Spring 5-31-2016

Simulation of a low voltage customer microgrid using petri nets

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ABSTRACT

SIMULATION OF A LOW VOLTAGE CUSTOMER MICROGRID USING PETRI NETS

by
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With renewable energy coming to the forefront of how power is generated and delivered to the modern consumer, Microgrids are emerging as an optimal and efficient method for implementing renewables and changing the infrastructure of the dated transmission and distribution grid. This thesis work presents mathematical models of Petri Nets for the simulation of a low voltage customer Microgrid. Using previous work created in this specific field, a Hybrid Petri Net is modified such that it consists of multiple distributed generators, storage, and the utility which is referred to as the main distribution grid in this thesis. A Discrete Petri Net is developed for load shedding which is critical for simulation purposes. Two types of Scheduling are developed, heuristic and reliability ones for the Microgrid to operate. Equations for firing rates are obtained for continuous transitions. Input weather data is obtained from outside sources and modified for the simulation. Computer programs are created for the microgrid simulation and the creation and presentation of the reachability graphs. A total of twelve simulations are run with the data analyzed and reachability graphs for the hybrid and discrete load shedding Petri nets developed for two simulations.

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A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Electrical Engineering

Department of Electrical and Computer Engineering

May 2016

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SIMULATION OF A LOW VOLTAGE CUSTOMER MICROGRID USING PETRI NETS

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Dedicated to all my friends and family, especially to my sisters Anita and Sarah, and my parents Samuel and Mercy Mark who urged me to follow a career in graduate work and are the reason I am the person I am today. I am truly blessed for all of you being a part of my life. Thank You.

ACKNOWLEDGMENT

I cannot thank my advisor enough, Dr. Mengchu Zhou, for whom I would not be completing a Master's thesis or degree. Dr. Zhou's guidance, patience, profound knowledge, and excellence in teaching was invaluable throughout this whole process.

To Dr. Edwin Hou and Dr. Haiwang Cao who gave their time and expertise in making this possible. To Xiaoyu Lu without whom this thesis would not be complete. He always answered my questions, guided me through this process, and laid the groundwork for this thesis.

Special Thanks to Dr. Wenda Cao from the NJIT Center for Solar Terrestrial Research. Dr. Serhiy Levkov for being an excellent professor, and never refusing to help me during this thesis. Professor Mohammed Feknous for always having an open ear to talk to and imparting knowledge to me during this journey. To Dr. Zhenhua Yu, Jingchu Ji, and Liang Qi. To Dr. David A Robinson and Mathieu Gerbush from the Office of the New Jersey State Climatologist.

To my peers and colleagues who always had the time to aid me during this thesis work, whose support and encouragement helped me throughout this process: Azmail Hadir, Gaurav Patel, Gabriel Esposito, Anthony Costello, and Daniel Lwaysi. And last but not least, to Kenneth Ford whose thorough knowledge with computer science, patience, innate ability to grasp new information, and kindness in helping others including myself made this thesis possible and cannot be appreciated enough.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter   **Page**

LIST OF SYMBOLS

●	Token
◯	Discrete Place
◎	Continuous Place
▬	Discrete Transition
▭	Continuous Transition

LIST OF DEFINITIONS

MG	Microgrid
DG	Distributed Generator
DS	Distributed Storage
DER	Distributed Energy Resource
IER	Intelligent Electronic Device
PCC	Point of Common Coupling
DC	Direct Current
AC	Alternating Current
kW	Kilowatts ($1x10^3$) Watts
PV	Photovoltaic
SMES	Super Magnetic Energy Storage
PN	Petri Net, usually a discrete Petri Net
HPN	Hybrid Petri Net
FCPN	Finite Capacity Petri Net

CHAPTER 1

INTRODUCTION

With the rise of global climate change due to the possibility of rising carbon emissions with a combination of increasing global load demand, renewables have come to the forefront of a possible change in energy generation for the electrical grid. With nations passing stricter regulations for fossil fuel emissions, renewable energy generation and storage have come to the public consciousness in reducing pollution levels.

There come dilemmas with integrating renewables into the transmission and distribution grid, including low efficiency and consistency of renewable generators and storage devices. Wind farms require a considerable amount of land, potentially causing harm to many bird and bat species susceptible to being killed by their spinning rotors, and have caused complaints from the members of communities living near wind farms, e.g., the sound level they generate and visual impact they produce. Solar farms require a great deal of land potentially contributing to land degradation and habitat loss. Locations for potential wind and solar sites are located far from load centers where most of the power demand is required. The region with the highest potential for solar power is located in the southwest U.S., and the Midwest states ranging from North Dakota to the panhandle of Texas for wind power located far from the most demanding U.S. load centers [20]. These investments require considerable monetary investment for providing infrastructure to enable this potential power to be delivered. Batteries and other storage devices require considerable size and energy density to store renewable power. They are expensive, requiring large amounts of land and need to be replaced after a certain number of cycles of

charging and discharging, and pose a serious hazard risk to the communities living next to them. Cloud cover and days with little sunlight decrease power solar output while wind power is susceptible to the predictability and consistency of wind itself causing problems for utility operators due to sudden changes from renewable power generation for the utility grid. This occurred in Texas, Tuesday February 26, 2008, during afternoon hours when peak load demand increased from 31,200 MW to a peak of 35,612 MW. Texas which has a substantial wind power capacity, experienced a decrease in wind power being produced in West Texas from 1,700 MW to 300 MW, requiring utility operators to enable a stage 2 emergency plan causing brownouts and blackouts resulting in 1,100 MW of power being shed in a 10 minute span. This is a prime example of the susceptibility of renewable power due to lack of consistency and reliability [22]. Using fossil fuel spinning reserves as a backup in case of the shortfalls form the consistency of renewable power poses the question "what is the point of using renewables if fossil fuels (which are more reliable due to changes in load demand) are used to backup renewables?"

Although optimization techniques exist for calculating the probability wind and PV generation due to weather. The transmission and distribution grid is susceptible to natural factors outside of human control. The constant switching of renewable power for the grid stresses components and has the potential to cause major dilemmas for grid operators. Localization of renewable power and energy storage directly to the load can mitigate many of these problems when treating renewable power generation as base and peak load generators for the main utility grid.

Microgrids (MG) pose a solution allowing a more direct and compact infrastructure, and control systems that can be utilized in a more optimal fashion. They are

poised as an evolutionary step in the development of power and energy systems. They facilitate integrating renewables with both power generation and distribution. Research, development, and utilization are currently being developed to implement MG's in changing the current model of the power grid. The first remnants of the Microgrid started in the 1980's, and this concept is seen as a potential change for the future of the power grid. The definition of a MG is varied and complex composed of multiple physical. They are built in different network configurations, and vary in size. Since MG's are currently being developed and progressing, many problems are posed that need to be addressed and resolved.

1.1 Definition of a Microgrid

The first microgrid concepts and experimentation started in the 1980's. Though there is no exact definition of a microgrid, it is seen as a "subsystem" within a larger system, or a smaller grid part of a larger grid that can generate and store its own power for the load it is meant to provide for with the ability to disconnect from the main utility grid. There is no set standard for the size of a microgrid; it can vary from a commercial building or residential home producing its own energy to a section of the larger utility owned by the utility service provider. A microgrid (MG) is dependent on the load, and varies by the load size of a residential house, residential building, commercial building, town or city (e.g., Hoboken, NJ), and whole communities e.g. Kodiak Island. Its size depends on the power that it has to produce for the required load. It can work in conjunction with the larger distribution grid or in an "island" mode in which it is completely disconnected the latter. A distributed generation network that cannot operate in an island mode is not considered an MG. The combination of Distributed Generation (DG) and Distributed Storage (DS) are called Distributed Energy Resources (DER) can be a mixture of renewables (photovoltaics, and wind), fossil fuel generators (diesel and natural gas generators), and storage devices (batteries and flywheels). Today's microgrids are primarily created by using distributed generation of renewables and energy storage in providing power and storage for its associated network, and in providing backup power for the network when the larger utility grid is offline.

There are three primary functions of a microgrid [33]:

- Power production – which meets the consumers demands

- Energy management – done both to the supply and demand sides taking into account power balance, voltage quality, flexibility, and electrical safety

- Plug and play functionality – safely and smoothly implementing new technologies which can be integrated into the grid and the system can enter an island mode

The ownership of a microgrid is based on the ownership of the microsources (DER) and resolved into four categories [33]:

- Distribution System Operator (DSO)

- End consumer

- Independent Power Producer

- Energy Supplier

In terms of the economic models, there are three cases:

1) DSO monopoly grid- in which the DSO owns the distribution and retail of the energy, and is solely responsible for the grid

2) Prosumer monsortium microgrid – multiple consumers have ownership of the Distributed Energy Resources potentially reducing electricity costs and having the potential for sales revenue; and

3) Free market microgrid – owned by various stakeholders. This system needs a Microgrid Central Controller (MGCC) for retail and distribution in which benefits are split among stakeholders

1.1.1 Configurations and Size

There are three configurations of microgrids. Radial in which power consumers and generators are connected in parallel to one main line where electrical current goes in one direction and protection is implemented at the substation making it a technically easier system to implement. The ring grid is more complicated and much more common among residential areas where power flow goes both ways. The mesh grid is the most complicated because of its alternative connection between nodes making grid operation and protection more difficult.

The size and capacity of a microgrid can vary depending on the load and power requirements of the consumer.

The four categories of microgrids in terms of size are [33]:

- Separated island microgid- a village, city, or island outside of the utility grid

- Low voltage customer microgrid – a single household containing a DER

- Low voltage microgrid – low voltage network containing multiple consumers and Distributed energy Resource

- Medium voltage feeder microgrid – a grid that uses a substation to connect a high voltage (transmission grid) to a medium voltage grid.

An MG can be setup to supply a single household with solar panels on the roof, or a windmill site to supply power to a whole community. Medium voltage MG's are the largest providing hundreds of megawatts, whereas the limit of Low voltage MG's require a few MW. Microgrids, such as Medium voltage MG's can diversify their DG's to multiple sources such as wind farms, KW fuel cells, KW reciprocating engines, etc. Energy storage is critical in providing power in an island mode during a fault in the main utility grid, and in reducing consumption from the utility grid when connected to it.

1.2 Components

The components of an MG are categorized into four parts. The loads of the grid are the devices in the system, which consume the power generated by the MG such as: water heaters, air conditioners, and refrigerators. The purpose of the MG in regards to the load is to: meet net import/export power in grid-connected mode, stabilize voltage and frequency in an island mode primarily by load/generation shedding, improve the power reliability and quality, and reduce peak load [33]. Distributed Energy Resource (DER) – composed of Distributed Generation (DG) and Distributed Storage (DS) units that provide and store power and energy for the load. They can be composed of both renewables and traditional fossil fuel generators.

Distributed Energy Resources (DER) are spilt into two categories [33]:

- Distributed Generation – power generation through photovoltaics, fuel cells, wind turbines, and even micro hydro-power. Other examples of DG's are: diesel generators, and natural gas generators. More than one type of DG's are recommended for the MG to distribute power to the load dependent on varying conditions, and are considered the primary component of the MG. Photovoltaics provide power when there is solar energy to generate electricity, and wind can provide power on a windy day when there is not enough solar energy to generate sufficient power for the load. Natural Gas or Diesel generators can supplement power for the load if solar, wind, and the battery storage do not provide enough.

- Distributed Storage – help manage load demands through batteries, flywheels, capacitors, magnetic super capacitors, hydrogen storage, compressed air, pumped hydroelectric storage, and even electric vehicles. DS's are integral for providing power to the grid due to varying load demand, and store excessive power produced.
  The size of DG's and DS's varies depending on the size and load requirement of the an

MG: from a few solar panels and a micro wind turbine on a rooftop for a single household, to a megawatts PV array and a wind farm on an island isolated from the utility.

The other components of a microgrid are:

- The physical network – to help distribute power from DG units, DS units, and even the utility grid to the loads by use of low voltage underground or overhead cables and

wires. The low voltage lines are connected by an interconnection switch to a central distribution substation called the point of common coupling (PCC) in which synchronization with the medium voltage utility grid occurs. The physical network uses intelligent electronic devices (IED) such as: circuit breakers, digital protective relays, remotely operated switches, current and voltage sensors, and condition monitoring units to help control and protect the network. Advanced power electronics are used for inversion/conversion of DG's and helps with the coordination of control and communication within the grid. Advanced microprocessor meters (smart meters) in conjunction with supervisory control and data acquisition (SCADA) [33] software and advanced demand response software help the system balance the supply and demand of power in real time.

- A small scale distribution network - consists of a communication control layer for the control of power distribution. The grid is operating in a grid-connected mode when connected to the main distribution network, and island mode when operating solo, disconnected from the grid. Power can be distributed throughout the MG by either DC or AC. The voltage scale for the MG varies with the load. Low voltage MG's can supply a single or multiple households, medium voltage ones can supply whole cities and communities.

- Active load – It consists of devices that consume power such as: refrigerators, heating and air conditioners (HVAC), water heaters, electric ranges (stove/ovens), microwaves, and lighting systems. Certain load devices are on at certain times of the day and vary with the load demand.

The following specific components that will be used in the simulation are next discussed in more detail.

1.3 Distributed Generators and Storage Used in Microgrids

1.3.1 Wind Power

Wind is best utilized in large numbers on sites called wind farms where there is a statistically more prevalent chance of wind. Wind power itself has tremendous potential. Using the most stringent land use constraints and restrictions and assuming 25 % turbine efficiency and 25% system losses, the potential amount of power that can be generated from wind turbine energy is estimated at 4600 billion kWh/yr compared to the total amount of energy generated in the U.S. in 2002 which was 3500 billion kWh/yr [20]. Though smaller micro wind turbines can be used for rural residences, the range of wind turbines can range from 1 KW micro turbines to 8 MW turbines. Wind speed is an important factor for the windmill to produce power. There are multiple definitions of wind power generation.

The following terms are used for to describe wind power generation [20]:

1) Cut in wind speed is the speed of the wind with the generator rotor rotating, but the generator is not producing power due to the offset of the power losses from the generator field windings.

2) Rated wind speed is the speed of the wind where the rotor is rotating enough for the generator to generate net power overcoming losses.

3) Furling wind speed, also known as cutoff wind speed is the speed of the wind in which the turbine can be damaged, and must be shutoff or have a device that limits the rotational speed of the generator.

Windmill generators can both be AC and DC in which power electronics are used for inversion and/or conversion for voltage and frequency control. Most wind turbine generators are AC because of their reliability, and are asynchronous meaning the frequency of the voltage output changes corresponding to the rotation of the generator speed. This

frequency must be altered to the utility frequency via power electronics. Wind turbines adhere to Betz's limit, or the maximum theoretical efficiency of a wind turbine (59.3%). Realistically wind turbines achieve 80% of this limit which results in 40-45% efficiency under optimal conditions [15].

1.3.2 Solar Power

The solar energy hitting the surface on the earth on a clear sunny day is approximately 1 kW/m^2 [10]. The sun is the source of the earth's solar energy and provides 6000 times the earth's total energy demand onto the earth's surface [3]. Photovoltaics are solar cells that convert this solar energy into electricity.

Photovoltaics are broken down into multiple categories including [3] [20]:

o Thickness

- Conventional – 200-500 μm thickness

- Thin film – 1 – 10 μm thickness

o Polycrystalline

- Single crystal

- Multicrystalline – cell is made of multiple areas of single crystal grains ranging from 1 mm to 10 cm
- Polycrystalline – crystal grains are in the range of 1um to 1mm

- Microcrystalline – grain sizes are less than 1um

- Amorphous – no single crystal regions

o Homojunction – p-n junction is made of same semiconductor material

o Heterojunction – p-n junction is made of two separate semiconductor materials

o Multiple junction solar cells – made of stacks of p-n junctions where each junction captures a different part of the solar spectrum

o Concentrated – uses mirrors and lenses to concentrate solar radiation directly onto cells (used mainly for satellites where there is direct solar radiation before Rayleigh scattering in earth's atmosphere)

One of the first materials used in the construction of the earliest Photovoltaic components is Silicone and retains 90% of the current PV market. The most commonly used PV in the industry today is the silicon single (mono) crystalline PV cell [20]. Crystalline silicon is doped with an impurity (in most cases phosphorous) possessing excess electrons called an n- type semiconductor. Crystalline silicon doped with an impurity (in most cases Boron) causing a shortage of electrons is called a p-type semiconductor. A p-n junction is formed when these two types of semiconductors are connected together in an electric field in the junction region. We neglect the duality nature of light and assume that it is made of photons which are particles of energy. These photons result from the sun hitting the lattice structure of the p-n junction transferring energy to electrons in the valence band, putting them in a higher energy state displacing other electrons to move resulting in current flow. When these electrons move, they result in holes which also move [3]. Solar PV cells are composed of: a glass or plastic cover, antireflective surface area, front contact for electrons to enter the circuit, and a black contact allowing the semiconductor layers to finish the electron flow. A photovoltaic module is made of multiple cells in series; depending on the module, the number of cells can be 33, 36, and 72 cells ranging from 12-24 V. Multiple modules, called arrays, can be put in combinations of series and parallel, increasing voltage and current resulting in an overall power output increase. Factors such as shading, azimuth angle of the sun, and ambient temperature effect output power and efficiency of the modules [3] [20]. PV is extremely flexible for power generation because of its ability to configure to almost any load from:

1) small modules used for charging consumer electronics, to larger modules for remote power of devices such as navigation buoys and telemetry stations,

2) kW arrays powering residential homes and commercial buildings, and

3) large MW arrays that generate power for the distribution grid.

PV is projected to be installed worldwide soon, thus supplying 30 million European, 82 million worldwide, and over 1 billion worldwide residents; and by 2040. PV is expected to produce 9000 TWh, about one quarter of projected world load demand [3].

1.3.3 Batteries

There are multiple forms of energy storage: large hydro, compressed air storage, pumped hydro, stored hydrogen, flywheels, supercapacitors, superconducting magnetic energy storage (SMES), heat and cold storage, and fuel cells [10]. The most used and economical distributed storage (DS) devices are batteries. Certain DS's have higher energy density for storage but are not practical or cost beneficial for multiple applications compared to batteries. Hydro storage requires a large amount of land, economic investment, and regulation for the construction of dams and turbines; superconductors used for energy storage work at extremely low temperatures and require significant power and money to keep the superconductor at the appropriate temperature. Batteries are quiet, have efficiencies in the range of 85%, are flexible for their environment, and have the ability to respond to changes in load in a 20 ms time period. Batteries used for MG's are secondary batteries meaning they are rechargeable.

Battery types used for energy storage based on chemical composition are [10]:

o Sodium Sulfur

o Lithium-Ion

- o Lithium Titanate

- o Lithium Iron

- o Lead Acid

- o Advanced Lead acid

- o Nickel Cadmium

- o Flow Batteries - electrolytes flow through a porous membrane generating electrical charge

  - ▪ Zinc-Bromine

  - ▪ Vanadium Redox

Chemical reactions in the battery cause a buildup of electrons at the anode (negative terminal), causing these electrons to move toward the cathode (positive terminal), but are slowed down by the electrolyte within the battery. It is important to note that charging and discharging of the battery is not linear, and depends on the properties of the battery itself. The amount of power that can be charged or discharged from the battery changes due to the amount of energy stored in the battery. There are instances when the battery cannot provide the amount of power demanded by the load during a specific time period due to the limit of discharge, or excess power being generated by the DG's cannot be fully utilized in charging the battery due to the limit of charge. The units for energy stored in the battery is given in Amp-hours (Ah) and/or Kilowatt hours (KWh). Calculating the size of the battery depends on the time duration (ex: day, week) needed for the battery to provide power to the load. Calculated load measurements and data recorded over a period of time must be analyzed to estimate the size of the battery needed for the load it is set to provide power for. Inverter or converter (depending if the MG is AC or DC)

efficiencies must be taken into account for accurate calculations. One single battery unit is a module with 12 modules equaling a stack. Modules are rated depending on the voltage of the battery itself (12V, 24V, and 48V), and can be connected in series for increasing voltage and parallel for increasing current. Each module has a rated capacity in terms of Ah and kWh. The number of modules can be configured depending on it's rated: capacity, voltage, and load (kWh). Certain factors such as temperature can decrease efficiency and output power of a battery. Batteries have a limited number of cycles for discharging and charging. The effective use of the battery diminishes after so a certain number of cycles and thus it has to eventually be replaced to guarantee a battery-supported system to function well [20].

1.3.4 Generators

The combination of DG and DS may not be enough to supply load demand. Backup generators are vital, especially an MG works in an island mode of, for providing power to the load when DER's are not capable. PV and wind are unpredictable in periods where wind and sunlight are not readily available, or the batteries may be fully discharged of energy and limited by the amount of power they can provide during discharge. Given enough fuel supply, generators can supply their maximum rated power to the load allowing them to be a stable source of power that is not dependent on wind or solar energy enabling them to be the most potentially reliant DG in the MG. Generators come in a variety of sizes ranging from a few hundred watts to KW generators. Most generators run on fossil fuels possibly making it the only non-renewable DER in the MG.

Multiple fuels are available [20]:

- Gasoline

- Diesel

- Bio Diesel

- Emulsified Diesel

- Propane

- Natural Gas

Since many businesses and residences use natural gas for heating and cooking provided by pipelines and underground infrastructure, one advantage of natural gas generators is the potential to run for a much greater time span compared to their counterparts (diesel, gas) that are powered by fossil fuels that are stored separately. This is especially advantageous for residences using MG's in an island mode resulting from long drawn out disasters, e.g. hurricanes, and earthquakes, where fuel maybe limited and in short supply. Generators are synchronous machines that supply the necessary power at a constant frequency even when the load is varying. The simulation to be conducted plans to use a Petri Net modeled after a Natural Gas backup generator.

CHAPTER 2

PETRI NET MODEL OF MICROGRDS

2.1 Discrete PN

A Petri Net is a mathematical and graphical method of modelling a system. It models "the flow of information and control of concurrent activities" which allow an individual to visually see the complexity of a system.
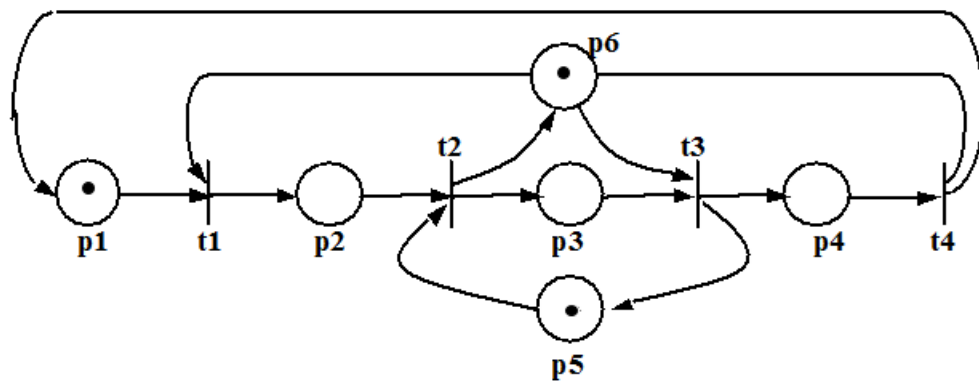
Figure 2.1 Example of a Discrete Petri Net Model [38].

PN's are bipartite meaning they consist of two nodes: a place which is represented by a circle, and transitions which are represented by a bar node. Arcs connect places to transitions only by a single direction. Places cannot connect to other places or transitions cannot connect to other transitions directly. A place must be connected to a transition by an arc, and vice-versa. Places can represent: buffers, channels, geographical locations, conditions or states. Transitions can represent: events transformations, or transportations. The action of executing a PN is controlled by tokens which are represented by dots, in places. A token in a place represents the availability of the resource or the fulfillment of the condition [38] [39] [13].

A place that contains no tokens indicates that the condition is not satisfied or the resource is unavailable. Petri nets can have a number of arcs connecting a place to a transition or vice- versa labelling them as a multi-graph. The number of arcs connecting a place to a transition is called the Arc Weighting and is indicated by an annotation on the arc. An ordinary Petri Net has arc weightings of 1.

The dynamic behavior of a PN is shown through the movement of tokens by firing transitions. A transition is enabled if all input places contain the number of tokens specified by the arc weighting for the transition to be fired. When a transition is fired it consumes tokens from the input place and outputs tokens depending on the weight of the arc to the output place. Enabled transitions do not necessarily have to fire, but depends on the conditions of the system.

Petri nets have the following behavioral properties:

1) Reachability – depends on the initial marking and helps find out if the system can reach a desired state as a result from required functional behavior.

2) Boundedness/Safeness – if the number of tokens in each place does not exceed a finite number k for any marking reachable from the initial marking. If any of the places does not exceed this number during its markings begin from the initial marking, then the system is considered bounded. If k=1, it is safe.

3) Liveness/Deadlock – It is live if the system has transitions that can always fire no matter what the marking is during an appropriate sequence. The system is in deadlock if no transition can be fired at a marking. It is important to note that a system is not necessarily live if it is deadlock-free.

4) Reversibility – It is reversible when the system can go back to its initial sate.

A reachability tree is a representation of all possible markings. Discrete Petri nets

model the discrete behavior of a system. "A variable is said to be discrete if it can take its

value from a countable set of values (which may be infinite) [13] [12] [39] [38]."

The definitions for a discrete Petri Net are directly taken from [18] [29] [39]:

1. $PN = (P, T, I, O, M)$

2. $P = \{p_1, p_2, ...p_n\}$ is a non-empty finite set of places

3. $T = \{t_1, t_2, ... t_m\}$ is a non-empty finite set of transitions with $P \cap T = \emptyset$

4. $I: P \times T \rightarrow \mathbb{N}$ is a function defining arcs from a place to a transition

5. $O: P \times T \rightarrow \mathbb{N}$ is a function defining arcs from a transition to a place

6. $M: P \rightarrow \mathbb{N}$ is a marking representing the number of tokens in places with M_0 denoting the initial marking.

A preset of transition t is a set of places of all input places to t

$$^\bullet t = \{p: p \in P \text{ and } I(p, t) > 0\} \tag{2.1}$$

A postset of transition t is a set of all output places from t

$$t^\bullet = \{p: p \in P \text{ and } O(p, t) > 0\} \tag{2.2}$$

A preset of place p is a set of transitions of all input transitions to p

$$^\bullet p = \{t: t \in T \text{ and } I(p, t) > 0\} \tag{2.3}$$

A postset of place p is a set of transitions of all output transitions from p

$$p^\bullet = \{t: t \in T \text{ and } O(p, t) > 0\} \tag{2.4}$$

2.1.1 Markings

An incidence matrix can be used to study the behavior of PN, and "defines all possible interconnections between places and transitions" [39] [13] [12] [38].

An incidence matrix of a PN has the dimensions:

(# of places) $\times$ (# of transitions), i.e. $|P| \times |T|$ where A is defined as: $a_{ij} = a_{ij}^{+} - a_{ij}^{-}$.

1) $a_{ij}^{+} = O(p_i, t_j)$ is the number of arcs connecting transition j to its output place I, and

2) $a_{ij}^{-} = I(p_i, t_j)$ is the number of arcs connecting transition j from its input place i

O is the output function of PN, and I is the input function of PN where A=O-I. When transition j fires:

1) a_{ij}^{+} is the number of tokens deposited on its output place i.

2) a_{ij}^{-} is the number of tokens taken away from its input place i.

3) a_{ij} is the change in the number of tokens in place i when transition t_j does a single firing

   The change in markings for a PN due to the firing of transitions is

$M' = M + A\mu$ where A is the incidence matrix, μ is an $n \times 1$ column vector having only a 1 at its i-th position symbolizing the firing of transition i and n is the number of transitions. *M* is the current markings and *M'* is the following marking, *M* and *M'* are represented by $m \times$ 1 column vectors where m is the number of places [12] [39] [38].

2.2 Hybrid and Finite Capacity PN

Systems can have continuous behaviors as well as discrete. An intrinsically continuous system does not exhibit discrete behavior. According to [7], "a variable is said to be continuous if it can take its value from a continuous set of values (thus not countable) and its variations do not present any discontinuity." Continuous Petri nets exist where transient behavior can be modeled, which discrete systems cannot. It is easier to use tokens that represent a varying finite number than individual tokens for a discrete system. For example Figure 2.4 shows a PN model of a solar module, p_4 shows that the PV module is not producing power, when there is enough solar energy. When there is a sufficient amount of solar energy transition t_{18} is enabled and fired consuming the token from place p_4 and placing a token into p_5. With a token in p_5 continuous transition t_3 fires and sends a certain amount of real number tokens, whereby symbolizing power (kW) to continuous place p_{13} modeling the sum of the generated power of the MG. A hybrid Petri net models both discrete and continuous behaviors of a system. The amount of tokens generated from the continuous transition t_3 is dependent on its firing rate (v). Note that t_3 does not fire if there is no token in discrete place p_5, and places p5 and p4 contain at most a single token. A token cannot exist in places $p4$ and $p5$ at the same time.
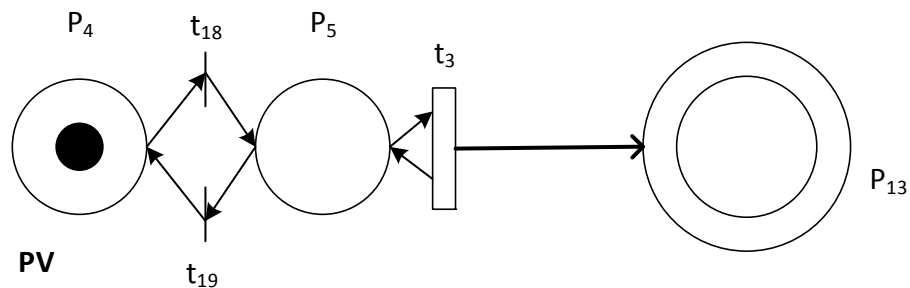
Figure 2.2 Example of a HPN of a PV Module with Both Discrete and Continuous Places and Transitions.

A discrete place is represented by a single circle, and a token in a discrete place is represented by a single dot. A continuous place is represented by two concentric circles, and a token in a continuous place is represented by a real number. A discrete transition is represented by a single bar, and a continuous transition is represented by a hollow bar. An arc from a discrete place to a continuous transition must have a reverse arc of the same weight coming from the continuous transition to the discrete place, thus forming a self-loop. This is done to make sure the markings of all discrete places are a non-negative integer. A finite capacity PN means that there are places in it whose token count is limited. Some places in the following HPN are such ones [7] [10] [36] [18].

1. $HPN = \{PN. P_D, P_C, S, C\}$ where $PN = (P,T,I,O,M)$.

2. P_c are a set of continuous places, and P_d are a set of discrete places with $P_D \cup P_C = P = \{p_1, p_2, ...p_N\}$.

3. $T = T_D \cup T_C = \{t_1, t_2, ...t_m\}$ is the set of transitions. T_c is a set of continuous transitions and T_d are a set of discrete transitions.

4. $M: P_C \rightarrow \mathbb{R}^+$ is a marking representing the number of tokens in continuous places

5. $S: T_C \rightarrow \mathbb{R}^+ \times \mathbb{R}^+$ is the set of firing speeds and enabled time intervals associated with continuous transitions, where $S(t_j) = (v_j, h)$, $v_j, h \in \mathbb{R}$, v_j is the firing speed associated with transition t_j and h is an enabled time interval.

6. $C: P \rightarrow \mathbb{R}^+$ is a capacity function where $C(p_i)$ represents the number of tokens that place p_i can hold at a time.

The marking is a positive integer for a discrete place $p_i \in P_D$, and is a real number for a continuous place $p_i \in P_C$. If place $p_i \in P_D$, then the number of tokens in p_i is a non-negative integer, and if $p_i \in P_C$, then its token represents a real number.

The marking before a discrete transition $t_j \in T_D$ starts is:

$$\forall p_i \in {}^\bullet t \cap P_D : M'(p_i) = M(p_i) - I(p_i, t_j) \tag{2.5}$$

After a discrete transition completes its firing $t + d_j$, we have the mar*king*

$$\forall p_i \in t^\bullet \cap P_D : M'(P_i) = M(p_i) - O(p_i, t_j) \tag{2.6}$$

A discrete transition $t_j \in T_D$ fires at its maximum speed, and a timed transition t_j

fires with a delay of d_j, when $d_j=0$ the firing of a discrete transition is an immediate

transition.. After a firing of a discrete transition t_j at marking M, the marking of p_i

$$M'(p_i) = M(p_i) - I(p_i, t_j) - O(p_i, t_j) \tag{2.7}$$

The marking before a continuous transition $t_j \in T_C$ finishes its firing is:

$$\forall p_i \in {}^\bullet t \cap P_C : M'(P_i) = M(p_i) - v_j(\tau) I(p_i, t_j) \tag{2.8}$$

If a continuous transition t_j finishes its firing at $t_j + h$ *t*hen $\forall\, p \in P$

$$\forall p_i \in t^\bullet \cap P_C : M'(P_i) = M(p_i) - V_j(\tau) I(p_i, t_j) \tag{2.9}$$

A continuous transition $t_j \in T_C$ is fired at time τ_s and ends at time $\tau_s + h$ where h

represents a length of time that has been enabled. After firing a transition t_j, we have p_i's

marking is

$$M'(p_i) = M(p_i) - v_j(\tau) I(p_i, t_j) h - v_j(\tau) O(p_i, t_j) h \tag{2.10}$$

For the finite capacity function, a discrete transition $t_j \in T$ in PN is enabled if $\forall p_i \in P$[27]:

$$M(p_i) \geq I(p_i, t_j) \tag{2.11}$$

and

$$C(p_i) \geq M(p_i) - I(p_i, t_j) + O(p_i, t_j) \tag{2.12}$$

When a enabled transition t fires at M, we have M':

$$M'(p_i) = M(p_i) - I(p_i, t_j) + O(p_i, t_j) \tag{2.13}$$

This means a transition is enabled if there are enough tokens in $^{\bullet}t_j$ and enough space in $t_j^{\bullet}$, when these conditions are met then t_j is enabled.

CHAPTER 3

HPN MODEL OF MICROGRIDS

A power system, specifically an MG, exhibits both discrete and continuous behavior. This work uses a Hybrid Petri Net model consisting of both discrete and continuous places and transitions. The DG's, DS's, load, and parameters of the MG (i.e. power dissipation, excess power of the MG, and total power produced in the MG), are modeled by these discrete and continuous places and transitions. Markov chains are not used for this simulation because a system of this complexity would require an exorbitant number of states. The PN model for load shedding is entirely discrete since turning off and on of devices that consume power can be modeled by discrete places and transistions. Scheduling 1 which is referred to as the Heuristic Schedule, and schedule 2 labeled as the Reliability Schedule are to be discussed in Chapter 5.

3.1 Microgrid HPN Model

3.1.1 Windmill

The three modes of the windmill are represented by discrete places p_1, p_2, and p_3, as shown in Figure 3.1 and Table 3.1. A token in p_1 represents mode 1 of the windmill, where the wind speed is below the cut-in wind speed, thus resulting in the windmill producing no power. A token in p_2 represents mode 2 wherein the wind speed is between the cut-in wind speed and furling wind speed. In this mode, the power produced by the windmill is between zero and the maximum power that can be produced by the windmill itself. Transition t_1 is continuous, and outputs firing rate v_1 of real tokens in power (kW) when a token is in p_2. A token in p_3 represents when the windmill is in mode 3; the wind speed is greater than furling wind speed, and the turbine is generating its maximum power output, which it cannot exceed. Transition t_2 is a continuous transition that outputs real power at a firing rate v_2 (a constant power) in watts of Power$_{max}$ when a token is in p_3. Transitions $t_{12} - t_{17}$ are discrete and allows the token to transition through the discrete places corresponding to whichever mode the windmill is in.

3.1.2 PV

The two modes of a PV system are modeled by discrete places p_4 and p_5. When solar energy is produced by sunlight hitting the surface of the PV cells producing power, a token is placed in p_5. Transition t_3 is continuous and has a firing rate v_3 in Power (Watts) when a token is placed in p_5. When insufficient solar irradiation (primarily during evening and night hours) results in zero power from the PV system, a token is placed in p_4. Transitions t_{18} and t_{19} are discrete transitions allowing the transfer of tokens between p_4 and p_5

corresponding to the mode (generating power or not generating power) in which the PV system is.

3.1.3 Natural Gas Generator

Depending on the scheduling and the amount of power provided by the other DG's and DS, a fossil fuel generator provides additional power to handle the load. A token in discrete place p_6 represents that the generator is not needed and is off, thus generating no power to the MG. A token in discrete place p_7 represents the generator is on, thus producing power for the MG. A token in p_7 outputs a real number token from continuous transition t_4 representing the power in Watts being produced from the natural gas generator. Discrete transitions t_{20} and t_{21} enable tokens to transfer between discrete places p_6 and p_7 respectively.

3.1.4 Continuous Model of a Battery

Though the battery can be modeled by discrete places to show its state (i.e. charging, discharging, or neutral), the battery in this HPN is modeled by continuous behavior. The amount of power used to charge the battery, discharge the battery, the amount of energy in the battery, and the amount of energy the battery needs to be completely charged is modeled, making all transitions and places in this model continuous. Tokens in place p_{12} represent the energy (kWh) in the battery at that moment. Tokens in place p_{11} represents the energy needed to fully charge the battery. The token quantity in p_{11} is the maximum amount of energy the battery can store (35 kWh for this model) minus the token quantity in p_{12}. Continuous transition t_6 has its firing rate in which power is converted from p_{14} into the

energy that is stored in the battery as modeled by adding tokens into p_{12} and subtracting tokens from p_{11}. Continuous transition t_5 represents the firing rate at which the battery discharges energy in the form of power (kW) subtracting tokens from p_{12} due to the battery depleting energy in the form of power simultaneously adding tokens to p_{11} representing the amount of energy needed for the battery to be fully charged. The continuous model of the battery is a Finite Capacity Petri Net with a finite number of tokens between p_{11} and p_{12}. The maximum number of tokens combined from these two places is 35 since the maximum amount of kWh that can be stored in the battery chosen for this simulation is 35 kWh. The minimum number of tokens for p_{12} is 6.3995. This amount is chosen as the lowest value the battery can charged, the battery cannot discharge energy when the token quantity of p_{12} is 6.3995. Thus the marking of p_{11} is equal to 35- 6.3995 = 28.6005 kWh or the battery needs 28.6005 kWh of energy to be fully charged. If p_{12} is 35, the battery is fully charged and P_{12} is 0 since the battery needs 0 kWh to be fully charged.

3.1.5 Main Distribution Grid and Power Dissipation

The utility uses the MG when it is in a grid-connected mode. The three modes of the utility are represented by discrete places p_8, p_9, and p_{10}. The neutral or disconnected state of the utility is represented by a token placed in discrete place p_8. The utility is neither producing nor consuming power in this state. A token in discrete place p_9 represents the utility providing power to the MG. When a token is in p_9, continuous transition t_7 outputs real number tokens at firing rate v_7 representing real power in Watts. A token in discrete place p_{10} represents the utility consuming power. This happens when the MG is producing excess power by the DG's (power produced by DG's is greater than the load) which cannot output

this power to the battery either because the battery is fully charged, or the charge rate for

the battery is less than the excess power being produced. When this excessive power is

produced, it is fed back to the main distribution grid. When a token is in discrete place p_{10},

continuous transition t_8 consumes real-number tokens by firing rate v_8 from p_{14}

representing real power in Kilowatts. Discrete transitions t_{22}-t_{27} transfer the tokens to

discrete places p_8, p_9, and p_{10} which correspond to the different modes in which the main

distribution grid is. Continuous transition t_9 represents the MG in an island mode and the

MG is disconnected from the main distribution grid. Excessive power cannot be sent back

into the main distribution grid. Power dissipation is hence created for this simulation as the

potential power that can be generated in this state though this situation may not occur in

reality. Distributed generators output power that is needed for the load (battery charging

acts as a load), and power flow in the MG is controlled by power electronics and advanced

control systems. This is done to demonstrate this effect for simulation purposes. Transition

t_9 fires tokens representing power in Watts by firing rate v_9. This transition fires only when

this excessive power cannot be used to charge the battery and the load demand is met in an

island mode. The tokens consumed by t_9 is labeled power dissipation in this model.

3.1.6 Generation and Consumption Models

Continuous transition t_{10} represents the load that is calculated by the total load devices

from the load schedule. Since certain devices are on and off during certain time a day, this

transition has a fluctuating firing rate for each marking. Continuous place p_{13} contains the

sum of the real-number tokens being generated from continuous transitions from the

various DG's and DS; t_1, t_2, t_3, t_4, t_5, and t_7. This represents the total power being generated

by all the DG's and DS of the MG. Continuous transition t_{11} provides real-number tokens representing power in Watts to continuous place p_{14} which supplies tokens to the continuous transitions: t_6, t_8, and t_9. The tokens in p_{14} represent the power that is consumed by various DG's and DS in the MG, power that is used for charging the battery, excessive power supplied to the main distribution grid in grid connected mode, and excessive power to be dissipated in an island mode.
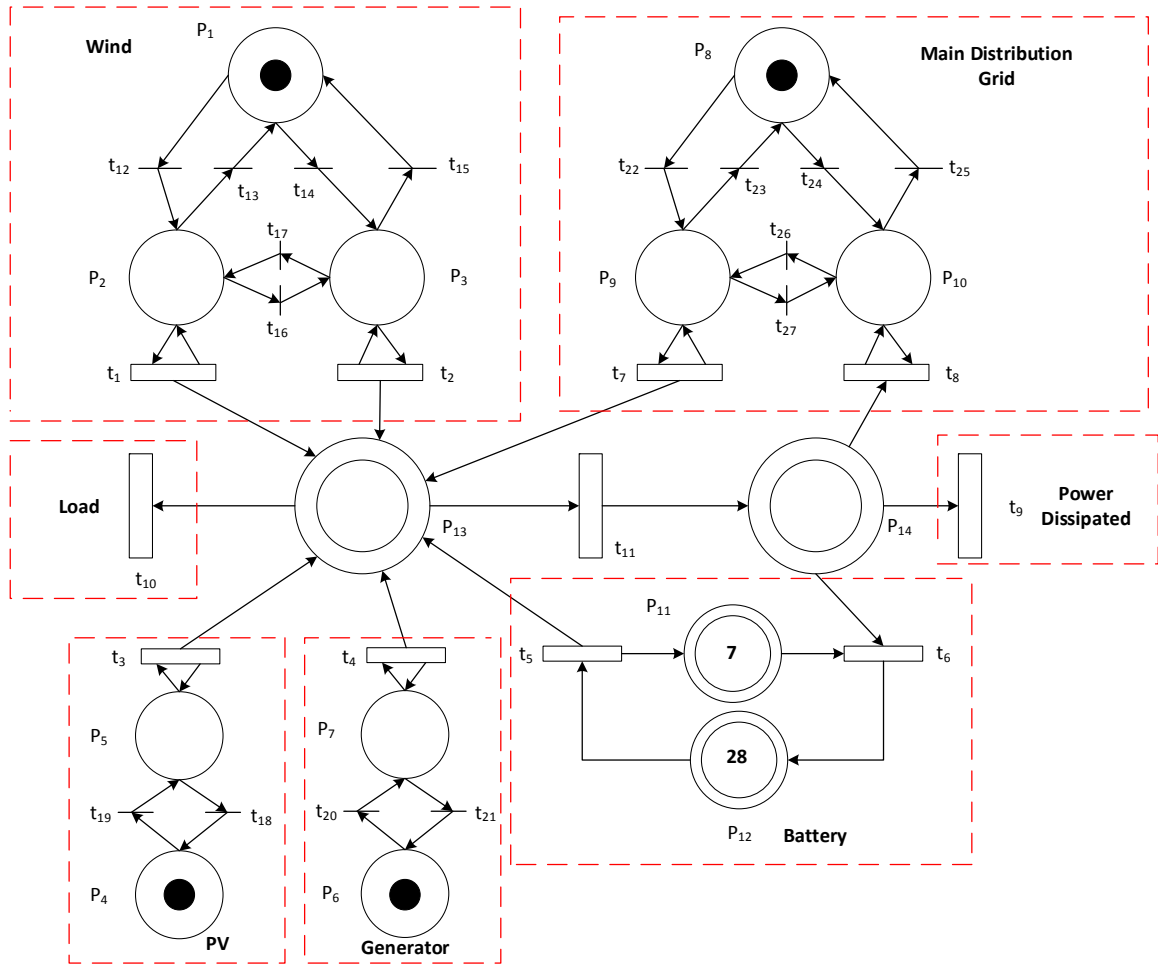
Figure 3.1 A 4 DG HPN Model with a Main Distribution Grid.

Table 3.1 Meanings of Places and Transitions of the HPN Model

P_d	p_1	1st mode of wind turbine
	p_2	2nd mode of wind turbine
	p_3	3rd mode of wind turbine
	p_4	PV cell off
	p_5	PV cell on
	p_6	Diesel Generator off
	p_7	Diesel Generator on
	p_8	Utility is in off state- utility mode 1
	p_9	Utility is providing power- utility mode 2
	p_{10}	Utility is consuming Power- utility mode 3
P_c	p_{11}	Energy needed in the battery to make it full capacity (kwh)
	p_{12}	Energy in the battery (kwh)
	p_{13}	Combination of power from DG's and DS
	p_{14}	Excess power produced from MG
t_d	t_{12}	Wind turbine switches from mode 2 to mode 1
	t_{13}	Wind turbine switches from mode 1 to mode 2
	t_{14}	Wind turbine switches from mode 3 to mode 1
	t_{15}	Wind turbine switches from mode 1 to mode 3
	t_{16}	Wind turbine switches from mode 2 to mode 3
	t_{17}	Wind turbine switches from mode 3 to mode 2
	t_{18}	PV goes from on to off
	t_{19}	PV goes from off to on
	t_{20}	Natural Gas Generator goes from off to on
	t_{21}	Natural Gas Generator goes from on to off
	t_{22}	Utility goes from off state to producing
	t_{23}	Utility goes from producing to off
	t_{24}	Utility goes from off to consuming
	t_{25}	Utility goes from consuming to off
	t_{26}	Utility goes from consuming to producing
	t_{27}	Utility goes from producing to consuming
t_c	t_1	Wind turbine in mode 2 is supplying power
	t_2	Wind turbine in mode 3 is supplying power
	t_3	PV is supplying power
	t_4	Natural Gas Generator is supplying power
	t_5	Battery is supplying power
	t_6	Battery is consuming power
	t_7	Utility is supplying power
	t_8	Utility consuming power
	t_9	Power is being dissipated
	t_{10}	MG Load
	t_{11}	Excess power is being produced and used for charging the battery, dissipated, or supplying the utility

3.1.7 Prior HPN

Based the work of X. Lu [29] who originally conceived the idea of an HPN for an MG, as shown in Fig. 3.2 and Table 3.2. This work presented the model and subsequent simulations. Both nets are hybrid, i.e. both discrete and continuous places and transitions are adopted. Their discrete models with continuous transitions are the same for the windmill, photovoltaic cell, battery, a load transition, and a continuous place for the summation of the power generated in the MG.
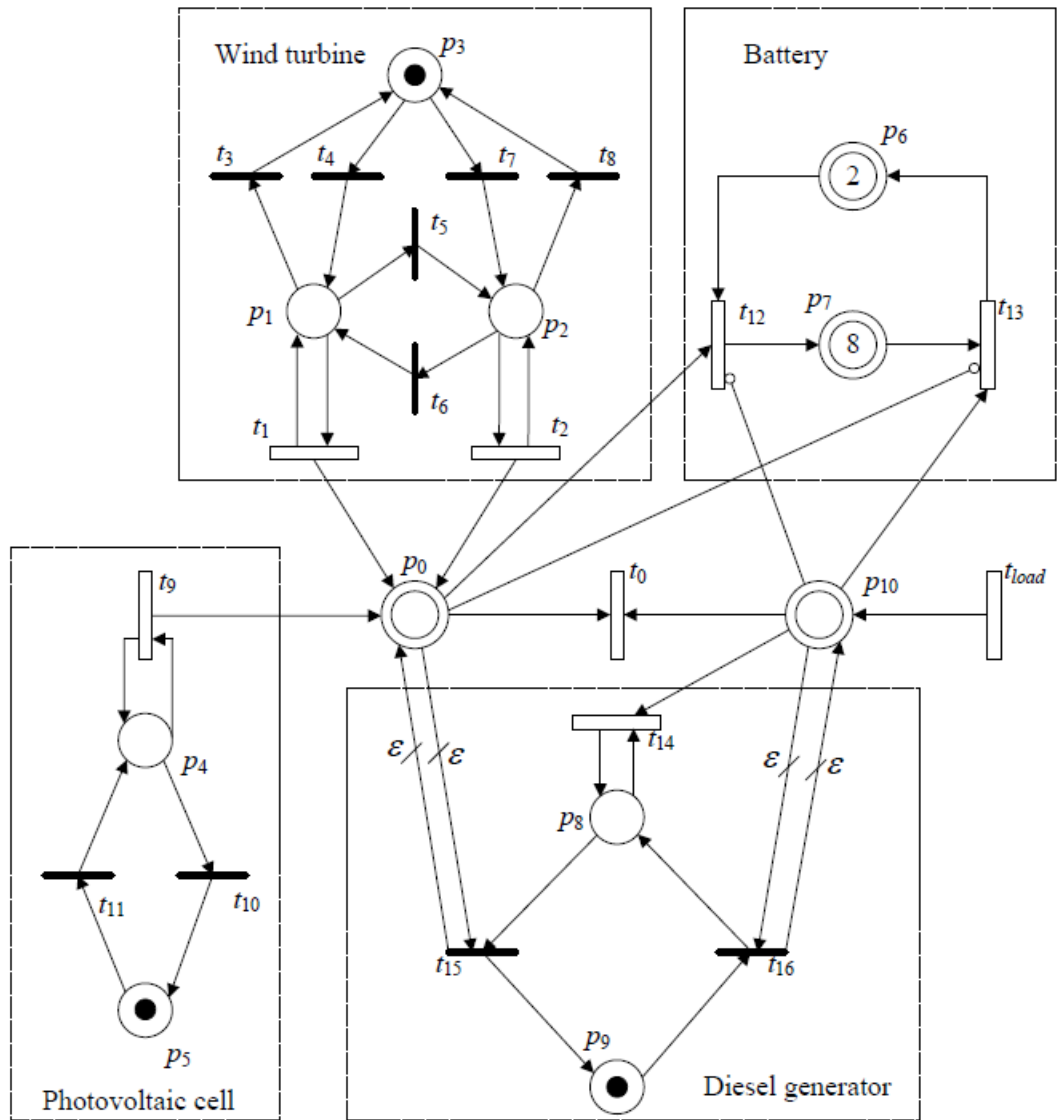
Figure 3.2 Xu's Model of a 4-DG HPN Model [18].

Table 3.2 Table of Xu's 4-DG HPN Meanings of Places and Transitions [18]

p_d	p_1	The first mode of wind turbine
	p_2	The second mode of wind turbine
	p_3	The third mode of wind turbine
	p_4	The photovoltaic cell on
	p_5	The photovoltaic cell off
	p_8	The diesel generator on
	p_9	The diesel generator off
p_c	p_0	The energy produced by both wind turbine and photovoltaic cell
	p_6	The storage capacity of the battery
	p_7	The amount of energy stored in the battery
	p_{10}	The shortage of energy demand
t_d	t_3	The wind turbine switches from the first mode to the third one.
	t_4	The wind turbine switches from the third mode to the first one.
	t_5	The wind turbine switches from the first mode to the second one.
	t_6	The wind turbine switches from the second mode to the first one.
	t_7	The wind turbine switches from the third mode to the second one.
	t_8	The wind turbine switches from the second mode to the third one.
	t_{10}	The photovoltaic cell on
	t_{11}	The photovoltaic cell off
	t_{15}	The diesel generator off
	t_{16}	The diesel generator on
t_c	t_0	Both wind turbine and photovoltaic cell respond to the load demand.
	t_1	The energy produced by the wind turbine at the first mode
	t_2	The energy produced by the wind turbine at the second mode
	t_9	The energy produced by the photovoltaic cell
	t_{12}	The charging of the battery
	t_{13}	The discharging of the battery
	t_{14}	The energy produced by the diesel generator
	t_{load}	Load demand

This work's PN model has added a main distribution grid model with discrete and continuous transitions to the MG, and a continuous transition with a continuous place for excessive power. Lu's model has a continuous place p_0 for the summation of power produced from the DG's and an arc that goes to transition t_{12} for battery charging. Continuous place p_{10} contains tokens if there is energy shortage to meet the load demand and thus represents the power that is needed from the various DG's for the MG, triggering

the Generator to turn on or the battery to discharge. Continuous transition t_0 provides a balancing act for the MG consuming power from the summation of power generated and subtracting power needed from the MG, which in theory should equal each other with small errors for places p_0 and p_{10} (this also occurs in the subsequent simulation). Arcs with circles at the end are inhibitor arcs and are seen from continuous place p_{10} to continuous transition t_{13}. This represents that t_{13} is not enabled (thus not firing to discharge the latter) if there are tokens in p_0, representing a surplus of power from the renewable sources for the MG, therefore not requiring power from the battery. This is also seen from continuous place p_{10} to continuous transition t_{12} representing if power is needed from the MG, t_{12} is not able to fire to charge the battery. If all the power from the renewables is needed for the MG, then the battery cannot be charged. It can be charged only when there is a surplus of power from the renewables.

An epsilon associated with a weighted arc represents a threshold. This can be seen from the arcs that go from p_0 to discrete transition t_{15}, representing there are surplus tokens in p_0 to be fired into transition t_0. Transition t_{15} will fire taking a token from place p_8 and placing a token into discrete place p_9, allowing the diesel generator to turn off. Weighted arcs with an epsilon perform the inverse action for the diesel generator from p_{10} to discrete transition t_{16}, turning on the generator when the power needed for the MG is greater than the power from the combination of the renewables. This work's, p_{13} acts like p_0, where the summation of the power is modeled by its token, but unlike Lu's model, power discharged from the battery is modeled via this place. This work's model does not have any threshold or inhibitor arcs, and does not have a continuous transition that subtracts power generated from the renewables from power needed for the MG. This action does not happen,

however, from other continuous places and transitions in the HPN model making the values in continuous place p_0 and p_{10} theoretically equaling zero. The continuous transition of the load generates power needed in Lu's work, while that in this work is directly connected to the summation of the power to take tokens from the power generated. There is a balancing act in Lu's model: if power is needed, battery discharge is triggered and the generator turns on, while the generator turns on in this work's model based on scheduling. Unlike Lu's HPN model, this work has a Power Dissipated transition. Its firing means dissipating excessive power that can potentially be created by the MG. This excessive power is not used for battery charging or sent back to the main distribution grid, It does not store in p_{14}, like a continuous place for a battery. In this works model, power is siphoned off from the total summation of the MG for excess power which is connected to continuous transitions for the main distribution grid and battery charging by a continuous place that receives excess power from p_{13}. This continuous place p_{14} provides excessive power to the main distribution grid, power dissipated, and battery charging. This work also has a discrete Petri net model that works in parallel to the HPN one. This model is a discrete load shedding model, whereas in Lu's model the continuous transition alters the load value, which also happens in this works' HPN model. But when the power from the DG and DS cannot meet load demand, the discrete load shedding model takes into effect and lowers the load demand to match the power generated from the DG's and DS. Load is divided into devices and categories in this work's model, and subtracting power from the load demand, enabling the MG to function. Reverse (de-load shedding) also occurs, turning on devices or allowing scheduled future devices that were previously shut off or not allowed to turn on, to activate when sufficient power is available. As will be read

further, a major difference between this work's and Lu's model is observed in the simulation.

3.2 Firing Rates

This work uses the following firing rates associated with continuous transitions:

P_{Wind} = Power Generated from the wind turbine

P_{Solar} = Power generated from PV

P_{Load} = Power needed for the load

P_{Combo} = the combination of P_{Wind} and P_{Solar}

P_{batt} = Power needed from the battery

$P_{battchargemax}$ = Maximum amount of power that can be used to charge battery

$P_{Genrated}$ = Rated value of the generator

$P_{battMax}$ = Maximum discharge power allowed from the battery

$P_{battprov}$ = Power provided from the battery

$P_{Dissipated}$ = Power that is dissipated

3.2.1 Wind Power

The firing rates for the wind turbine are v_1 and v_2, where v_2 is related to mode 3 of the wind turbine resulting in wind power always equaling 1 kW due to the wind speed equaling or being greater than its maximum wind velocity, and is rated in Watts. The maximum power output for the wind turbine is assumed to be 1 kW. The startup wind speed is 3 m/s. When the wind speed is less than 3 m/s, the turbine is not producing any power. The rotor

diameter of the wind turbine is 2.5m resulting in the radius is 1.25 m. To obtain the radius

of the swept area of the wind turbine:

$$A = \pi r^2 = 3.14 \times 1.25^2 = 4.9m^2 \qquad (3.1)$$

The power converted from the wind by the turbine is given by [16]:

ρ = Air density

V = wind speed

A = radius of the swept area

C_p = Power Coefficient = 0.4

$$P_{avail} = \frac{1}{2} \times \rho(kg/m^3) \times A(m^2) \times \left(V(m/s)\right)^3 \times C_P \qquad (3.2)$$

$$= \frac{1}{2} \times \rho(kg/m^3) \times 4.9(m^2) \times \left(V(m/s)\right)^3 \times 0.4$$

$$= Watts$$

$$kW = 1000\ Watts$$

The power coefficient is the same as Betz's limit. The maximum value for Betz's limit is

0.6, but 0.4 was chosen as in between 0 and 0.6. Air Density and wind speed are obtained

from data from Rutgers meteorology. This will be explained later.

3.2.2 Solar Power

The firing rate for solar power is v_3 and is rated in Watts. To first calculate the power of PV

generated, calculations of the generator active surface area which is the surface area of all

the solar panels must first be obtained. The area of the panels and number of the panels are

found by using the peak hours approach. Solar insolation is chosen with a value of 4.4.

Since the load schedule is done in 10 minute increments, each ten minute increment for the

evening and day schedule loads is summed in kW , and multiplied by (10/60 – meaning 10 minutes of an hour) to convert to kWh. The kWh's for each 10 minute increment for the day and evening load schedules for each corresponding season (Summer or Winter) are then summed up to give the total energy of the day. The summer day total energy per day is multiplied by 193, and winter total Energy per day by 192 (193 + 192= 365 days of the year). Though the energy usage fluctuates throughout the year due to the changing of the seasons that correspond to temperature change. Multiplying the daily energy usage of a Winter and Summer day (seasons where temperatures are at their most extreme of the year) provides an overestimated energy profile that should be larger than a more accurate energy profile resulting in a large PV array that provides sufficient energy for the load.

Losses are set to 1.00 for simplification purposes during the calculation of solar array size. The amount of kWh/yr is calculated by summing the amount of total power per unit time for summer load mornings and summer load evenings then multiplied by (10/60) for watt-hours for the energy in a ten minute period. All energy values for the ten minute time periods are summed to obtain the total amount of Wh used for the day for both summer and winter schedules. By dividing 365 (the amount of days in a year) by 2, the result is 182.5. This number is rounded down to 182 to represent the number of days in half the year. One-hundred and eighty-two is multiplied by the total watt-hours of the summer and winter days (Appendix C summation for Winter and Summer days). Though this is not an accurate representation of the energy used by the residence for a year, because it neglects the lower energy usage for the spring and fall seasons. This is a rough estimation which hypothetically result in an oversized solar array in terms of number of panels and

size. This is seen as an advantage since the larger number of panels, and the respective area covered by them, result in harvesting more solar power for the MG [10].

Energy use per year = 15,013 kwh/yr

Even though it is not realistic, for this simulation, conversion efficiency of the solar panels is was chosen as 100% for simplification.

$$Energy\left(\frac{kWh}{yr}\right)ac \tag{3.3}$$

$$= P_{dc,STC}(kW) \times (Conversion\ efficiency) \times \left(\frac{h}{day\ @1 - sun}\right)$$

$$\times\ 365\ days/yr$$

$$P_{DC,STC} = \frac{15,013\ kWh/yr}{100 \times 4.4\ h/day \times 365\ days/yr} = 9.35\ kW$$

Collector efficiency (η) = 21 %

$$A(m^2) = \frac{P_{dc,STC}}{1(kW/m^2) \times \eta} = \frac{9.35\ kW}{1 \times 0.21} = 43.34m^2 \tag{3.4}$$

The equation for the DC power supplied by the solar panels is [24]:

G_{eff} = Solar irradiance

N_g = Efficiency of the solar panels = 0.21

A_g = Generator Active Surface = 43.34m^2

$$P_{DC} = G_{eff} \times \eta \times A_g = G_{eff} \times 0.21 \times 43.34(m^2) \tag{3.5}$$

Inverter efficiency = 0.95

$$V_{2= P_{DC}} \times 0.95$$

The power for the solar panels is multiplied by the inverter efficiency. This work uses an optimistic value. Solar radiance is obtained from the Rutgers meteorology. To be discussed later in detail.

3.2.3 Natural Gas Generator

The firing rate for the natural gas generator is expressed as the firing rate v_4, and is expressed in Kilowatts. In the Heuristic schedule, the natural gas generator provides power if the combination of power from the distributed generation and storage cannot supply the load demand.

If $P_{Load} > P_{Combo} + P_{batt}$

Then $P_{Need} = P_{Load} - (P_{Combo} + P_{batt})$

If $P_{Need} = P_{Gen}$

Then $P_{Need} = v_3$

If $P_{Need} \leq P_{Gen}$

$v_3 = P_{Need}$

If $P_{Need} > P_{Gen}$

Then the system has to go into load shedding and $v_3 = P_{Gen}$

These firing rates are applied in the the Heuristic schedule and, the Reliability schedule if the energy in the battery is above the safe limit. If the generator generates less than 4kW or the load is greater than 4 kW, the Reliability schedule is not deployed. During the time periods where the load is exceeded by this value, the MG is switched to the Heuristic schedule. If the generator needs to generste less than 4kW, the MG uses the Heuristic schedule, and charging must happen when excess power is produced by the

DG's. The generator first supplies the load and uses whatever extra power it can provide to charge the battery. If this extra power is greater than the maximum power that can be used for charging, then this maximum power charge value, combined with the load, is outputted by the generator.

In an island mode with the Reliability schedule

$(P_{Combo}) < (P_{Load} + P_{battchargemax})$

$P_{Genrated}$ = rated value of the generator

$P_{Gen} = P_{Load} - P_{Combo}$

$P_{Genrated} - P_{Gen} = P_{Extra}$

If $P_{Extra} \geq P_{battchargemax}$

then $v_3 = P_{Gen} = (P_{Load} + P_{battchargemax}) - P_{Combo}$

If $P_{Extra} < P_{battchargemax}$

then $v_3 = (P_{Load} + P_{Extra}) - P_{Combo}$

If $P_{Gen} = P_{Genrated}$ then $v_3 = P_{Genrated}$

3.2.4 Battery Discharging

The firing rate for the battery discharging is v_4 and is rated in Watts. The energy (kWh) vs. Discharge (h) duration is [13]:

$$y = f(x) = 4.4929 + 17.969\log(x) \tag{3.6}$$

where y is the Energy (kWh) and x is the hour duration for discharge (h). To find the maximum allowable power (kW) that can be discharged, the initial energy in the battery has to be substituted for y, and x (time) has to be solved. Solving for x gives:

$$x = \log^{-1}\left(\frac{y - 4.4929}{17.696}\right) = 10^{\left(\frac{y-4.4929}{17.969}\right)} \tag{3.7}$$

Taking the derivative of y with respect to x for (2.19) gives you power according to time duration.

$$\frac{dy}{dx} = \frac{7.81}{x} \tag{3.8}$$

By substituting the initial energy in the battery for y into (3.7) and solving for x, plugging x into (3.8), the maximum power the battery can discharge is obtained.

The battery discharging does not always equal the power that is needed for the load. If the power needed for the load is less than the maximum discharge power of the battery combined with power outputted from the renewables the battery discharges the amount of power that is needed. If the power needed from the battery is greater than the maximum power the battery is able to discharge, v_4 then equals the maximum power discharge power of the battery

$P_{batt} = P_{Load} - P_{Combo}$

If $P_{batt} < P_{battMax}$ then $v_4 = P_{batt}$

If $P_{batt} \geq P_{battMax}$ then $v_4 = P_{battMax}$

Battery discharge is a positive quantity. If the battery is not discharging any power, $v_4 = 0$. Battery discharging does not occur during the Reliability scheduling. The purpose of the Reliability scheduling is to potentially charge the battery to its maximum value, and is only discharged during the Heuristic scheduling.

3.2.5 Battery Charging

The firing rate for the battery charge is v_5, and is rated in Watts. The energy (kWh) vs. Charge (h) duration is [13]:

$$y = f(x) = 6.3995 + 19.531\log(x) \tag{3.9}$$

where y is the Energy (kWh) and x is the hour duration for charge (h). To find the max power (kW) that can be charged, the initial energy in the battery has to be substituted for y, and x (time) has to be solved. Solving for x gives:

$$x = \log^{-1}\left(\frac{y - 6.3995}{19.531}\right) = 10^{\left(\frac{y - 6.3995}{19.531}\right)} \tag{3.10}$$

Taking the derivative of y with respect to x from (2.22) gives the power according to x time duration.

$$\frac{dy}{dx} = \frac{8.41}{x} \tag{3.11}$$

Substituting in the value of x that is solved by plugging the initial value of the battery for the energy discharge equation into the derivative of the function leads to the maximum allowable power for charging (kW.

The maximum charge limit does not mean the amount of power charging the battery equals the maximum amount allowed to charge. In the Heuristic Schedule simulations, only excess power is used to charge the battery. If the Excess power is less than the maximum charge rate than the firing rate will be Excess Power; if maximum charge rate is greater than or equal to the excess power than the firing rate is $P_{battchargemax}$.

If $P_{Load} < P_{Wind} + P_{Solar}$

$P_{Excess} = P_{Combo} - P_{Load}$

if $P_{Excess} < P_{battchargemax}$ then $v_5 = P_{Excess}$

if $P_{Excess} \geq P_{battchargemax}$ then $v_5 = P_{battchargemax}$

The process is the same during the Reliability schedule simulation. If the energy in the battery does not discharge below the same limit (6.3995 kWh), when it does $P_{battchargemax} = v_5$ because the main distribution grid will provide the power to reach the max charge power even if there is not enough excess power to achieve maximum charge rate. In the island mode, if the generator cannot provide the power to reach $P_{battchargemax}$ due to its rating or is providing most of its power to support the load, then the generator will provide whatever power it can supply in conjunction with any excessive power being produced from the remaining DG's. If the generator rated value is below 4KW or the load is above 4 kW, the MG is not in the Reliability schedule and the battery is not charged under the Heuristic Schedule. Under these conditions the MG uses the Heuristic Schedule.

If $P_{Excess} = P_{Combo} - P_{Load} > 0$

In the Reliability schedule grid-connected mode

Then $v_5 = P_{battchargemax}$

In the Reliability schedule island mode

If $P_{Extra} \geq P_{battchargemax}$

Then $v_5 = P_{battchargemax}$

If $P_{Extra} < P_{battchargemax}$

Then $v_5 = P_{Extra}$

3.2.6 Main Distribution Grid

The firing rate for the utility is v_6, and is rated in Kilowatts. When the MG is in an island mode, the main distribution grid is disconnected and does not provide or consume any power, making $v_6 = 0$. When the system is grid-connected in the Heuristic schedule with the main distribution grid providing power to the MG

If $P_{Load} - (P_{Combo} + P_{battprov}) > 0$

Then $p_6 = P_{utility} = P_{Load} - (P_{Combo} + P_{battprov})$

If there is excess power that cannot be utilized to fully charge the battery and the MG is grid connected, such power is supplied to the main distribution grid.

If $P_{Load} < P_{Wind} + P_{Solar}$

$P_{Excess} = P_{Combo} - P_{Load}$

if $P_{Excess} \geq P_{battchargemax}$

$P_{Excess} - P_{battchargemax} = P_{utility} = v_6$

They are also applied under the Reliability schedule, except that the battery is not providing power because the Reliability scheduling is based on charging the battery and does not discharge it during the time duration. Excessive power to be supplied to the distribution grid is the same as that under the Heuristic Schedule.

In the Reliability scheduling grid connected mode

$P_{battchargemax} = v_5$

In the Reliability schedule island mode

If $P_{Excess} > P_{battchargemax} + P_{Load}$

$P_{utility} = P_{Combo} - (P_{Load} + P_{battchargemax}) = v_6$

If $P_{Combo} < (P_{Load} + P_{battchargemax})$

$$P_{Utility} = P_{Load} + \text{P}_{\text{battchargemax}} - P_{Combo} = v_6$$

The utility can compensate it such that the battery is charged at its maximum charge rate.

3.2.7 Power Dissipated

Power dissipation is a function created for these simulations. The simulation is setup by the firing rates, using equations that output data according to the input data. Wind speed uses input data for air density and wind speed, and PV uses solar radiance (substituted for solar irradiance). The power produced from the wind turbine and PV output the maximum power generated from the input data, but this does not reflect what occurs in reality in an island mode. When excessive power can be produced in a grid connected mode, it is sent to the main distribution grid, but in an island mode excess power is not produced, although there is enough wind speed or solar energy capable of doing so. The renewable DG power provides enough power for the load (battery charging acts like a load) plus losses. This is not taken into account due to the equations for firing rates of the wind turbine and PV. Also, the work counts this extra power to show this specific power that can be potentially produced if load were to increase for simulation purposes. Power dissipation occurs only in an island mode, when there is excessive power that cannot be used to charge the battery. Since the system is disconnected from the main distribution grid, such power cannot be supplied to the utility. Power dissipated is expressed as v_7, and is rated in Watts. The power dissipation mode is the same under both schedules.

If $P_{Load} < P_{Wind} + P_{Solar}$

$P_{Excess} = P_{Combo}$ - P_{Load}

if $P_{Excess} \geq P_{battchargemax}$

$$P_{Excess} - P_{battchargemax} = P_{Dissipated} = v_7$$

CHAPTER 4

LOAD SHEDDING

4.1 Load Profile

A load profile is developed to model a load demand of a house. A list of devices was compiled from observations from the author's own home. Through a collection of surveys, questioning, and personal observation of the author's residential load use; a collection of what devices and what times the devices are used is recorded. A 24 hour schedule using this data is put forth by hourly increments as seen in (Appendix B (under checklist for Summer and Winter)) where checkmarks are for when the device is on, and diamonds are to indicate the device is in a standby mode. Each hour is subdivided into ten minute increments in order to accurately indicate when the device is in use by the author's own family, thereby modeling load and consumption. Many of the white good's schedule, time duration, and load values are taken from [26], and from the author's observations of his personal residential house load consumption. The devices are categorized and summarized:

White Goods – Electronics that are defined as major appliances

- Dishwasher

- Dryer

- Washing Machine

- Electric Oven/Stove

- Refrigerator

- Hot Water Heater

- HVAC (Air Conditioner/Heater)

Outlets – Consumer electronics connected to various home outlets that are not vital to survival (i.e., televisions and entertainment systems) gaming systems and televisions

- Iron

- Television + cable box

- Desktop + Monitor

- Gaming System (PS4)

- Hair Dryer

Emergency Outlets – A single outlet that powers electrical devices that are considered significantly important during periods where power is not available from the main distribution grid. These devices are crucial for outside communication, especially during weather emergencies, where the distribution grid might be down for an extended period of time.

- Smartphones

- Laptop

- Tablet

Kitchen Outlets – Outlets located in the kitchen used for food preparation and cooking

- Coffee Machine

- Toaster

- Blender

- Microwave

Lights – They include all lights in the house that required an outlet to function. Battery operated lamps are not included.

An Electric Vehicle (EV) is originally intended to be part of the load and MG itself, acting as a battery during certain periods where power is needed, but the decision was made not to incorporate the EV into the load profile. Though it is on the load profile schedule, its corresponding values are not included in the simulation. Many of the devices are in standby mode when turned off and consume power in this state. These devices

including the PS4 gaming system, desktop and monitor, etc. Laptops and smartphones include more than one device for some particular time. The value for charging one smart phone is 12 Watts, but for certain time periods, four smartphones are charging resulting in 48 Watts in total for all four smartphones. Every other device is listed as a single device in the house. The values (Watts) for the power consumed for some of the devices and the power consumed in their standby mode, are listed in Table 2.4 [16] [26].

Table 4.1 Power Consumption of Devices

Device	Wattage (Watts)	Standby Wattage (Watts)
Cablebox	140 W	5.2 W
DVD player	16 W	5.5 W
Telephone answering machine	4.5 W	2.2 W
TV (plasma)	300 W	6.4 W
Video Game System	20 W	0 W
Computer	68 W	1.2 W
Printer-ink	13 W	4.2W
Printer-Laser	250 W	4.2 W
Router/DSL/Cable Modem	6 W	2 W
Hair Dryer	710 W	0 W
Vacuum-upright	297 W	0 W
Vacuum Canister	818 W	0 W
Aquarium	63 W	0 W
De humidifier	46 W	0 W
Iron	1100 W	0 W
Computer Monitor	84 W	2 W
Kitchen		
Coffee-Drip	1500 W	0 W
Coffee-Percolator	600 W	0 W
Compactor	400 W	0 W
Microwave	1000 W	0 W
Toaster	1100 W	0 W
Toaster Oven	1500 W	0 W
White Goods		
Dishwasher	300-1200 W	0 W
Dryer	3000 W	0 W
Washing Machine	500-620 W	0 W
Lights	30 W	0 W
Electric Range	2300-6400 W	0 W
Refrigerator	145 W	2.7 W
Hot Water Heater	4500 W	0 W
Heater	875 W	0 W
Air Conditioner	1800-2300 W	0 W

Although most of the U.S. residents uses fossil fuels for ovens, stoves, water heaters, and heaters: these devices are all electric in the simulation in this work. This is done to increase the electric load and stress the system. For the load shedding schedule, certain devices may not be on during certain time periods. When simulating a load shedding process, if a selected device is not using power, the MG still needs to decrease load demand, it goes to the next device and repeat the evaluation process until enough devices are off to match the load demand to the power supplied by the MG. These devices that are not on, but are included in the load shedding column of the output excel files signifying these devices cannot be turned on, a fact which is taken into account by the simulation program, until reverse load shedding occurs.

The time periods for the simulation are done in ten minute increments over a 24 hour period. Ten minute values are used since they can accurately model the load consumption for certain devices that are using power for a short amount of time. For example, an electric range which can be on for 20 minutes (two 10 minute periods). This creates a simpler and more accurate model than using larger increments such as ½ hour or 1 hour [21] increments because such devices as microwaves and blenders are not on and consuming power for a full hour and would be harder to implement into the load demand. Accuracy increases as the increments are smaller, such as five or single minutes and even seconds, but are not chosen since there would a substantial amount of data, and this work has deemed it unnecessary for these specific sets of simulations. Four scenarios are adopted for two seasons of the year: summer day, summer night, winter day, and winter night. Each scenario is over a 12 hour period divided by ten minute increments. These two seasons are chosen because they produce the most extreme temperatures of the year and

affect load consumption primarily for HVAC and lighting. With high temperature and humidity during the summer, air conditioning is turned on more frequently and lighting is less because of the longer hours of sunlight during the day. This is the inverse for the lighting consumption during the winter day; the HVAC is on and consuming power more during night when temperatures are lower. Seasons such as the Spring and Fall produce milder temperatures where load consumption for HVAC is less. Extremes are chosen in all areas of the simulation to test the effectiveness of the MG, primarily by saturating the load with a high demand. The key goal is to see how the system would respond and if the response is effective to such extremes in load consumption. Corresponding seasonal day and night schedules are combined to make 24 hour simulation periods. The schedule for the outlets, kitchen outlets, emergency outlets, and lights, are scheduled from the author's own four person household from several months of observation, and survey questions answered by friends and colleagues (Appendix B, Thesis Surveys sets 1, 2, 3, and 4). Many of the time intervals for white goods are set from [21]. The load values in summer.csv and winter.csv files that are used for the input load data for all simulations are done in Watts, but the simulation program converts all these values into Kilowatts resulting in all load data in KW.

4.2 Load Shedding Schedule

There is significant research conducted and several papers written on load shedding. Load shedding is critical for an MG, especially in island mode, where the process is required. When the load power is greater than the power supplied, load shedding equalizes the power between supply and demand. Devices considered non-critical are shut down to reduce load demand based on what can be supplied, and the most "essential" devices are left on. This is especially important when the MG is disconnected from the main distribution grid switching from a grid-connected mode to island one. If the DG's and DS' cannot supply the load, devices are turned off such that the load can equal the combined DG and DS supplied power. Load shedding is done where devices can be shutoff so as quickly that the system can sustain itself. The scheduling of load shedding was conceived from questioning various colleagues, and the author's own experiences from Hurricane Sandy during October of 2012. The process is split into three tiers. The third tier being the least significant devices to be on and the first tier being the most essential for survival. The devices deemed most important for load shedding have to do with food preservation, and climate control which are deemed vital when limited power is available. White goods are separated in the load shedding scheme and are not grouped together since certain devices are considered more critical than others. In all the other categories (ex. Consumer Outlets, Kitchen Outlets, etc.), the individual devices within the group are summed up and added. This is done due to the fact that most of the devices are connected to outlets, and when the outlet is not supplied, power to all electronic devices are shut off. This load shedding schedule is based on a blackout, where the MG is disconnected from the distribution grid and has stopped supplying power to the MG. The scheduling also takes into account that

the household has prepared itself for disconnection from the grid by having emergency supplies and food in case of power outage.

Tier 3

Dishwasher ⟶ Dryer ⟶ Washing Machine ⟶ Consumer Electronics Outlet ⟶ Lighting ⟶ Kitchen Outlets
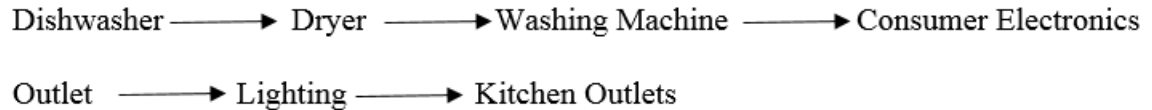
Figure 4.1 Level 3 Tier Orders of Load Shedding.

The first tier of load shedding is seen in Figure 4.1 as Tier 3 load shedding and represents the order of devices to be shutoff. The dishwasher is seen as the least crucial load device since dishwashing can be replaced by hand using soap and water. Washing dishes by hand can reduce the load even more by using cold or lukewarm water reducing the stress on the water heater. The dryer and washing machine can be replaced by hand and is not essential for the two key goals of load shedding: climate control and food preservation. Consumer electronics outlets are seen as creature comforts and can be off. Devices such as the desktop computer and television that are used for news during emergency situations can be replaced by a transistor radio or Tier 2 emergency outlet devices to be discussed later. Lighting is considered non-essential since households should have flashlights, candles, and extra batteries for lighting in case of a power outage. Though food preservation and cooking is a key goal, the kitchen outlets support devices that can be replaced by the electric stove/oven; and devices connected to the kitchen outlets also consume much power.

Tier 2A

Electric Oven/Stove ⟶ Emergency Outlet

Tier 2B

Emergency Outlet ⟶ Electric Oven/Stove

Figure 4.2 Level 2 Tier Orders of Load Shedding.

Tier 2 is separated into two groups: A and B. This decision in the scheduling is based on projected weather forecasting and is derived according to the author's own experience. Tier 2A is chosen if there is a projected forecast such as a hurricane, blizzard, or other forms of severe weather. The Electric Stove/Oven is put on a lower priority due to the fact that members of the household should stock on non-perishable food before a severe weather storm. The Emergency Outlet is important since it is the last outlet that draws power and is used to charge laptops, tablets, and cellphones which are used to communicate to the outside world (family members, friends, and emergency services) through: phone calls, emails, and social media. This is taking into context that many household phones are voice over IP supplied by cable companies. When landline internet services are down landline phones are subsequently also down. This is also taking into account that a local wireless network within the area is still running due to backup generators which was the case for the author after Hurricane Sandy (in the case of the author, the local McDonald's provided free Wi-Fi). These devices also use less power than the desktop computer and can be disconnected from the load if sufficiently charged. Tier 2B is the opposite of 2A and is set for a random blackout. Tier 2A is setup for a major disaster that can result in long term power outage leaving thousands of homes and whole

communities without power. Stressing main distribution provider (utility) crews, resulting in many sections of a distribution grid (utility) and households having to wait for power to be restored. From the author's own experience, the waiting period took one week for power to be restored to the home (that had no backup generator) after Hurricane Sandy due to the time it took for the main distribution grid provider (utility) crews to restore power. Tier 2B is set for a spontaneous utility blackout, where power outage is more isolated in the distribution grid, and the period of power outage is shorter. In this situation convenience of food preparation is more precedent than keeping mobile devices on for communication since blackout time is not expected to be very long, though the possibility exists.

Tier 1A

Refrigerator ⟶ Hot Water Heater ⟶ HVAC

Tier 1B

Hot Water Heater ⟶ HVAC ⟶ Refrigerator

Tier 1C

Hot Water Heater ⟶ Refrigerator ⟶ HVAC

Figure 4.3 Level 1 Tier Orders of Load Shedding.

Tier 1 is setup for weather temperature. Tier 1A is for the cases when the outside ambient critical temperature is lower than 65 degrees Fahrenheit. The refrigerator is the first to be shutoff followed by the hot water heater and HVAC is last. In this scenario, providing enough warmth by HVAC in the household and warm water for hygiene is paramount importance over food preservation, especially in extreme winter temperatures

where inadequate heating in the home can lead to hypothermia or leave an individual susceptible to sickness (which is dangerous for infant children and the elderly). In Tier 1B, the Hot Water Heater is shutoff first, followed by the HVAC, and the refrigerator is the last. This setup takes into account the critical temperature that does not go below 65 or higher than 80 degrees Fahrenheit. In this situation the temperature is in a milder range that is more tolerable, and household members can easily cope with temperature fluctuations by: opening and closing windows, using blankets or wearing lighter and/or heavier clothing, and staying in the shade. Food preservation trumps hot water for hygiene, and air conditioning and heating is not needed for climate control because of the milder temperatures. Tier 1C is defined by having a critical temperature greater than 80 degrees. Climate control is the most important since high temperature extremes can cause dehydration and heat stroke resulting in the HVAC (air conditioning) which is the last device to turn off. With such high temperatures, hot water is not as necessary as in winter conditions. With such high temperatures, the refrigerator is of importance in preserving food. When all devices are shutoff in a Tier 1 category, all devices are shut off in the household.

Situations occur where various inputs are not accounted for, such as powering the refrigerator at all times for insulin preservation for diabetics. This is a generic model that is a guideline for load shedding the in worst-case scenarios, and can be altered depending on certain circumstances. The load shedding schedule is adjusted depending on the predicted forecast. This means that load scheduling should take into account weather and temperature change in the Tier 1 scheduling. For example, if the day after a hurricane, the temperature high was 82 degrees Fahrenheit, then the Scheduling would enter 1C. But, if

the next day was to have a low of 45 degrees, then the scheduling would enter the scheduling tier 1A for the temperature change. This fluctuation of weather change is not reflected in the simulation because it is conducted on a 24 hour schedule, and these changes reflect a scenario where the simulation uses a greater time span.
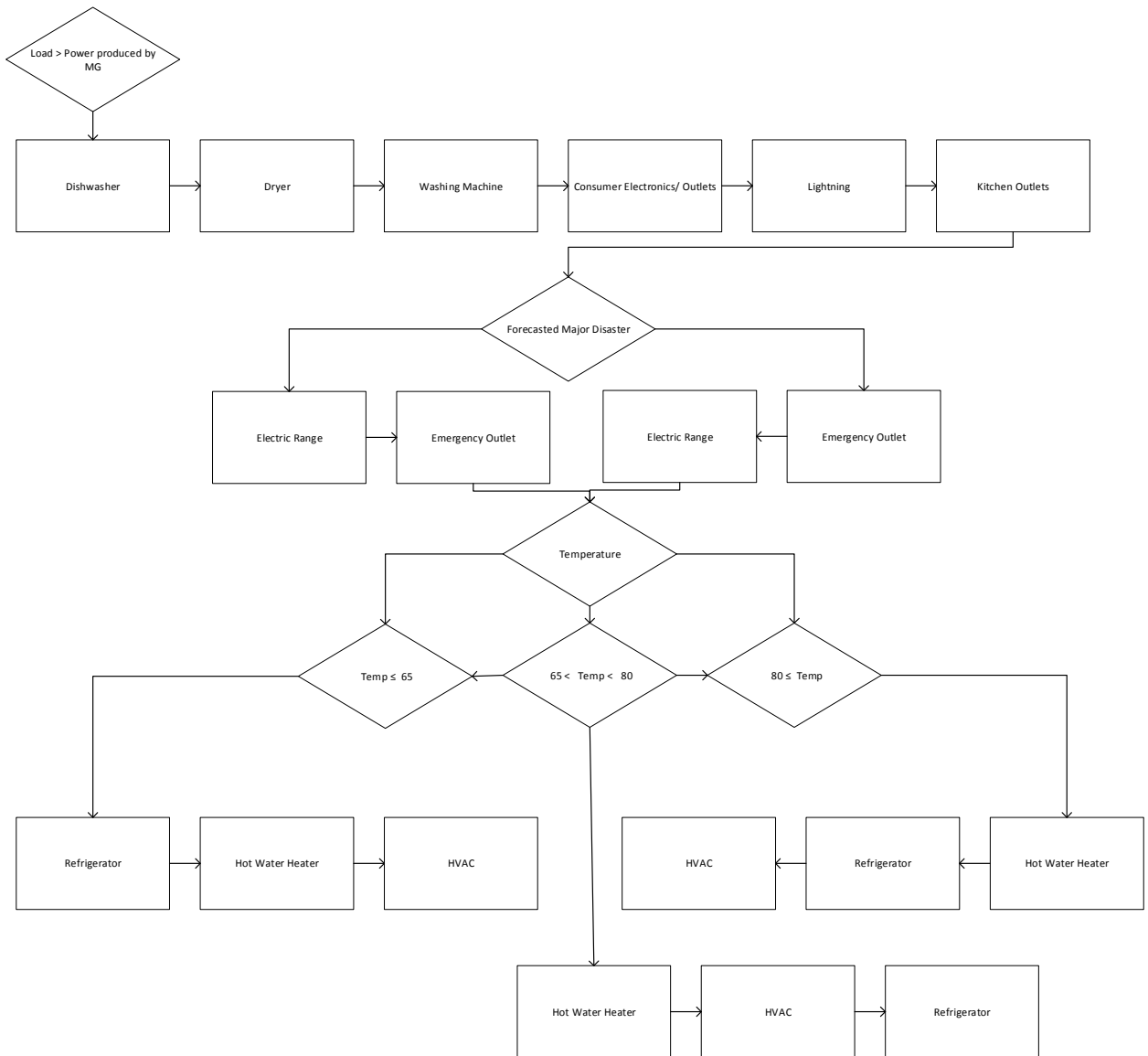
Figure 4.4 Diagram of Load Shedding Schedule.

4.3 De-Load Shedding

The de-load shedding (or reverse shedding) schedule is the reversal of a load shedding process. This process occurs when there is enough energy to turn a device on that was previously shut off during the load shedding process. This is done in the simulation by marking what devices are turned off, and carrying them over to every ten minute interval. If there is power that can be potentially supplied by the MG equal to 1.2 times of the amount of power for the device that is to be turned on, the device is turned on. The program checks and puts in order what devices have been shutoff, and reverses them accordingly. The simulation program carries over the load schedule by time period and starts the device again depending on the schedule the MS has set instead of starting the device at the time that it is put back on. For example, if the dishwasher is shutoff twenty minutes into an hour long schedule at 15:10pm, but is turned back on at 18:10pm, the dishwasher will continue its cycle at 18:10pm and continue on for 40 minutes till 18:50pm; till its cycle is complete, even though the simulation program itself with the input data is running at 18:10pm for all other devices that were not shutoff. Devices that are not able to turn on and consume power when load shedding occurred, but are reversed, are turned on according to the schedule. For example, if the electric stove/oven is not consuming power during the time of load shedding, but was passed over to shutoff a device in level 1 at 17:00pm, then with reverse load shedding occurring at 19:00pm and the electric stove/oven starts consuming power at 19:00pm. These devices that are load shed while they are in its off state are not be able to turn on and consume power until they are reverse shed. The simulation adds the load of the electric stove/oven to the devices that are currently scheduled to be consuming power at the specific time interval and evaluate if the electric stove/oven can turn back on or remain off.

In real life scenarios, certain devices are turned off during a blackout, and do not necessarily turn back on when the power is restored. Many Hi definition televisions do not turn back on after the power is abruptly shut off, and they remain shutoff even when power is restored. This consideration is neglected in the simulation, meaning when a device is restored it is consuming the full amount of power it was consuming before it was shutoff. This was done to stress the load demand on the system to test the reliability of the MG. When the battery is fully charged in any of the four mentioned scenarios, the MG will switch to the Heuristic schedule.

4.4 Discrete Load Shedding Petri Net Model

4.4.1 Load Shedding

All places and transitions in this model are discrete, and the model is bounded by 1. Initial markings with a token in a place are places: p_1, p_5, p_{12}, p_{15}, p_{18}, p_{22}, and p_{26}. Load shedding is divided into multiple levels: level 3 has one tier named Tier 3, Level 2 is separated into Tier 2A and 2B. Level 1 is separated into Tier 1A, 1B, and 1C. A token in p_1 signifies that no load shedding is occurring. When t_1 is fired a token moves from p_1 to p_2 signifying Tier 3 load shedding is occurring. A token in p_5 means no load shedding is occurring in Tier 3. When t_1 is fired, t_7 is fired simultaneously moving the token from p_5 to p_6, signifying that the dishwasher is shut down. Transitions t_7- t_{12} allow the token to move from p_6 to p_{11} signifying that Tier 3 devices are shut down. Please read the load shedding schedule to see the order the devices are shut off in Appendix B. Discrete transitions t_{13} - t_{18} is reverse load shedding, when the token is MOVED from p_{11} to p_5, devices are turning back on. When the token is in p_5 signifying all Tier 3 devices are back on; t_6 fires moving the token from p_2 to p_1 representing load shedding has reversed and all devices are back on. If there is a token in p_{11}, signifying all devices in Tier 3 are shut down and more devices need to be shut off in Tier 2 to reduce the load, t_2 fires to move a token from p_2 to p_3, thereby- enabling Tier 2 load shedding to take place. If there is a forecasted major disaster, Tier 2A load shedding occurs. When t_2 fires, t_{19} simultaneously fires, moving a token from p_{12}, representing that all devices are on in Tier 2A, to p_{13}, which represents shutting down the electric oven/stove by firing t_{19}. A token is placed in p_{14} by firing t_{20}, signifying that the emergency outlet is shut down. Transitions t_{21} and t_{22} allow the token to move from p_{14} to p_{12}, representing Tier 2A is reverse load shedding and the devices are back on until the token is back in p_{12}.

The same applies for discrete transitions t_{23}-t_{26} and places p_{15}, p_{16}, and p_{17}. A token in p_{15} represents that all devices in Tier 2B are on, and places p_{16} and p_{17}, the order of the electric oven/stove and emergency outlet, are switched from Tier 2A. Transition t_{23} fires simultaneously when t_2 does, thus allowing the load shedding of Tier 2B, to occur for the Petri net. When tokens are in places p_{14} and p_{17} and reverse load shedding is to take place, t_5 fires, thereby emptying a token from p_3 and placing a token in p_2 to allow for reverse load shedding to occur in level 3 devices. Level 1 load shedding is separated into Tier 1A, 1B, and 1C. Transition t_3 fires, removing a token from p_3 into p_4 representing that Level 1 load shedding is occurring. Initial markings with a token in a place are in places: p_{18}, p_{22}, and p_{26} signaling that load shedding is not occurring within any level 1 devices. Level 1 Tiers are arranged depending on the temperature extreme. If the temperature is expected to fall below 65 degrees, load shedding Tier 1A occurs in places p_{19}, p_{20}, and p_{21}, using t_{27} - t_{29} for load shedding and t_{30} - t_{32} for reverse load shedding. The same concept applies for Tier 1B, using places p_{22}, p_{23}, and p_{25}, and transitions t_{32}- t_{34} for load shedding and de-load shedding, in which the order of devices shed compared to Tier 1A is changed. Transition t_{32} is fired if level 1 load shedding is occurring with the high and low temperatures between 65 and 80 degrees Fahrenheit. The same concept is used for Tier 1C, using places p_{26}, p_{27}, and p_{28} using transitions t_{38}- t_{43} for load shedding and reverse shedding, t_{38}, is fired when level 1 devices are being shed with the temperature exceeding 80 degrees Fahrenheit. If a token is in either p_{21}, p_{25}, or p_{29}, all level three load devices are off, resulting in all load devices being shutoff with no load being consuming power in the MG. Tokens are in places p_{18}, p_{22}, and p_{26}, meaning that all level 3 devices are in either load shedding or de load shedding process is for devices in level two to turn on. A token is removed from p_4 and t_4 fire. Thus

putting a token in p_3 allowing the load shedding and reverse load shedding process to occur in level two electronics.
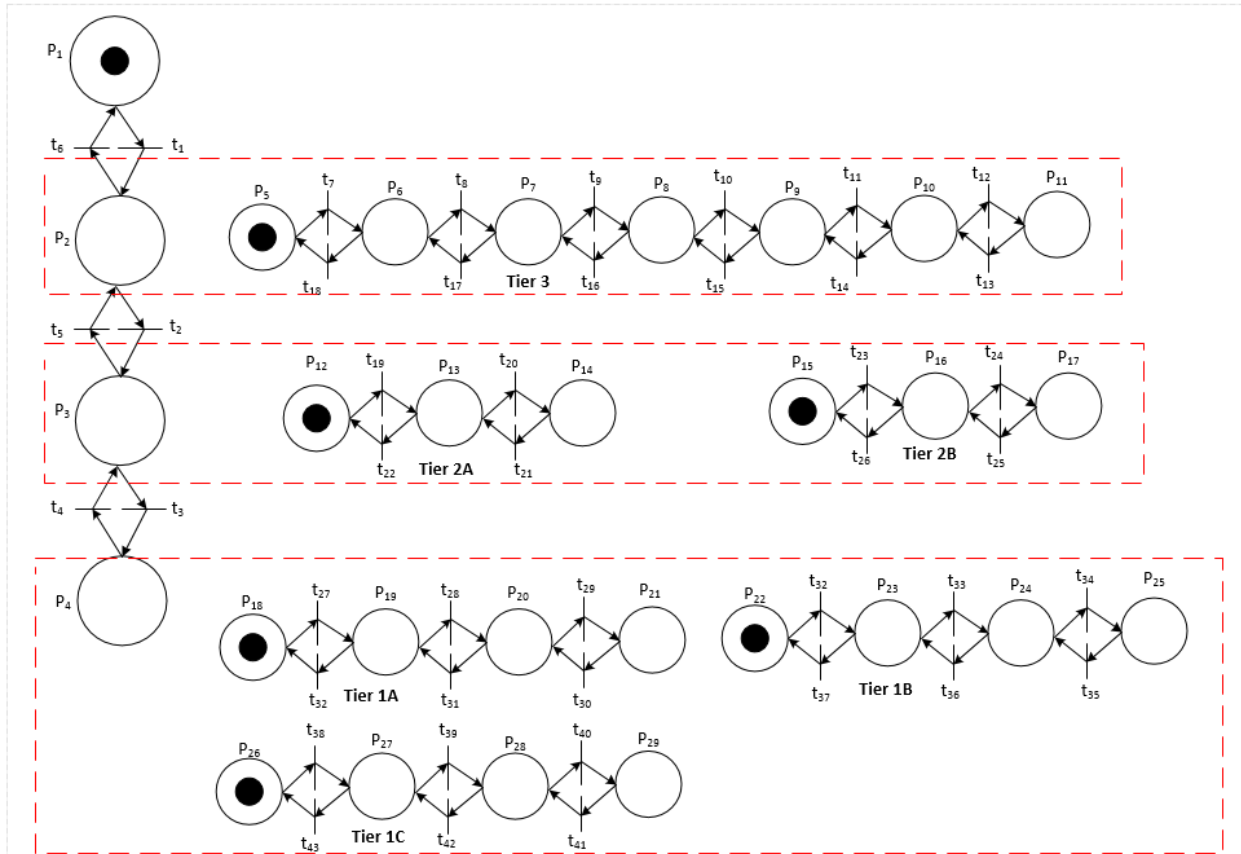
Figure 4.5 Model of Discrete Load Shedding.

Table 4.2 Meanings of Places and Transitions for Discrete Load Shedding Model

P_D	p_1	System is not in load shedding phase
	p_2	System is in load shedding phase tier 3 – loads have to be shed
	p_3	System is in load shedding phase tier 2– loads have to be shed

	p_4	System is in load shedding phase tier 1– loads have to be shed
	Tier 3	
	p_5	Tier 3 electronics are not in load shedding phase
	p_6	Dishwasher is turned off, all proceedings devices are off, all other devices are on
	p_7	Dryer is turned off, all proceedings devices are off, all other devices are on
	p_8	Washing machine is turned off, all proceedings devices are off, all other devices are on
	p_9	Consumer electronic/ outlets are off all proceedings devices are off, all other devices are on
	p_{10}	Lighting is turned off, all proceedings devices are off, all other devices are on
	p_{11}	Kitchen outlets are turned off, all proceedings devices are off, all other devices are on
	Tier 2 A	
	p_{12}	Tier 2A electronics is not in load shedding
	p_{13}	Electric Oven/ Stove is off, all proceedings devices are off, all other devices are on
	p_{14}	Emergency Outlet is shutoff, all proceedings devices are off, all other devices are on
	Tier 2 B	
	p_{15}	Tier 2B electronics is not in load shedding
	p_{16}	Emergency Outlet is shutoff, all proceedings devices are off, all other devices are on, all proceedings devices are off, all other devices are on
	p_{17}	Electric oven/ Stove is shutoff
	Tier 1 A	
	p_{18}	Tier 1A electronics is not in load shedding
	p_{19}	Refrigerator is shutoff, all proceedings devices are off, all other devices are on
	p_{20}	Hot water heater is shutoff, all proceedings devices are off, all other devices are on
	p_{21}	HVAC is shutoff
	Tier 1 B	
	p_{22}	Tier 1B electronics is not in load shedding
	p_{23}	Hot water heater is shutoff, all proceedings devices are off, all other devices are on
	p_{24}	HVAC heater is shutoff, all proceedings devices are off, all other devices are on
	p_{25}	Refrigerator is shutoff, all proceedings devices are off, all other devices are on
	Tier 1 C	
	p_{26}	Tier 1C electronics is not in load shedding
	p_{27}	Hot water heater is shutoff, all proceedings devices are off, all other devices are on
	p_{28}	Refrigerator is shutoff, all proceedings devices are off, all other devices are on
	p_{29}	HVAC is shutoff, all proceedings devices are off, all other devices are on
T_D	Transitions	
	t_1	Load shedding is entering tier 3 load shedding
	t_2	Load shedding is entering tier 2 load shedding
	t_3	Load shedding is entering tier 1 load shedding
	t_4	Load shedding is ending and all electrical devices are on
	t_5	Load shedding is reversing all Tier 2 devices are on and Tier 3 are being turned on
	t_6	Load shedding is reversing all Tier 1 devices are on and Tier 1 are being turned on

Table 4.2 Continued Meanings of Places and Transitions for Discrete Load Shedding Model

	Tier 3	
	t_7	Dishwasher is shutting off
	t_8	Dryer is shutting off
	t_9	Washing machine is shutting off
	t_{10}	Consumer electronics/outlets are shutting off
	t_{11}	Lighting is shutting off
	t_{12}	Kitchen outlets are shutting off

t_{13}	Kitchen outlets are turning back on
t_{14}	Lighting is turning back on
t_{15}	Consumer electronics/outlets are turning back on
t_{16}	Washing machine is turning back on
t_{17}	Dryer is turning back on
t_{18}	Dishwasher is turning back on/ all tier 3 electrical devices are back on
Tier 2 A	
t_{19}	Electric Oven/Stove is shutting down
t_{20}	Emergency Outlet is shutting down
t_{21}	Emergency Outlet is turning back on
t_{22}	Electric Oven is turning back on/ all tier 2A level electronics are back on
Tier 2 B	
t_{23}	Emergency Outlet is shutting down
t_{24}	Electric Oven/Stove is shutting down
t_{25}	Electric Oven/Stove is turning back on
t_{26}	Emergency Outlet is turning back on
Tier 1 A	
t_{27}	Refrigerator is shutting down/Tier 1A load shedding phase is beginning
t_{28}	Hot water heater is shutting down
t_{29}	HVAC is shutting down
t_{30}	HVAC is turning back on
t_{31}	Hot water heater is turning back on
t_{32}	Refrigerator is turning back on/all tier 1A level electronics are back on
Tier 1 B	
t_{33}	Hot water heater is shutting down/ Tier 1Bload shedding phase is beginning
t_{34}	HVAC is shutting down
t_{35}	Refrigerator is shutting down
t_{36}	Refrigerator is turning back on
t_{37}	HVAC is turning back on
t_{38}	Hot water heater is turning back on/ all tier 1B level electronics are back on
Tier 1 C	
t_{39}	Hot water heater is shutting down/ Tier 1C load shedding phase is beginning
t_{40}	Refrigerator is shutting down
t_{41}	HVAC is shutting off
t_{42}	HVAC is turning back on
t_{43}	Refrigerator is turning back on
t_{44}	Hot water heater is turning back on/ all tier 1C level electronics are back on

4.4.2 Load Shedding and De Load Shedding Values for Output Data

Load shedding occurs the in island mode, where the combination of power from the DG's

and power provided from battery discharging cannot provide enough power for the load;

load demand is greater than power provided. Devices are shutoff to lessen the load with the

simulation program taking note of which devices are shutoff, and hypothetically adding them to the next time segment to see if it can de load shed. The simulation program creates a phantom load that is not indicated in the output. The devices that are shed are multiplied by 1.2 and added to whatever devices are currently on during the next time segment. The phantom load is larger than the actual load to be de shed. This is to test to see if the system can provide consistent power for the devices to be de shed, such that they do not end up in the process of switching on and off every ten minutes. The initial number for multiplication is 2, but that is deemed too high and devices are shutoff for the remainder of the simulation once they were shed. If the hypothetical load is still greater than what the MG can provide in power, the program keeps the devices off in the load shedding phase which is indicated in the load shedding column of the output excel sheets. If one device can be turned back on during load shedding the program turns that device back on. Power available is the summation of: the power produced by the combination of wind and solar, the maximum power the battery can discharge, and the addition of the maximum power the generator can provide (its rated value). An example of this is done in simulation 1 with inputs in Table 4.3.

Table 4.3 Simulation 1 Program Inputs

Simulation #	Temperature	Disaster	Grid Connected	Schedule	Generator	Season	Battery
1	94	Yes	No	1	8	Summer	12

This means that the simulation is using the summer input data for the simulation with the critical temperature at 94 degrees Fahrenheit and is in an island mode. Since it is not connected to the distribution grid, it has to use the generator with a rated value of 8 kW

in this simulation. The temperature affects the order of load shedding for Tier 1 and the disaster affects the order of load shedding in Tier 2. For a temperature of 94 degrees, which is greater than 80 degrees Fahrenheit, and a "yes" in the disaster input, the order of load shedding in Tier 2 is 2A and 1C in Tier 1. By corresponding the output results of simulation 1 with the load summer schedule one can see at 17:10 as shown in Table 4.4.

Table 4.4 MG Load at 17:10

Device/ Category	Power Consumption (kW)
Refrigerator	0.145
Dishwasher	0
Washing Machine	0
Dryer	0
Water Heater	0
Range/Oven	6.4
HVAC	2.3
Lights	0
Kitchen Outlets	0
Outlets	0.877
Emergency Outlets	0.084
Total	9.806

By adding these values, the total load is equal to 9.806 kW which is v_{10} in the simulation results. The MG gives enough power to supply this as shown in Table 4.5.

Table 4.5 Firing Rate Output at 17:10

Firing Rate	Firing Rate Representation	Output power (kW)
v_1	Wind Power mode 1	0
v_2	Wind Power mode 2	0
v_3	PV Power	2.282
v_4	Generator Output	6.876
v_5	Battery Discharge	0.646
Sum Firing Rates	$v_1 + v_2 + v_3 + v_4 + v_5$	9.806

Now let's look at the next time segment, 17:20, for the load as shown in Table 4.6.

Table 4.6 MG Load at 17:20

Device/ Category	Power Consumption (kW)
Refrigerator	0.145
Dishwasher	0
Washing Machine	0
Dryer	0
Water Heater	4.5
Range/Oven	6.4
HVAC	0
Lights	0
Kitchen Outlets	0.300
Outlets	0.877
Emergency Outlets	0.084
Total	12.22

The water heater has turned on along with the kitchen outlets consuming power, and the HVAC turned off, the resulting load total now is equaling 12.22 kW. Now let us look at the available power the MG can provide as shown in Table 4.7.

Table 4.7 Firing Rate Output at 17:20

Firing Rate	Firing Rate Representation	Output power (kW)
v_1	Wind Power mode 1	0
v_2	Wind Power mode 2	0
v_3	PV Power	1.461
v_4	Generator Output	8

For the battery discharging rate v_5, calculate the potential power the battery can offer. Using the value of the energy in the battery (kWh) from the energy in the battery from 17:10, the battery has 23.82 kWh of energy stored. Using (3.7) and (3.8), and plugging in 23.82 kWh for f(x), we have: $7.81/(10^{(23.82-4.4929)/17.969}) = 0.656\ kW$. Adding the potential power together, we obtain: 0+0+1.461+8+0.656 = 10.117 kW that the MG can provide, which is less than the load, thus resulting in the MG having to load shed devices. Load shedding all Tier 3 devices and the electric range/oven in tier 2A leaving the refrigerator and water heater on. This new load is shown in Table 4.8.

Table 4.8 MG Load at 17:20 after Load Shedding

Device/ Category	Power Consumption (kW)
Refrigerator	0.145
Dishwasher	0

Device/ Category	Power Consumption (kW)
Washing Machine	0
Dryer	0
Water Heater	4.5
Range/Oven	0
HVAC	0
Lights	0
Kitchen Outlets	0
Outlets	0
Emergency Outlets	0.084
Total	4.729

The new load total equals 4.729 kW which is v_{10} at time segment 17:20, shaving 7.491 kW.

To mimic the devices turning back on during reverse load shedding, the value of the power

of the devices that are zeroed out are carried over to the next time segment. To illustrate

this, consider the original load schedule for 17:30 in Table 4.9.

Table 4.9 MG Load at 17:30 Using Original Load Scheduling

Device/ Category	Power Consumption (kW)
Refrigerator	0.027
Dishwasher	0
Washing Machine	0
Dryer	0
Water Heater	0
Range/Oven	6.4
HVAC	0
Lights	0
Kitchen Outlets	0
Outlets	0.877
Emergency Outlets	0.084
Total	10.061

The load total is 10.061 kW but since the devices that were shutoff: Dishwasher,

Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, and Range/Oven, values that

were in 17:20 will carry over into the next time segment. This is done for the devices that

were not load shed resuming the values of the original schedule. The new load is given in

Table 4.10.

Table 4.10 MG Load at 17:30 after De-Load Shedding

Device/ Category	Power Consumption (kW)
Refrigerator	0.027
Dishwasher	0
Washing Machine	0

Dryer	0
Water Heater	0
Range/Oven	6.4
HVAC	0
Lights	0
Kitchen Outlets	0.300
Outlets	0.877
Emergency Outlets	0.084
Total	7.663

The new load total is 7.663 kW, but the program multiplies the load of devices that are to be load shed by 1.2 and adds it to the time segments devices that were not load shed. The phantom load looks like: $[(6.4 + 0.300 + 0.877) \times 1.2] + 0.027 + 0.084 = 9.2034$ kW. If the potential power of the MG is equal or greater to this value, then the MG de load shed all devices. The potential power of the MG is found in Table 4.11.

Table 4.11 Firing Rate Output at 17:10

Firing Rate	**Firing Rate Representation**	**Output power (kW)**
v_1	Wind Power mode 1	0
v_2	Wind Power mode 2	0
v_3	PV Power	0.864
v_4	Generator Output	8
Sum of firing rates	$v_1 + v_2 + v_3 + v_4 + v_5$	9.528

For the power, the battery can discharge. Take the energy in battery from 17:20, i.e., 23.72 (kWh), and plug it into (3.7) and (3.8.), thereby leading to: $7.81/\left(10^{(23.72-4.4929)/17.969}\right) = 0.664 \, kW$. The total potential power of the MG is 9.528 kilowatts, which means that the power that can be supplied by the MG is greater than 9.2034 kW, allowing the system to de load shed all devices, resulting in $v_{10} = 7.663$ kW in time segment 17:30. If the potential power of the MG is less than 9.2034 kW, the system de load sheds in reverse order, which means the system would exclude the outlets, leaving it off, and the phantom power would be $[(6.4 + 0.300) \times 1.2] + 0.027 + 0.084 = 8.15$ kW. If this value is still less than the potential MG power, than the system would leave the Kitchen outlets off, leaving the phantom load equation as: $(6.4 \times 1.2) + 0.027 + 0.084 =$

7.791 kW. If this value is still greater than the MG potential power, than the system would keep the range/oven off. All devices off for that particular time segment are shown in the load shedding column in the output excel file. This is seen in Simulation 10 where load shedding occurs till the end of the simulation. Devices that have been included in the load shedding process, but were not consuming power when the load shedding process occurred such as the: Dishwasher, Washing Machine, Dryer, HVAC, and Lights have the value of zero in the 17:20, but are still load shed. In reality, this shows the devices that were off will not be able to turn on until they are reversed by de load shedding process.

CHAPTER 5

PETRI NET SIMULATION

5.1 Scheduling

5.1.1 Heuristic Scheduling

There are two microgrid simulation scheduling paradigms: a basic heuristic scheduling, and one based on reliability rather than optimization considerations.

The first one is straightforward: it produces a load for the microgrid. Wind and solar power provides power to the grid first, if excessive power is produced, (i.e., the combination of distributed generation being greater than the load), then it charges the battery. If the battery is fully charged or there is excessive power that is greater than its charging rate, then this excessive power is sent back to the main distribution grid as long as the MG is connected to it. If the MG is disconnected from the main distribution grid ("island mode"), the excessive power is dissipated, since it cannot be used for anything else. Power dissipation is a function setup specifically for this simulation, only.

Potential power generated by the distributed renewable generators is calculated by using firing rate data. In practice, the combination of distributed generators provides the amount of power that is needed by the load (including battery charging) along with losses, but firing rates are set-up such that the distributed generators provide more power than what is needed for the load.

In grid-connected and island modes, a battery can be charged, but the power that can be used for charging is limited. Although the simulation assumes a full power load based on the total capacity, in a practical scenario, only enough power is used to fulfill the load. When distributed generation produces less power than the load, energy is discharged

from the battery in the form of power to compensate for the power deficit. When the battery cannot provide the power needed to compensate for the load (due to the limit of power it can discharge or being depleted of energy), in a grid connected mode, the main distribution grid provides all the remaining power for the load. When the microgrid is in an island mode, the backup generator compensates for the load demand. If the generator cannot match the power for the load, a load shedding scheme occurs until the power from the combination of DG, DS, and generator power matches or is greater than the load demand.

5.1.2 Reliability Scheduling

Many papers discuss the optimization of power usage in microgrids [6] [31]. Reliability scheduling derives from the work of Chris Maynard and Aquion Energy, Inc [11] [19]. It is based on reliability and structure, rather than efficiency and optimization. It is intended to limit transients and switching. Reliability scheduling is designed to charge the battery to provide enough power to the MG during peak load time periods, which is normally during afternoon and evening hours. It is used during times when the load is at its lowest, especially during late night and early morning hours when people are asleep, and most devices are shut off.

An MG is programmed to automatically switch between Reliability Scheduling and Heuristic Scheduling, according to the output/load balance. The battery does not discharge during Reliability Scheduling, but is being charged or remains idle. To achieve this, the system first checks to see how much renewable power is produced. If this combination exceeds battery charging power while the battery is at its maximum charge level in addition to providing all power for the load, it then provides the main grid with this extra

power in a grid-connected mode, or dissipates it in an island mode. During Reliability

Scheduling, if the renewable generators cannot sufficiently charge the battery at its

maximum recharge rate, the battery supplements its recharging rate up to the maximum by

using the main grid, when it is in a grid-connected mode. In an island mode, the MG uses

the natural gas generator to provide for the load and supplement the battery recharge.

Two criteria must be met before the system use supplemental recharging protocols:

> 1) The rated power of the generator must be greater than or equal to 4kW (4 kW is
> selected from the observations of the Winter and Summer load schedules. From 11:00
> to 4:00, with the exception of a few time periods, the load has consistently been under 4
> kW); and

> 2) The load must be less than 4 kW.

These criteria ensure that the generator has sufficient power to provide for the load

while charging the battery simultaneously. If the generator is rated less than 4kW, the

scheduling is switched to Heuristic one. In Reliability Scheduling mode, if the rated value

of the generator is greater than 4kW but the load exceeds or equals 4kW, the system is

reverted to Heuristic one until the load is below 4kW.

Battery charge rate is determined by the total battery charge level, that is, the

maximum charge rate decreases as the battery approaches its maximum charge. This

decreases the load on the system. When the generator produces less power than the existing

load plus the maximum battery recharging rate, priority is given to the load first, and any

excessive power is used to charge the battery at a lower than the maximum rate. Fig. 5.1

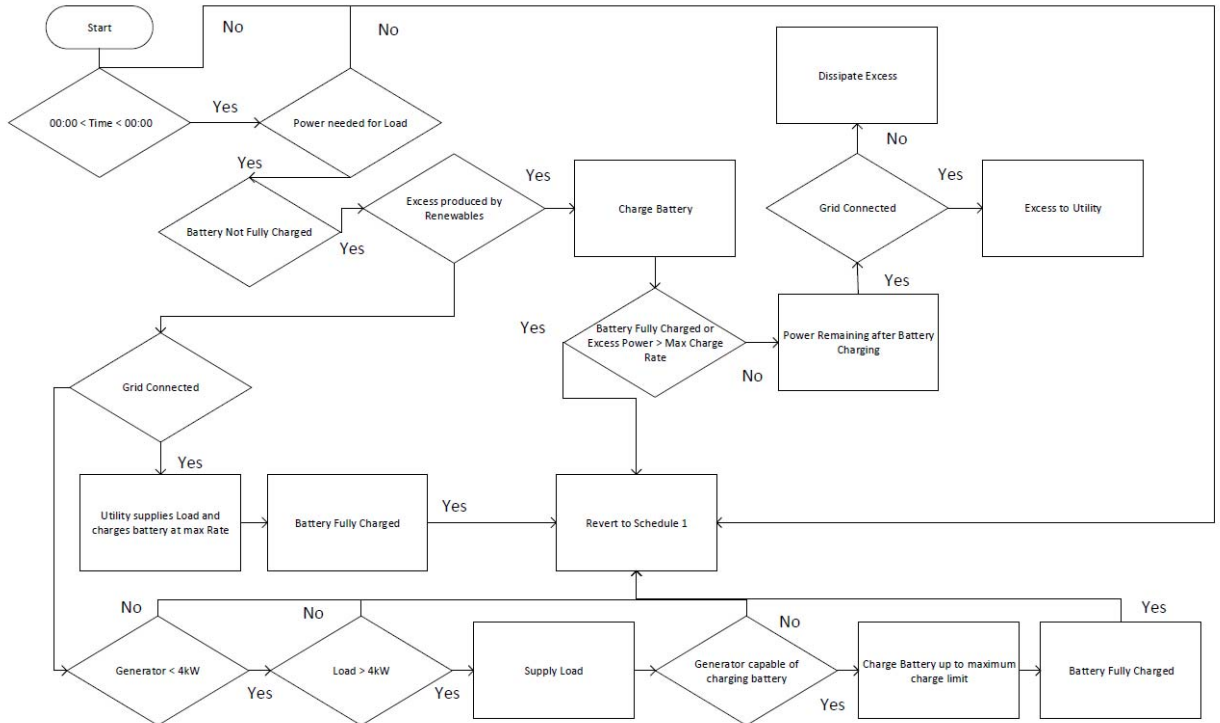gives Reliability Scheduling for the HPN model.

Figure 5.1 Reliability Scheduling for the HPN model.

5.2 Weather Data

Input data is collected from the New Jersey Weather and Climate program [21] run by the Rutgers meteorology program. The days selected are January 11, 2015 with a low of 12 degrees Fahrenheit for simulation of a cold winter day, and July 2, 2014 with a high of 94 degrees Fahrenheit for a hot summer day with the measurements for the meteorological data obtained from its website http://www.njweather.org/station/1101. This is found at the 5-minute data portal on the meteorological data, and selecting the meteorological data and date desired. The two sample days are chosen for the simulation criteria because of ideal simulation conditions: little to no precipitation, ample solar energy, and high and low temperatures typical of the season. Measurements taken for the simulation: are temperature given in Fahrenheit, 5 min barometric pressure given in inHg, 5 minute precipitation, 5 minute Solar Radiation given in W/m^2, 5 minute temperature average given in Fahrenheit, 5 minute wind speed average given in mph, 5 minute wind direction, 5 minute dew point given in Fahrenheit, and 5 minute dew point given as a percentage. All the data is detailed in four files (excel and .pdf) downloaded from the New Jersey Weather and Climate program. Data is given in five minute increments, and every other increment is used (i.e. 10 minute periods) for the simulation. Five minute wind speed (converted from mph to meters per second), and 5 minute barometric pressure, and dew point are used for air density calculations [25]. It is important to note that though the firing rate for Solar power uses Solar irradiation, solar radiation given by the meteorology data is used as solar irradiation inputs for the simulation for simplification purposes.

Solar radiation data is simplified for three reasons:

1) Solar radiation measurements are given in W/m^2. Both solar radiation and solar irradiation use the same metric

2) Solar radiation measurements are between 0 and 1000 W/m^2 which adheres to realistic measurements (Solar irradiance hitting the surface of the earth is normally not greater than 1kW/m^2, and is stressed because certain environmental factors such as altitude reflection off snow can cause solar irradiation hitting the earth's surface to be greater than 1kW/m^2, but this is not considered in these simulations); and

3) The solar irradiation data follows the path of solar irradiation data for the time periods of the day when the output is greater than 0. Note that the output is zero during night and early morning hours, and greater than zero during daylight hours.

Data that is used for calculations and converted for the firing rate equations are then put into Microsoft Excel csv files the program uses for its input data of the firing rates. The data presented in the excel csv files are: time, temperature, air density, precipitation, solar radiation, temperature, wind speed average, and wind direction. Please note that only solar radiation, air density, and wind speed average are extracted by the program for the firing rate calculations. The csv files are arranged in 5-minute increments corresponding to their days, summer and winter and are labeled summerwindspeed.csv and winterwindspeed.csv, respectively. Each day (24 hours) is split into 5 minute data points totaling 288 rows of data, and the program only selects every other time period or multiple of ten minutes (ex: 00:00, 00:10, 00:20, etc.) with the program outputting 145 rows of markings; from 00:00 to 23:50. Each 10-minute increment is the average of that 10 minutes, meaning the solar power output of 00:00 should be interpreted as the average solar power from 00:00 to 00:09. Temperature should be read by users and the extreme temperature meaning the highest temperature in a summer day (94 for the summer simulation), or lowest temperature (12 for the winter simulation) in a winter day should be selected for the temperature input that is typed in the beginning of the simulation used for the load shedding process (critical temperature). Five-minute precipitation was used to observe if there was precipitation during the days, simulations were based on days with little to no

precipitation (rain, snow etc.). This work intends to conduct the simulation by using data that is unaffected by snow or rain storms.

5.3 Barometric Pressure Calculations

Air Density is crucial for wind turbine calculations. By using five-minute Barometric Pressure and temperature in Fahrenheit, this work finds air density for each time period for January 11, 2015 (winter day) and July 2, 2014 (summer day). The steps taken corresponding to the calculations are done in excel, and can be found in Appendix C.

5.3.1 Dew Point Conversion

Convert Dew Point Average from Fahrenheit to Celsius:

$$T_C = (T_F - 32) \times \left(\frac{5}{9}\right) \tag{5.1}$$

5.3.2 Vapor Pressure

Using the Herman Wobus polynomial, this work for finds the vapor pressure [4]:

$$p = c_0 + T(c_1 + T(c_2 \tag{5.2}$$
$$+ T(c_3 + T(c_4 + T(c_5 + T(c_6 + T(c_7 + T(c_8 + T(c_9)))))))))$$

T = air temperature (degrees in Celsius)

$c_0 = 0.99999683$

$c_1 = -0.90826951 \cdot 10^{-2}$

$c_2 = 0.78736169 \cdot 10^{-4}$

$c_3 = -0.61117958 \cdot 10^{-6}$

$c_4 = 0.43884187 \cdot 10^{-8}$

$c_5 = -0.29883885 \cdot 10^{-10}$

$c_6 = 0.21874425 \cdot 10^{-12}$

$c_7 = -0.17892321 \cdot 10^{-14}$

$c_8 = 0.11112018 \cdot 10^{-16}$

$c_9 = -0.30994571 \cdot 10^{-19}$

Column Temp is the temperature in Fahrenheit which is converted to Celsius in column Temp C. Columns C_0 through C_9 for ease of calculation are constant numbers for calculations. Column C_9 multiplied by the corresponding temperature from column Temp C. Column C_0 is the result of column 1b added to C_8 multiplied again by the corresponding temperature from column Temp C following (3.2). Column 1j is the result of using equation (3.2) with all the addition and multiplication of the constants (C_9 through C_1) and temperature added to C_0 completing 1d.

$e_{so} = 6.1078$

The value for e_{so} is in column e_{so}.

$$E_s(hP_a) = \frac{e_{so}}{p^8} \qquad (5.3)$$

Column Es is the value of e_{so} divided by Column 1j raised to the eighth power equaling E_s (saturation pressure) [5].

$$P_v(hPa) = E_s \text{ at } T_{dewpoint} \qquad (5.4)$$

Dew point is in column 5minDewPoint as Fahrenheit and column next to 5mindewpoint as a percentage, column 5mindewpoint divided by 100.

$$P_d(hPa) = P(hPa) - P_v(hPa) \qquad (5.5)$$

P$_v$ or air pressure due to water vapor is E$_s$ multiplied by 100 to convert in Pa in column Pv(hPa). Column 5minBPa Avg is barometric pressure given by Rutgers meteorology in inHg. Column P (hPa) takes the data in 5 MinBP Avg and converts it into Pa by multiplying the corresponding value by 3386.389. Column Pd takes the total barometric pressure in Pa (P which is column 5 MinBP Avg) and subtracts it from the barometric pressure of water vapor, P$_v$ (column Pv(hPa)) to obtain the barometric pressure of dry air, column Pd in pascals.

5.3.3 Air Density

This work uses the equation for density from [28]:

Density = D

Mass = M

Velocity = V

$$D = \frac{m}{v} \qquad\qquad (5.6)$$

The specific gas constant [14]:

$$R = \frac{R_G}{M} \qquad\qquad (5.7)$$

R= Specific Gas Constant

R$_G$ = Universal Gas Constant

M = Molar Mass

$$\frac{1}{R} = \frac{M}{R_G} \qquad\qquad (5.8)$$

Using the equation for air density in moist air from [25] and substituting $z=1$ and $f=1$, we have the equation for air density in moist air as follows:

$$Rho(kg/m^3) = \left(\frac{P_d}{R_d + T_k}\right) + \left(\frac{P_v}{R_v + T_k}\right)$$ (5.9)

P_d = pressure of dry air, Pascals

P_v = pressure of water vapor, Pascals

T = Temperature, Kelvins

R_v = gas constant for water vapor= 461.4964 (J/kgK)

R_d = gas constant for dry air=287.0531 (J/kgK)

The temperature in column A, Fahrenheit, is converted to Kelvins. Column AL labeled as "1" is the numerator value of the equation for Rho, and Rho is the denominator value labeled as "2". This Column is the air density which is the corresponding value from column 1 divided by 2.

The last column Rho is the values in the first Rho column flipped. This is done for both for the summer day and the winter day (See Appendix C Air Density Calculations).

5.4 Simulation Programs

The simulation consists of three programs, two of which are written in Python, with the remaining program written in php. The first simulation program, main2_gfu2.py, uses the input data and outputs the results into an excel sheet with: time period, discrete places p_1-p_{10}, continuous places p_{11}-p_{14}, firing rates v_1-v_{11}, load total, which is the same as v_{10}, and load shedding column which shows the devices and order they are shed in. The first part of the program defines the inputs that are put in by a user. The second part is the code for the load shedding and de-load shedding processes. The third segment extracts the input data from the csv file for the wind calculations, and the functions for wind and solar. There is also an eminuscalc function which prevents the simulation from allowing the battery to go below 6.3995 kWh which is the lowest value for the energy in the battery for the simulation. Chargehour and dischargehour define the maximum amount of power the battery can discharge or charge for that specific time segment in the simulation seen in Appendix E. The fourth part of the code defines and sets the scheduling for Heuristic and Reliability scheduling for the simulation while also defining the outputs for the discrete and continuous places, and certain firing rates such as: v_4, v_5, and v_6. The fifth part of the program defines the functions and outputs for places and firing rates for: the main distribution grid, generator, and power dissipation. Increasetime allows the program to take input data from every 10-minute segment in order for the simulation, and exceldebug outputs the data to the excel sheet. The sixth and final parts define and outputs the firing rates for the program.

The second Python program, csvTest.py, takes the results from the output csv file from Program 1, and shows the transitions that are fired, while also setting the values for

the firing rates and places for placement into the reachability graphs. Wind power, solar, the main distribution grid, and generator are discrete places that use discrete transitions. The program shows which transitions are fired by taking the input data of one segment and comparing it to the next segment, for example if p_1, p_2, and p_3 for the wind turbine are 1 0 0 for 04:00 which means the wind turbine is in mode 1, but switches to mode 2 to 0 1 0 at 04:10, transition t_{13} is fired. There are six possibilities of the combination for p_1, p_2, and p_3 because there are six discrete transitions, but only one transition can be fired per segment. This is the same for the main distribution grid. The PV and generator have only two discrete transitions each because they have only two places. The program sees the value for each set of places for each device:

Table 5.1 Places for Discrete Transitions php Program

DG or Main Distribution Grid	Places
Wind	$p_1\ p_2\ p_3$
PV	$p_4\ p_5$
Generator	$p_6\ p_7$
Main Distribution Grid	$p_8\ p_9\ p_{10}$

The program observes how the order of the values changes and labels the corresponding transition if a change occurs. If the continuous transitions are firing and producing or consuming power, the transition is outputted. For example, the PV is producing power, t_3 is outputted in the excel sheet. The output excel file for the second program is the same as the first but with added columns for each time segment: the places that are both continuous and discrete are put together in one column. All the values for the firing rates are put into the next column. Discrete transitions that are fired, and continuous transitions are in the last column. These columns are created to show the transitions that are fired, and to show the values of the places and firing rates for the php program. Php is chosen because of the ease of outputting the data in a reachability form onto a website. A

84

reachability graph for an HPN has the time segment tau displaying both discrete and continuous places, and whichever discrete transitions that are fired are displayed on the left of the first arrow. Another arrow goes down from the place showing the time segment tau again, and both continuous and discrete places; but on the right of the arrow the continuous transitions that are fired are displayed with the values of the firing rates below. The testColumns.php file outputs the results in one single column onto the website. This setup is done for ease of outputting reachability graphs for two or more simulations. The Simulation Programs can be seen in Appendix E.

5.4.1 How to Run the Simulation Programs and Obtain Reachability Graphs

The first part of the process is to run the code for the first program to obtain an output csv file and then close it. The main HPN simulation program, main2_gfu2.py is opened by using IDLE. The program is then run. When the program is run, the output data Excel sheet automatically opens. This Excel sheet is saved in the test_Gabe.csv in the hard drive. Then open the second Python program, and run the program. After closing the Excel data sheet. The csvTest.py program is opened. This program is to show the discrete and continuous transitions that are fired during each time delay. The csvTest.py program is then run. When this program is compiled a new Excel sheet is created with labeled transition_output.csv that is the same as the output.csv Excel sheet but now with the transitions that are fired corresponding to the time as columns. This file is saved in the hard-drive. This takes data from the first excel csv file and create a new csv file that outputs the data that was explained previously. The WinSCP program is opened, and the user has to login. The user can to connect with the NJIT server for the php programs to output the data from the transition_output.csv to an online website by using program test.php for a single column

outputted on the website https://web.njit.edu/~jsm53/thesis/test.php. The php files and transistionoutput.csv file are on the right column. The user has to click the transistionoutput.csv file on the left and drag it to the transitionoutput.csv file on the right, and then click "yes" when asked to replace. This is done by clicking the transition_output.csv from the left of the c:\Python27\joshThing on the left and dragging it the right and placing it over transition_output.csv and releasing the right mouse clicker. The program asks if the user wants to overwrite the program, and by clicking "Yes", the new output data from transition_output.csv can be used to create the Reachability Graphs. The user then goes on to the websites to view the reachability graphs. These graphs are captured by using Google screenshot on Chrome, and saved as a JPEG file. Using Google Chrome with the Chrome Screenshot app, screenshots were taken of the reachability graph that is outputted on the website https://web.njit.edu/~jsm53/thesis/test.php. By clicking on the camera icon on the top right of the browser (Chrome screenshot), a screenshot of the webpage is taken. This is then placed and edited with Microsoft Word for the arrows going from delay to delay.

The pictures of the program are then put on Microsoft word and additional arrows are placed for the reachability graphs on Microsoft Word, and a reachability graph of the HPN is edited on MS Word (draw red boxes around certain values and draw arrows).

5.5 Introduction to Simulation

Thirteen scenarios are simulated with the inputs chosen to reflect the system in different situations. Please note that simulation 13 is used for Reachability Graph comparison purposes.

These simulations are intended to test the reliability of the MG under varying conditions. Most of the simulations are done in an island mode (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 13) to show how the system would respond when disconnected from the main distribution grid. Simulations 11 and 12 show the MG responding when it is connected to the main distribution grid. The simulation has seven inputs to enter before the actual simulation starts. They are:

Temperature: The critical temperature (highest in the summer, lowest in the winter, effects load shedding tier 1)

Disaster: Yes or No (Is there a projected forecast of a natural disaster for the day such as a blizzard or hurricane, affects load shedding tier 2)

Grid connected: Yes or No (Is the MG connected to the distribution grid? If No, generator, power dissipation, and load shedding are included. If Yes, main power grid distribution is included)

Schedule: 1 (Heuristic) or 2 (Reliability) (Follows the schedule for how the DG's, DS, and main distribution grid are used for the MG)
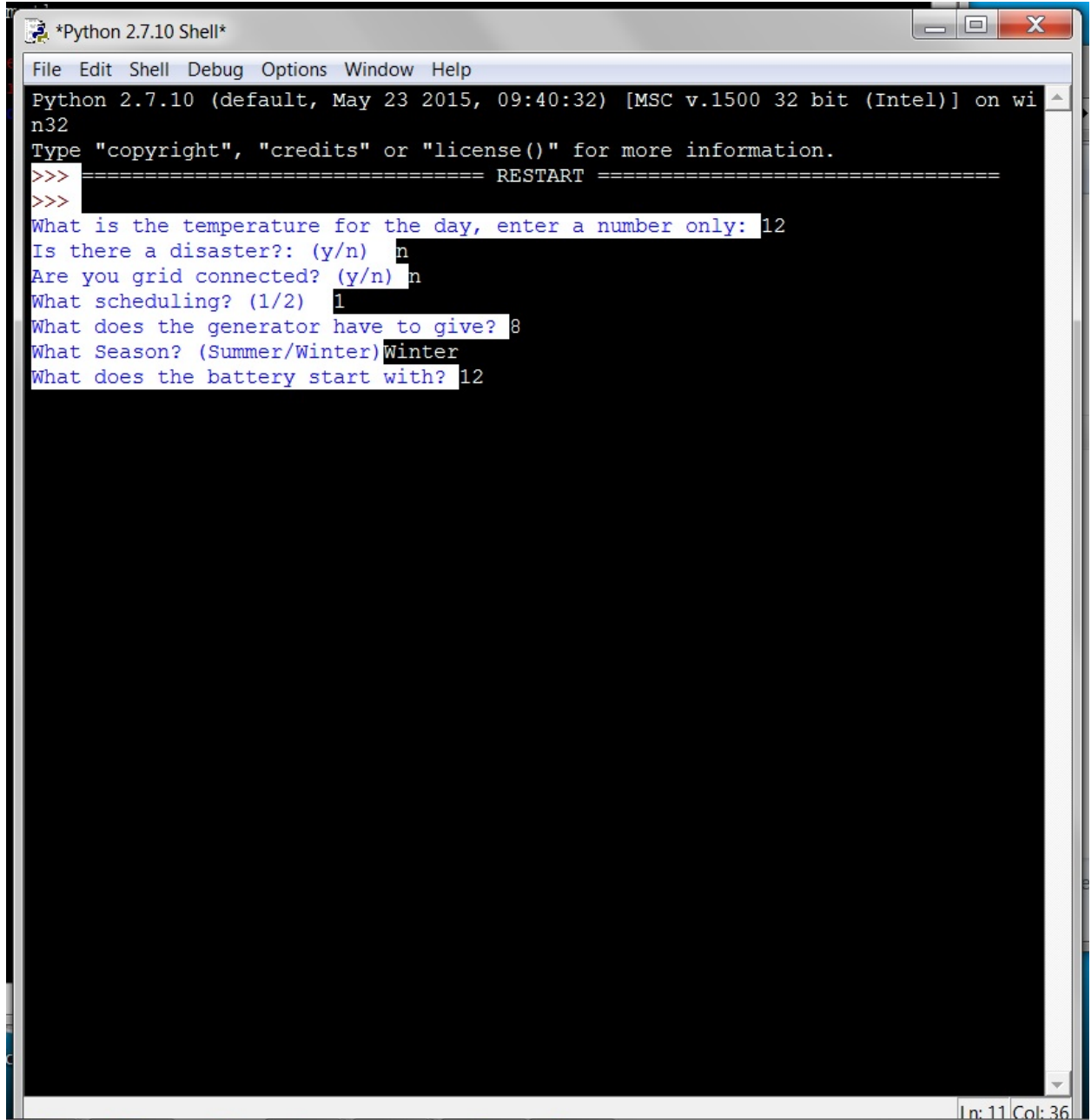
Generator: Can be any value. Values simulated are ranged from 1 to 14kW. They affect load shedding. The generator is used only in an island mode.

Season: Whatever season the simulation is set in, this is to decide which set of input data the system uses (Only Summer and Winter are used in this simulations)

Battery: The amount of energy in the battery (kWh) when the simulation begins, e.g., the lowest value the battery (6.3995kWh) or the maximum (35kWh) when it is fully charged. The program adheres to strict parameters for the maximum and minimum battery kWh values. If a value below the minimum or above the maximum is typed in, the code will output inaccurate data.

Twelve simulations in total are performed. For simplification purposes the input for the battery is 12 kWh for all simulations. This is to test the battery in a middle scenario between worst case (6.7 kWh lowest energy for the battery) and best case (35 kWh best case scenario for the battery). Likewise simulations 1-8 use 8 kW for the generator input. This value reflects a state where the system would undergo some load shedding, but would not be overwhelmed by constant load shedding.

An example of the inputs for a simulation is shown below:

Figure 5.2 Screenshot of simulation input.

The first four simulations use the summer schedule input data with the temperature

input of 94 degrees Fahrenheit and summer for the season. All four are not grid-connected

with a generator rating of 8 kW and 12 kWh for the initial battery input. Simulation 1 has

an input disaster yes and uses Heuristic Scheduling. Simulation 2 has a disaster input of "yes" using the Reliability schedule, Simulation 3 has a disaster input of "no" using Heuristic Scheduling, and Simulation 4 has a disaster input of "no" using Reliability Scheduling. Simulations 1 and 3 are very similar stressing Heuristic Scheduling but are different in the input for disaster which affects the load shedding process, likewise for Simulations 2 and 4, which stress Reliability Scheduling. Simulations 5- 8 are similar to 1- 4 but with the seasons changed. The purpose of Simulations 5- 8 are analogous to 1- 4 but use a different season. Simulations 5- 8 have a generator value of 8kW and the energy in the battery is 12 kWh, which is analogous to Simulations 1- 4, but simulated in winter with a temperature of 12 degrees Fahrenheit and uses the winter.csv load schedule and winterwindspeed.csv input data. Simulation 5 follows Simulation 1 with the disaster input as 1 and using Heuristic Scheduling. Likewise Simulation 6 follows 2, 7 follows 3, and 8 follows 4 in terms of the schedule and disaster input, using winter values instead of summer.

Simulation 9 is the maximum temperature simulation of 94 degrees Fahrenheit, "yes" in the disaster input, in an island mode, using Heuristic Scheduling, with a generator rating value of 14 kW, and the energy in the battery is 12 kWh. The purpose of this simulation is to show how the system would react an in island mode with a generator capable of handling all load requirements without any load shedding. Simulation 9 is similar to simulation 1 but differs in that the generator rating value is higher. Simulation 10 shows the effect of load shedding when the combination of DG and energy in the battery cannot handle the load in an island mode. Simulation 10 is the same as simulation 7 with the difference being the generator value is 1 kW instead of 8 kW. Simulation 13 is similar

to simulation 10 except that the generator value is 14 kW instead of 1kW. Simulations 11 and 12 deals with the grid-connected mode.

Even though Simulation 13 uses Heuristic Scheduling while Simulation 10 uses Reliability Scheduling, Since Reliability Scheduling requires a generator rating of 4KWh or greater, the 1 kW rating of the generator of Simulation 10 converts it into a Heuristic Scheduling simulation instead. Because Simulation 10 does not meet the requirements for Reliability Scheduling, the entire 24 hour period uses the Heuristic Scheduling mode instead.

Simulations 9, 11, 12, and 13 demonstrate the system when operating under nominal conditions, and serve as the control groups against which the other simulations should be compared. In these simulations, either the generator output is high enough to handle every possible load, or else, the system is in a grid-connected mode, and the main distribution grid can compensate for any excessive load. Simulation 11 has the same inputs as Simulation 5, but with the grid-connected input as "yes" (connected to the main distribution grid), and a generator value of 1 kW. The generator value is intentionally set to a low value in Simulations 11 and 12 to show the generator has a negligible effect when the system is connected to the main distribution grid. Similarly, Simulation 12 is the same as Simulation 4 with the grid connected input as "yes" in Simulation 12, and the generator value as 2 kW. Simulation 11 is connected to the distribution grid for a summer day, and Simulation 12 is for a winter day.

CHAPTER 6

OUTPUT DATA ANALYSIS AND REACHABILITY GRAPHS

6.1 Wind Data

Although solar power output from the solar panels is vital for the MG, wind power is not

emphasized because of its insignificance for the MG during these simulations. The average

American residential home can fit no bigger than a 1kW-sized wind turbine. Thus the

maximum wind turbine output is limited to 1kW. The wind turbine is therefore limited in

its capacity to provide power for the grid due to its low rating compared to the battery,

generator, and solar output. The days selected for input weather data provide very little

wind and wind speed, and wind speeds for winter and summer are comparable. As can be

seen by the summer simulation, a maximum output power of 0.097 kW is achieved at

18:50, this corresponds to a wind speed of 4.47 m/s. This is the highest wind speed for the

10 minute intervals in the data. This is a minute amount of power compared to the total

power generated during Simulation 1 of 5.375kW under a 5.375 kW load, when this record

is observed. This same result occurs twice in the winter simulation at time periods 13:30

and 14:40 with output power of 0.079 kW corresponding to air wind speeds of 4.0235 m/s

with Simulation 5 having a total MG generated power of 2.076 kW and a load of 0.909 kW.

As can be seen from the wind power vs. time graphs seen in the simulations (in Appendix

D), the wind power is insignificant to a MG system that produces multiple kW's from solar

power. Large amounts of power are never generated by wind, with the maximum observed

output less than 0.1 kW in both summer and winter falling far short of the 1kW total

capacity of the wind turbine. This is why a token is never placed in p_2, and no values are

observed in v_2 for either summer or winter simulations. On average, for 16 ½ hours there is no wind power output in the summer simulation, nor for 17 ½ hours for the winter simulation. Using meteorological data from days containing wind constant gusts with a high wind speed throughout the day and night can change the relevance of the wind turbine for the MG system in delivering power to the load, charging the battery, or supplying the distribution grid, but this never occurred in any of the source data collected.

6.2 Load Data

6.2.1 Scheduled Load Data

As the format of the load schedule was previously explained, this section describes the load values over a 24 hour day. These graphs correspond with the summer.csv and winter.csv files which are the load schedules the program uses for the simulations. The Electric Vehicle is excluded from the load data. The csv values are in watts but are converted into kilowatts in the simulation program. As is shown in the winter load schedule, from 00:00 to 3:50, the load switches from a minimum 0.07 kW to a maximum of 1.087 kW, providing loads for the: refrigerator, HVAC, outlets for electronic devices on standby such as the HD television, and emergency outlets for electronic devices such as cellphones and tablets.

Around 4:00 the load increases to a total of 4.7067 kW with the water heater adding 4.5 kW (for individuals getting ready for work) and the lights adding 0.03 kW, the emergency outlets are not consuming power since the cellphones and tablets are charged. These increases are seen intermittently between 4:00 to 9:30 with the biggest spike in the load at 8:20 due to the water heater consuming 4.5 kW for showers and electric range/oven consuming 2.3 kW, and kitchen outlets and refrigerator consuming 1.1 kW, and consumer outlets totaling 8.1067 kW simulating individuals of the household preparing for work or school in the morning. From 9:50 to 16:00 load consumption decreases with the refrigerator, HVAC, consumer outlets, and lights being shut off and ceasing to consume power at 11:20; with the load consumption at a low of 0.064 kW and a peak of 1.0937 kW being used in this time period. Emergency outlets increase load demand from zero as individuals who arrive home plug cellphones and tablets into the outlet for charging.

At 16:00 to 21:00 peak load time occurs with white goods being used such as: refrigerator, range/oven, and kitchen outlets consuming power simulating the preparation and making of dinner for the individuals of the household who have returned from work or school. The water heater is turned on to heat water for: the dishwasher for the cleaning of utensils and chinaware after dinner; the washing machine to wash clothes; and hot water for showers before individuals go to bed. Electronic outlets are increased in load consumption for devices such as televisions and gaming systems which cease their standby mode and are turned on for entertainment purposes. An iron is used (which does not have a standby mode) for ironing clothes. The dryer is turned on to dry clothes that just came out of the washing machine. The peak load during this time period occurs at 17:20 when the refrigerator consumes 0.145 kW, the water heater 4.5 kW, the electric range/oven 6.4 kW, lights 0.03 kw, the kitchen outlets 0.300 kW, the consumer outlets 0.875 kW, and the emergency outlets 0.084 kw totaling for a load demand total of 12.336 kW. After 21:10 when most of the individuals of the household are asleep and multiple devices are off, with load demand continuing until the end of the simulation at 23:50 with peak load time occurring at this cycle at 21:00 with: refrigerator, water heater, lights, consumer outlets, and emergency outlets consuming power totaling 2.045 kW. The refrigerator fluctuates its values in the csv files between 0.145 and 0.0027 kW as the refrigerator cycles between cooling and standby mode.
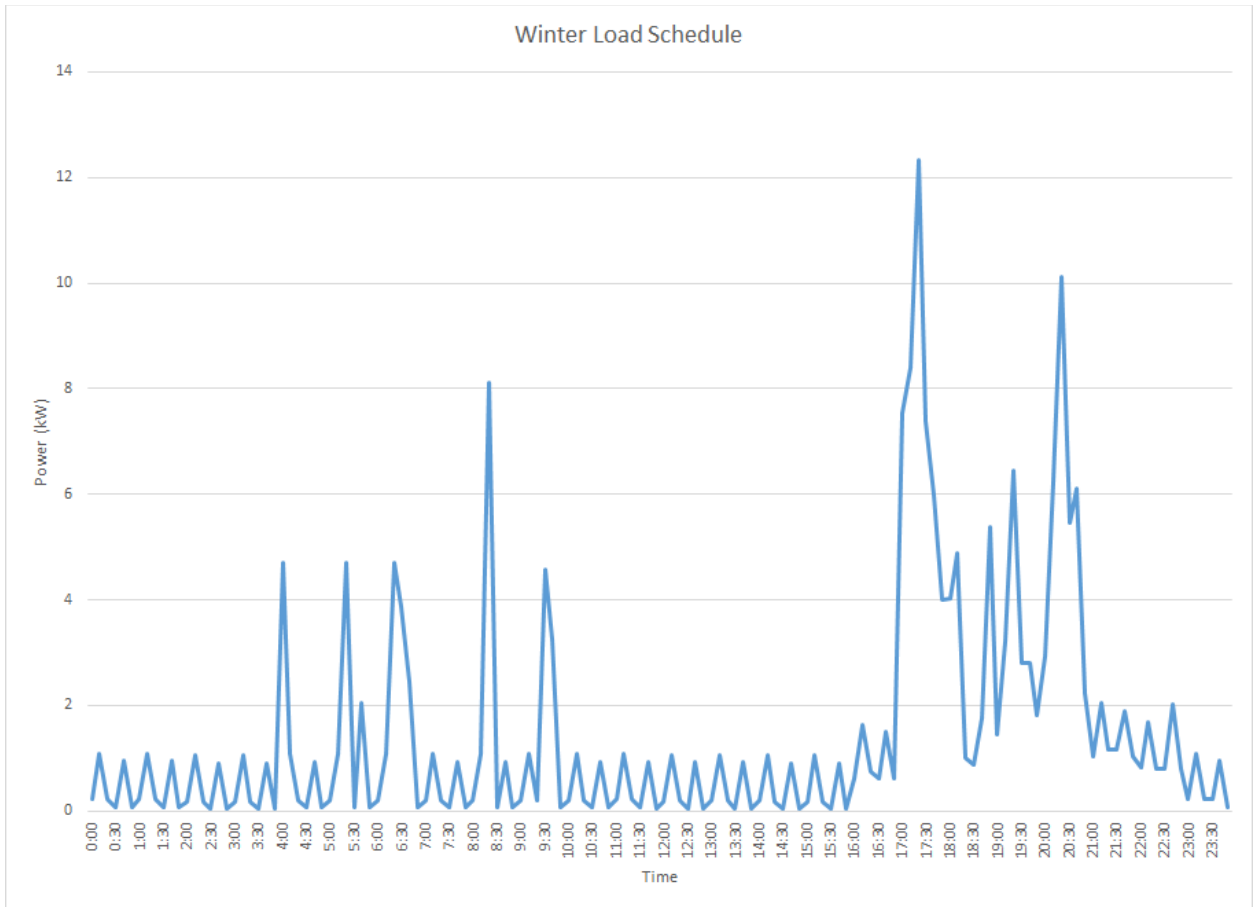
Figure 6.1 Graph of Scheduled Winter Load Consumption vs. Time.

The summer load graph is very similar but the numbers are increased due to the fact that the HVAC for the summer uses an air conditioner to cool the house which consumes 1.8 kW at its minimum to 2.4 kW at its maximum peak when the temperature outside is the hottest. Note that in the winter load schedule the HVAC is a heating unit that consumes a constant 0.875 kW, making summer load totals greater than winter load totals. Certain devices are less active such as the lights in the summer schedule compared to the winter schedule, accounted for by longer daylight hours. Other than these differences, the white goods, consumer outlets, kitchen outlets, and emergency outlets consume the same power at the same time periods as in the winter load schedule. The peak load value for a summer schedule simulation using the summer.csv load file for the input data occurs at the same

time as in the winter simulation at 17:20 with a similar value of 12.306 kW. These graphs and schedules are load schedules that are not affected by load shedding and de-load shedding which decrease and increase load values. Instead, these are the original load schedule input data for the simulations.

Figure 6.2 Graph of Scheduled Summer Load Consumption vs. Time.

6.3 Data Analysis

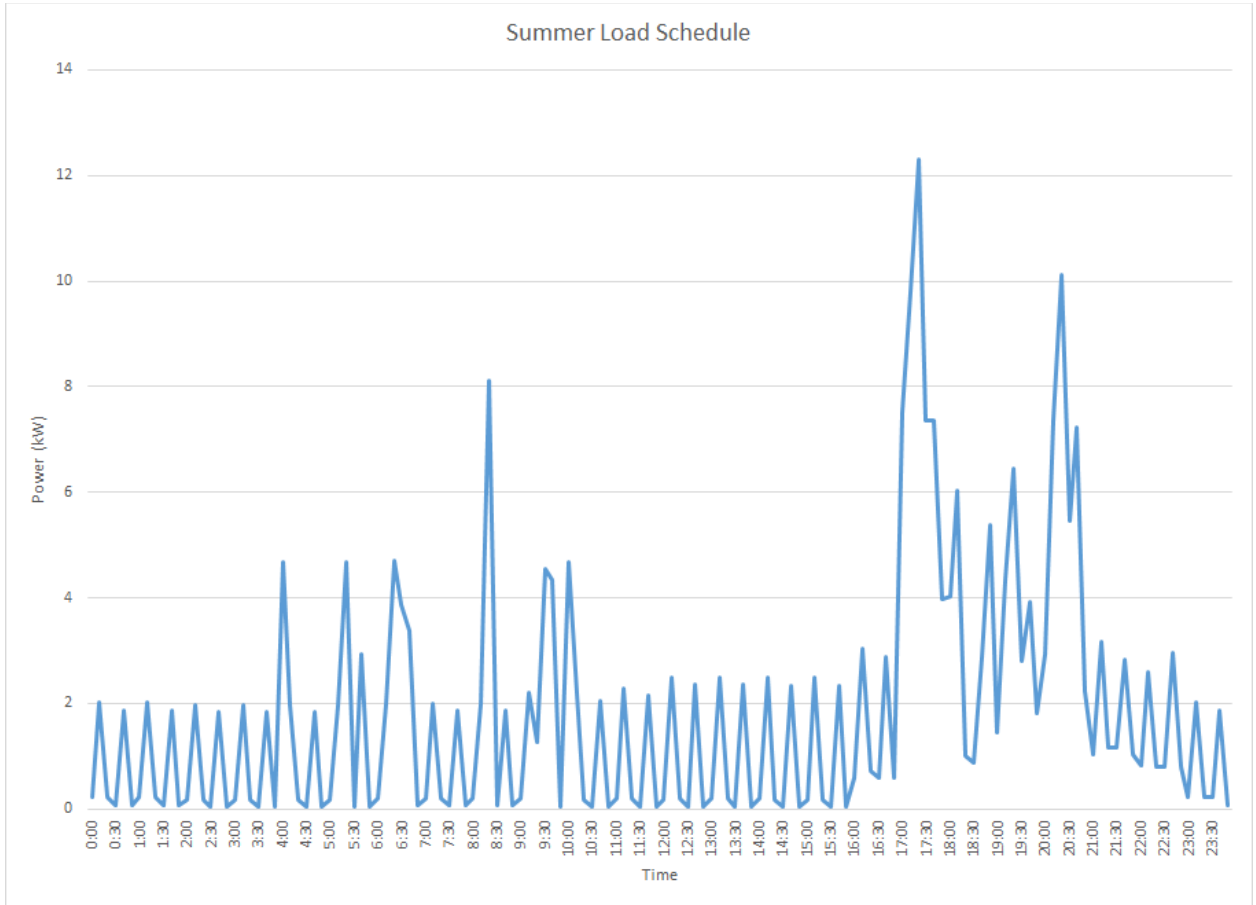Due to the multiple DG's and single DS contributing to the load for the MG, analysis of the data is divided into four parts for the simulations. Morning hours are the time period from the beginning of the simulation at 00:00 to about 6:30 for summer and winter schedules. This time period happens when there is not much sunlight during early morning hours and the load demand is not high because most of the residents of the household are sleeping. The peak consumption for this period occurs when load consumption increases due to household members waking up and preparing for the day: this is when they use lights and take showers before they leave for work or school.

The excess power analysis is needed for the time period 6:30 to 17:00 in the summer simulations, and 7:30 to 17:00 in the winter simulations, when the sun starts shining producing PV output that contributes to the excessive power produced by the MG during the day. The time segment from 17:00 to the end of the simulation is called the peak load time when individuals come home and load increases due to the preparation of dinner, use of consumer electronics such as the television, and household chores such as the dryer and washing machine. Sunlight fades at this time, lowering the PV power output until it becomes zero when the sun ceases to shine. Eventually, the load decreases as the individuals prepare and go to sleep for the next day. The battery is charged toward the end of the Reliability Scheduling period.

Although load shedding was described in detail earlier, load shedding for the data and analysis needs to describe: what devices are shed, time they are shed, and the differences in the values of the load while load shedding and de-load shedding take place.

Table 6.1 List of Simulation Inputs

Simulation #	Temp	Disaster	Grid Connect	Schedule	Generator	Season	Battery
1	94	Yes	No	1	8	S	12
2	94	Yes	No	2	8	S	12
3	94	No	No	1	8	S	12
4	94	No	No	2	8	S	12
5	12	Yes	No	1	8	W	12
6	12	Yes	No	2	8	W	12
7	12	No	No	1	8	W	12
8	12	No	No	2	8	W	12
9	94	No	No	1	14	S	12
10	12	No	No	2	1	W	12
11	12	Yes	Yes	1	2	W	12
12	94	No	Yes	2	2	S	12
13	12	No	No	1	14	W	12

6.3.1 Simulations 1, 3, and 9

Simulations 1, 3, and 9 are very similar; 1 and 3 are differentiated by the order of load shedding, to be discussed later determined by the input of a disaster or not, in the beginning of the simulation. Simulation 9 differs from Simulation 1 by the rating of the generator, and Simulation 3 as Simulation 1 with the input for disaster affecting load shedding order. Solar power is produced from 6:00 to 19:00 during daylight hours. There are slight fluctuations for the output of the natural gas generator for simulations 1 and 3 due to the order of load shedding and de-load shedding. The Distributed Generation is almost

identical in most cases for simulations 1, 3, and 9, except for the output of the natural gas generator.

There is no solar power output in the early morning hours until 6:30 due to the fact that the sun is not out to provide input energy for the solar panels. There are peak times for the load due to increased load activity from 4:00 to 8:40, the load is small enough for the battery to solely accommodate it. The battery discharges power to sufficiently meet load demand from times 0:00 to 6:40; as seen from the data in Appendix, not requiring the generator to turn on except for the time periods 4:00, 5:40, and 6:00 to 6:40, which is due to the load being greater than what the battery can discharge; the combination of wind and solar power is zero, and from 6:00 to 6:40 the energy in the battery is at its lowest point that it can discharge power. Please recall that the lowest energy in the battery before ceasing to discharge is 6.399 kWh. As seen in Figures 4.1- 4.3 the battery is discharging power for the load in the morning hours, and the value for the energy needed in the battery to be fully charged increases as energy in the battery decreases.
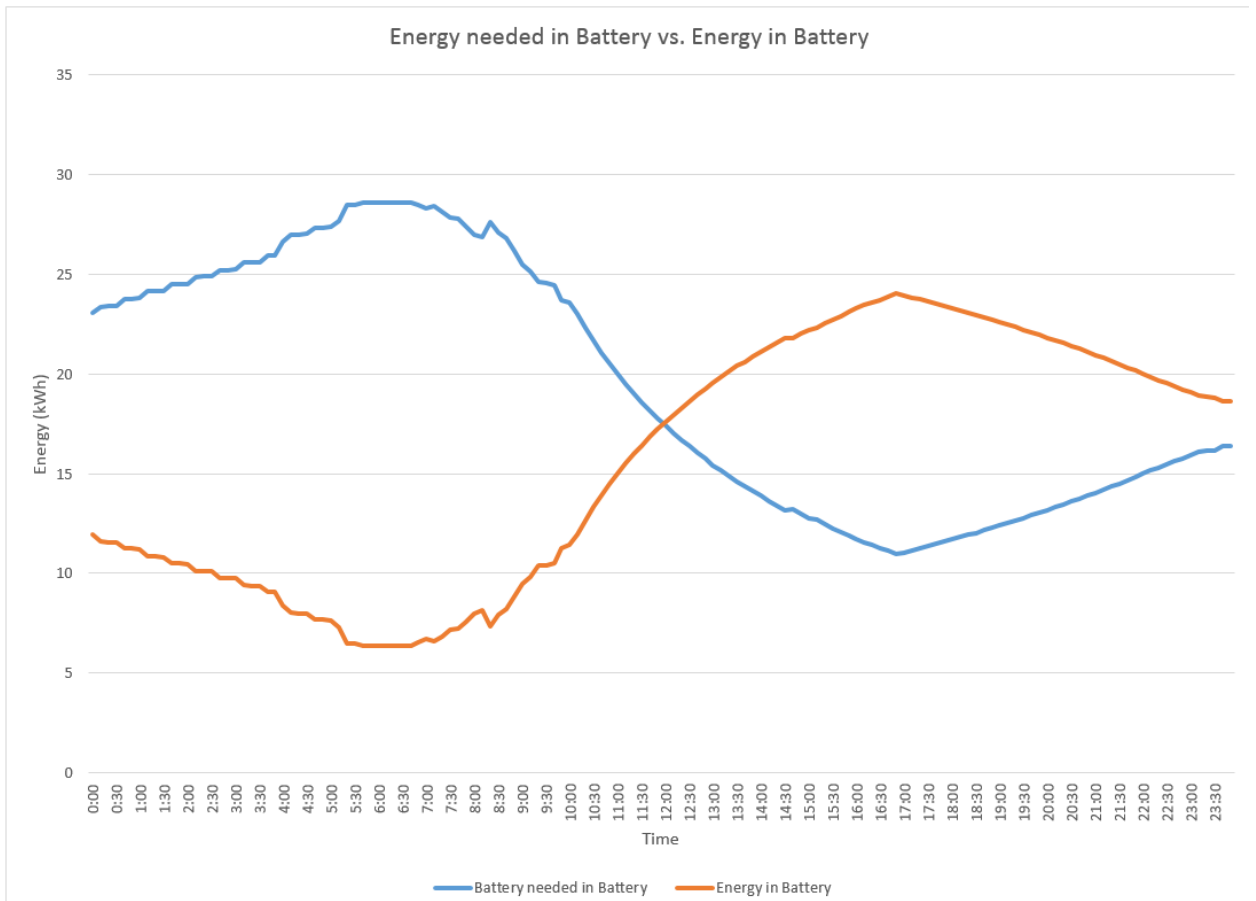
Figure 6.3 Graph of Energy Needed in Battery vs. Energy in Battery for simulation 1.
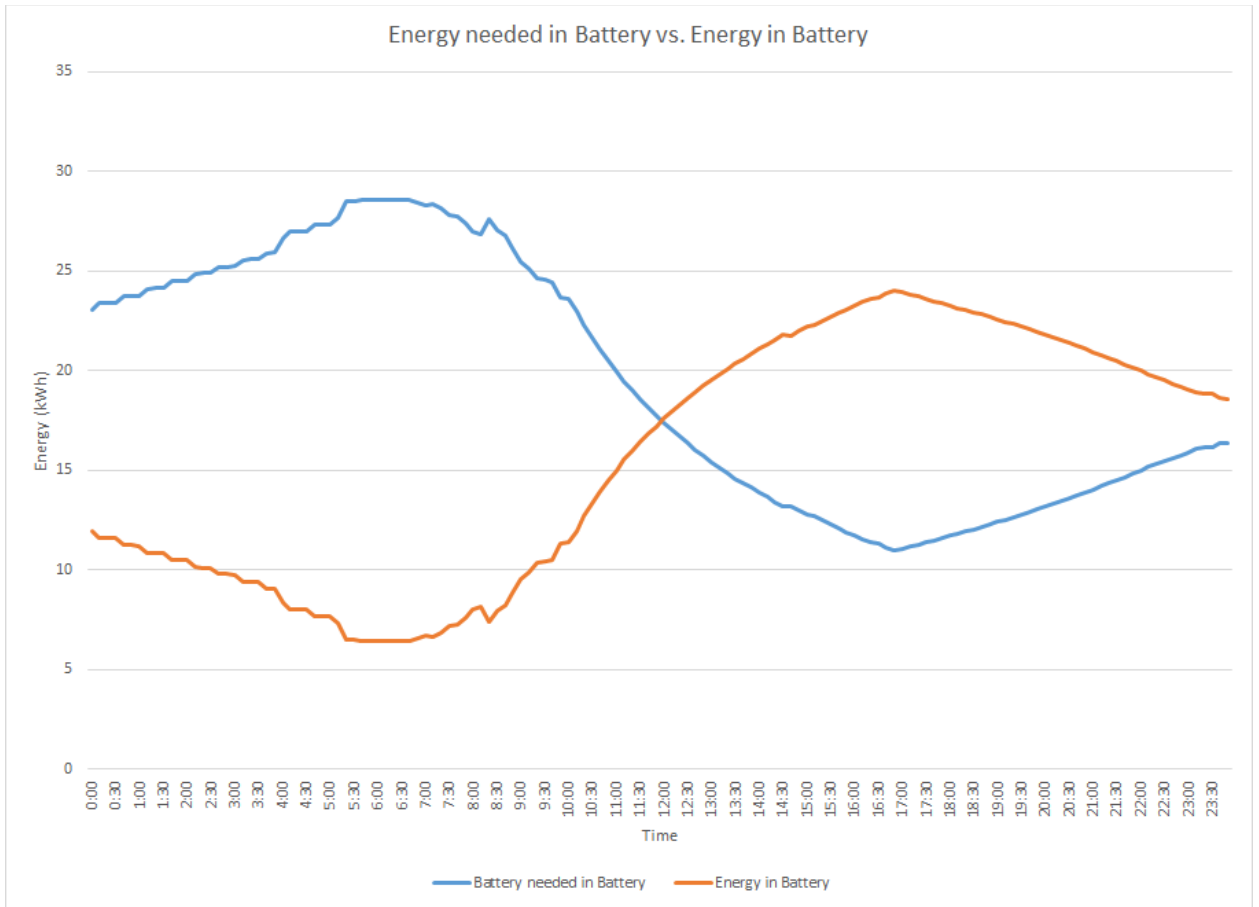
Figure 6.4 Graph of Energy Needed in Battery vs. Energy in Battery for simulation 3.
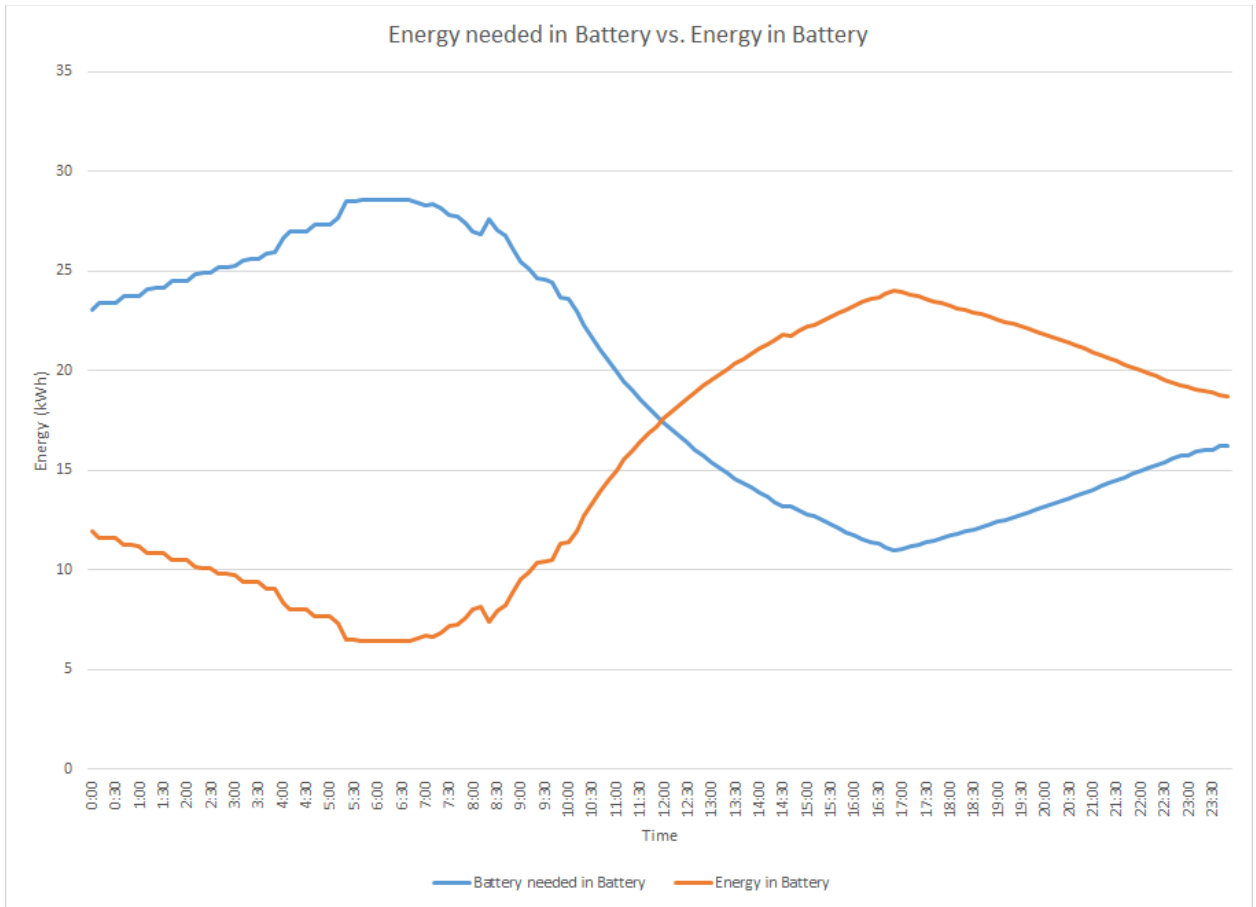
Figure 6.5 Energy Needed in Battery vs. Energy in Battery for simulation 9.

Excess power is produced between 9:00 and 17:00 when the load is minimal enough for the DG to support it. As can be seen from Figures 4.3- 4.5, from 6:30 to 10:00, the amount of power used to charge the battery is in synchronization with the excessive power being produced by solar power.
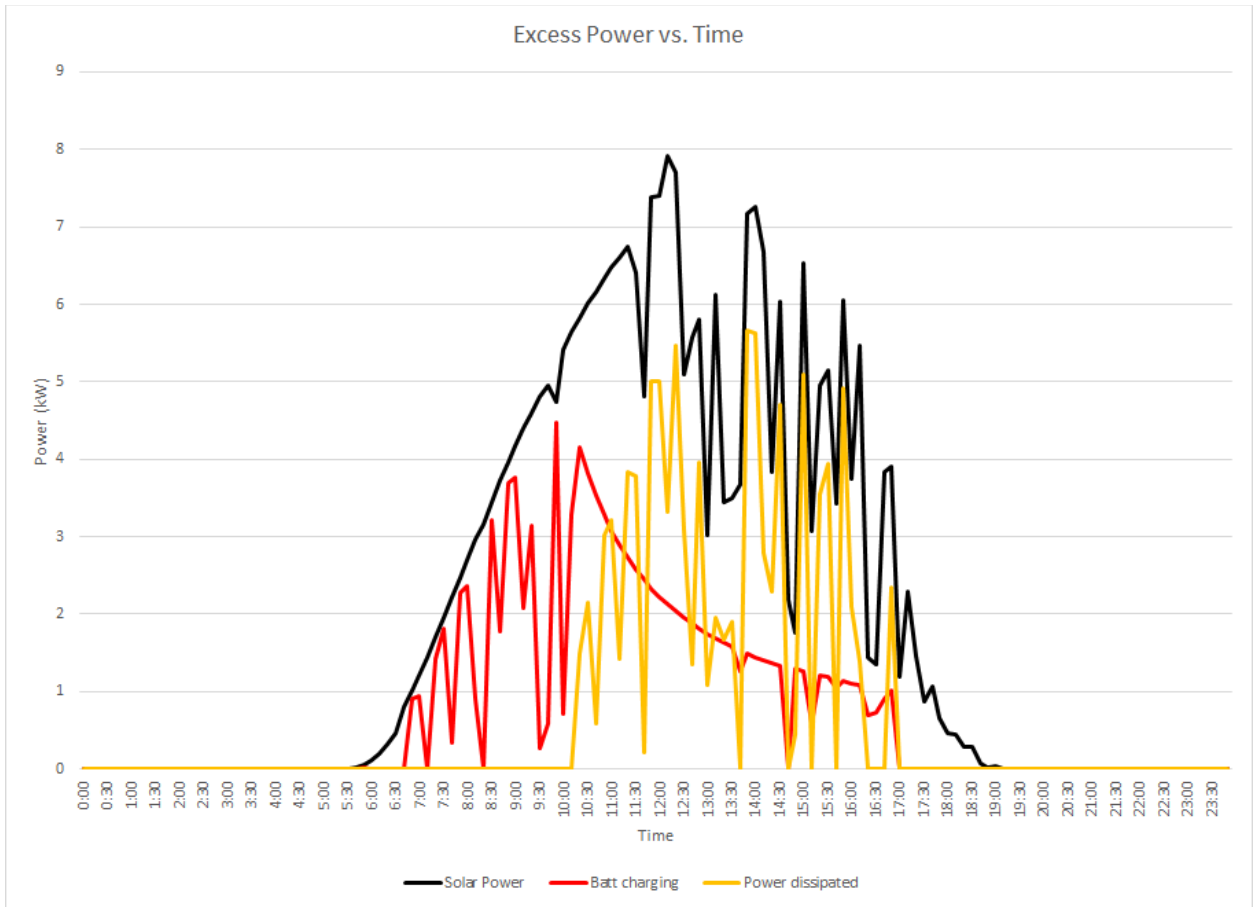
Figure 6.6 Excess Power vs. Time Graph for simulation 1.
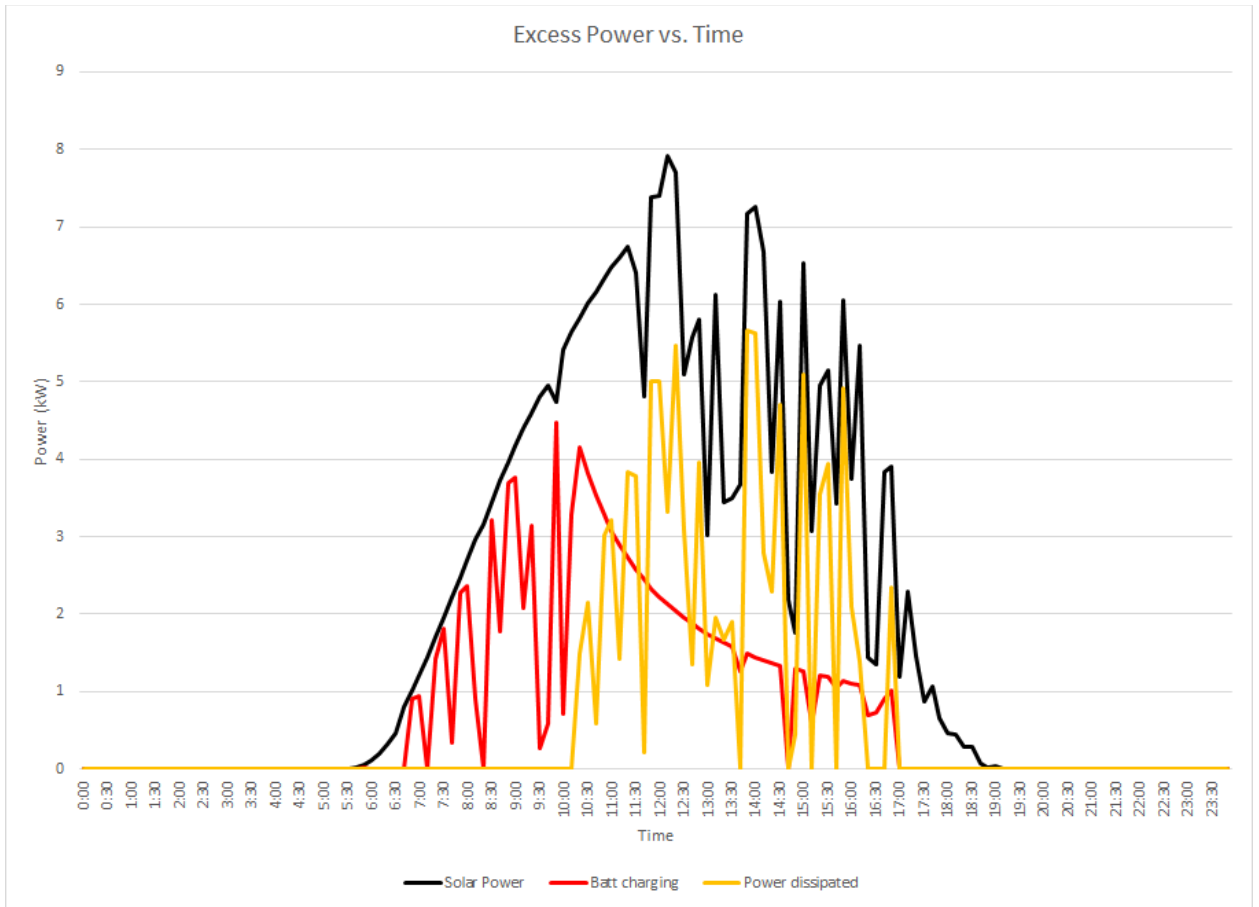
Figure 6.7 Excess Power vs. Time Graph for simulation 3.
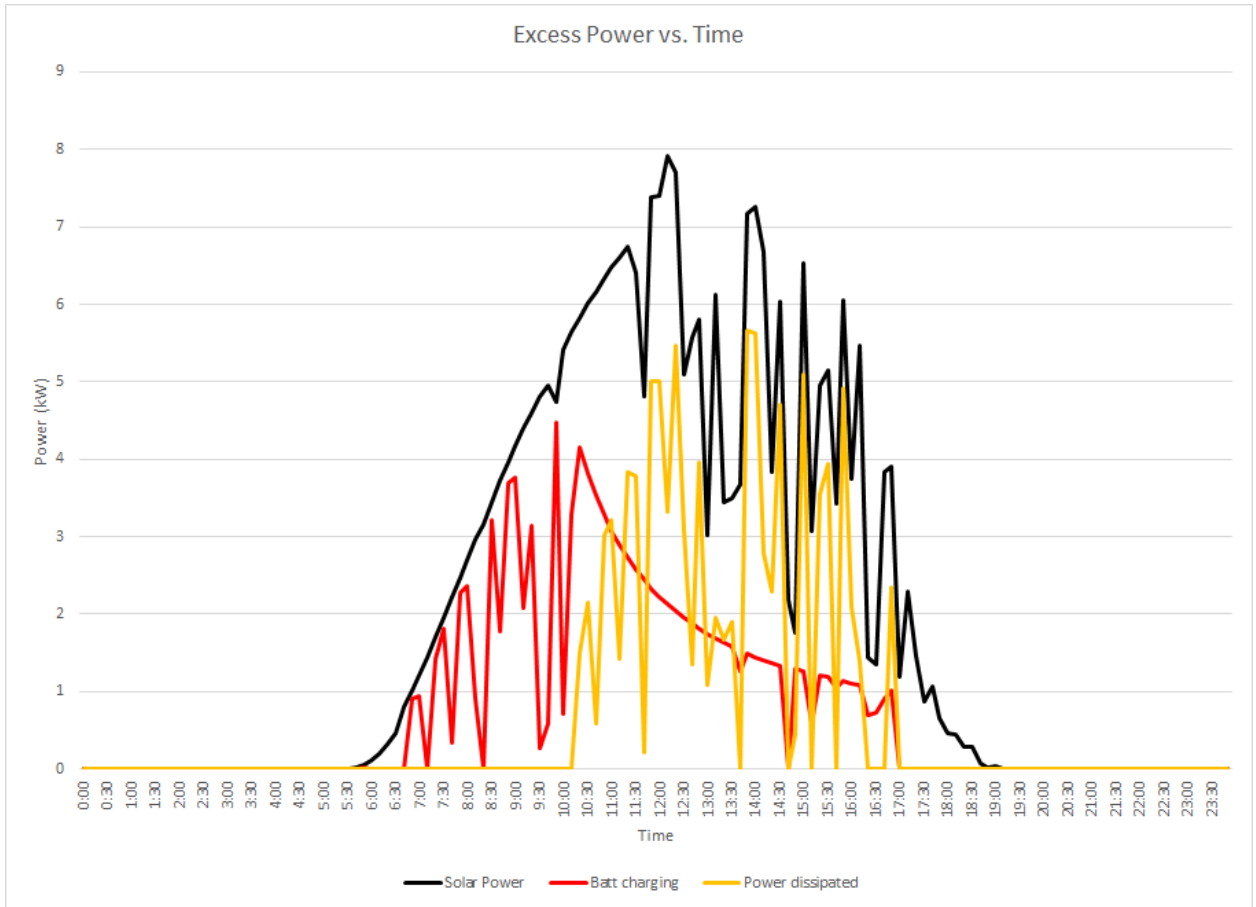
Figure 6.8 Excess Power vs. Time Graph for simulation 9.

Around 10:00 the amount of power used for charging the battery, i.e., excessive power, decreases as the equation for the charging of the battery is logarithmic, and as energy in the battery increases, the amount of power that can be used to charge the battery decreases. With solar power still generating an excessive amount of power (peaking around 7.91 kW at 12:10), power is dissipated which continues to 17:00, the time solar power stops generating due to decreased sunlight, thus ending excessive power production. During this same time frame excessive power is produced due to the amount of solar power being generated from the availability of sunshine during these hours. As seen in Figures 4.1- 4.3, at 12:00, these curves intersect and the value for the energy in the battery is larger

than the energy needed in the battery due to the charging of the battery itself. These values are inverse to the excessive power being produced from solar energy during daylight hours.

Evening peak load at 16:45, the load demand increases, and the battery switches from charging mode to discharging mode to try to meet this spike in load demand. The combination of renewable power and the discharging power from the battery is not enough to meet this demand. During certain time periods of the peak load cycle from 17:00 to 23:00 load shedding occurs (17:20 and 20:20) in simulations 1 and 3 for load demand to match the power the MG can supply, primarily from the natural gas generator which supports most of the load demand during this time period in combination with discharge power from the battery as can be seen in Figures 4.7- 4.9.
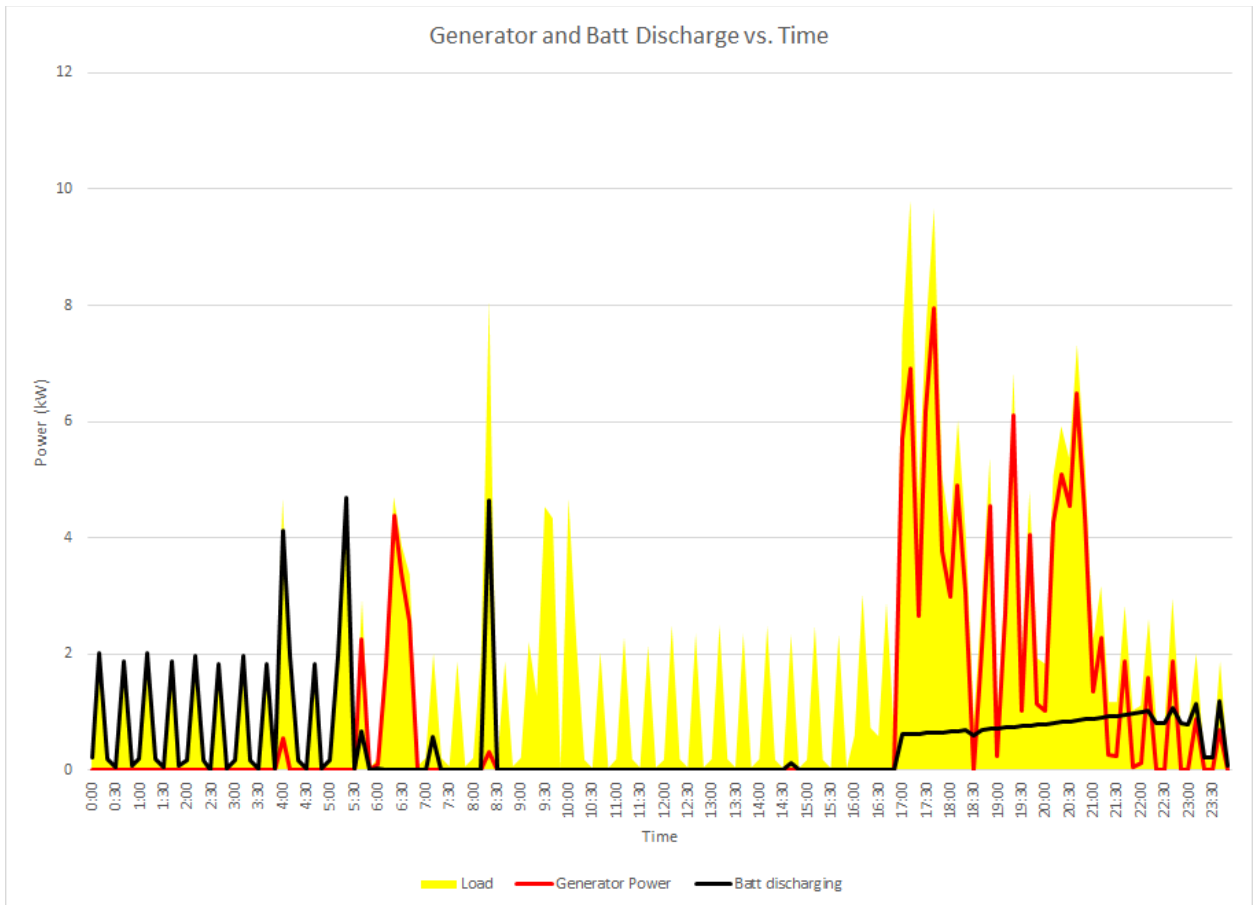
Figure 6.9 Generator and Batt Discharge vs. Time for simulation 1.
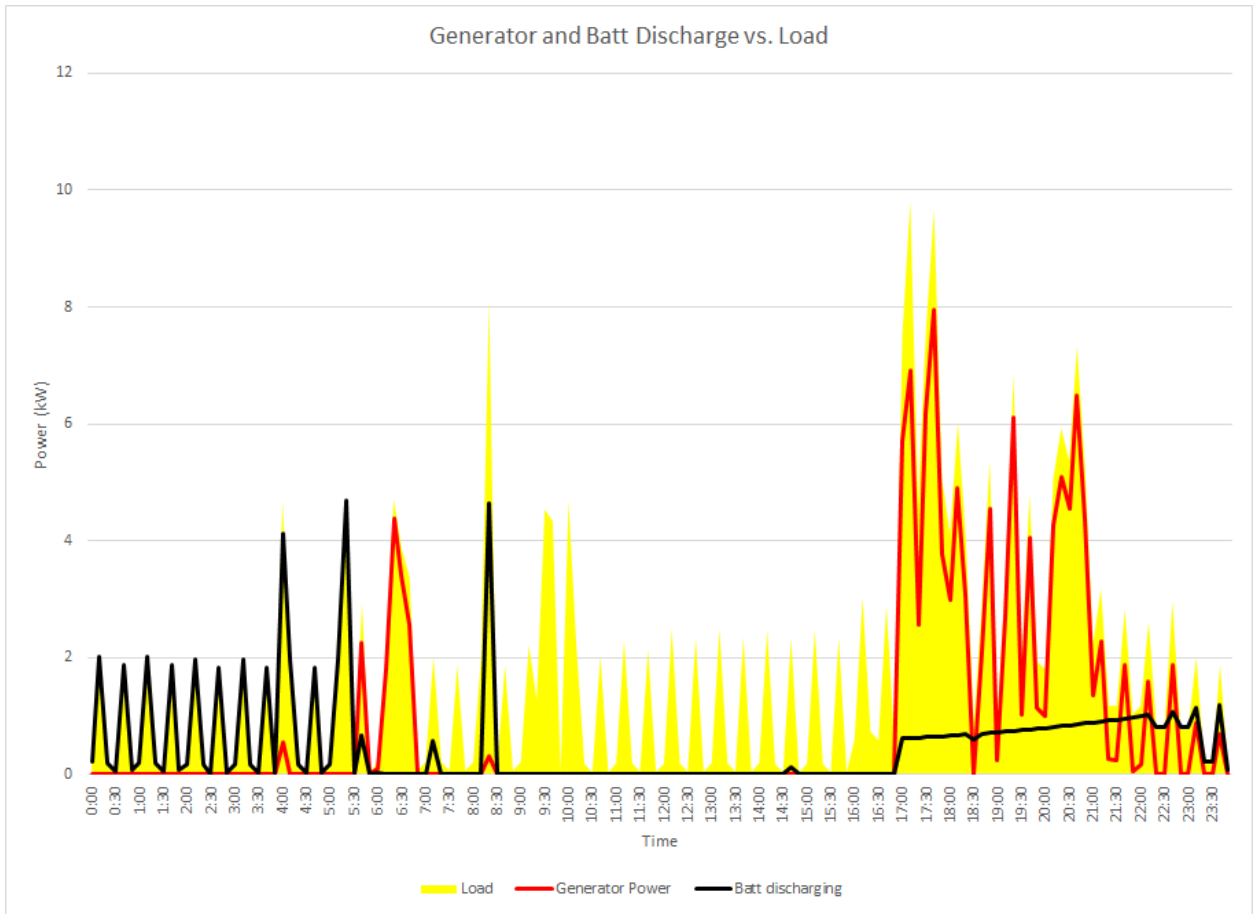
Figure 6.10 Generator and Batt Discharge vs. Time for simulation 3.
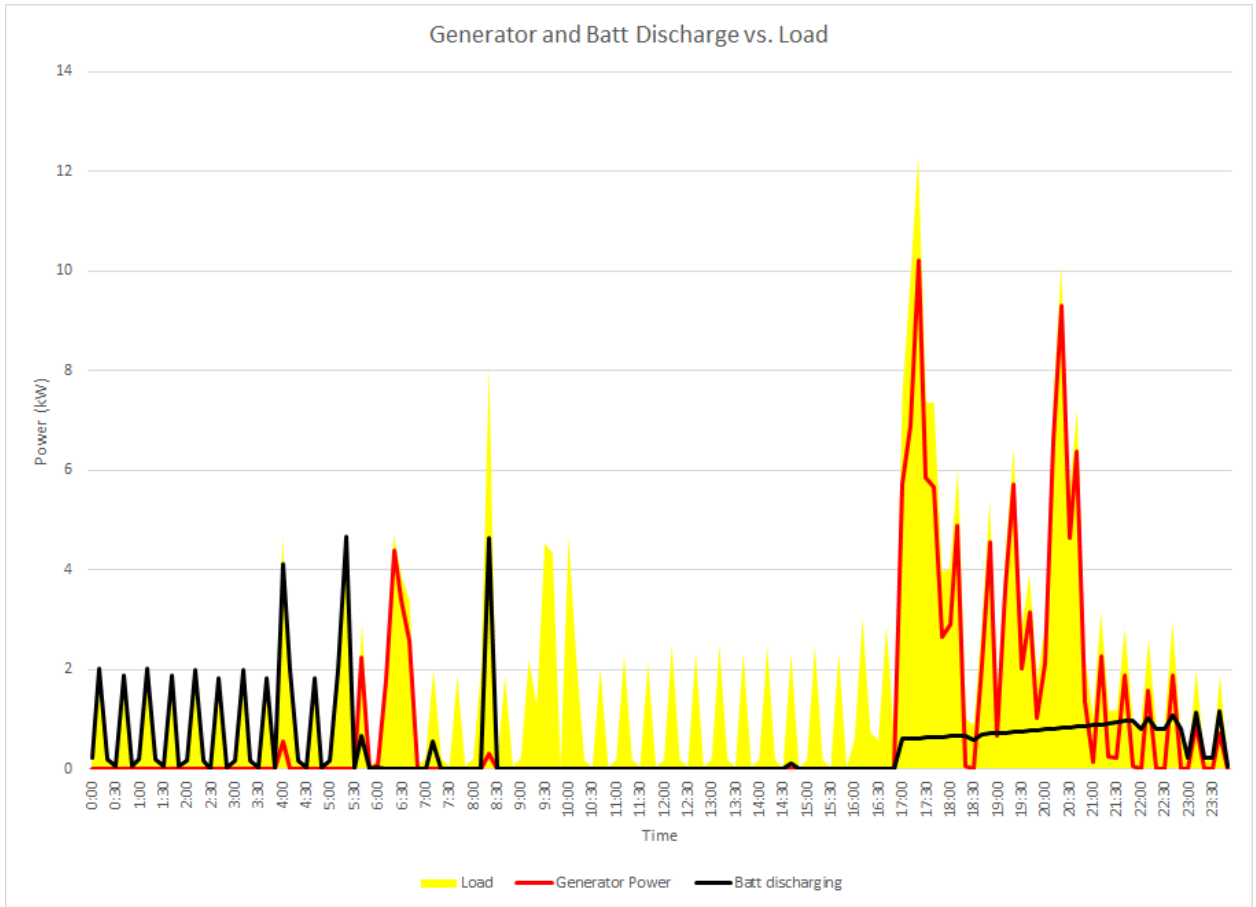
Figure 6.11 Generator and Batt Discharge vs. Time for simulation 9.

The discharging output power from the battery is a logarithmic function. This means that as more energy is in the battery, the less the battery can discharge in terms of power. The battery does not meet load demand during peak load afternoon times from 16:45 to 23:00 as well as during morning hours from 0:00 to 8:30 because its optimal function during this 24 hour simulation is during the time periods when it contains the least amount of energy.

Since the generator in Simulation 9 has a rating of 14kW, this rating is sufficient to match the value of the load demand that otherwise causes load shedding in Simulations 1 and 3 (17:20 and 20:20). To compensate for this low output of battery discharging, the MG employs the natural gas generator to compensate, as shown in Figures 4.8- 4.10. The

generator values for Simulation 9 are different from those for Simulations 1 and 3 during the time periods of load shedding (17:20, 20:20). No load shedding occurs for this simulation as the rating of the generator is 14 kW and can support the load when the combination of DG's cannot. As can be seen in Figures 4.4- 4.6 power generated from solar power decreases during afternoon and evening hours corresponding to decreasing sunlight during this time frame as it eventually ceases during the night (starting at 19:00). As seen in Figures 4.1- 4.3, these values are reversed again around 17:00 when the battery discharges power for the MG to match the load.

No load shedding occurs during Simulation 9 since the main distribution grid can provide power sufficient to meet load demand. Load shedding occurs only twice at the same time periods for both Simulations 1 and 3. The first instance of load shedding occurs at time 17:20, with Simulation 1 following Tier 3, 2A – projected disaster, and 1A – 65 degrees and lower (load shedding never reaches level 1 devices in this simulation) with the order of devices shut off as follows: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlet, and Range/Oven. De-load shedding occurs in the time period immediately following, 17:30, with all devices being de-load shed and turning back on. The load shedding order for simulation 3 at 17:20 is Tier 3, Tier 2B – spontaneous disconnect, and Tier 1C- 80 degrees and higher for the temperature (though as previously stated Tier 1 load shedding does not occur during this simulation). The order of devices shed is: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, Emergency Outlet, and Range/Oven. Please note that the difference in the load shedding is the Emergency Outlet is shut down before the Range/Oven whereas in Simulation 1 the Emergency Outlet is not shutdown but the Range/Oven is instead. This results from the

order of the load shedding for Tier 2 that is decided between 2A and 2B from the Disaster

input in the beginning of the simulation. The next instance of load shedding occurs at time

20:20 and is the same for both simulations. Tier 3 load shedding is the same order

regardless of input for all simulations: in this case only two devices are shed: Dishwasher

and Dryer. De-load shedding occurs immediately, at 20:20, with the MG able to power all

devices, and the de-load shedding process turns on all devices that are shut off due to the

load shedding. Discrepancies in the output values are due to differences in power that is

shed versus de-load shed in Tier 2 load-shedding. This simulation therefore simplifies

values of the load (v_{10}). Discrepancies in values still occur elsewhere, as in other firing rates

and places for different time periods. Simulations 1 and 9 are compared to Simulation 1 to

illustrate these differences.

Table 6.2 Comparison of v_{10} Values between Simulation 1, 3 and 9

Time	1	3	9
17:20	4.729	4.645	12.3
17:30	7.663	7.663	7.363
17:40	9.663	9.663	7.363
17:50	5.063	5.063	3.963
18:00	4.116	4.106	4.017
18:20	4.017	4.017	1.017
19:00	1.017	1.017	1.446
19:10	3.446	3.446	4.346
19:20	6.846	6.846	6.446
19:30	1.803	1.803	2.803
19:40	4.803	4.803	3.923
19:50	1.923	1.923	1.803
20:00	1.827	1.803	2.927
20:10	5.07	5.07	7.37
20:20	5.92	5.92	10.12
20:30	5.37	5.37	5.47
20:40	7.327	7.327	7.227
20:50	5.227	5.227	2.227
21:00	2.227	2.227	1.027
22:00	1.11	1.17	0.813
22:10	2.603	2.613	2.603
23:00	0.791	0.803	0.212

6.3.2 Simulations 5 and 7

Simulations 5 and 7 are comparable to simulations 1 and 3, respectively. Simulation 5 is analogous to simulation 1, as simulation 7 is to simulation 3. The difference lies in the input data: 1 and 3 run on data for a summer day, and 5 and 7 are from a winter day. A heating system is used during the winter schedule, and an air conditioning unit is used for the summer schedule. The air conditioning unit uses more energy than the heater, which affects load values, and thus the behavior of the output of the MG.

Additionally, morning hour's period is extended for simulations 5 and 7 compared to 1, and 3, since the sun rises later in the morning and sets earlier in the evening during winter months. The excess power period is thus shorter for 5 and 7 than 1 and 3,

The Morning Hour time period lasts between 0:00 and 7:00 before excess power is produced. Because of this difference solar power is not produced until after 7:00, almost an hour later compared to the summer Simulations of 1 and 3. The battery is able to supply load demand for most of this time period, except at time periods: 4:00 and 5:20, where load demand is too great for the battery to supply enough power, and from 6:30 to 7:40, where the energy in the battery is too low. During these time periods, the generator is used to provide the needed power.

Similar to Simulations 1 and 3, the energy demand on the battery increases and the total energy in the battery decreases as the battery discharges to meet the load during the Morning Hours' time period.

Simulations 5 and 7 mirror 1 and 3 during the excessive power generation period, with some differences. Excessive power appears around 7:30 in Sims 5 and 7, as opposed to 5:30 in Simulations 1 and 3. As in Simulations 1 and 3, excessive power production is

correlated with solar power output. When sunlight starts to shine around 7:30, the load value is low enough for solar power to meet the demand alone. Excessive solar power is used to charge the battery, as shown in Excessive Power vs. Time Graphs for Simulations 5 and 7 (Appendix D).

As the battery uses the excessive power to charge, energy in the battery increases while the energy needed in the battery decreases, as shown in Energy needed in Battery vs. Energy in Battery graphs for simulations 5 and 7 (Appendix D). At 12:00, the battery cannot use all the excessive power to charge the battery because of the logarithmic nature of battery charging. The power needed to charge decreases, and falls below the amount of power being generated by the solar array. This unused power is dissipated when the MG is in an island mode, and returned to the main power grid in a grid-connected mode. This power dissipation begins around 12:00 and ends around 15:00, with intermittent periods when excessive power equals the power needed for battery charging.

The battery charging period ends around 16:00 and discharging begins when the load increases. Load shedding occurs in this time period, which equalizes the load demand to the power that the MG is able to provide. The generator and the battery combine to provide the power for the load demand. Solar power drops to zero at sunset, and no solar energy is provided to the PV.

One key difference between simulation sets 5 and 7 and 1 and 3 is the discharging power from the battery. Because 5 and 7 occur in the winter, and 1 and 3 occur in the summer, the battery discharges more power in 5 and 7 because of the logarithmic nature of the battery, i.e., the battery discharges power faster if the less energy is stored in it. The

battery has less energy stored in the winter months because of the more abundant sunlight and longer daylight hours in the summertime.

The sequence in which devices are shut off due to load shedding is identical in both 5 and 7 and 1 and 3. Simulations 1 and 3 shed Tier 3 devices, 2B- projected disaster, though simulation 5 and 7 adhere to 1A due to the temperature being 12 degrees and simulation 1 and 3 adhere to 1C due to the temperature being 94 degrees (Tier 1 is disregarded because load shedding does not occur under Tier 1 conditions). Simulations 3 and 7 follow the 2B order of load shedding, which is called Spontaneous Disconnect.

As in simulations 1 and 3, there are two moments of load shedding that occur at the same time for both simulations 5 and 7. The first load shedding for both simulations happens at 17:20 with simulation 5 following Tier 3 and Tier 2A in order of the devices shed: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, and Range/Oven. Simulation 7 follows Tier 3 and 2B: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, Emergency Outlet, and Range/Oven. The difference in load shedding for both simulations 5 and 7 is the order of the devices shed, with simulation 7 shedding the Emergency Outlet before the Range/Oven, as opposed to simulation 5, where the Emergency outlet is not shut off. This order is affected by the projected forecast at the beginning of the simulation. De-load shedding occurs afterward at, 17:30.

In Tier 3, both 5 and 7 follow the same sequence for the second instance of load shedding. The second instance of load shedding occurs at time 20:20, which is identical for simulations 1 and 3. De-Load shedding occurs afterward with the dishwasher switching on at 20:30. The dishwasher is a bellweather for all the other Tier 3 devices: if it is on, all the other devices are back on.

Values for the load and subsequent firing rates are different through both simulations 5 and 7 due to the order the devices are shed, and v_{10} illustrates the differences as shown in Table 6.4. See the complete reachability graph markings corresponding to the allotted *Taus* for more detail.

Table 6.3 Comparison of v_{10} Values between Simulation 5 and 7

Time	Simulation 5 Load (KW)	Simulation 7 Load (KW)
17:20	4.729	4.645
18:00	4.146	4.136
20:00	1.827	1.803
22:00	1.11	1.17
22:10	1.678	1.688
23:00	0.791	0.803

6.3.3 Simulations 2 and 4

Simulations 2 and 4 are similar, with slight differences in the values of certain firing rates of continuous transitions. This is due to the difference of the order of device shut-off during load shedding.

Simulations 2 and 4 adhere to Reliability Scheduling which charges the battery during the early morning hours when two conditions are both met: the generator rated value is 4 kW or above, and the load is less than 4kW. Heuristic Scheduling replaces Reliability Scheduling when these conditions are not met. These requirements are met for this pair of simulations: the generator was rated at 8 kW, and the early morning load is typically less than 4 kW. The generator charges the battery during the time periods: 0:00 to 4:50, 5:10-5:20, 5:40-5:50, and 6:10- 6:40.

The generator supplies power to charge the battery while simultaneously accommodating the load that can be seen by comparing the Generator and Batt Discharge vs. Time graphs for simulations 2 and 4 as detailed in Appendix D.

As in prior simulations, solar power is not produced in the early morning hours. The battery charging rate is shown in the Energy needed in Battery vs. Energy in Battery graphs for simulations 2 and 4 Appendix D, where the intersection point between Energy Needed in Battery and Energy in Battery is at an earlier time (1:30) than in summer simulations.

Excessive power is produced starting at 5:50 and constant battery charging starts at 6:50. Solar power, and excessive power produced are of the same values as in summer simulations. The differences occur in Power Dissipated and in Power Used for charging the battery. More energy is stored in the battery before 6:30 than in simulations of Heuristic Scheduling, because charging occurs before the morning hours' excessive period and the logarithmic nature of battery charging.

When battery charging power is solely dependent on excess power being produced from the MG, the result is shown in the Excessive Power vs. Time graphs for Simulations 2 and 4 Appendix D. Due to the nonlinear nature of the battery, with more energy stored than that in Heuristic Scheduling simulations, power that can be used for charging the battery is limited. Due to this feature, less power is used to charge the battery from excessive power than that in Heuristic Scheduling summer simulations. See Excessive Power vs. Time graphs for simulations 2 and 4 in Appendix D. The excessive power is dissipated when the system is not connected to the main distribution grid. Excessive power that is produced is the same as in simulations involving Heuristic Scheduling summer input data, in that excessive power ends around 17:00 as the load is increased and the batteries switch from charging to discharging to meet this load requirement. Solar power ends around 18:40 that is the same as in summer Heuristic Scheduling simulations since the input data is the same.

Since there is more energy in the battery during Reliability Scheduling, where the priority is to charge the battery during lower load times, and due to the nonlinear property of the battery discharging itself, the battery does not discharge the amount of power that is observed in Heuristic Scheduling simulations. Greater demand is put on the generator to compensate for this deficiency. Because the battery does not discharge more power than in summer Heuristic Scheduling simulations, more load shedding occurs than that in summer Reliability Scheduling simulations.

In the evening, power only comes from the battery and generator. In the Energy needed in Battery vs. Energy in Battery graphs for Simulations 2 and 4 in Appendix D, the amount of energy in the battery decreases around 17:00 due to the increase in load during this time.

Load shedding occurs in both Simulations 2 and 4 at the same time periods. In Simulation 2, load shedding first occurs at 17:20 with load shedding following Tiers 3, 2A – forecasted major disaster, and 1C, since the temperature is greater than 80 degrees. The order that devices shut off in Simulation 2 is: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, and Range/Oven. Load shedding occurs at 17:20 in simulation 4 and follows Tiers 3, 2B – Spontaneous Disconnect, and 1C since the temperature is greater than 80 degrees. In simulation 4, devices are shut-off in the following order: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, Emergency Outlet, and Range/Oven.

The difference between load shedding for the different simulations is the order in which the loads are shed. Simulation 4, in Tier 2, has the emergency outlets disconnected before the Range/Oven due to a Spontaneous Disconnect. Tier 3 devices are shed in the

same order no matter what the parameters are for the simulation. If load shedding were to occur in Tier 1 devices, they would be shed in the Tier 1C order due to the 94 degrees Fahrenheit critical temperature, but load shedding does not occur in Tier 1 Simulations 2 and 4. De-load shedding occurs in the next time increment 17:30 and all devices are turned back on in the reverse order that they shut-off.

The next instance of load shedding occurs at time 17:40, in Tier 3, and is the same order of shedding: Dishwasher, Dryer, Washing Machine, Outlets. De-load shedding occurs at 17:50. The third and final instance of load shedding is at 20:20, in Tier 3, for both Simulations 2 and 4 simultaneously. At 20:20, de-load shedding occurs, and all devices turn back on. Values between simulation2 and 4 are given in Table 6.6.

Table 6.4 Comparison of v_{10} Values between Simulation 2 and 4

Time	Simulation 2 Load (KW)	Simulation 4 Load (KW)
17:20	4.729	4.645
18:00	4.116	4.106
20:00	1.827	1.803
22:00	1.11	1.17
22:10	2.603	2.613
23:00	0.791	0.803

6.3.4 Simulations 6 and 8

Simulations 6 and 8 are comparable to Simulations 2 and 4. They occur in the winter, as opposed to summertime Simulations for 2 and 4. The output graphs for simulations 6 and 8 differ during load shedding due to the disaster input.

Load values are lower in winter compared to summer loads, resulting in the generator's ability to use more power to charge the battery. The battery is charged constantly until 5:00 and intermittently from 5:10 to 9:40, before increases in load demand of 4kW and over trigger Heuristic Scheduling. Like all other simulations daylight is not available in the early morning hours.

Simulations 6 and 8 differ from 2 and 4 in the times when excessive power is produced, and the amount that is produced during this period due to shorter hours of daylight during the winter. This produces a longer time gap between the battery charging from Reliability Scheduling and when excess power is produced from solar power. The battery is charged faster during shorter excessive power periods because it is charged faster if it has less energy. The battery discharges more power in the winter because there are greater spikes in load demand between the time the generator charges the battery in the early morning hours and when excess power is produced during peak sunlight. Also, the time gap is longer in the winter ranging from 5:00 to 8:00 as compared to 5:00 to 6:30 in the summer simulations. For details on the greater winter discharging rates and lower total battery energy in winter simulations, see the graphs Energy needed in Battery vs. Energy in Battery for simulations 6 and 8 in Appendix D compared to the summer simulations 2 and 4 graphs Battery vs. Energy in Battery in Appendix D. Due to the logarithmic nature of the battery, the battery is able to use more power to charge with the least amount of energy stored in it. The battery consumes more power from Excessive Power and reduces Power Dissipated as compared to simulations 2 and 4.

Like in the summer simulations, in the evenings the generator and battery provide power to the load, since daylight has ceased. The battery charges until 15:50 and discharges at 16:00 when the load demand rises. The battery charges again at 23:00 when the system enters Reliability Scheduling. See Battery Charging vs. Discharging graphs for Simulations 6 and 8 Appendix D.

Load shedding for simulations 6 and 8 are similar to that for 2 and 4, except that the former occurs in the winter instead of the summer. Simulations 2 and 4, which also use

Reliability Scheduling, have three periods of load shedding whereas simulations 6 and 8 have two periods of load shedding only. Simulation 6 load shedding is identical to simulation 2's following Tier 3, Tier 2B – projected disaster. The first load shedding occurs at 17:20: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, Range/Oven. De-load shedding occurs at 17:30 with all devices turning back on. Simulation 8's load shedding at 17:20 is identical to simulation 4's following Tier 2A – Spontaneous Disconnect: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, Emergency Outlet, Range/Oven. The second load shedding for simulations 6 and 8 is the same as that for 2 and 4, and occur at the same time, 20:20, with the same set and order of devices being shed on Tier 3: Dishwasher and Dryer, only. De-load shedding occurs in the following time period, 20:30, with all devices turning back on. The v_{10} values between simulations 6 and 8 are given in Table 6.8.

Table 6.5 Comparison of v_{10} Values between Simulation 6 and 8

Time	Simulation 6 Load (KW)	Simulation 8 Load (KW)
17:20	4.729	4.645
18:00	4.146	4.136
20:00	1.827	1.803
22:00	1.11	1.17
22:10	1.678	1.688
23:00	0.791	0.803

6.3.5 Simulation 10

Simulation 10 represents a worst-case scenario with a low generator rating that cannot compensate for low wind and solar power output, and limited power discharge from the battery. Because of the lower power output from the combination of DG's and DS, load

shedding occurs extensively in Simulation 10. Although it is a Reliability Scheduling simulation, the fact that the generator is below the 4 kW requirement does not allow the system to follow Reliability Scheduling, and it reverts back to Heuristic Scheduling for the whole 24-hour simulation.

Simulation 10 is more similar to Simulations 5 and 7, which are Heuristic Scheduling, than 6 and 8 which are Reliability Scheduling simulations. See Generator and Batt Discharge vs. Time graphs for Simulations 6, 8, and 10 in Appendix D. This is because Reliability Scheduling does not take place at all, effectively making this simulation a Heuristic Scheduling simulation.

Simulation 10 mimics Simulations 5 and 7 except for 4:00 where load shedding occurs. In simulations 5, 7, and 10 the battery discharges 3.522 kW. The generator provides 1.184 kW of power in simulations 5 and 7; but in simulation 10, with a limited rating of 1 kW, a load of 4.7067 kW has to be reduced to 4.5 kW through load shedding. The generator provides 0.977 kW, or approximately 98% of its rated capacity. Load shedding occurs again at 6:40 to 7:50, unlike simulations 5 and 7. The energy in the battery reaches its lowest point of 6.399 kWh at 6:20 for simulations 5, 7, and 10, but with an increased load at 6:40, the generator is not rated highly enough to compensate for the battery's output, which cannot discharge sufficient power. During periods when the power discharged from the battery is insufficient to meet load demand, the battery is supplemented by the natural gas generator. No solar power is generated during these winter morning hours.

Although solar power starts being generated at 7:10, load shedding occurs at 8:20 to 8:50 with zero load demand at times 8:20 and 8:30. The battery is actually being charged

during these times. The system calculates the power of the wind and solar and the potential power that can be discharged from the battery plus the 1 kW from the generator. Since the DGs and DS cannot provide sufficient power, no device from the load schedule can be turned on. Thus, the MG does not consume power, and instead the battery recharges using the renewable energy sources. The system de-load sheds at 9:00 with all devices previously shut-off turning back on. By this time, sufficient solar power is generated to supply the MG with 2.645 kW. At 9:40, power generation dips to 2.023 kW, and then increases to a maximum of 5.325 kW at 11:00.

The load in Simulation 10 varies drastically from the load in Simulations 5 and 7 because of the effects of load shedding and de load shedding. Solar power produces excessive power from 7:10 to 17:00 that provides for the load and charges the battery. When the excessive power exceeds the battery's maximum charging rate, power is dissipated intermittently between 12:00 and 15:00. See Excessive Power vs. Time graph for Simulation 10 in Appendix D. Solar power ceases production at 17:00.

Load shedding occurs at 17:20 in Simulations 5 and 7, but in Simulation 10 it occurs instead at 17:40 because of the load shedding and de load shedding. The values of the load v_{10} are not the same as those in Simulations 5 and 7. From 17:40 to the end of the simulation, the electric range/Oven is shut-off due to load shedding at time periods: 17:50, 19:00, and 19:30. At 20:30 the refrigerator and water heater are also shut-off. No power from wind or solar is produced. There is no excessive power to charge the battery, and the only power supplied is discharged from the battery to meet the load (which has been substantially minimized due to load shedding). The generator is not providing power to the MG at this point. This is because the system has shed all devices such that the battery alone

can provide power for the remaining devices. Any device requiring more than 1 kW of power is shed, because the generator rating is too low for it to provide sufficient power. Simulations 5 and 7 have far less load shedding because of the higher rating of the generator (8kW) in those simulations. Generator and Batt Discharge vs. Time graphs for Simulation 5, 7, and 10 in Appendix D show how the rating of the generator affects load shedding. In Simulations 5 and 7 the combination of the generator and battery provides for most of the load, whereas in Simulation 10 the generator remains off with only the battery providing power.

Simulation 10 is a prime example of load shedding that occurs when load exceeds available power. The first load shedding instance occurs at time at 4:00 and affects only Tier 3 devices: Dishwasher, Dryer, Washing Machine, Outlets, and Lights. Subsequently, at 4:10, de-load shedding occurs and all devices that were shut-off are turned back on. Load shedding occurs again at 6:40 and again shuts off Tier 3 devices. These devices remain shut-off until 8:00 when reverse load shedding occurs and all devices are turned back on. Devices are again shut-off at 8:20 with Tier 3, Tier 2B, and Tier 1A: Dishwasher, Dryer, Washing Machine; Outlets, Lights, Kitchen Outlets; Emergency Outlet, Range/Oven, Refrigerator, Water Heater; with only the water heater left on.

Reverse load shedding occurs again at 8:50 with all Tier 1C devices turning back on but devices in Tier 3 and 2B remain shed, which include Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, Emergency Outlet, and Range/Oven. At 9:00 reverse load shedding occurs with all devices turning back on. Load shedding does not occur again until 17:00, and the same devices are shut-off at 17:10; not only are Tier 3 devices shut off, but 2B devices are also turned off since the input for Simulation 10 is

Spontaneous Disconnect: Dishwasher, Dryer, Washing Machine, Outlets, Lights, Kitchen Outlets, Emergency Outlet, and Range/Oven.

At 17:40 more devices are shed from Tier 1A. Since the temperature input is 12 degrees Fahrenheit, the load shedding schedule follows Tier 1A in the order of shedding: Dishwasher; Dryer; Washing Machine; Outlets; Lights; Kitchen Outlets; Emergency Outlet; Range/Oven; Refrigerator; and even the Water Heater now off. Reverse load shedding occurs at 18:00 with Tier 1A devices turning back on with Tier 3 and 2B devices still off: Dishwasher; Dryer; Washing Machine; Outlets; Lights; Kitchen Outlets; Emergency Outlet; Range/Oven. These devices remain off for the rest of the simulation until 23:50, with Tier 1A devices, the refrigerator and water heater being shed at 19:00, and de-load shed at 19:10. This process of the refrigerator and water heater being shed and then de-load shed repeats for the time periods: 19:30-19:40 and 20:30-20:40, but not shed again for the remainder of the simulation. The electric Range/Oven, at 6.4kW, is the critical device that triggers load shedding and leaves the system unable to recover for the remainder of the simulation.

6.3.6 Simulation 11

Discussion and analysis of Simulations 11 and 12 results are briefer than those for all other previous simulations because they simulate the system when connected to the man power grid, whereas the primary focus of the study is the MG sustaining itself in island mode. A micro-grid that can support itself by controlling load levels or generating enough power to match load demand when disconnected from the main distribution grid is proof of concept of a closed renewable energy MG.

In Simulation 11, the morning phase is predominantly the same as that in Simulation 5, except power now comes from the main distribution grid as opposed to power being generated from the natural gas generator.

Power is no longer dissipated in Simulation 11. Because it is connected to the main power grid, excessive power is now fed into it instead when the battery charging capacity is exceeded. Since the data input for weather and load is the same for Simulations 5, 7, and 11, graphs for the excess data period are the same for all three simulations.

The afternoon peak load time period is similar for both Simulations 11 and 5. The power from the generator is replaced by power from the main distribution grid; except for the values at 17:20 and 20:20, where load shedding occurs in Simulation 5. Load shedding does not occur in Simulation 11 since the main distribution grid can provide the power that the 8 kW generator in Simulation 5 cannot. In Simulation 5, with the battery able to discharge so much power, and the generator rated at 8 kW, load shedding occurred at these times such that the MG can provide power to the remaining load devices. Simulation 5 load values during time periods when load shedding and de-load shedding occur are different when compared to Simulation 11 load values during these same time periods because the load shedding and de-load shedding process affects the values of the load. Load shedding and reverse load shedding do not occur in Simulation 11, for the main distribution grid is able to power all load devices, unlike the 8 kW generator in Simulation 5. Because of this difference, no load shedding occurs in Simulation 11.

6.3.7 Simulation 12

Simulation 12 is similar to Simulation 4 except that Simulation 12 is in a grid-connected mode, and the main distribution grid provides power instead of a generator (as in Simulation 4). There is no load shedding in Simulation 12, unlike Simulation 4, because the main distribution grid can provide all required power whereas the 8 kW generator offers the limited one.

The difference between simulations 12 and 4 during morning hours is the absence of load shedding in Simulation 12. This is seen at time period 4:00 (in simulation 4) where the load is greater than 4 kW, but since the main distribution grid is capable of providing enough power for the load and battery under the reliability schedule, the main distribution grid is capable of charging the battery at its maximum charge rate while supplying the load. In Simulation 4, the generator is limited to the availability of power after load demand has been met.

The excessive power generation period for Simulation 12 is the same as that for simulation 4, except for values involving the charging of the battery, and energy in the battery. In Simulation 4, when the load is greater than 4 kW, battery charging ceases, and the generator combined with the battery now discharging power provides the power to deal with the load. In Reliability Scheduling, if the MG is connected to the main distribution grid, charging of the battery does not cease when the load is greater than 4 kW because the main distribution grid is capable of handling the load combined in conjunction with the power needed to charge the battery.

Load shedding does not occur in simulation 12, during afternoon load times, due to the main distribution grid providing for the loads that are shed in Simulation 4 at 17:20, 17:40, and 20:20. These values can be seen in comparing Main Distribution Grid and Batt

Discharge vs. Time graph for simulation 12 and 4 in Appendix D. The load is greater (in simulation 12) and the main distribution grid provides the power for the load compared to Simulation 4 where the generator is limited in power output to an 8 kW and load shedding occurs.

No load shedding occurs during Simulation 12 because the main distribution grid provides all power that is needed for the load demand without having the MG to load shed.

6.3.8 Simulation 13

Not much discussion on Simulation 13 is needed due to the fact it is simulated for Reachability Graph comparisons to Simulation 10 to be discussed later in the next section. Simulations 10 and 13 use different scheduling, simulation 10 uses Reliability Scheduling whereas Simulation 13 uses Heuristic Scheduling. But it is important to note that simulation 10 reverts to using the heuristic scheduling due to the generator rating of 1 kW which is less than the 4 kW or greater rating required for Reliability Scheduling to take place effectively making Simulation 10 a Heuristic Scheduling simulation. The results for Simulation 13 are comparable to Simulation 11 except that the values of the main distribution grid supplying and consuming power are substituted by the power produced from the generator and excessive power dissipated.

No load shedding occurs during this simulation since the natural gas generator has a high enough rating to compensate for periods of low power output from the combination of renewables and battery discharge to meet load demand.

6.4 Comparison of Battery Performance between Scheduling

It is important to compare the battery discharging between the two scheduling methods. This analysis compares Simulations 1 (Heuristic scheduling) and 2 (Reliability scheduling), and Simulations 5 (Heuristic scheduling) and 6 (Reliability scheduling) that use the same corresponding inputs (Simulations 1 and 5 and 2 and 6) except for the

scheduling methods. Simulations 1 and 2 have the same load profiles. Simulation 2 uses much of the early morning hours for the generator to charge the battery, producing instances where the battery has to discharge power when the load is greater than 4 kW. Figures 6.12- 6.14 illustrate the power output values of the battery discharging and load demand for Simulation 2 compared to 1 are shown. The times used correspond to time periods where the battery discharges for Simulation 2.

Figure 6.12 Battery Discharge simulation 1 Using Heuristic Schedule vs. simulation 2 Using Reliability Schedule from Time 04:00 to 08:20.

Figure 6.13 Energy in Battery simulation 1 Using Heuristic Schedule1 vs. Energy in Battery simulation 2 Using Reliability Schedule from 04:00 to 08:20.

Figure 6.14 MG Load values simulation 1 Using Heuristic Schedule vs. simulation 2 using Reliability Schedule from Time 04:00 to 08:20.

Comparing the energy in the battery to the energy discharged shows that the lower the amount of energy stored in the battery, the more power the battery is able to discharge for the load. This process can be seen during the peak load demand hours when excessive power is not able to produce sufficient power as the load increases requiring the battery to discharge power during both simulations. The system works with a generator by using a high enough rating to provide for the load when the battery is not able to. This is seen in Simulation 9 results, where load shedding occurs due to the low rating of the generator, which cannot compensate for the low power combination between renewables and the battery discharging.
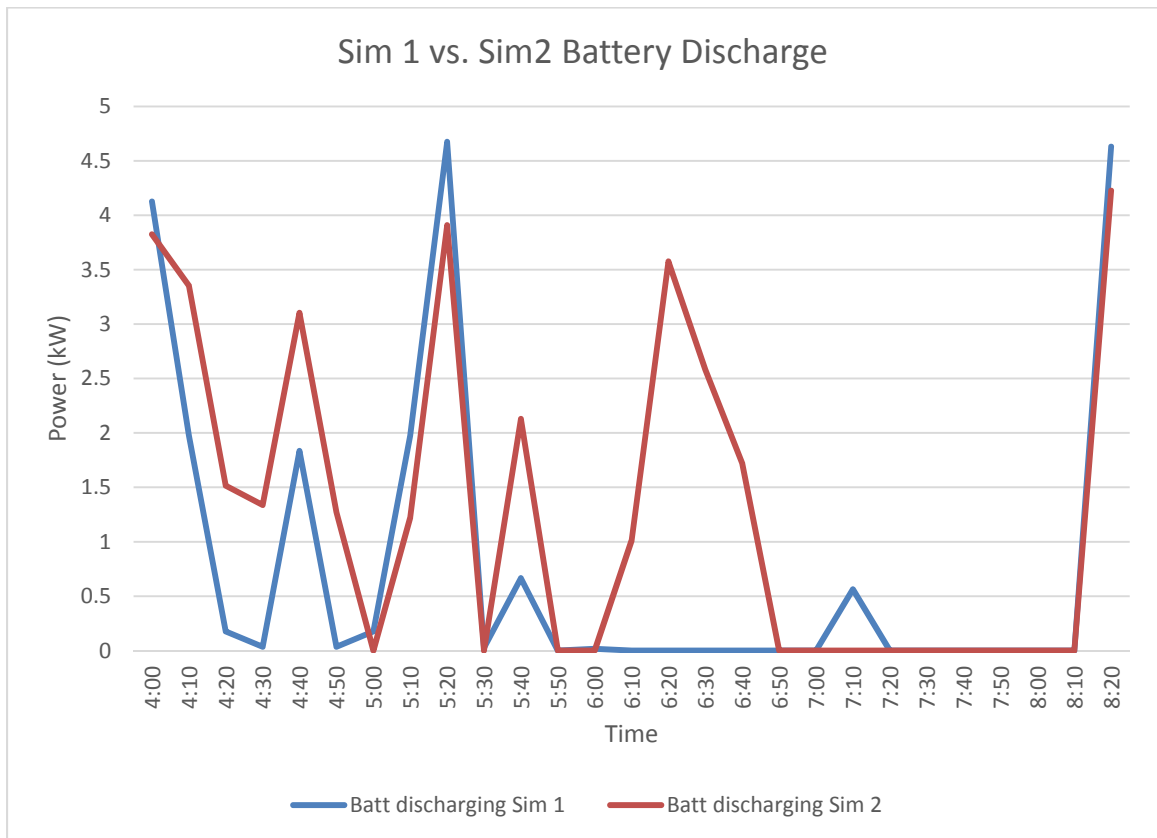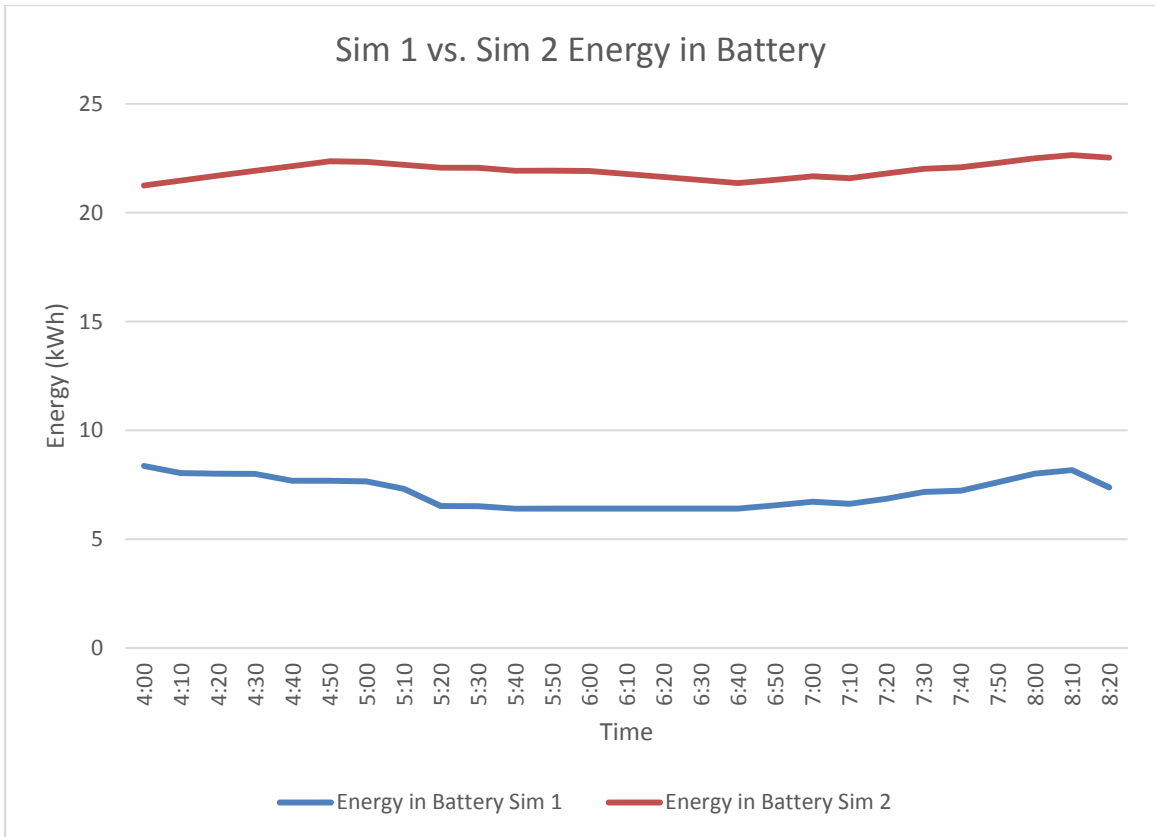
Figure 6.15 Battery Discharge simulation 1 Using Heuristic Schedule vs. simulation 2 using Reliability Schedule from Time 04:00 to 22:50.

Figure 6.16 Energy in Battery simulation 1 Using Heuristic Schedule vs. Energy in Battery Reliability Schedule Using Reliability Scheduling from 17:00 to 22:50.
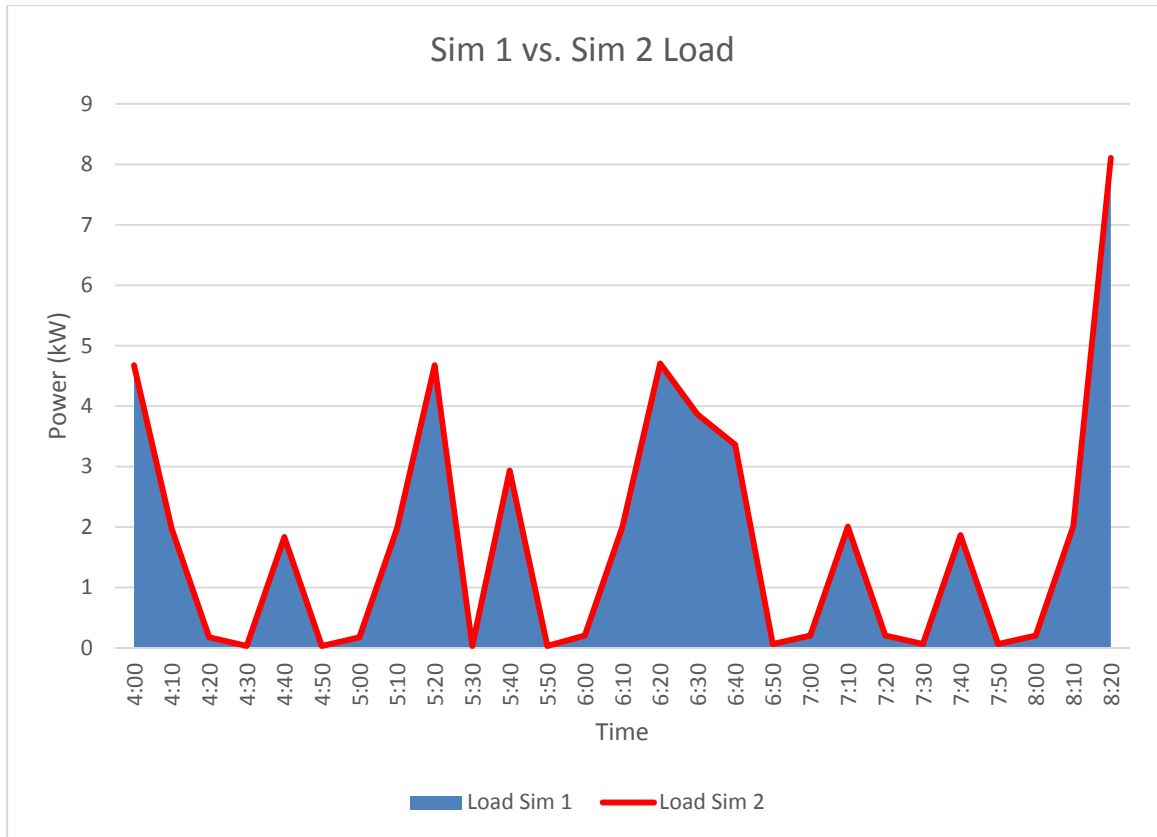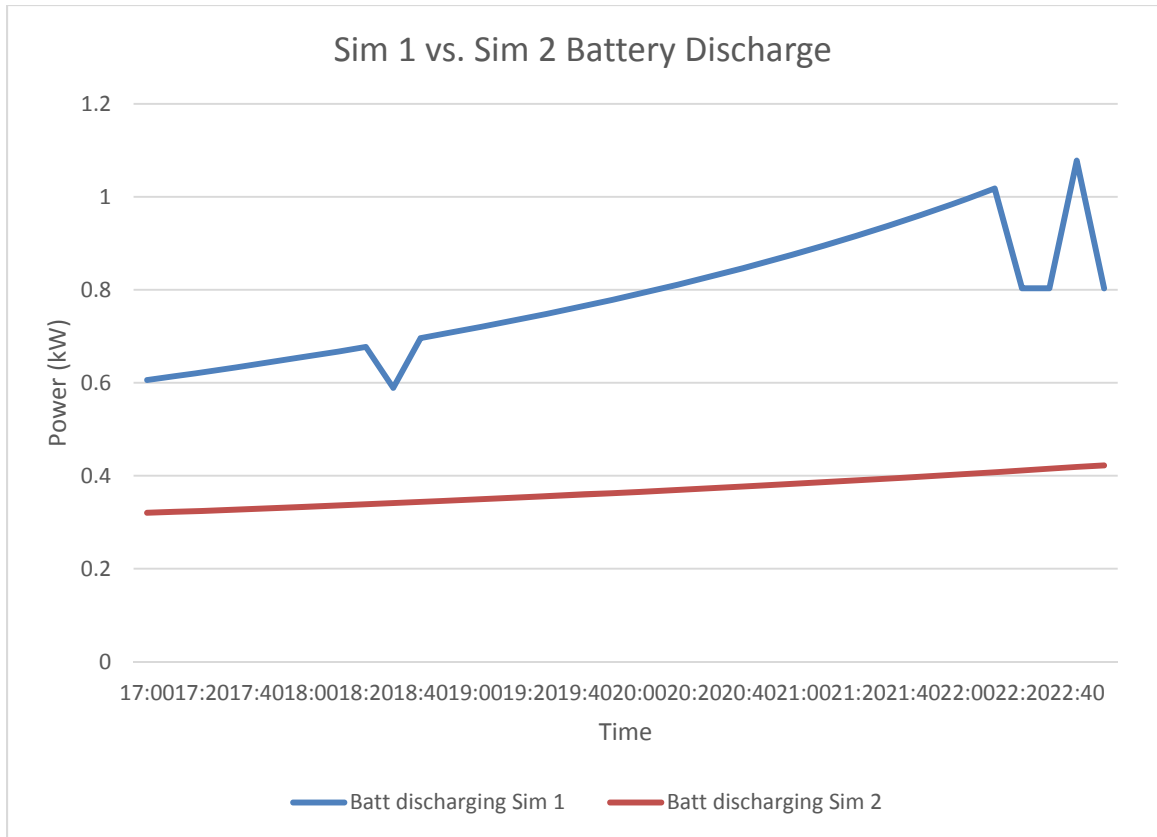
Figure 6.17 MG Load values of simulation 1 Using Heuristic Schedule vs. simulation 2 Using Reliability Schedule from Time 17:00 to 22:50.

The lower the amount of energy in the battery, the greater the ability to discharge. In Simulation 1, there is more energy in the battery compared to that under Reliability Scheduling which has less energy stored in the battery. The Reliability Scheduling is based on the concept that having more energy stored in the battery, would enable the battery to provide more power during peak load demand hours resulting in the MG to be less reliant on the generator. Reliability Schedule simulations were to theoretically perform better in battery discharging due to increases in load demand. But the logarithmic nature of the battery is not taken into account when this scheduling is formed. Heuristic Scheduling performs better during these situations as the battery discharges more power by a smaller amount of energy expenditure. Primarily during hours in peak load demand for both

simulations, the battery is charged by a substantial amount of excess power created from the solar source. This is best demonstrated in early morning hours compared to Reliability Scheduling simulations where the battery is discharging most of the time period to meet load demand.

Battery discharging for the Heuristic Scheduling provides more power than that for Reliability Scheduling in certain simulations. By observing the data from Simulation 10 where the low rating of the generator affects load shedding using Heuristic Scheduling, the performance of the battery overall is limited. A simulation similar to 10 using Reliability Scheduling is not possible since the Reliability Scheduling reverts to the Heuristic Scheduling when the generator has a rating of 4 kW or less. Based on the simulations that have been analyzed, primarily Simulation 10, where the battery is charged to 20.56 kWh at its peak before peak load hours come. The more energy stored in the battery from charging during Reliability Scheduling inhibits battery power discharging. The results for Simulations 5 and 6 are shown to compare simulations using winter data between Heuristic and Reliability Scheduling.
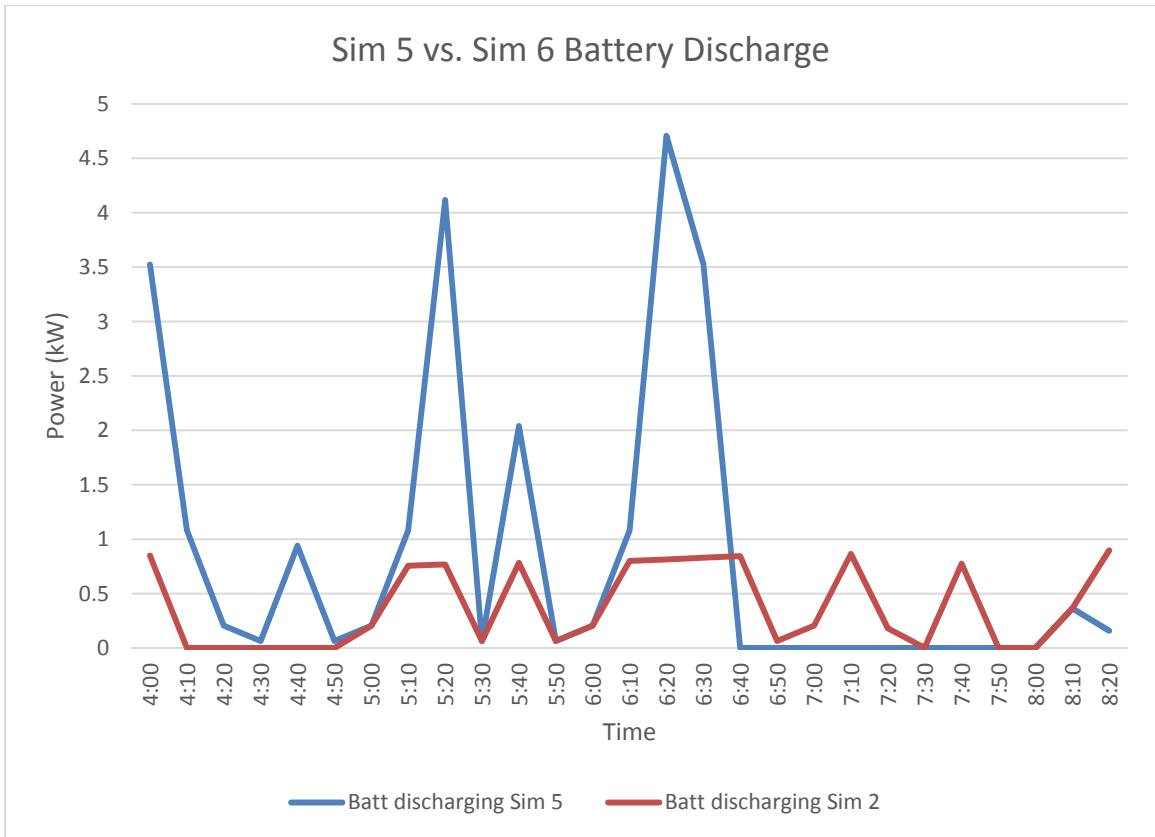
Figure 6.18 Battery Discharging simulation 5 Using Heuristic Scheduling vs. simulation 6 using Reliability Scheduling from Time 04:00 to 08:20.
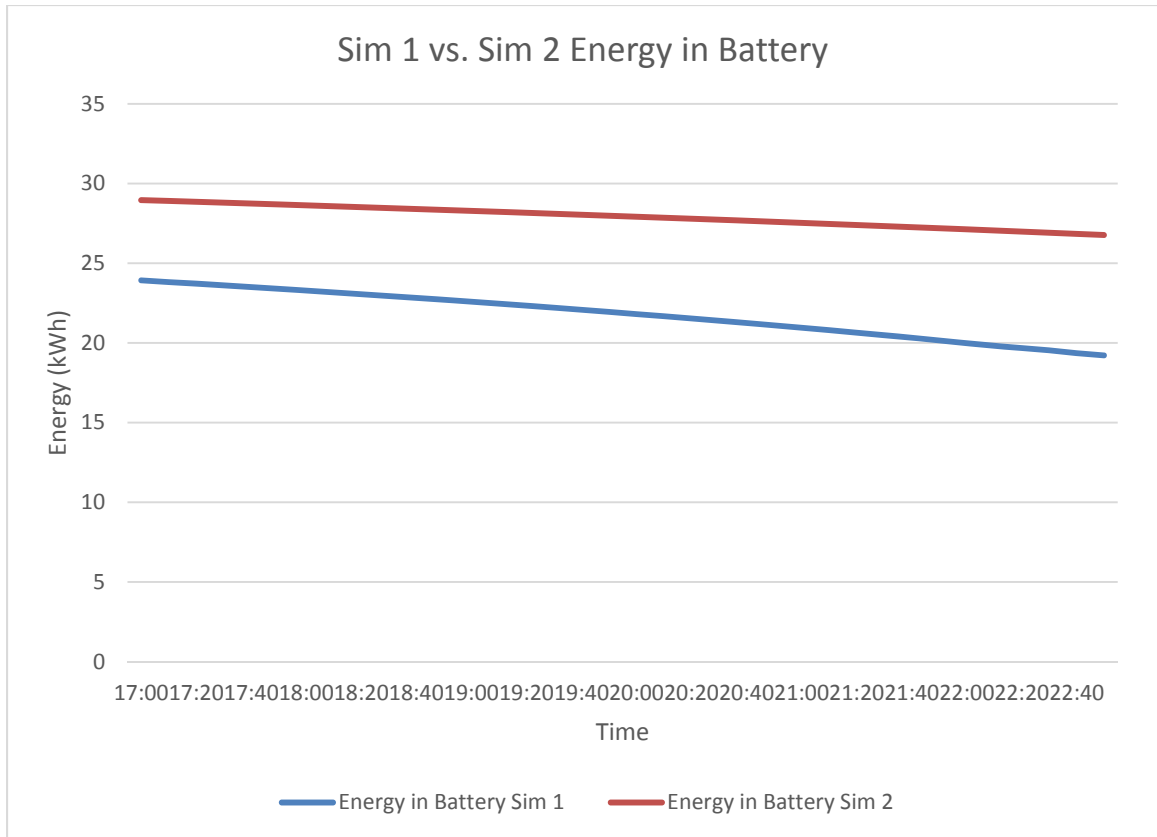
Figure 6.19 Energy in Battery of simulation 5 Using Heuristic Scheduling vs. Energy in Battery simulation 6 Using Reliability Scheduling from 04:00 to 08:20.
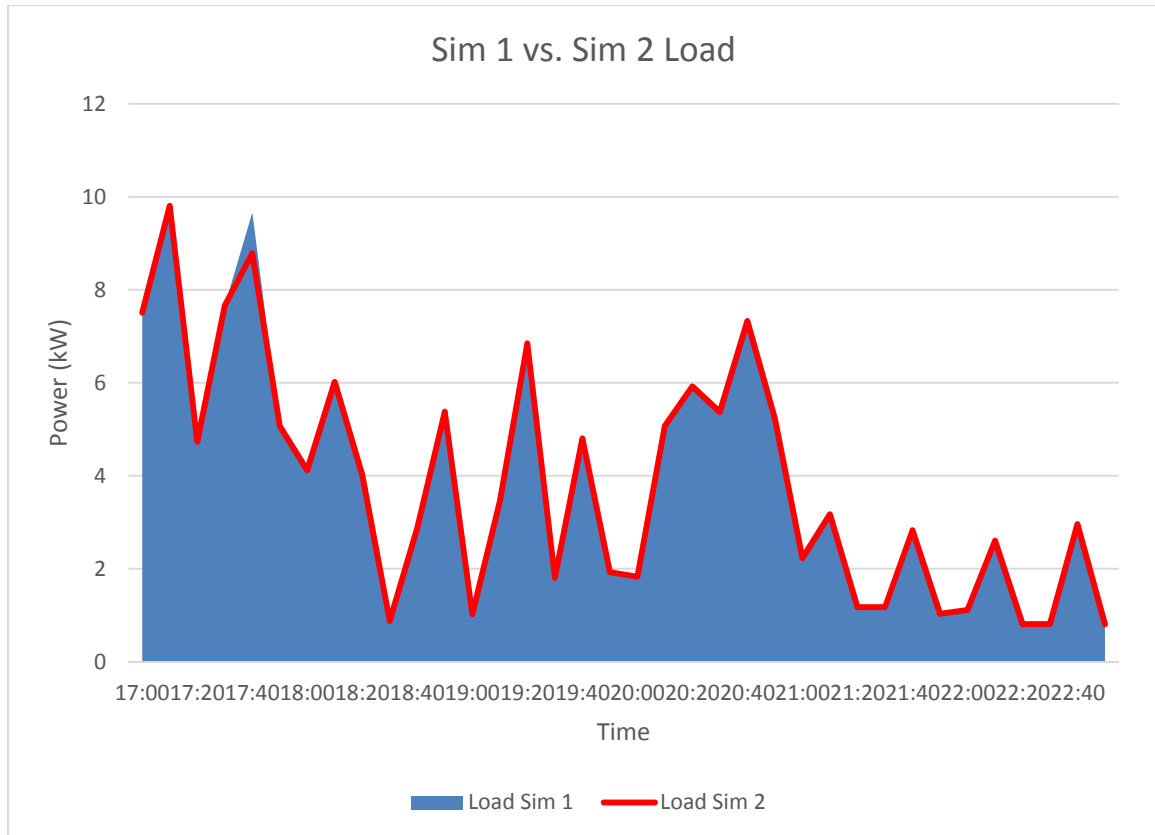
Figure 6.20 MG Load Values of simulation 1 Using Heuristic Scheduling vs. simulation 2 Using Reliability Scheduling from Time 04:00 to 08:20.

Figure 6.21 Battery Discharge simulation 1 Using Heuristic Scheduling vs. simulation 2 Using Reliability Scheduling from Time 17:00 to 22:50.

Figure 6.22 Energy in Battery simulation 5 Using Heuristic Scheduling vs. Energy in Battery simulation 6 Using Reliability Scheduling from 17:00 to 22:50.
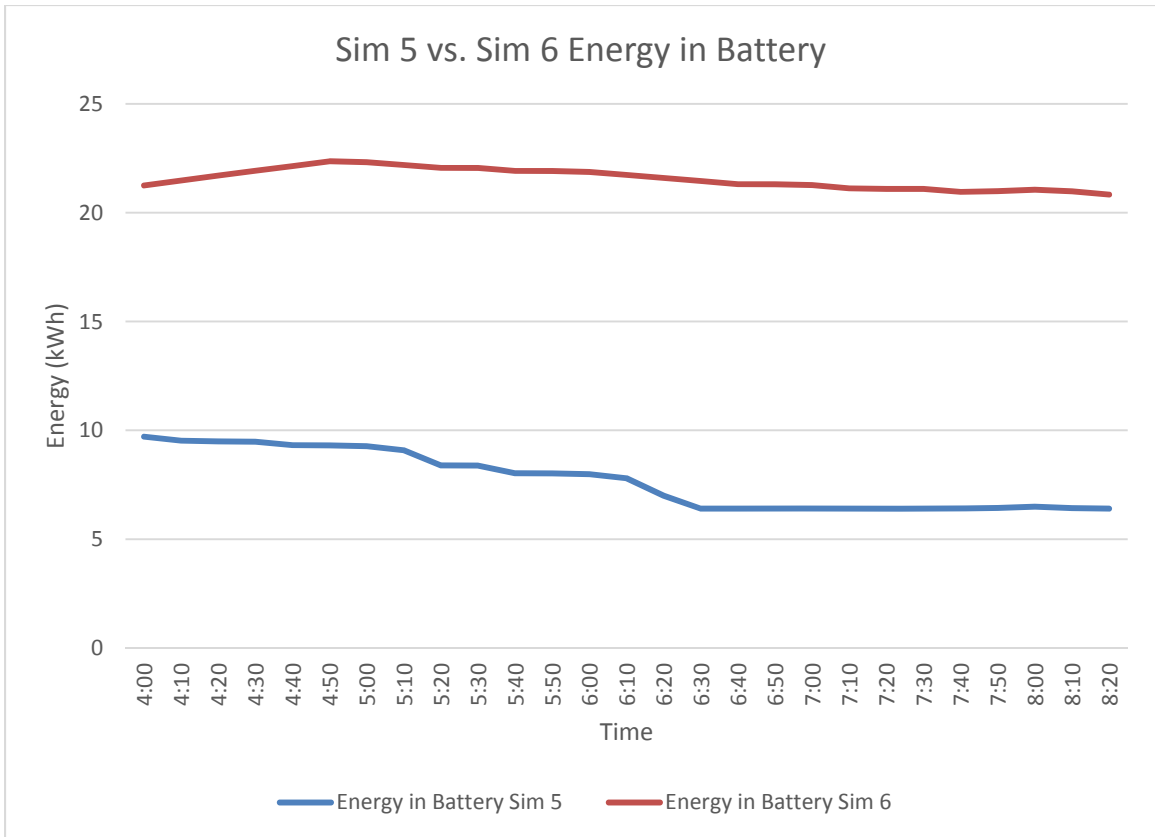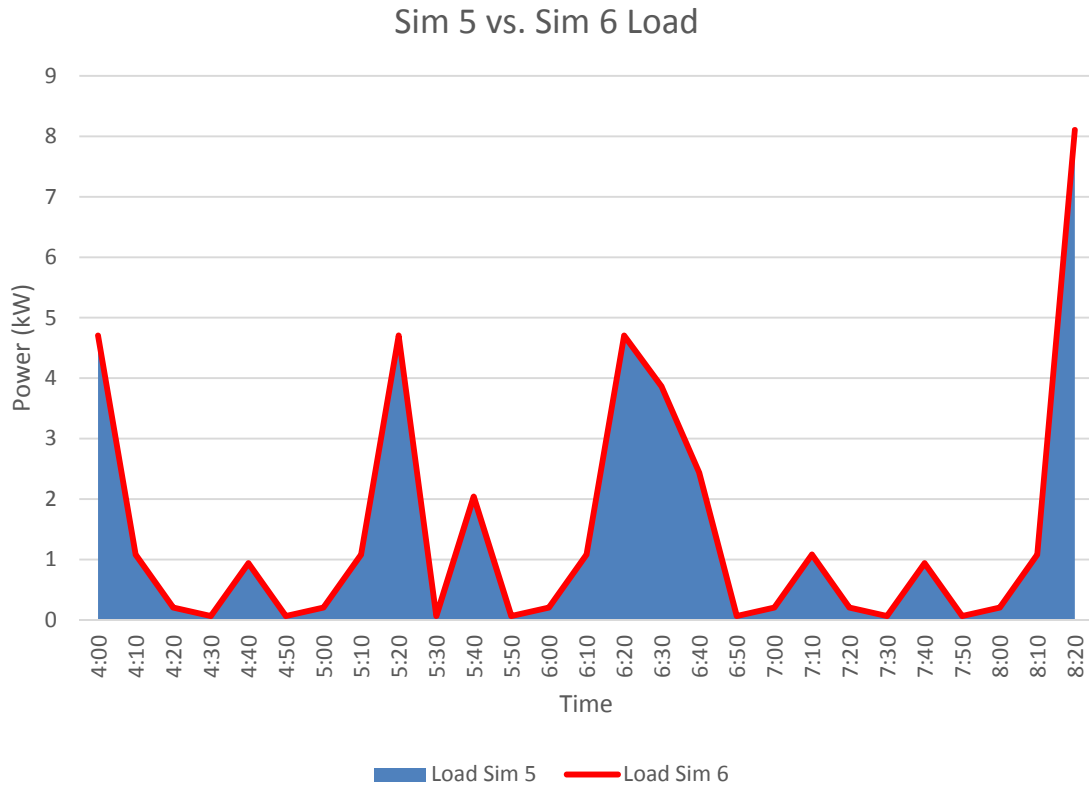
Figure 6.23 MG Load Values simulation 5 using Heuristic Scheduling vs. simulation 6 Using Reliability Scheduling from Time 17:00 to 22:50.
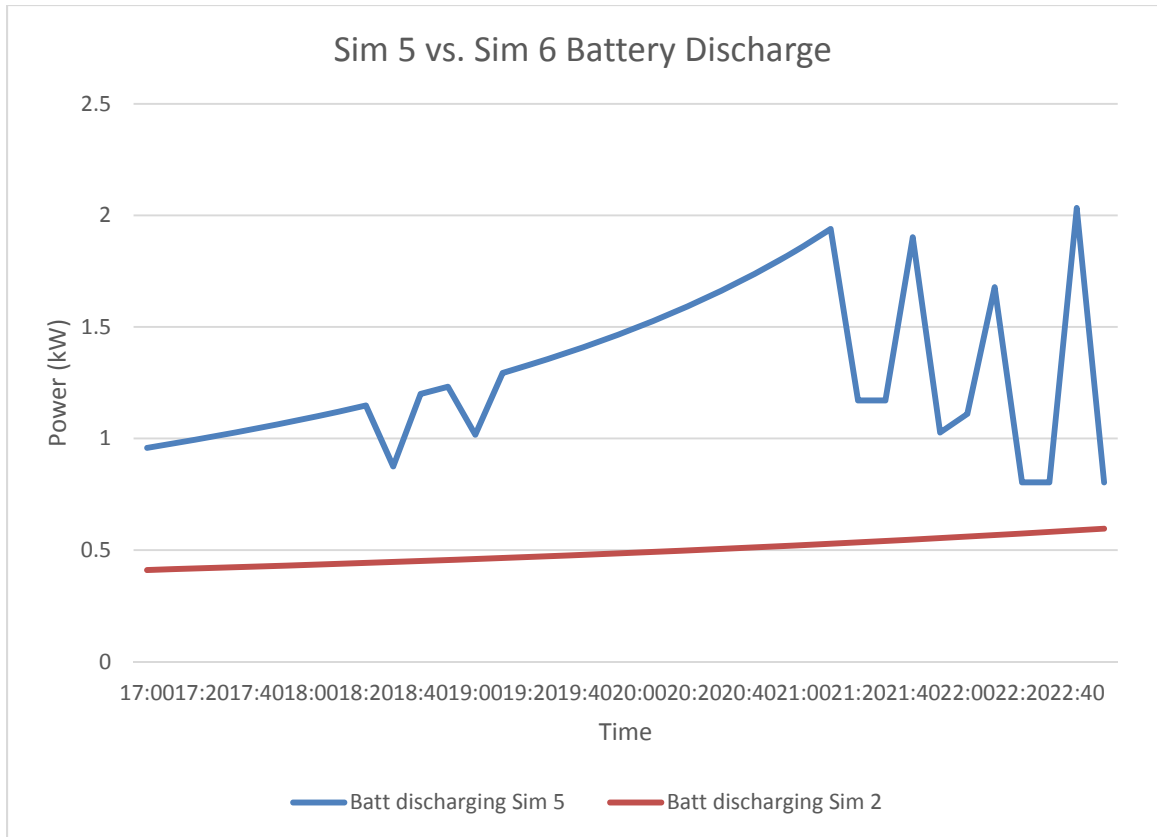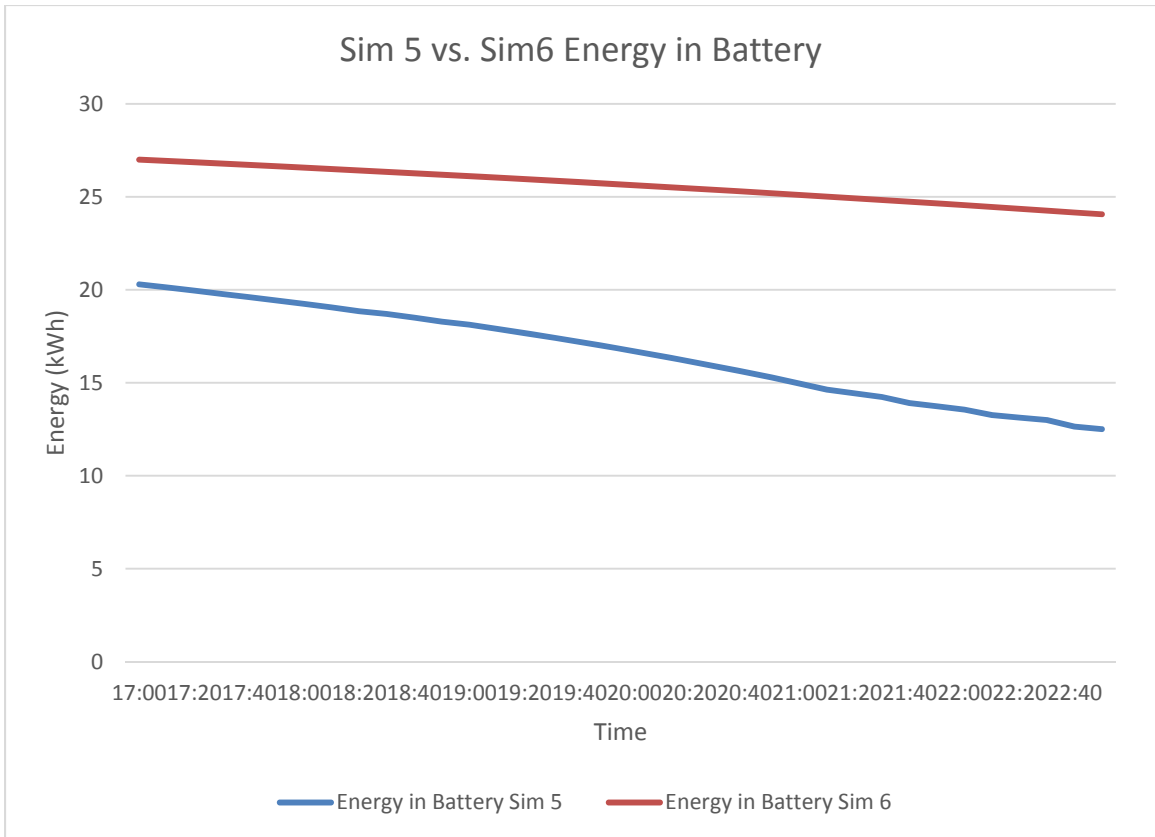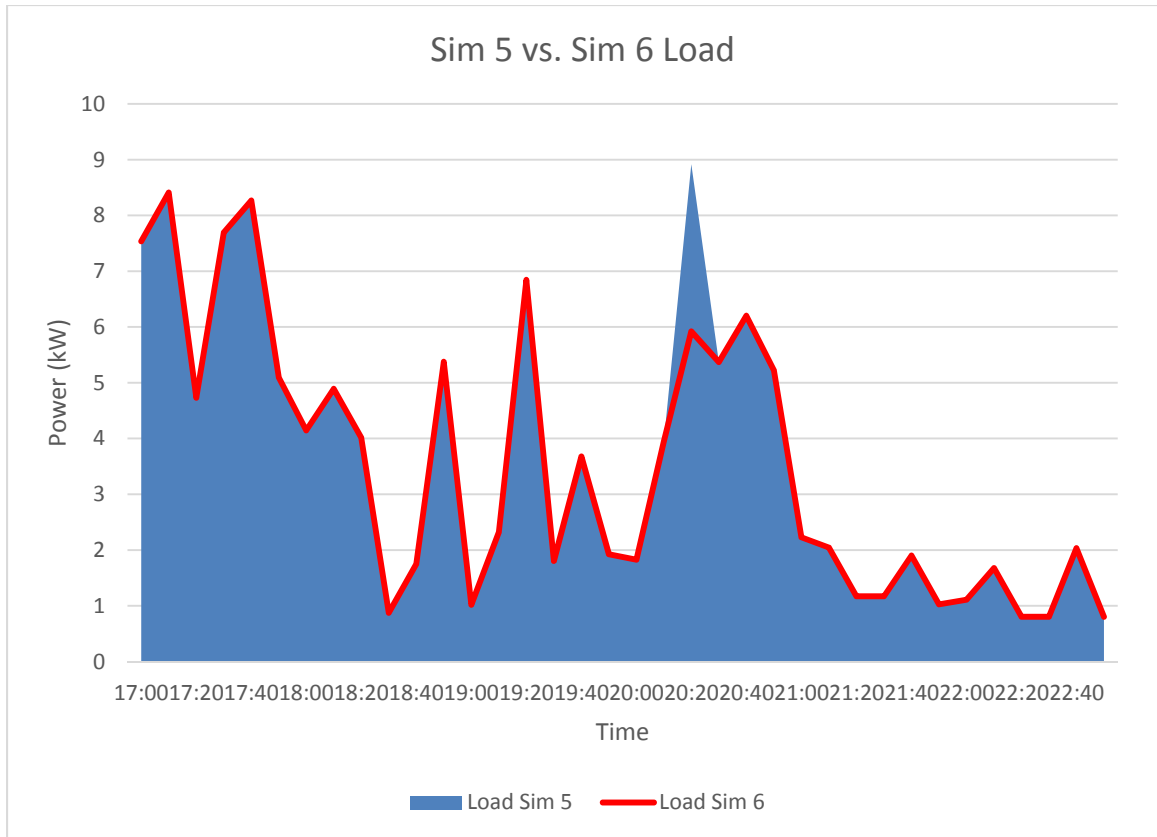
6.5 Reachability Graphs

6.5.1 HPN Model Reachability Graph Tables

Table 6.6 Meanings of Discrete Places for HPN Model. *Indicated by a 1 in the place

P_d	p_1	1st mode of wind turbine
	p_2	2nd mode of wind turbine
	p_3	3rd mode of wind turbine
	p_4	PV cell off
	p_5	PV cell on
	p_6	Diesel Generator on
	p_7	Diesel Generator off
	p_8	Utility is in off state- utility mode 1
	p_9	Utility is providing power- utility mode 2
	p_{10}	Utility is consuming Power- utility mode 3

Table 6.7 Meanings of Continuous Places for HPN Model. * Real values for Continuous places and firing rates

P_c	p_{11}	Energy needed in the battery to make it full capacity (kwh)
	p_{12}	Energy in the battery (kwh)
	p_{13}	Combination of power from DG's and DS minus load and excess power
	p_{14}	Excess power produced from MG – minus charging of the battery and power dissipated

Table 6.8 Meanings for Firing Rates

V_c	v_1	Amount of power produced by windmill in mode 2
	v_2	Amount of power produced by windmill in mode 3
	v_3	Amount of power produced PV
	v_4	Amount of power produced by the generator
	v_5	Amount of power discharged by battery
	v_6	Amount of power used to charge the battery
	v_7	Amount of power being given by the Utility
	v_8	Amount of power consumed by Utility
	v_9	Amount of power being dissipated y MG in MG
	v_{10}	Amount of power consumed by Load
	v_{11}	Amount of Excess power produced by MG

6.5.2 Format for HPN Reachability Graph

A reachability graph shows the changes in the system behavior through markings and is used to study the dynamic properties of the system. The initial marking is critical for the output of the behavior and states of the system. A reachability graph is formed from the firing of the transitions representing the required functional behavior. With M_0 representing an initial marking, the proceeding marking M_i is the specific state after the firing of the transitions. These simulations do not use actual time delays for the firing of

discrete and continuous systems. A reachability graph for a Hybrid Petri Net shows the delay, tokens in discrete and continuous places, discrete and continuous transitions that have fired, and firing rates. The format of a single marking is shown in Figure 6.24.

The markings for a hybrid Petri Net are different from those for a discrete Petri Net. Tau is the time period of the reachability, for example as $\tau = 01:00$ indicates that the marking represents the first hour of the simulation. Places $p_1 - p_{10}$ have markings of discrete places and are represented by a token value of 1 or 0 in them. Places p_{11}-p_{10} are continuous places and the marking is represented by a real number. An arrow goes down from the center of the markings with parentheses on the left showing the discrete transitions that have fired during the time period. The first arrow going down points to a repetition of the tau and markings for the places. To the right of this arrow is t_E representing the continuous transitions that have fired in the PN during the specific time period, with the markings of the firing rates represented by real numbers below it.

143
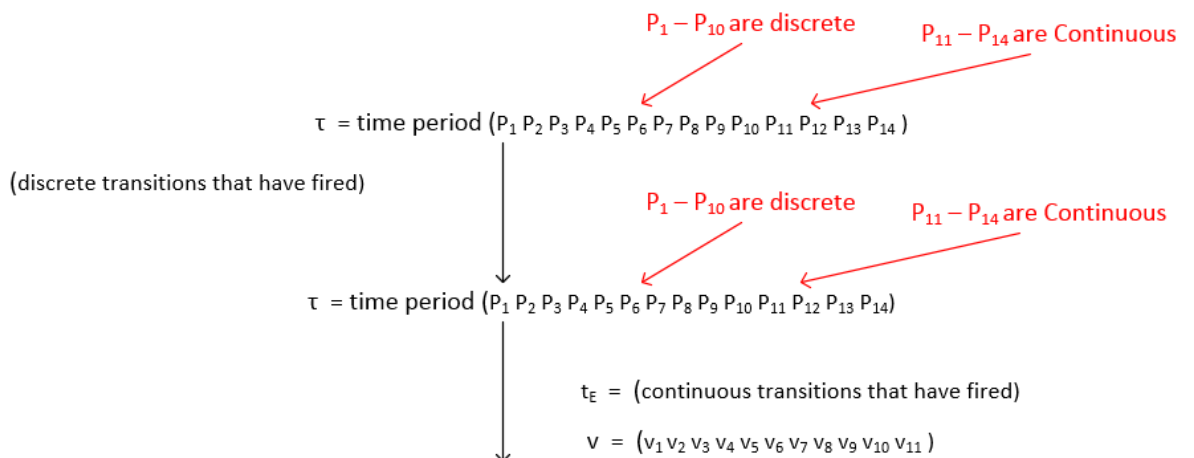
Figure 6.24 Shows the Format for One Time Delay for the HPN Model Reachability Graph.

6.5.3 HPN Reachability Graph

Since the data and analysis of the simulations are described in 6.2.1 Simulations 5 and 7 are quantified to describe the Reachability Graphs. Due to the length of the output data from multiple markings, a single reachability graph for the two simulations is used. The reachability graph is based on simulations 5 and 7, using the same inputs excluding the disaster input. A reachability graph is drawn with the php files for a single column. Two simulations are used to show difference in the markings and firing rates between the two during defined time periods. These differences are due to the fluctuations in the values resulting from the order of load shedding and are marked in the graph by red boxes. A token value of 0 or 1 is used for the discrete places (p_1-p_{10}), and real numbers are used for continuous (p_{11}-p_{14}) places and firing rates (v_1-v_{11}). If a token with a value of one in a discrete place represents that the generator is on, no token in the same place represents that the generator is off.

The values for both places and firing rates are the same for both simulations from τ = 00:00 to τ = 17:10. As seen in initial marking at τ= 00:00, M_0 = (**1 0 0 1 0 1 0 1 0 0 23.03 11.96 0 0**) where p_1=0 indicates the windmill is not producing power in mode 1, thus p_2 and p_3 contain a token value of 0 indicating the windmill generator is not in mode 2 or 3; place p_4 is 1 and p_5 is zero. Places p_8 is 1, p_9 and p_{10} are 0 showing the main distribution grid is neither giving nor consuming power. This will be the case for all values of p_8, p_9, and p_{10} for both simulations since they are in island mode, resulting in the main distribution grid not contributing to the MG. Continuous places p_{11} = 23.03 representing the amount energy

in kWh the battery needs to be fully charged. Place p_{12} = 11.96 kWh showing the amount of kWh in the battery. Resulting in a value of 0.04 kWh of energy discharged from the battery to the MG (the simulation started with 12kWh in the battery minus 12.96 kWh). Place p_{13} = 0 kW, this value is derived by summing the power from the DG's and DS minus the load and excess power produced. Place p_{14}=0 kW, a value derived from the excess power minus the power used for battery charging, power dissipated in island mode, and main distribution grid consuming in grid connected mode.

The firing rates at τ= 00:00 are v_0 = (**0 0 0 0 0.212 0 0 0 0 0.212 0**), v_1- v_4 are zero kW indicating that the windmill is not producing power in mode 1 or 2, and solar and generator power output is zero kW. Firing rate v_5 is 0.212 kW indicating the battery is discharging 0.212 kW to the MG. Firing rates v_6- v_9 are zero meaning that the battery is not charging (the battery cannot both charge and discharge at the same time during a simulation), the main distribution grid is not providing or consuming power for the MG since the simulation is in an island mode (v_7 and v_8 are zero kW for all τ's for both simulations due to this), and there is no power dissipated since there is no excessive power produced in the MG. The only power provided to the grid, is from the DS outputting 0.212 kW (v_5 = 0.212 kW) providing for the load indicated by v_{10} = 0.212 kW, and v_{14} = 0) signifying the excessive power produced by the MG minus the power used for power dissipation with battery charging equal zero.

For many of the time delays p_{13} and p_{14} are zero. At certain times they are not zero with an error due to rounding of numbers in the calculations for the firing rates. This is seen at τ = 7:50, M_{47} = (1 0 0 0 1 1 0 1 0 0 28.56 6.433 **0.010 0.010**) with both p_{13} and p_{14} equaling 0.010 kW. The reachability graph shows the change in the discrete state of the

145

windmill and its output power. One example of this is at τ= 10:50 M_{65} = (0 1 0 0 1 1 0 1 0 0

24.67 10.32 0.205 0.205) where p_1 has switched from 1 to 0 and vice versa for p_2 indicating

the windmill is in mode 2 and outputting power indicated by v_{65} = (0.023 0 4.150 0 0 3.904

0 0 0 0.064 0.205). Place p_1 in the prior marking indicates the power output of the windmill

in mode 2 is 0 for all the time periods, is now producing 0.023 kw (Place p_3 and v_2 have a

token value of zero for all simulations due to the input data of wind speed and air density).

At τ= 11:00, the windmill ceases to produce power indicated by p_1 =1 and p_2 = 0 shown by

M_{66} = (**1 0 0** 0 1 1 0 1 0 0 23.84 11.15 0.256 0.256) with firing rate v_1 = 0 and v_2 indicated

by v_{66} = (**0** 0 5.352 0 0 4.876 0 0 0 0.218 0.256). As described previously for the data and

analysis, solar power is generated from τ = 07:10, M_{43} = (1 0 0 **0 1** 0 1 1 0 0 28.60 6.399 0

0), with p_4 indicating that the PV is not producing power resulting in 0 and p_5 indicating the

opposite by having a 1 value. This is verified by v_{43} = (0 0 **0.008** 1.073 0.0 0 0 0 0 1.081 0)

with v_3 being the value of the power generated by PV at 0.008 kW. The power produced by

the PV peaks at τ= 12:20 with v_{74} = (0.023 0 **5.256** 0 0 **3.211** 0 0 **1.880 0.188** 0); v_3 = 5.256

kW of power produced by the solar source. Load v_{10} = 0.188 kW; and the battery is charged

at its maximum charging rate with v_6 = 3.211 kW. Excessive power is indicated by P$_{dissipated}$

= v_9 =1.880 kW (since the MG is in an island mode). The discrete and continuous places

indicate these actions by τ= 12:20, M_{74} = (0 1 0 **0 1** 1 0 1 0 0 **20.31 14.68** 0 0) with p_4

showing that the PV is not generating power with a token value of 0; and p_5 indicating the

PV is producing power with a token value of 1. Comparing the energy needed in the

battery, p_{11}, decreasing from 20.86 kWh at τ= 12:10, M_{73}= (1 0 0 0 1 1 0 1 0 0 **20.86 14.13**

0 0) to 20.31 kWh at τ= 12:20; and the energy in the battery p_{12} = 14.13 kWh increasing to

at τ= 12:10 to p_{12} = 14.68 kwh at τ= 12:20, due to excessive power generated. At τ = 17:20

load shedding occurs in Simulation 5 and v_{104} = (**0 0 0 3.728 1.000** 0 0 0 0 **4.729** 0). Firing

rate v_{10} indicates that the load is 4.729 kW, with v_1 and v_2 both with a token value equal to

zero. Similarly, v_3 is zero meaning that no power is produced from the PV; and the battery

indicated by v_5 is discharging 1.000 kW of power with the remaining 3.728 kW of power

provided by the generator, v_4 (the discrepancy of the 0.001 kW is due to error in

calculations from the rounding up of significant figures). The discrete transition is seen in

M_{104} = (**1** 0 0 **1** 0 0 **1** 1 0 0 15.03 19.96 0 0), where p_1 and p_4 indicate that power is not being

generated by the PV and wind with a token value of 1.

An example of the generator turning on is indicated by p_7 with a value of 1 and p_5

representing that the generator is off with a token value of 0. The reachability graphs

diverge for Simulation 5 and 7 at τ= 17:20 with differences in values for p_{13}, v_4, and v_{10}

(these differences are indicated by red boxes). The values for the markings and firing rates

for the next time period τ = 17:30 are the same, resulting in the reachability graph

converging at this marking. This behavior happens intermittently throughout the

reachability graph for both simulations due to load shedding caused by the input of either

yes or no indicating disaster or not in the beginning of the simulations (Simulation 5 is yes

and Simulation 7 is no). The diverging of the graphs with the differences of values for the

markings and firing rates is indicated by red boxes with the differences in markings

happening in continuous places $p_{11} - p_{13}$, and firing rates v_4, v_5, and v_{10}.

6.5.4 Load Shedding RG

Table 6.9 Meanings of Discrete Places for the Discrete Load Shedding PN.

P_D	p_1	System is not in load shedding phase
	p_2	System is in load shedding phase tier 3 – loads have to be shed
	p_3	System is in load shedding phase tier 2– loads have to be shed
	p_4	System is in load shedding phase tier 1– loads have to be shed
	Tier 3	
	p_5	Tier 3 electronics are not in load shedding phase
	p_6	Dishwasher is turned off, all proceedings devices are off, all other devices are on
	p_7	Dryer is turned off, all proceedings devices are off, all other devices are on
	p_8	Washing machine is turned off, all proceedings devices are off, all other devices are on
	p_9	Consumer electronic/ outlets are off all proceedings devices are off, all other devices are on
	p_{10}	Lighting is turned off, all proceedings devices are off, all other devices are on
	p_{11}	Kitchen outlets are turned off, all proceedings devices are off, all other devices are on
	Tier 2 A	
	p_{12}	Tier 2A electronics is not in load shedding
	p_{13}	Electric Oven/ Stove is off, all proceedings devices are off, all other devices are on

p_{14}	Emergency Outlet is shutoff, all proceedings devices are off, all other devices are on
Tier 2 B	
p_{15}	Tier 2B electronics is not in load shedding
p_{16}	Emergency Outlet is shutoff, all proceedings devices are off, all other devices are on, all proceedings devices are off, all other devices are on
p_{17}	Electric oven/ Stove is shutoff
Tier 1 A	
p_{18}	Tier 1A electronics is not in load shedding
p_{19}	Refrigerator is shutoff, all proceedings devices are off, all other devices are on
p_{20}	Hot water heater is shutoff, all proceedings devices are off, all other devices are on
p_{21}	HVAC is shutoff
Tier 1 B	
p_{22}	Tier 1B electronics is not in load shedding
p_{23}	Hot water heater is shutoff, all proceedings devices are off, all other devices are on
p_{24}	HVAC heater is shutoff, all proceedings devices are off, all other devices are on
p_{25}	Refrigerator is shutoff, all proceedings devices are off, all other devices are on
Tier 1 C	
p_{26}	Tier 1C electronics is not in load shedding
p_{27}	Hot water heater is shutoff, all proceedings devices are off, all other devices are on
p_{28}	Refrigerator is shutoff, all proceedings devices are off, all other devices are on
p_{29}	HVAC is shutoff, all proceedings devices are off, all other devices are on

The RG for Simulations 5 and 7 are discrete markings with the values for the places as 1 or 0. Tau represents the delay. The description for the load shedding PN is the same that found in the data and analysis of Simulations 5 and 7. The arrow goes down from the marking to the next time delay in which tokens leave places, transitions are fired, and new tokens enter the new places. The format of a single marking is shown in Figure 6.25.
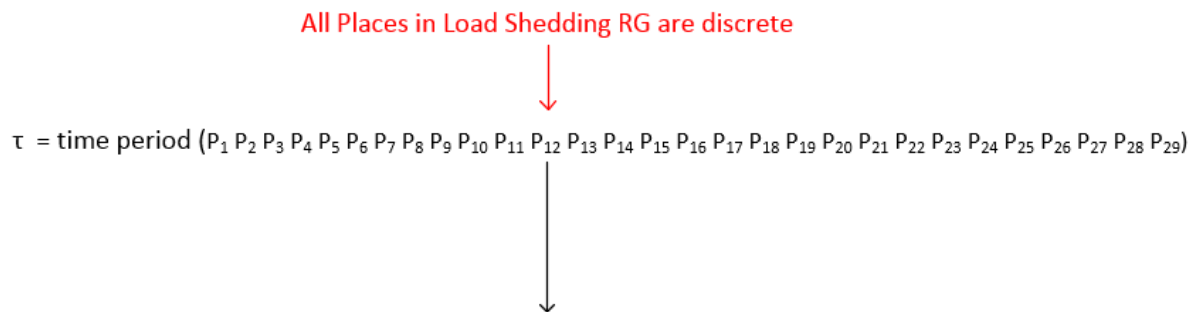

Figure 6.25 The Format for the Discrete Load Shedding Model's Reachability Graph.

Figure 6.26 is the Reachability Graph for load shedding for simulations 5 and 7. The description for the actual load shedding is provided in the data and analysis under load shedding for Simulations 5 and 7.
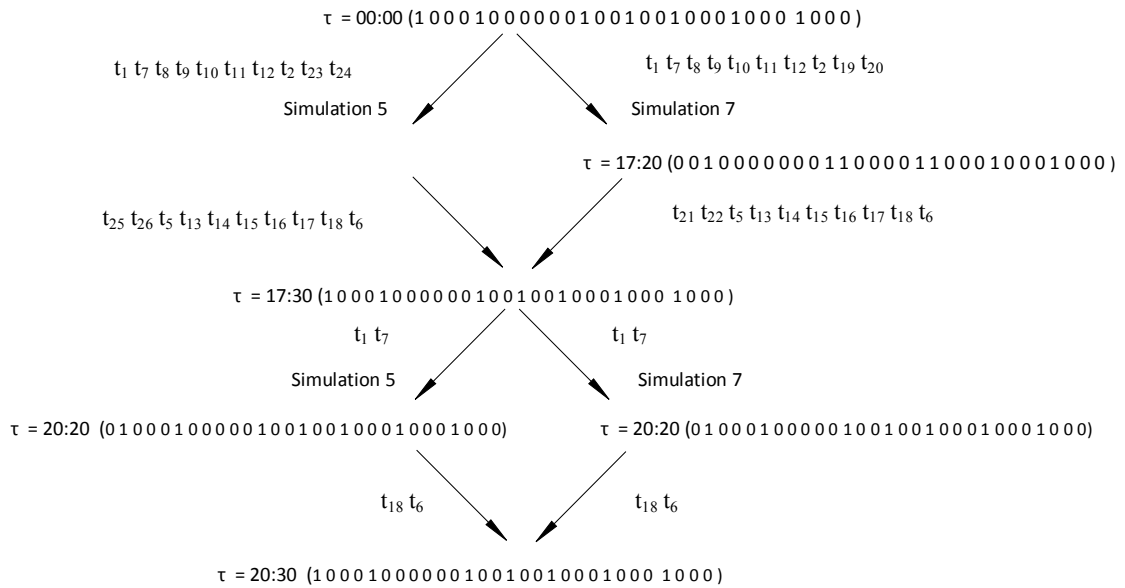
τ = 00:00 (1 0 0 0 1 0 0 0 0 0 0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 1 0 0 0)

t_1 t_7 t_8 t_9 t_{10} t_{11} t_{12} t_2 t_{23} t_{24} t_1 t_7 t_8 t_9 t_{10} t_{11} t_{12} t_2 t_{19} t_{20}

Simulation 5   Simulation 7

τ = 17:20 (0 0 1 0 0 0 0 0 0 0 1 1 0 0 0 0 1 1 0 0 0 1 0 0 0 1 0 0 0)

t_{25} t_{26} t_5 t_{13} t_{14} t_{15} t_{16} t_{17} t_{18} t_6 t_{21} t_{22} t_5 t_{13} t_{14} t_{15} t_{16} t_{17} t_{18} t_6

τ = 17:30 (1 0 0 0 1 0 0 0 0 0 0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 1 0 0 0)

t_1 t_7 t_1 t_7

Simulation 5   Simulation 7

τ = 20:20 (0 1 0 0 0 1 0 0 0 0 0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 1 0 0 0)   τ = 20:20 (0 1 0 0 0 1 0 0 0 0 0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 1 0 0 0)

t_{18} t_6 t_{18} t_6

τ = 20:30 (1 0 0 0 1 0 0 0 0 0 0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 1 0 0 0)

Figure 6.26 Load Shedding's Reachability Graph for Simulations 5 and 7.

6.5.5 RG for Simulations 10 and 13

Simulation 13 is run for the purpose of comparing its output Reachability Graph against that of Simulation 10. The RGs for load shedding and the HPN main model are side by side. These RG's show markings from delays τ = 17:20 to τ = 19:10, a time period where major load shedding occurs due to the Electric Range/Oven turning on. Simulation 13 is set up similarly to Simulation 10. The input for the schedule in the beginning of Simulation 13 is 1, with Reliability Scheduling for Simulation 13. The generator rating for Simulation 10 is 1 kW, which does not meet the requirement for 4 kW or greater generator rating. Simulation 10 reverts to the Heuristic Scheduling for the whole simulation. Simulation 13 uses a 14 kW generator capable of handling the load demand

when the combination of renewable power and battery discharge power is insufficient for providing power to the load. For Simulation 10, all devices are on at τ = 17:20 with v_{10} = 0.612 kW, compared to Simulation 13 with v_{10} equal to 12.33 kW.

These specific RG's do not show the load shedding that has occurred prior to the delays shown. The load shedding process alters the load schedule used for the simulations. Due to the high rating of the generator no load shedding occurs during any period of Simulation 13 as shown in the Load Shedding RG as the markings are the same from τ = 17:20 to 19:10. When the Electric Stove/Oven is finally added to the load in simulation 10 at delay τ = 17:40 load shedding occurs with all devices till Refrigerator in Tier 1A is shut off firing transitions: t_1, t_7- t_{12}, t_2, t_{23}, and t_{24} in the Load Shedding PN reducing the load to 1.02 kW with the load, v_{10} = 5.968 kW as seen in in the RG. At τ = 17:50 in Simulation 10, the refrigerator and water heater are shed leaving the HVAC as the only device to be on by firing transitions: t_3, t_{27}, and t_{28} shutting off Tier 1A devices, with the HVAC running. The load is 0.002 kW compared to 3.993 kW for the load in Simulation 13. Reverse load shedding takes at τ = 18:00 with the Water Heater and Refrigerator reverse shedding by firing transitions t_{31}, t_{32}, and t_4. The devices remains shed in Tier 2B and Tier 3 remain off until time τ = 19:00 when the Refrigerator and Water Heater for Tier 1A are shed again by firing transitions t_3, t_{27}, and t_{28} with a load of 0 kW indicating that although the HVAC is not shed, it is not on during this period compared to a load of 1.446 kW in Simulation 13. Tier 1A devices are reverse load shed in the next time of τ = 19:10 by firing transitions t_{31}, t_{32}, and t_4.

The MG reacts differently due to load shedding, as seen at τ = 17:40 in simulation 10 when devices are shed, and a load of 1.02 kW is provided by the battery. Compared to

Simulation 13 when the combination of the generator and battery provides 12.33 kW of power with the generator providing 11.33 kW. When comparing the generator output from Simulations 10 and 13, Simulation 10 does not use the generator as much due to a cascading effect where the battery provides sufficient power to the load in Simulation 10. This is due to the load being reduced from the load shedding process, resulting from the low generator rating that is not able to provide sufficient power for a larger load. The low rating of the generator results in load shedding causing the MG to drop load demand to a point where only a single DG or DS can supply the load compared to simulations that have a larger generator rating.

CHAPTER 7

CONCLUSION

This work extends the prior developed Hybrid Petri Net (HPN) of a microgrid (MG) to include: an excess power continuous transition and place, a power dissipated transition, and a main distribution discrete model. Firing rates are obtained for: wind power, solar, battery charging, battery discharging, power dissipation, the natural gas generator providing power, the main distribution grid consuming power, and the main distribution grid providing power. Two schedules are developed: a Heuristic Schedule where the Distributed Generators and Distributed Storage respond to the load, and a second Reliability Schedule in which the battery is charged during late night and early morning hours to provide more energy for the battery allowing a better response for the load due to a rise in demand. A load shedding model is developed for the simulation. This allows the MG to respond to a shortage of power generated. Two schedules are developed: a load shedding schedule in which the load is divided into multiple devices and categories that are placed into tiers and levels, and shed in an order dependent on forecasted weather and outside ambient temperature when the MG is in an island mode.

Data is taken from Rutgers meteorology for two days: a summer day of a high temperature, and a winter day of low temperature, with both days having moderate weather. These values are used (dew point, temperature, and barometric pressure) to provide for new data (air density) used for calculations in the simulation. Time periods taken from the data are in 5 minutes, with every other time segment used resulting in a 24 hour simulation using 10 minute spans. Using surveys answered from various colleagues,

observing the author's personal residential load use, reading papers published on load schedules and devices, and using sources that list the power consumed in a standby mode for those devices, a load schedule is formed.

Three programs are created, two using Python, and one in php code. The first program is the main simulation code that takes input data from excel csv sheets and uses firing rates in conjunction with the Heuristic or Reliability Schedules combined with load shedding and de load shedding programed into the simulation. The output data is provided on an excel csv file. The second program uses Python code and the output excel sheet data and maps out the discrete and continuous transitions that have fired placing them into a single format. These values are used by the php program to output the data in a single column format for the reachability graphs on an online website. Each simulation has seven inputs: critical temperature, if a disaster is forecasted, if the MG is grid-connected or in an island mode, Heuristic or Reliability scheduling, the rating of the generator for the simulation, the season for the data input (Summer or Winter), and the value of the energy in the battery. Thirteen simulations with varying inputs are done to test how the MG would react to different inputs. It is observed that the battery discharge power performance is optimal with the smaller amount of energy it contains due to the logarithmic nature of the battery charging and discharging firing rates. Load shedding occurs more in simulations where the rating of the generator is low and could not compensate for lack of combined renewable battery discharge power. The simulations reveals how critical the generator and/or main distribution grid is for the MG, especially during times of peak load demand. A reachability graph for the HPN and load shedding models is created and explained. Multiple graphs for the simulation results are provided and also explained.

Future work is to be done with further models that can be developed to expand the simulations and simplify the HPN's. Due to time constraints an Electric Vehicle is not added to the main MG model. This EV acts as a second battery to the MG, supplying power during peak load times, but acting as a load during charging resulting in more complex scheduling. The load shedding model can be simplified by using a Colored PN which would classify each load device with a separate colored token, further simplifying the model. Altering the main MG model to a Hybrid Colored PN will allow the simulation to use real power, apparent power, reactive power, voltage, and current using separate colored tokens. Future work may also include using models for power protection with transients which is critical in power systems. Scheduling can be optimized for battery performance with more accurate firing rates for the DG's and DS.

APPENDIX A

PN MODEL DIAGRAMS AND SCHEDULING DIAGRAMS

Online repository is found at: https://web.njit.edu/~jsm53/thesis/index.php

Appendix A shows the PN models and Scheduling

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/HPN.pdf for HPN model

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/LoadSheddingPN.pdf for Discrete

Load Shedding Model

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Schedule1.pdf for Schedule 1

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Schedule2.pdf for Schedule 2

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/LoadSheddingSchedule.pdf for

Load Shedding Schedule

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/DeLoadScheduling.pdf for

De-Load Shedding Schedule

APPENDIX B

LOAD SCHEDULING

Appendix B refers to the Load Schedule and materials that contributed to the making of the Load Schedule

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/ThesisSurveysSet1.PDF for Thesis Surveys Set 1

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/ThesisSurveySet2.PDF for Thesis Surveys Set 2

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/ThesisSurveySet3.PDF for Thesis Surveys Set 3

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/ThesisSurveySet4.PDFblah for Thesis Surveys Set 4

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Mastersthesissurvey.pdf for Excel Sheet of Thesis Surveys

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Load24hr-Summer.pdf for checklist of Load devices on for 24 hour Summer Day

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Load24hour-Winter.pdf for checklist of Load devices on for 24 hour Winter Day

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Summer.pdf for schedule and values of load devices for a 24 hour Summer Day

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/SummerLoadMorning.pdf for schedule and values of load devices for a Summer Day Morning

Refer to	https://web.njit.edu/~jsm53/thesis/Docs/SummerLoadEvening.pdf for

schedule and values of load devices for a Summer Day Evening

Refer to	https://web.njit.edu/~jsm53/thesis/Docs/WinterLoadMorning.pdf for

schedule and values of load devices for a Winter Day Morning

Refer to	https://web.njit.edu/~jsm53/thesis/Docs/WinterLoadEvening.pdf for

schedule and values of load devices for a Winter Day Evening

Refer to	 https://web.njit.edu/~jsm53/thesis/Docs/Summer.pdf for program input

load data for a 24 hour Summer Day

Refer to	https://web.njit.edu/~jsm53/thesis/Docs/Winter.pdf for program input load

data for a 24 hour Winter Day

Refer to	https://web.njit.edu/~jsm53/thesis/Docs/Summation.pdf for 24 hour

Summer and Winter Day summation of W and Wh for PV calculations

WEATHER DATA

Appendix C shows the Calculation and data sheets for the seasonal weather input

Refer to

https://web.njit.edu/~jsm53/thesis/Docs/Data%20Viewer%20%20New%20Jersey

%20Weather%20and%20Climate%20Network3.pdf for New Jersey Meteorology

data for Temp , 5 Minute Barometric Pressure Avg, 5 Minute Precipitation, 5

Minute Solar Radiation Average, 5 Minute Temperature Average, 5 Minute

Windspeed Average, and 5 Minute Wind Direction Average for 7/02/2014

(summer Day)

Refer to

https://web.njit.edu/~jsm53/thesis/Docs/Data%20Viewer%20%20New%20Jersey

%20Weather%20and%20Climate%20NetworkW1.pdf for New Jersey

Meteorology data for Temp , 5 Minute Barometric Pressure Avg, 5 Minute

Precipitation, 5 Minute Dew Point Average, and 5 Minute Relative Humidity

Average 7/02/2014 (summer Day)

Refer to

https://web.njit.edu/~jsm53/thesis/Docs/Data%20Viewer%20%20New%20Jersey

%20Weather%20and%20Climate%20Network4.pdf for New Jersey Meteorology

data for Temp , 5 Minute Barometric Pressure Avg, 5 Minute Precipitation, 5

Minute Solar Radiation Average, 5 Minute Temperature Average, 5 Minute

Windspeed Average, and 5 Minute Wind Direction Average for 1/11/2015

(Winter Day)

Refer to

https://web.njit.edu/~jsm53/thesis/Docs/Data%20Viewer%20%20New%20Jersey

%20Weather%20and%20Climate%20NetworkW1.pdf for New Jersey

Meteorology data for Temp , 5 Minute Barometric Pressure Avg, 5 Minute

Precipitation, 5 Minute Dew Point Average, and 5 Minute Relative Humidity

Average 1/11/2015 (Winter Day)

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/FADCSummer.pdf for Air

Density Calculations for Summer Day

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/FADCWinter.pdf blah for Air

Density Calculations for Winter Day

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/SummerWindSpeed.pdf for Input

weather data for program simulation for Summer Day

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/WinterWindSpeed.pdf for Input

weather data for program simulation for Winter Day

APPENDIX D

SIMULATION RESULTS

Appendix D are the Simulation results for the thirteen simulations

Refer to https://web.njit.edu/~jsm53/thesis/Docs/Simulation1.pdf for simulation 1
results

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Refer to https://web.njit.edu/~jsm53/thesis/Docs/Simulation2.pdf for simulation 2
results

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Simulation3.pdf for simulation 3

results

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Simulation4.pdf for simulation 4

results

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Simulation9.pdf for simulation 9

results

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS vs. Time

Page 20 Excess Power vs. Time

Page 21 Generator and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/Simulation10.pdf for simulation

10 results

Pages 1-19 Program Output data

Page 20 Summer Load Schedule vs. Time

Page 21 Load Schedule vs. Actual Load

Page 22 Windpower mode 1 vs. Time

Page 23 DG & DS vs. Time

Page 24 Excess Power vs. Time

Page 25 Generator and Batt. Discharge vs. Time

Page 26 Battery Charging vs. Discharging

Page 27 Energy in needed in Battery vs. Energy in Battery

Pages 28-41 Labeled Program Output Data

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS & Main Distribution Grid vs. Time

Page 20 Excess Power vs. Time

Page 21 Main Distribution Grid and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Refer to https://web.njit.edu/~jsm53/thesis/Docs/Simulation12.pdf for simulation 12   results

Pages 1-15 Program Output data

Page 16 Summer Load Schedule vs. Time

Page 17 Load Schedule vs. Actual Load

Page 18 Windpower mode 1 vs. Time

Page 19 DG & DS & Main Distribution Grid vs. Time

Page 20 Excess Power vs. Time

Page 21 Main Distribution Grid and Batt. Discharge vs. Time

Page 22 Battery Charging vs. Discharging

Page 23 Energy in needed in Battery vs. Energy in Battery

Pages 24-33 Labeled Program Output Data

Refer to https://web.njit.edu/~jsm53/thesis/Docs/Simulation13.pdf for simulation 13 results

Pages 1-19 Program Output data

Page 20 Summer Load Schedule vs. Time

Page 21 Load Schedule vs. Actual Load

Page 22 Windpower mode 1 vs. Time

Page 23 DG & DS vs. Time

Page 24 Excess Power vs. Time

Page 25 Generator and Batt. Discharge vs. Time

Page 26 Battery Charging vs. Discharging

Page 27 Energy in needed in Battery vs. Energy in Battery

Pages 28-41 Labeled Program Output Data

Refer to https://web.njit.edu/~jsm53/thesis/Docs/HPNRG5-7.pdf for RG of

 simulations 5 and 7

Refer to https://web.njit.edu/~jsm53/thesis/Docs/V10%20comparison.pdf for

comparison of v_{10} for simulations

Refer to https://web.njit.edu/~jsm53/thesis/Docs/Comparison7-5RG.pdf for

comparison of firing rates for simulations 5 and 7 for RG

Refer to https://web.njit.edu/~jsm53/thesis/Docs/RGLSSim13.pdf for Reachability

Graph for Load Shedding and HPN for Simulation 13

Refer to https://web.njit.edu/~jsm53/thesis/Docs/RGLSSim10.pdf for Reachability

Graph for Load Shedding and HPN for Simulation 10

APPENDIX E

PN MODEL CODE

Online repository is found at: https://web.njit.edu/~jsm53/thesis/index.php

Appendix E shows the code for the Python and php Programs

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/firstprogramPython.pdf for the

first HPN Simulation Python Code

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/secondprogramPython.pdf for the

Second Python Code that groups together the Fired Continuous and

Discrete Transition

Refer to   https://web.njit.edu/~jsm53/thesis/Docs/phpthirdprogram.pdf for the php

code that Outputs the Excel Data as a Reachability Graph

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