ABSTRACT

Title of Thesis: SYSTEM DESIGN AND ANALYSIS OF A RENEWABLE ENERGY SOURCE POWERED MICROGRID

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Thesis Directed By: Dr. John S. Baras
Institute for Systems Research

Today there is a great need for alternative new energy sources at cheaper development prices than those required from a traditional power plants. The renewable generation technologies are and will become both cheaper and more beneficial for our environment than other traditional means of productions. As Renewable Energy Generation technologies advance, it is important that Power Systems Engineers investigate carefully the Smart Grid and specially the Islanded Microgrid. Microgrid System Design Solutions that seek zero Emissions are more important as pollutants from traditional plants contribute to the contamination of the environment. In this thesis we use a Systems Engineering approach to design and analyze a typical Islanded Microgrid in order to seek zero emission Microgrids at the lowest possible cost. This study designs the Microgrid as a Smart Grid; we use and follow the design by considering engineering Standards from NIST and IEEE. Then we develop initial Microgrid System design and architecture. The System then is Analyzed and simulated in HOMER. Finally, a Tradeoff analysis is performed to

search design variations and their effect on system cost as well as on environmental emissions.

SYSTEM DESIGN AND ANALYSIS OF A RENEWABLE ENERGY SOURCE POWERED MICROGRID

by

Miguel Norman Franco Venegas Zambrana

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2018

Advisory Committee:
Dr. John S. Baras, Advisor/Chair
Dr. Mark Austin
Dr. Huan Xu

Dedication

To my dear mother, Norma Zambrana Rojas, and my dear grandparents Clementina Rojas, and Jaime Zambrana. Thank you for all your love, sacrifice and dedication that allow us keep flourishing.

Para mi querida mamá, Norma Zambrana Rojas, y mis queridos abuelitos Clementina Rojas, and Jaime Zambrana. Gracias por todo su amor, sus sacrificios y su dedicacion a nosotros, que nos permite a nosotros seguir floreciendo.

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I would also like to acknowledge my peers and colleagues Iakovos, Sana, Chrysa, Chrystos, Dipankar, Fatima, Ren, Andre, Wentao, and many more students of our Advisor Dr. Baras who have always been a great source of support and encouragement throughout my journey in ISR at UMD. I am grateful for having met them and for having provided me a great example to follow through.

I would like to express my gratitude for the support received throughout my MS studies and research to my sponsors. This material is based upon work supported by the US Air Force Office of Scientific Research award #FA9550-09-1-0538 to Georgia Tech, the National Science Foundation (NSF) award number CNS-1035655 to the

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Finally, there are not enough words of sincere gratitude towards my mother, Norma Zambrana Rojas, and my grandparents, Clementina Rojas and Jaime Zambrana. You have provided the greatest examples of love, perseverance and hard work that I hope one day be able to duplicate. You are the inspiration in my life and I will cherish all the moments we have lived together and the guidance and opportunities you have provided me. Los adoro mis queridas mamás y papá sin su apoyo este logro no hubiera sido posible.

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Chapter 1

Overview

1.1 Introduction

The Future Forward Towards Smart Grids and Microgrids

Traditional Means of Energy Production are typically centralized. Many of these are the in the form of Coal power plants, and nuclear plants. This way of generating power has served well the humanity during the last century. However, they are mostly inefficient and pollutant. To generate power, those systems use mainly fossil fuels, which are heavy environmental pollutants and also are available in reduced quantities year by year. 50% to 70% of the fuel used to produce power is lost as heat waste and around 8% of the generated power is lost in transmission lines. The infrastructure has large maintenance costs and its complexity makes the whole system vulnerable and prone to failures and black-outs. New enterprises in this market are difficult due to regulations and the large initial capital needed. [21].

As Renewable Energy Generation technology advances, it is important that Power Systems Engineers investigate carefully the Smart Grid and especially the Islanded mode Microgrid. The renewable generations technologies are and will become both cheaper and more beneficial for our environment than other traditional means of energy production. And attempts to design Microgrid System Solutions that allow for zero Emissions are becoming more important as pollutants from traditional plants will effectively contribute to the contamination of the environment and the need for new energy sources at cheaper starting prices than those required from a traditional power plant.

What is a Microgrid?

The Department of Energy defines a microgrid as “A group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [and can] connect and disconnect from the grid to enable it to operate in both grid connected or island mode.”

The Importance

Microgrids are becoming much cheaper to deploy and their increasingly cheaper generation capabilities for communities will help both consumers and places where energy is hard to reach, be able to afford and enjoy much needed clean energy.

Our Objective: A Systems Engineering Approach for The Microgrid

The main objective of this study is to use Systems Engineering towards the design and operation of a typical Microgrid in order to find both an appropriate System Architecture and Economics involved in the microgrid that will allow the system designer to find and study Microgrids variations with the goal of comparing and searching for zero emission Microgrids at the lowest cost.

The design of a Microgrid with a systems engineering approach involves several aspects of consideration. The design of a microgrid with the NIST Smart Grid standard as the entry point for system requirements. The identification of the system stakeholders. The behavior of the system. The architecture. And the analysis of the system economical aspects as well as the tradeoff and optimization of the system.

1.2 Problem Statement

Modeling Smart Grid Systems especially islanded Microgrids, from a Systems Engineering point of view, has not been fully studied. This thesis seeks the study of low emissions Islanded Microgrid Systems. Most studies do not consider Engineering Standards like IEEE and NIST when analyzing Microgrids. They also do not provide in general the architecture involved in the design of a microgrid system. The tools for simulation as well as analysis of the economics of a microgrid have not been fully developed cohesively. Additionally, most tools available to study Microgrids are not very congruent with each other. In this thesis, we will be approaching these problems from a Systems Engineering point of view with the intention of developing a Smart Grid Microgrid System through the use IEEE and NIST Standards, as well as providing an economical analysis of the microgrid, through simulations with Homer Pro.

1.3 Contributions of this Thesis

The major contribution of this thesis is the analysis and simulation through Model Based Systems Engineering (MBSE) methods and processes of the Islanded Microgrid. This thesis incorporates in the architecture design the IEEE and NIST standards, and provides thorough representation of the Microgrid Subsystems involved.

This thesis work brings together power engineering research and models in order to provide models and subsystems components Physical modeling, System Dispatch model, as well as an Economic Model of the Microgrid System.

Finally, this thesis performs system simulations, Sensitivity Analysis, Optimization and Tradeoff Analysis in order to find the final system configurations that lead to a Microgrid System with zero emissions at the lowest cost.

Chapter 2

Smart Grid Conceptual Model for the Microgrid

2.1 Overview

The conceptual domain model presented here, which is based on NIST Standard 1108r3, supports planning, requirements development, documentation, and organization of the diverse, expanding collection of interconnected networks and equipment that will compose a smart grid. As such we use this smart grid conceptual model as basis for the conceptual model of the Microgrid. That is, the microgrid is designed to satisfy the smart grid standards.

Each domain—and its sub-domains—encompasses smart grid conceptual roles and services. They include types of services, interactions, and stakeholders that make decisions and exchange information necessary for performing identified goals, such as: customer management, distributed generation aggregation, and outage management. Services are performed by one or more roles within a domain [19].

2.2 Domains and Roles/Services in the Smart Grid Conceptual Model

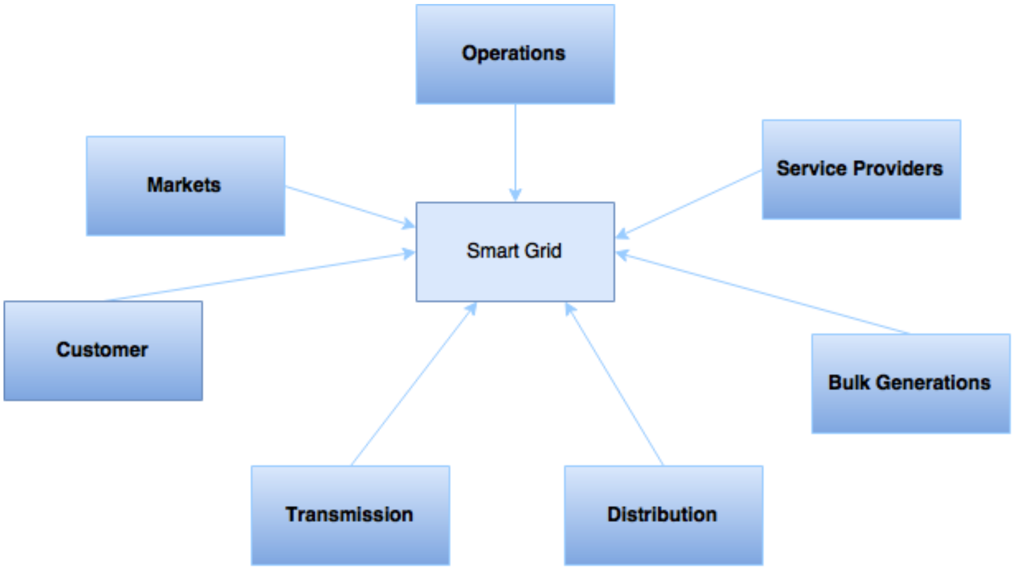


Figure 2.1: Smart Grid Model

1 **Customer:** The end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own domain: residential, commercial, and industrial.

2 **Markets:** The operators and participants in electricity markets.

3 **Service Provider:** The organizations providing services to electrical customers and to utilities.

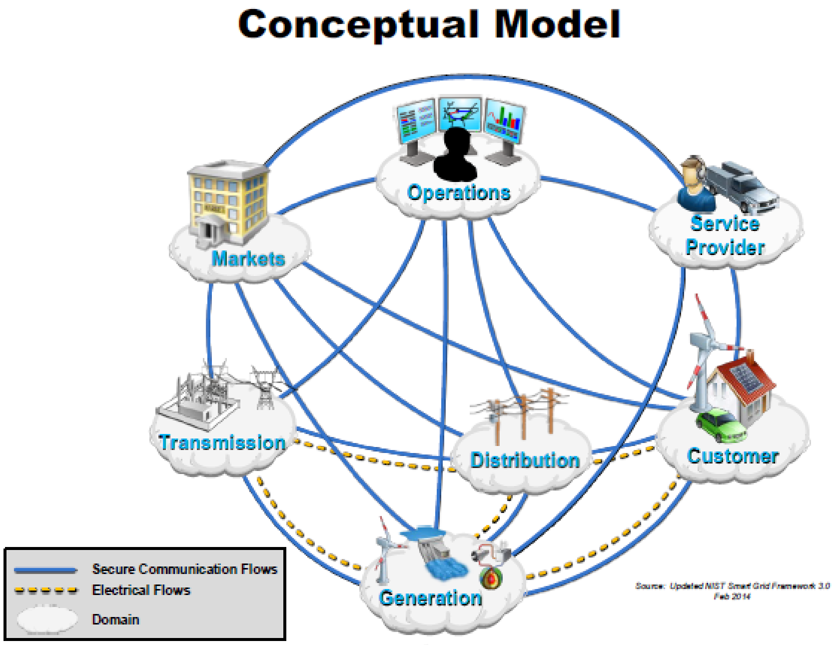
4 **Operations:** The managers of the movement of electricity.

5 **Generation:** The generators of electricity. May also store energy for later distribution. This domain includes traditional generation sources (traditionally referred to as generation) and distributed energy resources (DER). At a logical level, “generation” includes coal, nuclear, and large-scale hydro generation usually attached to transmission. DER (at a logical level) is associated with customer and

distribution-domain-provided generation and storage, and with service-provider-aggregated energy resources.

6 **Transmission:** The carriers of bulk electricity over long distances. May also store and generate electricity.

7 **Distribution:** The distributors of electricity to and from customers. May also store and generate electricity.



Source: Updated NIST Smart Grid Framework 3.0 Feb 2014

Figure 2.2: Smart Grid Conceptual Model

2.3 Smart Grid Operational Concept:

The Operations of a Smart Grid are comprised of generating, storing, distributing, and controlling/managing its own supply of energy services. In the case of Microgrids, it can be expected to be capable of functioning as a standalone system. However, Smart

Grids (and Microgrids) more than often remain connected to the public utility provider for scenarios in which the system may not be able to operate at its optimal performance, and even present a risk towards its user, as defined under different operational scenarios and modes of operation of the specific Smart Grid. It is also expected that the generation, distribution, and storage of energy can be controlled in a remotely, digital and real time manner by the control and management systems via the Network Operations Center [9].

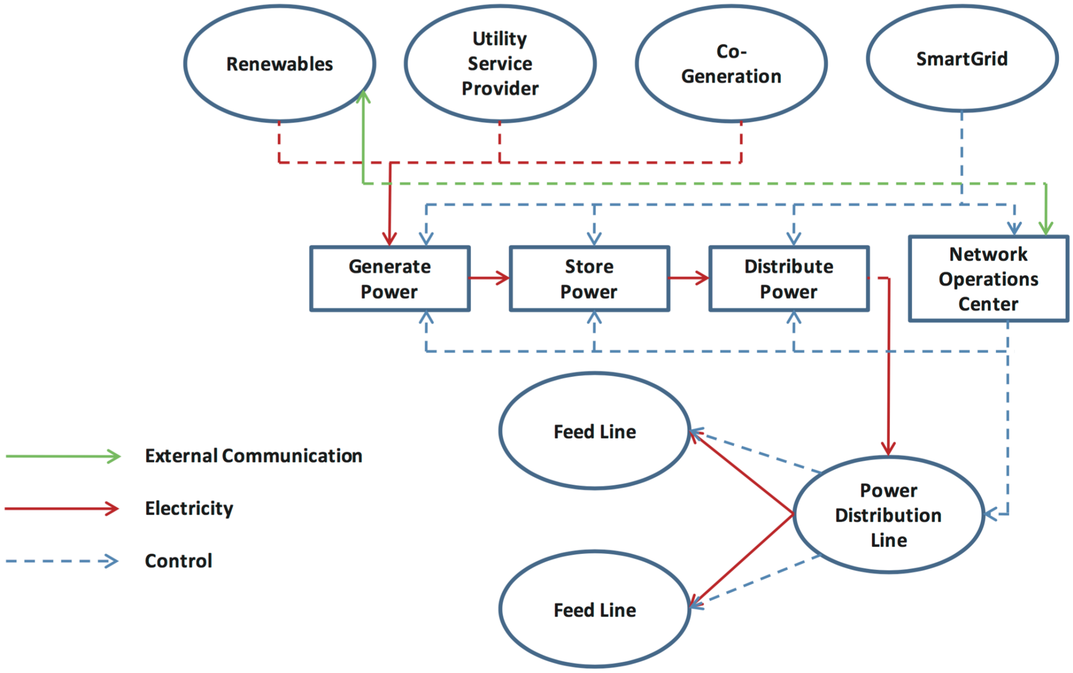


Figure 2.3: Smart Grid Operational Concept

2.4 Operational Scenario for Microgrids

The following figure illustrate the main Microgrid Use Case diagram which allows for design of a system which generates renewable resources. The diagram also showcases the interconnection of the typical actors of the smart grid such as the customers, utility providers, and grid operators.

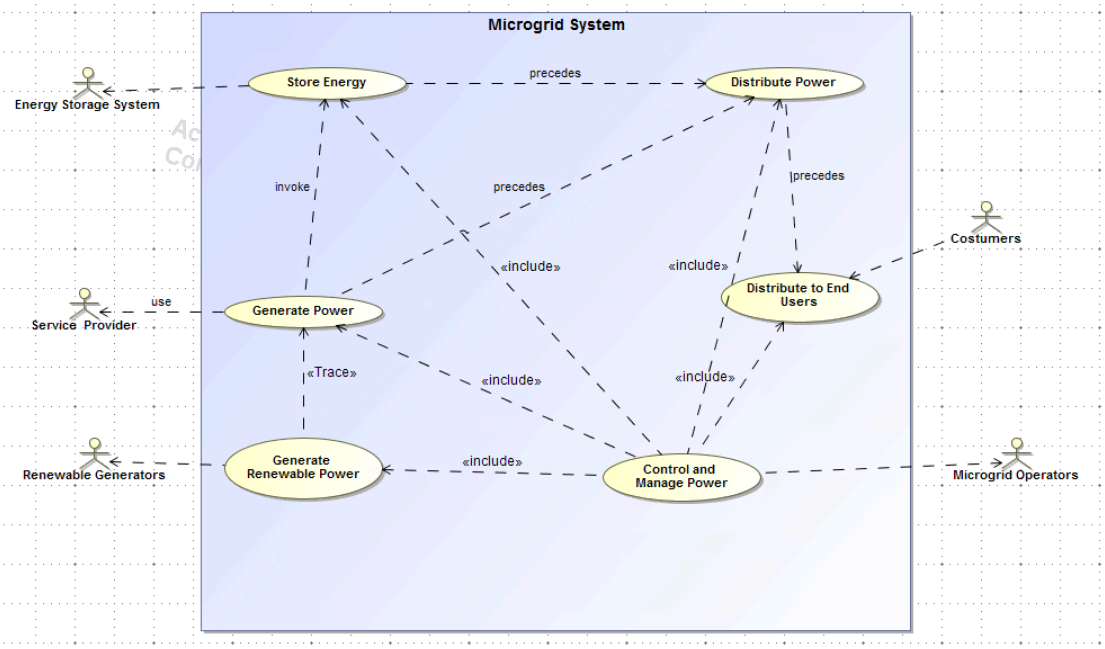


Figure 2.4: Microgrid System Use Case

2.5 Understanding the Microgrid System Model of Distributed Generators Network

Let us present a simplified overview of the Distributed Generators Connectivity in the Microgrid System.

When developing a Microgrid System, we consider that each Distributed Generator corresponds to an independent energy resource. The DGs are interconnected by the microgrid physical electric power network. Above this network, there is a cyber-layer consisting of a communication network between the DGs, which is both sparse and distributed so that it is less susceptible to a single point of failure [7].

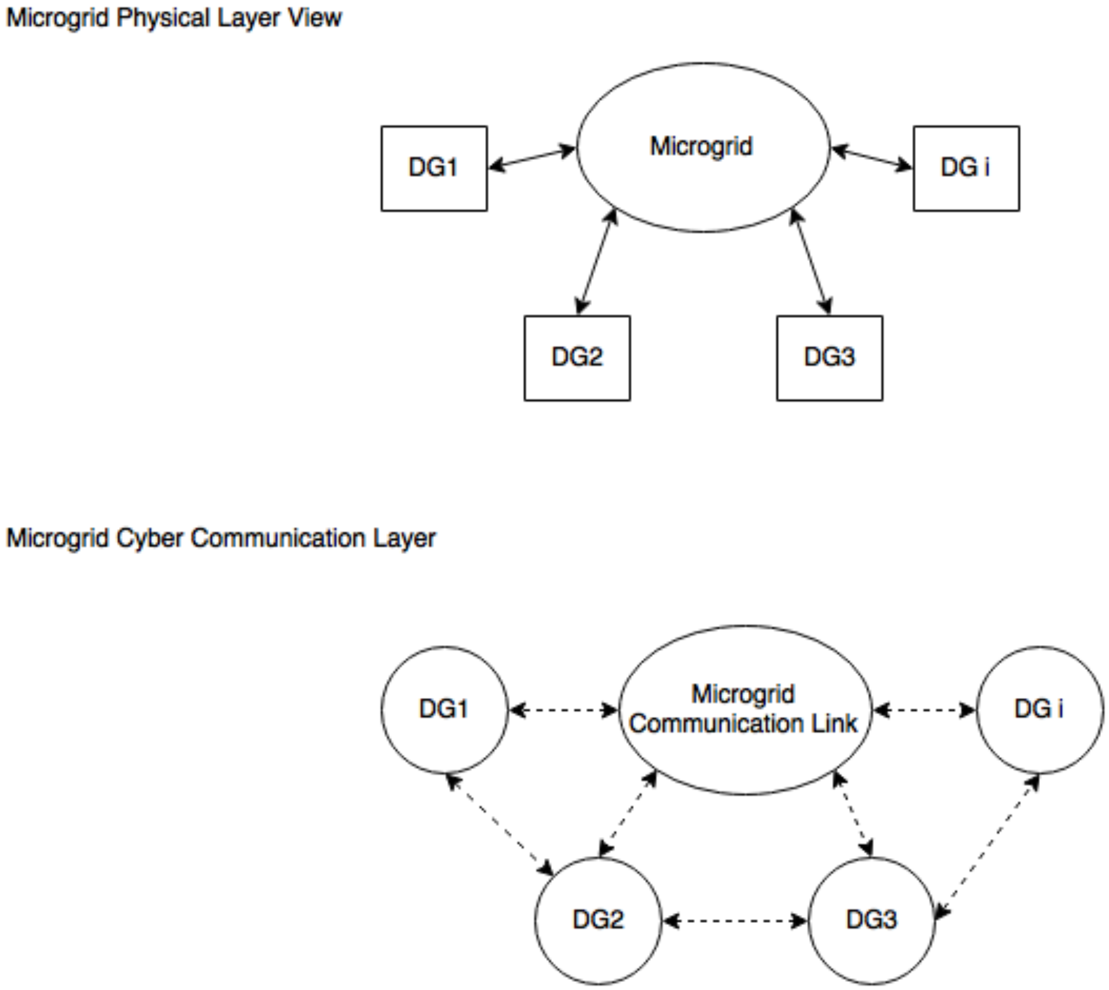


Figure 2.5: Microgrid Physical and Cyber Communication Layer

In figure 2.6 we show a multiagent environment for a microgrid system with distributed generators (DGs) as agents, illustrating the distributed control framework. Each DG corresponds to an energy resource. In the Physical Layer, The DGs are interconnected by the microgrid physical electric power network.

And above is the Cyber Communication Layer which consists of the communication network between the DGs [7].

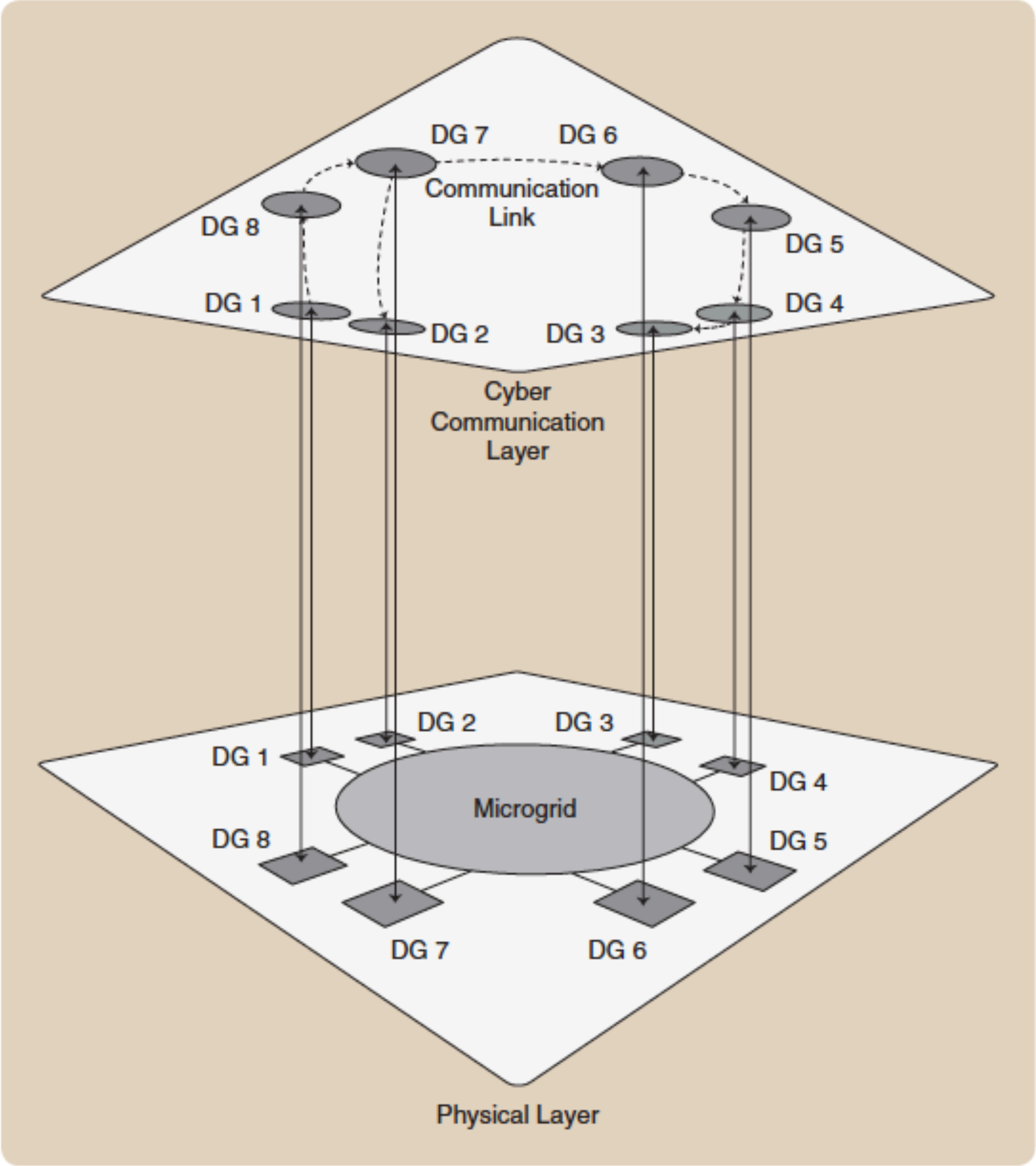


Figure 2.6: Microgrid Physical and Cyber Communication Layer

The following figure shows the Microgrid System with specific Distributed Generation resources expected in the Microgrid (Photovoltaic, Wind and Storage)

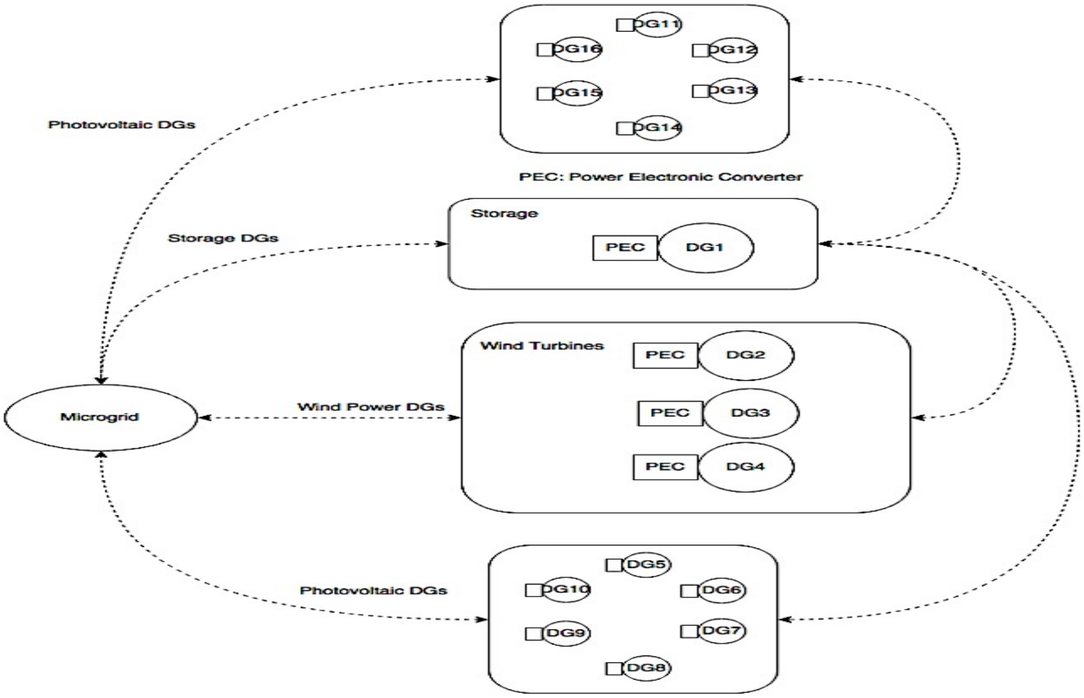


Figure 2.7 Microgrid System with Distributed Generators

2.6 Microgrid Component Architecture

With the massive penetration of distributed generation (DG) units, the current fit-and-forget principle of integrating these units into the electric power system is no longer a sustainable option, and a coordinated approach is required. One method to capture the emerging potential of DG, and to cope with the problems caused by the unconventional behavior and increasing penetration of DG, is to take a system approach instead of considering each unit separately. In the system approach, the generators and loads are regarded as subsystems, or microgrid components, as depicted in the following. Microgrids are small-scale electricity networks, consisting of an aggregation of (converter-interfaced) DG units, (controllable) loads, and storage elements, which are connected to the utility network through a single point of connection. In comparison with a single DG unit, a Microgrid has more control flexibility to ensure the system's reliability and power quality requirements [2].

A Microgrid with (power-electronically interfaced) loads, storage, and DG units can be in stand-alone (islanded) or grid-connected mode.

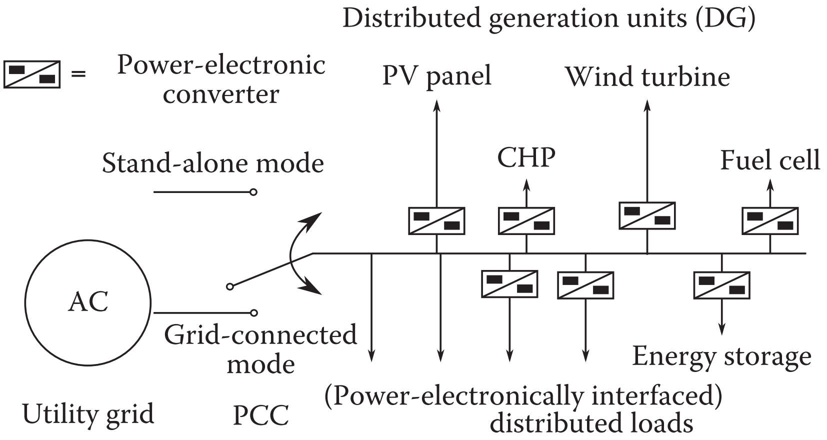


Figure 2.8 Microgrid Conceptual System

Chapter 3

Creating a Microgrid System Design Model

3.1 Modeling with Homer

The HOMER Micropower Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide range of applications. HOMER models a power system's physical behavior and its life-cycle cost, which is the total cost of installing and operating the system over its life span. HOMER allows the modeler to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs [24].

HOMER allows the undertaking of three principal tasks: simulation, optimization, and sensitivity analysis. In the simulation process, HOMER models the performance of a particular micropower system configuration each hour of the year to determine its technical feasibility and life-cycle cost.

With HOMER we are able to simulate a wide variety of micropower system configurations, such as combinations of a PV array, one or more Wind turbines, Diesel Generators, and a Battery bank, as well as an ac–dc converter. The system can be grid-connected or autonomous and can serve ac and dc electric loads and a thermal load.

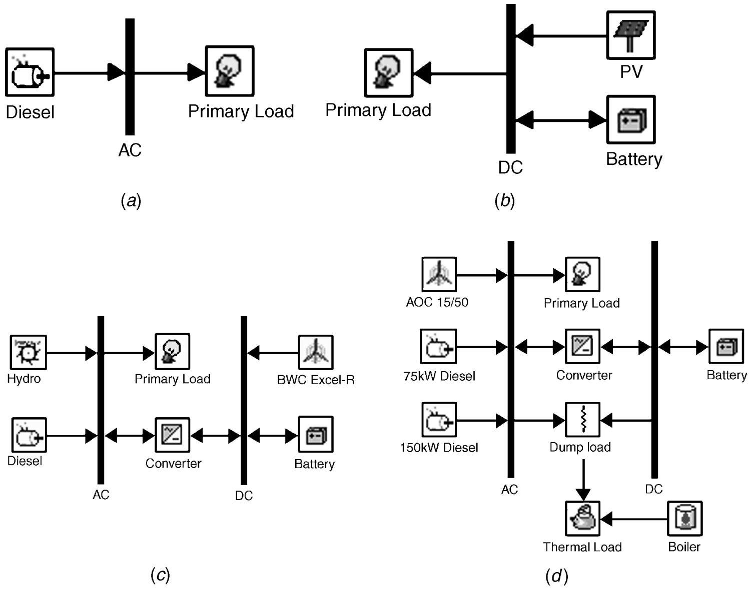


Figure 3.1 Schematic Diagrams of Homer Models

Figure 3.1 shows Examples of Schematic diagrams of some micropower system types that HOMER models: (a) a diesel system serving an ac electric load; (b) a PV–battery system serving a dc electric load; (c) a hybrid hydro–wind–diesel system with battery backup and an ac–dc converter; (d) a wind–diesel system serving electric and thermal loads with two generators, a battery bank, a boiler, and a dump load that helps supply the thermal load by passing excess wind turbine power through a resistive heater.

We can through HOMER analyze functional and Economical effectiveness through simulations of the various configurations possible in our microgrid system. The simulations would also allow us to consider both wind and solar profiles for our location. For our analysis we consider a residential microgrid located in Boulder Colorado due to its wind and solar profiles.

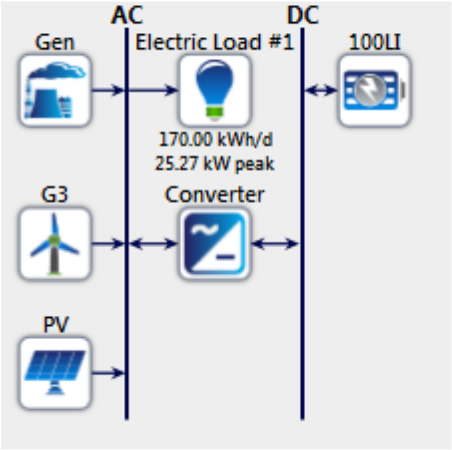


Figure 3.2 Microgrid System Scheme in Homer

The microgrid considered has as main components PV arrays, Wind Turbines, a Battery and the option of a Diesel Generator. With HOMER we can simulate how the system operates over one year and apply this analysis into a system lifetime analysis.

While the previous Matlab Based Microgrid Simulation Models would have been able to simulate the control of the system, they have harder computer requirements, as they are not able to easily simulate various years and especially because they do not provide the realistically needed Economical and Environmental considerations, for an extended analysis of the system.

We choose the HOMER Pro for both Modeling and Simulation of the System. It is capable of modeling various system configurations as well as various commercially available microgrid components, as well as help with the tradeoff analysis through system sensitivity analysis and optimization, which should allow for both Economical and Environmental considerations to be analyzed.

3.2 Architectural Components for the Islanded Microgrid

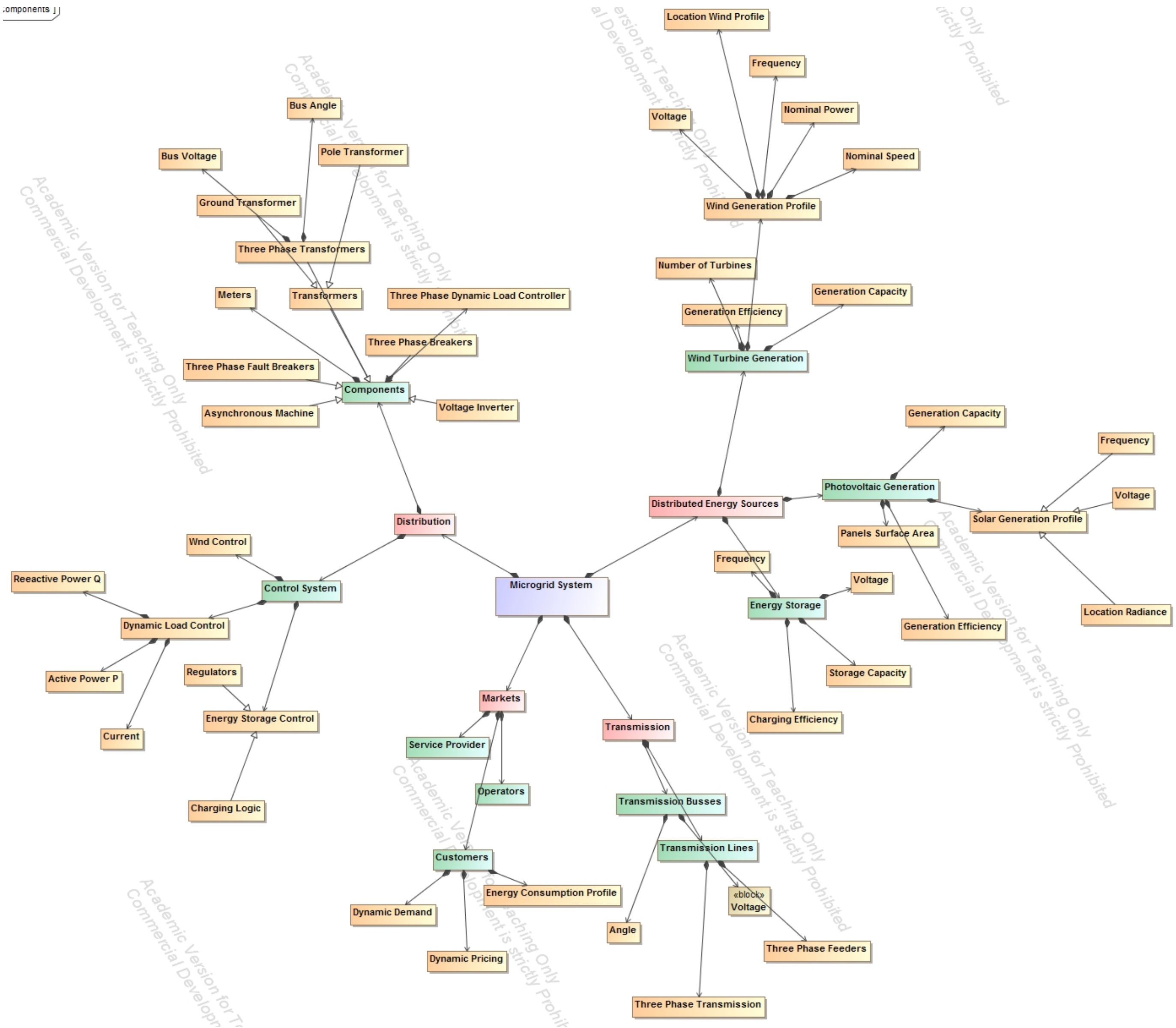


Figure 3.3 SysML Architectural view of the Components for the Microgrid

The architectural subsystem components presented here for our Microgrid are based on Matlab Power system models, as well as, HOMER System documentation, which have followed IEEE standards, and which have used renewables as generating resources. These were One Year microgrid simulation[15], 24 Hr Simulation of a Vehicle to grid system[16], and documentation from the Sim Scape Power System[17] and HOMER [25].

Microgrid Model Components:

Markets: The operators and participants in electricity markets.

Customer: The end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own domain: residential, commercial, and industrial.

Dynamic Demand

Dynamic Pricing

Customer Energy Consumption Profile: Demand Profile Specific to Customer Location, based on Data from the U.S. Energy Department.

Service Provider: The organizations providing services to electrical customers and to utilities.

Operations: The managers of the movement of electricity.

Generation: The generators of electricity. May also store energy for later distribution. This domain includes traditional generation sources (traditionally referred to as generation) and distributed energy resources (DER). At a logical level, "generation" includes coal, nuclear, and large-scale hydro generation usually attached to transmission. DER (at a logical level) is associated with customer and distribution-domain-provided generation and storage, and with service-provider-aggregated energy resources.

Distributed Energy Sources and Generators:

Photovoltaic Generation:

Panels Surface Area, Generation Capacity,

Location Radiance Profile, Generation Efficiency

Voltage Profile, Frequency Profile

Wind Turbine Generation:

Generation Capacity,

Location Wind Profile, Generation Efficiency

Voltage Profile, Frequency Profile

Nominal Power, Nominal Wind Speed

Energy Storage:

Capacity, Charging Efficiency, Efficiency, Rated Power

Voltage Profile, Frequency Profile

Transmission: The carriers of bulk electricity over long distances. May also store and generate electricity.

Transmission Busses: (Bus Voltage, Bus Angle)

Transmission Lanes

Three-Phase Feeders (Microgrid Model)

Three-Phase Transmission Lines (Microgrid Model)

Transmission Busses/Lanes(Bus Voltage, Bus Angle)

Distribution: The distributors of electricity to and from customers. May also store and generate electricity:

Three-Phase Transformers (2 windings, 3 windings)

Three Parallel RLC Load

Three-Phase Measurement(Microgrid Model)

Three-Phase Fault Breakers(Microgrid Model)

Pole Mounted Transformer

Ground Transformer

Three Phase Dynamic Load(Matlab)

Active Power P and Reactive Power Q Control

Specific Components for Photovoltaic Distribution:

Three Phase Transformer(Bus Voltage, Bus Angle)

Specific Components for Wind Generator Distribution:

Three Phase Source

Three Phase Transformer

Transmission Busses(Bus Voltage, Bus Angle)

Wind Control System

Specific Components for Energy Storage System:

Control System (Charging Logic, Regulators) (Microgrid Model)

240v inverter (Microgrid Model)

Current Converters

Three Phase Transformer (Microgrid Model)

Specific Components for Distribution in Residential Loads:

Three Phase Breakers /Circuit Breaker

Three Phase Fault

Three Phase Asynchronous Machine

Dynamic Load Control (Microgrid Model)

Energy Meters

Three Phase Residential Transformer

Three Phase Dynamic Load(Matlab)

Chapter 4

Physical Modeling

4.1 Primary Load: Consumer Energy Demands

Primary Load is the electrical demand that the power system must meet at a specific time. Electrical demand associated with lights, radio, TV, house- hold appliances, computers, and industrial processes is typically modeled as primary load.

For our analysis we consider a residential zone located in Boulder Colorado [24].

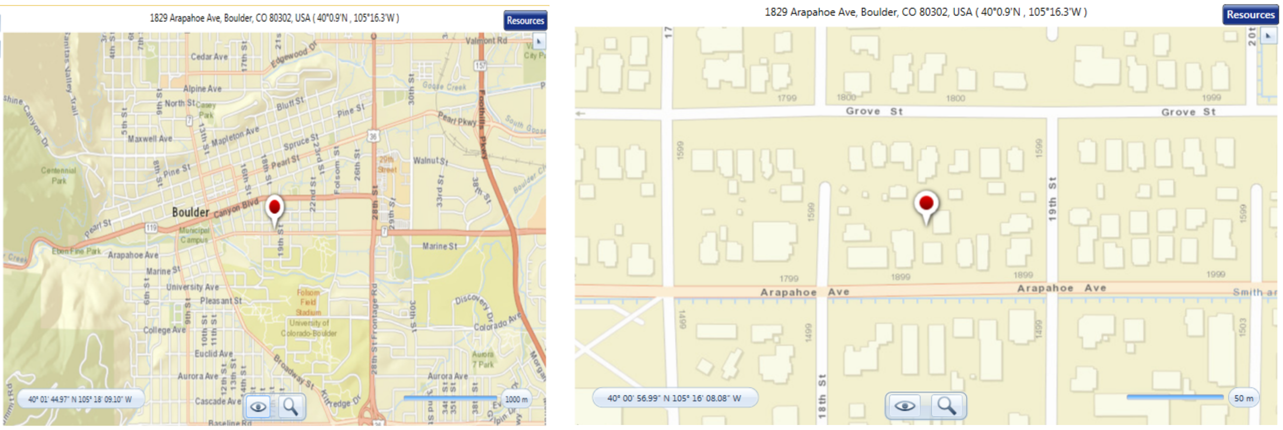
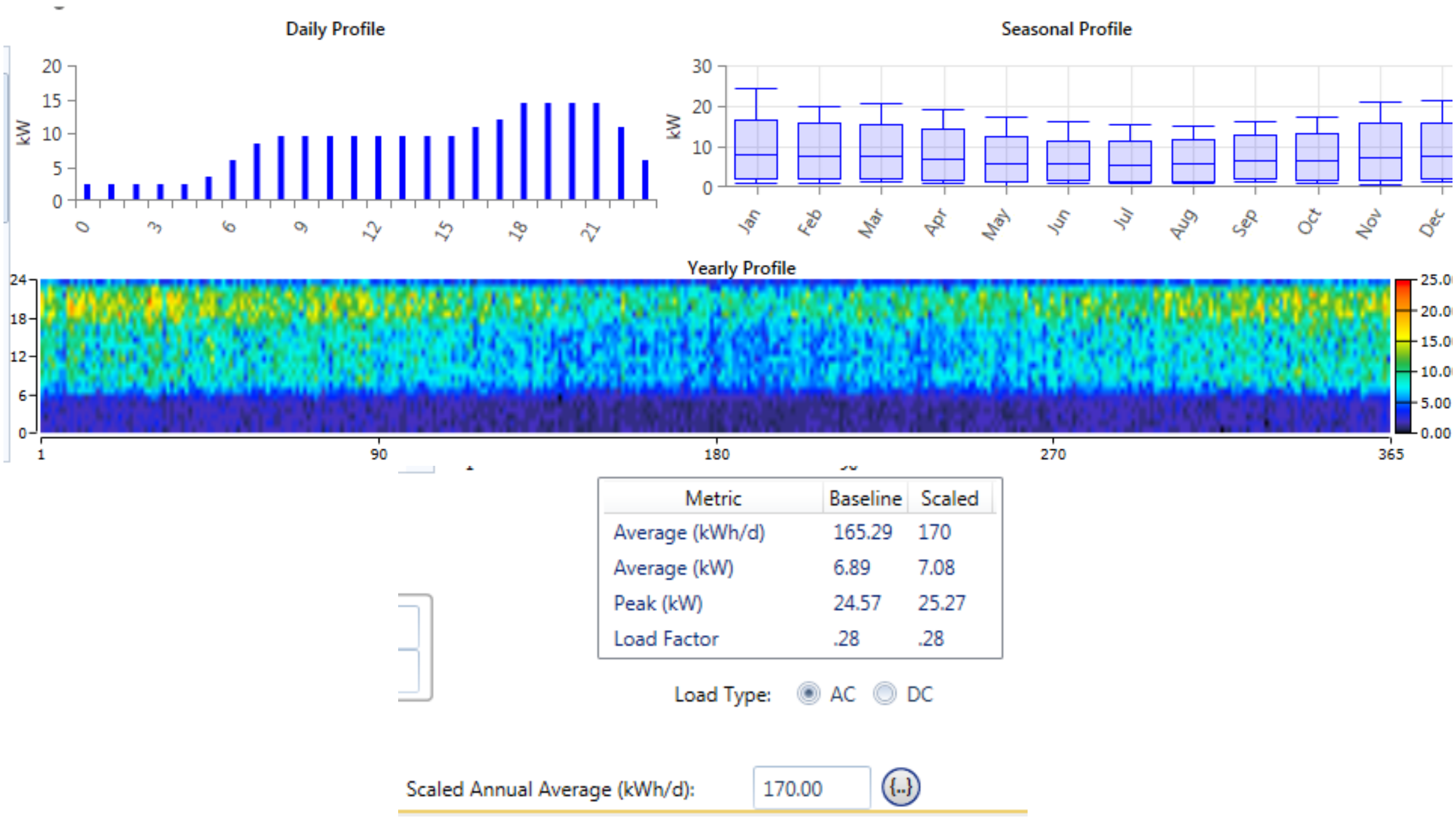


Figure 4.1 Neighborhood for Primary Load



Metric	Baseline	Scaled
Average (kWh/d)	165.29	170
Average (kW)	6.89	7.08
Peak (kW)	24.57	25.27
Load Factor	.28	.28

Load Type: ● AC ○ DC

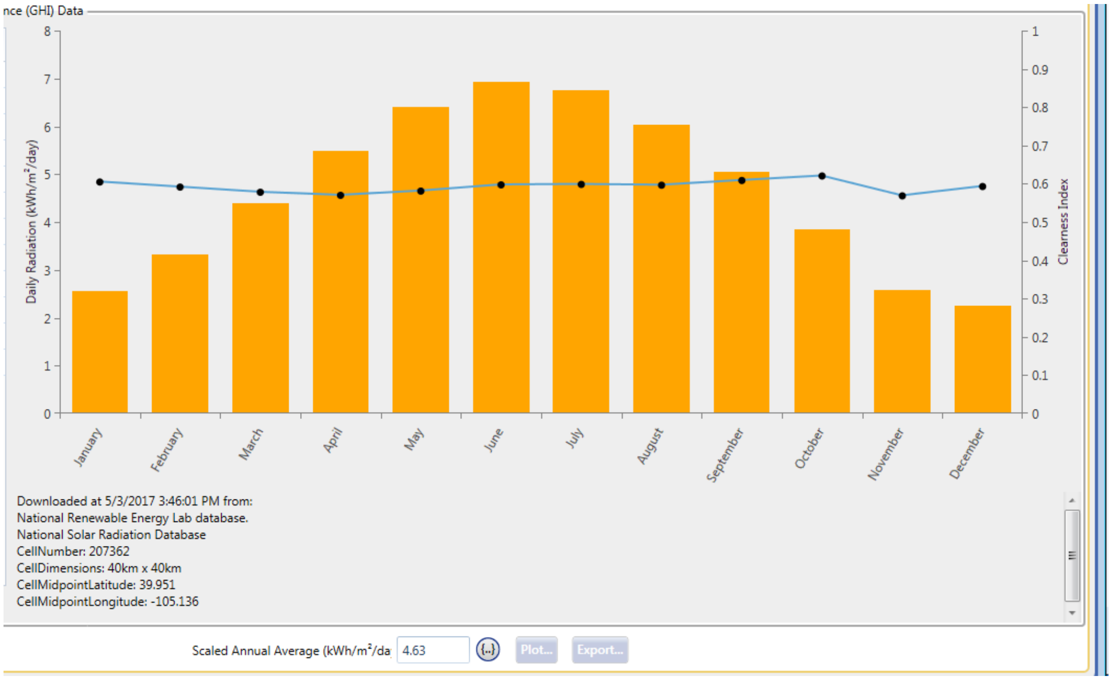
Scaled Annual Average (kWh/d): 170.00

Figure 4.2 Daily and Seasonal Load Profiles

The source for our Primary Load profile is obtained from the U.S Department of energy.

4.2 Resources

Solar Resource: To model a system containing a PV array, we must provide solar resource data for the location of interest. Solar resource data indicate the amount of global solar radiation (beam radiation coming directly from the sun, plus diffuse radiation coming from all parts of the sky) that strikes Earth's surface in a typical year. Solar Profile data for the area of interest in Colorado comes from National Renewable Energy Lab database.



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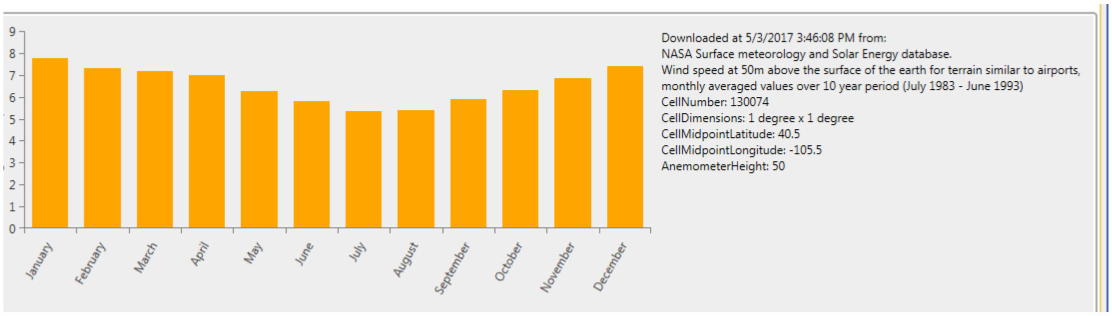
National Renewable Energy Lab database.
National Solar Radiation Database
CellNumber: 207362
CellDimensions: 40km x 40km
CellMidpointLatitude: 39.951
CellMidpointLongitude: -105.136

Scaled Annual Average (kWh/m²/da 4.63

Figure 4.3 Solar Profile

Wind Resource To model a system comprising one or more wind turbines, we must provide wind resource data indicating the wind speeds the turbines would experience in a typical year. Wind Profile data comes from the NASA Surface metereology and Solar Energy Database



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NASA Surface meteorology and Solar Energy database.
Wind speed at 50m above the surface of the earth for terrain similar to airports, monthly averaged values over 10 year period (July 1983 - June 1993)
CellNumber: 130074
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 40.5
CellMidpointLongitude: -105.5
AnemometerHeight: 50

Figure 4.4: Wind Profile

4.3 Microgrid Component: PV Array

The physical model is a generic flat plate PV

The PV array is modeled as a device that produces dc electricity in direct proportion to the global solar radiation incident upon it, independent of its temperature and the voltage to which it is exposed. The power output of the PV array is calculated using the equation

$$P_{\mathrm{PV}} = f_{\mathrm{PV}} Y_{\mathrm{PV}} \frac{I_T}{I_S}$$

where, f_{PV} is the PV derating factor,Y_{PV} the rated capacity of the PV array (kW), I_{T} the global solar radiation (beam plus diffuse) incident on the surface of the PV array (kW/m^2), and I_{S} is 1 kW/m^2, which is the standard amount of radiation used to rate the capacity of the PV array. [24]

The rated capacity (sometimes called the peak capacity) of a PV array is the amount of power it would produce under standard test conditions of 1 kW/m^2 irradiance and a panel temperature of 25 C. The size of our PV array is specified in terms of rated capacity. The rated capacity accounts for both the area and the efficiency of the PV module. [24]

Each hour of the year, HOMER calculates the global solar radiation incident on the PV array using the HDKR model**.** This model takes into account the current value of the solar resource (the global solar radiation incident on a horizontal surface), the orientation of the PV array, the location on Earth’s surface, the time of year, and the time of day. The orientation of the array may be fixed or may vary according to one of several tracking schemes [24].

The derating factor is a scaling factor meant to account for effects of dust on the panel, wire losses, elevated temperature, or anything else that would cause the out- put of the PV array to deviate from that expected under ideal conditions [24].

4.4 Microgrid Component: Wind Turbine

The physical model is a generic 3kw wind turbine.

The wind turbine is modeled as a device that converts the kinetic energy of the wind into ac or dc electricity according to a particular power curve, which is a graph of power output versus wind speed at hub height. Figure 4.5 is an example power curve. The wind turbine model assumes that the power curve applies at a standard air density of 1.225 kg/m^3, which corresponds to standard temperature and pressure conditions [24].

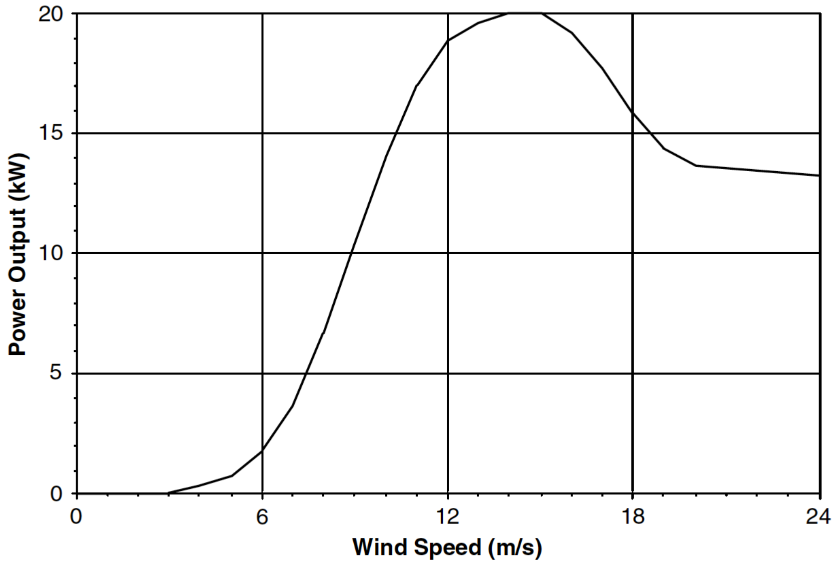


Figure 4.5: Wind turbine power curve

For Each hour, the wind turbine model calculates the power output of the wind turbine in a four-step process. First, it determines the average wind speed for the hour at the anemometer height by referring to the wind resource data. Second, it calculates the corresponding wind speed at the turbine's hub height using either the logarithmic law or the power law. Third, it refers to the turbine's power curve to calculate its power output at that wind speed assuming standard air density. Fourth, it multiplies that power output value by the air density ratio, which is the ratio of the actual air density to the standard air density. With HOMER we can calculate the air density ratio at the site elevation using the U.S. Standard Atmosphere [6]. HOMER assumes that the air density ratio is constant throughout the year. [24]

In addition to the turbine's power curve and hub height, we are allowed to specify the expected lifetime of the turbine in years, its initial capital cost in dollars, its replacement cost in dollars, and its annual O&M cost in dollars per year.

In our Model, the fundamental equation governing the mechanical power capture of wind turbine rotor blades which drives the electric generator is given by

$$P_m = \frac{1}{2} C_p . \rho . A . V_{wind}^3$$

where q is the air density (kg/m^3), A is the rotor sweep area, V is the wind velocity (m/s), and C_p represents the power coefficient of the wind turbine. Thus, if the air density, swept area, and wind speed are assumed constant, the output power of the wind turbine will be a function of the power coefficient [23].

The wind turbine is normally characterized by its C_p–TSR characteristic, where the TSR is the tip speed ratio and is given by:

$$TSR = \frac{\omega . R}{V}$$

where, R and w are the turbine radius and the mechanical angular speed, respectively and V is the wind speed. To keep power coefficients at its maximum value, operating TSRs must be held at its optimal value by controlling rotor speeds according to reference rotor speeds at incoming wind speeds using a maximum power point tracking (MPPT) controller [23].

4.5 Microgrid Component: Generator

A generator consumes fuel to produce electricity, and producess heat as a by-product [24].

The principal physical properties of the generator are its maximum and minimum electrical power output, its expected lifetime in operating hours, the type of fuel it consumes, and its fuel curve, which relates the quantity of fuel consumed to the electrical power produced [24].

HOMER assumes the fuel curve is a straight line with a y-intercept and uses the following equation for the generator's fuel consumption:

$$F = F_0 Y_{\text{gen}} + F_1 P_{\text{gen}}$$

where F_0 is the fuel curve intercept coefficient, F_1 is the fuel curve slope, Y_{gen} the rated capacity of the generator (kW), and P_{gen} the electrical output of the generator (kW). The units of F depend on the measurement units of the fuel. If the fuel is denominated in liters, the units of F are L/h. If the fuel is denominated in m^3 or kg, the units of F are m^3/h or kg/h, respectively. In the same way, the units of F_0 and F_1 depend on the measurement units of the fuel. For fuels denominated in liters, the units of F_0 and F_1 are L/h kW [24].

With the HOMER generator model it is possible to schedule the operation of the generator to force it on or off at certain times. During times that the generator is neither forced on or off, HOMER decides whether it should operate based on the needs of the system and the relative costs of the other power sources. During times that the generator is forced on, HOMER decides at what power output level it operates, which may be anywhere between its minimum and maximum power output.

The user specifies the generator's initial capital cost in dollars, replacement cost in dollars, and annual O&M cost in dollars per operating hour. The generator O&M cost should account for oil changes and other maintenance costs. Fuel cost is calculated separately. As it does for all dispatchable power sources, HOMER calculates the generator’s fixed and marginal cost of energy and uses that information when simulating the operation of the system. The fixed cost of energy is the cost per hour of simply running the generator, with- out producing any electricity. The marginal cost of energy is the additional cost per kilowatthour of producing electricity from that generator [24].

Our Model uses the following equation to calculate the generator’s fixed cost of energy:

$$c_{\text{gen,fixed}} = c_{\text{om,gen}} + \frac{C_{\text{rep,gen}}}{R_{\text{gen}}} + F_0 Y_{\text{gen}} c_{\text{fuel,eff}}$$

where $c_{\text{om;gen}}$ is the O&M cost in dollars per hour, $C_{\text{rep;gen}}$ the replacement cost in dollars, R_{gen} the generator lifetime in hours, F_0 the fuel curve intercept coefficient in quantity of fuel per hour per kilowatt, Y_{gen} the capacity of the generator (kW), and $c_{\text{fuel;eff}}$ the effective price of fuel in dollars per quantity of fuel. The effective price of fuel includes the cost penalties, if any, associated with the emissions of pollutants from the generator.

We calculate the marginal cost of energy of the generator using the fol- lowing equation:

$$c_{\text{gen,mar}} = F_1 c_{\text{fuel,eff}}$$

where F_1 is the fuel curve slope in quantity of fuel per hour per kilowatthour and $c_{fuel;eff}$ is the effective price of fuel (including the cost of any penalties on emissions) in dollars per quantity of fuel [24].

4.6 Microgrid Component: Battery Bank

The battery bank is a collection of one or more individual batteries. With HOMER we can model a single battery as a device capable of storing a certain amount of dc electricity at a fixed round-trip energy efficiency, with limits as to how quickly it can be charged or discharged, how deeply it can be discharged with- out causing damage, and how much energy can cycle through it before it needs replacement. HOMER assumes that the properties of the batteries remain constant throughout its lifetime and are not affected by external factors such as temperature. [25]

4.7 Microgrid Component: Grid

While it is not our objective to have the microgrid connected to the grid, a SE may consider to model the grid, as a component in our system architecture, from which the micropower system can purchase AC electricity and to which the system can sell AC electricity. The cost of purchasing power from the grid can comprise an energy charge based on the amount of energy purchased in a billing period and a demand charge based on the peak demand within the billing period. We can consider Grid power price for the price (in dollars per kilowatt/hour) that the electric utility charges for energy purchased from the grid, the demand rate for the price (in dollars per kilowatt per month) the utility charges for the peak grid demand. And, the sellback rate, which is the price (in dollars per kilowatt/hour) that the utility pays for power sold to the grid [24].

4.8 Microgrid Component: Electronic Converter

A converter is a device that converts electric power from DC to AC in a process called inversion, and/or from ac to dc in a process called rectification. HOMER can model the two common types of converters: solid-state and rotary. The converter size, which is a decision variable, refers to the inverter capacity, meaning the maximum amount of ac power that the device can produce by inverting dc power.

The user specifies the rectifier capacity, which is the maximum amount of dc power that the device can produce by rectifying ac power, as a percentage of the inverter capacity. The rectifier capacity is therefore not a separate decision variable.

We assume that the inverter and rectifier capacities are not surge capacities that the device can withstand for only short periods of time, but rather, continuous capacities that the device can withstand for as long as necessary [24].

The HOMER user indicates whether the inverter can operate in parallel with another ac power source such as a generator or the grid.

Doing so requires the inverter to synchronize to the ac frequency, an ability that some inverters do not have. The final physical properties of the converter are its inversion and rectification efficiencies which HOMER assumes to be constant. The economic properties of the converter are its capital and replacement cost in dollars, its annual O&M cost in dollars per year, and its expected lifetime in years [24].

Chapter 5

System Dispatch

5.1 Overview

In addition to modeling the behavior of each individual component, we must simulate how those components work together as a system. That requires hour-by-hour decisions as to which generators should operate and at what power level, whether to charge or discharge the batteries, and in the case of grid connected system, whether to buy from or sell to the grid. In this section we describe briefly the logic used to make such decisions.

5.2 Operating Reserve

Operating reserve provides a safety margin that helps ensure reliable electricity supply despite variability in the electric load and the renewable power supply. Virtually every real micropower system must always provide some amount of operating reserve, because otherwise the electric load would sometimes fluctuate above the operating capacity of the system, and an outage would result [24].

At any given moment, the amount of operating reserve that a power system provides is equal to the operating capacity minus the electrical load. Consider, for example, a simple PV and Battery system capable of producing 10-kW where PV cells supplies an electric load. In that system, if the load is 5 kW, the system will produce 5 kW of electricity and provide 5 kW of operating reserve. In other words, the system could supply the load even if the load suddenly increased by 5 kW. When using HOMER, we can specify the required amount of operating reserve, and HOMER simulates the system so as to provide at least that much operating reserve [24].

For each hour, we can use HOMER to calculate the required amount of operating reserve as a fraction of the primary load for that hour, plus a fraction of the annual peak primary load, plus a fraction of the PV power output that hour, plus a fraction of the wind power output that hour. We specify these fractions by considering how much the load or the renewable power output is likely to fluctuate in a short period, and how conservatively he or she plans to operate the system. The more variable the load and renewable power output, and the more conservatively the system must operate, the higher the fractions the modeler should specify. While HOMER does not attempt to ascertain the amount of operating reserve required to achieve different levels of reliability; it can use our system specifications to calculate the amount of operating reserve the system is obligated to provide each hour [24].

Once it calculates the required amount of operating reserve, HOMER will attempt to operate the system so as to provide at least that much operating reserve. Doing so may require operating the system differently (at a higher cost) than would be necessary without consideration of operating reserve. Consider, for example, a wind– diesel system for which the user defines the required operating reserve as 10% of the hourly load plus 50% of the wind power output. HOMER will attempt to operate that system so that at any time, it can supply the load with the operating generators even if the load suddenly increased by 10% and the wind power output suddenly decreased by 50%. In an hour where the load is 140 kW and the wind power output is 80 kW, the required operating reserve would be 14 kW þ 40 kW 1⁄4 54 kW. The diesel generators must therefore provide 60 kW of electricity plus 54 kW of operating reserve, meaning that the capacity of the operating generators must be at least 114 kW. Without consideration of operating reserve, HOMER would assume that a 60-kW diesel would be sufficient [24].

We assume that both dispatchable and nondispatchable power sources provide operating capacity. A dispatchable power source provides operating capacity in an amount equal to the maximum amount of power it could produce at a moment's notice. For a generator, that is equal to its rated capacity if it is operating, or zero if it is not operating. For the grid, that is equal to the maximum grid demand. For the battery, that is equal to its current maximum discharge power, which depends on state of charge and recent charge–discharge history, as described in the components section. In contrast to the dispatchable power sources, the operating capacity of a nondispatchable power source (a PV array, wind turbine) is equal to the amount of power the source is currently producing, as opposed to the maximum amount of power it could produce [24].

If a system is ever unable to supply the required amount of load plus operating reserve, we record the shortfall as capacity shortage. With HOMER we can calculate the total amount of such shortages over the year and divides the total annual capacity shortage by the total annual electric load to find the capacity shortage fraction. We specify the maximum allowable capacity shortage fraction. And discard as infeasible any system whose capacity shortage fraction exceeds this constraint [24].

5.3 Control of Dispatchable System Components -

For each hour of the year, it is required to determine whether the (nondispatchable) renewable power sources by themselves are capable of supplying the electric load, the required operating reserve, and the thermal load. If not, it determines how best to dispatch the dispatchable system components (the generators, battery bank, grid, and boiler) to serve the loads and operating reserve. This determination of how to dispatch the system components each hour is one of the most complex aspects of the simulation of microgrid systems. We can use HOMER for this as control of these aspects are possible in it's simulation logic [25].

The nondispatchable renewable power sources, although they necessitate complex system modeling, are themselves simple to model because they require no control logic they simply produce power in direct response to the renewable resource available. The dispatchable sources are more difficult to model because they must be controlled to match supply and demand properly, and to compensate for the intermittency of the renewable power sources [24].

An important aspect when we consider the dispatching systems is cost. For this HOMER can be helpful as it allows us to see the options available for minimizing cost. HOMER represents the economics of each dispatchable energy source by two values: a fixed cost in dollars per hour, and a marginal cost of energy in dollars per kilowatt hour. These values represent all costs associated with producing energy with that power source that hour. The sections above on the generator, battery bank, and grid detail how HOMER calculates the fixed and marginal costs for each of these components. Using these cost values, we use HOMER to search for the combination of dispatchable sources that can serve the electrical load, thermal load, and the required operating reserve at the lowest cost. Satisfying the loads and operating reserve is paramount, meaning that HOMER will accept any cost to avoid capacity shortage. But we can use HOMER to find the combinations of dispatchable sources that can serve the loads equally well, HOMER at the lowest cost [24].

As our system we consider a Wind-PV-diesel–battery system. This system comprises two dispatchable power sources, the battery bank and the diesel generator. Whenever the net load is negative (the power output of the wind turbine is sufficient to serve the load), the excess power charges the battery bank. But whenever the net load is positive, the system must either operate the diesel or discharge the battery, or both, to serve the load. In choosing among these four alternatives, HOMER considers the ability of each source to supply the ac net load and the required operating reserve, and the cost of doing so. If the diesel generator is scheduled off or has run out of fuel, it has no ability to supply power to the ac load. Otherwise, it can supply any amount of ac power up to its rated capacity. The battery's ability to supply power and operating reserve to the ac load is constrained by its current discharge capacity (which depends on its state of charge and recent charge–discharge history, as described in the battery component section) and the capacity and efficiency of the ac–dc converter. If both the battery bank and the diesel generator are capable of supplying the net load and the operating reserve, we can use HOMER to decide which to use based on their fixed and marginal costs of energy [24].

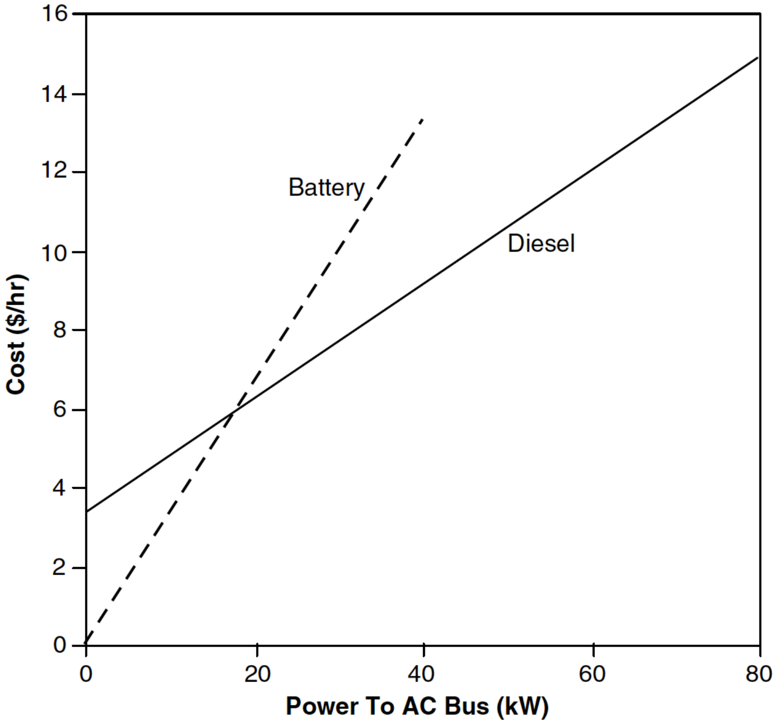


Figure 5.1: Cost of energy comparison

Figure 5.1 shows one possible cost scenario, where the diesel capacity is 80 kW and the battery can supply up to 40 kW of power to the ac bus, after conversion losses. This scenario is typical in that the battery's marginal cost of energy exceeds that of the diesel. But because of the diesel's fixed cost, the battery can supply small amounts of ac power more cheaply than the diesel. In this case the crossover point is around 20 kW. Therefore, if the net load is less than 20 kW, the system will serve the load by discharging the battery. If the net load is greater than 20 kW, the system will serve the load with the generator instead of the battery, even if the battery is capable of supplying the load [24].

The Microgrid system uses the same cost-based dispatch logic regardless of the system configuration. When simulating a system comprising multiple generators, when using HOMER, it will help choose the combination of generators that can most cheaply supply the load and the required operating reserve [24].

When Simulating with HOMER it is idealized that the system engineer will operate the system so as to minimize total life-cycle cost, when in fact a real system controller may not. However, taking an ‘‘economically optimal’’ scenario serves as a useful baseline with which to compare different system configurations [24].

5.4 Dispatch Strategy

For systems comprising both a battery bank and a generator, an additional aspect of system operation arises, which is whether (and how) the generator should charge the battery bank. One cannot base this battery- charging logic on simple economic principles, because there is no deterministic way to calculate the value of charging the battery bank. The value of charging the battery in one hour depends on what happens in future hours. In a wind–diesel– battery system, for example, charging the battery bank with diesel power in one hour would be of some value if doing so allowed the system to avoid operating the diesel in some subsequent hour. But it would be of no value whatsoever if the system experienced more than enough excess wind power in subsequent hours to charge the battery bank fully. In that case, any diesel power put into the battery bank would be wasted because the wind power would have fully charged the battery bank anyway [24].

Rather than using complicated probabilistic logic to determine the optimal battery-charging strategy, we can use HOMER which provides two simple strategies and lets us model them both to see which is better in any particular situation. These dispatch strategies are called Load-following LF and Cycle-charging CC. Under the load-following strategy, a generator produces only enough power to serve the load, and does not charge the battery bank. Under the cycle-charging strategy, whenever a generator operates, it runs at its maximum rated capacity (or as close as possible without incurring excess electricity) and charges the battery bank with the excess. HOMER treats the dispatch strategy as a decision variable, we can easily simulate both strategies to determine which is optimal in a given situation [24].

The dispatch strategy does not affect the decisions described in the preceding section as to which dispatchable power sources operate each hour. Only after these decisions are made does the dispatch strategy come into play. If the load-following strategy applies, whichever generators HOMER selects to operate in a given hour will produce only enough power to serve the load. If the cycle-charging strategy applies, those same generators will run at their rated output, or as close as possible without causing excess energy [24].

An optional control parameter called the set-point state of charge can apply to the cycle-charging strategy. If the modeler chooses to apply this parameter, once the generator starts charging the battery bank, it must continue to do so until the battery bank reaches the set-point state of charge. Otherwise, HOMER may choose to discharge the battery as soon as it can supply the load. The set-point state of charge helps avoid situations where the battery experiences shallow charge–discharge cycles near its minimum state of charge. In real systems, such situations are harmful to battery life. [24]

5.5 Load Priority

When defining the system with HOMER, it makes a separate set of decisions regarding how to allocate the electricity produced by the system. The presence of both an ac and a dc bus complicates these decisions somewhat. Using HOMER we will assume that electricity produced on one bus will go first to serve primary load on the same bus, then primary load on the opposite bus, then deferrable load on the same bus, then deferrable load on the opposite bus, then to charge the battery bank, then to grid sales, then to serve the electrolyzer, and then to the dump load, which optionally serves the thermal load [24].

Chapter 6

Economic Modeling

6.1 Overview

In Economics play an integral role for both the simulation process, wherein it operates the system so as to minimize total net present cost, and in its optimization process, wherein it searches for the system configuration with the lowest total net present cost. Through economic analysis we can find which life-cycle cost is the appropriate metric with which to compare the economics of different system configurations, the total net present cost as the economic figure of merit, and how we calculate total net present cost [24].

Renewable and nonrenewable energy sources typically have dramatically different cost characteristics. Renewable sources tend to have high initial capital costs and low operating costs, whereas conventional nonrenewable sources tend to have low capital and high operating costs. In the optimization process, it is advisable to compare the economics of a wide range of system configurations comprising varying amounts of renewable and even nonrenewable energy sources. We need to compare and analyze both the capital and operating costs. A Life-cycle cost analysis can do so by including all costs that occur within the life span of the system [24].

We use the total net present cost (NPC) to represent the life-cycle cost of a system. The total NPC condenses all the costs and revenues that occur within the project lifetime into one lump sum in today's dollars, with future cash flows discounted back to the present using the discount rate. (The System engineer specifies the discount rate and the project lifetime). The NPC includes the costs of initial construction, component replacements, maintenance, fuel, plus the cost of buying power from the grid and miscellaneous costs such as penalties resulting from pollutant emissions. Revenues can include income from selling power to the grid, plus any salvage value that occurs at the end of the project lifetime. With the NPC, costs are positive and revenues are negative. This is the opposite of the net present value. The net present cost is different from net present value only in sign [24].

We assume that all prices escalate at the same rate over the project lifetime. With that assumption, inflation can be factored out of the analysis simply by using the real (inflation-adjusted) interest rate rather than the nominal interest rate when discounting future cash flows to the present. When using HOMER we can specify the real interest rate, which is roughly equal to the nominal interest rate minus the inflation rate [24].

For each component of the system, we specify the initial capital cost, which occurs in year zero, the replacement cost, which occurs each time the component needs replacement at the end of its lifetime, and the O&M cost, which occurs each year of the project lifetime. We can specify the lifetime of most components in years, but when using HOMER, it calculates the lifetime of the battery and generators (as described in the Physical Modeling Section) [24].

To calculate the salvage value of each component at the end of the project lifetime, the following equation is used:

$$S = C_{\mathrm{rep}} \frac{R_{\mathrm{rem}}}{R_{\mathrm{comp}}}$$

where S is the salvage value, Crep the replacement cost of the component, Rrem the remaining life of the component, and Rcomp the lifetime of the component. For example, if the project lifetime is 20 years and the PV array lifetime is also 20 years, the salvage value of the PV array at the end of the project lifetime will be zero because it has no remaining life. On the other hand, if the PV array lifetime is 30 years, at the end of the 20-year project lifetime its salvage value will be one-third of its replacement cost [24].

For each component, we combine the capital, replacement, maintenance, and fuel costs, along with the salvage value and any other costs or revenues, to find the component's annualized cost. This is the hypothetical annual cost that if it occurred each year of the project lifetime would yield a net present cost equivalent to that of all the individual costs and revenues associated with that component over the project lifetime. When using HOMER, it can sum the annualized costs of each component, along with any miscellaneous costs, such as penalties for pollutant emissions, to find the total annualized cost of the system. This value is an important one because HOMER uses it to calculate the two principal economic figures of merit for the system: the total net present cost and the levelized cost of energy [24].

When using HOMER the following equation is used to calculate the total net present cost:

$$C_{\mathrm{NPC}} = \frac{C_{\mathrm{ann,tot}}}{\mathrm{CRF}\left(i, R_{\mathrm{proj}}\right)}$$

where Cann;tot is the total annualized cost, i the annual real interest rate (the discount rate), Rproj the project lifetime, and CRF( ) is the capital recovery factor, given by the

$$\mathrm{CRF}(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$

equation

where i is the annual real interest rate and N is the number of years [24].

The following equation is used to calculate the Levelized Cost of Energy:

$$\mathrm{COE} = \frac{C_{\mathrm{ann,tot}}}{E_{\mathrm{prim}} + E_{\mathrm{def}} + E_{\mathrm{grid,sales}}}$$

where Cann,tot is the total annualized cost, Eprim and Edef are the total amounts of primary and deferrable load, respectively, that the system serves per year, and Egrid,sales is the amount of energy sold to the grid per year. The denominator in this COE equation is an expression of the total amount of useful energy that the system produces per year. The levelized cost of energy is therefore the average cost per kilowatthour of useful electrical energy produced by the system [24].

When simulating with HOMER, it uses the total NPC as its primary economic figure of merit. In the optimization process, with HOMER we can rank the system configurations according to NPC rather than levelized cost of energy. (This is because the definition of the levelized cost of energy is disputable in a way that the definition of the total NPC is not). In developing the formula that HOMER uses for the levelized cost of energy, we decided to divide by the amount of electrical load that the system actually serves rather than the total electrical demand, which may be different if the user allows some unmet load. We also decided to neglect thermal energy but to include grid sales as useful energy production. Each of these decisions is somewhat arbitrary, making the definition of the levelized cost of energy also somewhat arbitrary. Because the total NPC suffers from no such definitional ambiguity, it is preferable as the primary economic figure of merit [24].

Other Economical Considerations in the Simulation System Design

Nominal Discount Rate %	6.00
Expected Inflation Rate %	2.00
Real Discount Rate %	3.92
Project Lifetime (Years)	25
System Fixed Capital Costs	0
System fixed O&M costs	0
Capacity Shortage Penalty	0

Chapter 7

Simulation, Sensitivity Analysis Optimization and Trade Off Analysis

7.1 Overview

So far we have stablished the models to be used for our architecture. That is, the Electric Hourly Load Profile of the System, the Hourly Solar and Wind Profiles of the Location. Power Generation Options such as PV, Wind Turbines, Diesel Generator, Lithium Battery, Converter, and other system Economical variables. We perform the system simulations with HOMER.

The simulations performed investigate the different configurations and variables possible based on the component modeling of the previous sections and the hourly data sets, such that the Microgrid has the ability to satisfy the Load Profile under both Solar and Wind Profiles. Each simulation outputs a range of feasible solutions (that do not bring risk of capacity shortage), both based on the component modeling and the hourly datasets.

7.2 Sensitivity Analysis:

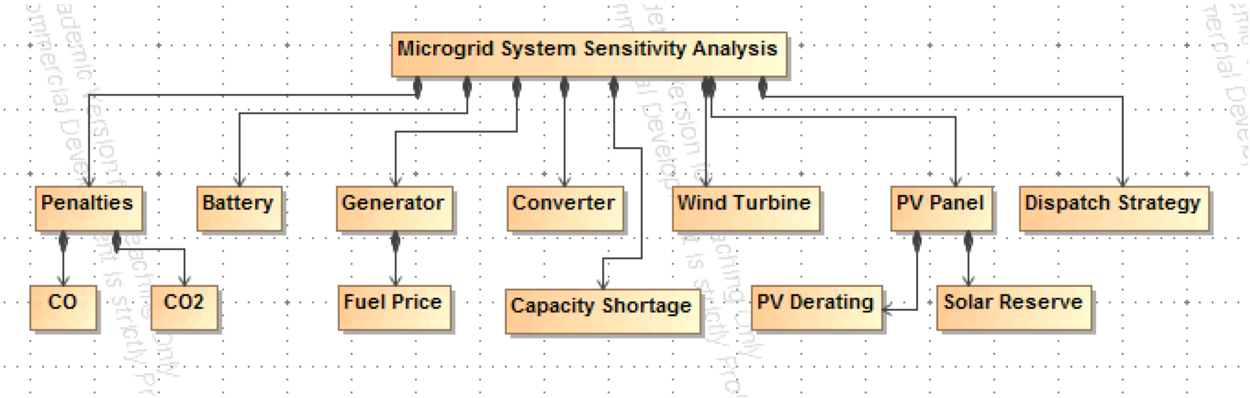


Figure 7.1: Sensitivity Analysis Block definition diagram (BDD)

The sensitivity analysis allows us to provide some possible options for some of the inputs in the simulation without having to investigate their whole range of values. This aids to optimize the simulation search. For example: in the case of Emissions CO and CO2 penalties, we can consider fixed penalties per ton, such as 20 and 50 instead of all the range of variables between both. By specifying a range of values for a variable, we can determine how important that variable is, and how the solution changes depending on its value. In other words, we can determine how "sensitive" the outputs are to changes in that variable.

Through HOMER we are Capable of Performing sensitivity analyses on Hourly Data sets such as those of our Microgrid. However, as satisfying the loads and operating reserve is paramount, HOMER will accept any combination and cost to avoid capacity shortage. We use HOMER to find the combinations of our system components sources that will serve the loads equally well and at the lowest cost [25].

The Sensitivity Cases table on the Results page ranks all the feasible systems from HOMER's sensitivity analysis. A sensitivity analysis can result in a large amount of output data. Every simulation that HOMER performs results in several dozen summary outputs (like the annual fuel consumption and the total capital cost) plus about a dozen arrays of time-series data (e.g., the output of the wind turbine). HOMER typically performs hundreds or thousands of these simulations per sensitivity case. A sensitivity analysis can easily involve hundreds of sensitivity cases [25].

7.3 Optimization

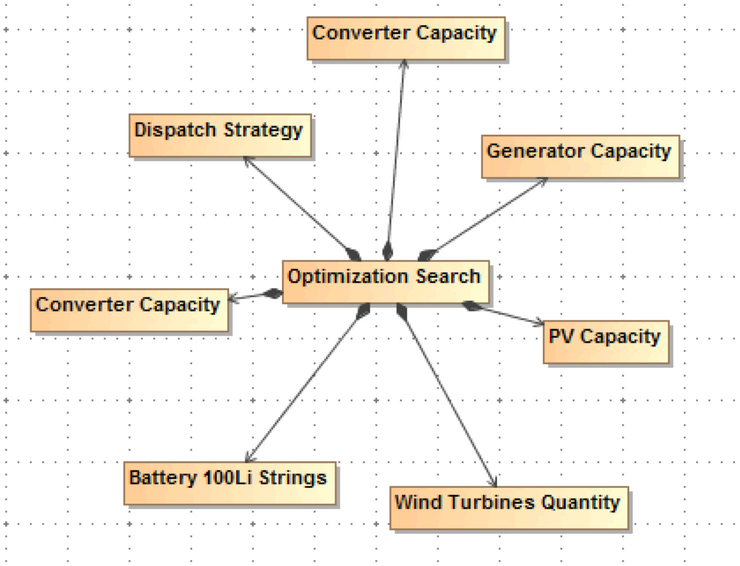


Figure 7.2: Optimization Search BDD Diagram

The goal of the optimization process is to determine the optimal value of each decision variable that interests the system engineer. A decision variable is a variable over which the system engineer has control and for which can consider multiple possible values in the optimization process. We consider the following decision variables:

- The size of the PV array
- The number of wind turbines

- The size and use of each generator
- The number of batteries
- The size of the ac–dc converter
- The dispatch strategy (the set of rules governing how the system operates)

Using the variables from the sensitivity analysis in HOMER helps during the optimization process as it will take those sensitivity inputs and optimize the system with the hourly data and system architecture models.

Optimizing the system with HOMER allows us to rank the system configurations according to the effect of the various optimization variables in the system. The Goal for using HOMER is to optimize the system for both the lowest Net Present Cost, as well as the most Renewable Generators possible, and the lowest system Emissions Possible.

The simulation and optimization of the variables along with the sensitivity analysis variables, aid in finding the various different inputs and load demands in the microgrid that govern the final system recommendation. That is, these results will later aid in the Tradeoff Analysis of the system.

When we look into the dispatching system components cost, HOMER can be helpful as it allows us to see the options available for minimizing the cost of the system and also the Net Present Cost. HOMER will present the economics of each dispatchable energy.

7.4 Tradeoff Study

Optimal System for Efficient and Clean Generation

The objective is to find and compare the different effects of the architecture taking into account the economic considerations performance, and effects in the Environment from the various system design alternatives.

In HOMER Pro with the Aid of the Sensitivity and Optimization Analysis we can perform a 25 Year Simulation/Tradeoff Study varying different setups in order to find the optimal setup for:

PV Photovoltaics:

Quantity

Generation Percentage in System

Cost

G3 Wind Turbine:

Generation Capacity: Given the Location Yearly Wind Profile,

Cost

100 Li Battery Energy Storage

Number of Strings

Cost

Emissions Cost and Production

Renewables: Percentage in the system

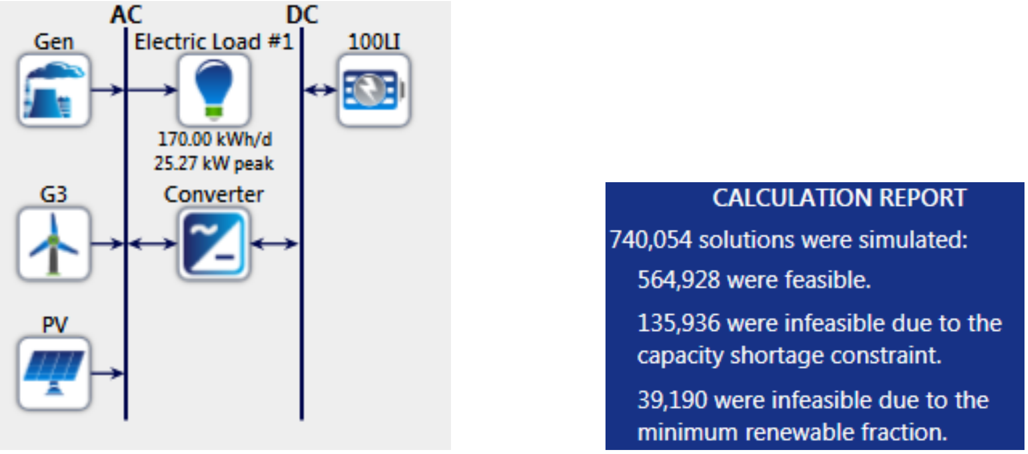
With the final aim to compare the feasibility of a 100% Renewables Microgrid system.

Chapter 8

Simulation Results

8.1 Overview

The microgrid considered for analysis has as main components: PV Arrays, Wind Turbines, Batteries the option of a Diesel Generator an Electronic Converter and a Microgrid Controller. With Homer we can simulate how the system operates over one year and apply this analysis into a 25 Year analysis.



CALCULATION REPORT

740,054 solutions were simulated:

564,928 were feasible.

135,936 were infeasible due to the capacity shortage constraint.

39,190 were infeasible due to the minimum renewable fraction.

Figure 8.1: Microgrid System Schematic in HOMER

8.2 System Simulation

8.2.1 Total Loads Served Through One Year

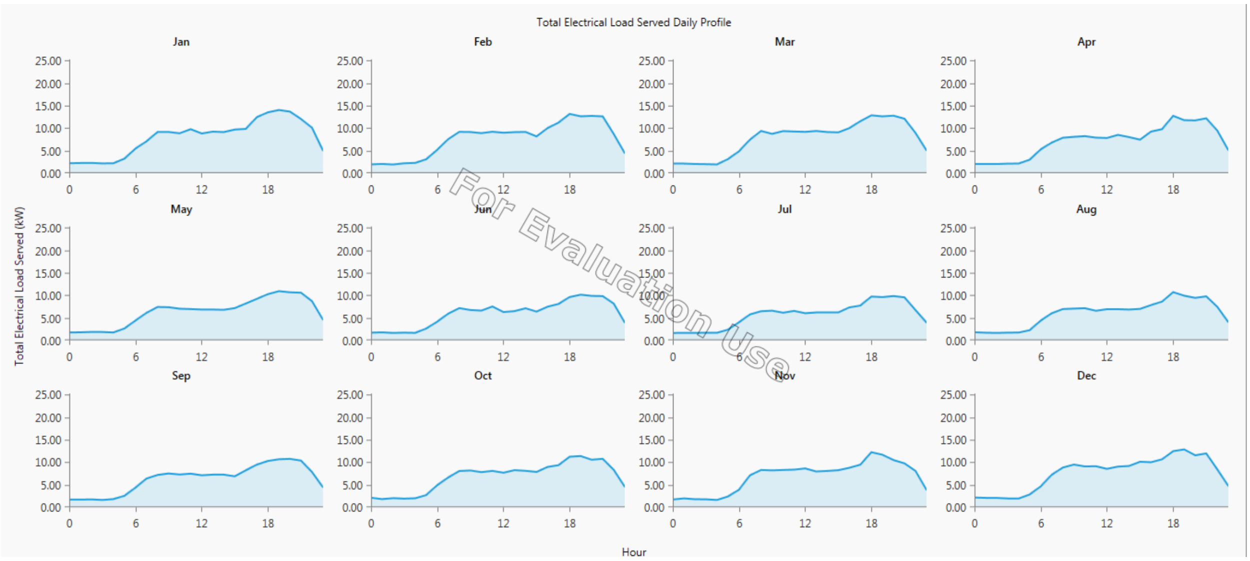


Figure 8.2: Total Loads served through one year

The Graphic above shows the amount of total electrical loads in kW served by the system through the course of one Year. Each graph represents an average daily profile for the month served and the electrical load served.

8.2.2 Wind and Solar Power Generation Output

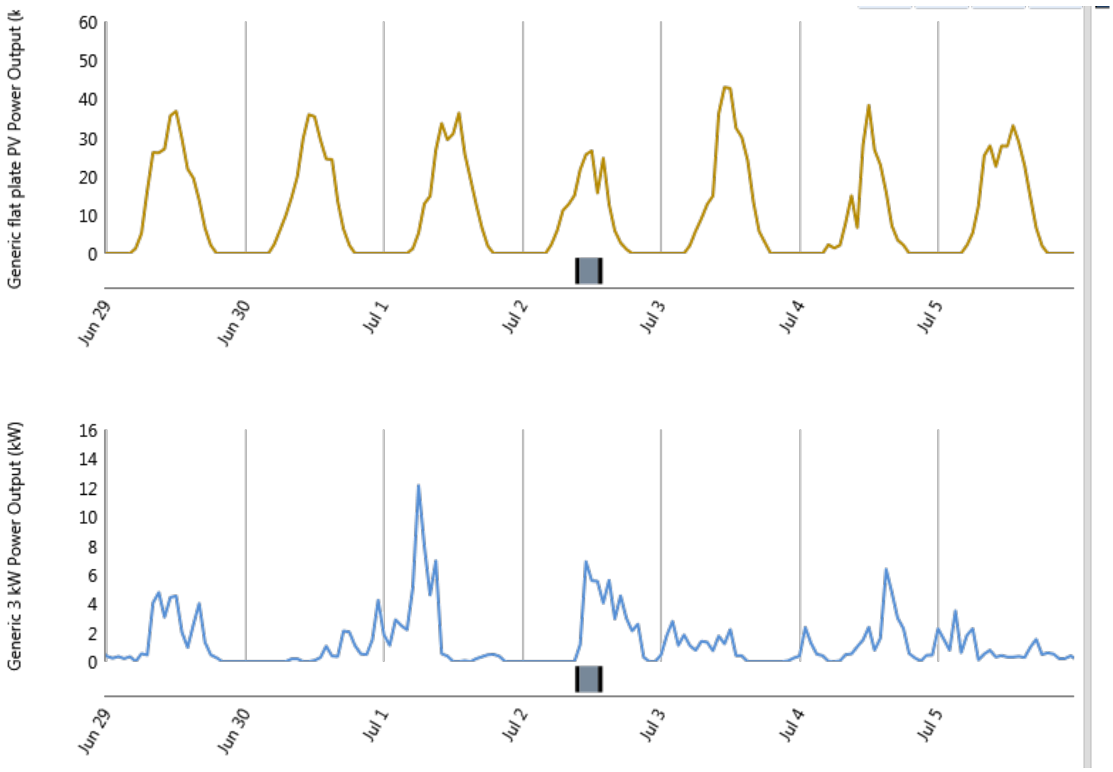


Figure 8.3: Wind and Solar Power Generation Output

Here we see the energy generation in kW from both the Photovoltaics (PV) as well as the Wind Turbines. The graphics above show an example of the energy generation variations from a day to day basis. We can clearly see the different energy variations from the PV and the Wind Turbine.

8.2.3 Loads Served and Battery Discharge

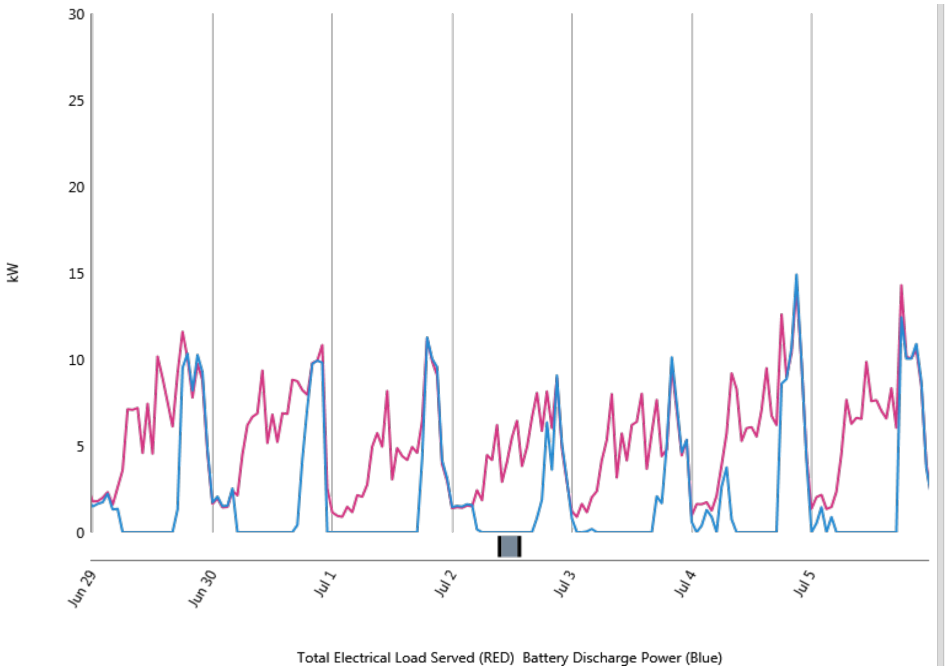


Figure 8.4: Loads Served vs Battery Discharge

In the figure above shows graphically when the Battery (in Blue) discharges energy to the system as well as how much energy was discharged. The figure also shows the Loads served (in Red) by the system when the Battery discharge occurs.

8.2.4 Battery State of Charge

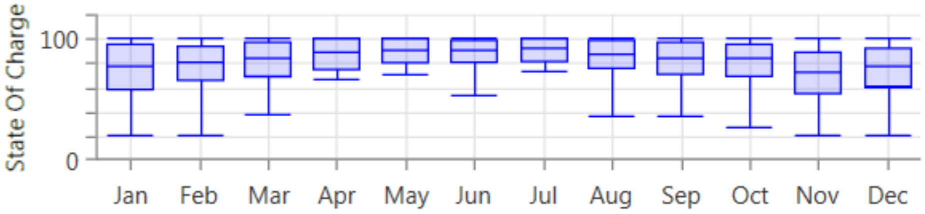


Figure 8.5: Battery State of Charge

The figure above shows the Battery State of Charge through the course of one year. We can see clearly that during the summer days the battery is used the most.

8.3 Sensitivity and Optimization

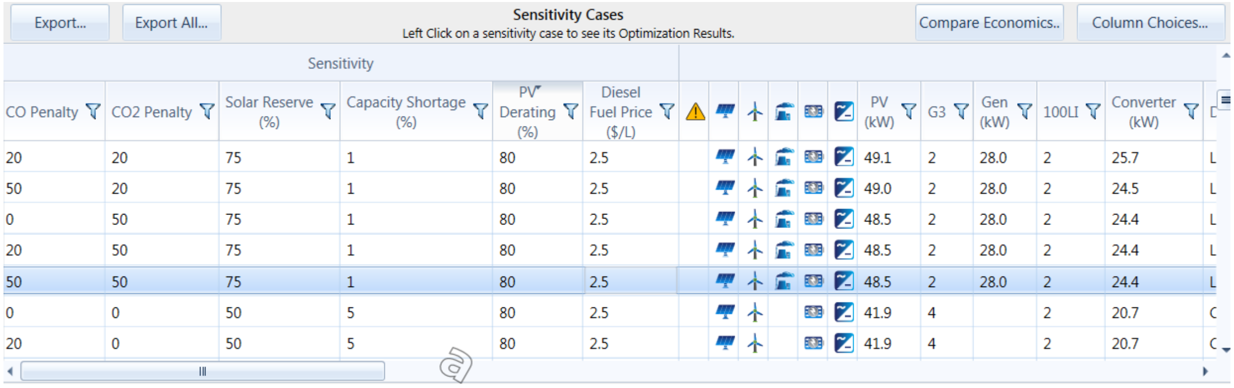
Sensitivity Cases Tables

The Sensitivity Cases table on the following result tables ranks all the feasible systems from HOMER's sensitivity analysis.

The Sensitivity Cases results consist of a list of the lowest-cost system for each sensitivity case. In the following tables:

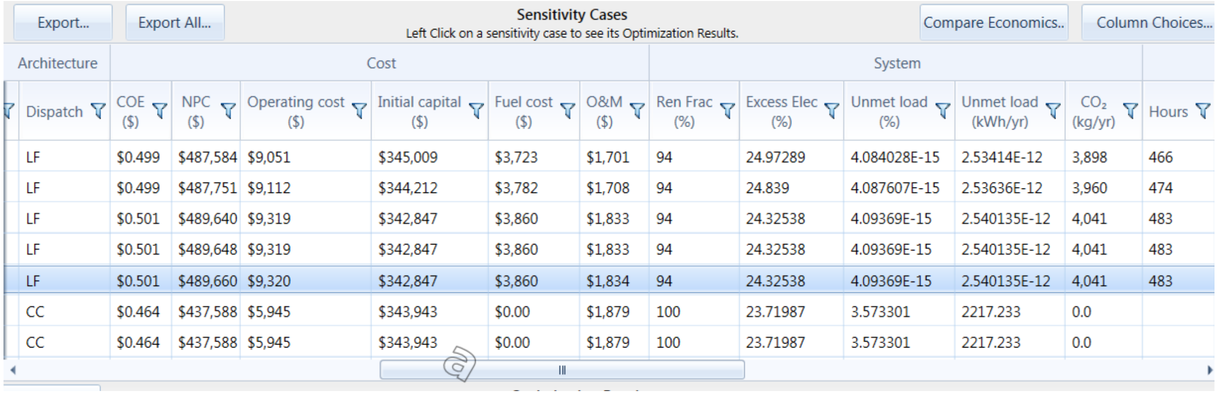
- The first six columns display the values of the Sensitivity variables as described in section 7.2: the CO and CO2 penalties, Solar Reserve, Capacity Shortage, PV Derating, and Diesel Fuel Price.
- The next five columns contain values indicating the presence and size of the five components under consideration in the lowest-cost system for the Islanded Microgrid. From left to right, they are PV Panels, Wind Turbines, the Diesel Generator, the Batteries, and the Converter.
- The following several columns show summary values drawn from the simulation results of the Least-cost system including: Initial Capital, Operating cost, and Total Net Present Cost.
- Finally, in the System section of the tables below, it shows the percentage of the Renewable Energy (Ren Frac (%)) used in the system, and the amount of CO2 Emissions output from the system.

Sensitivity Cases Tables:



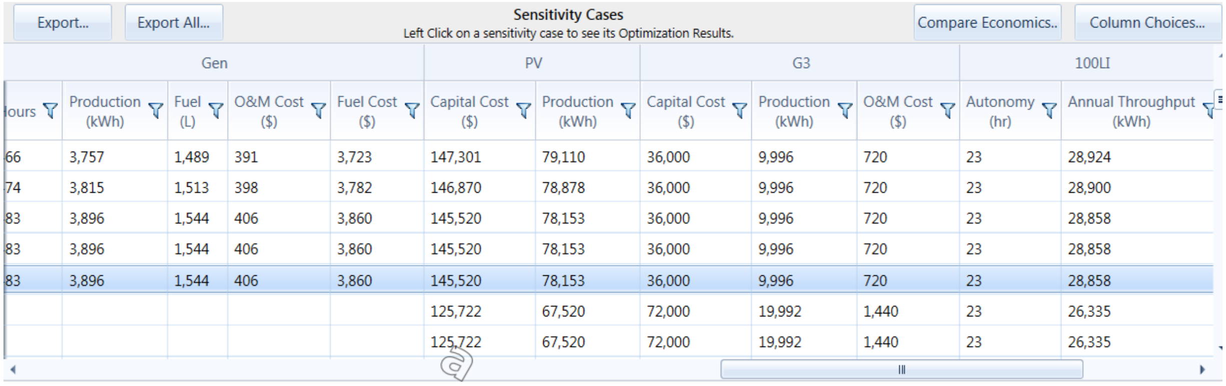
Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Sensitivity												
CO Penalty	CO2 Penalty	Solar Reserve (%)	Capacity Shortage (%)	PV Derating (%)	Diesel Fuel Price ($/L)	PV (kW)	G3	Gen (kW)	100LI	Converter (kW)	D
20	20	75	1	80	2.5	49.1	2	28.0	2	25.7	L
50	20	75	1	80	2.5	49.0	2	28.0	2	24.5	L
0	50	75	1	80	2.5	48.5	2	28.0	2	24.4	L
20	50	75	1	80	2.5	48.5	2	28.0	2	24.4	L
50	50	75	1	80	2.5	48.5	2	28.0	2	24.4	L
0	0	50	5	80	2.5	41.9	4		2	20.7	C
20	0	50	5	80	2.5	41.9	4		2	20.7	C



Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Architecture	Cost						System					
Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Fuel cost ($)	O&M ($)	Ren Frac (%)	Excess Elec (%)	Unmet load (%)	Unmet load (kWh/yr)	CO_2 (kg/yr)	Hours
LF	$0.499	$487,584	$9,051	$345,009	$3,723	$1,701	94	24.97289	4.084028E-15	2.53414E-12	3,898	466
LF	$0.499	$487,751	$9,112	$344,212	$3,782	$1,708	94	24.839	4.087607E-15	2.53636E-12	3,960	474
LF	$0.501	$489,640	$9,319	$342,847	$3,860	$1,833	94	24.32538	4.09369E-15	2.540135E-12	4,041	483
LF	$0.501	$489,648	$9,319	$342,847	$3,860	$1,833	94	24.32538	4.09369E-15	2.540135E-12	4,041	483
LF	$0.501	$489,660	$9,320	$342,847	$3,860	$1,834	94	24.32538	4.09369E-15	2.540135E-12	4,041	483
CC	$0.464	$437,588	$5,945	$343,943	$0.00	$1,879	100	23.71987	3.573301	2217.233	0.0	
CC	$0.464	$437,588	$5,945	$343,943	$0.00	$1,879	100	23.71987	3.573301	2217.233	0.0	



Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Gen					PV		G3			100LI	
ours	Production (kWh)	Fuel (L)	O&M Cost ($)	Fuel Cost ($)	Capital Cost ($)	Production (kWh)	Capital Cost ($)	Production (kWh)	O&M Cost ($)	Autonomy (hr)	Annual Throughput (kWh)
66	3,757	1,489	391	3,723	147,301	79,110	36,000	9,996	720	23	28,924
74	3,815	1,513	398	3,782	146,870	78,878	36,000	9,996	720	23	28,900
83	3,896	1,544	406	3,860	145,520	78,153	36,000	9,996	720	23	28,858
83	3,896	1,544	406	3,860	145,520	78,153	36,000	9,996	720	23	28,858
83	3,896	1,544	406	3,860	145,520	78,153	36,000	9,996	720	23	28,858
					125,722	67,520	72,000	19,992	1,440	23	26,335
					125,722	67,520	72,000	19,992	1,440	23	26,335

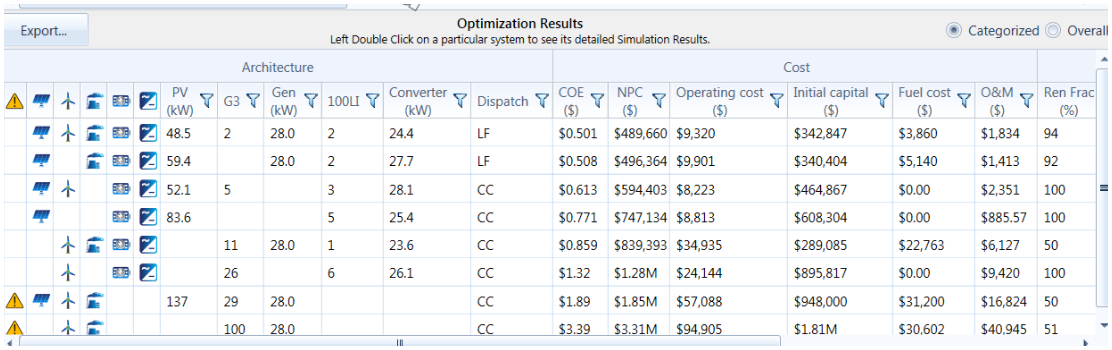
Optimization Results

The Optimization Results table lists all the feasible simulations for the sensitivity case (highlighted in blue in the previous Sensitivity Cases table). Non-feasible systems are not shown. The results are categorized and filtered by system type. HOMER shows the top-ranked system configurations according to net present cost.

The numbers under the Architecture section indicate the presence of each type of component under consideration. In the table, the icons indicate the presence of, from left to right: PV, Wind Turbines, Diesel Generator, Batteries, and the Converter. To the right are several columns that indicate summary values drawn from the simulation results of the least-cost system, such as the Initial Capital cost, Operating Cost, Total Net Present Cost (NPC), and Renewable Energy Fraction percentage (Ren Frac).

The overall optimization rankings are dominated by three system types. In the results table, the top systems are either PV/Wind/Generator/Storage or PV/Generator/Storage and PV/Wind/Storage systems.

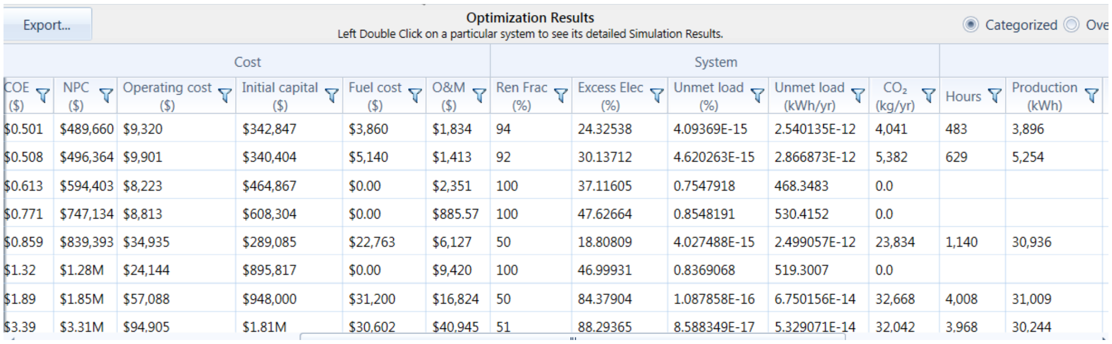
Optimization Results Tables:



Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

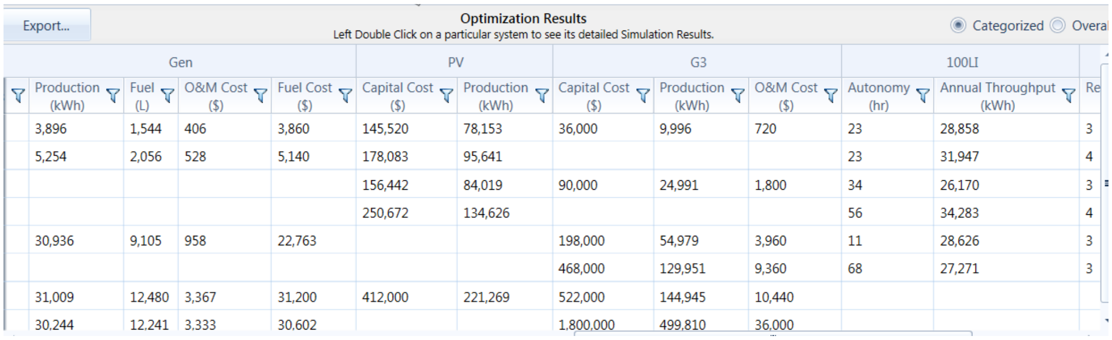
						Architecture						Cost						
⚠						PV (kW)	G3	Gen (kW)	100LI	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Fuel cost ($)	O&M ($)	Ren Frac (%)
	●	●	●	●	●	48.5	2	28.0	2	24.4	LF	$0.501	$489,660	$9,320	$342,847	$3,860	$1,834	94
	●		●	●	●	59.4		28.0	2	27.7	LF	$0.508	$496,364	$9,901	$340,404	$5,140	$1,413	92
	●	●		●	●	52.1	5		3	28.1	CC	$0.613	$594,403	$8,223	$464,867	$0.00	$2,351	100
	●			●	●	83.6			5	25.4	CC	$0.771	$747,134	$8,813	$608,304	$0.00	$885.57	100
		●	●	●	●		11	28.0	1	23.6	CC	$0.859	$839,393	$34,935	$289,085	$22,763	$6,127	50
		●		●	●		26		6	26.1	CC	$1.32	$1.28M	$24,144	$895,817	$0.00	$9,420	100
⚠	●	●	●			137	29	28.0			CC	$1.89	$1.85M	$57,088	$948,000	$31,200	$16,824	50
⚠		●	●				100	28.0			CC	$3.39	$3.31M	$94,905	$1.81M	$30,602	$40,945	51



Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Cost						System							
COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Fuel cost ($)	O&M ($)	Ren Frac (%)	Excess Elec (%)	Unmet load (%)	Unmet load (kWh/yr)	CO₂ (kg/yr)	Hours	Production (kWh)
$0.501	$489,660	$9,320	$342,847	$3,860	$1,834	94	24.32538	4.09369E-15	2.540135E-12	4,041	483	3,896
$0.508	$496,364	$9,901	$340,404	$5,140	$1,413	92	30.13712	4.620263E-15	2.866873E-12	5,382	629	5,254
$0.613	$594,403	$8,223	$464,867	$0.00	$2,351	100	37.11605	0.7547918	468.3483	0.0		
$0.771	$747,134	$8,813	$608,304	$0.00	$885.57	100	47.62664	0.8548191	530.4152	0.0		
$0.859	$839,393	$34,935	$289,085	$22,763	$6,127	50	18.80809	4.027488E-15	2.499057E-12	23,834	1,140	30,936
$1.32	$1.28M	$24,144	$895,817	$0.00	$9,420	100	46.99931	0.8369068	519.3007	0.0		
$1.89	$1.85M	$57,088	$948,000	$31,200	$16,824	50	84.37904	1.087858E-16	6.750156E-14	32,668	4,008	31,009
$3.39	$3.31M	$94,905	$1.81M	$30,602	$40,945	51	88.29365	8.588349E-17	5.329071E-14	32,042	3,968	30,244



Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Gen					PV		G3			100LI		
	Production (kWh)	Fuel (L)	O&M Cost ($)	Fuel Cost ($)	Capital Cost ($)	Production (kWh)	Capital Cost ($)	Production (kWh)	O&M Cost ($)	Autonomy (hr)	Annual Throughput (kWh)	Re
	3,896	1,544	406	3,860	145,520	78,153	36,000	9,996	720	23	28,858	3
	5,254	2,056	528	5,140	178,083	95,641				23	31,947	4
					156,442	84,019	90,000	24,991	1,800	34	26,170	3
					250,672	134,626				56	34,283	4
	30,936	9,105	958	22,763			198,000	54,979	3,960	11	28,626	3
							468,000	129,951	9,360	68	27,271	3
	31,009	12,480	3,367	31,200	412,000	221,269	522,000	144,945	10,440			
	30,244	12,241	3,333	30,602			1,800,000	499,810	36,000			

Optimizing for Maximum Renewable Penetration

The Optimization Plot shows each simulation as a single point on the following graph. All of the optimization variables are feasible solutions, so we see a dot for every simulation that was feasible for the sensitivity cases chosen: CO and CO2 Penalties, Solar Reserve, Capacity Shortage percentage, PV: Derating, and Diesel Fuel Price.

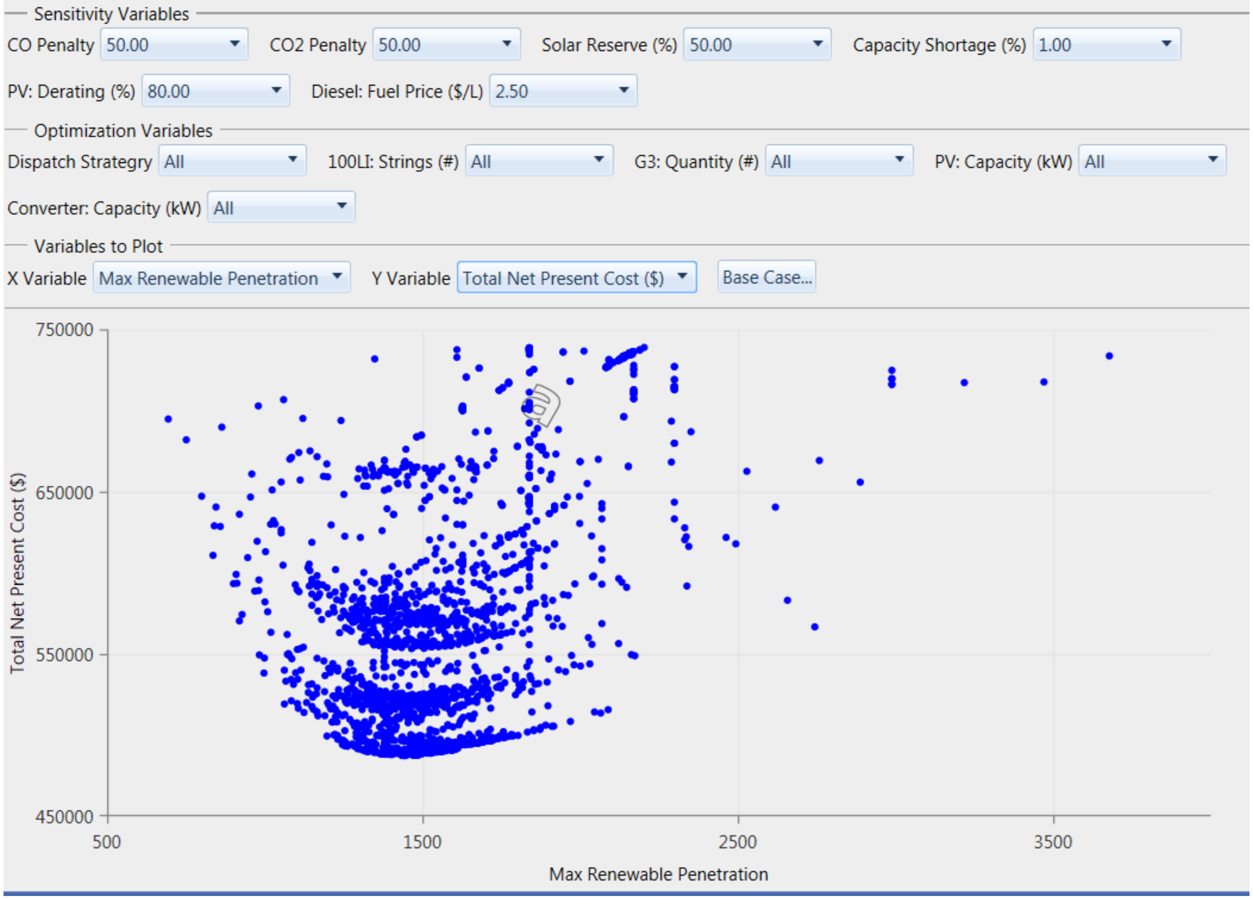
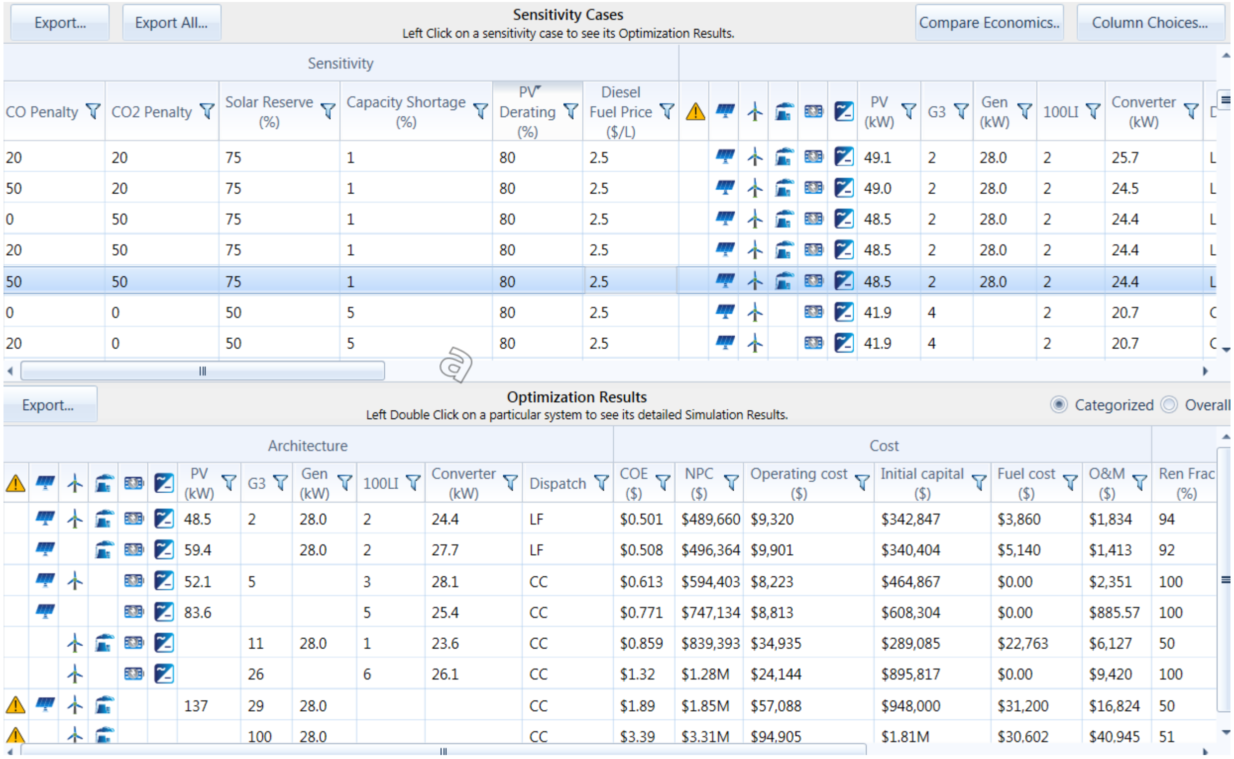

Sensitivity Variables
CO Penalty: 50.00
CO2 Penalty: 50.00
Solar Reserve (%): 50.00
Capacity Shortage (%): 1.00
PV: Derating (%): 80.00
Diesel: Fuel Price ($/L): 2.50
Optimization Variables
Dispatch Strategy: All
100LI: Strings (#): All
G3: Quantity (#): All
PV: Capacity (kW): All
Converter: Capacity (kW): All
Variables to Plot
X Variable: Max Renewable Penetration
Y Variable: Total Net Present Cost ($)

Figure 8.6: Total Net Present Cost vs Max Renewable Penetration

In the graph above, the x-axis represents Maximum Renewable Penetration, and the y-axis represents the Total Net Present cost. The winning system for this sensitivity case are the lowest dots on the plot, corresponding to the lowest net present cost (NPC).

However, while the simulation outputs the lowest net present cost, we must observe that the solution at minimum cost still would produce CO2 and CO emissions.

To find a system which has zero emissions from the set of Optimal Solutions, we perform a System Design Trade Off mainly involving in the Net Present Energy Cost, Emissions and percentage of Renewables in the System.



Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

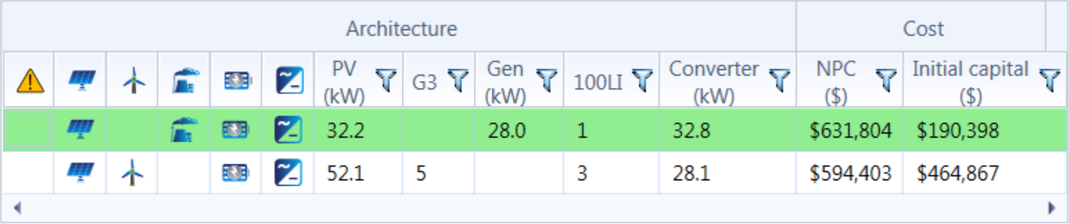
Sensitivity																		
CO Penalty	CO2 Penalty	Solar Reserve (%)	Capacity Shortage (%)	PV Derating (%)	Diesel Fuel Price ($/L)	⚠						PV (kW)	G3	Gen (kW)	100LI	Converter (kW)	D
20	20	75	1	80	2.5		✓	✓	✓	✓	✓	49.1	2	28.0	2	25.7	L
50	20	75	1	80	2.5		✓	✓	✓	✓	✓	49.0	2	28.0	2	24.5	L
0	50	75	1	80	2.5		✓	✓	✓	✓	✓	48.5	2	28.0	2	24.4	L
20	50	75	1	80	2.5		✓	✓	✓	✓	✓	48.5	2	28.0	2	24.4	L
50	50	75	1	80	2.5		✓	✓	✓	✓	✓	48.5	2	28.0	2	24.4	L
0	0	50	5	80	2.5		✓	✓		✓	✓	41.9	4		2	20.7	C
20	0	50	5	80	2.5		✓	✓		✓	✓	41.9	4		2	20.7	C

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

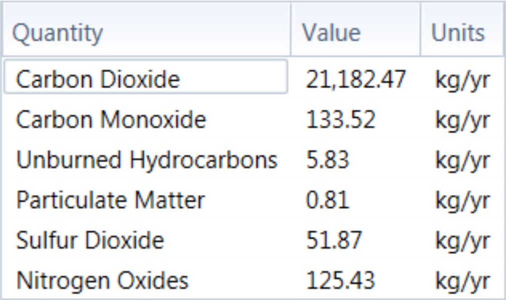
Architecture												Cost						
⚠						PV (kW)	G3	Gen (kW)	100LI	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Fuel cost ($)	O&M ($)	Ren Frac (%)
	✓	✓	✓	✓	✓	48.5	2	28.0	2	24.4	LF	$0.501	$489,660	$9,320	$342,847	$3,860	$1,834	94
	✓		✓	✓	✓	59.4		28.0	2	27.7	LF	$0.508	$496,364	$9,901	$340,404	$5,140	$1,413	92
	✓	✓		✓	✓	52.1	5		3	28.1	CC	$0.613	$594,403	$8,223	$464,867	$0.00	$2,351	100
	✓			✓	✓	83.6			5	25.4	CC	$0.771	$747,134	$8,813	$608,304	$0.00	$885.57	100
		✓	✓	✓	✓		11	28.0	1	23.6	CC	$0.859	$839,393	$34,935	$289,085	$22,763	$6,127	50
		✓		✓	✓		26		6	26.1	CC	$1.32	$1.28M	$24,144	$895,817	$0.00	$9,420	100
⚠	✓	✓	✓			137	29	28.0			CC	$1.89	$1.85M	$57,088	$948,000	$31,200	$16,824	50
⚠		✓	✓				100	28.0			CC	$3.39	$3.31M	$94,905	$1.81M	$30,602	$40,945	51

This system found with zero emissions has a Net Present Cost of $594,403. From the simulation results, this system has the lowest cost at 100% Renewable Fraction in the system, which results in the lowest Net Present cost when there incur Emissions penalties.

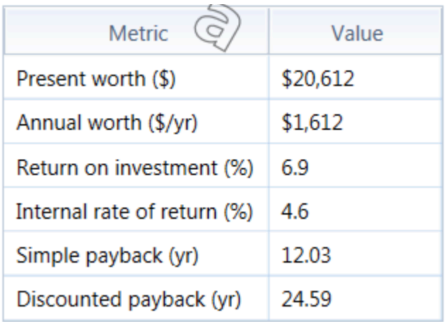
8.4 Economics Comparison with traditional Base System



	Architecture											Cost	
	⚠						PV (kW)	G3	Gen (kW)	100LI	Converter (kW)	NPC ($)	Initial capital ($)
Base system		✓		✓	✓	✓	32.2		28.0	1	32.8	$631,804	$190,398
Current system		✓	✓		✓	✓	52.1	5		3	28.1	$594,403	$464,867



Quantity	Value	Units
Carbon Dioxide	21,182.47	kg/yr
Carbon Monoxide	133.52	kg/yr
Unburned Hydrocarbons	5.83	kg/yr
Particulate Matter	0.81	kg/yr
Sulfur Dioxide	51.87	kg/yr
Nitrogen Oxides	125.43	kg/yr



Metric	Value
Present worth ($)	$20,612
Annual worth ($/yr)	$1,612
Return on investment (%)	6.9
Internal rate of return (%)	4.6
Simple payback (yr)	12.03
Discounted payback (yr)	24.59

On the Tables above it is shown that our System has Zero Emissions and while the more traditional system has cheaper Initial Capital cost, it has much more emissions and is, due to the Emissions penalties, more expensive in the long run.

8.5 Final System Design Recommendation Details

The Final System Design Recommendation details are shown on the report tables below and they are based on the ability to have maximum 100% renewables; that is, our system does not produce CO and CO2 Emissions.

Summary of System Report Components:

- The System Architecture: The amount of PV panels, Wind Turbines, Battery Strings, Converter capacity, and recommended Dispatch Strategy.
- The Cost Summary: it displays the total cash flow, categorized either by component or by cost type. It displays the Total Net Present Cost, and the Levelized Cost of Energy.
- Net Present Cost: It shows the expected cost of the System over 25 Years. It shows the cost involved in each architecture components such as: Initial Costs, Maintenance, Salvage costs, and Total Costs.
- Annualized Cost: it shows the year-by-yea costs for each component as well as the system cash flows.
- The Electrical section: it shows details about the production and consumption of electricity by the system and the individual system components production per year.

Individual System Architecture Components Details:

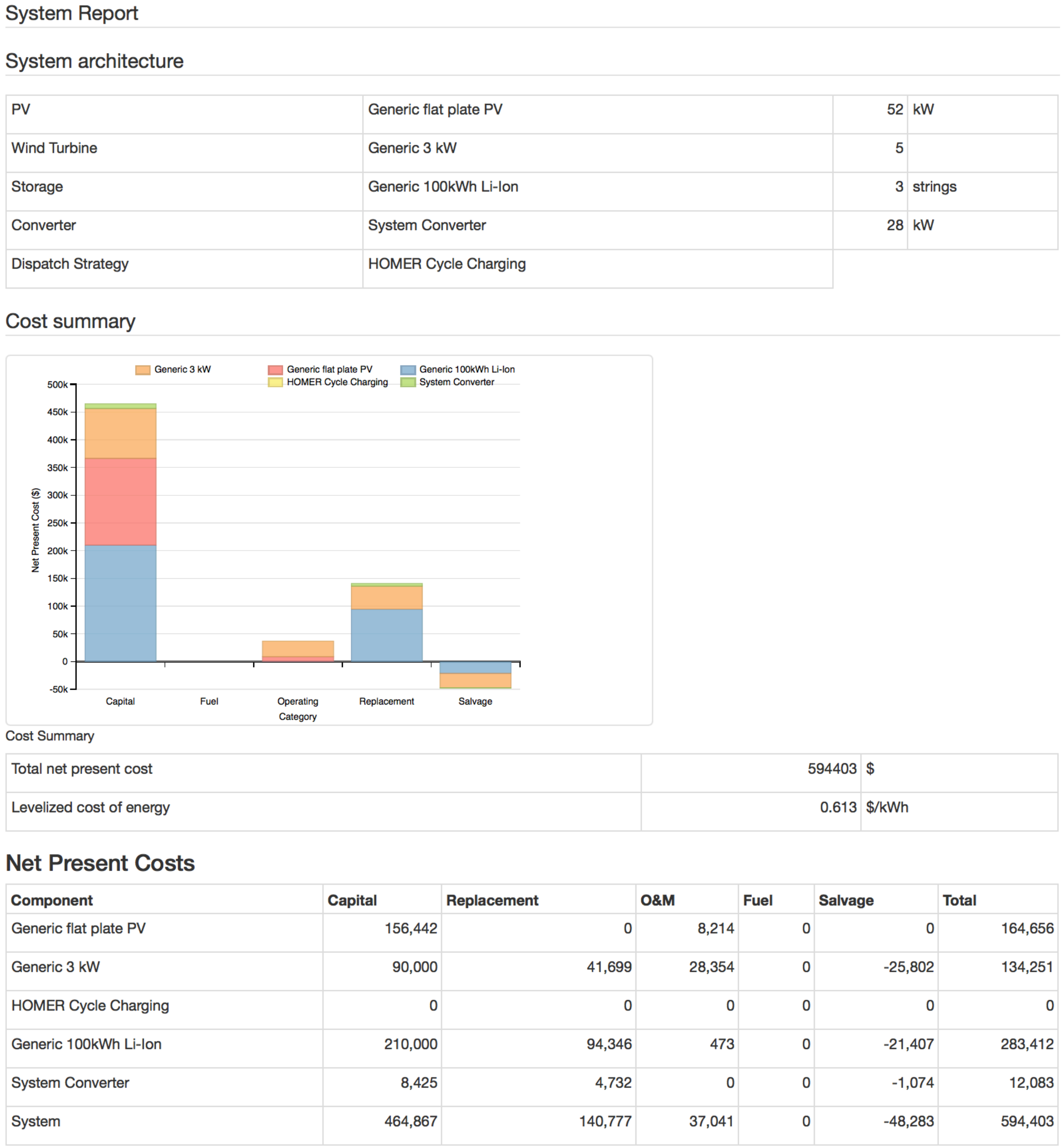
- PV Generation Details:
  - Rated Capacity: The rated capacity of the PV array under standard conditions, in kW

    - Mean Output: The average power amount of the PV array over the year, in kW and kWh/day
    - Capacity Factor: The average power output of the PV array (in kW) divided by its rated power, in %
    - Total Production: The total power output of the PV array over the year, in kWh/yr
    - Minimum Output: The minimum power output of the PV array over the year, in kW
    - Maximum Output: The maximum power output of the PV array over the year, in kW
    - PV Penetration: The average power output of the PV array divided by the average primary load, in %
    - Hours of Operation: The number of hours of the year during which the PV array output was greater than zero
    - Levelized Cost: The levelized cost of energy of the PV array, in $/kWh
- Wind Turbine Generation Details:
    - Total Rated Capacity: The highest possible power amount from the wind turbine(s), in kW
    - Mean Output: The average power amount of the wind turbine over the year, in kW
    - Capacity Factor: The average power output of the wind turbine(s) divided by the total wind turbine capacity, in %

    - Total Production: The total power output of the wind turbine(s) over the year, in kWh/yr
    - Minimum Output: The minimum power output of the wind turbine over the year, in kW
    - Maximum Output: The maximum power output of the wind turbine over the year, in kW
    - Wind Penetration: The average power output of the wind turbine(s) divided by the average primary load, in %
    - Hours of Operation: The number of hours of the year during which the wind turbine output was greater than zero
    - Levelized Cost: The levelized cost of energy of the wind turbine(s), in $/kWh
- Battery Generation Details:
    - Batteries: The number of batteries in the array is the string size multiplied by the number of strings
    - String Size: The number of batteries connected in series in each string
    - Strings in Parallel: The number of storage strings connected in parallel
    - Bus Voltage: The voltage of the storage array, calculated by multiplying storage voltage by string size, in volts
    - Autonomy: The capacity of the storage bank divided by the average electrical load, in hours

- Storage Wear Cost: The cost of cycling energy through the storage bank, in $/kWh
- Nominal Capacity: The amount of energy that could be withdrawn from the storage at a particular constant current, starting from a fully charged state, in kWh
- Usable Nominal Capacity: The storage capacity adjusted to exclude all capacity below the minimum state of charge of the storage, in kWh
- Lifetime Throughput: The total amount of energy that can be cycled through the storage before it needs to be replaced, in kWh
- Expected Life: The number of years the storage bank will last before it requires replacement
- Average Energy Cost: The average cost of the energy that goes into the storage, in $/kWh
- Energy In: The total amount of energy charged to the storage, in kWh
- Energy Out: The total amount of energy discharged from the storage, in kWh
- Storage Depletion: The difference in the storage state of charge at the beginning and end of the year, in kWh/yr
- Losses: Annual energy losses due to storage inefficiency, in kWh/yr
- Annual Throughput: The total amount of energy that cycled through the storage bank during the year, in kWh/yr

- Converter Details: displays the following variables for both the inverter, which converts DC to AC electricity, and the rectifier, which converts AC to DC electricity.
    - Capacity: The maximum possible power output, in AC kW for the inverter and DC kW for the rectifier
    - Mean, Min and Max Output: The inverter values are in AC kW, and the rectifier values are in DC kW
    - Capacity Factor: The mean output divided by the capacity, in %
    - Hours of Operation: The number of hours of non-zero power output
    - Energy In: The total amount of energy into the device, in DC kWh/yr for the inverter and AC kWh/yr for the rectifier
    - Energy Out: The total amount of energy out of the device, in AC kWh for the inverter and DC kWh for the rectifier
    - Losses: The total energy lost in the device, in kWh/yr
- Finally, the Emissions section shows the total amount of each pollutant produced annually by the power system in kg/yr. Pollutants would originate from the consumption of fuel and biomass in generators. Pollutants consist of carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide, and nitrogen oxides.



System Report

System architecture

PV	Generic flat plate PV	52	kW
Wind Turbine	Generic 3 kW	5	
Storage	Generic 100kWh Li-Ion	3	strings
Converter	System Converter	28	kW
Dispatch Strategy	HOMER Cycle Charging		

Cost summary

Cost Summary

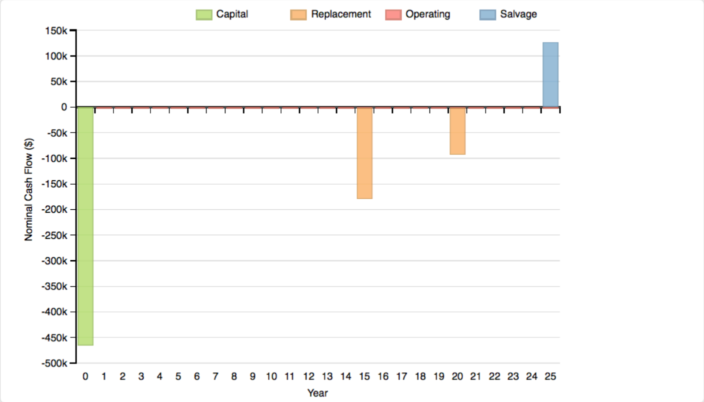
Total net present cost	594403	$
Levelized cost of energy	0.613	$/kWh

Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic flat plate PV	156,442	0	8,214	0	0	164,656
Generic 3 kW	90,000	41,699	28,354	0	-25,802	134,251
HOMER Cycle Charging	0	0	0	0	0	0
Generic 100kWh Li-Ion	210,000	94,346	473	0	-21,407	283,412
System Converter	8,425	4,732	0	0	-1,074	12,083
System	464,867	140,777	37,041	0	-48,283	594,403

Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic flat plate PV	9,931	0	521	0	0	10,453
Generic 3 kW	5,713	2,647	1,800	0	-1,638	8,523
HOMER Cycle Charging	0	0	0	0	0	0
Generic 100kWh Li-Ion	13,331	5,989	30	0	-1,359	17,992
System Converter	535	300	0	0	-68	767
System	29,511	8,937	2,351	0	-3,065	37,734

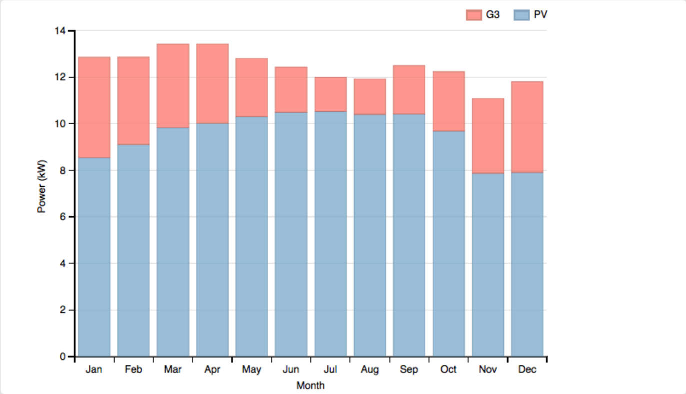


Electrical

Quantity	Value	Units
Excess electricity	40460	kWh/yr
Unmet load	468	kWh/yr
Capacity shortage	680	kWh/yr
Renewable percent	100	%

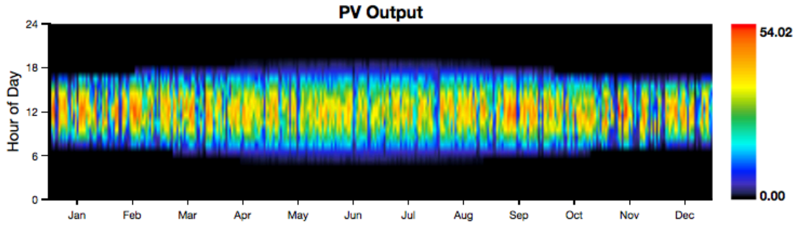
Component	Production(kWh/yr)	Percent (%)
PV	84,019	77
Wind Turbine	24,991	23
Total	109,009	100

Load	Consumption(kWh/yr)	Percent (%)
AC primary load	61,582	100
DC primary load	0	0
Total	61,582	100



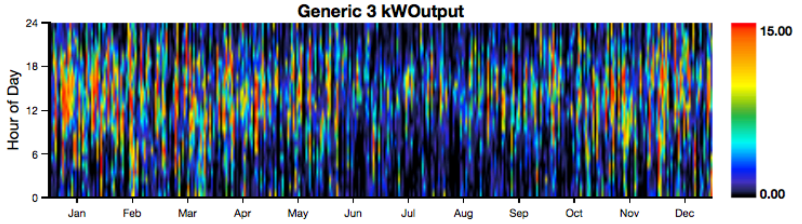
PV:Generic flat plate PV

Quantity	Value	Units
Rated capacity	52	kW
Mean output	10	kW
Mean output	230.19	kWh/d
Capacity factor	18.39	%
Total production	84019	kWh/yr
Minimum output	0.00	kW
Maximum output	54.02	kW
PV penetration	135.40	%
Hours of operation	4386	hrs/yr
Levelized cost	0.124	$/kWh



Wind Turbine:Generic 3 kW

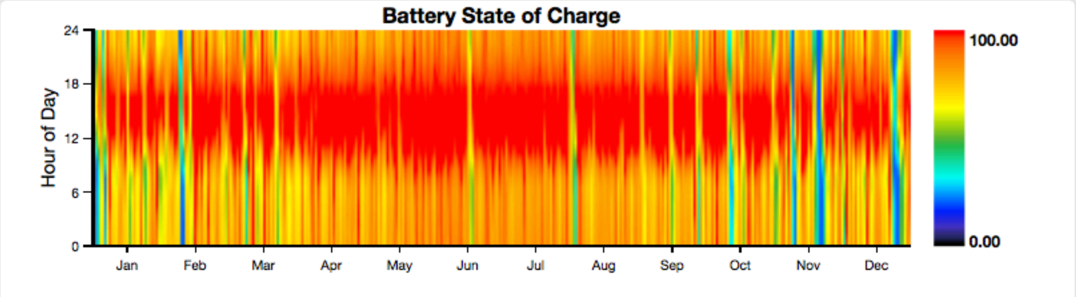
Quantity	Value	Units
Total rated capacity	15	kW
Mean output	3	kW
Capacity factor	19.02	%
Total production	24991	kWh/yr
Minimum output	0.00	kW
Maximum output	15.00	kW
Wind penetration	40.27	%
Hours of operation	7119	hrs/yr
Levelized cost	0.341	$/kWh



Battery:Generic 100kWh Li-Ion

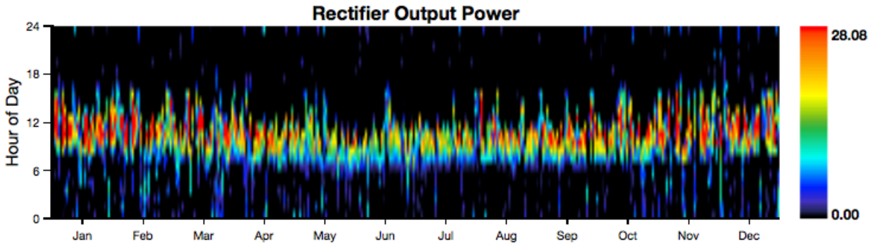
Quantity	Value
String size	1
Strings in parallel	3
Batteries	3
Bus voltage	600

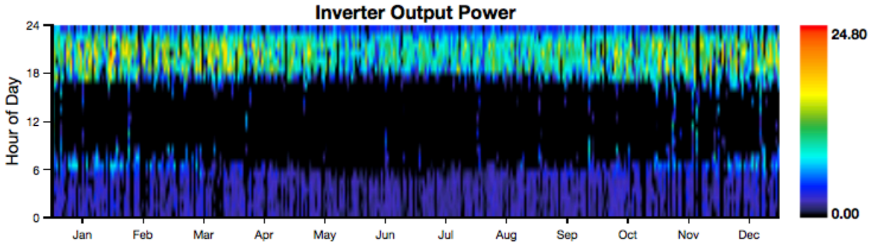
Quantity	Value	Units
Nominal capacity	300	kWh
Usable nominal capacity	240	kWh
Autonomy	34	hr
Battery wear cost	0.197	$/kWh
Average energy cost	0.000	$/kWh
Energy in	27498	kWh/yr
Energy out	24827	kWh/yr
Storage depletion	83	kWh/yr
Losses	2754	kWh/yr
Annual throughput	26170	kWh/yr



Converter

Quantity	Inverter	Rectifier	Units
Capacity	28	27	kW
Mean output	3	3	kW
Minimum output	0	0	kW
Maximum output	25	28	kW
Capacity factor	10	11	%
Hours of operation	4,524	2,572	hrs/yr
Energy in	24,827	30,554	kWh/yr
Energy out	23,586	27,498	kWh/yr
Losses	1,241	3,055	kWh/yr





Emissions

Pollutant	Emissions	Units
Carbon dioxide	0	kg/yr
Carbon monoxide	0	kg/yr
Unburned hydrocarbons	0	kg/yr
Particulate matter	0	kg/yr
Sulfur dioxide	0	kg/yr
Nitrogen oxides	0	kg/yr

Chapter 9

Conclusions and Future Work

As Renewable Energy Generation technology advances, it is important that Power Systems Engineers investigate carefully the Smart Grid and especially the Islanded mode Microgrid. The renewable generations technologies are and will become both cheaper and beneficial for our environment. Attempts to design Microgrid System Solutions that allow for zero Emissions are becoming more important as pollutants from traditional plants will effectively contribute to the contamination of the environment.

The design of a Microgrid involves several aspects of consideration. The design of a microgrid with the NIST Smart Grid standards and with a Systems Engineering approach requires not only the understanding of its technical applications required but also of the economical and environmental considerations of the system in both its immediate life cycle and deployment.

Throughout this study our purpose was to present an analysis from both the modeling of the basic system components and architectures such as Energy Loads, Wind and Solar Data Photovoltaics, Wind Turbines, Batteries and their interactions and effects on the system. Our analysis of the Islanded Mode Microgrid System discovered solutions that involve minimum pollutant emissions as well as systems with zero emissions considerations. And additionally we learned that more traditional pollutant systems can be more expensive in the long run.

There are many ways we may consider to advance this study. In the optimization search space and sensitivity analysis the set of variables considered can be expanded, while it might take more time to perform simulations the results maybe more precise. We can analyze the individual system components by using actual commercially available products. Additionally, it can be further advanced by both linking the HOMER Simulation tools with software such as Magic Draw, and Matlab which should aid the Systems Engineers interested on both a direct link to their systems analysis as well as being able to tinker with smaller electronics subsystems present in the renewable technologies of the microgrid.

Appendices

A.1 Modeling and Simulation with HOMER

The HOMER Micropower Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide range of applications. HOMER models a power system's physical behavior and its life-cycle cost, which is the total cost of installing and operating the system over its life span. HOMER allows the modeler to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs. [24]

HOMER allows the analysis of three principal tasks: simulation, optimization, and sensitivity analysis. In the simulation process, HOMER models the performance of a particular micropower system configuration each hour of the year to determine its technical feasibility and life-cycle cost [24].

With HOMER we are able to simulate a wide variety of micropower system configurations, such as combinations of a PV array, one or more Wind turbines, Diesel Generators, and a Battery bank, as well as an ac–dc converter. The system can be grid-connected or autonomous and can serve ac and dc electric loads and a thermal load.

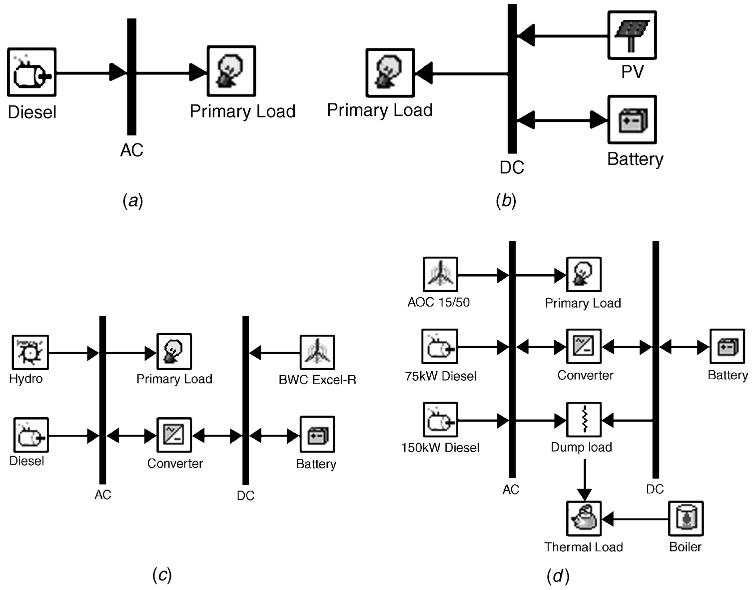


Figure Examples of Schematic diagrams of some micropower system types that HOMER models: (a) a diesel system serving an ac electric load; (b) a PV–battery system serving a dc electric load; (c) a hybrid hydro–wind–diesel system with battery backup and an ac–dc converter; (d) a wind–diesel system serving electric and thermal loads with two generators, a battery bank, a boiler, and a dump load that helps supply the thermal load by passing excess wind turbine power through a resistive heater;

A.2 Planning and Engineering of the Microgrid

Microgrid Distributed Resources (DR) Island systems (Based on (5) IEEE 1547.4)

A.2.1 Planning and Engineering of the Microgrid (DR) Island systems (Based on (5) IEEE 1547.4)

In order to study the development of the islanded Microgrid system, we consider the following:

A.2.1 Energy Loads, Requirements and Management for the Islanded Microgrid

Load considerations

– Load characteristics and requirements for proper operation

– Distributed Generation (DG) sources energy characteristics for Solar, Wind, and Storage

– DG island system, black start, abnormal voltage, and frequency ride-through capabilities

Control System Scheme for energy monitoring information and exchange

Reactive power considerations

– Acceptable voltage, frequency, and harmonic range (normal and transient)

– The maximum acceptable rate of change of frequency for supplied power

– The acceptable imbalance of voltage at a specific point in the system

– The acceptable dynamic stability limits

– A means to confirm the intended DR island system is still substantially the same as the previously studied planned DR island system

This information should prove sufficient for developing a system to understand how much power production capacity is needed to meet the system user’s energy load requirements. In general, if there is not sufficient DGs in the planned island to cover the full loads, then a load-shedding scheme needs to be developed. For this we must determine critical and non-critical loads. In our System, to avoid load shedding, the Storage DG source should aid as emergency energy source to support critical loads [18].

DR island systems operating outside normal utility parameters may cause equipment performance problems because of equipment operating ranges, safety concerns, or customer needs; however, DR island systems may operate outside normal utility parameters if acceptable to all interested parties.

Area EPS operators have an obligation to serve load, and DR availability and reliability needs to be taken into consideration if the DR is not under area EPS control. Planning considerations should be made to serve the load on an area EPS circuit without relying on the DR island system.

A.2.2 Energy Loads, Requirements and Management for the Islanded Microgrid

We now discuss the characteristics of loads as they pertain to the Islanded Microgrid system. Issues with loads related to how they should be operated in island mode are discussed. (Other documents that can provide guidance on loads are: IEEE

Std 446™ *(IEEE Orange Book™),* IEEE Std 1100™ *(IEEE Emerald Book™),* and ANSI/NEMA MG 1-2006) [18].

The Microgrid Islanded system needs to meet the users energy demands. Likewise, we must consider dealing with the loads from the DGs in the islanded system. The load control scheme should manage all participating DG (Wind/Solar/Stored) loads. The system functionality should include an critical load energy source via the use of the energy storage source when the common DG (Wind/Solar) cannot serve all connected loads. The Microgrid needs to be able to maintain acceptable voltage and frequency throughout the system during all expected load and DR changes [18].

Loads may have a variety of issues, including active and reactive demand profiles, step loads, voltage imbalance, current imbalance, and power factor. On a Microgrid islanded system, the loads may cause more issues than on Grid Connected Microgrid Schemes because these have a stronger source (i.e., higher fault levels), are larger, and aggregate more loads, which can have a balancing effect [18].

A.2.3 Load and User Demand considerations (IEEE 1547.4)

Load analysis should be completed for DR island systems that includes three-phase detail, historical demand profiles, customer composition, large spot loads such as motors, and a realistic profile of the instantaneous loads (both real and reactive) [18].

When planning a DR island system, load imbalance within the island should be given careful attention. One issue with loads in a DR island system is that the loads may be extremely imbalanced. The individual phase currents of the loads may have considerable imbalance even though the phase-to-neutral voltages or phase to phase voltages may be reasonably balanced. Therefore, the load configuration needs to be studied and may need to be modified to facilitate an island configuration [18].

Single-phase loads may vary significantly during different times of the day or week, or season. Operation of a single-phase protective device (e.g., fuse) may cause a significant amount of load to be lost and substantially increase system imbalance. Large voltage imbalance (>3%) can cause problems to three-phase inverter-based DR by placing high ripple currents on the dc bus. These ripple currents may have an adverse affect on the inverter and energy source (e.g., battery and fuel cell). Most rotating equipment, specifically generators, is designed to operate with no more than as specified current imbalance (ANSI/NEMA MG 1- 2006) [18].

Imbalances in the distribution system or load imbalance can cause negative sequence currents that might damage equipment. Three-phase DR and motors have limited negative sequence capability and may be damaged by imbalanced load conditions. Use of a negative sequence current relay can mitigate damage to three-phase rotating machinery. DR island system customers may need to make modifications to protect their equipment for an intentional island [18].

Cold load pickup is the sudden surge in load on a distribution feeder after service restoration in which some loss of diversity among thermostatic controlled loads and motor starts has occurred. The DR island system needs to have sufficient capacity to pick up the load or have other means to manage the load such as sectionalizing the load into segments and soft-start motors, which will allow the system to start in staged steps. If multiple islands exist, a strategy may be adopted to intentionally stagger the return of the islands [18].

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