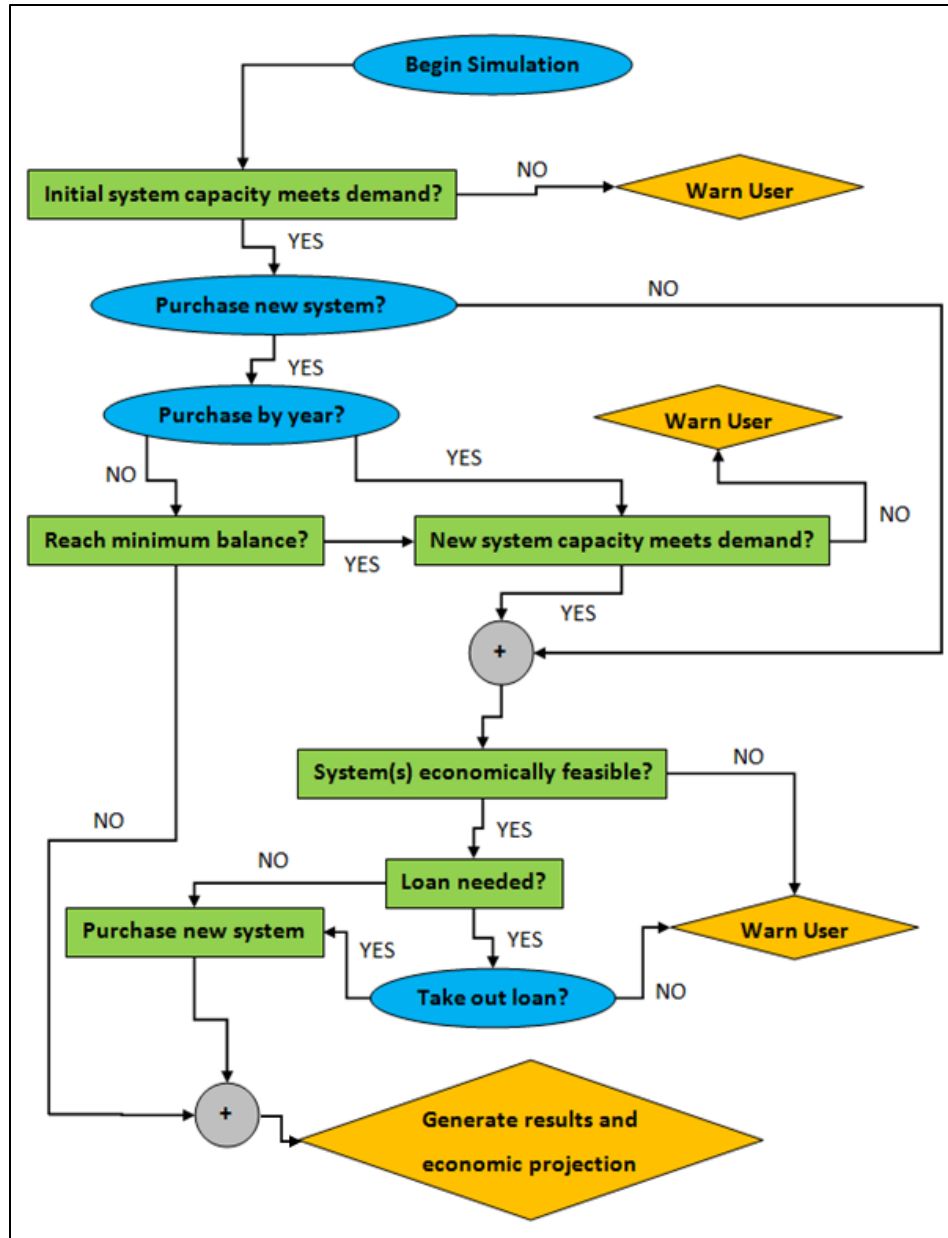


Figure 13: Flowchart of model logic

## Analysis and Results

The dynamic energy model is realistic and useful. With the help of *HOMER*, it is fairly easy to use. Once it was developed, I thought it would be interesting to use the model to run a set of

simulations for an existing NGO that already has a renewable energy system and would like to expand their infrastructure. The model could be used to project their current setup, as well as predict possible future scenarios. Recently, an NGO named NEGES, has expressed interest in improving their current hybrid renewable energy system. This analysis is going to simulate various scenarios in order to help NEGES determine how to meet their rising energy demand while yielding the most profit.

### **Background Information**

This following section provides background information about NEGES, the non-governmental organization that the model analysis is based off of.

#### **The NEGES Foundation**

Founded in 1998, the NEGES Foundation is a Brooklyn-based organization that was started by Marie Yoleine Gateau-Esposito and James Philemy, both of whom are immigrants from Haiti. Madam Yoleine Gateau and Mr. Philemy are committed to bringing community development, ecological awareness, and improved education to their homeland. The word NEGES is an acronym for *Nest for Educational Growth and Environmental Safety*, a name which describes the organization's ultimate goals. With a focus on the youth, Madam Yoleine Gateau and Mr. Philemy feel that, "protecting the environment is as integral as education. We feel that the best way to begin developing consciousness about the environment is to start teaching children when they are young." The non-governmental organization (NGO) started their first summer camp in 1998. During the camp children from ages five to twelve planted and cultivated trees, and also learned about the importance of vegetation in sustaining human life. Over the years,

NEGES has partnered with many universities and organizations to take on various projects. A couple of these projects include the construction of a new primary school and the creation of the first recycling center in their area. Now NEGES is looking for ways to make themselves more self-sufficient and energy independent.

### **A Developing Community**

A local community is developing within the confines of the NEGES compound. The compound is called Mon P'tit Village (My Little Village) and is located off of Route Nationale #2 in Léogâne, Haiti. It is approximately the size of one to two city blocks and houses approximately 40 people. NEGES hires local people to run its programs and events, care for volunteers, and also maintain the compound. Because of this, the community size can be larger during the day. Most of the people that live within the compound reside in tents donated from various governmental organizations such as USAID and the United Nations. They are displaced peoples due to the impact of the 2010 Haitian earthquake. Immediately following the earthquake, NEGES took in hundreds of people, providing immediate disaster response and relief. Over time, some of the displaced have gotten back on their feet and have been able to leave NEGES' compound. Unfortunately many have not been able to recover from the earthquake and still remain on site. Many now work for NEGES and are required to contribute to the community and NEGES' efforts as payment to continue living on the compound. The end result is an incredibly diverse community consisting of low-class to high-class Haitians, Haitian-Americans, students, and professionals from all over the world.

## Current Situation

NEGES has come a long way in its steps toward self-sufficiency and an overall better quality of life. Land has been developed for self-subsistence farming. Wells have been drilled and gravity-fed plumbing has been installed. However, NEGES still lacks the necessary energy infrastructure to meet the demand of the community and their projects. This can be seen the SWOC (strengths, weaknesses, opportunities, and challenges) matrix below (Table 5).

Strengths	Weaknesses	Opportunities	Challenges
Financial resources	Poor energy conservation	Open land for expansion	Training technicians
Organization	Insufficient energy supply	Local income generation	Behavior change of energy use
Access to food and water	Lack of access to healthcare	Increased job creation	Finding appropriate healthcare
Social connections	Foreign dependency	Higher level of education	Obtaining equipment and spare parts

**Table 5: SWOC Analysis**

The information in the SWOC matrix was gathered from participatory action research (PAR) data previously obtained from earlier trips to Haiti. Although there are other noticeable challenges, energy is important because almost all of NEGES' infrastructure and programs rely on energy availability. Examples of energy dependency include the school's computer class, the

pumping of well water, lighting, cooling, volunteers' equipment, and cooking at NEGES' new restaurant.

### ***The Original System***

Originally, NEGES had six - 75 watt panels, and a seventh - 40 watt panel installed on their roof.

This amounts to 490 watts of theoretical output (see Figure 14). The brand of these solar panels is unknown, and the solar panel array was wired to a Xantrex C40 charge controller, which does not have maximum power point tracking capability (MPPT). The charge controller was connected to a battery bank of five - 12 volt, 77 amp-hour batteries that were wired in parallel. The battery bank was then

wired to a 3000 watt, 120 volt, AIMS Power inverter for distribution throughout NEGES.

NEGES also had a Generac 4000XL gasoline generator with a theoretical maximum output of 4000 watts, which was used in conjunction with the photovoltaic array.



**Figure 14: NEGES' current PV array**

Energy from the battery bank was accessed first until it is depleted. Then, someone from the community would manually disconnect the inverter and connected the generator to the electrical distribution box as well as the battery bank. This way, they were able charge the battery bank and power the community concurrently.



The community was using the existing system mainly to charge the battery bank so that energy could be made available during the evening. The energy was used to light the campus, power fans, and charge electronics such as cell phones. Of these three uses, the fans have had the largest toll on the system. The fans are not efficient, and can load a couple hundred watts on the system. Compared to LED lighting and the charging of cellular phones, this has been their biggest energy expense. Energy from the battery bank was consumed until the bank was depleted. Then the generator was powered up and ran through the night until morning. During the day energy consumption was much less. It was mainly used to power Internet equipment and volunteers' electronics such as laptops. NEGES' school (located on campus) also pulled energy for an hour each morning to teach their computer class. Although functioning, the pre-existing systems had many problems.

One major issue with the system was that the charge controller was not fully charging the battery bank each day. On an average night, NEGES was only able to power their community for approximately two to four hours. They would then be forced to start up the gasoline generator in order to power the campus and charge the battery bank to 100% capacity. The system also lacked necessary switches and breaker boxes to properly and safely distribute the electrical energy. To compound the problem, new wiring had been laid on three separate occasions, each by a different "electrician." Each electrician wired their additions according to their own code and preferences, leaving NEGES' setup in a jumbled mess when trying to review the infrastructure layout. Only one person on the compound was educated in how to run the system regularly. Unfortunately they still lacked the knowledge to properly maintain and operate their system on a long-term basis.

### *Plans for the Future*

NEGES has been planning on opening a restaurant to create a source of locally generated income. However, the addition of a restaurant will increase the energy demand on their system dramatically. This leaves NEGES with a few options. They could keep their existing system but burn more fuel (if the generators capacity is sufficient), purchase a new system, or improve their existing one. The model can help NEGES optimize their system(s) to meet their energy demand while still being economically feasible. The model will assume that if NEGES chooses not to power the restaurant off of their existing infrastructure, it will sell their old system for its salvage value and purchase a new one.

Five different scenarios are analyzed and compared in order to determine the best possible situation. The five scenarios can be divided up into three categories: a base case, realistic scenarios, and worst-case scenarios. In the base case category, the model does not purchase a new system, nor does it assume that NEGES builds a restaurant. Their entire setup remains the same. Energy production, system load, and income remain constant throughout the simulation. In the other two categories, a simulation is run twice for each category. The first time, a new system is purchased five years in the future. The second time, the model waits ten years before purchasing the new system. In each of these categories, the model assumes that energy demand doubles due to the construction of the restaurant. The five scenarios will be discussed in detail below. Then the results will be compared in order to draw conclusions regarding an optimal setup for NEGES.

## Common Setup Between Cases

Many of the modeling variables are left unchanged between each scenario. Such variables include global horizontal radiation and demand behavior. The same initial system and new system are purchased regardless of the scenario (except for the base case, where a new system is not purchased). The new system was chosen to meet the demand requirements of the new restaurant, but was not over designed for the application. Most of the variables that change between each case are economic related variables. These include changes in fuel and component prices, loan variables, as well as the time period at which the new system is purchased. Table 6 defines the constant variables used for each scenario.

<u>Variable</u>	<u>Initial System</u>	<u>New System</u>
<b>PV Array</b>		
Rated STD output [kW]	0.49	10
Derating factor [%]	85%	85%
Slope of PV panels [°]	18	18
Azimuth [°]	0	0
Ground reflectance [%]	20%	20%
Lifetime [yrs]	20	20
<b>Battery Characteristics</b>		
Nominal capacity [Ah]	77	180
Maximum capacity [Ah]	82.866	201.702
Lifetime throughput [kWh]	516	643

Nominal Voltage [V]	12	6
Round trip efficiency [%]	85%	85%
Minimum state of charge [%]	40%	30%
Setpoint stage of charge [%]	90%	80%
Float life [yrs]	10	10
Maximum charge rate [A/Ah]	1	1
Maximum charge current [A]	54	54
Capacity Ratio	0.43	0.7225
Rate Constant	0.87	0.1516
<b>Battery Bank Arrangement</b>		
Batteries per string	1	8
Number of strings	5	4
Batteries in bank	5	32
Bank voltage [V]	12	48
Bank capacity [Ah]	414.33	806.81
Maximum bank energy [kWh]	4.97	38.73
<b>Converter Characteristics</b>		
Maximum throughput [kW]	3	5
Inverter efficiency [%]	92%	92%
Rectifier efficiency [%]	85%	85%
Lifetime [yrs]	20	20

<b>Generator Characteristics</b>		
<b>Maximum output power [kW]</b>	4	5
<b>Lifetime [yrs]</b>	15,000	15,000
<b>Fuel curve intercept coefficient [L/hr/kW]</b>	0.08	0.08
<b>Fuel curve slope [L/hr/kW]</b>	0.25	0.25
<b>Economics</b>		
<b>Initial balance [\$]</b>	\$6,416.10	
<b>Non-system related income [\$]</b>	\$11,000	\$20,000
<b>Non-system related expenses [\$]</b>	\$4,000	\$8,000

**Table 6: Constant variables across each scenario**

In order to account for the load that the new restaurant puts on the system, the energy demand is increased by 200% when the new system is purchased. The starting balance is set equal to the capital cost of the initial system. Because NEGES' budget is not available to the public, non-system related income and expenses were derived from an educated guess. The cost of constructing, operating and maintaining the restaurant is included in the "non-system related expenses" variable of the new system.

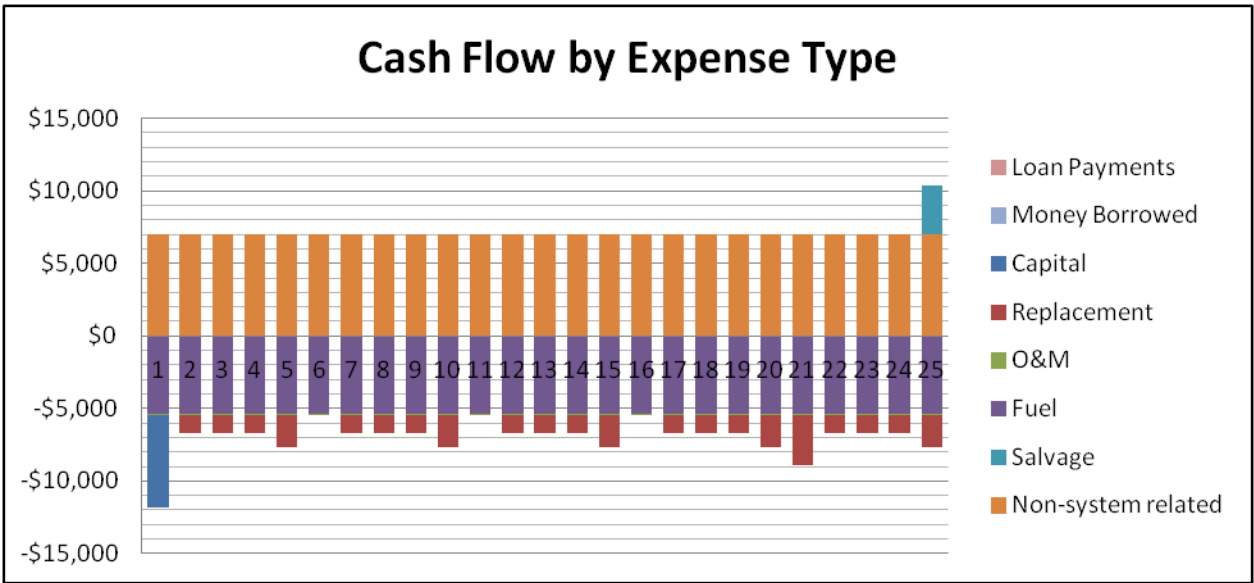
**Base Case**

The first scenario establishes a base line for the other cases. It models a twenty-five year projection assuming that NEGES keeps their existing system and does not construct a new restaurant. Energy demand, energy production, and income levels remain constant throughout the simulation. Table 7 shows the volatile variables that are used for the base case.

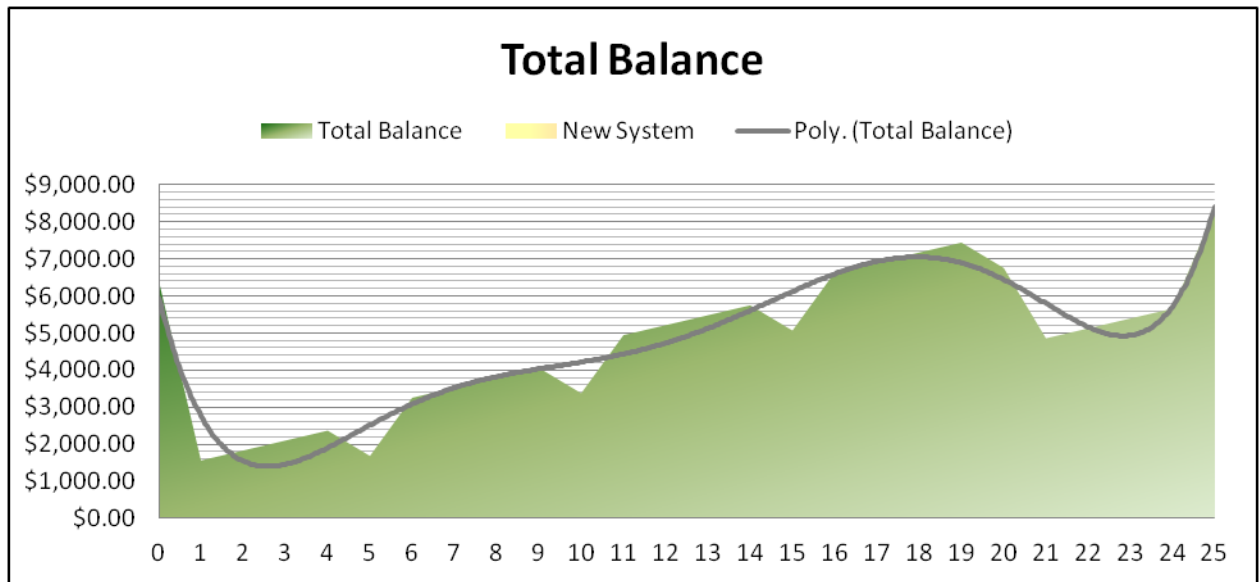
<u>Variable</u>	<u>Value</u>
<b>Make future investment?</b>	FALSE
<b>Fuel cost [\$/L]</b>	\$1.32
<b>PV cost [\$/kW]</b>	\$2,890
<b>Individual battery cost [\$]</b>	\$300

**Table 7: Base case - volatile variables**

The simulation starting balance is set equal to the total capital cost of the initial system, which is \$6,416. The breakdown of the cost of the system by component, and by expense type can be seen in Appendix A. The cost of fuel, photovoltaic panels, and individual batteries were set according to the current market prices in Haiti. The model assumes that these values do not fluctuate over the simulation timeframe, besides accounting for natural inflation. Figure 15 and Figure 16 display the results of the simulation.



**Figure 15: Base case - cash flow**



**Figure 16: Base case - balance**

From the results one can see that NEGES' initial system is economically feasible. Their net balance increase over the twenty-five year time period is \$1,915.94. This averages to approximately \$76.64 profit per year. Unfortunately this sort of profit margin does not leave much room for growth. Looking at Figure 15 one can see that almost all reoccurring costs are fuel related. Their system is capable of meeting the energy demand, but not without extreme supplemental help from the generator. Fuel costs are \$5,342.20 per year, assuming that gas prices remain constant at \$1.32 per liter. This is unlikely considering the historical trend of fossil fuel prices increasing. From this information, one is able to see that the base case scenario is both technologically and economically feasible. However it does not seem like a very optimized solution. The setup is too dependent on the generator and leaves no room for expansion.

## Realistic Scenarios

The realistic scenario category contains two different scenario types. Each simulation runs off of the same variable values, but the new system is purchased at a different time period.

### Scenario Two

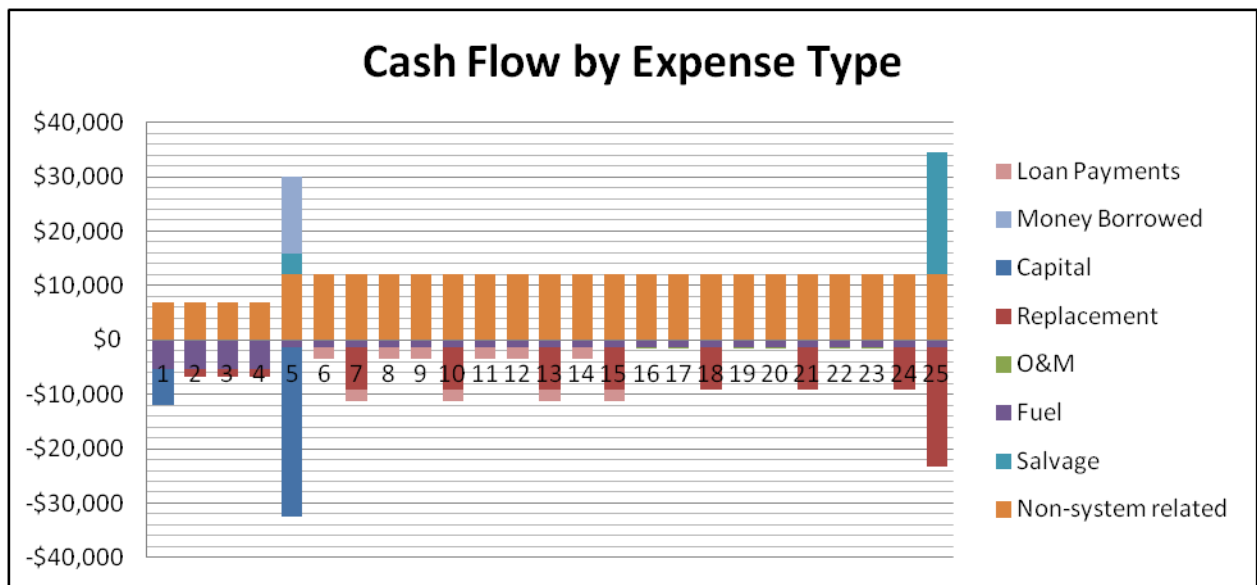
The second scenario assumes that NEGES constructs a new restaurant and purchases a new energy system in order to meet the increased energy requirements. The scenario assumes that NEGES will purchase their new system and begin operation of their restaurant at year five. Until then, the model assumes that they will rely on their initial system for energy. After the new system is purchased, energy demand, energy production, and income and expense cash flows will increase. Figure 17 defines the variables specific to scenario two.

<u>Variable</u>	<u>Initial System</u>	<u>New System</u>
<b>Make future investment?</b>	TRUE	
<b>Purchase year</b>	5	
<b>Take out a loan if needed?</b>	TRUE	
<b>Loan interest rate</b>	8%	
<b>Loan payback period</b>	10	
<b>Fuel cost [\$/L]</b>	\$1.32	\$2.62
<b>PV cost [\$/kW]</b>	\$2,890	\$2,000
<b>Individual battery cost [\$]</b>	\$300	\$250

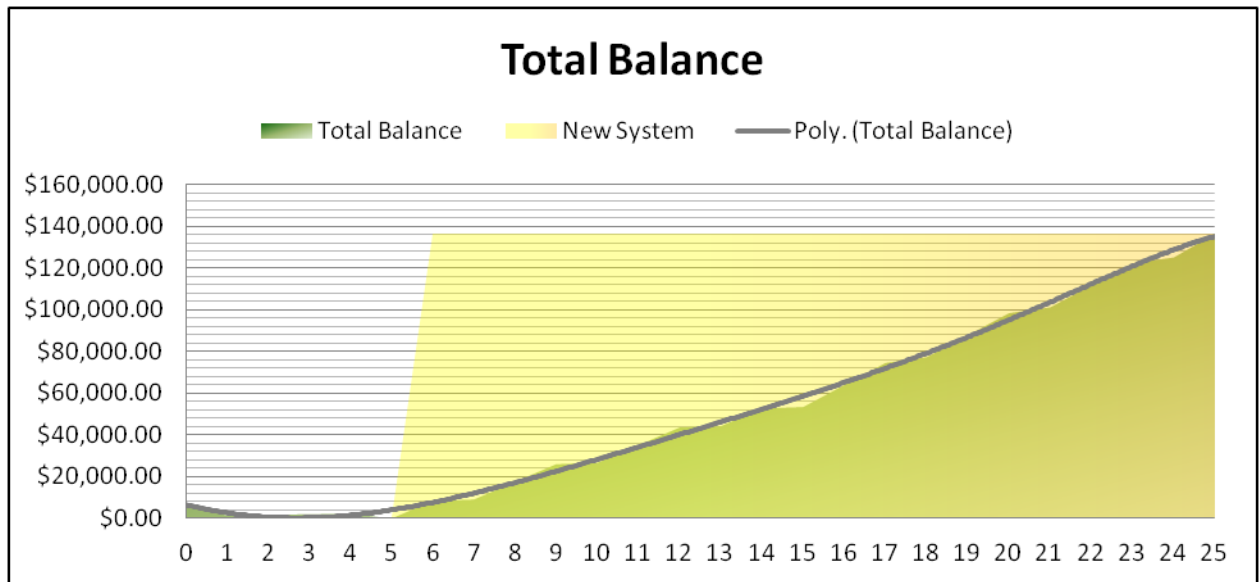
**Figure 17: Scenario two - volatile variables**



Similar to the base case, the simulation starting balance is set equal to the initial system capital cost of \$6,416. The same initial system costs used in the base case (Appendix A) are also used in this scenario. The model assumes that by the time the new system is purchased, fuel prices will have doubled. It also assumes that the price of solar panels and batteries will have slightly decreased. The breakdown of the cost of the new system by component and expense type can be seen in Appendix B. The simulation will take out a loan to purchase the new system if the user lacks the necessary funds. The results of scenario two can be seen in Figure 18 and Figure 19.



**Figure 18: Scenario two - cash flow**



**Figure 19: Scenario two - balance**

After a quick glance at Figure 19, it is clear that building a new restaurant and purchasing the new energy system is a good economic choice. NEGES' total profits were \$130,362.21 over the simulation time period, yielding \$5,214.49 per year. This success is due to a couple of factors. First, it is assumed that the restaurant increases profits (7k/yr to 12k/yr). In addition, even though fuel prices have doubled, the amount of fuel consumed drops dramatically due to less reliance on the generator. The amount of fuel consumed drops from 4,047.12 L/yr with the initial system to a mere 493.35 L/yr with the new system. Looking at the cash flow (Figure 18), one can see that the battery bank lifetime increases once the new system is purchased. This is because the battery bank is larger in size and allows for greater energy throughput. Although it is more expensive to replace the bank, it does not have to be done as frequently.

In order to purchase the new system and pay for the new restaurant at year five, a loan had to be taken out. The loan amount was for \$14,079.93. However, it is easily argued that it was a

good choice to take out the loan considering the economic success of the projection. The next scenario will look at the same situation, except NEGES will wait until year ten to purchase the new system. The purchase delay decision is made with the intent to save money so that NEGES can take out a smaller loan and avoid paying excessive interest.

### Scenario Three

Scenario three is executed exactly the same as scenario two except that the new energy system is purchased at year ten rather than year five. The reason for this is so that NEGES can see if it is beneficial to save money, and wait to buy their new system. Saving for an additional five years will diminish the amount of money needed to be borrowed, and therefore reduce the size of interest payments. The same system costs are used as scenario two and can be seen in Appendix A and Appendix B. Figure 20 and Figure 21 show the results of scenario three.

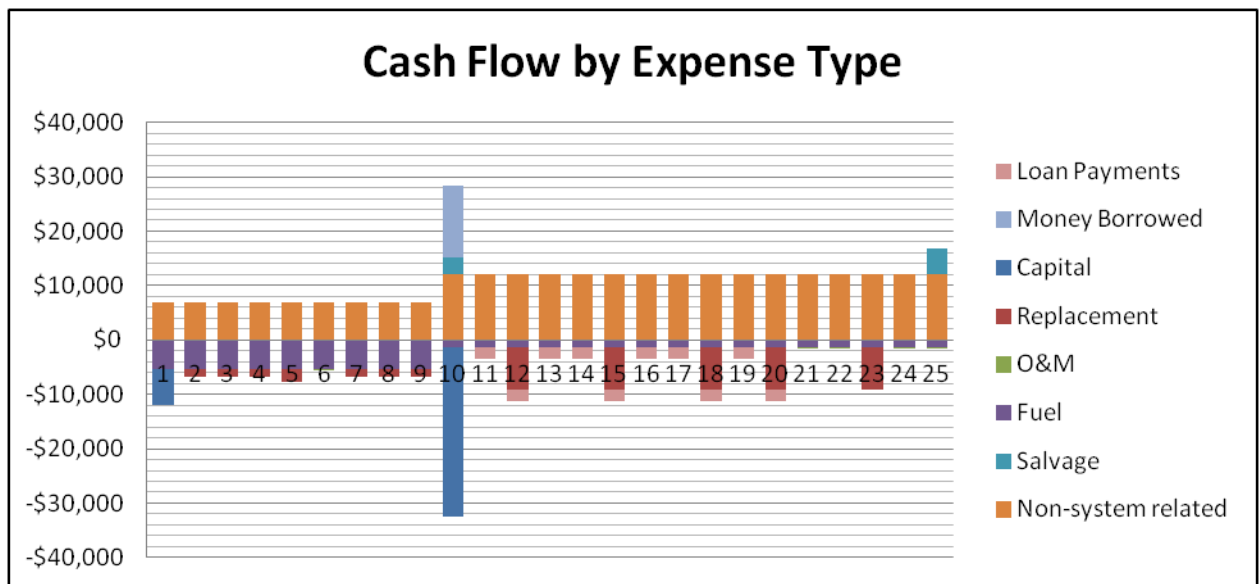
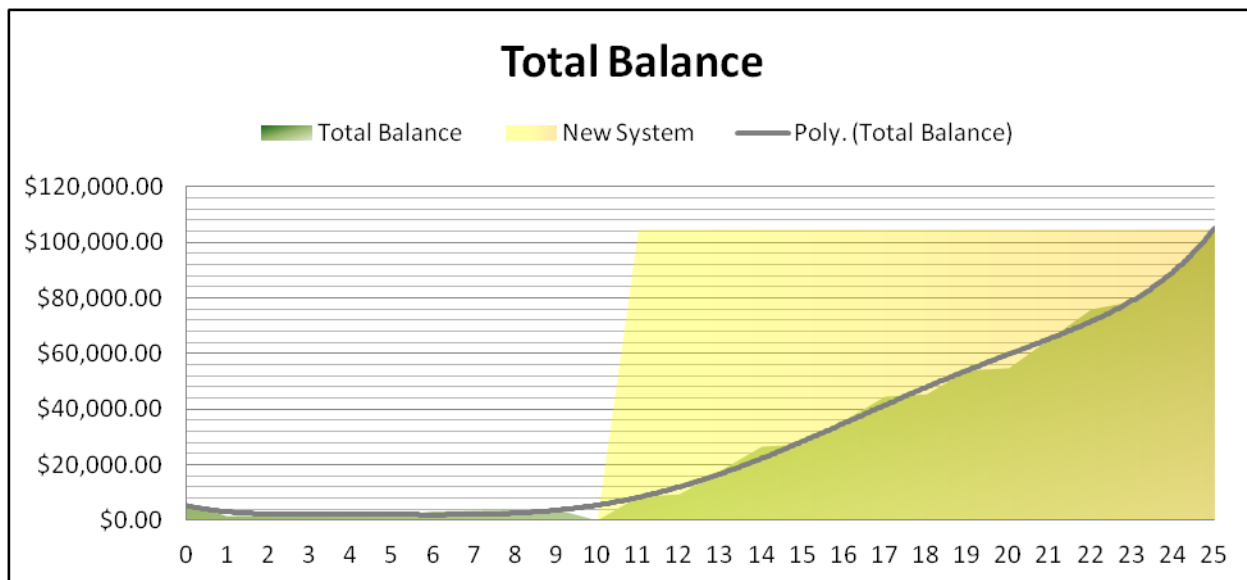


Figure 20: Scenario three - cash flow



**Figure 21: Scenario three – balance**

Like its predecessor, scenario three looks to be very successful in an economic sense. The new system's capacity is also sufficient for meeting the energy demand of the restaurant. Total profits over the simulation lifetime are \$98,222.49, yielding \$3,928.90 per year. Although the simulation can be deemed a success, it is 25% less profitable than scenario two. After saving for an additional five years, NEGES would only reduce their loan annuity by \$116.71. This is because the price of fuel and lack of business income severely limit NEGES' ability to save money. Even after five additional years, they were only able to save a couple thousand dollars. Comparing scenarios two and three reveal that it is much more beneficial for NEGES to take out the larger loan and expand as soon as possible.

## Worst-Case Scenarios

Like the realistic category, the worst-case category also contains two different scenarios. Each scenario is run off the same inputs. The only difference is that the new system is purchased at a different time.

### Scenario Four

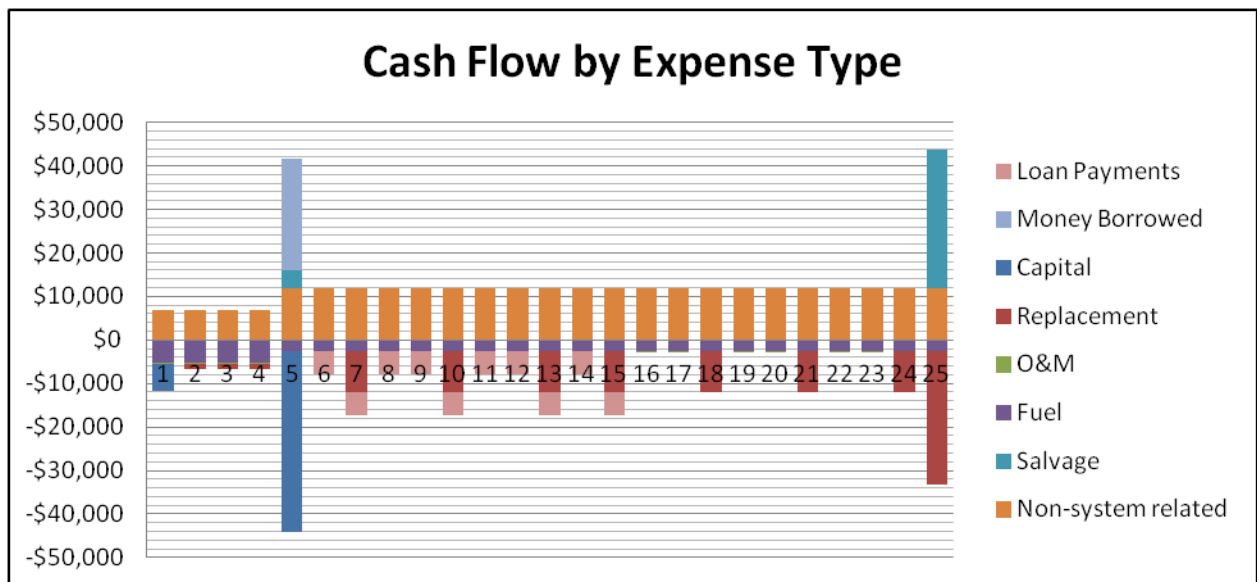
The fourth scenario is setup to model a situation in which NEGES encounters a harsh economic environment, making the purchase of a new renewable energy system much more difficult. These harsh economic factors include increased gas prices, high interest rates, and a couple other variables. Table 8 defines these variables.

<u>Variable</u>	<u>Initial System</u>	<u>New System</u>
<b>Make future investment?</b>	TRUE	
<b>Purchase year</b>	5	
<b>Take out a loan if needed?</b>	TRUE	
<b>Loan interest rate</b>	16%	
<b>Loan payback period</b>	10	
<b>Fuel cost [\$/L]</b>	\$1.32	\$5.00
<b>PV cost [\$/kW]</b>	\$2,890	\$2,890
<b>Individual battery cost [\$]</b>	\$300	\$300

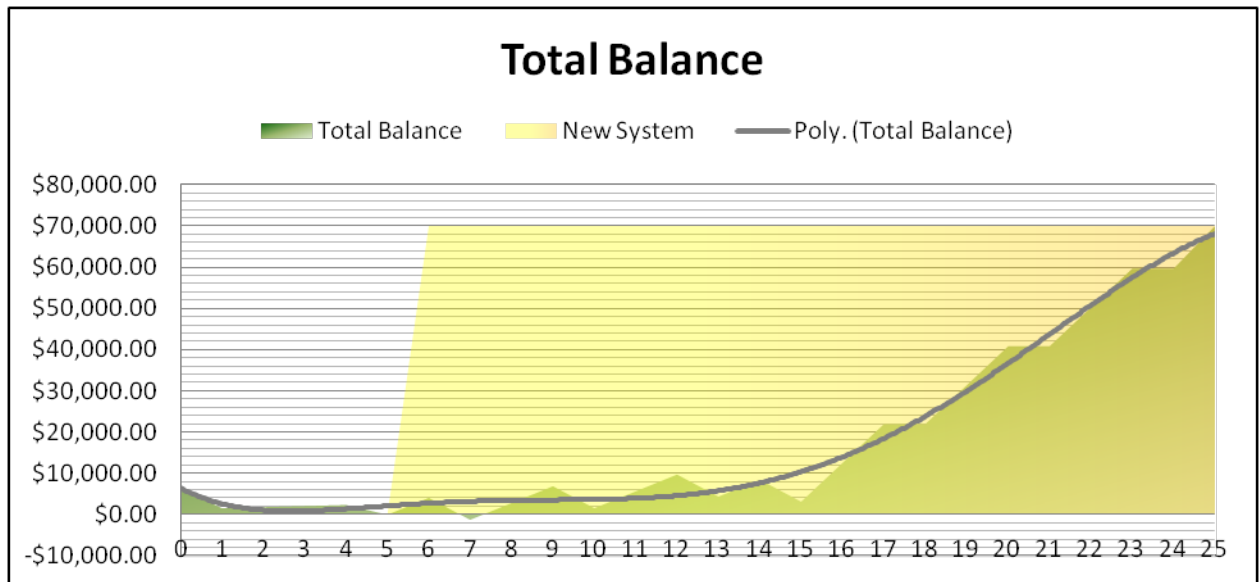
**Table 8: Scenario four - volatile variables**

By viewing the above table, one can see that interest rates have doubled, gas prices have sky rocketed to almost \$19/gallon, and the cost of renewable energy components has not

decreased. Because the cost of renewable energy components did not go down over time as expected, the capital cost of the new system is higher. A breakdown of the new system costs can be seen in Appendix C. Like scenario two, the model attempts to purchase NEGES' new energy system at year five and will take out a loan if needed. The results of the simulation can be seen in Figure 22 and Figure 23.

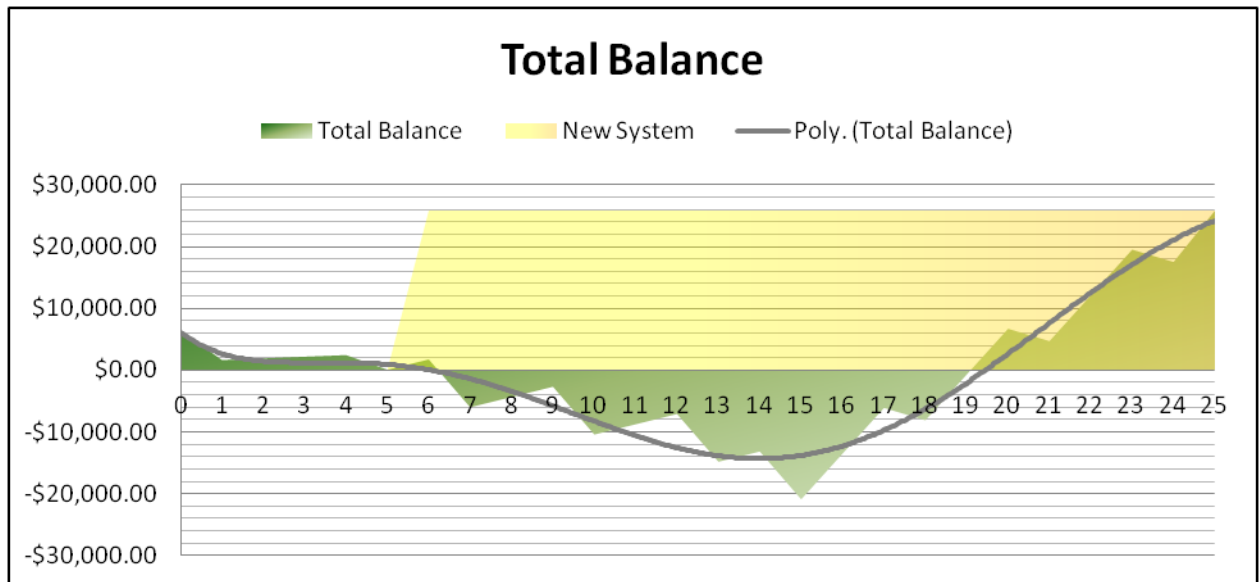


**Figure 22: Scenario four - cash flow**



**Figure 23: Scenario four – balance**

Although the results from Figure 23 look convincing, scenario four does not yield a good situation for NEGES. Their balance turns negative at year seven even though a loan was taken out at year five. Even if the loan amount is increased beyond the price of the new system, it does not prevent them from running a deficit. Next and most importantly, the simulation becomes sensitive to the amount of profit NEGES gains from their restaurant. If the restaurant doesn't bring in as much money as expected, it can severely affect the end results of the simulation. Figure 24 shows what would happen if NEGES' annual profit margin dropped by \$2,000 (\$12k/yr to \$10k/yr).



**Figure 24: Scenario four - balance with smaller profit margin**

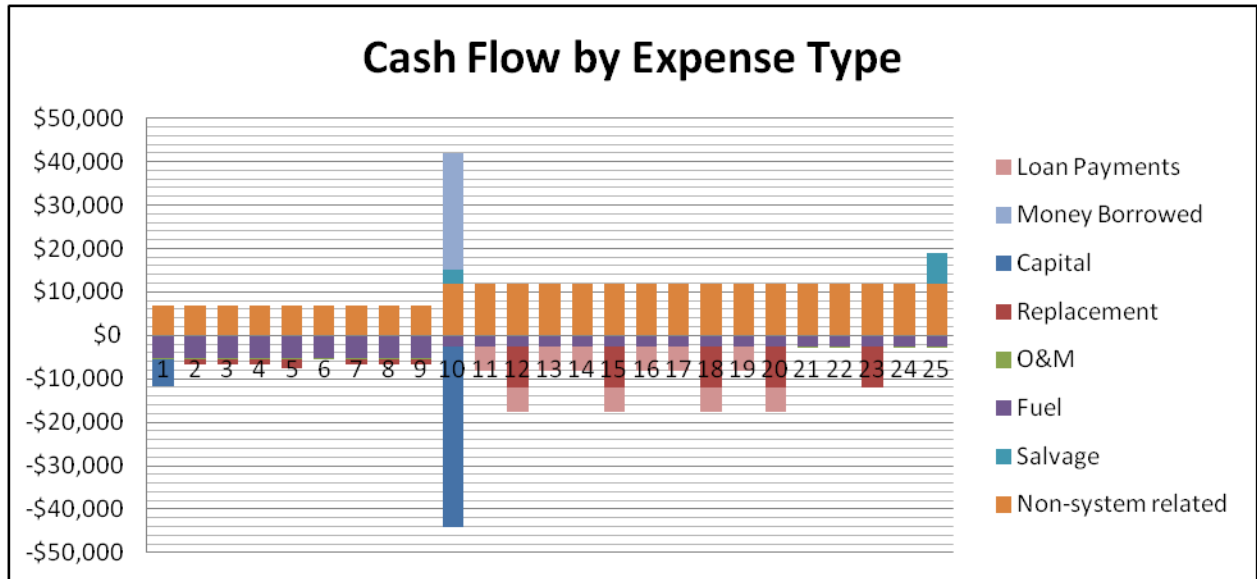
As a result of the decreased profit margin, NEGES goes into considerable debt. The model warns the user that the current setup is not economically feasible, and that it will not take out multiple loans. Therefore the excess debt seen in Figure 24 is being modeled interest free. This is unrealistic. The reason the model shows NEGES beginning to recover from its deficit at year fifteen is because that is the point at which the ten year loan is paid off. In a real world situation, multiple loans would have to have been taken out, with the interest from each compounding on one other. More than likely, this is a situation that NEGES could not recover from.

### **Scenario Five**

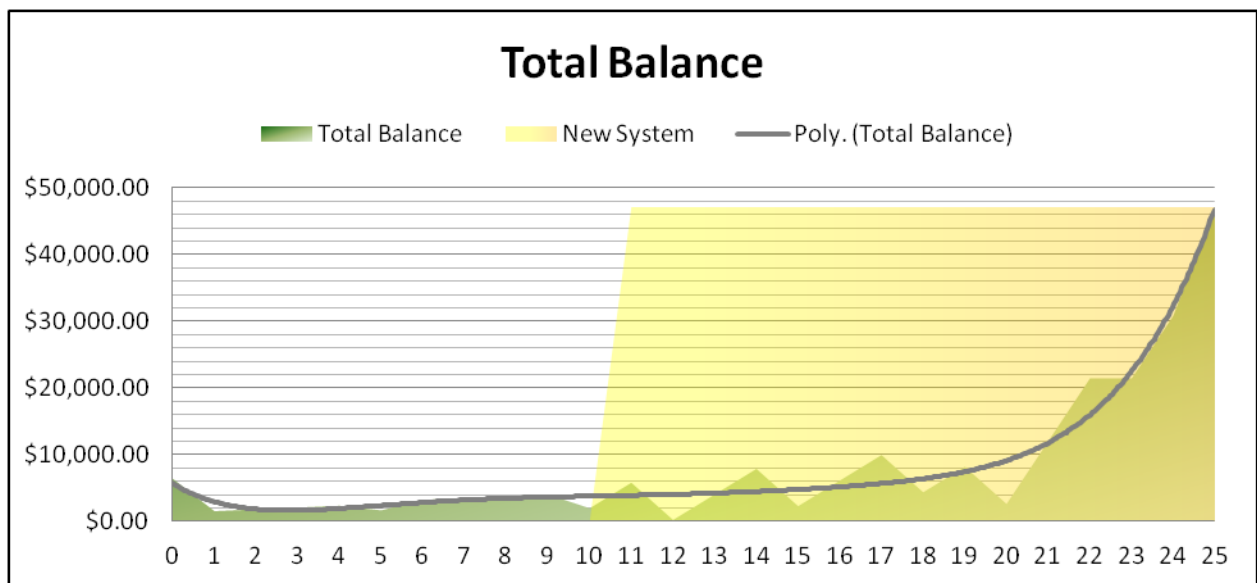
The fifth and final scenario mimics scenario four except that NEGES waits until year ten to construct the restaurant and purchase their new energy system. Like scenario three, scenario five examines what would happen if NEGES saved their money for an additional five years



before attempting to purchase a new system. The breakdown of system costs for this scenario can be seen in Appendix A and Appendix C. The results of the simulation can be seen in Figure 25 and Figure 26.

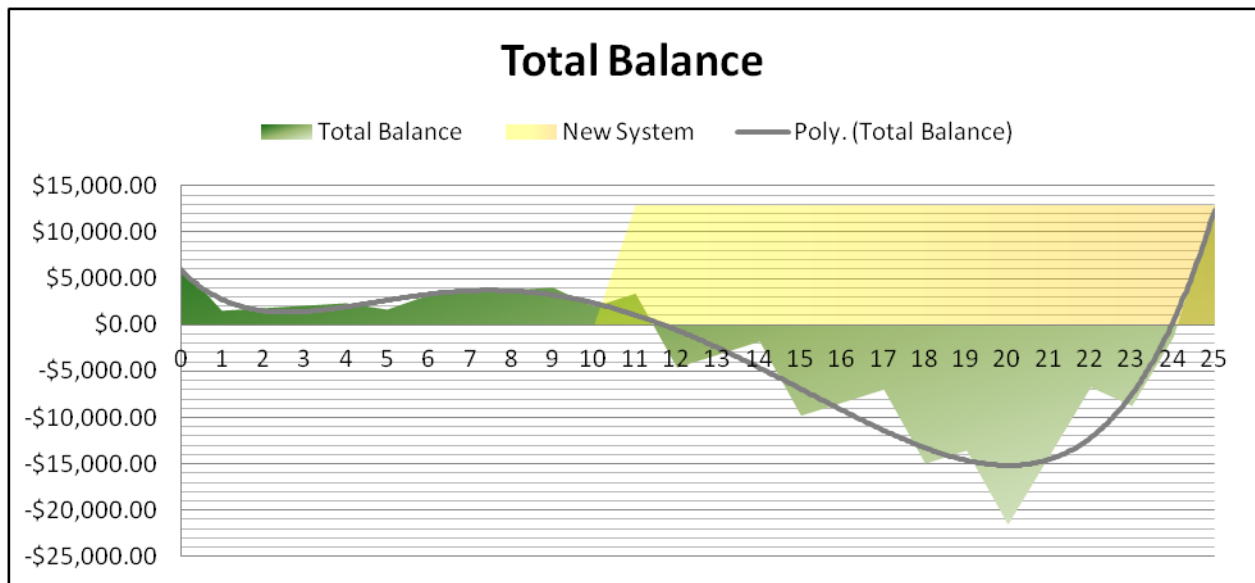


**Figure 25: Scenario five - cash flow**



**Figure 26: Scenario five -balance**

The results of scenario five are slightly better than scenario four. Saving for an additional five years to purchase the new energy system prevented NEGES from running a deficit. But the model is barely feasible. An additional \$2,000 had to be taken out on top of the loan amount for the new system. If the additional funds were not borrowed, NEGES would run a negative balance by year twelve. Like scenario four, the simulation is extremely sensitive to profit margin. Figure 27 shows what would happen if NEGES' annual profit margin were to drop by \$2,000.



**Figure 27: Scenario five - balance with smaller profit margin**

The model quickly becomes unfeasible if annual profits are reduced from \$12k per year to \$10k per year. Any extra deficits run interest free in the model, so it is unrealistic that NEGES would reach a positive balance by year twenty-four. The initial loan gets paid off by year twenty, which is the reason why NEGES' balance begins to recover. In the end, both of the worst-case

scenario simulations are barely, if at all feasible, and are very dependent on income produced by the restaurant.

## **Discussion of Findings**

After using the dynamic model to simulate various scenarios for NEGES, a couple of reoccurring observations can be made. These findings can be generalized for anyone wishing to use the model for their own energy system projections.

### **Timing of Purchase**

For each of the scenarios conducted, the timing of purchase affected the economic performance of the simulation. The earlier that NEGES purchased their new system, the better off they would be economically in the long run. It is more advantageous to take out a larger loan at an earlier time than try to save money and combat interest rates. There are two reasons for this. NEGES lacks the ability to save money while using their initial system, and the return on investment value of the restaurant is extremely high. Notice that the total profits from scenarios one through three are \$1,915.94, \$130,362.21, and \$98,222.49 respectively. Scenario one has the lowest profit margin because the new system was never purchased and a restaurant was never opened. Scenario two's profit margin is higher than scenario three's because NEGES opened their restaurant five years earlier.

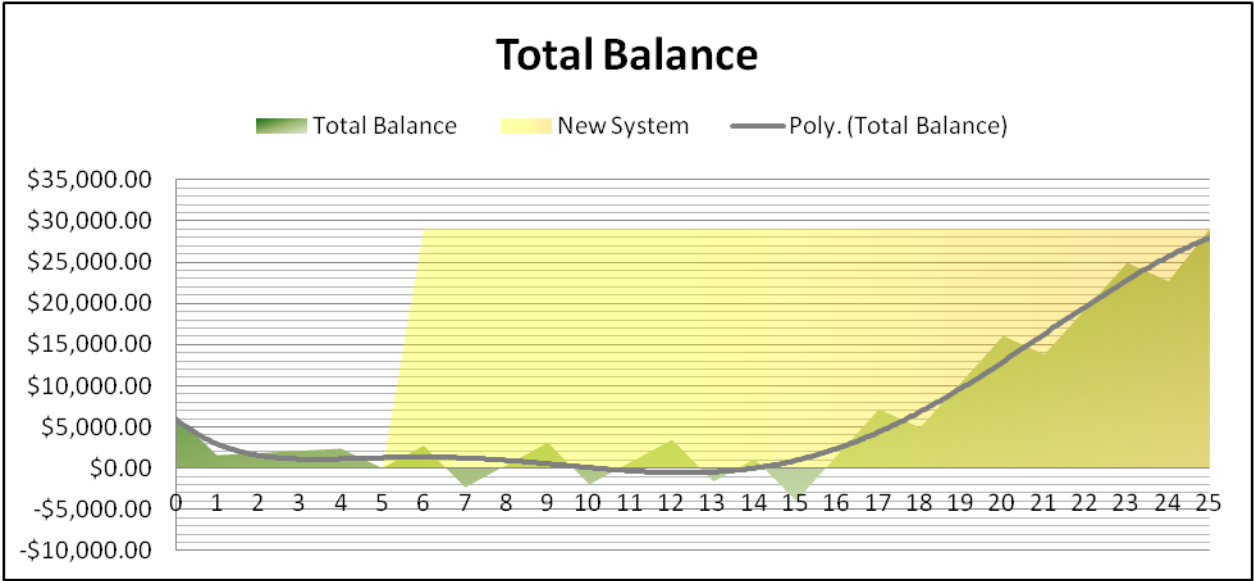
When looking at the "worst-case" scenarios, is it more difficult to draw such clear conclusions. Scenario four was economically unfeasible no matter the loan amount. Scenario five was hardly economically feasible, and only worked if an additional \$2,000 was borrowed on top of

the loan required to purchase the new system. Both scenarios were unfeasible if the annual income was decreased from 12k per year to \$10k per year. However, even though it runs into debt, scenario four can be considered to be the "better" option because the new system was purchased earlier, therefore yielding a higher balance by the end of the simulation.

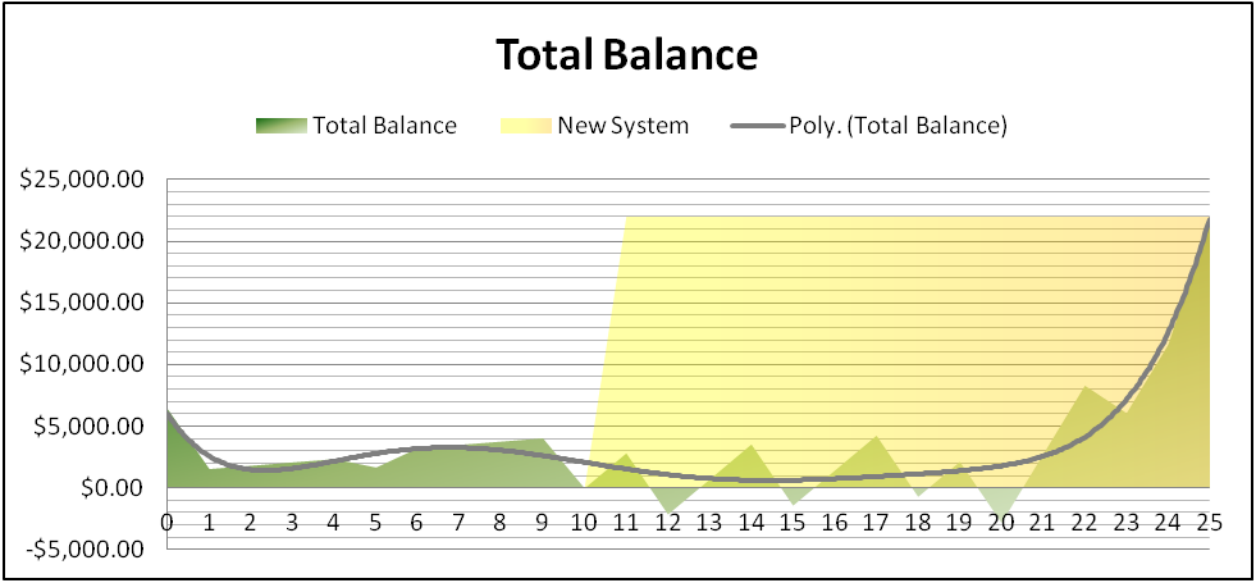
### **Income Sensitivity**

All scenarios conducted in the analysis were highly sensitive to the amount of income generation NEGES' restaurant provided. The "worst-case" scenarios were the most sensitive, as decreases in income severely affected the economic outcomes by the end of the simulation (see Figure 24 and Figure 27). A decrease of \$2,000 in annual profits quickly made both scenarios economically disastrous. In each of these cases it would be difficult, if not impossible, for NEGES to recover from the debt.

The "realistic" scenarios were less prone to failure when annual profits were decreased, however they still relied on the income generated by the restaurant. If scenarios two and three are re-run without any sort of profit increase as a result of opening the restaurant, they both become unfeasible. Figure 28 and Figure 29 show the results from the simulations.



**Figure 28: Scenario two - no profit increase**



**Figure 29: Scenario three - no profit increase**

No loan amount can keep NEGES from running a negative balance, even if they save for an additional five years before making the purchase. After analyzing all five scenarios, one can conclude that it is not worth purchasing a new system unless a return on investment can be

expected. Scenarios two and three are less sensitive to the effects of income because the profit to expense ratio is so high. However as Figure 28 and Figure 29 show, even these scenarios have the potential to fail if the return on investment is zero.

## **Suggestions for Improvement**

The dynamic model is still in its beta stages and could be improved on in many areas. This section gives suggestions on how the model could be enhanced in order to better model hybrid renewable energy systems.

### **Energy Related**

- Account for temperature effects on the PV array's power output
- Provide the ability to model a dump load such as a water heating system
- Add other energy storage and production types such as hydro-electric, wind turbines, fuel cells, and ultracapacitors
- Allow for partitioning of the system load. Each load could be separately modeled rather than entering the total load on the system

### **Economic Related**

- Allow for better integration of existing systems as the "initial system." Account for the lifetime left of each component at time zero of the simulation, rather than renewing the system's lifecycle
- Provide an option not to salvage systems at the end of the simulation timeframe or when a new system is purchased

## General

- Improve the user interface
  - Excel forms could be used rather than entering user input directly into cells
  - Improve the way model outputs and results are displayed

## Conclusion

Dynamic system modeling provides an excellent solution to the problems associated with simulating hybrid renewable energy systems. The goal of this dynamic model was to fill the gaps where other modeling software is currently lacking. Most of the modeling solutions today are static in design. They cannot account for changes over time, which limits a user's flexibility in what they can model over a simulation timeframe. With this model, it is possible to integrate energy calculations with economics, as well as their influences on one another. This is particularly beneficial for developing communities, as growth in these areas can occur at a rapid pace. For this reason, a static model can become inaccurate when looking at longer simulation timeframes. The dynamic model can take into account changes in a NGO's or community's income and expenses. It can also account for the purchasing or upgrading of a system mid-simulation.

Five scenarios were analyzed and compared as a real-world test for the model. The scenarios were divided into three categories: a base case, realistic scenarios, and worst-case scenarios. Each scenario was analyzed for economic and technological feasibility. If technologically capable, system performance was measured by the size of profit margins. Scenario two was considered the most successful as it was capable of meeting the energy demand increase from

the restaurant, while yielding the highest return on investment. Numerous findings were discovered as a result of the study. The timing of system purchases and level of income were found to be important variables, as they had the greatest impact on simulation outputs.

Although the model has room for improvement, it shows the effectiveness dynamic modeling can have on hybrid renewable energy system analysis. With further development, this model could prove to be a useful tool for a variety of non-governmental organizations, communities, universities, and companies.



## Bibliography

- Arizona State University, and University of New South Wales. "Welcome to PVCDROM." Welcome to the Photovoltaic Education Network. Web. 26 Dec. 2012.
- Duffie JA, Beckman WA (1991) Solar Engineering of Thermal Processes 2nd edition, Wiley, New York, NY.
- Erbs DG, Klein SA, Duffie JA (1982) Estimation of the diffuse radiation fraction for hourly, daily, and monthly-average global radiation, *Solar Energy*, 28, 293.
- Graham VA, Hollands KGT (1990) A method to generate synthetic hourly solar radiation globally, *Solar Energy*, 44 (6), 333-341.
- HOMER ENERGY. "Energy Modeling Software for Hybrid Renewable Energy Systems." HOMER Energy. 2012. Web. 20 Dec. 2012.
- Isee Systems. "Isee Systems - The World Leader in Systems Thinking Software." Isee Systems - The World Leader in Systems Thinking Software. 2012. Web. 19 Dec. 2012.
- Jongerden, Marijn R., and Boudewijn R. Haverkort. "Which Battery Model to Use?" Thesis. Loughborough University, 2008. Print.
- Khan, M.J., and M.T. Iqbal. "Dynamic Modeling and Simulation of a Small Wind-fuel Cell Hybrid Energy System." *Renewable Energy* 30.3 (2005): 421-39. Print.
- Li, Chun-Hua, Xin-Jian Zhu, Guang-Yi Cao, Sheng Sui, and Ming-Ruo Hu. "Dynamic Modeling and Sizing Optimization of Stand-alone Photovoltaic Power Systems Using Hybrid Energy Storage Technology." *Renewable Energy* 34.3 (2009): 815-26. Print.
- Manwell JF, McGowan JG (1993) Lead acid battery storage model for hybrid energy systems, *Solar Energy*, 50, 399-405
- MathWorks. "Simulink." Simulation and Model-Based Design. 2012. Web. 22 Dec. 2012.
- "NEGES Foundation." *NEGES Foundation*. WordPress, 2012. Web. 24 Dec. 2012.

Radosavljević, Jasmina, and AmelijaĐorđević. "Defining of the Intensity of Solar Radiation on Horizontal and Oblique Surfaces on Earth." *Working and Living Environmental Protection* 2.1 (2001): 77-86. Print.

Simulistics. "Simulistics." *Welcome to Simulistics: System Dynamics and Object-based Modelling and Simulation Software*. 2012. Web. 26 Dec. 2012.

Sterman, John D. *System Dynamics Modeling for Project Management*. Publication. Cambridge: Massachusetts, 1992. Print.

Tsao, Teng-Fa, Po-Hung Chen, and Hung-Cheng Chen. *Dynamic Modeling and Simulation of Hybrid Power Systems Based on Renewable Energy*. Proc. of International Conference on Energy and Environment Technology. Print.

## Appendix A: Costs of the Initial System

<u>Component</u>	<u>Category</u>	<u>Cost [\$]</u>
<b>PV Array</b>	Capital	\$1,416.10
	Replacement	\$1,166.10
	O&M	\$10.00
<b>Battery Bank</b>	Capital	\$1,500.00
	Replacement	\$1,300.00
	O&M	\$20.00
<b>Converter</b>	Capital	\$2,500.00
	Replacement	\$2,300.00
	O&M	\$10.00
<b>Generator</b>	Capital	\$1,000.00
	Replacement	\$950.00
	O&M	\$50.00
<b>Total Initial Cost</b>		<b>\$6,416.10</b>

## Appendix B: Costs of New System (Realistic)

<u>Component</u>	<u>Category</u>	<u>Cost [\$]</u>
<b>PV Array</b>	Capital	\$20,000.00
	Replacement	\$19,000.00
	O&M	\$15.00
<b>Battery Bank</b>	Capital	\$8,000.00
	Replacement	\$7,800.00
	O&M	\$30.00
<b>Converter</b>	Capital	\$3,000.00
	Replacement	\$2,800.00
	O&M	\$15.00
<b>Generator</b>	Capital	\$1,200.00
	Replacement	\$1,150.00
	O&M	\$70.00
<b>Total Initial Cost</b>		<b>\$32,200.00</b>

## Appendix C: Costs of New System (Worst-Case)

<u>Component</u>	<u>Category</u>	<u>Cost [\$]</u>
<b>PV Array</b>	Capital	\$28,900.00
	Replacement	\$27,900.00
	O&M	\$15.00
<b>Battery Bank</b>	Capital	\$9,600.00
	Replacement	\$9,400.00
	O&M	\$30.00
<b>Converter</b>	Capital	\$3,000.00
	Replacement	\$2,800.00
	O&M	\$15.00
<b>Generator</b>	Capital	\$1,200.00
	Replacement	\$1,150.00
	O&M	\$70.00
<b>Total Initial Cost</b>		<b>\$42,700.00</b>

