Electric Car Proliferation and Acceptability

A Major Qualifying Project

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Abstract

The goal of this project was to predict the effects of electric vehicle proliferation through a typical New England 15kV-class feeder. By means of simulation, it was possible to predict the power flow corresponding to different load demands. The study focused on the higher demand days of the year, and was determined that during the hottest summer days the maximum admissible demand became exceeded above a critical number of electric vehicles. In order to accommodate above this critical point, it was necessary to consider renewable generation, maximum demand power shifting, and inclusion of battery storage.

Acknowledgements

We would like to thank WPI Professor John Orr for providing us with additional access to simulation software. We would also like to thank James Robinson for providing us with sample feeder data.

Finally, we would like to give special thanks to our advisor, Professor Alexander Emanuel, without whom this project would not have been possible. Without his encouragement and support, this project would not have turned out as well as it did.

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1 Introduction

The United States and its' citizens have a long history with personal automobile use and ownership, particularly since 1908 when Henry Ford created the affordable Model T [1]. Ever since the advent of affordable automobiles, the United States has developed one of the largest automobile markets in the world [2].

Figure 1 below shows the personal vehicle growth trend compared to the growth in household drivers in the United States, showing that the number of personal vehicles has surpassed both the number of households and drivers since 1969 [3].

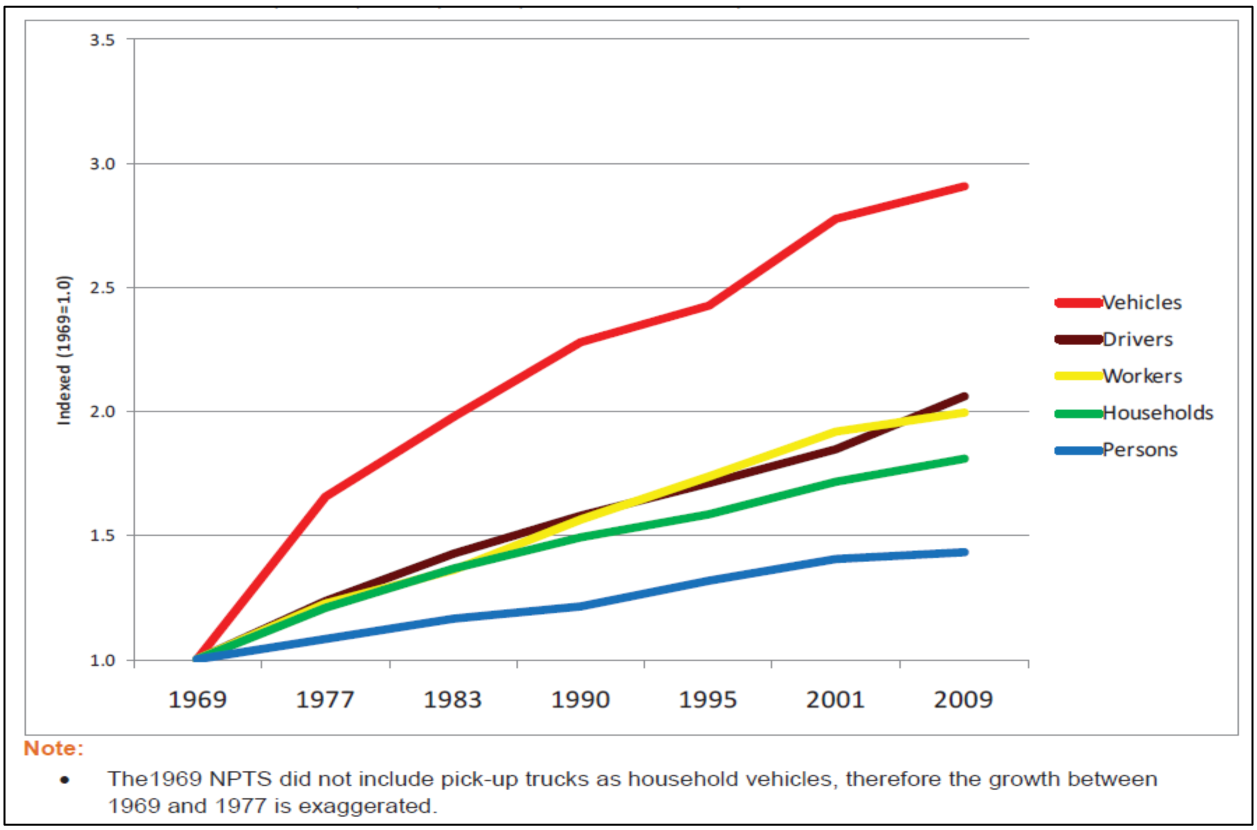

Figure 1: Proliferation of Vehicles and Households since 1969 [3]

The vast majority of the vehicles in the United States use petroleum products to fuel and lubricate their engines, which contribute to greenhouse emissions that can contribute to global warming and other environmental issues [4]. Figure 2 below shows a distribution of total greenhouse gas emissions in the United States in 2013.It can be seen that transportation accounts for 27% of greenhouse gas emissions, only second to generation emissions of electricity. The types of transportation that account for Figure 2 include cars, trucks, trains, planes, and ships, and is estimated that more than 90% of the fuel used to power these vehicles comes from petroleum in the form of either gasoline or diesel [4].

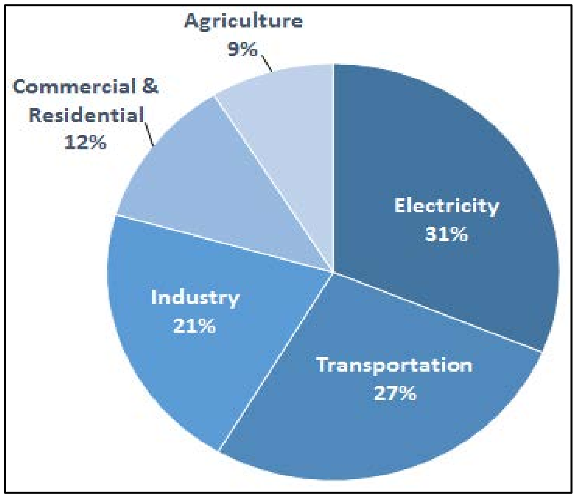

Figure 2: Total U.S. Greenhouse Gas Emissions by Economic Sector in 2013 [4]

Figure 2 also shows the percentage of greenhouse emissions gases from electrical energy generation to be the largest contributor to total greenhouse gas emissions. It is estimated that of the 31% share of greenhouse gas emissions that electrical energy generation produces, over two-thirds of the emissions is due to the burning of coal, natural gas, and other fossil fuels [4].

Figure 3 below shows energy consumption with the major forms of energy sources being used on the left and the generalized sectors that utilize the energy on the right [5]. As shown in the figure, a staggering majority of about 80% of primary energy consumption comes from a fossil fuel source, while renewable energy sources and nuclear energy fill most of the remaining 20% of other sources. Considering renewable and nuclear sources do not produce greenhouse gases, it can only be concluded that using fossil fuels in energy generation is more affordable for the consumer or more economically abundant; but how many more years will fossil fuels be a reliable energy source? When should a transition to renewable energy sources begin to decrease the United States' 80% dependence on fossil fuels for energy sources?

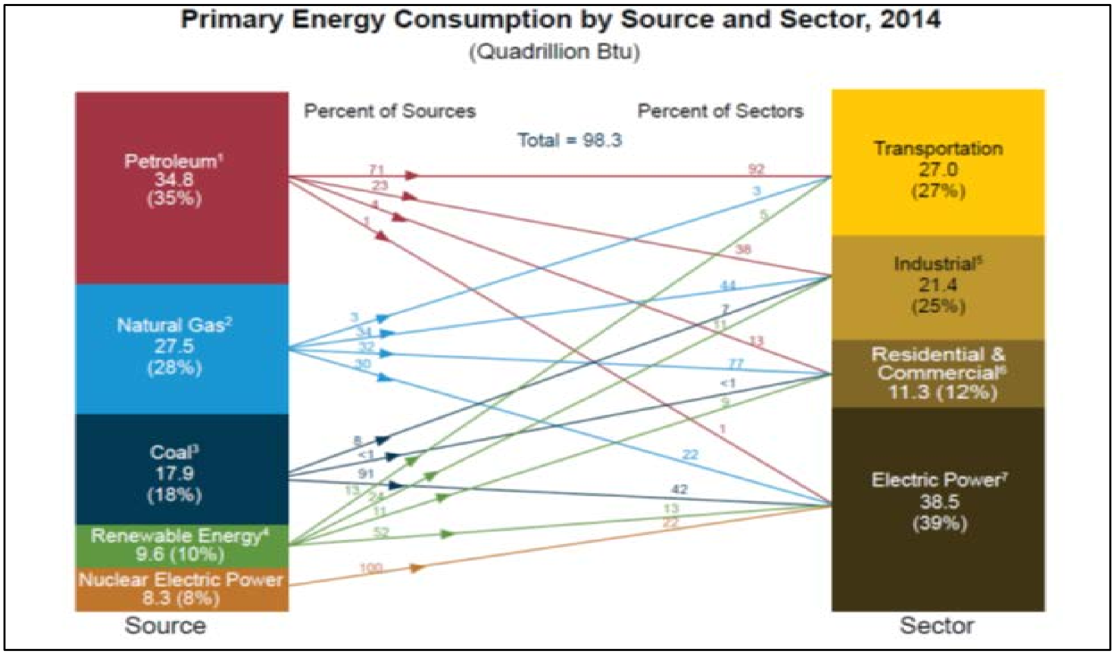

Figure 3: Energy Consumption by Source [5]

Concerning the modern automobile, work has been done and is currently being done to create a reliable vehicle that uses electrical energy as opposed to fossil fuel combustion, and studies show that converting the broad spectrum of transportation to electrical energy sources would improve air quality by reducing greenhouse gas emissions [6]. There have been several advances leading up to the technology to create electric vehicles (EVs), but the largest drawback for customers is the cost of an EV, especially when considering buying an EV compared to an economy combustion vehicle [6]. Though EVs may be cheaper to own in the long run due to lower fuel and maintenance costs, the price for an electric vehicle is not on a head-to-head competitive level with combustion vehicles [6]. It is suspected, however, that the price of an electric car will eventually be lower than a combustion vehicle due to advances in battery technology [6].

Though switching to EV’s would produce less greenhouse emissions where the cars operate, the energy to run the EV’s would most likely come from electric generation plants. Table 1 below shows the CO2 emissions in the United States produced by electrical generation, totaling an estimated 2,043 million metric tons of CO2 [7]. In comparison, the estimated greenhouse emissions from car fuel (both gasoline and diesel fuel) for 2014 was 1,519 metric tons of CO2 [8]. The ratio of the electrical generation emissions to the transportation emissions (roughly 1.3:1) corresponds to the primary energy consumption in Figure 3 above for the same comparison elements, which suggests that an EV will have the same overall greenhouse emissions effect through a power plant proxy if the energy is supplied by fossil fuel electrical generators.

Table 1: CO2 emissions from U.S. electricity generation by source, 2014 [7]

Source	**Million metric tons (CO_2)**	**Share of total**
Coal	1,562	76%
Natural gas	444	22%
Petroleum	23	1%
Other[3]	11	<1%
Total	2,043	100%

Figure 4 below displays the electrical energy consumption trend for the United States from 1949 to 2011 [9], and Figure 5 directly below displays this information in kilo-Watt-hours [10]. It can be seen that there is a positive overall slope to the line in the figure, concluding that electrical consumption can be seen to increase 10,000 Trillion Btu's approximately every ten to fifteen years. Figure 4 may imply that there has been an increasing and constant expansion of electrical distribution systems since about 1950.According to the figure below, a predictable strain on the electrical distribution systems may be extrapolated for the future planning of electrical distribution.

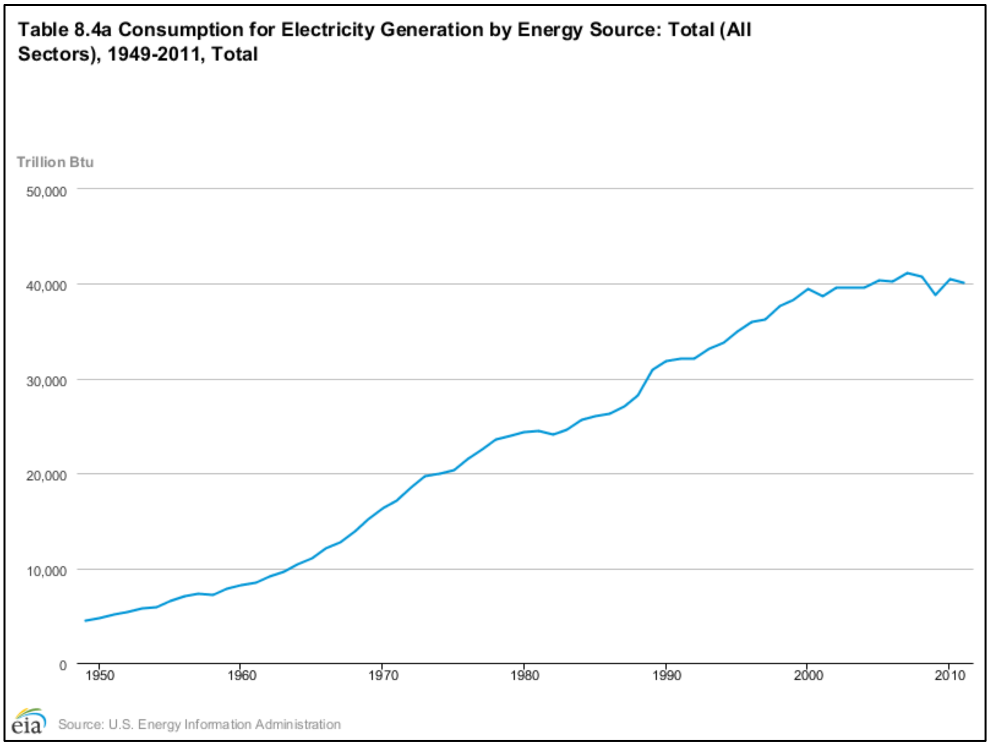

Figure 4: U.S. Electricity Use History in Btu [9]

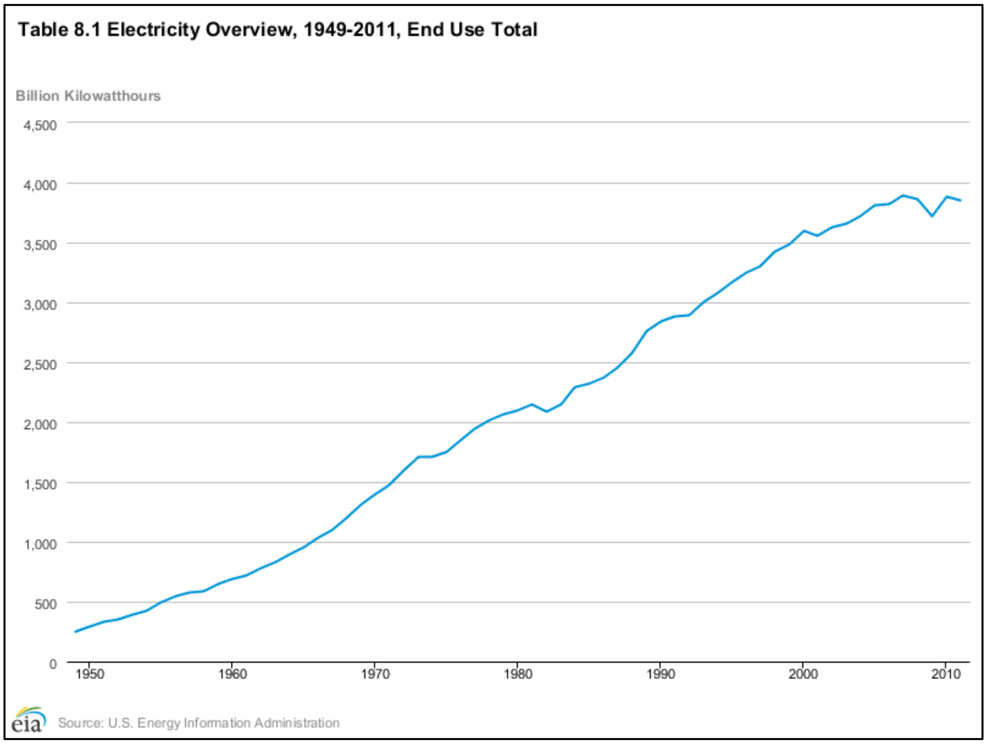

Figure 5: U.S. Electricity Use History in kWh [10]

Continuing the thought from Figure 4 and Figure 5, Figure 6 below show four possible paths that electrical demand could follow up to 2050 [11].Figure 6 can be seen to imitate Figure 5 until 2010, where the projected futures split into four different projected action-result scenarios. The black line labeled 'Maintain' describes no proactive decisions to conserve energy, resulting in the predicted electricity demand increase of 0.9%, set from the electricity demand trend from 1950 to 2010; whereas, the green line labeled 'Transform' describes intense focus on energy efficiency, resulting in an overall drop and eventual leveling of electricity demand [11].Though the path to 'Transform' looks promising, the projection relies on almost total integration of renewable energy sources, such as wind turbines and solar panels combined with battery, and further seems to imply that the vast majority of individual property owners would assume responsibility to transform with the same intensity as the distribution supplier [11].The paths to 'Mitigate' and 'Renew' are intermediary steps between 'Maintain' and 'Transform', describing smaller changes overall [11].Having taken into account that the actions of individual owners is unpredictable, a realistic conclusion to these four paths would be that it is more likely to see an increase in electricity demand rather than a decrease, up to the year 2050.

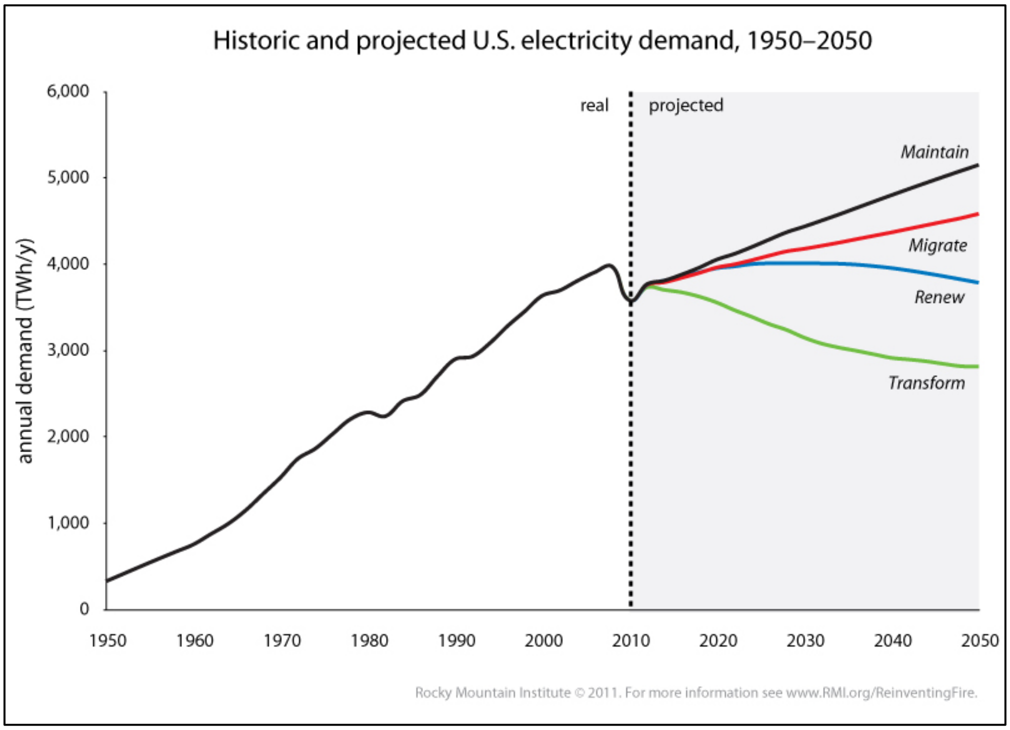

Figure 6: Possible U.S. Electricity Demand Scenarios [11]

Figure 7 below displays information about average gasoline prices in the United States in dollars per gallon [12], which American consumers use to fuel their vehicles. A measure of great inconsistency can be seen in the figure, especially since approximately 2008, where the price increases, decreases, and plateaus without pattern. From 1994 to 2005, the average price of gasoline at the pump rose consistently and predictably, and overall, from 1995 to 2015, prices can be seen to be climbing overall. Figure 7 at the very least infers gasoline to be an increasingly costly and unreliable commodity, therefore eventually leading consumers to find an alternative fuel for their vehicles.

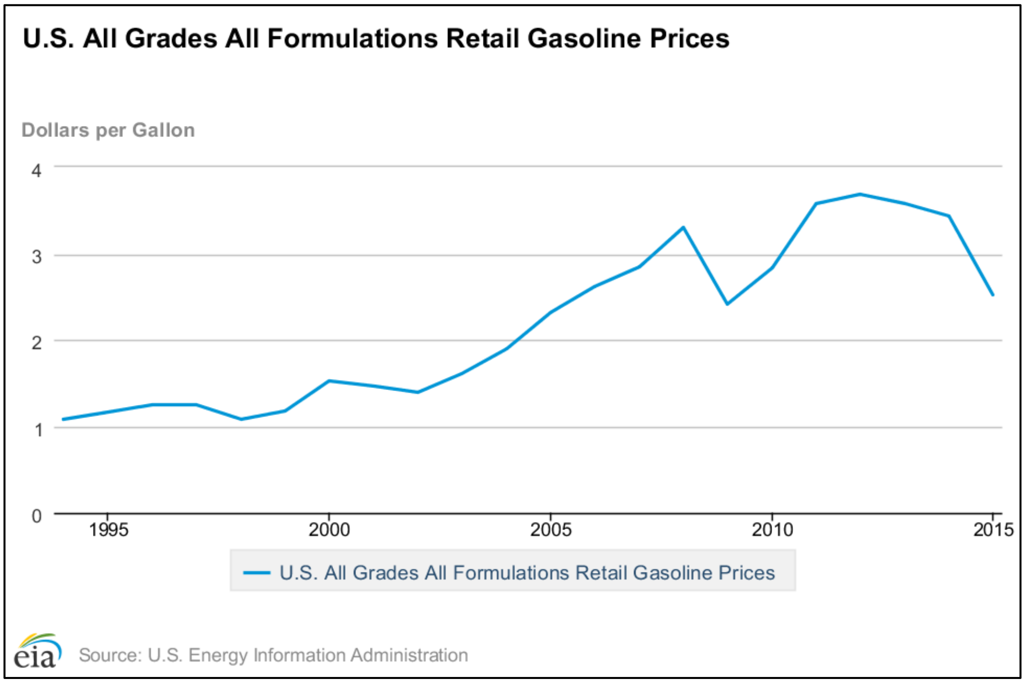

Figure 7: History for Gasoline Cost by the Gallon [12]

Figure 8 below projects the United States population up to 2050, separated by age [13]. The projected population shows a relatively steady increase from 2010 to 2050, set at an average annual rate of 0.6%, though the increase from 1950 to 2010 is at an average annual rate of 1.1% [13].These estimates imply a rising number of vehicles as the population rises.

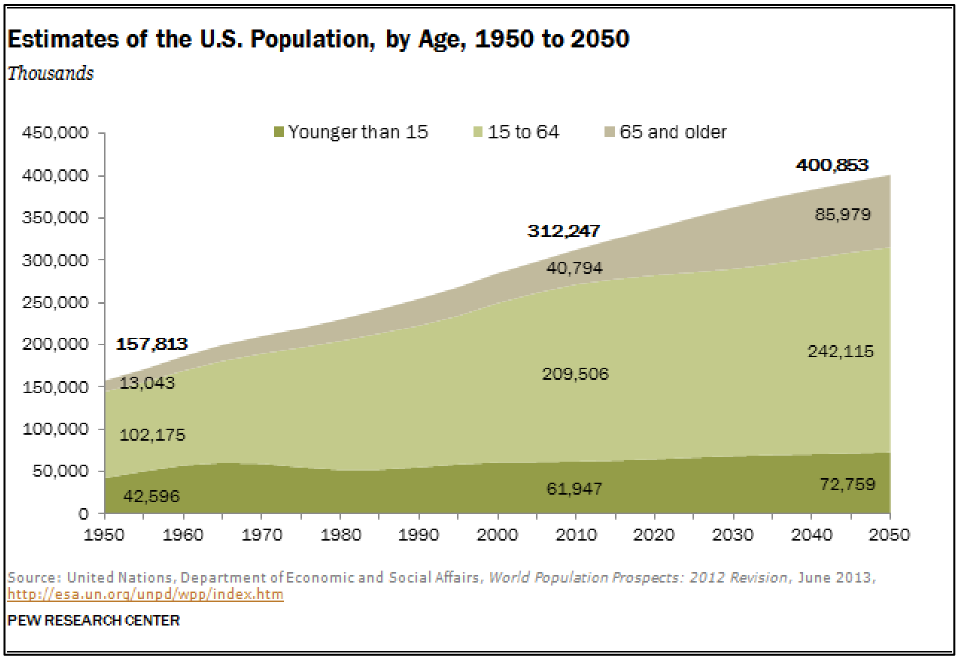

Figure 8: U.S. Population History and Projection [13]

Figure 9 below displays a cutaway view of the Model S made by Tesla [14], showing the battery pack on bottom, the electric motor drive, some suspension, and front bumper frame. Compared to a typical internal combustion vehicle, less materials and space are used, resulting in fewer parts. On the Model S, the hood space and trunk are storage compartments, demonstrating how much less material is needed to operate an electric vehicle. The missing components in Figure 9 are the body, innards, and electrical controls, which every car requires.

Figure 9: Tesla Model S Cutaway View [14]

Though EV's are simpler to build contain less parts, the all-electric technology is still being developed, resulting in a much higher price compared to internal combustion vehicles. The 2015 Model S ranges in price between $70,000 and $138,000 [15], whereas the average new car price in the United States is 33,560 [16]. As EV technology develops, prices for EV components will become competitive, and could become more cost effective than an internal combustion vehicle.

Combining the elements discussed in this section provides evidence to suggest a rapid shift from internal combustion vehicles to electric vehicles. Rising cost for petroleum products, rising population, and a probable rise in electricity demand implies incremental additional load to the electrical distribution system. Likewise, as EV technology progresses, prices drop to surpass competition and eventually dominate the personal vehicle market. Some EV models are already in competitive price range; including the Chevrolet Volt and the Nissan Leaf, which both have a stock price of around $30,000 [17]. If electricity demand continues to rise and EVs add to the electrical distribution load, then there may be locations in the United States forced to consider overhauling their existing electricity delivery systems and infrastructure.

1.1 Capstone Project Goals

This Senior Design Project is a study of the effect on an electrical distribution system of a residential area, from the perspective of the growing popularity of electric cars and the burden of an increasing load on the electric grid when the cars are collectively plugged in at a particular time. The estimation is that most people come home within a few 'peak hours' in the evening, generally around 4pm to 6pm, and plug in their electric cars to charge during these hours. During this time, the electrical energy draw from the electrical distribution system would spike, potentially causing a recurring blackout scenario.

The goals of this project are listed as follows:

1. **Analyze a modern residential feeders' electrical energy use and power limits.** The outcomes for this goal were to choose a feeder and create a working distribution map and graphical charts describing the average energy consumed by each residence daily. Then, using an integration method to extrapolate information from the data supplied by the feeders' distribution utility, predict the number of electric vehicles in that feeder. Finally, using a scenario that would indicate when the majority of the people in the neighborhood would eventually own electric cars, create an electrical distribution model and supporting simulations that portray the majority of the feeder charging their electric vehicles during peak demand hours.

2. **Develop a model to approximate the average energy consumption dedicated to EVs.** The outcomes for this goal were to research and decide an average energy charging value for a few top-selling EV's based on an average commute, so that a simulation load may be calculated.
3. **Develop a model for three different EV demand scenarios and their corresponding energy needs.** The outcomes for this goal were to decide three different proliferation trajectories of electric vehicles to account for the different repercussions of different proliferation speeds. The proliferation trajectories should model an accelerated pace, a nominal pace, and a lagging pace.
4. **Incorporate the EV energy needs and three demand scenarios to create a model for the feeders' power consumption over the next twenty-five years.** The outcomes for this goal were to take the data from the first three goals and create realistic models that explain the additional feeder loads and possible effects on the feeder distribution system. The total EV integration through proliferation of the nominal trajectory should be set to twenty-five years.
5. **Assess the limits of the feeder by extrapolating the feeder model over the next twenty-five years.** The outcomes for this goal were to address and describe the limits of the feeder model when experiencing an accelerated increase in energy demand over the next twenty-five years, by analyzing the data from the three proliferation trajectories of EV integration. This analysis should include the effects of higher loads on the feeders' main components.
6. **Provide a utility-controlled solution to the issues that arise in the three EV proliferation scenarios, using the feeder model over the next twenty-five years.** The outcomes for this goal were to create responsible and realistic recommendations for the local utility to deliver the required amount of electrical power while mitigating the strain on the electric distribution system. The recommendations should include a predicted timeline of necessary action based on the electric distribution system limitations.

1.2 Project Summary

This Major Qualifying Project shall study an electrical power distribution system feeder in conjunction with an unhindered and predicted EV proliferation. Through data analysis, suggestions and conclusions shall be made to allow full distribution power deliver while mitigating the negative effects of the additional load from the EV proliferation. As the electric distribution feeder supplies an increasing load due to EV proliferation, changes may need to be implemented to improve distribution system function and lifespan. Through further analysis and prediction, a suggested timeline to make distribution system improvements shall be made. Recommendations and conclusions shall then be made to mitigate electric distribution system error over the projected course of the nominal twenty-five-year span.

2 Background

2.1 Electric versus Gasoline Powered Vehicles

One of the two major focuses of this project is Electric Vehicles (EVs). Before going into their effect on the distribution system, we must define what they are and how they work. As the name implies, EVs run on electricity only, compared to gasoline that is used in conventional vehicles that have internal combustion engines (ICEs), through the implementation of one or more electric motors, which is powered using several rechargeable battery packs. Depending on the size of the batteries these vehicles have ranges anywhere up to around 300 miles depending on the EV model that you own. A normal battery charge will only take a few hours but charging the entire battery can take the whole night (8 to 10 hours) [18] [19].

One of the major differences between Electric and Gasoline Vehicles are the internal components and possible required maintenance. Compared to that of a gasoline-power car, which requires many components to run, an EV requires considerably fewer internal components to run (charger, battery, controller, and motor), as seen in Figure 10 below. Since there are much fewer moving parts in an EV, maintenance is less frequent than that of a gasoline powered vehicle meaning the costs are much lower. The biggest cost in maintaining an EV is replacing the battery occasionally, as their useful life is limited. There has been an effort in recent years to develop new EV batteries that will hopefully not only extend the life of the battery pack, but ultimately eliminate the issue of having to replace the battery during the life of the vehicle [18].

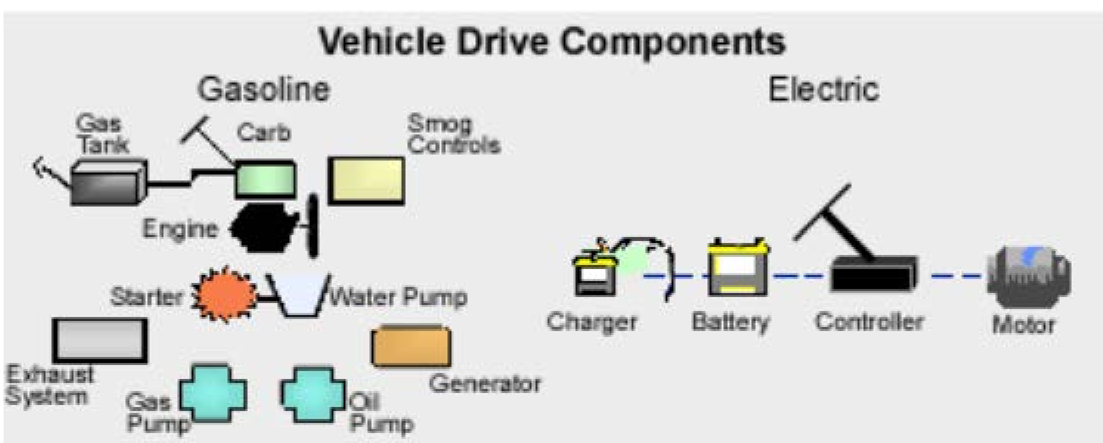

Figure 10: Vehicle Drive Components [19]

2.2 Electric Vehicle Brands

In our research we looked at two fully electric cars as well as one plug-in hybrid-electric car for comparison. We wanted to see the difference in capabilities and specifications between the vehicles as well as their affordability to the public at large. For more detail on these vehicles, see the Appendix (Section 8.4, EV Models).

Table 2: EV/EV-Hybrid Side-by-Side Comparison

Specifications [20]	Tesla Model S – 70D [21]	Nissan Leaf [22]	Chevrolet Volt [23]
MSRP Price	$70,000-$75,000	$29,010-$36,790	$33,995-$38,345
MPGe (City/Highway)	101/102	126/101	106 combined
MPG (City/Highway)	N/A	N/A	42 combined
kWh/100 mi	33 kWh/100 mi	30 kWh/100 mi	31 kWh/100 mi
Gal/100 mi	N/A	N/A	2.4 gal/100 mi
Total Range	240 Miles	84 Miles	Electric- 53 miles Gas- 420 miles
Drive	All-Wheel Drive	Front-Wheel Drive	Front-Wheel Drive
Transmission	Front/Rear: 1-speed direct drive	Front: 1-speed direct drive	Front: 1-speed direct drive
Motor Type:	Front/Rear: induction AC, 257 hp., 203 lb-ft	Front: 80 kW 110 hp.210 lb-ft	Front: 48 and 87 kW 3-Phase AC
Battery	70 kWh microprocessor controlled lithium	24 kWh lithium ion Rated at 90 kW (120 hp.)	18.4 kWh 300 V lithium-ion
Annual Fuel Cost	$650	$600	$600 (including gas)
Cost to Drive 25 Miles	$1	$0.96	Electric- $1.01 Gas- $1.11

2.3 Electric Vehicle Charging

2.3.1 Home Chargers

The following section describes the differences between the home chargers of the three EVs we researched, shown in Table 2 above. All of the cost, energy, and time calculations were done using the charge time & cost calculator on the Tesla website [24].

2.3.1.1 Tesla Model S

The Tesla Model S comes standard with a single 10-kilowatt charger that comes with mobile connectors for both 110 and 240 Volt outlets as well as public station charging capabilities. Before you start using the car, you should have a wall connector or 240 Volt outlet installed in your home. The Tesla is capable of charging at your home using any of the following setups. The first uses normal 110 Volt – 12 Amp outlets that are standard in every home. While the Tesla is capable of using this setup, it is much less effective and optimal than the other charging setups. If you were to try and charge the battery from empty to full (using the 240 mile range stated in Table 2 above) using this setup, it would take almost 74 hours (over 3 days) to do so, costing you $12.73 (using the national average energy cost of $0.12), and would require 106.1 kWh of energy. Using the 240 Volt - 40 Amp (Single Charger, 40A) setup, the charging time drops by over nine times to about 8 hours, costing only $9.50, and only requiring 79.2 kWh of energy to charge. The third and final setup uses the installed wall connector and a 20 kW dual charger which doubles the input current to 80 amps while maintaining the same 240 Volt input. Using the same scenario, the charge time is cut in half from the previous setup to just over 4 hours at about the same cost and required energy. Figure 11 below shows a metaphoric example of the difference between single and dual charging in that the amount of power is the same but the rate at which the power is delivered is much greater (twice as fast) in the dual charging scenario [24].

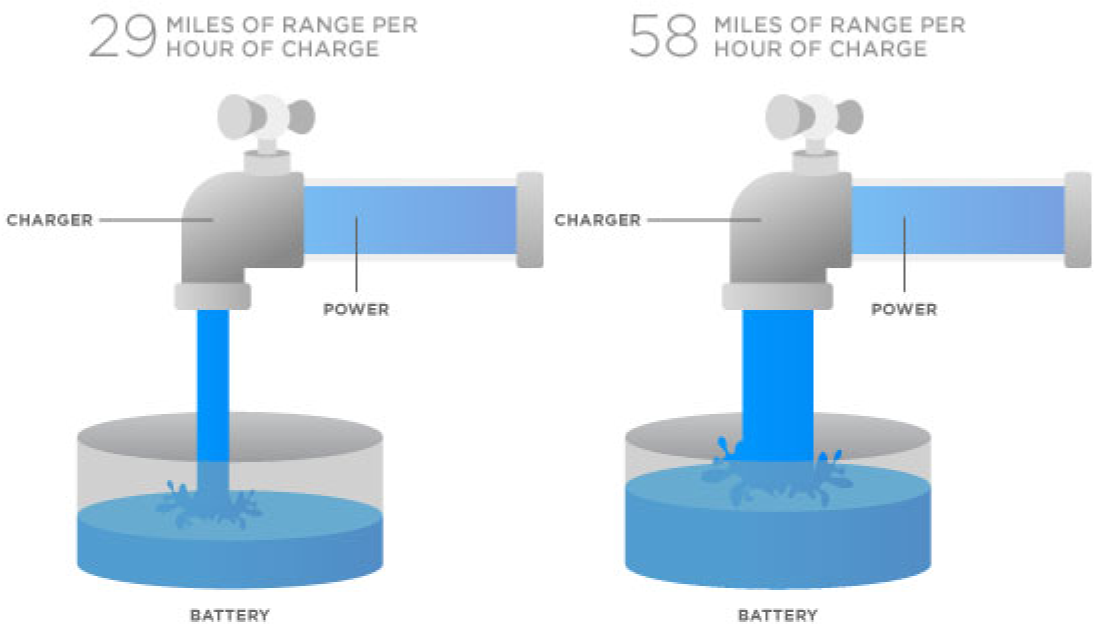

Figure 11: Single vs. Dual Charging [24]

2.3.1.2 Nissan Leaf

Due to its smaller range, 84 miles (about a third of the Tesla), the Nissan Leaf has a much smaller on-board charger of 3.6 kW operating at 240 V – 30 A. A full charge takes 8 hours, costing about $3.23, and requires about 27 kWh of energy. Optionally there is a 6.6 kW charger, which reduces the charge time to 5 hours [20] [24].

2.3.1.3 Chevrolet Volt

Due to its nature as an electric hybrid, the Volt understandably has a small electric range of 53 miles, though it can go much further because of its gas engine (which has a range of 420 miles). The Volt has a nearly identical charger to that of the Leaf, 3.6 kW, 240 V – 30 A but due to its smaller size, it only takes 4.5 hours to fully charge, costing $1.97, and requiring 16.43 kWh of energy [20] [24].

2.4 Storage of Energy

Modern energy storage can be achieved using a multitude of devices and systems that includes batteries, capacitors, flywheels, compressed air systems, and pumped hydro. Each of these systems have advantages and trade-offs that make them ideal for specific applications [25]. The majority of these systems are still experiencing further development and improvement but because of the popularity and normalization of consumer electronics, electrochemical battery technology – specifically lithium ion batteries—have experienced the most rapid advancements of any other type.

Battery storage for grid applications, however, is a technology that is still in its demonstrational phase; while large batteries that serve the power grid do exist they are mainly installed and operated to prove that the technology is feasible [26]. As such, grid battery storage systems are not commercially sold on the whole, though a number of companies have either just begun to or will soon begin to sell grid battery storage systems that use less common or proprietary battery technology, such as Eos Energy Storage which has begun marketing a modular and customizable storage system using a proprietary zinc hybrid cathode battery [27].

Lead acid batteries are the oldest and most mature battery technologies still in use today. Due to their maturity they are some of the most common and low-cost battery options available. They do, however, have multiple disadvantages such as a short life cycle, high maintenance requirements, and a low specific energy and power [33]. The most typical applications of lead acid batteries are in starting, lighting, and ignition systems such as engine starting, deep cycle batteries to power electronics, and stationary batteries for standby emergency power such as emergency floodlights or uninterruptible power supplies in switching [26].

The development of advanced lead acid batteries have enabled the technology for use in power grid applications. Advanced lead acid batteries are enhanced with carbon to create an internal capacitor within the battery cell to buffer high rates of charge and discharge [28]. This creates a battery with an improved life cycle and efficiency that requires minimum modification to existing manufacturing processes and techniques. While the capacitor does enable these improvements, it does not address the challenges of slow recharge time or small energy and power density.

The power grid applications of advanced lead acid batteries include angular and voltage stability, short and long duration power quality, or combined applications depending on the specific variety of lead acid. The majority of batteries that are in use for these applications are in the demonstration phase to prove the feasibility of the technology [29]. These batteries are in the commercial phase for use in renewable energy regulation and storage, such as for use in storing the energy generated by solar panels [30].

Lithium ion batteries are much less mature technology compared to lead acid batteries. Their high energy density, cycling tolerance, and low standing losses make them the primary choice for modern consumer electronics [31]. There are several drawbacks to them, however, such as high cost per density, a lifetime dependent on the depth of discharge, and unstable and possibly volatile nature when under certain conditions. Lithium ion's advantage over all other batteries is the fact that because they are used for both small consumer electronics such as cell phones and larger electronic systems such as electric cars, battery research has been focused on making these batteries smaller, lighter, more energy dense, and less expensive in order to produce and sell more batteries at a fraction of the cost in previous years. Furthermore, lithium ion batteries come in a variety of chemical compositions that each have applications that work more optimally for the chemistry. For example, the lithium titanate and lithium nickel cobalt aluminum oxide varieties both have the potential for high-energy and long-lifespan systems, making them the more ideal varieties for power grid and renewable energy storage [32].

Currently all large-sized grid-connected batteries are in the demonstration stage to prove the feasibility of such batteries in energy time shifting, load leveling, system reliability, etc. [29]. These projects range in size from less than 5kW, 9kWh to over 8MW, 32MWh of power and energy density. The applications and power/energy densities of these installations are similar to those we encounter in our project problem. Earlier installations have shown validation in these applications for this technology, which is promising for the acceptance of lithium-ion batteries to be used in large-scale grid operations as the technology develops and the cost decreases.

2.5 Transformer Life

Transformers are the gateways of the electric distribution system, such that they control the voltage levels delivered for practical use. Transformers limit the losses through transmission lines by raising the voltage levels and lowering current, making the voltage drop through transmission lines negligible while conserving power. Lowering the current through the transmission lines lowers the total heat losses in the lines, making the transmission system more efficient. The problem posed by this report is such that power consumption will be raised over time due to the proliferation of electric cars, which would eventually raise current levels, and thereby raise heat losses in the transformer. According to the IEEE standard C57.91-1995, overheated transformers can cause the transformer to last much less time due to the breakdown of transformer insulation [33].The standard that explains loading mineral-oil-immersed transformers is explored in this section.

As an introduction to Std. C57.91-1995, some of the risks of exceeding transformer loading beyond the nameplate rating could be described as the following [33],

1. Formation of gas inside the transformer as a result of heated components, reducing dielectric material strength.

2. Loss of transformer life due to aging and deterioration of winding insulation as a function temperature, moisture, and oxygen.
3. Mechanical wear of the transformer due to heat, caused by overcurrent scenarios and including conductor expansion and warping and pressure buildup. Warping and pressure can lead to component shifting, loss of oil, and rapid failure of the transformer.
4. Exceeding 105-Celsius degrees (°C), a 65°C rise over 40°C ambient temperature, may cause transformer unit to swell, loose oil, and create a faulty and dangerous situation.

Insulation life can be used to make a reasonable transformer lifespan prediction. The equations below describe transformer aging, based on the Arrhenius reaction rate theory and setting a reference temperature of 110°C for the winding hottest spot temperature (Θ_H) [33].

Equation 1: Per Unit Life of transformer insulation [33]

$$\text{Per unit life} = 9.80 \times 10^{-18} EXP^{\left[\frac{1500}{\Theta_H + 273}\right]}$$ [1]

The per-unit-life equation can be used to summarize the behavior of the degree of polymerization of insulation inside the transformer [33]. Figure 12 below is a graphical representation of the per-unit-life equation, and can shows what lifespan can be expected if the transformers' hottest spot is constantly at one temperature. Note the per-unit life to be 1.00 at 110°C.

[1] The IEEE standard referenced for this equation provides this exact equation for per unit life. A correction must be made, changing 1500 to 15000, as the numbers do not properly calculate otherwise. The discrepancy must be considered a typographical error in IEEE Std. C57.91-1995

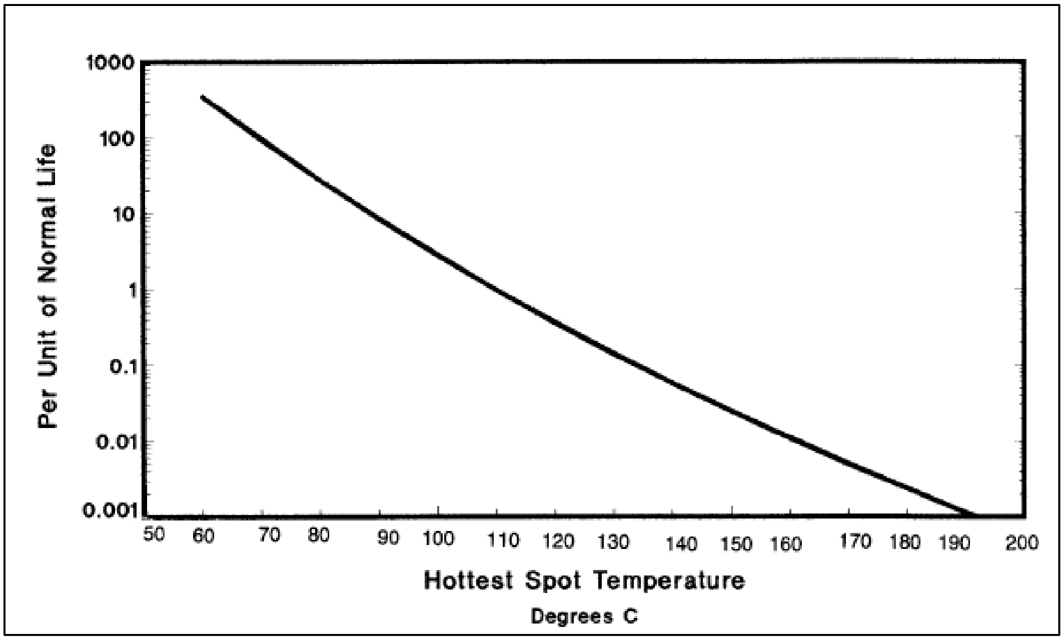

Figure 12: Per Unit Life as a Function of Θ_H [33]

The per-unit-life equation can be used to derive the Aging Acceleration Factor equation (F_{AA}) below. The behavior of the F_{AA} can be seen in Figure 13 below, and is representative of the loss of transformer life due to insulation polymer breakdown. This is the opposite of the per unit life, and can be used to calculate the equivalent aging equation (F_{EQA}) [33]. Since loading varies through time, the F_{EQA} may be used to represent averaged aging over a period of time [33].

Equation 2: Aging Acceleration Factor [33]

$$F_{AA} = EXP^{\left[\frac{1500}{383} - \frac{1500}{\Theta_H + 273}\right]}$$ [2]

[2]For reasons previously explained in the footnote for Equation 1, all values of 1500 must be changed to 15000 for the FAA calculation.

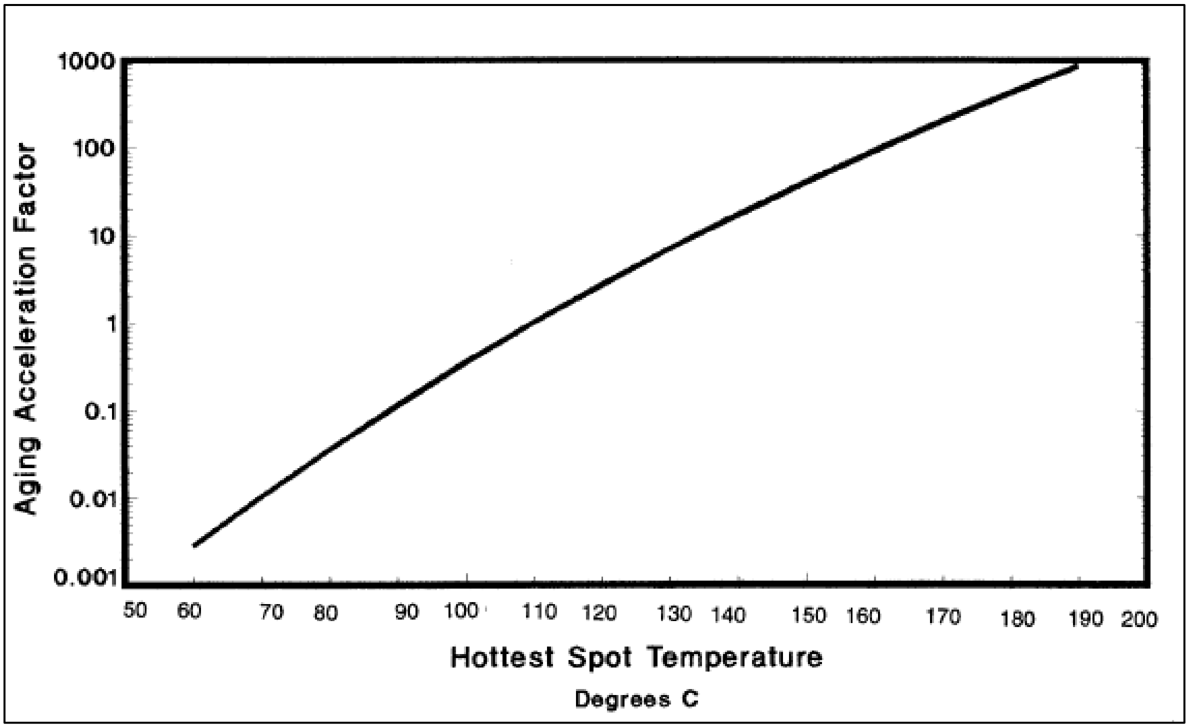

Figure 13: Aging Acceleration Factor as a Function of Θ_H [33]

Equation 3 below shows the equivalent aging over time, realistically describing how a variable load affects aging [33]. The notion that the transformer will encounter the same load for the duration of its lifespan would be unrealistic. Equation 4 below similarly describes the total percent loss of per unit life over a span of finite time in hours [33].

Equation 3: Equivalent Aging over Time [33]

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n}$$

Equation 4: Percent Loss of Total Life Over t Hours [33]

$$\% \text{ Loss of life } = \frac{F_{EQA} \times t \times 100}{\text{Normal insulation life}}$$

Using the Percent Loss of Life equation, the per-unit loss of life may be calculated for one day by simulating one twenty-four hour span. Due to the typical cyclic behavior of loading, any period of time may be used in Equation 4.For the rated hottest-spot temperature of 110 °C, normal life rating would be 180,000 hours and percent loss of life would be 0.0133% for one day [33].

The lifetime calculation for a transformer using IEEE Std. C57.91-1995 is entirely dependent on temperature calculation at the top oil point and the hottest spot point of the transformer to determine insulation breakdown, which includes a multitude of precursor parameters over time [33].These parameters and the calculation method for this paper are extensive, and a summary of the variables required and calculated data have been attached to an appendix of this paper. Figure 14 below summarizes the percent loss of life as a function of the hottest spot temperature as a function of time [33].

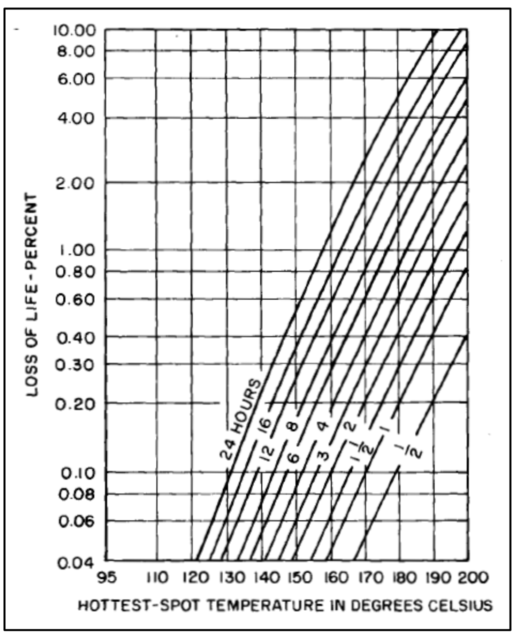

Figure 14: Summary of Percent Loss of Life Behavior as Function of Hottest Spot Temperature [33]

2.5.1 Suggested Transformer Loading

Loading limitation for four generalized scenarios may be summarized in the Table 3 below [33].The table describes situations that sequentially use less time in their overloading, and thus sequentially allowing for higher temperatures when overloading. The idea that the transformer may be overloaded takes advantage of the time needed for temperature rise in the winding, affecting the temperature of the hottest spot [33].It must be noted that the suggestions in the table below only concern hottest spot windings and mineral oil temperatures, and not any other transformer ancillaries or aging issues [33].

Table 3: Suggested Maximum Temperature Limits for the Four Types of Loading [33]

	Normal life expectancy loading	Planned loading beyond nameplate rating	Long-time emergency loading	Short-time emergency loading
Insulated conductor hottest-spot temperature, °C	120*	130	140	180†
Other metallic hot-spot temperature (in contact and not in contact with insulation), °C	140	150	160	200
Top-oil temperature,°C	105	110	110	110

*100°C on a continuous 24 h basis
†Gassing may produce a potential risk to the dielectric strength of the transformer. This risk should be considered when this guide is applied refer to annex A.

The types of loading above have additional risk considerations associated with them; with the exception of Normal Life Expectancy (which is not considered a risk), the other loading types are prone to excess free gas inside the transformer, excess internal moisture, and thus at risk for failure due to an extenuating circumstance [33].Planned loading beyond nameplate rating would be considered a minor calculated risk, and results in lower life expectancy compared to normal loading. Long-time emergency loading would be a rare and unplanned load caused by failure of an arbitrary system element, which happens from time to time, and is acceptable as long as top oil temperature stays under 110 °C. Short-time emergency loading would be considered an extremely rare spike in load that results in the greatest risk and hottest spot temperature, thus resulting in the highest risk of the loading types. All loading types may be encountered by a distribution transformer, and the guidelines in the table above must be used with loss of life calculations to accurately predict overall transformer life [33].

2.5.2 Transformer Model

This section shall describe the specific transformer data needed to perform load modeling per IEEE Std. C57.91-1995.Table 4below shows electrical and physical parameters for the modeled transformer. Normal insulation life refers to the standard number of hours if the transformers hottest-spot temperature was consistently 110 °C [33].The cooling type helps to define some parameters in transformer life equations, and is described in detail in Appendix 7.1 and 7.2.Core/coil weight, tank/fittings weight, and volume of oil are needed to determine Parameter C, which describes transformer thermal capacity [33].The open circuit voltage in line-neutral, short circuit current, and short circuit impedance demonstrate rated values for the transformer. The short circuit impedance (X_{SC}) was considered to be purely inductive, while resistance from transformer windings was considered to be negligible.

Table 4: Transformer Model Parameters

Feeder Rated kVA	12000
Normal Insulation Life (h)	180000
Cooling Type for 12MVA	ONAN
core/coil (lb)	34770
tank/fittings (lb)	37290
Oil (gallons)	6028
Short Circuit Impedence (Xsc)	7.9%, 5.29Ω
Open Circuit Voltage (VLN)	7967
Short Circuit Current (A)	1503

2.6 Project Loading and Test Area

This section shall explain the loading scenario utilized for this project, though the specific location will remain confidential. Figure 15 below displays a GIS map with annotations of the sample feeder, including five lumped load areas showing the percentage of the total feeder load for each area. The percentages of the total load were estimated by counting residences on the GIS map and assuming an averaged load per residence. Two substations are also marked on the map by bold squares, as well as the main feeder lines marked by bold lines on top of streets. It must be noted that one substation is a few decades older than the other, and was assumed (unless otherwise stated) that the newer substation delivers 70% of the total load and the older substation delivers 30% of the total load.

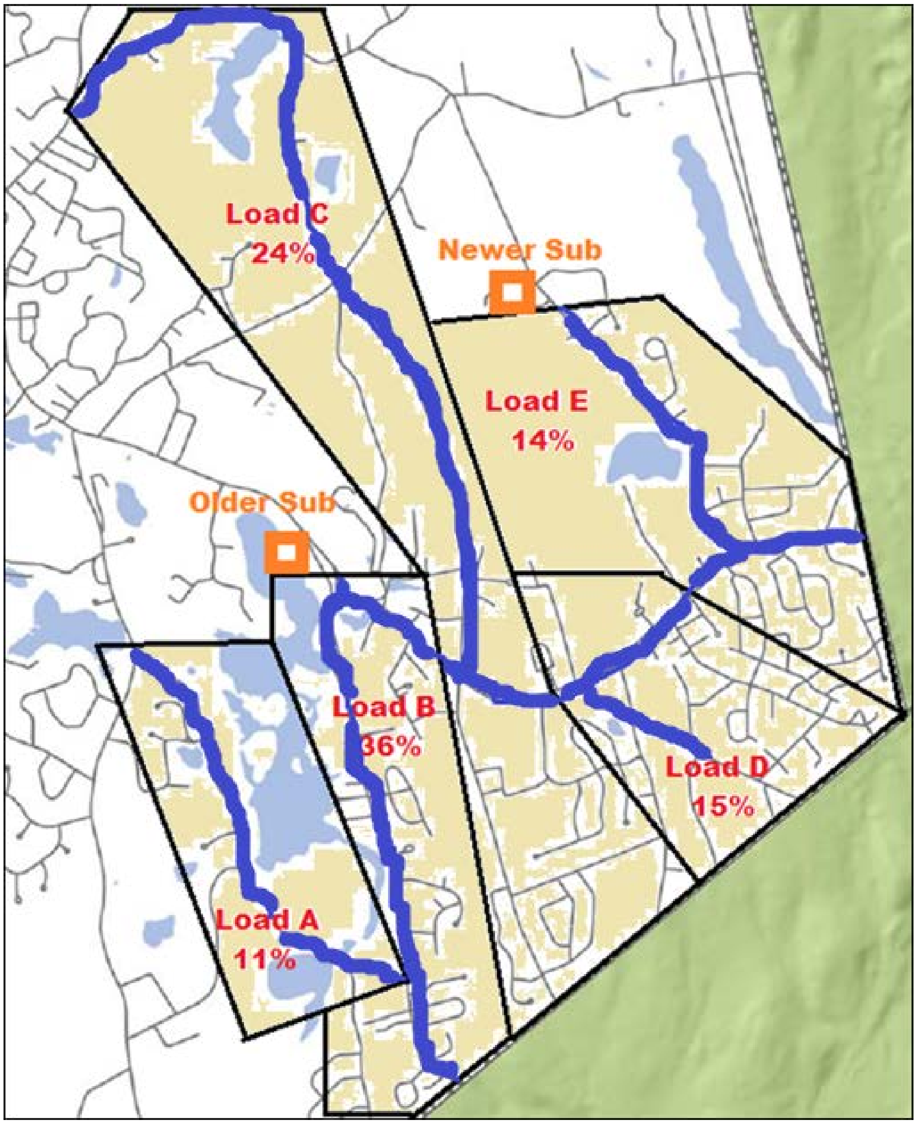

Figure 15: Annotated GIS Map of the Sample Feeder

Figure 16 below correlates to the annotated GIS map of the sample feeder. It displays five loads representing the five areas on the GIS map, the two substation transformers, distribution lines that represent the feeder in length, and a power supply. The PowerWorld model also displays Mega-Volt-Amperes (MVA), Current (Amps), Voltage (Volts), Megawatts (MW), and Mega-Volt-Amperes-Reactive (MVAR) at certain reference points. The model below shall serve as the base model for the analysis in the results section, representing the year 2015.

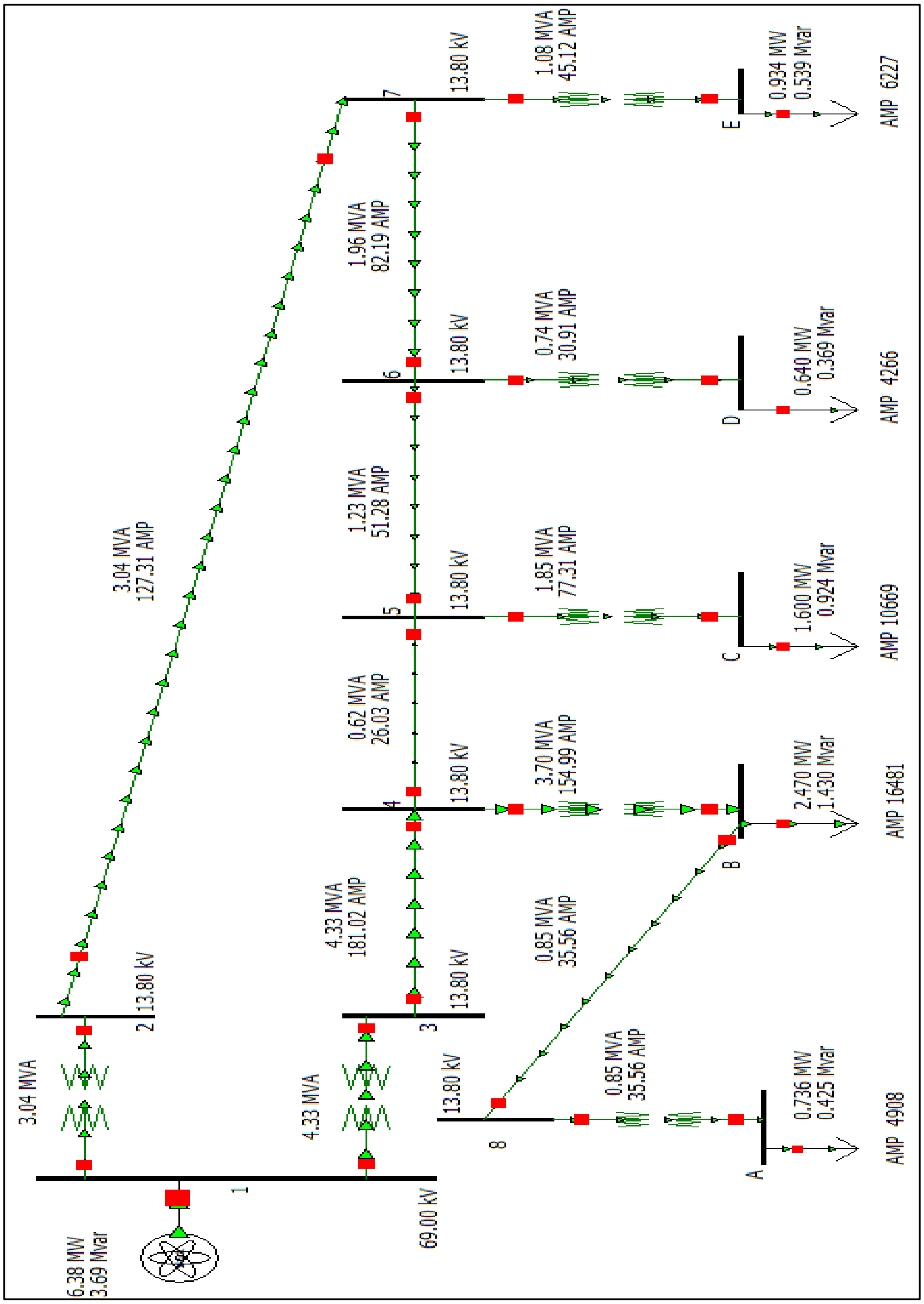

Figure 16: PowerWorld Lumped Load Model [3]

[3] The key for the PowerWorld symbols in the analysis may be referenced in the Appendix

The information provided for this project was limited to MW values, while many physical limitations in the distribution system rely on MVA values. The substation transformers, distribution line current, and load current rely on MVA; therefor, the assumption was made that the power factor (Pf) would generally be around 0.9 to try to simulate our model realistically, and the convenient approximation used for Pf was a 30 degree angle resulting in 0.866.The equations below outline the derivation of the power calculations for this project, using the power triangle.

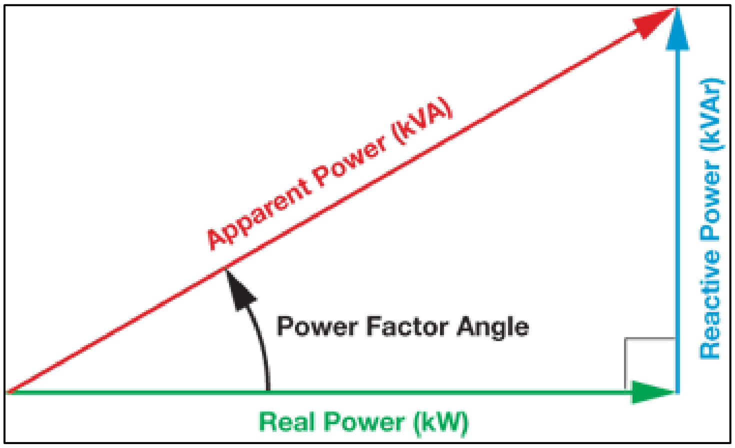

Figure 17: Power Triangle [34]

Table 5: Power Triangle Equations

Power Factor (Pf)	cos(30°) = .866
Watts	VA cos(30°)
VARs	VA sin(30°)
VA	Watts/cos(30°)

Figure 18 below displays the PowerWorld base model with line names and how the lines are connected to the loads. Line E can be seen as two connections in the model, as each connection correlates to a different segment in the GIS map. The line sizes were picked from a standard Aluminum Conductor Steel-Reinforced (ACSR) chart to accommodate max current through the lines, with a safety factor coefficient of 1.5. The method for picking line sizes involved disconnecting one of the substation transformers to simulate a worst-case failure scenario, thus heavily loading the distribution lines on one side. Table 6 and Table 7 below outline the line information chosen for the base model described in this section.

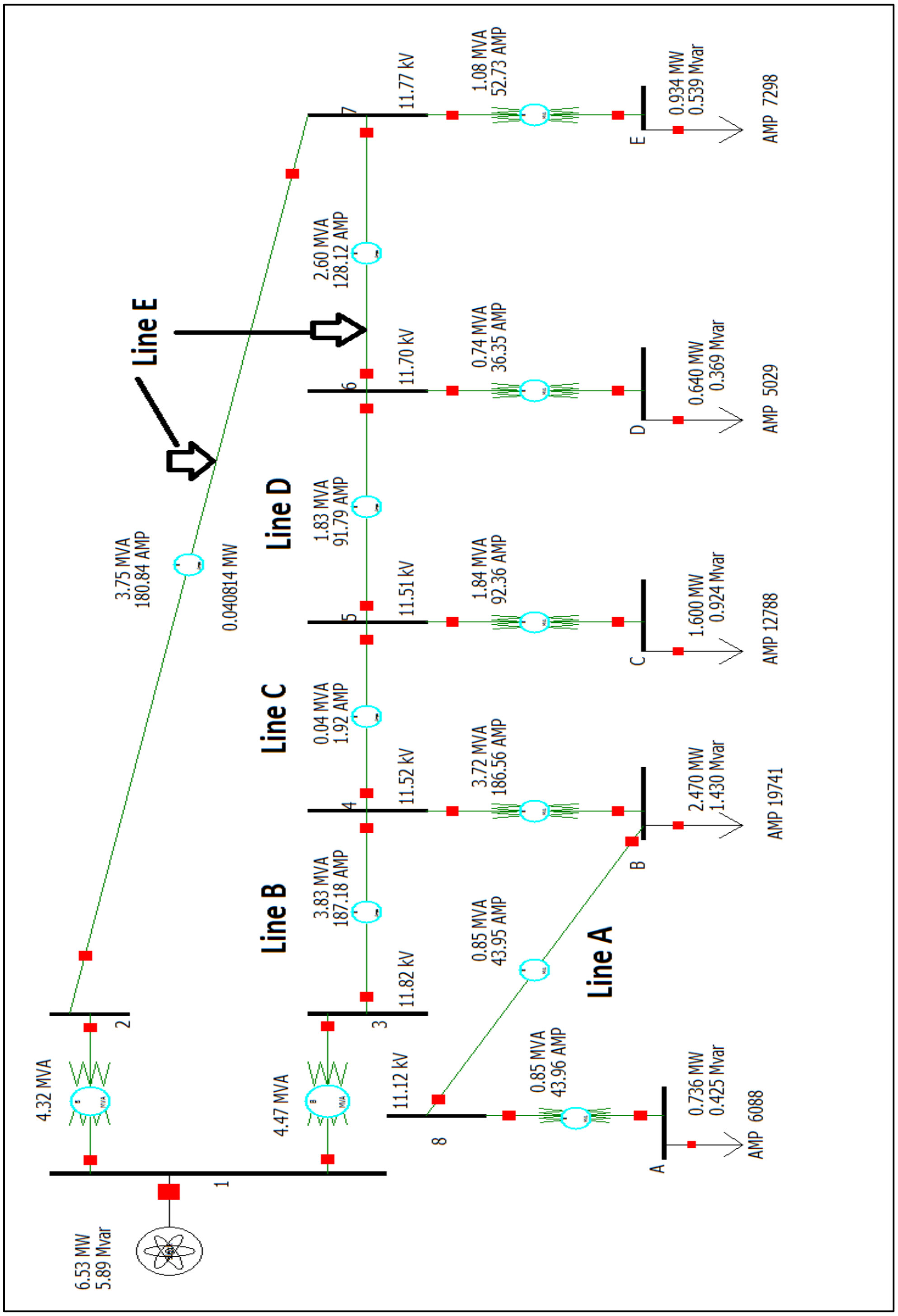

Figure 18: PowerWorld Model with Annotated Line Names

Table 6: PowerWorld Distribution Line Information

name	Line Lenth (ft)	size
A	10000	swan
B	8000	waxwing
C	10000	raven
D	8000	penguin
E (total)	8000	waxwing

Table 7: ACSR Size Descriptions

ACSR	R/1000ft	X/1000ft	stranding	ampacity
swan	0.5218	0.1369	6 to 1	140
raven	0.2161	0.1163	6 to 1	225
penguin	0.1157	0.1053	6 to 1	357
waxwing	0.0788	0.0934	18 to 1	449

2.7 Energy Usage and Growth

The consumption of and demand for electrical energy in the US has been on a steady increase since the industrial revolution. The annual electrical energy in 2014 was 3,863 billion kWh. According to the US Energy Information Administration's Annual Energy Outlook report for 2015, the projected increase in electrical demand between 2013 and 2040 will increase by approximately 0.9 percent each year. This increase in energy demand would cause currently installed power lines and transformers to break down quicker as the limits of their rated power are reached. Because of the scope of our project, this demand increase must be considered in conjunction with the introduction of substantial energy demand of electric vehicles; our projection must consider both the increase of demand from charging electrical vehicles as they are accepted by the general public and the increase of demand.

2.8 Financial Estimates

2.8.1 Battery Storage

The cost of energy storage per kWh is the primary factor when considering the various battery storage options. As development in each technology occurs and the battery becomes more commonplace, the overall price of production and retail cost decreases. While lead acid batteries are some of the most researched and commonplace batteries available, lithium ion batteries have experienced extremely rapid development, especially over the last decade, to where they have surpassed lead acid in energy density per cost [31]. The surge in lithium ion research has been fueled by the push to produce battery powered consumer electronics and vehicles at a cheaper price so that they can be retailed at a reasonable cost to the consumer [34]. The price of lithium ion battery storage for use, specifically for electric vehicles, has dropped from an average of $400/kWh in 2014 to an average of $350/kWh. Current projections made in 2015 predict the cost to reach $150/kWh by 2030, at which lithium ion would be considered to be priced for commercialization in a grid storage application [66].

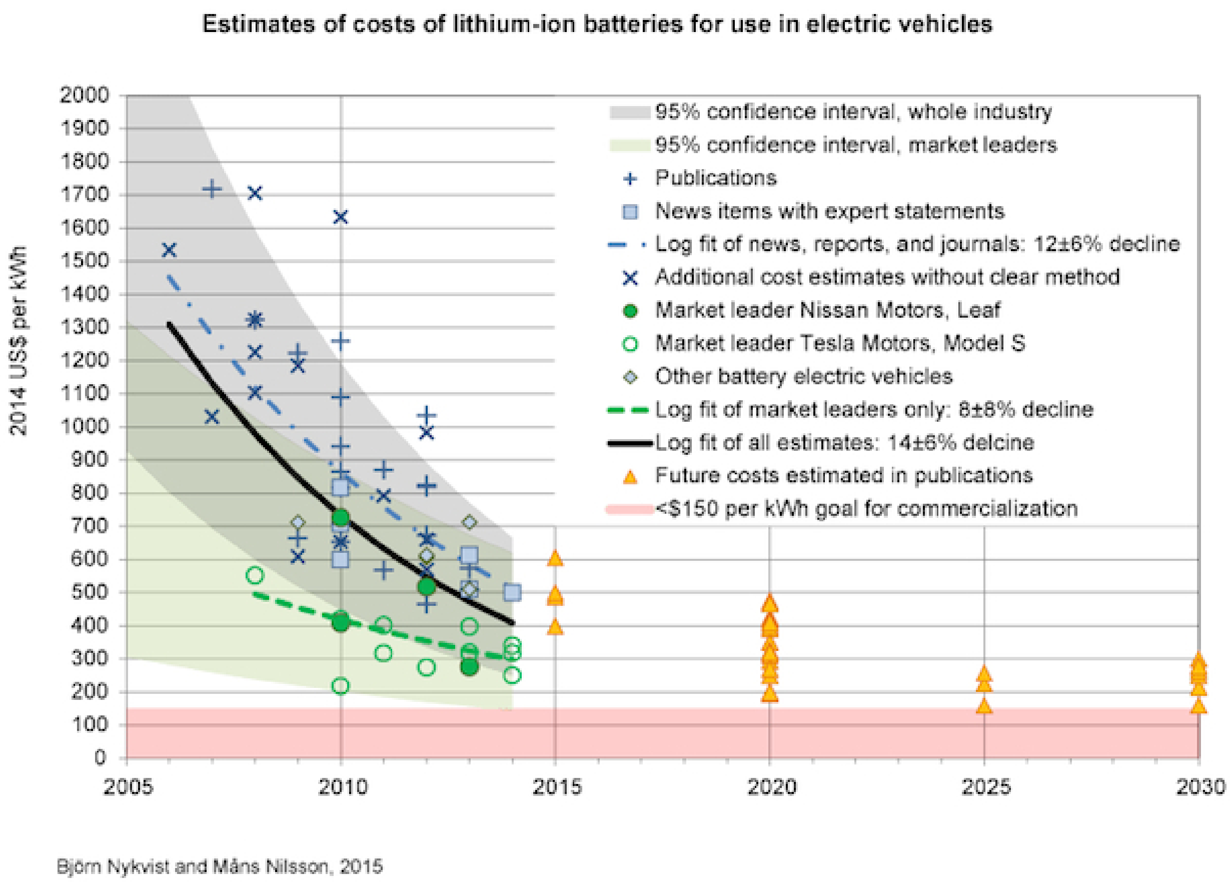

Figure 19: Estimates of costs of lithium-ion batteries for use in electric vehicles [66]

2.8.2 Annual Costs

The financial burdens brought on by buying and building to improve an electric distribution system have an influence on not only how to solve the problem, but when as well. Distribution costs can be expensive enough to consider outside investors or multimillion dollar bank loans. Given the scenario that a large amount of capital is required to improve an electric distribution system, this section shall outline methods for calculating costs. Since the maintenance for the electric distribution system would be intermittent and unpredictable, variable costs shall not be considered in the following calculations.

In the event that the project building requires financing, interest must be paid in addition to the principle to pay the lenders for the convenience of borrowed capital. The Equation below describes the Capital Recovery Factor (CRF), wherein a large sum of money may be paid back through annual payments over the course of an agreed upon number of years, while using one averaged interest rate [35]. There may be several loan or investment interest rates, which can be combined into one interest rate to help closely approximate an annual fixed payment [35].

Equation 5: Capital Recovery Factor [35]

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Where,
i is the collective interest rate
n is the time period to pay the principle in years [35].

The Fixed Charge Rate (FCR) is the total interest due for fixed expenses, which accumulates the CRF, fixed operation and maintenance costs (O&M), one-time insurance, and one-time taxes [35]. For the purposes of this paper, a chosen FCR of 17% shall be used in Annual Fixed Cost (AFC) calculation. The Equation below shows the AFC calculation, where the principle expense is multiplied by the FCR. The AFC would be the amount the distribution company would pay annually for the expense of construction, and can estimate whether the construction would be affordable [35].

Equation 6: Annual Fixed Cost

$$AFC = Principle \times (CRF + O\&M + tax + insurance)$$

3 Methods

3.1 Tools and Analysis

3.1.1 Seasonal Peaks

In order to obtain the results that we set out to find, we were provided with a Microsoft Excel Workbook with raw hourly energy usage data, in kilowatt-hours (kWh), for each month from one feeder over a one-year period, September 2014-August 2015. This provided us with a basis that we could use to simulate various scenarios and show the results in an organized fashion (tables, charts, etc.). We developed an interactive, editable spreadsheet that made it easier to manipulate the data that we were given. As a jumping off point from which all scenarios would be run, we calculated the hourly seasonal averages and peaks. Using various calculations and assumptions (which will be discussed below in Section 3.2), we were able to different scenarios and create the corresponding demand curve graphs. The main scenarios we looked at here for each season were an evenly distributed peak, a peak-off peak percentage adjustment, home-work percentage adjustment, and a dual adjustment (both peak-off peak and home-work percentage adjustments). The main sheet in the workbook is shown in Figure 20, Figure 21, and Figure 22 below.

The main sheet works in the following way. Before anything else, the seasonal peak must be selected. This can be changed using the drop down menu that appears when the yellow cell that currently reads “Summer Max” near the top left of Figure 20 is selected. From there any of the 8 seasonal peaks (Summer Max, Winter Min, etc.) can be selected. Selecting any of the peaks automatically updates the data in the same column as the drop down menu as well as the seasonal average column (one column to the left) based on the chosen seasonal peak. Based on the values of these columns, the values of the columns for the different scenarios are populated. The first being the Evenly Distributed Peak column, which is based on the raw energy (kWh) data and whether that hour is a peak or off peak hour, shown in the “Peak/Off Peak?” column. The total energy added to each hour is equal to the total average kWh over the entire year as a percentage of the energy used during peak hours versus off peak energy usage (calculations are shown in Section 3.2). These percentages are multiplied by the Total MWh Added and then divided by the number of hours during peak and off peak. These final numbers are multiplied by 1000 to bring the unit to kWh. This final number is added to the peak day number (column 3).

Hour	Summer Average	Summer Max	Evenly Distributed Peak	Peak/Off Peak % Adjustment	Peak/Off Peak?
1	2,882	3,881	5,213	5,626	Off Peak
2	2,634	3,589	4,921	5,334	Off Peak
3	2,490	3,424	4,756	5,169	Off Peak
4	2,407	3,305	4,637	5,050	Off Peak
5	2,404	3,280	4,612	5,025	Off Peak
6	2,526	3,362	4,694	5,107	Off Peak
7	2,860	3,737	5,069	5,482	Off Peak
8	3,213	4,154	5,486	5,899	Off Peak
9	3,455	4,345	6,172	5,822	Peak
10	3,625	4,626	6,453	6,103	Peak
11	3,700	4,968	6,795	6,445	Peak
12	3,841	5,278	7,105	6,755	Peak
13	3,960	5,566	7,393	7,043	Peak
14	4,034	5,746	7,573	7,223	Peak
15	4,093	5,875	7,702	7,352	Peak
16	4,170	6,023	7,850	7,500	Peak
17	4,340	6,401	8,228	7,878	Peak
18	4,602	6,750	8,577	8,227	Peak
19	4,653	6,764	8,591	8,241	Peak
20	4,639	6,462	8,289	7,939	Peak
21	4,694	6,221	8,048	7,698	Peak
22	4,501	5,890	7,222	7,635	Off Peak
23	3,949	5,076	6,408	6,821	Off Peak
24	3,342	4,216	5,548	5,961	Off Peak
Total	87,017	118,939	157,339		

Figure 20: Peak kWh Days Worksheet (Part 1)

Home/Work % Adjustment	Work/Home?	Dual Adjustment
3,881		5,626
3,589		5,334
3,424		5,169
3,305		5,050
3,280		5,025
3,362		5,107
3,737		5,482
4,154		5,899
5,442	Work	5,716
5,723	Work	5,997
6,065	Work	6,339
6,375	Work	6,649
6,663	Work	6,937
6,843	Work	7,117
6,972	Work	7,246
11,143	Home	7,623
11,521	Home	8,001
11,870	Home	8,350
11,884	Home	8,364
11,582	Home	8,062
11,341	Home	7,821
5,890		7,635
5,076		6,821
4,216		5,961

Figure 21: Peak kWh Days Worksheet (Part 2)

Peak/Off Peak % Adjustment		
	Peak	Off Peak
% of Total	50%	50%
Total MWh Added	19.20	19.20
Hourly MWh Added	1.48	1.75
Number of Hours	13	11

Home/Work % Adjustment		
	Home	Work
% of Total	80%	20%
Total MWh Added	30.72	7.68
Hourly MWh Added	5.12	1.10
Number of Hours	6	7

Dual Adjustment		
	Peak	Off Peak
% of Total	50%	50%
Total MWh Added	19.20	19.20
Hourly MWh Added	1.48	1.75
	Home	Work
% of Total	50%	50%
Total MWh Added	9.60	9.60
Hourly MWh Added	1.60	1.37
Number of Hours	6	7

Figure 22: Peak kWh Days Worksheet (Part 3)

The "Peak/Off Peak?" column is also used for the peak-off peak % adjustment column. Using the table at the top right, you can adjust the percentage of energy used on peak versus off peak. This uses the same math as before but instead of having a static percentage of energy evenly distributed throughout a day, you can adjust the percentage to see how that affects the output graph, shown in the top right of Figure 22. You can explore how the daily demand curve would look if more energy was used off peak instead of on peak, etc.

The next scenario is the peak home-work % adjustment, shown in Figure 21 above. This breaks down the hours during peak time to when people are most likely at work or at home. Instead of the energy being spread out over the entire day (24 hour period), it is only spread out during peak hours (13 hour period). Using the second table from the top shown on the right side of Figure 22, the percentage of energy that is being used to charge EVs at work (8 AM to 3 PM) versus the energy used at home (3 PM to 9 PM) can be adjusted. As the same amount of energy (about 38 MWh) is being added but over a much smaller time frame, the peak is immense and skyrockets past the theoretical subscription line of this feeder.

The final scenario, shown in Figure 21, allows dual adjustment, which combines the two previous scenarios, allowing much more control over when energy is used. In this scenario, both the peak-off peak percentage as well as the percentage of the peak that is home versus work can be adjustment. This adjustment can be made using the bottom table in Figure 22 above. Think of it as a fine tune adjustment.

The shading of all of these data columns is a 3-color scale with red being the highest single kWh over a 24-hour period, orange being the middle, and green being the lowest. This data from this table is shown in a 24-hour demand graph. An example seasonal graph for the Summer Max with every scenario active is shown in Figure 23 below.

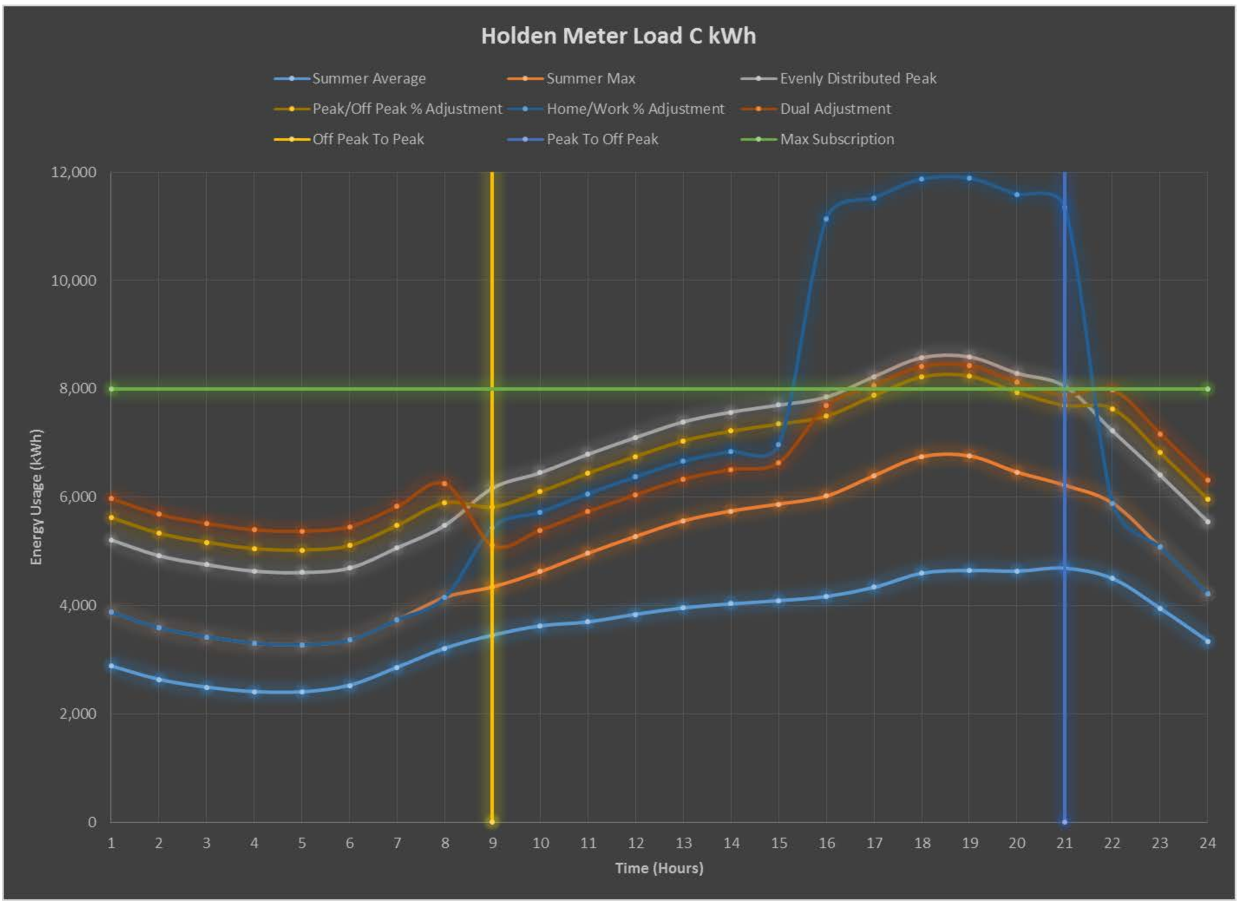

Figure 23: 24-Hour Electrical Demand

3.1.2 Peak Demand

In our analysis, we also wanted to look at the peak day of the year to determine how it will be affected by the predicted growth rate of energy usage in the United States as well as the growth rate of EVs using the diffusion of innovations and the logistic function. In short, diffusion of innovations is a theory that attempts to explain how, why, and at what rate new ideas and technology spread throughout cultures [36]. The logistic function is one of the equations used to numerically and graphically show the diffusions of innovations theory. The basic logistic equation is graphically shown as an “S” curve and is expressed by the following equation:

Equation 7: Basic Logistic Equation

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}$$

where

L = the curve’s maximum value

k = the steepness of the curve

x_0 = the midpoint of the curve.

We used a modified form of this equation, which is written as follows:

Equation 8: Modified Logistic Function

$$X(t) = \frac{X_S}{1 + \left(\frac{X_S}{X_0} - 1\right) e^{-at}}$$

where

X_S = the curve’s maximum value

X_0 = the initial value of the curve

a = the proliferation rate

t = time in years

The proliferation rate, a, is defined as:

Equation 9: Proliferation Rate

$$a = \frac{1}{t_{mid}} * \ln\left(\frac{X_S}{X_0} - 1\right)$$

where

t_{mid} = the midpoint of the curve in years

X_S = the curve's maximum value

X_0 = the initial value of the curve

The diffusion rate, or proliferation rate, is the rate at which an idea or innovation is spread. These calculations allowed us to develop our realistic and ideal scenarios, which will be described in more detail in Section 4.1.

As for the growth rate of change of energy usage in the United States, we were able to find that through our research that it was projected to be about 0.9% from now until 2040 (25 year period) [11]. Using this information, we were able to determine the future electrical growth for our feeder. This gave us one of two variables to use for our analysis of future electrical demand.

In order to show different possible rates of proliferation for EVs, we chose three evenly spaced midpoints along the 25-year period. So therefore, our midpoints (t_{mid}) take place at 6.25, 12.5, and 18.75 years representing a faster, normal, and slower proliferation rate of EVs, respectively.

Combining these aspects we were able to develop new peak demand graphs for the hottest day of the year of data we were given (July 20, 2014), where the energy usage reached 6764 kWh during a one-hour period. The resulting graph is shown in Figure 24 below. The graph shows a linear line just depicting the yearly energy growth, while the three other curves represent the normal, faster, and slower proliferation rate of EVs expressed in terms of energy usage (MWh).

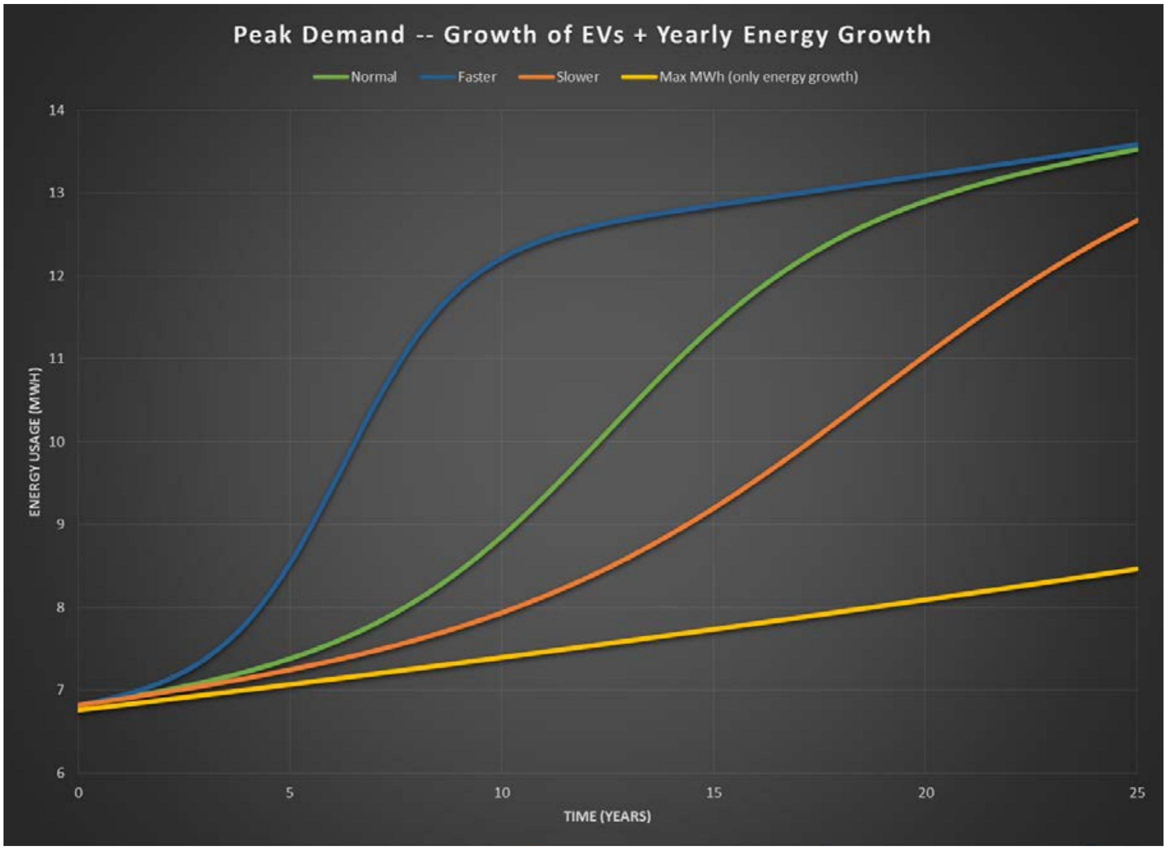

Figure 24: Diffusion of Innovations for EVs plus 0.9% Annual Increase in Energy Usage

When modeling the new effective loads, many realistic conditions had to be established. The first of the assumptions are about the charging and discharging information about the solution simulation results. Since the batteries can be used constantly throughout the year to level the demand, the realistic goal of the battery storage is average the load over 24 hours. Since the critical points are at the peak demand, this was the date of interest. When the total energy consumption of the grid is above the 8MW Subscription Max or above the 12 MVA Feeder max, the battery will be discharging at a 90% efficiency rate. This only occurs when the battery can support the needed demand of the grid to keep under the limits. If the batteries cannot support the full demand, they discharge the remaining amount. When the consumed Grid power is below 8MW or the total MVA is below 12, the batteries' power is scaled to meet but not exceed the limits. The other assumption for this mode is that the battery is not fully charged. If the battery cannot handle the entire excess MW of the grid, it only takes enough to top off. All of this is done at 90% efficiency each way, making for a max round-trip efficiency of 81%.

3.2 Data Assumptions

3.2.1 Seasonal Peaks

In order to make this spreadsheet happen, we had to determine various assumptions we would be using for all of our calculations. These were determined through research and our discussions with the sample distribution owner. The following are the assumptions we used for the entirety of our project (unless specifically stated otherwise):

Table 8: Data Assumptions – Seasonal Peaks

Data Assumptions – Seasonal Peaks	
Average Daily Commute (in Miles):	30 Miles (as of July 2015)
Average EV kWh/100 Miles:	~32 kWh/100 Miles
Average Daily Charge (in kWh):	9.6 kWh
Average Cars per Household:	~2.00
Number of Households in Test Region:	2000 Homes
Total Number of Homes:	7500 Homes
MWh Subscription Total:	30 MWh
MWh Subscription of Test Region:	8 MWh
MVA Feeder Maximum:	12 MVA
Total Energy Added to Grid from EVs: *	38.4 MWh
Phase Angle (Power Factor):	30
Peak/Off Peak Hours: **	Peak: 8 AM – 9 PM (13 Hours) Off Peak: 9 PM – 8 AM (11 Hours)
Peak-Off Peak % for Evenly Distributed Load:	Peak: ~62% Off Peak: ~38%
Peak Hours (Work/Home):	Work: 8 AM – 3 PM (7 Hours) Home: 3 PM – 9 PM (6 Hours)

*Extreme worst-case scenario if everyone in test region has an EV

**Monday through Friday only excluding holidays; weekends and holidays are always off peak hours

Average Daily Commute (in Miles):

The average of 30 miles was determined by finding the median of the percentages shown in Table 9 below. Since the figure is only for a one-way commute, we took the high end of the range and doubled it to get the average round trip daily commute.

Table 9: Average American Commute Distance [37]

American Commute Distance (One Way)	Percent
1-5 Miles	29 %
6-10 Miles	22 %
11-15 Miles	17 %
16-20 Miles	10 %
21-25 Miles	7 %
26-30 Miles	5 %
31-35 Miles	3 %
35 + Miles	8 %

Average EV kWh/100 Miles:

This value was determined by taking the average of the three EVs we researched, the Tesla Model S (33 kWh/100 mi), Nissan Leaf (30 kWh/100 mi), and Chevrolet Volt (31 kWh/100 mi) and rounding up to the nearest whole number. (See Table 2 in Section2.2, Electric Vehicle Brands)

Average Daily Charge (in kWh):

This was determined using the following calculation, using the average EV kWh/100 Miles and Average Daily Commute in Miles numbers determined previously:

$$\frac{32\ kWh}{100\ mi} = \frac{x\ kWh}{30\ mi} \rightarrow x = \frac{30\ mi * 32\ kWh}{100\ mi} = 9.6\ kWh$$

Average Cars per Household:

The most recent data we were able to find on average vehicles per household was from the end of 2012, where the number stood at 1.98, or approximately 2.00. According to the article, which cites research done by Michael Sivak for the University of Michigan Transportation Research Institute, this number was down from 2007, when it stood at 2.07 [38].

Number of Households in Test Region, Total Number of Homes, MWh Subscription, and MVA Feeder Maximum:

All of these numbers were provided by a distribution company, and the test region refers to one feeder in the sample data.

MWh Subscription of Test Region:

This number was determined using the following calculation using the number of households and the test region as well as the MWh subscription. This number is theoretical as the feeder is not technically limited to this max subscription. But since we are assuming the rest of the town will stay constant in their energy usage, it should be viewed as a max so that the town does not come close to going over their max subscription usage.

$$\frac{30\ MWh}{7500\ Homes} = \frac{X\ MWh}{2000\ Homes} \rightarrow X = \frac{2000\ Homes * 30\ MWh}{7500\ Homes} = 8\ MWh$$

Total Energy Added to Grid from EVs:

This number was found by multiplying the average daily charge (in kWh) by the number of homes in the test region and the average cars per household and then dividing that by 1000 to move into MWh as shown in the calculation below:

$$Total\ MWh\ Added = \frac{9.6\ kWh * 2000\ Homes * 2\ Cars\ Per\ Household}{1000} = 38.4\ MWh\ added$$

Phase Angle:

To replicate the effects of a grid that is under moderate power factor, a phase angle of 30 was chosen. This value was found to be realistic and accurate. This was used to approximate the MVAR.

Peak/Off Peak Hours:

The peak/off peak hours that we used in our project are the hours used by National Grid, which operates in Massachusetts (as well as many other states).

Peak-Off Peak % (Evenly Distributed Load):

These percentages refer to the amount of power used on peak versus off peak. These values were determined using the raw data provided. They were found using the following calculations:

$$\%\ of\ Total\ kWh\ (Peak) = \frac{Total\ Average\ kWh\ (Peak)}{\left(Total\ Average\ kWh\ (Peak) + Total\ Average\ kWh\ (Off\ Peak)\right)}$$

$$= \frac{161{,}421}{161{,}421 + 99{,}631} = 61.83\% \cong 62\%$$

$$\%\ of\ Total\ kWh\ (Off\ Peak) = \frac{Total\ Average\ kWh\ (Off\ Peak)}{\left(Total\ Average\ kWh\ (Peak) + Total\ Average\ kWh\ (Off\ Peak)\right)}$$

$$= \frac{99{,}631}{161{,}421 + 99{,}631} = 38.17\% \cong 38\%$$

Peak Hours (Work/Home):

Based off our own assumptions as to when most people are likely to be home versus at work during peak hours.

3.2.2 Peak Demand

Here are the assumptions we made when doing the calculations for the Diffusion of Innovations and Logistic Function analysis calculations.

Table 10: Data Assumptions – Peak Demand

Data Assumptions – Peak Demand	
Midpoint for Normal EV Proliferation:	12.5 Years
Midpoint for Faster EV Proliferation:	6.25 Years
Midpoint for Slower EV Proliferation:	18.75 Years
Initial Number of EVs (in Feeder):	40 EVs
Total Number of EVs: *	4000 EVs

* Extreme worst-case scenario if everyone in test region has an EV

Midpoints:

We based the midpoints of the diffusion of innovations calculations on the 25-year period we were given for the growth rate of energy usage in the United States. As a result, it was determined that the normal proliferation midpoint would be exactly half of the given period while the faster and slower proliferation midpoints would be minus and plus 6.25 years, respectively, evenly spacing them for consistency.

Initial Number of EVs in Feeder:

This number is a prediction on our part as to the number of EVs currently in the Feeder area. To simplify our calculations we said that the initial number of EVs was about 1% of the total number of EVs, or 40 EVs.

Total Number of EVs:

This final value is found by multiplying the number of houses in the test region by the average number of cars per household as show below:

$$\#\ of\ EVs = 2000\ Homes * 2\ Cars\ Per\ Houshold = 4000\ EVs$$

4 Results

4.1 Logistic Function Analysis

4.1.1 Ideal Scenario

The following graphs and tables assume an ideal situation where there is no energy growth over time (years). By rewriting the logistic function (expressed in Section 3.1.2,Peak Demand) in terms of time (t), we were able to determine when the peak energy usage would reach both the Subscription Max (8 MW) and the Feeder Max (~10.392 MWh) for all three curves, Normal, Faster, and, Slower proliferation rate of EVs. For the bottom three graphs, the time when these maxes are reached is shown on the graph and in Table 11 at the end of Section 4.1.2. For this scenario, we determined that it would take approximately 25% (1000 EVs) of the maximum number of EVs (4000 EVs) to reach the Subscription Max and approximately 70% (2800 EVs) to reach the Feeder Max. These graphs express, depending on the proliferation of EVs, when utilities would have to start being concerned with EVs and their effect on the grid.

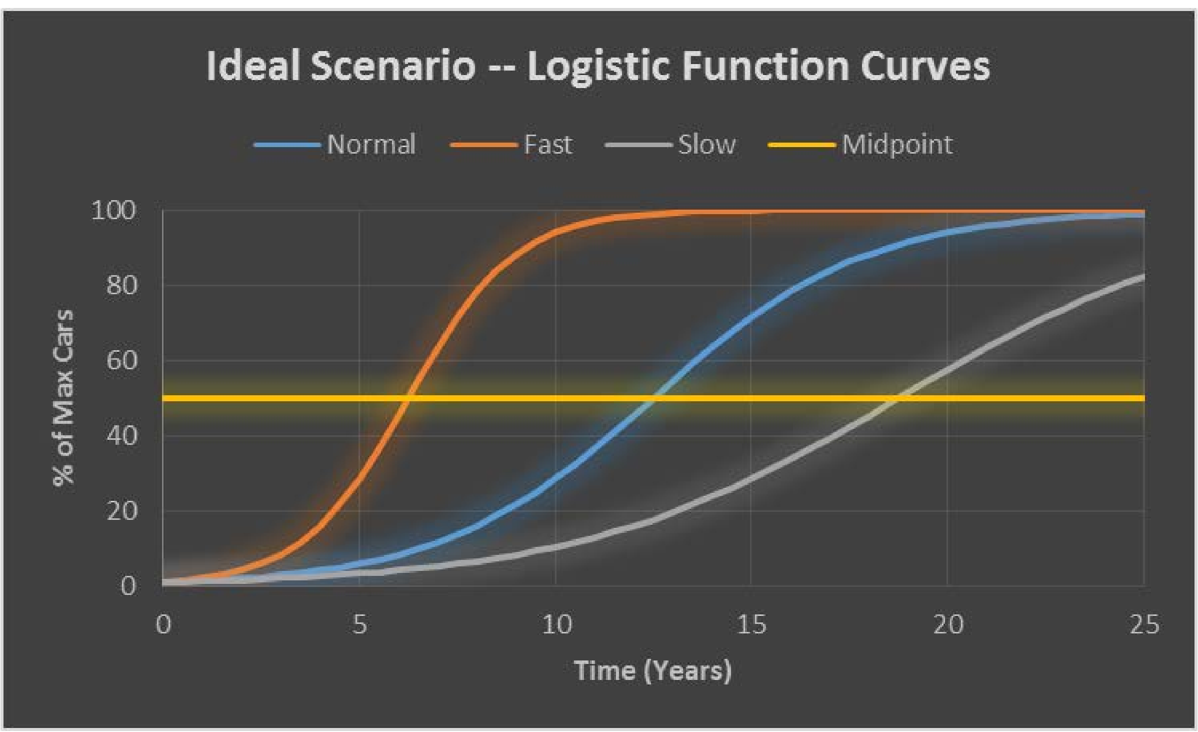

Figure 25: Logistic Function Curves – Ideal Scenario

Figure 25 shows all three curves of the logistic function with a fourth line indication the midpoint of the curves. For these calculations, the logistic function was set up as the percentage of max cars over time (years), meaning $X_0 = 1\%$ and $X_S = 100\%$. As there is no energy growth in this scenario it was irrelevant whether the y-axis was number of cars, percentage of max cars, or energy usage. In order to simplify the calculations and make further analysis of the data easier, we elected to use the percentage of max cars.

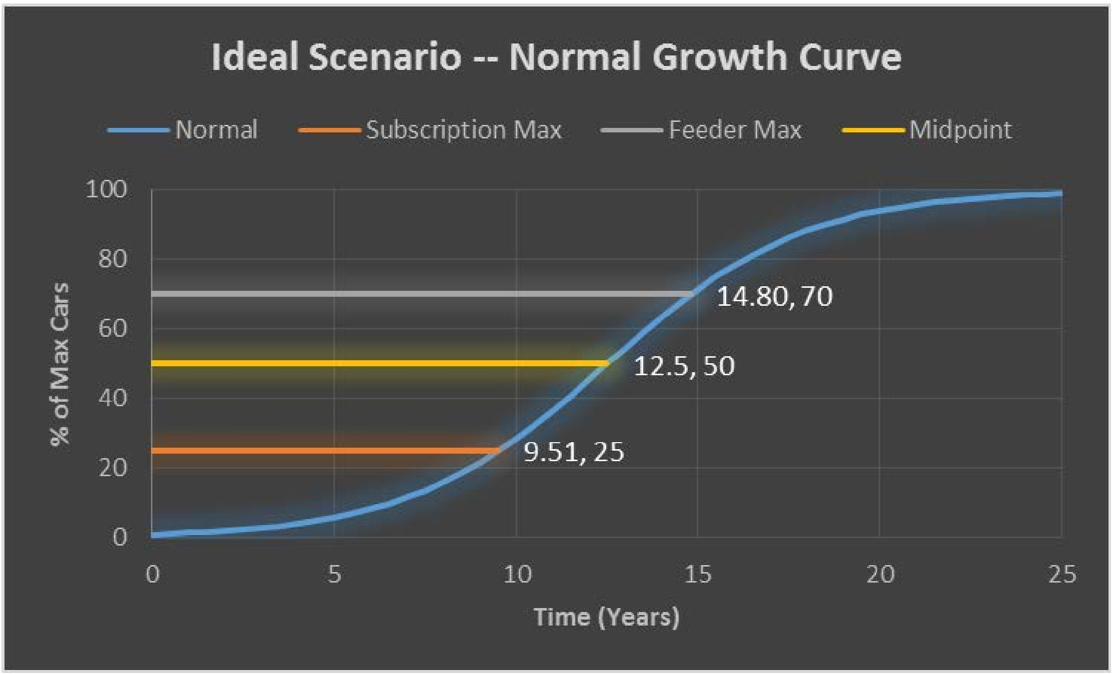

Figure 26: Ideal Scenario – Normal Proliferation Curve

This is the scenario when there is normal rate of proliferation in the number of EVs over time (years). Figure 26 shows the first curve of the logistic function when the curve hits the midpoint of max cars (2000) at 50% (12.5 years) of the total time (25 years) and cars (4000). For this curve, it takes 9.51 years to reach the Subscription Max and 14.80 years to reach the Feeder Max.

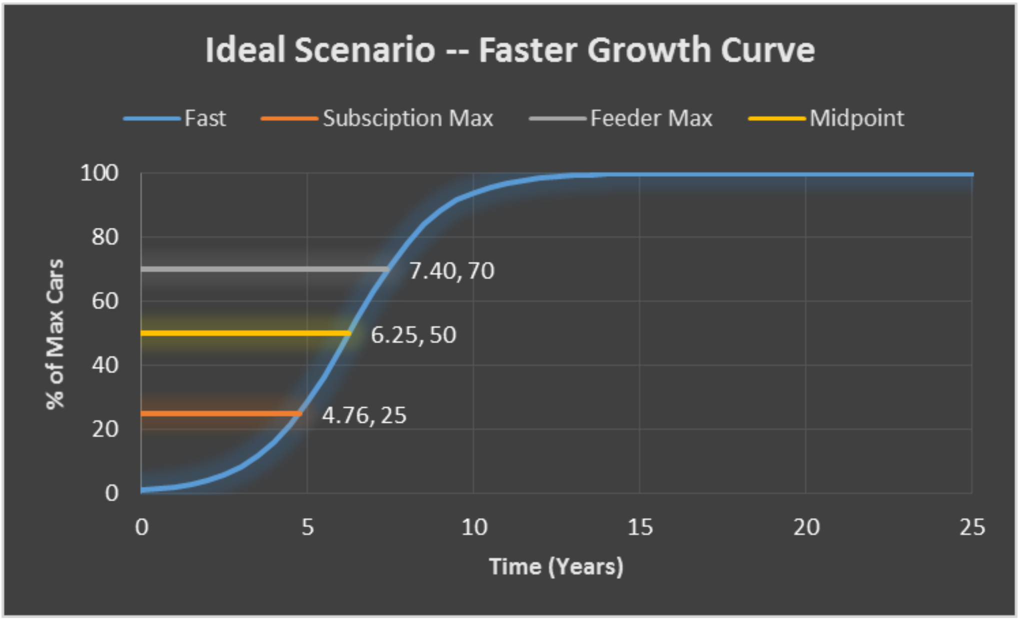

Figure 27: Ideal Scenario – Faster Proliferation Curve

This is the scenario when there is faster rate of proliferation in the number of EVs over time (years). Figure 27 shows the second curve of the logistic function when the curve hits the midpoint of max cars at 25% (6.25 years) of the total time and cars. For this curve, it takes 4.76 years to reach the Subscription Max and 7.40 years to reach the Feeder Max.

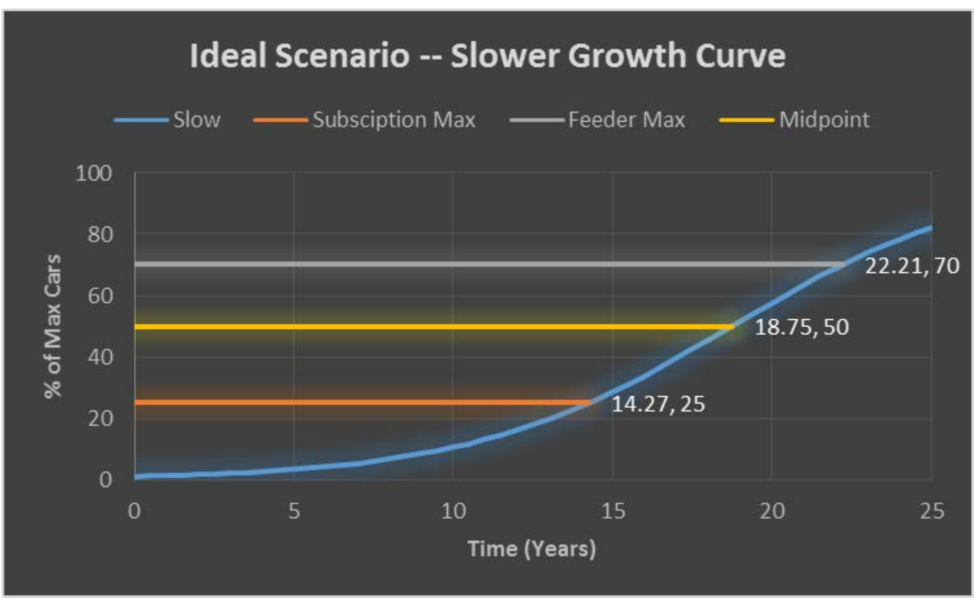

Figure 28: Ideal Scenario – Slower Proliferation Curve

This is the scenario when there is slower rate of proliferation in the number of EVs over time (years). Figure 28 shows the third curve of the logistic function when the curve hits the midpoint of max cars at 75% (18.75 years) of the total time and cars. For this curve, it takes 14.27 years to reach the Subscription Max and 22.21 years to reach the Feeder Max.

4.1.2 Realistic Scenario

The following graphs and tables assume a more realistic scenario where there is a yearly 0.9% increase in energy usage between 2015 and 2040. Since the logistic function and energy growth are independent of each other, we determined that it would be best to use energy usage (MWh) on the y-axis as well as the percentage of max EVs as a second y-axis. Because of their independence, we would not be able to just use the logistic function to determine the time when the Subscription and Feeder Maxes would be reached. Instead we found the most accurate polynomial trend lines that we could for each curve and used the equation of that line to closely approximate the time when these maxes would be reached. As expected, by including the yearly energy growth both the Subscription and Feeder Maxes were hit quicker than they were in the ideal scenario. As shown in the figures below, the subscription max is now hit with less than 20% of the max cars and the feeder max is hit just above 50% of the max cars.

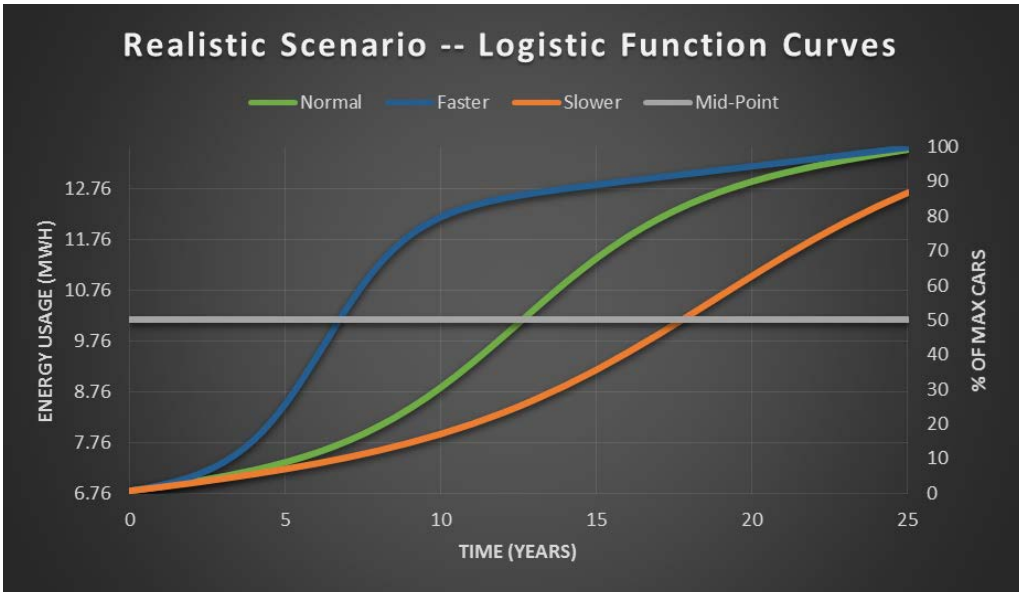

Figure 29: Logistic Function Curves – Realistic Scenario

Figure 29 above shows each of the three logistic function curves added with the yearly energy growth and a fourth line indicating the midpoint of the curves when 50% of the max cars is reached.

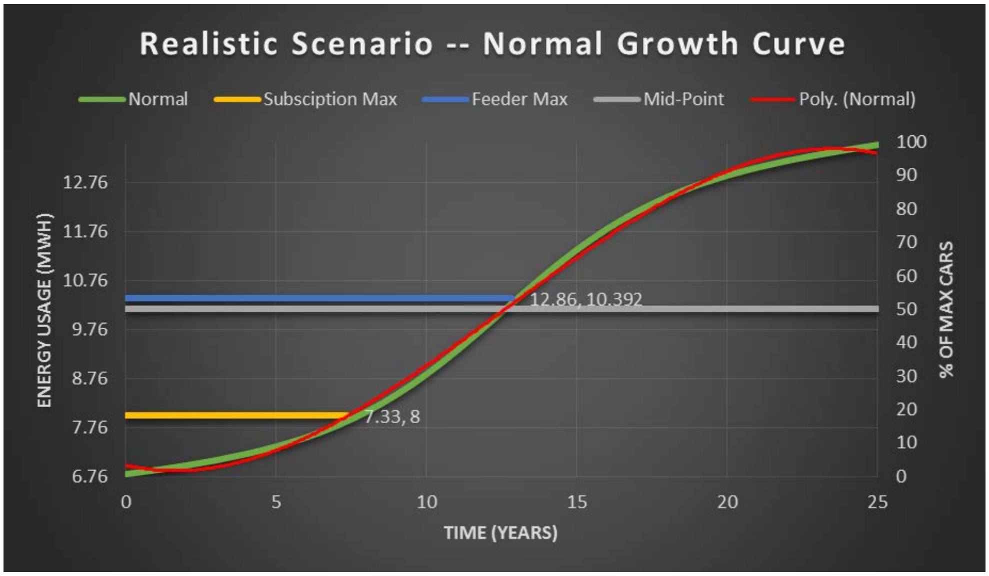

Figure 30: Realistic Scenario – Normal Proliferation Curve

For the Normal Curve, shown in Figure 30, it only takes 7.33 years to reach the Subscription Max and 12.86 years to reach the Feeder Max. This is compared to the 9.51 and 14.80 years it takes to reach the same maxes in the ideal scenario. The trend line function used to determine these values is as follows:

$$y = 2 * 10^{-9}x^4 - 0.0012x^3 + 0.0471x^2 - 0.1429x + 6.991$$

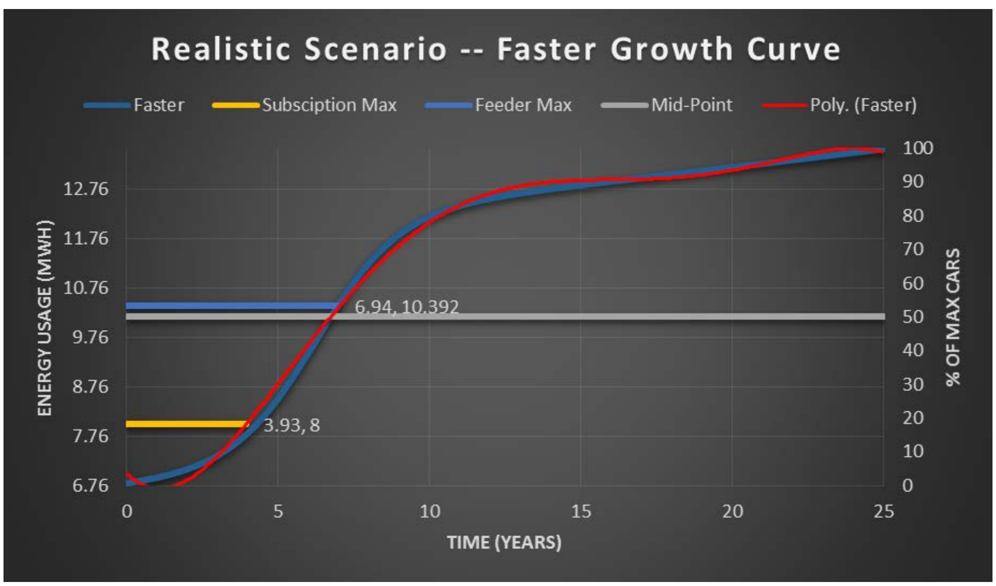

Figure 31: Realistic Scenario – Faster Proliferation Curve

For the Faster Curve, shown in Figure 31, it only takes 3.93 years to reach the Subscription Max and 6.94 years to reach the Feeder Max. This is compared to the 4.76 and 7.40 years it takes to reach the same maxes in the ideal scenario. The trend line function used to determine these values is as follows:

$$y = -2 * 10^{-5}x^5 + 0.0013x^4 - 0.0318x^3 + 0.319x^2 - 0.5823x + 7.0016$$

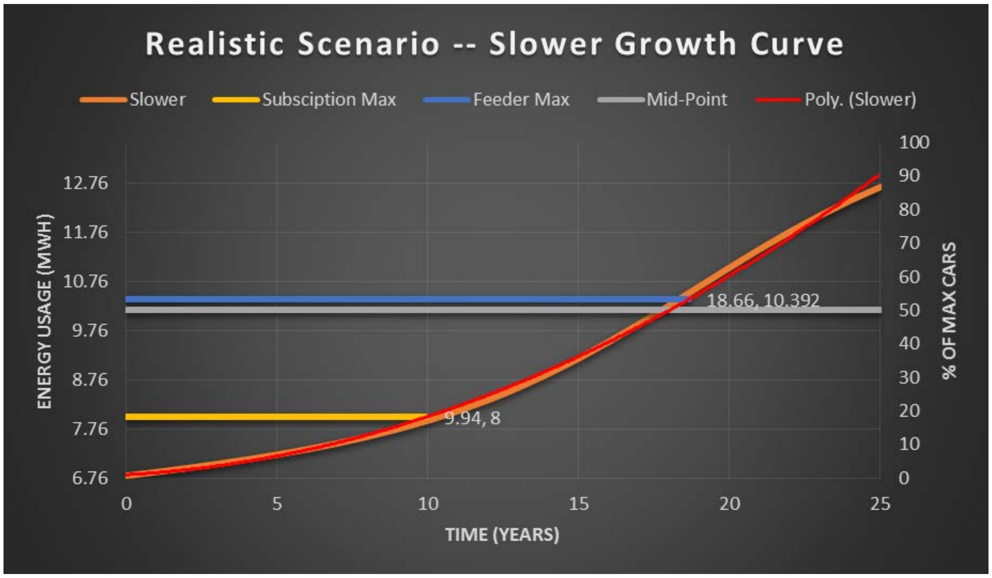

Figure 32: Realistic Scenario – Slower Proliferation Curve

For the Slower Curve, shown in Figure 32, it only takes 9.94 years to reach the Subscription Max and 18.66 years to reach the Feeder Max. This is compared to the 14.27 and 22.21 years it takes to reach the same maxes in the ideal scenario. The trend line function used to determine these values is as follows:

$$y = 0.0084x^2 + 0.0343x + 6.8288$$

The differences for when the subscription and feeder maxes are hit in both the ideal and realistic scenario is summarized in Table 11below.

Table 11: Difference between Ideal and Realistic Scenarios

Curve	*Scenario*	*Subscription Max (Years)*	*Feeder Max (Years)*
Normal	**Ideal**	9.51	14.8
	Realistic	7.33	12.86
	Difference	**2.18**	**1.94**
Faster	**Ideal**	4.76	7.4
	Realistic	3.93	6.94
	Difference	**0.83**	**0.46**
Slower	**Ideal**	14.27	22.21
	Realistic	9.94	18.66
	Difference	**4.33**	**3.55**

4.2 PowerWorld Analysis

To gather exact current, voltage, and power data, PowerWorld v19 was used to simulate the feeder of interest. To determine the effects of electric cars charging on the demand curve, the entire assumption day's demand curve was input into the model as shown in Figure 34. The model breaks up the feeder into accurate loads based on geographic major junctions. The base load was increased by adding electric car demand as well as the natural increase in demand to be expected.

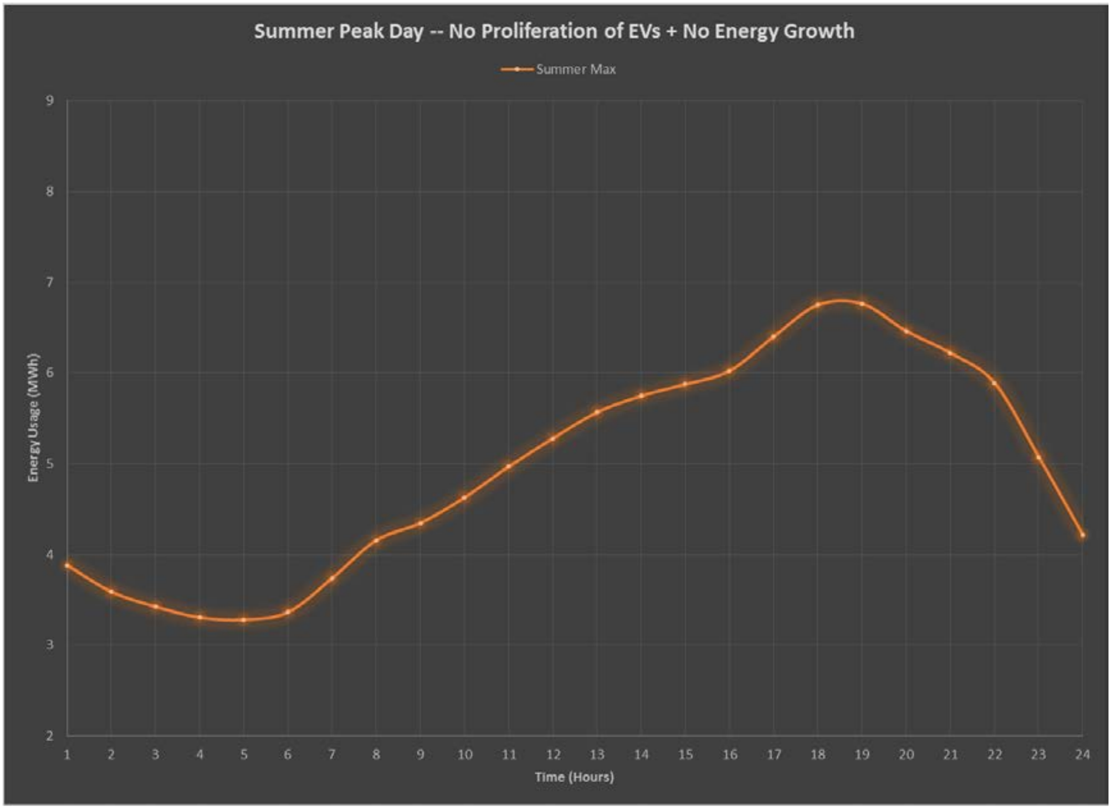

Figure 33: Summer Peak Day – No Proliferation of EVs + No Energy Growth

4.2.1 Subscription Max Simulations

The first group of simulations run was performed to predict under what scenarios the feeder would hit the current subscription max of 8MW. The first group of simulations ran focused on natural electricity growth of 0.9% per year without the addition of electric cars. In Figure 34 below, the 24-hour demand of the feeder is shown in 17 years from July 20, 2015. This equates to the peak of summer during 2032.

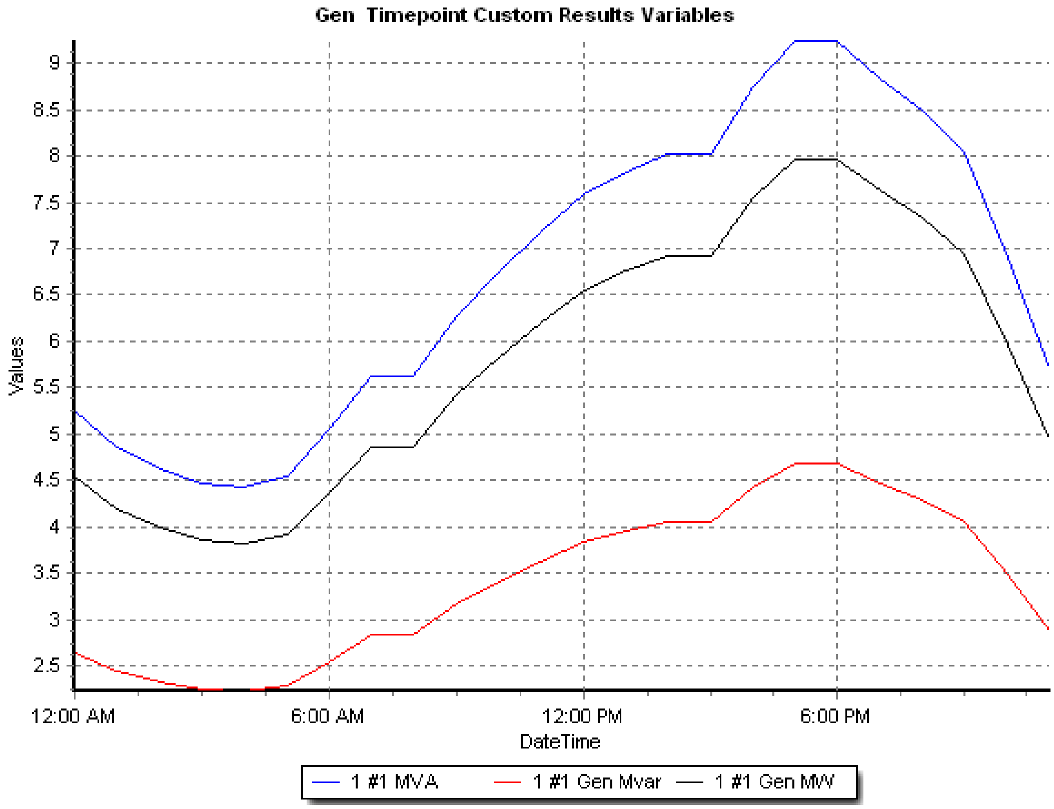

Figure 34: Subscription Max at 0% Saturation and 17 years

In addition to these year-only simulations, saturation-only simulations were performed to highlight the differences in the growth patterns of natural growth and electric cars. Simulations show that if the percent of electric cars skyrocketed to 27% in 2015, the feeder would hit its Subscription Max. This equals about 1080 electric cars. This simulation is shown below in Figure 35.

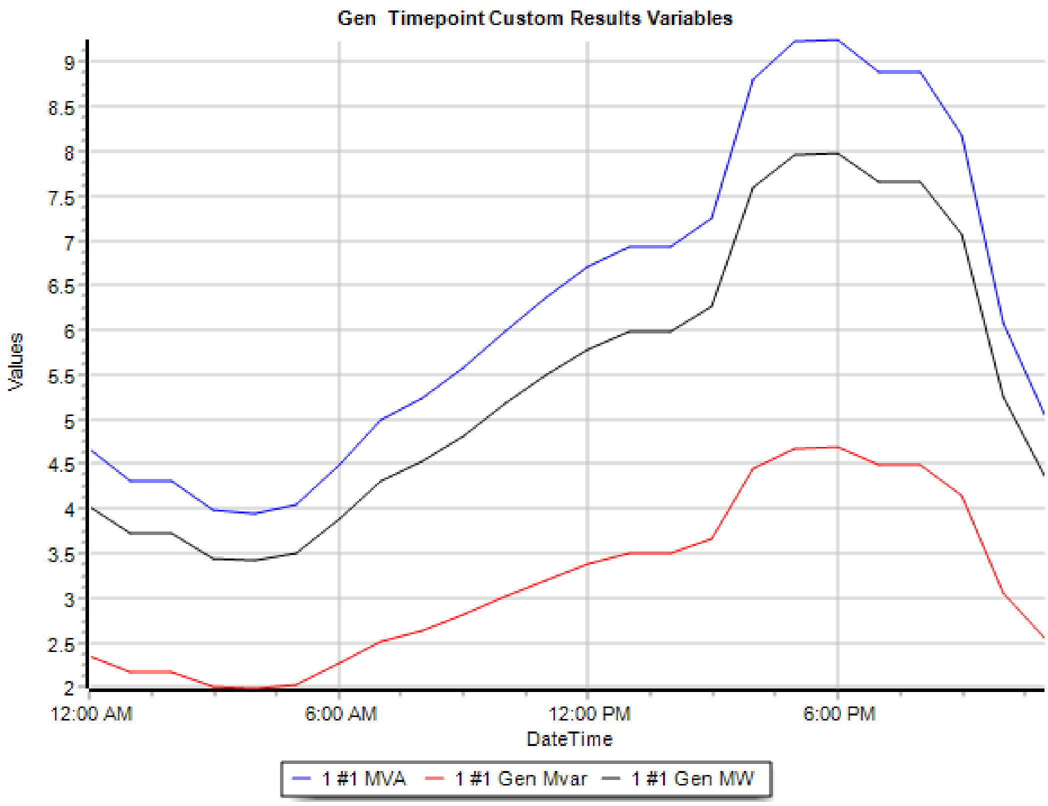

Figure 35: Subscription Max at 27% Saturation and 0 Years

The next group of simulations focuses on the Subscription Max estimates given by the Logistic Function analysis in the previous section. The first period that is examined is the fast proliferation curve. This predicts that the subscription max will be hit in 3.93 or approximately 4 years from 2015. For this limit to be hit in this short of a timeframe, the car saturation must hit 20%. This is slightly faster than the 15% predicted. The graph of this simulation is shown below in Figure 36. Comparing Figure 36 to the previous 0% saturation simulation shows the effect of adding electric cars to the grid versus natural growth.

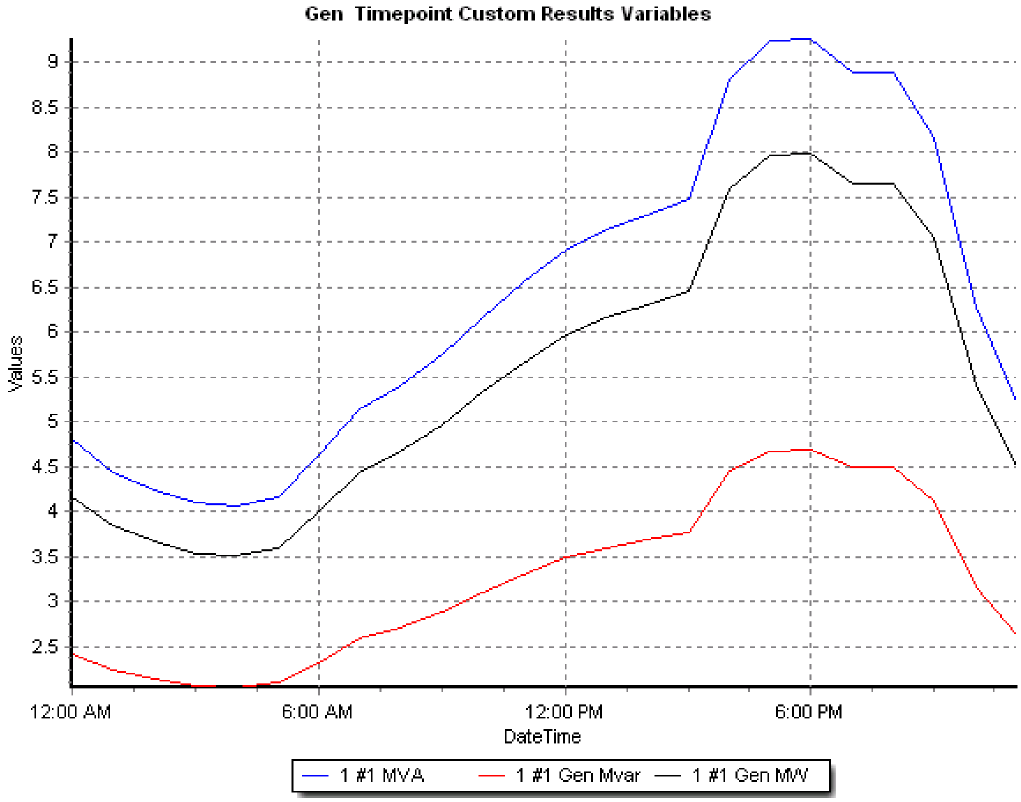

Figure 36: Subscription Max at 20% Saturation and 4 Years

The next Subscription Max to examine was the Logistic function representing slow adoption rates for electric cars. This was projected to take 9.94 years or approximately 10 years. Simulations were run to determine the percent of saturation required to hit the Subscription Max in 10 years. The graph for the resulting year is shown below in Figure 37. Simulations determined it would require a saturation rate of 10% to hit this limit in ten years. This follows the saturation rate predicted by the slow proliferation path.

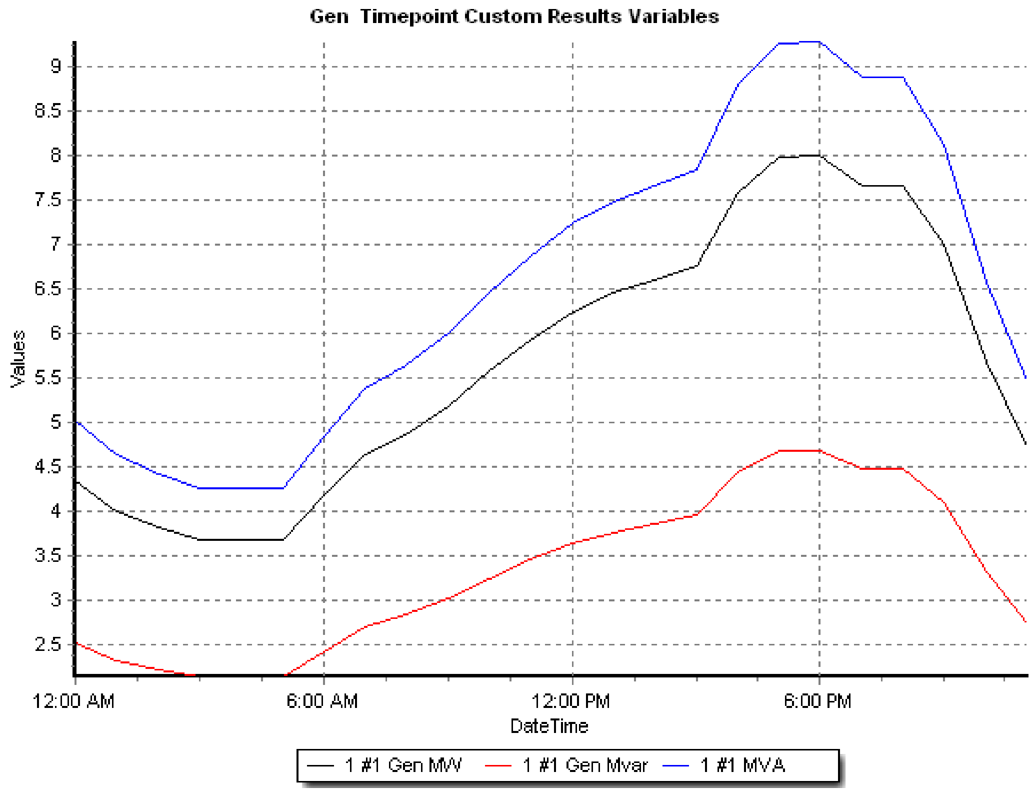

Figure 37: Subscription Max at 10% Saturation and 10 Years

The last Subscription Max simulation ran was to confirm the normal proliferation pattern. It was expected to take 7.33 years to hit the Subscription Max. Simulations confirmed that the Subscription Max would be hit in 7.33 years if there was a 14% saturation rate. If this saturation rate is compared to the existing normal proliferation S-curve, we find that the prediction is remarkably accurate. The results of this simulation are shown below in Figure 38.

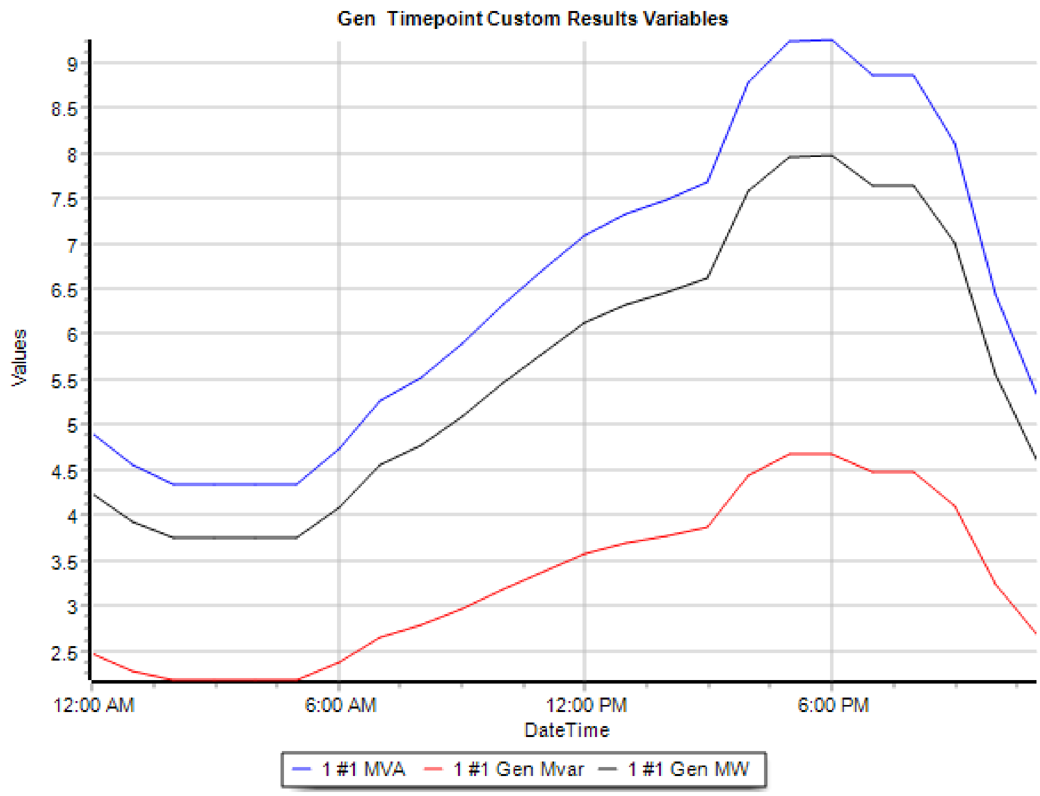

Figure 38: Subscription Max at 14% Saturation and 7.33 Years

4.2.2 Feeder Max Simulations

The next grouping of simulations focused on the Feeder Max. This is the maximum amount of apparent power the system can transmit at any point before components start operating outside of their normal ranges of operation. When this limit is reached, the only solution is to increase the capacity of the feeder or add additional feeders. The first simulation run focused on a very low saturation rate compared to time. While the saturation rate stays at a low 25% percent, it would take approximately 29 years of electrical growth to hit the feeder capacity limit. This simulation is shown in Figure 39 below.

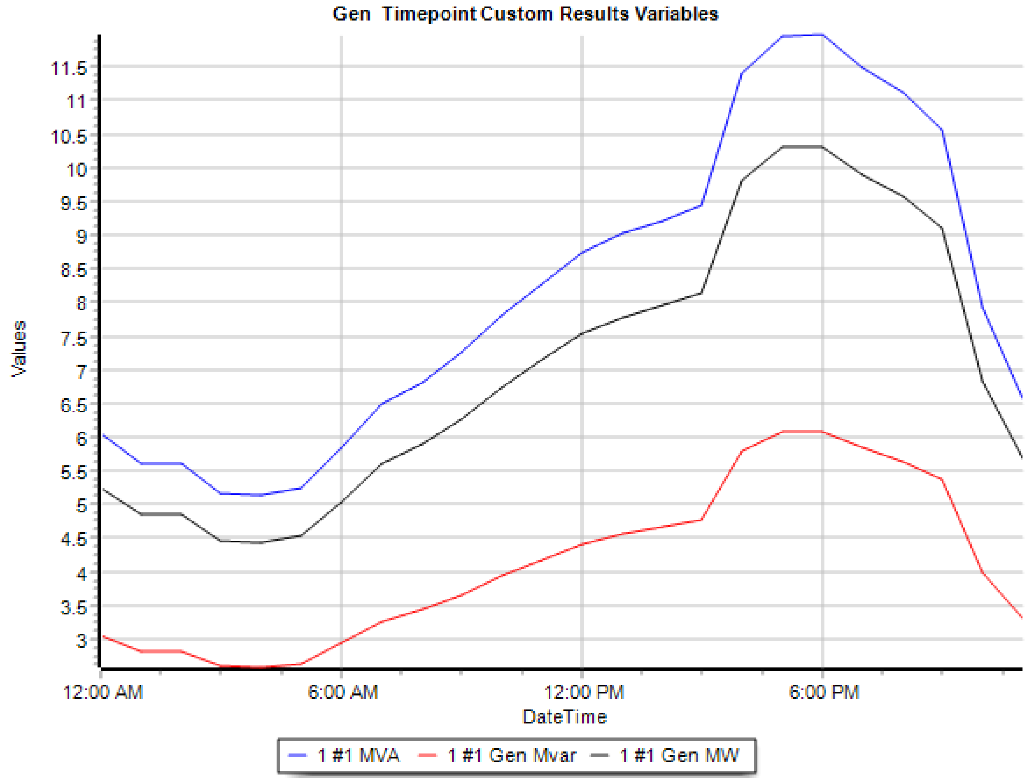

Figure 39: Feeder Limit at 25% Saturation and 29 Years

The next group of simulations focused on the results predicted by the Logistic curves. The first of these is the fast proliferation curve that predicted the Feeder Max to be hit in 6.94 years. This occurs when there is a 69% saturation rate. Due to the assumption that 80% of electric cars total charging energy will be drawn immediately after normal business hours, there is a large spike in demand during normal peak hours. This causes Figure 40 below to resemble an exaggerated version of the current peak 24-hour demand curve. Once again, the fast model falls behind the actual saturation rate needed in the year predicted.

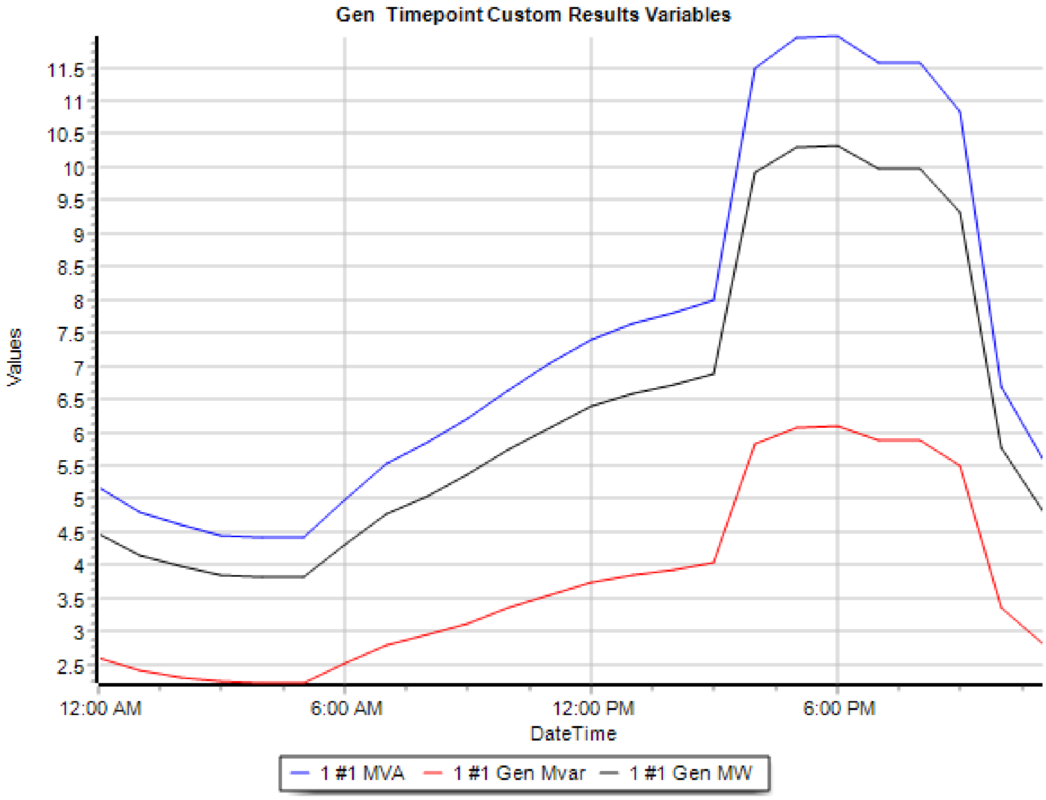

Figure 40: Feeder Limit at 69% saturation and 6.94 years

The next group of simulation results is derived from the slow proliferation curve that has a projected number of 18.66 years. The resulting required saturation to achieve this limit is 45%. This is slightly below the projected value of 50%. This result is illustrated below in Figure 41.

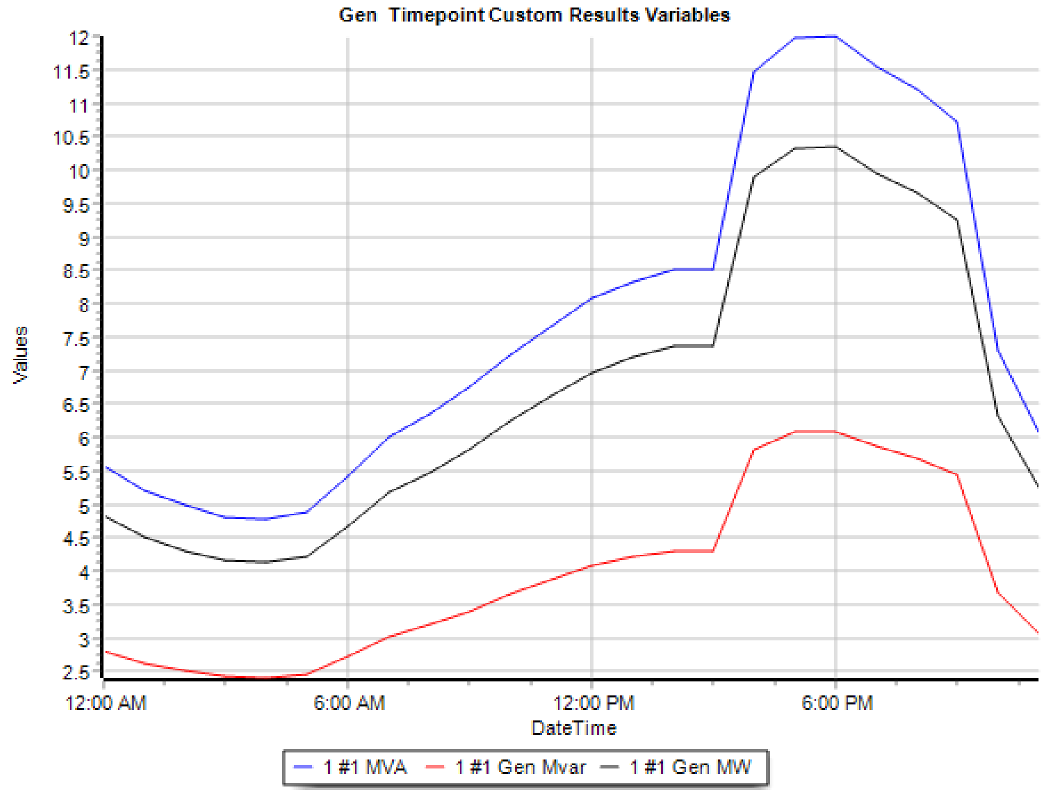

Figure 41: Feeder Limit 45% Saturation and 18.66 Years

The last group of simulations run was on the normal proliferation curve. This is expected to take 12.86 years. To achieve this limit in this time period a saturation of 56% is required. This is exactly as predicted by the logistic function. These results are shown below in Figure 42.

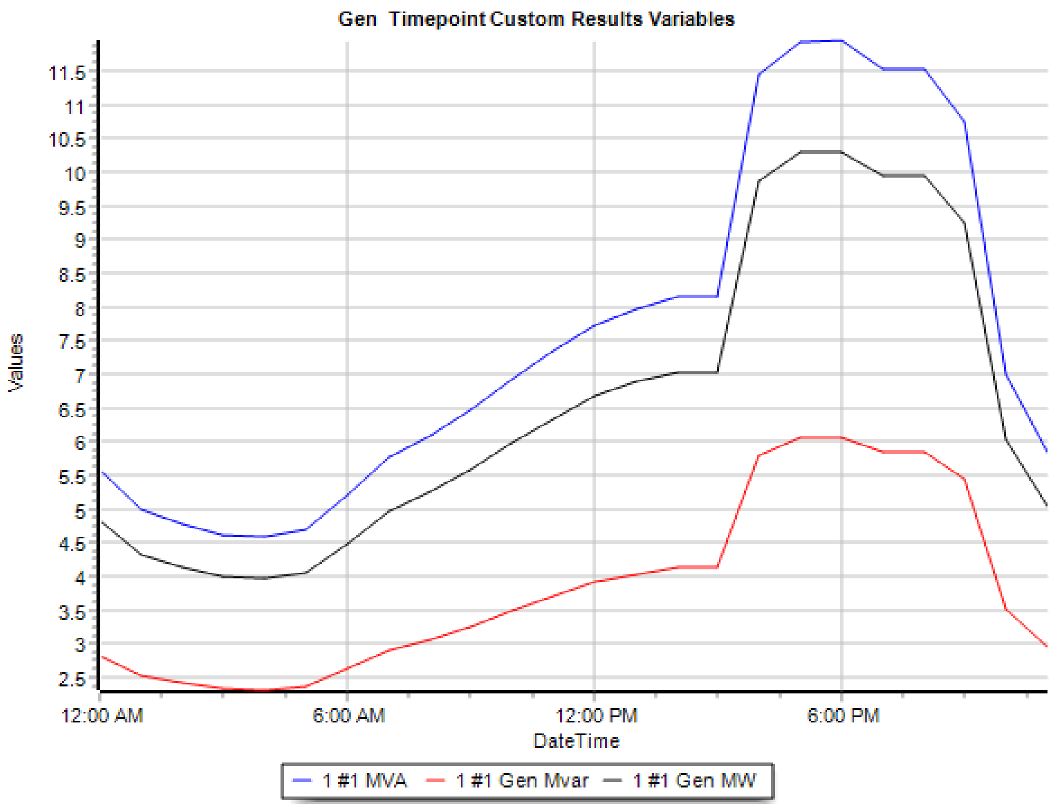

Figure 42: Feeder Limit 56% Saturation and 12.86 Years

4.2.3 Lithium-Ion Battery Simulations

To evaluate the effects of the electric cars on the grid as well as our proposed solution, it became necessary to model a battery and implement this on the test distribution grid. To determine estimate power values for the loads and batteries, the aforementioned Excel spreadsheet was used. These values were run through PowerWorld to determine if they would go over our determined limits, 8MW and 12MVA.

The first group of simulations focused on a centralized battery, the Feeder Storage solution. A prime geographic location would be near the middle of the feeder. This lowers the current flowing across the main substation lines during discharge. The Subscription Max was initially tested under two conditions, 75% and 100% car saturation. The first simulation result is shown in Figure 43 below, 75% saturation and 34 years in the future. As you can see, the MW is average is slightly lower than 8MW across the entire day, effectively staying under the Subscription limit. The battery does not control MVARS.

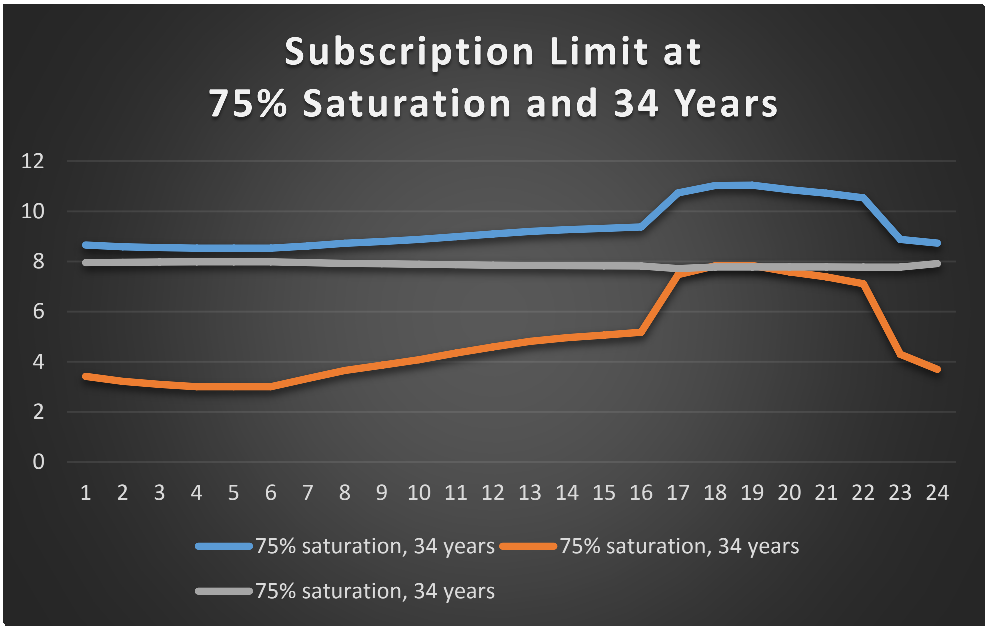

Figure 43: Subscription Limit with Feeder Storage Solution at 75% Saturation and 34 Years

The second group of simulations is similar to the first but focuses on the most extreme version of car saturation, 100%. Using the Subscription Max and the feeder storage solution, it was found that it our proposed solution would work for 26 years. The results of this simulation are shown below in Figure 44.

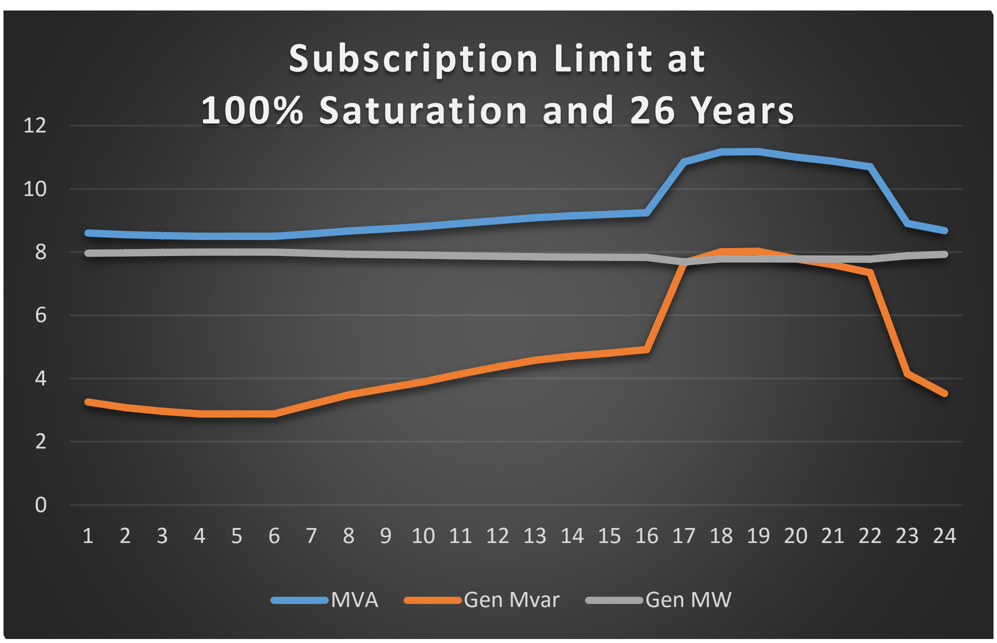

Figure 44: Subscription Limit with Feeder Storage Solution at 100% Saturation and 26 Years

The next group of simulations focused on the same solution, Feeder storage, but uses a different limit, 12 MVA. As observed in the previous group of results, the MVA using the Subscription Limit does not go near 12 MVA. If we use MVA as our new limit, we find it takes longer to hit this value. The first of these simulations is shown below in Figure 45. This shows the result of 75% saturation, resulting in 42 years of staying under 12 MVA on the feeder.

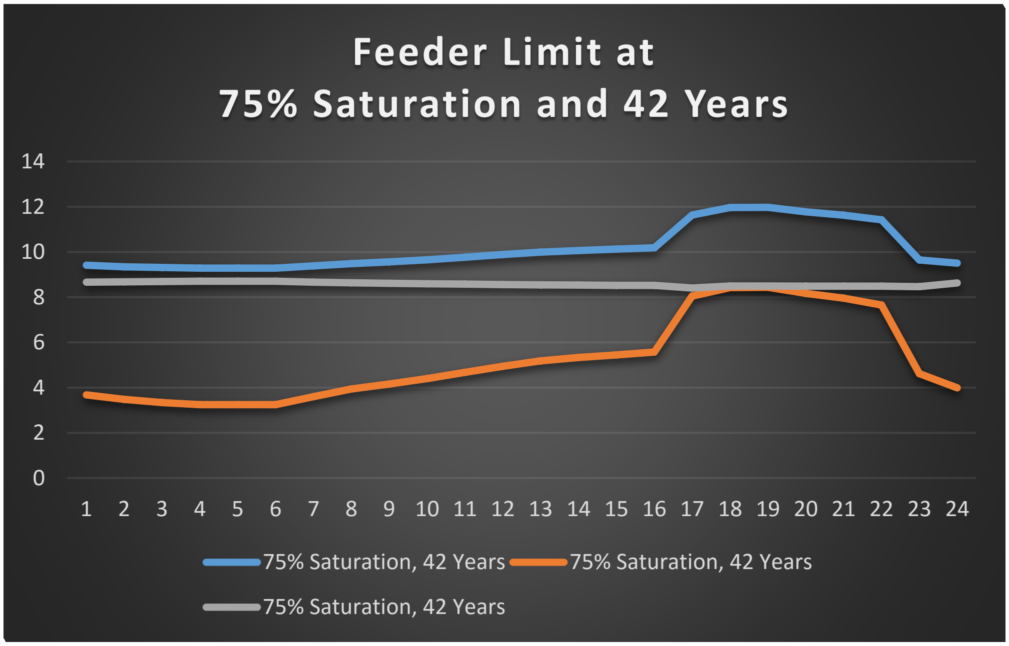

Figure 45: Feeder Limit with Feeder Storage at 75% Saturation and 42 Years

The last group of simulations for this solution focuses on 100% car saturation. Like the previous simulation, this was done using a Feeder limit of 12MVA. It was found that the feeder could support cars and natural growth for 33 years. This would require, however, for the Subscription Max to be raised. As previously found, the largest impact on MVA is now the MVARs, not the MW load. The results of this are shown below in Figure 46.

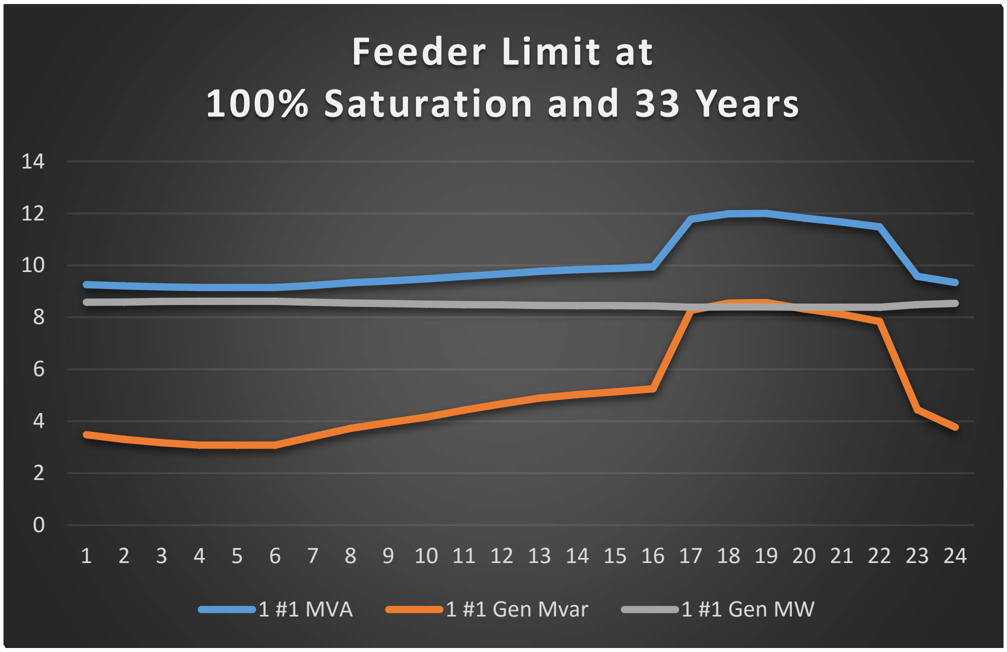

Figure 46: Feeder Limit with Feeder Storage at 100% Saturation and 33 Years

4.2.4 Micro-Grid Battery Simulations

The next set of simulations is related to the other placement of batteries along the Feeder, a micro-grid system. The same limits and tools were used to evaluate the following as the above centralized Feeder storage solution. This is different however in that the ratio of current does change along the lines but only increases and decreases by the same ratio at the loads.

The first simulation result comes from testing the storage solution with a Subscription Max of 8MW. According to power consumption at the substations, the micro-grid solution can delay the need to increase the Subscription Max by slightly longer times than the centralized solution. The first simulation result, Figure 47 below, shows how the batteries would keep the instantaneous demand below the Subscription limit at 75% saturation and 35 years. This is only 1 year longer than the centralized solution.

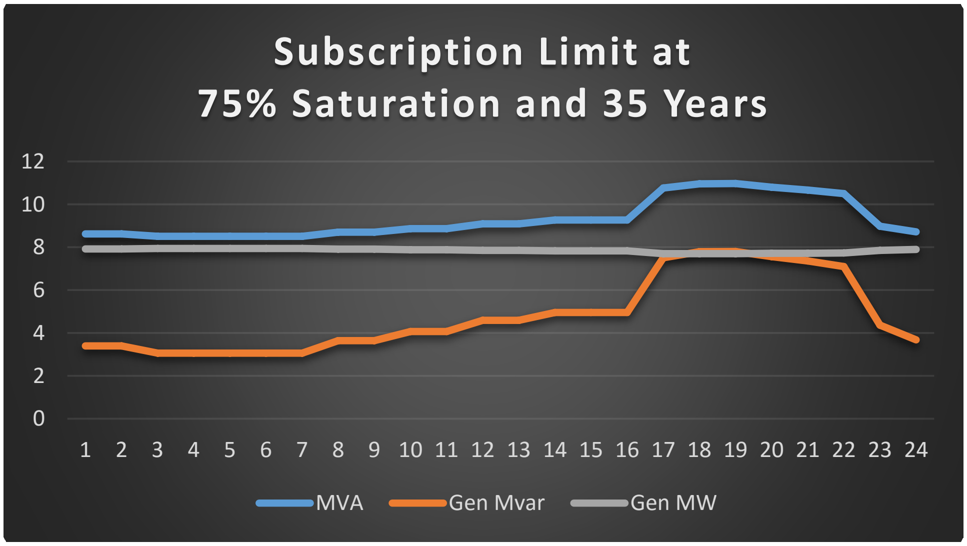

Figure 47: Subscription Limit for Micro-Grid Solution at 75% Saturation and 35 Years

The next set of results is essentially the same as above but with a different saturation rate, 100%. Using the same limits and tools, it was found that a 100% saturated grid would still work in 27 years. The results of this are shown in Figure 48 below.

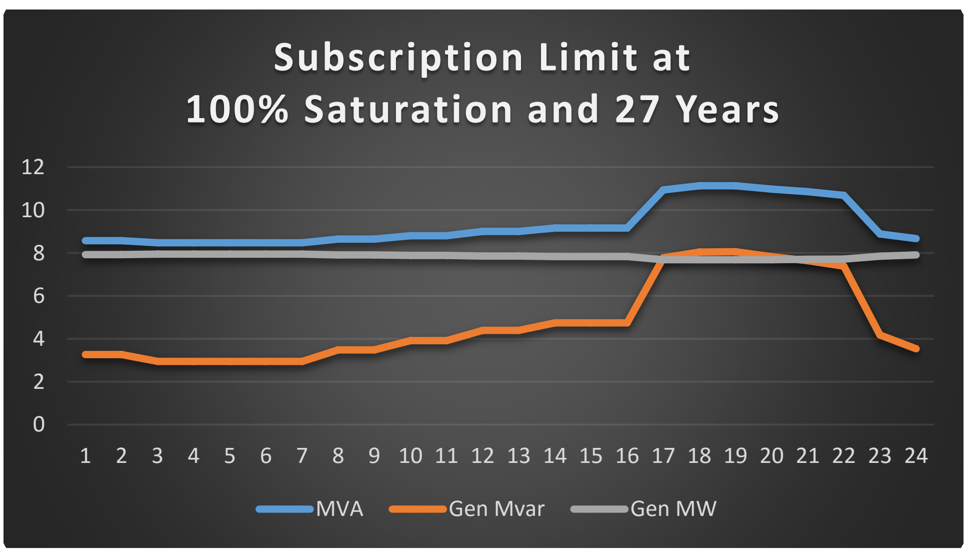

Figure 48: Subscription Limit for Micro-Grid Solution at 100% Saturation and 27 Years

The last group of simulations focuses on the Feeder Limit of 12 MVA again. Results show that the micro-grid solution can mitigate the need to upgrade the feeder for 43 years at 75% saturation. The largest issue that limits this max is the MVARs, which makes up a substantial amount of the energy compared to what is used, MW. This increases MVA, which lowers the remaining capacity. The results of this simulation are shown below in Figure 49.

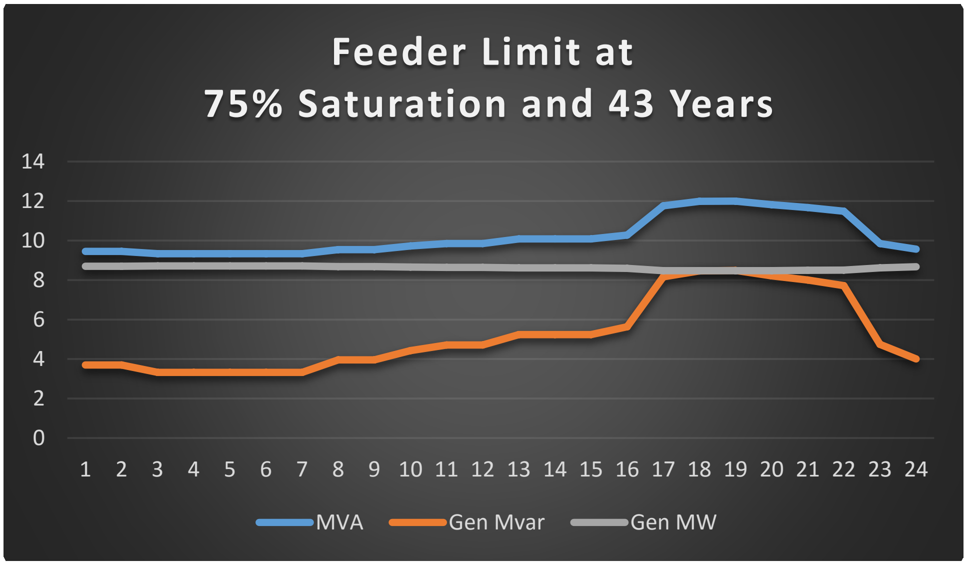

Figure 49: Feeder Limit for Micro-Grid Solution at 75% Saturation and 43 Years

The final simulation shows the final time period before the grid will fail under stress. This was found to be 34 years at 100% Saturation. This result is shown below in Figure 50.

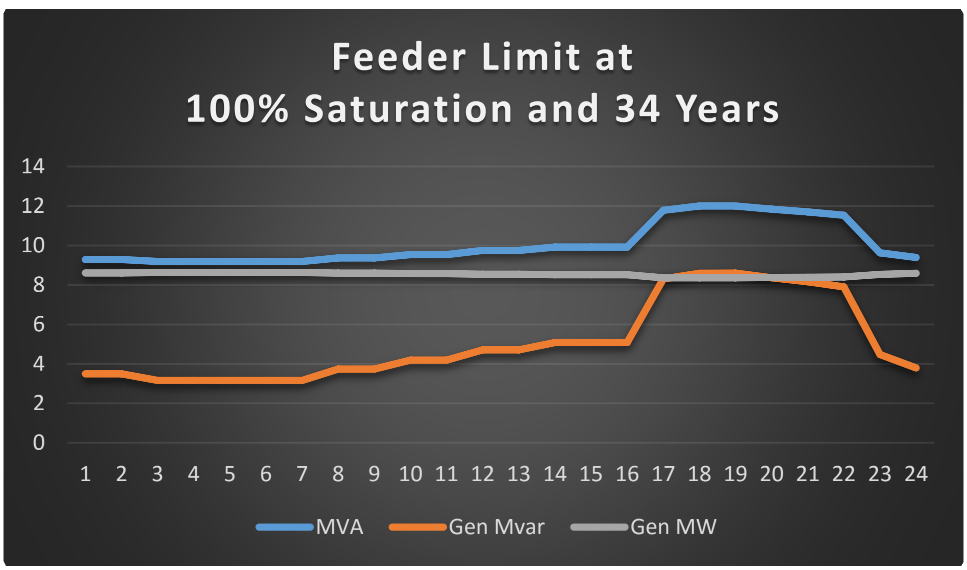

Figure 50: Feeder Limit for Micro-Grid Solution at 100% Saturation and 34 Years

4.3 Transformer Lifetime Analysis

In this section, the transformer and lifetime equations outlined in Section 2.5 are implemented for the three S-curve proliferation speeds with an annual electrical demand increase of 0.9%.It must be noted that the subscription limit is set in kW, while the feeder limit is set in kVA. The sample feeder has two substation transformers, thus only one transformer was modeled with 50% of the total load. In addition, the scenario involving an older transformer and a thirty years newer transformer leads to an analysis of one transformer operating with 70% of the load, while the other transformer at 30% was not considered.

The transformer life equations are designed to calculate based on averaged loads, though some unusually high loads should be modeled separately and added to the total life loss. Since the data available for study represents hourly readings of kW for the feeder from September 2014 to August 2015, all data has been scaled and analyzed from the year of origin (2015) onward. As a reminder, the transformer life modeling through the IEEE standard represents the best estimation of transformer life to date based on the degree of polymerization breakdown, and further specified modeling would be required for each individual circumstance to account for inconsistencies and abnormalities in loading.

The normal transformer life is rated for 180,000 hours, or 7,500 days, and is based on a constant load that creates a consistent 110 °C hottest-spot temperature. To model the transformer life, hourly calculations were averaged to calculate the life data for a day. The seasonal data was calculated by averaging every hour for every day in the season to find the averaged seasonal day, which was then multiplied by a factor of 91 for the days in a season. The seasonal averaged life calculations were then added to form the averaged life for one year. As a point of reference, the Table below represents the IEEE standard by which the modeling comparisons in this section were made.

Table 12: Standard Normal Transformer Life

IEEE Standard, Normal Transformer Life	
FEQA	1
%Loss/day	0.0133
%Loss/year	4.866
Lifespan (h)	180000
Lifespan (pu)	1

As an example, the figure below shows the IEEE Standard Normal Transformer Life for the Table above. Note that although the peak hottest spot goes over 110°C, the average of the day is taken to produce the values in the Table above.

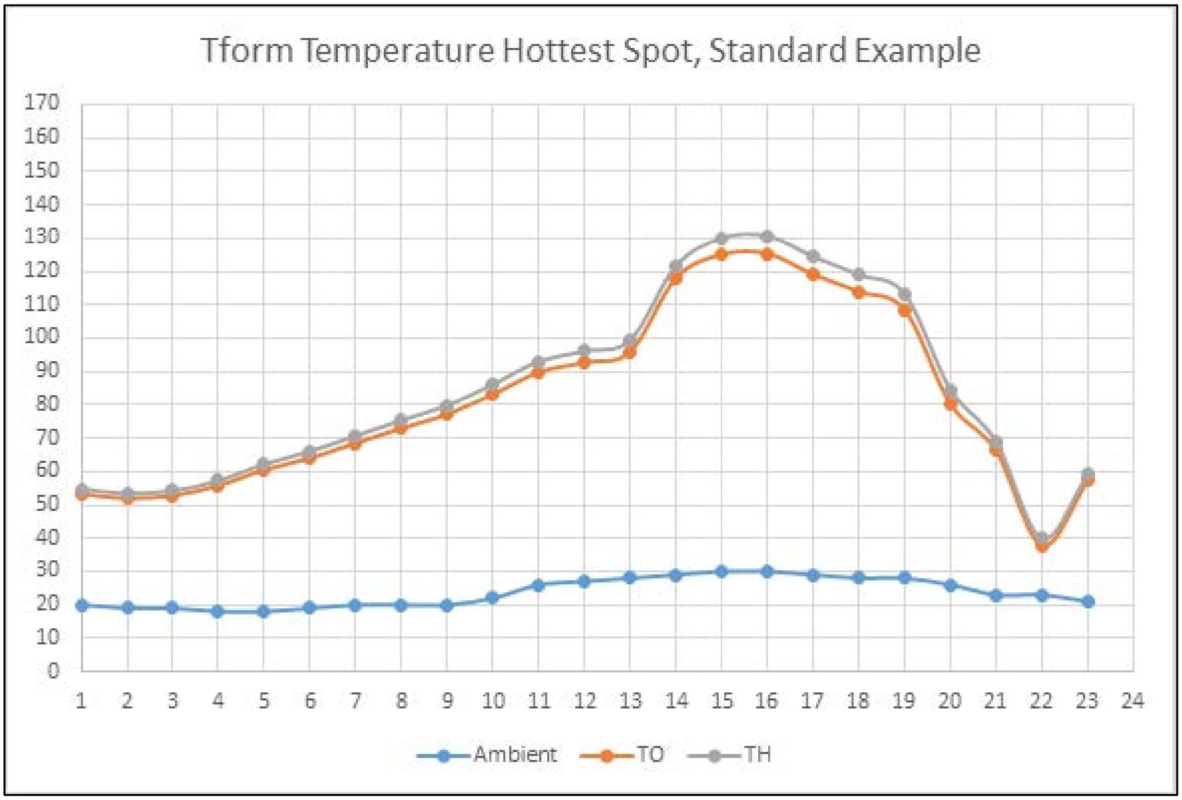

Figure 51: Example Temperature Curves for IEEE Standard

The Table below represents the transformer life estimated for the day with the highest energy use for the year 2015.Every other highest energy use day for the specified year was modeled by scaling this base model. The Table below shows the different loading choices, and includes data for the entire daily load on one transformer to model and emergency situation that forces one substation transformer to be responsible for the entire feeder. The 100% load scenario data represents unusual emergency loading, and could result in transformer failure. The 50% and 70% load scenarios show a lack of strain on the transformer, extending the rated life in both cases. As a result, normal operation presents a higher life rating, and even the worst-case scenario of 100% load would most likely be tolerated.

Table 13: Transformer Life for 2015 Highest kWh Day

Max Day 2015	50% Load	70% Load	100% Load
FEQA	0.0101	0.2164	25.751
%Loss/day	0.0001	0.0029	0.3433
Lifespan (h)	17837203	831982	6990
Lifespan (pu)	99.096	4.6221	0.0388

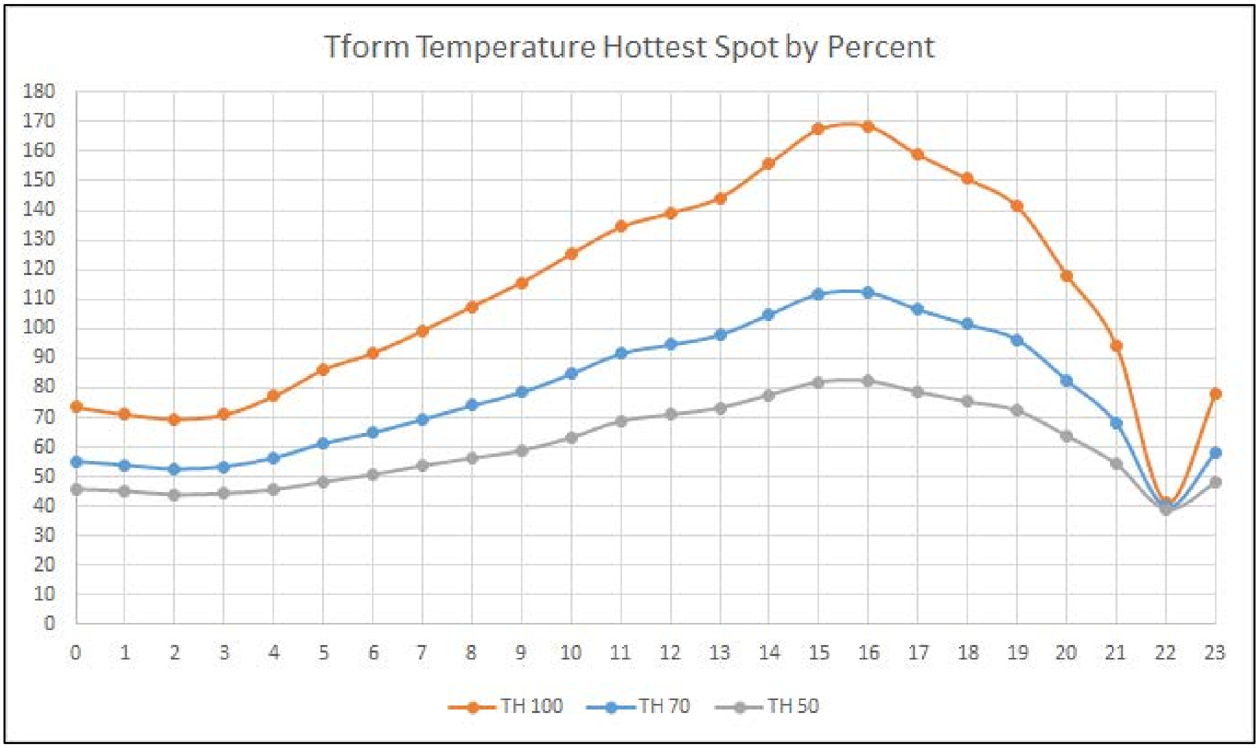

Figure 52: Hottest Spot for the 3 Loads in Table 13

The yearly total for 2015 in the Table below shows a doubling of the rated life for 50% loading, while the 70% loading shows the rated life to have reduced the rated life by a factor of 4.The Table below shows a much larger average energy use in the winter season, resulting in the loss of rated life. Though it would appear that a 50% load would have been better, it must be considered that the 70% load may have been more desirable by making a calculated sacrifice with the newer transformer to prolong the life of the older transformer. The winter may have also been long and harsh, resulting in unusually high-energy demand.

Table 14: Transformer Life Aggregate for the Year 2015

Average Life of Year 2015 By Season						
		Spring	Summer	Fall	Winter	**Total**
50% Load	FEQA	0.0788	0.1344	0.0889	0.2394	**0.5415**
	%Loss	0.0011	0.0018	0.0012	0.0032	**0.0072**
70% Load	FEQA	0.3532	0.8610	0.4509	2.4378	**4.1029**
	%Loss	0.0047	0.0115	0.0060	0.0325	**0.0547**

The Table below shows the day with the highest energy use for the year 2015, by setting the highest demand hour to the subscription and feeder limits (as discussed in Section 4.1) and scaling the rest of the hours .The numbers below represent all three proliferation cases for subscription and feeder limits due to the methods used to scale and average transformer life, creating similar results for different timelines. For both limits, the 50% load scenario improves rated life, while the 70% load scenario degrades the rated life. In the case of the 70% load for the feeder limit, the loading could be considered catastrophic by losing over 1% of transformer life a day.

Table 15: Transformer Life for a Day at Crucial Points

	Subscription Limit		Feeder Limit	
	50% Load	70% Load	50% Load	70% Load
FEQA	0.037	1.586	0.611	82.877
%Loss/day	0.00049	0.021	0.00815	1.1050
Lifespan (h)	4930174	113464	294653	2172
Lifespan (pu)	27.390	0.630	1.637	0.0121

The Table below shows turning points when the highest kWh demand day starts to produce lower life expectations than that of the rated life model, when the FEQA displays a value more than 1. At this point in the transformer life analysis, it may be deduced that for every S-curve type and a 70% feeder load, the time and percent of electric car proliferation show as significantly less than a 50% feeder load. The time limit for all 70% feeder loading to surpass the rated FEQA may be set to the year 2025. It must also be noted that the limit for the 50% feeder loading resembles (but surpasses) the feeder limits for all S-curve types, while the 70% feeder loading resembles the subscription limits for all S-curve types.

Table 16: IEEE Standard Life Threshold for 1 Day

Year and Proliferation when FEQA > 1							
Load	S-curve Type	FEQA	%Loss/day	Lifespan (h)	Lifespan (pu)	Year	%Proliferation
70%	Normal	1.1737	0.0156	153361	0.8520	2022	12
	Fast	1.1933	0.0159	150846	0.8380	2019	16
	Slow	1.0480	0.0140	171758	0.9542	2024	8
50%	Normal	1.1262	0.0150	159828	0.8879	2029	63
	Fast	1.0002	0.0133	179965	0.9998	2022	70
	Slow	1.2842	0.0171	140170	0.7787	2035	57

Since the Table above describes the 70% load limits as loading similar to the subscription limit S-curves, the Table below shows the a transformer life for the year 2022 at the subscription limit using 70% load by scaling the 2015 seasonal data for the normal S-curve type.

Table 17: Feeder Subscription Limit Average Life Loss for 1 Year

Average Life of Year 2022, By Season						
Normal S-curve (table		Spring	Summer	Fall	Winter	**Total**
70% Load	FEQA	1.2024	3.2578	1.6792	11.556	17.6950
	%Loss	0.0160	0.0434	0.0224	0.1541	**0.2359**

The Table below describes the transformer life loss for the peak kWh day, scaled for the conditions in the Table above. The highest kWh day would be considered an outlier, and should be calculated separate from the seasonal average and added to the yearly seasonal total. For the origin year of 2015, there were about 35 other outlier days similar to the peak kWh day. The Table below shows the estimated transformer loss for the year 2022 with the seasonal average aggregate in addition to the loss of the outlier days.

Table 18: Transformer Life for 2022 Peak kWh Day

Peak Day 2022, 70% Load		
FEQA		1.173703133
%Loss/day		0.015649375
Lifespan (h)		153360.7561
Lifespan (pu)		0.852004201

Table 19: Transformer Life Loss for the Year 2022

Average Life of Year 2022 Subscription Limit With Outliers			
Normal S-curve	Seasonal-Yearly Avg	Outliers (35)	**Total**
%Loss (70% Load)	0.2359	0.5477	0.7837

As can be seen by the Table above, the total life loss for the year 2022 using a normal type S-curve amounts to 0.7837% of the total, overall extending the rated transformer life expectancy by about 300 days. The data in the Tables below explore the transformer life loss for the year 2025, 10 years after the origin year 2015. The S-curve type tested is normal and the corresponding percent proliferation of EV's is about 31%.

Table 20: Transformer Life for 2025 Peak kWh Day

Peak Day 2025, 70% Load	
FEQA	8.1879
%Loss/day	0.1092
Lifespan (h)	21984
Lifespan (pu)	0.1221

Table 21: Transformer Life Loss for Averaged Year 2025

Average Life of Year 2025, By Season						
Normal S-curve (table		Spring	Summer	Fall	Winter	**Total**
70% Load	FEQA	6.9223	19.816	10.206	78.846	115.79
	%Loss	0.0923	0.2642	0.1361	1.0513	**1.5439**

Table 22: Transformer Life Loss for the Year 2025

Average Life of Year 2025 Subscription Limit With Outliers			
Normal S-curve	Seasonal-Yearly Avg	Outliers (35)	**Total**
%Loss (70% Load)	1.5439	3.8210	5.3649

The total loss for the year 2025 shows a dramatic increase in transformer life loss compared to 2022, shortening the rated transformer life expectancy by about 37 days. The transformer life expectancy went from above rated to below rated in a matter of 3 years, setting the year 2025 to be the turning point to start considering methods to alleviate stress on the transformer. If the newer transformer continues to support 70% of the feeder load to extend the older transformer, the expected life would exponentially decrease from the year 2025 and on.

4.4 Battery Charging Analysis

This section of the results was focused on the challenges that are presented when considering the EV battery on a lower level. The battery and the power needed to charge the battery would be in DC form; whereas, the power supplied to the household with the EV would be in AC form. In addition, extra circuitry would be required to accommodate the model battery of the Tesla Model S at 400Vdc from a 240Vac rated supply. The effects of battery charging on the feeder as a whole may influence later decisions regarding feeder upgrades and crucial timelines for further decision-making, with special attention to the effect on current. Further, the effects from a residence as seen from the pole transformer were taken to model the larger effects on feeder components.

The figure below shows a simplified model of one car charging. The 240Vrms signal enters a transformer with a ratio of 1:2. The secondary side then rectifies the signal to 480Vpeak, which then goes into the 400V battery.

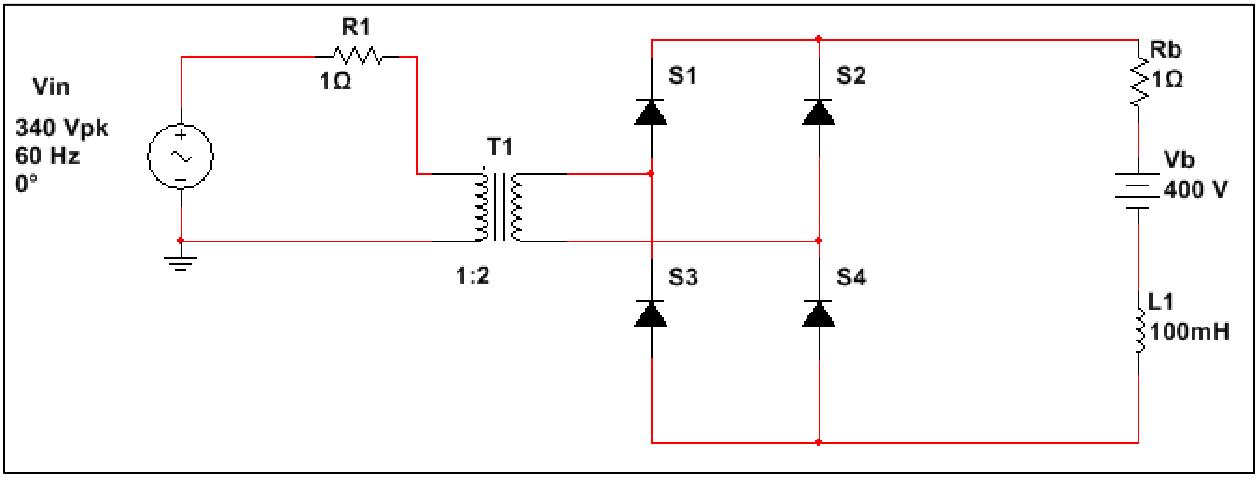

Figure 53: Simplified Charger Model

The figure below shows the current through the resistive element Rb from .24 seconds to 1.5 seconds. The current curve of Rb represents the current that is delivered to the battery. The response shown in the figure below indicates an interference, which may be considered to represent harmonic losses through the conversion of AC waveforms to DC power. The signal can be seen to stabilize around 25A.

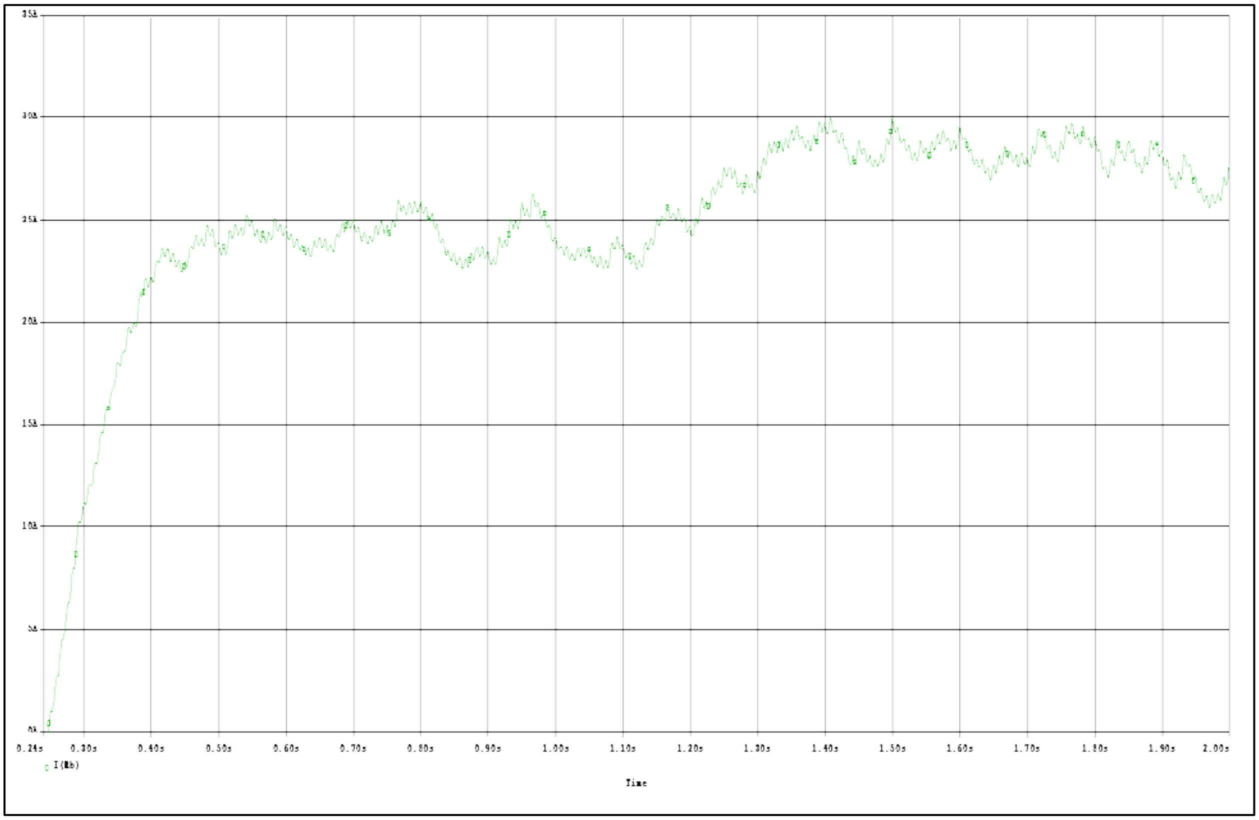

Figure 54: Current through Rb [4]

Since this project is concerned with analysis at the distribution level, the current through the resistor R1 will be the focus of the energy consumed by the house. Focusing on R1 (before rectification) allows the data to represent the energy used from a feeder perspective. The Figures below display the current as seen by the feeder and the Fourier Transform for the current curve of R1, which illustrates the power lost through primarily the first and third harmonic.

The figure below shows the fundamental to use 48A, the first harmonic to use 8A, and the third, fifth, and seventh harmonic to use an aggregate 8A. This shows losses through harmonics to be roughly 1/4 of the power used to charge one car battery when considering RMS values.

[4] The code for the PSPICE graphs may be found in Appendix 8.6

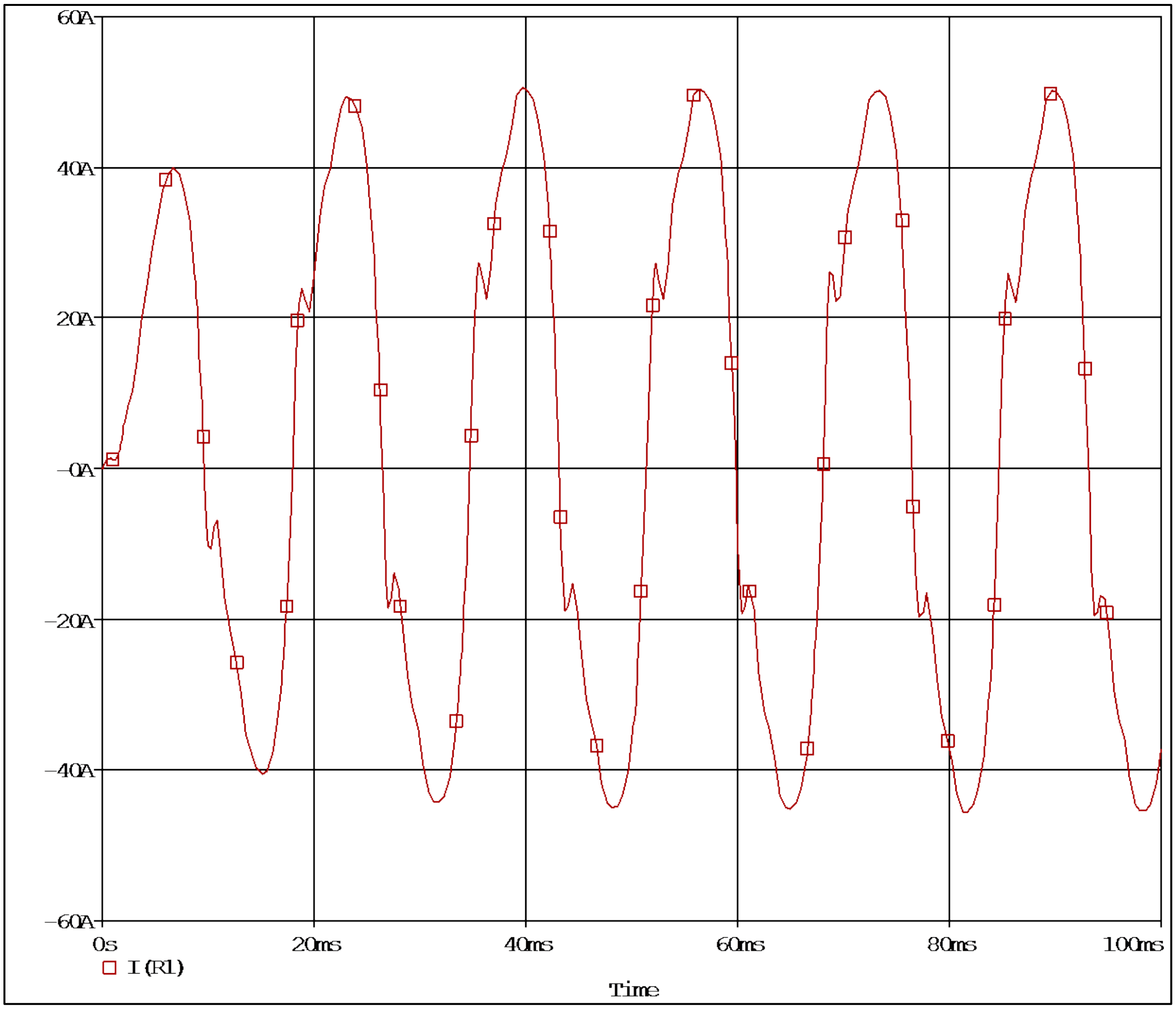

Figure 55: Single Car Charger from a Feeder Perspective

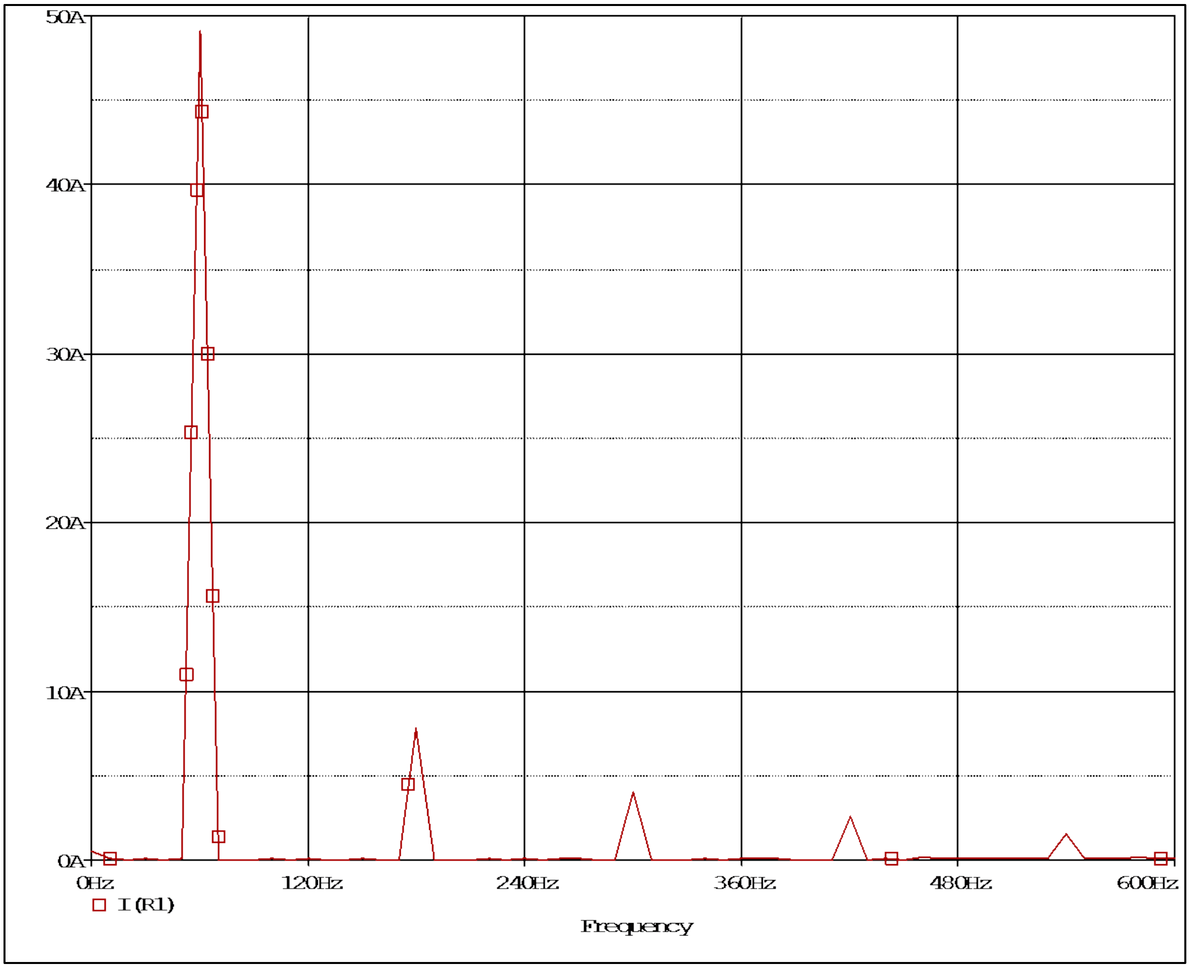

Figure 56: Fourier Response of One Car Charger from Feeder Perspective

The figure below may be used to model the power used to charge the vehicle, and the power losses due to harmonics. This model displays AC Amperes, so the RMS current for the fundamental would be much closer to the rated 30A of the charger. The RMS values of the current are changed in the figure below.

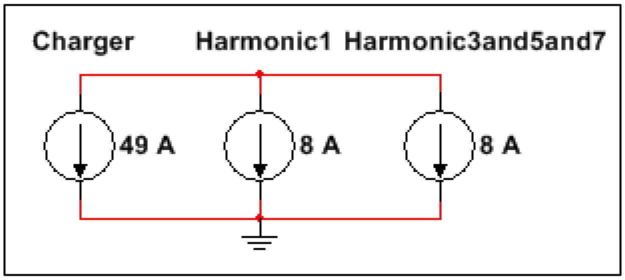

Figure 57: Battery Charger Model with Harmonics (Losses)

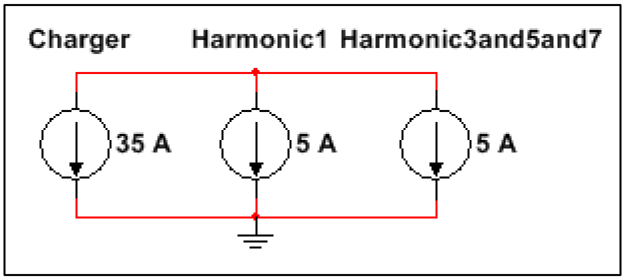

Figure 58: RMS Values for the Current

If 25% of the power used to charge the battery is lost to heat, the EV battery would need to charge for longer, effectively increasing the energy needed to charge the EV. If the assumed energy for each battery during normal commute circumstances requires 9600W to charge without charger losses, adding the charger losses would amount to 12000W to charge the battery under normal commute status. Since the charging rate through the charger is fixed, this translates to about 20 additional minutes to charge the car battery, totaling 1 hour and 40 minutes. While the difference may not seem to be much, the overall time expected to reach certain S-curve limits would be shortened. Additionally, if battery storage were considered an option, more storage capacity would need to be considered to accommodate for peak power demand.

Charging the battery for longer periods increases the energy demand, which affects the S-curve limits. Though instantaneous charging does not change, the overlapping of charging vehicles will ultimately draw more power from the distribution system. The results of the modified S-curve analysis are listed below in the Table.

Table 23: Modified Feeder Limit Times per Effects of Harmonics

Curve	*Scenario*	*Subscription Max (Years)*	*Feeder Max (Years)*
Normal	**Realistic**	7.33	12.86
	W/Harmonics	6.9	11.8
Faster	**Realistic**	3.93	6.94
	W/Harmonics	3.5	6.2
Slower	**Realistic**	9.94	18.66
	W/Harmonics	9.3	17

5 Solutions

5.1 Solution 1: Fast Proliferation (Feeder Addition)

The most extreme version of the EV proliferation proposed by this project involves strong motivation to switch from combustion to electric vehicles. This motivation would most likely be a combination of lower cost of operation, lower cost to own, lower cost to insure, changing technology trends, and environmental consciousness. Whatever the reasons may be, the issues posed by the sudden rise of EVs based on the fast proliferation model could cause disruptive failure in the sample distribution system feeder.

As described in Section 5.2.2 in the results, the fast proliferation model approaches the to-date subscription limit in less than 4 years, while the feeder limit may be reached in less than 7. Immediate action would need to take place on the order of restructuring the feeder to accommodate the electrical demands of charging EVs. Since the proliferation affects the feeder at such a rapid rate, modern methods must be used to change the feeder by adding additional capacity. This section proposes to split the feeder area into two separate feeders, thus doubling MVA capacity and mitigating transformer life loss.

One recommendation would be to continue the original feeder transformers to remain on the same side of the split with the same 70:30 loading ratio to continue to prolong the lifespan of the old transformer. Although 50:50 loading proved to provide a vastly superior transformer lifespan, information about the remaining life of the transformers is unavailable. To compensate for age, 70:30 loading was assumed to provide the best overall system life. The figure below displays a mapped plan that suggests how the feeder should be split.

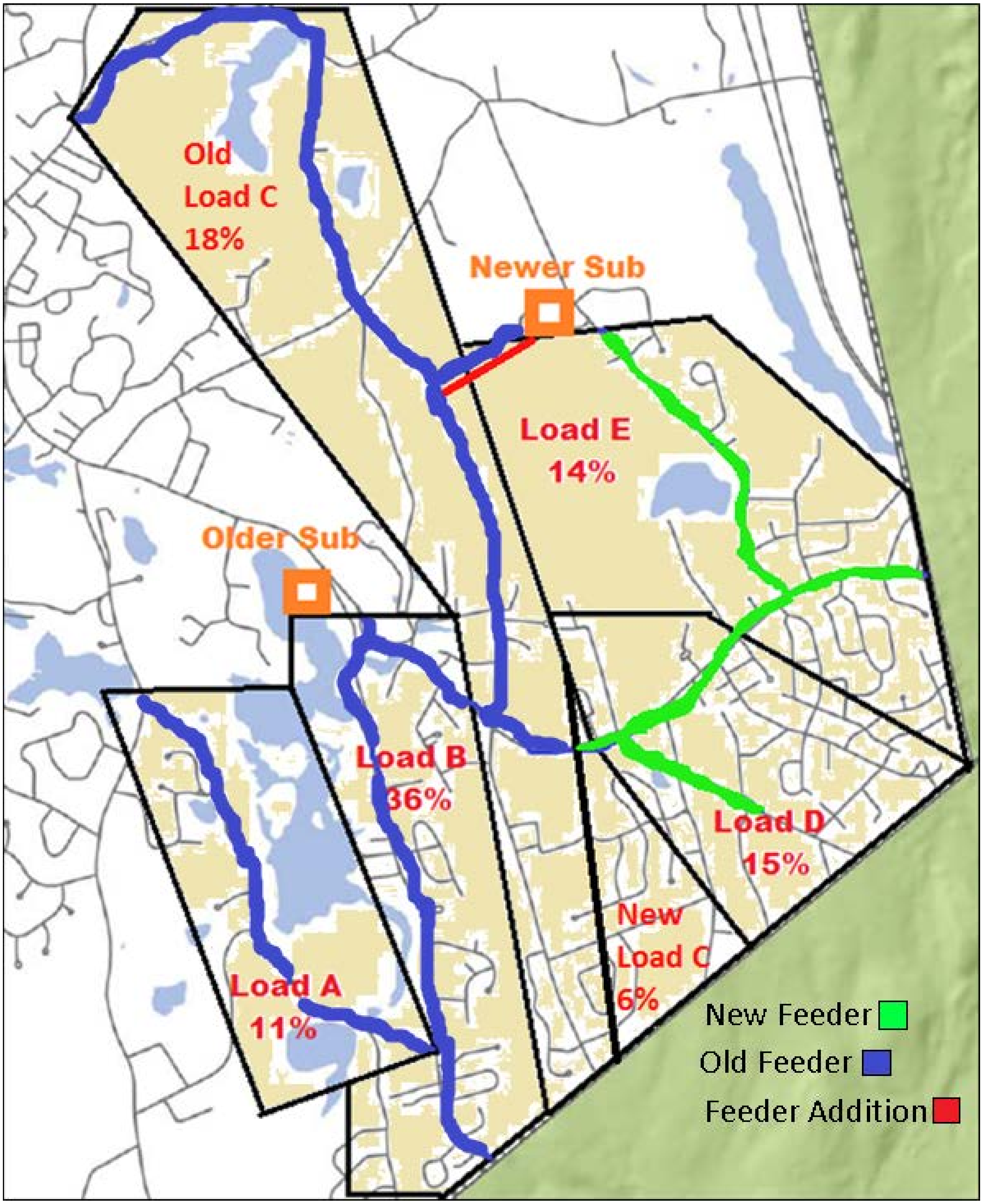

Figure 59: Split Feeder Annotated Map

The figure below describes the split feeder map in one-line diagram format. The figure below further shows a new transformer on the new feeder, while the two original transformers are still together with the same 70:30 split. The feeder split may be described as connecting the new substation to the old C load with a new distribution line that works with the old substation transformer, while a new transformer starts at Line E and continues to a modified C load. The transformer used for the new feeder was chosen to be the same transformer as the original feeder model, making all the transformers identical.

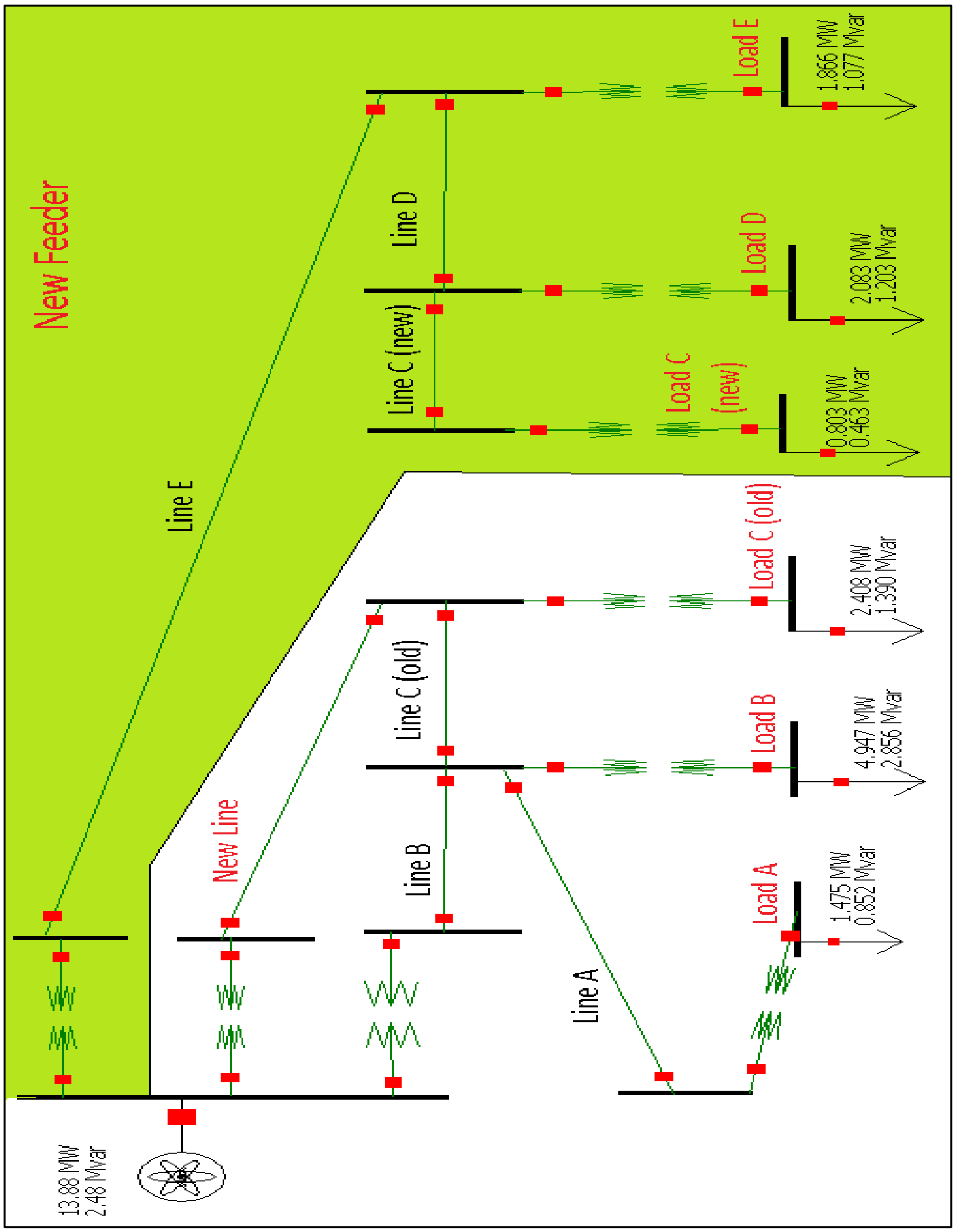

Figure 60: The Original Feeder Split in Two, PowerWorld Sketch

The Tables below list the recommended distribution lines for the split feeder model. The line ‘old C’ describes most of the old feeder C load, ‘new C’ describes the part of the old feeder C load that was split into the new feeder section, and ‘add C’ refers to the new distribution line that must be installed to connect the new substation to the ‘old C’ load. The sizes were chosen based on the highest loading for 100% EV proliferation and in the year 2040. As done in the original feeder model, an attempt was made to turn one of the transformers off on the feeder with the split load to rate the lines for a possible emergency transformer failure scenario; however, the PowerWorld model would not simulate that situation with stability.

Table 24: Split Feeder Line Recommendations

Line	Line Lenth (ft)	Line Length (mi)	Size
A	10000	1.893939394	Sparrow
B	8000	1.515151515	Waxwing
old C	20000	3.787878788	Raven
add C	3000	0.568181818	Waxwing
new C	2000	0.378787879	Turkey
D	8000	1.515151515	Pigeon
E	10000	1.893939394	Merlin

Table 25: Split Feeder ACSR Information

ACSR size	R/1000ft	R/mi	Stranding	Ampacity
Turkey	0.806	4.25568	6 to 1	105
Sparrow	0.332	1.75296	6 to 1	184
Raven	0.217	1.14576	6 to 1	242
Pigeon	0.144	0.76032	6 to 1	315
Waxwing	0.0787	0.415536	18 to 1	449
Merlin	0.0625	0.33	18 to 1	519

The PowerWorld feeder model used for this solution was tuned to maximum loading for the purposes of this paper, with 100% EV proliferation and in the year 2040. As can be seen in Table 26, the voltages for the loads (A, B, C, 16, D, E) with a nominal voltage of 120V sink to the 80V to 90V range, creating a brownout scenario by providing a voltage that is not useable by electronics. Table 27 below shows that after capacitor correction, the nominal voltage of 120V may be restored.

Table 26: Split Feeder Buses and Loading

Bus #	Name	Nom kV	Volt (kV)	Load MW	Load Mvar	Gen MW	Gen Mvar	Description
1	1	69	69			14.3	16.29	
2	2	13.8	10.513					
3	3	13.8	10.625					
4	4	13.8	10.177					
5	5	13.8	10.452					
6	6	13.8	9.504					
7	7	13.8	9.856					
8	8	13.8	9.666					
14	14	13.8	9.366					New C Bus
15	15	13.8	10.169					New Tform
9	A	0.12	0.084	1.48	0.85			A Load
10	B	0.12	0.088	4.95	2.86			B Load
11	C	0.12	0.091	2.41	1.39			old C Load
16	16	0.12	0.081	0.8	0.46			new C Load
12	D	0.12	0.083	2.08	1.2			D Load
13	E	0.12	0.086	1.87	1.08			E Load

Table 27: Split Feeder Buses with Capacitive Collection

Bus #	Name	Nom kV	Volt (kV)	Load MW	Load Mvar	Gen MW	Gen Mvar	Shunts Mvar	Cap Value
1	1	69	69			13.88	2.48		
2	2	13.8	13.566					0.48	2.040E-05
3	3	13.8	13.534					0.48	2.040E-05
4	4	13.8	13.317					2.33	9.903E-05
5	5	13.8	13.52					1.44	6.120E-05
6	6	13.8	13.293					0.93	3.953E-05
7	7	13.8	13.543					0.96	4.080E-05
14	14	13.8	13.194					0.46	1.955E-05
15	15	13.8	13.765					1	4.250E-05
8	8	13.8	12.938					0.88	3.740E-05
9	A	0.12	0.113	1.48	0.85				
10	B	0.12	0.116	4.95	2.86				
11	oldC	0.12	0.118	2.41	1.39				
16	newC	0.12	0.115	0.8	0.46				
12	D	0.12	0.116	2.08	1.2				
13	E	0.12	0.118	1.87	1.08				

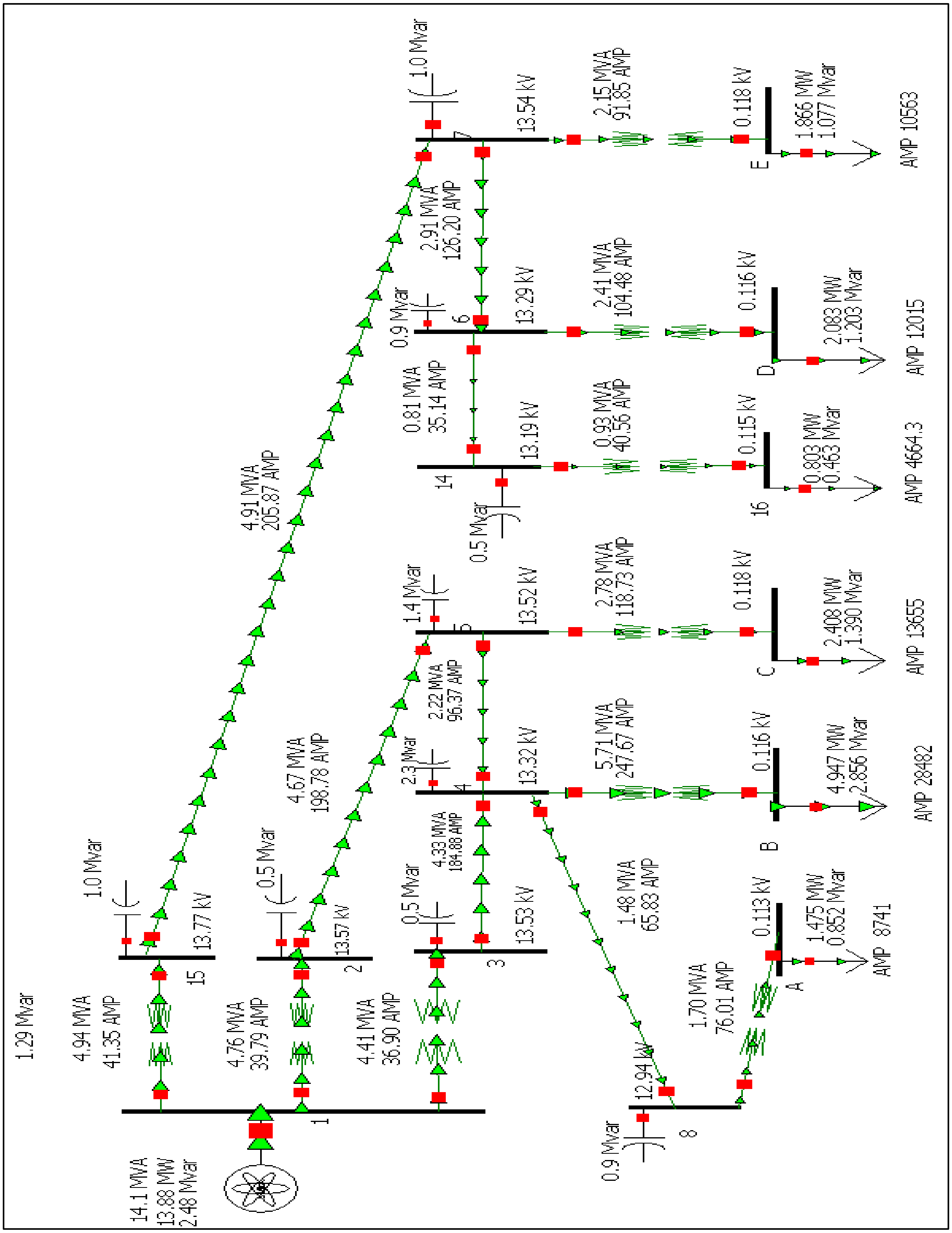

Figure 61: PowerWorld Model Solution for Fast Proliferation

To analyze further, transformer life for the split feeder model may explored in Table 28 and 29 below. Table 28 below describes the new feeder with one transformer on the peak kWh day of 2040. The proposed new feeder was recommended to be 35% of the total load because the transformer life for this peak day extends the transformer life by a factor of 4. The recommendations for the original feeder were to even the load to 50:50 loading to better extend the life of each transformer. The risk presented for the original feeder transformers on the peak kWh day would be more than tolerable, and even more so than the same total load for the transformer on the new feeder shown in Table 29 below.

It must also be noted that these figures include the assumed Pf of .866. With lowered MVA through Pf correction, the loading would be even more tolerable than the results shown below in Tables 28 and 29.

Table 28: Transformer Life for the New Feeder with One Transformer

Peak kWh for 2040, 35% Load (New Feeder)	
FEQA	0.2166
%Loss/day	0.0029
Lifespan (h)	831081
Lifespan (pu)	4.6171

Table 29: Transformer Life for the Original Feeder for Both Transformers

Peak kWh for 2040, 50% of 65% Load	
FEQA	0.0959
%Loss/day	0.0013
Lifespan (h)	1877031
Lifespan (pu)	10.4280

Figure 61 below shows the curve of the hottest spot, which peaks around 112°C. The average temperature would be expected to be much lower, ultimately extending IEEE rated transformer life.

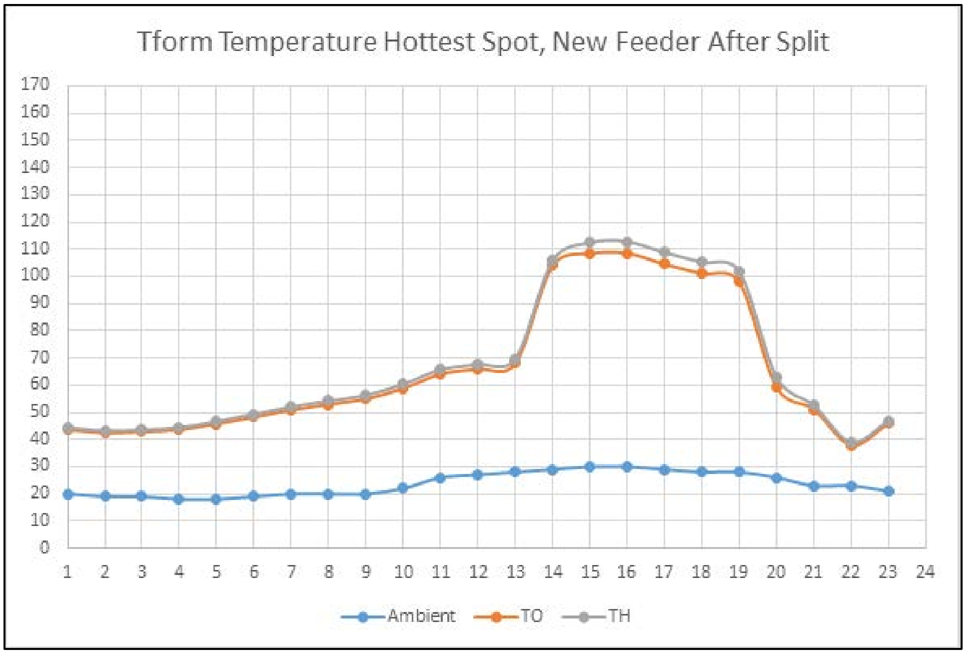

Figure 62: One Transformer, 35% Total Load, 100% Proliferation, 25 Years

In Figure 62 below, the hottest spot temperature does not even reach the 110°C line, which would produce an average much lower than 110°C. This model shows an improvement in IEEE rated transformer life.

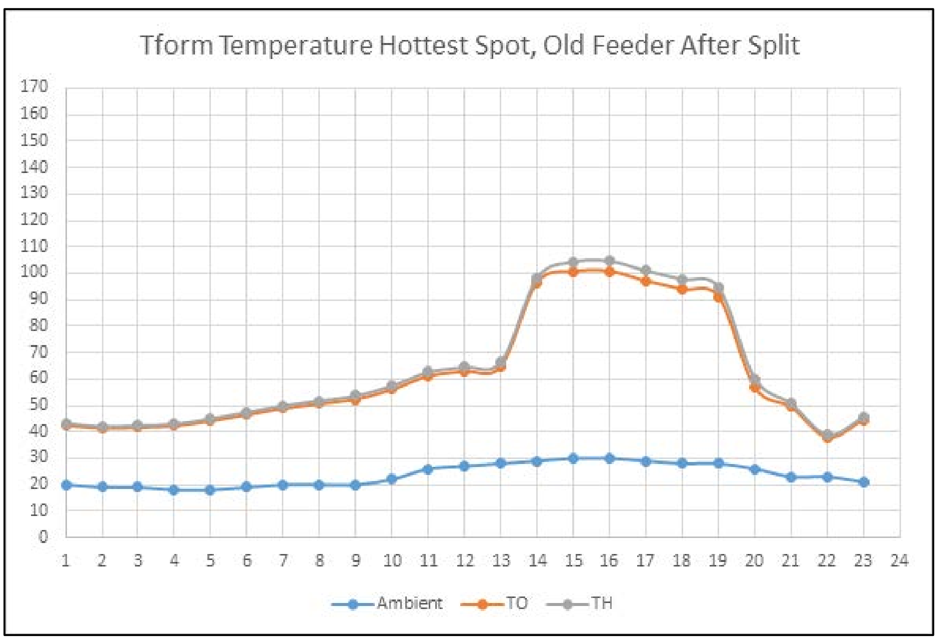

Figure 63: One Transformer, half of 65% Total Load, 100% Proliferation, 25 Years

Table 30 below describes current cost estimates for feeder elements needed to implement the solution for the fast proliferation of EVs.

Table 30: Solution 1 Costs

Solution 1 Costs					
	Base Cost ($)	**Distance (ft.)**	**Net weight (lbs.) per 1000 ft.**	**Total kvar**	**Total Cost ($)**
Line A (Sparrow) [39]	$248/100 lb. (CWT) * [40]	10,000	91.3	N/A	$2,264.24
Line B (Waxwing) [39]	$280/100 lb.	8,000	289.5	N/A	$6,484.80
Line C – Old (Raven) [39]	$235/100 lb.	20,000	145.3	N/A	$6,829.10
Line C – Add (Waxwing) [39]	$280/100 lb.	3000	289.5	N/A	$2,431.80
Line C – New (Turkey) ** [39] [41]	$330/100 lb.	2000	36	N/A	$237.50
Line D (Pigeon) [39]	$229/100 lb.	8,000	230.8	N/A	$4,228.26
Line E (Merlin) [39]	$270/100 lb.	10,000	365.2	N/A	$9,680.40
13.8kV Transformer [42]	$1,000,000	N/A	N/A	N/A	$1,250,000 ***
Capacitors [43]	$10/kvar	N/A	N/A	8,960	$89,600
				Estimated Total Cost:	$1,371,756.10

* CWT (hundredweight) – a unit of measurement for weight equal to 100 lbs.
**Not included in sources; estimated cost based on other ACSR prices
*** Total cost is 25 to 30 percent higher (includes taxes, transportation, special features and testing, etc.)

In the event that the feeder upgrades would include the added elements from Table 30, a financing option may be considered including investor payback and other taxes. For the purpose of adding labor costs in a simplified way, the Estimated Total Cost listed in Table 30 shall be rounded to $2M. Using the CRF referenced in section 2.8, using an aggregate interest rate of 17% for the FCR, and assuming a 20 year payback period, the AFC would be:

$$AFC = \$2{,}000{,}000 \times 17\% = \$\mathbf{340{,}000/yr}$$

The utility would have to decide whether or not paying the AFC listed above would be an affordable option, or whether another solution would be in their best interests.

The Figures below describe the changes to the feeder limit due to the solution proposed to split the feeder in two. The first Figure shows the older feeder with two transformers for the 25 years tested from 2015 to 2040, and the second Figure shows the newer feeder with one transformer for the same time period. The figures show that the feeder limit would not be reached in the 25 year span simulated in this paper, proving the proposed solution would support the proliferation of EVs in the area of this feeder.

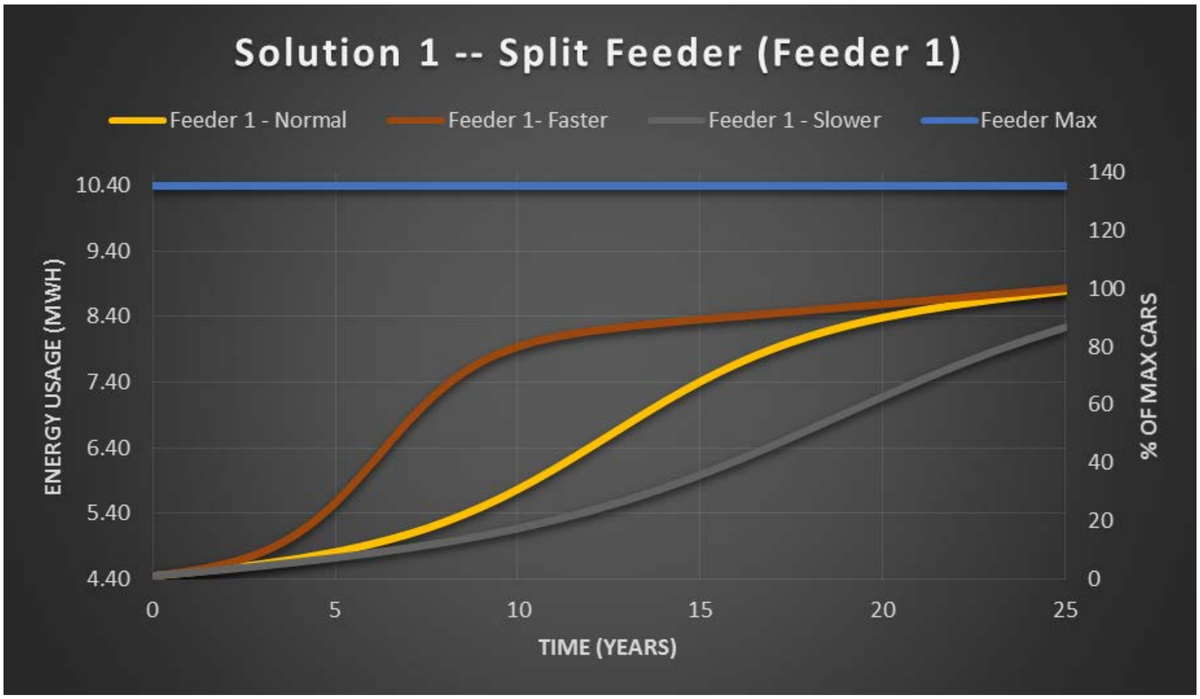

Figure 64: Solution 1 – Older Feeder S-curve with Feeder Maximum After Splitting

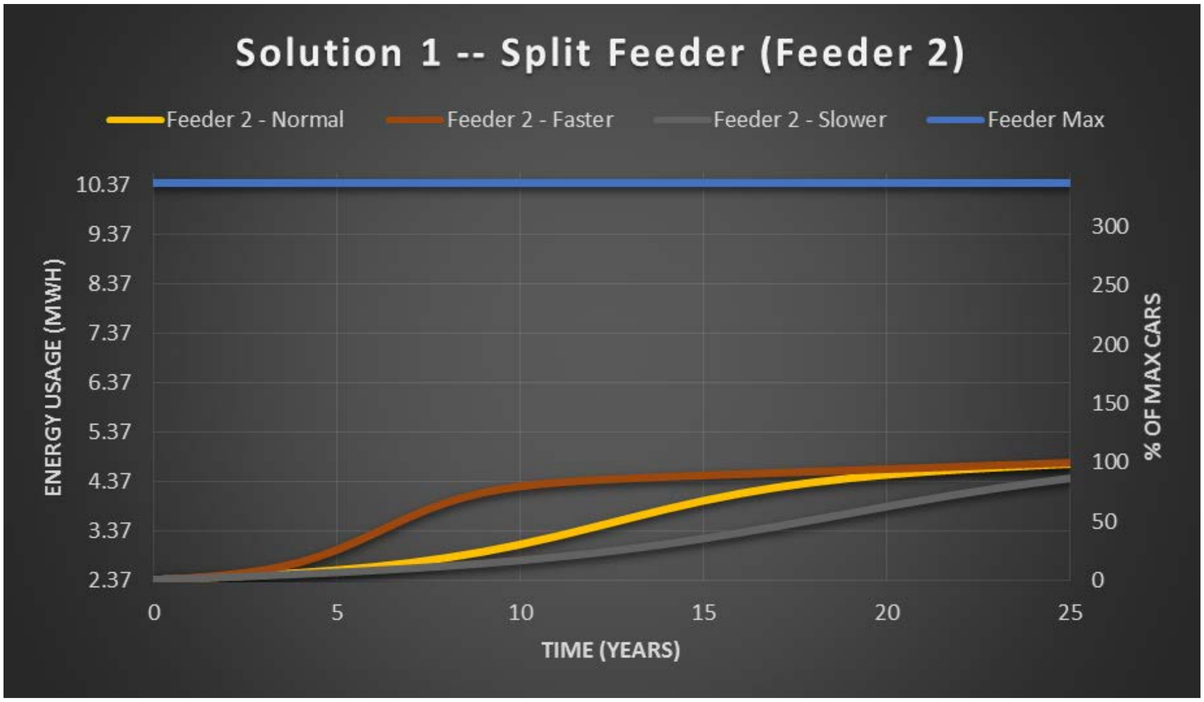

Figure 65: Solution 1 – New Feeder S-curve with Feeder Maximum After Splitting

As a closing statement to the recommended solution for the fast proliferation of EVs, splitting the feeder would be an option worth considering due to the additional life it may lend to the original substation transformers. Splitting the feeder also allows for further upgrading as time goes on, while accommodating for new growth in the area of the feeder. By splitting the feeder in two, ample amounts of time would be available to deliberate future upgrades, and perhaps wait for a less expensive and longer-term solution to future problems. The amount of material to build this project would be extensive when considering upgrading most of the distribution lines with larger and more expensive distribution conductors, and also installing another transformer to accommodate its own feeder. Though requiring lots of money, there is little risk in improving on an already working system with proven technology and electric distribution methods, providing a safe and long-term solution for the fast proliferation of EVs.

5.2 Solution 2: Normal Proliferation (Feeder Storage – Battery)

Currently all large-sized grid-connected batteries are in the demonstration stage to prove the feasibility of such batteries in energy time shifting, load leveling, system reliability, etc. These projects range in size from less than 5kW, 9kWh to over 8MW, 32MWh of power and energy density. The applications and power/energy densities of these installations are similar to those we encounter in our project problem. Earlier installations have shown validation in these applications for this technology, which is promising for the acceptance of lithium-ion batteries to be used in large-scale grid operations as the technology develops and the cost decreases.

Through research and analysis of the power draw and energy consumption during peak hours, we concluded that we must displace 38MWh each day in order to shift the feeder load to off-peak hours. The effective lifespan of a lithium ion battery is based on the depth of discharge; the deeper the depth of discharge of this type of battery, the shorter the effective lifespan of the battery. The lifespan, however, is also dependent on the age of the battery regardless of how often it is used or how deep it is repeatedly discharge. Lithium ion batteries are currently no longer effective for grid storage applications after approximately ten years. Our research indicates that a depth of discharge of 75% corresponds to about 4000 battery cycles. Assuming the battery will be cycled every day for ten years, the battery will need to undergo 3650 cycles throughout its lifetime, meaning a depth of discharge of 75% is appropriate for this application. Furthermore, lithium ion batteries have an average efficiency of 90%. Given an approximate round-trip efficiency of 81% and a depth of discharge of 75%, the amount of energy storage needed to displace 38MWh each day is approximately 63 MWh.

Both feeder and micro-grid solutions were designed to adequately shift the feeder load from peak hours to off-peak hours. Both solutions take into account the 63MWh that needs to be displaced, the current maximum energy capacity for lithium ion batteries of 24 MWh and the current maximum discharge time of approximately four hours. The computation for each solution can be found in Appendix 8.6.

The feeder solution would be a central location that serves the entire feeder. Using our example feeder provided by Holden, it would require three batteries connected in parallel. Each battery would need a minimum of 19 MWh storage to cover both the 10% loss in power due to efficiency and the 25% of capacity remaining in the battery to maintain lifetime. Each battery would provide approximately 5.43 MW for 2.333 hours, operating one at a time and switching to one not currently in operation as one in operation approaches the depth of discharge limit.

Table 31below summarizes the pertinent qualities for the feeder storage solution.

Table 31: Feeder Storage Solution

Feeder Storage	
Total unit capacity needed	63 MWh
Number of batteries per unit	3 Batteries
Discharge time per battery	2.333 Hours
Total power from unit	6.70 MW
Useful power from unit	5.43 MW
Power losses	1.27 MW
Total energy in each battery	21 MWh
Revolving energy in each battery	15.75 MWh
Size of unit	5544 ft^3
Weight of unit	930510 lbs.

In the event of battery failure such that the battery must be disconnected from the feeder, we must ensure that the overhead lines will have the ampacity needed to support the load without further failure. The PowerWorld models below show the feeder power and amp ratings while the battery is disconnected and while the battery is connected and discharging. The loads reflect estimated loads experienced for each section in the year 2040 with each household charging two electric vehicles simultaneously and each house drawing approximately 38 A.

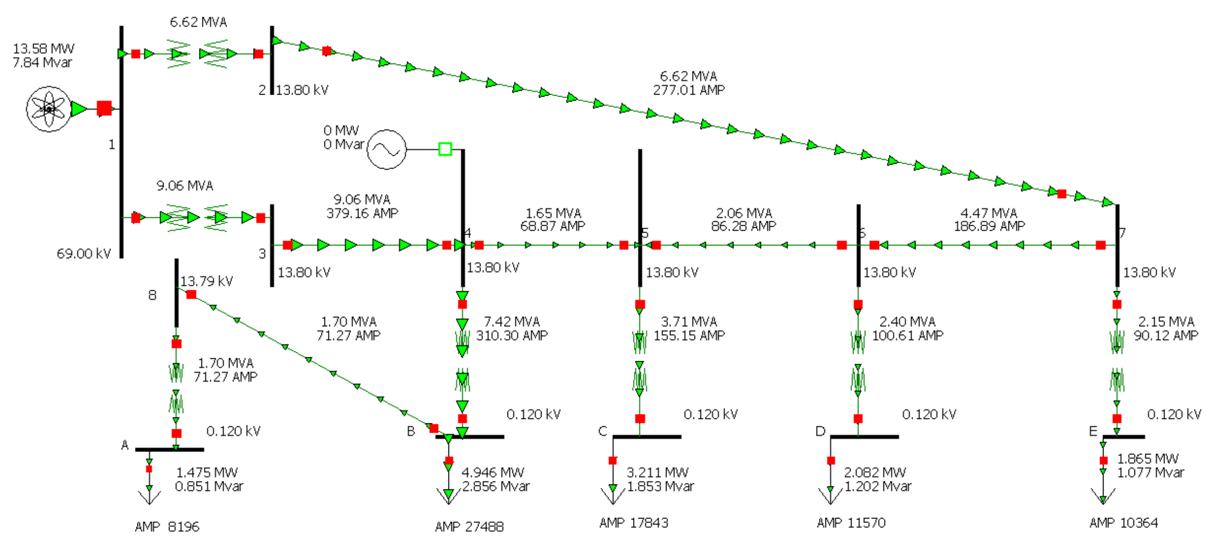

Figure 66: PowerWorld model – Peak Power Demand with the Feeder Battery Disconnected

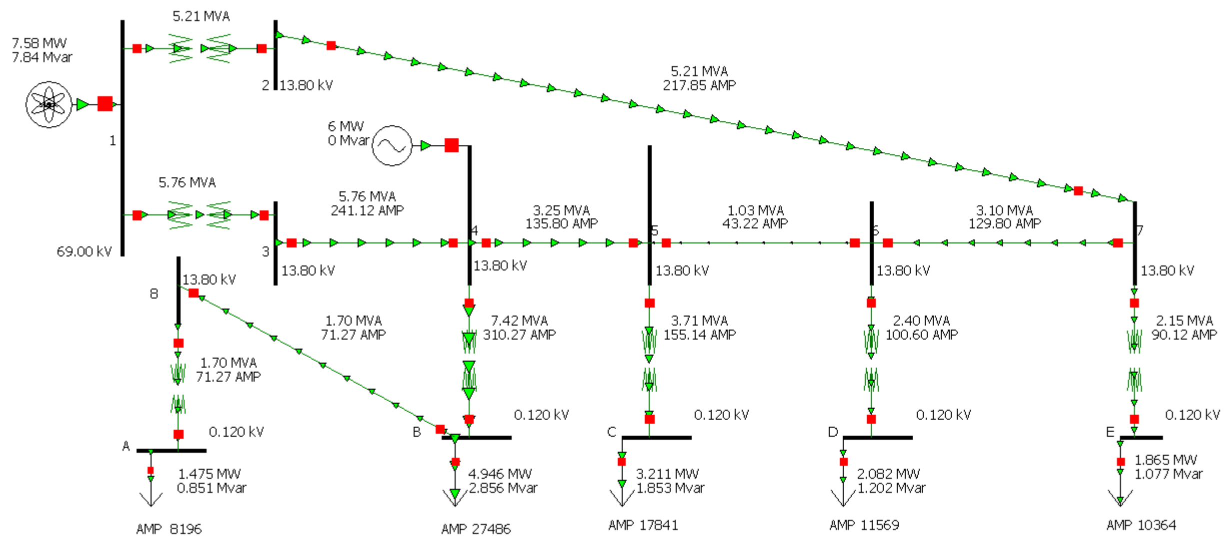

Figure 67: PowerWorld model – Peak Power Demand with the Feeder Battery Connected

Comparing the amp ratings in the results above with those estimated to be currently installed on the line, which is found in Tables 6 and 7 in Section 2.6 of this report, we found that the only line that would need to be replaced is the line on feeder section B. The current cable size of Waxwing has an ampacity of approximately 449 A. The cable size Oriole has an ampacity of 535A, which is a close approximation to the peak current draw on section B of 379.2 A times the safety factor of 1.5 [41].

In order to ensure that the feeder lines and transformers do not experience premature failure do to overloading, the battery must supply the feeder customers using a dedicated feeder that runs in parallel with the current feeder. From the results above the line sizes currently in use are appropriate for this application.

Figure 68 below shows the S-curve EV proliferation after the implementation of the feeder storage solution. It can be seen that the feeder storage solution may accommodate up to 600% proliferation before reaching the feeder maximum of 12MVA, proving the viability of the storage feeder solution.

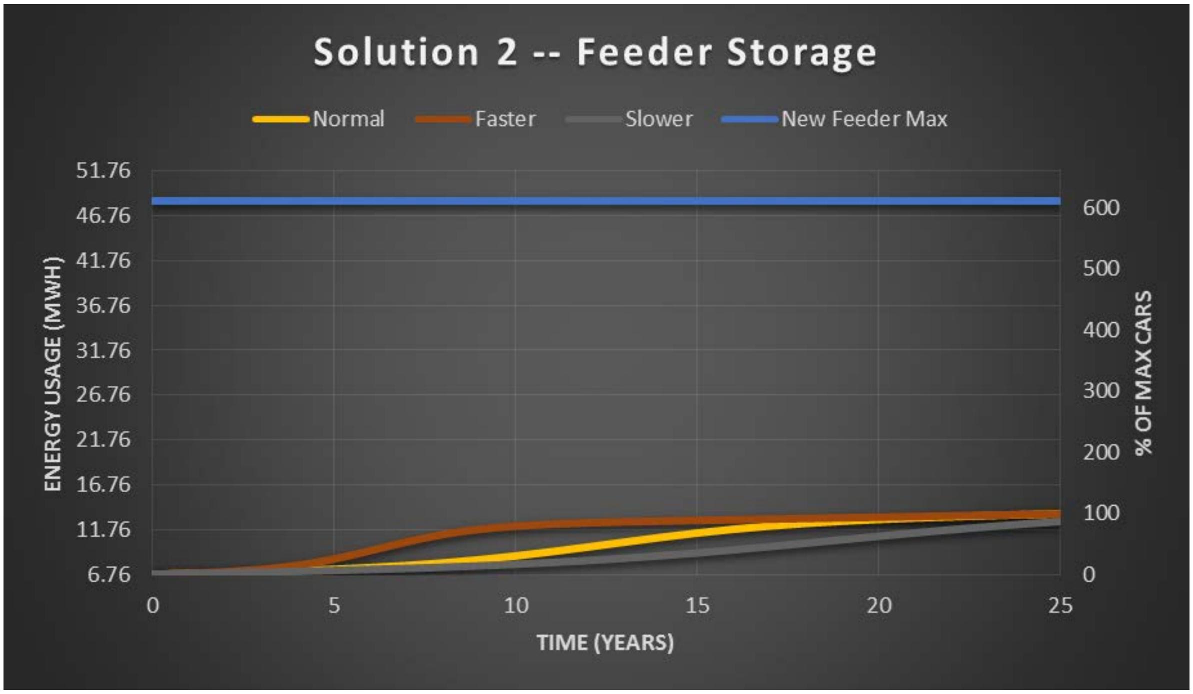

Figure 68: Solution 2 – Feeder Storage

5.3 Solution 3: Slow Proliferation (Micro-Grid)

The micro-grid solution requires smaller battery units that serve roughly ten houses each. Using our example feeder, which serves approximately 2000 houses, the feeder would require 200 battery units, each composed of two batteries connected in parallel. Each battery would need a minimum of 157.5 kWh storage to cover both the 19% round trip loss in power due to a 90% efficiency and the 25% of capacity remaining in the battery to maintain lifetime. Each battery would provide approximately 27.14 kW for 3.5 hours, operating one at a time and switching as with the feeder solution. Table 32 below details the specifications for the micro-grid storage solution.

Table 32: Micro-Grid Storage Solution

Micro-Grid Storage	
Battery units needed per 10 houses per feeder	200 units
Number of batteries per unit	2 Batteries
Total unit capacity needed	315 kWh
Discharge time per battery	3.5 Hours
Total power from unit	33.51 kW
Useful power from unit	27.14 kW
Power losses	6.367 KW
Total energy in each battery	157.5 kWh
Revolving energy in each battery	118.125 kWh
Size of unit	27.72 ft^3
Weight of unit	4662 lbs.

A major concern regarding the micro-grid solution is the effects on increased current draw on the overhead lines. A current that is higher than the rated ampacity can cause the lines to heat and physically sag, posing a hazard for high clearance vehicles and bystanders if the lines should fail completely. A micro-grid battery placed on the lines after the 120V pole transformer adds more current to the lines, both while charging and discharging. The required ampacity will fluctuate depending on the time of day but will generally increase due to both the annual increase in electrical energy consumption and the proliferation and acceptance of electrical vehicle.

A series of simulations were created and analyzed using Multisim to test the effects of a charging and discharging micro-grid battery at peak and off-peak energy consumption. The battery is connected in parallel between a 120 V pole transformer and ten houses, each with two electric vehicles. The purposes of our analysis is to see how much current draw the overhead can support, which is represented by battery in charging phase as well as the number of EVs connected to the same transformer at the same time. From this we can see what the worst-case scenario current draw would be both present day and in 2040 and how much ampacity the overhead lines would need in order to support complete EV saturation.

The transformer was modeled as a 120 V_{rms} AC source, each house and car was modeled as a 30 A current source flowing to ground to simulate the current draw from the grid, and the battery was modeled as a 305 A_{rms} current source during the discharge phase and a 3.544Ω resistor during the charge phase to model the instantaneous power draw 36.6 kW of if the battery were to be charged for nine continuous hours. Each car is connected to a switch to simulate the car being connected or disconnected to the grid. The following figures display the resultant simulations.

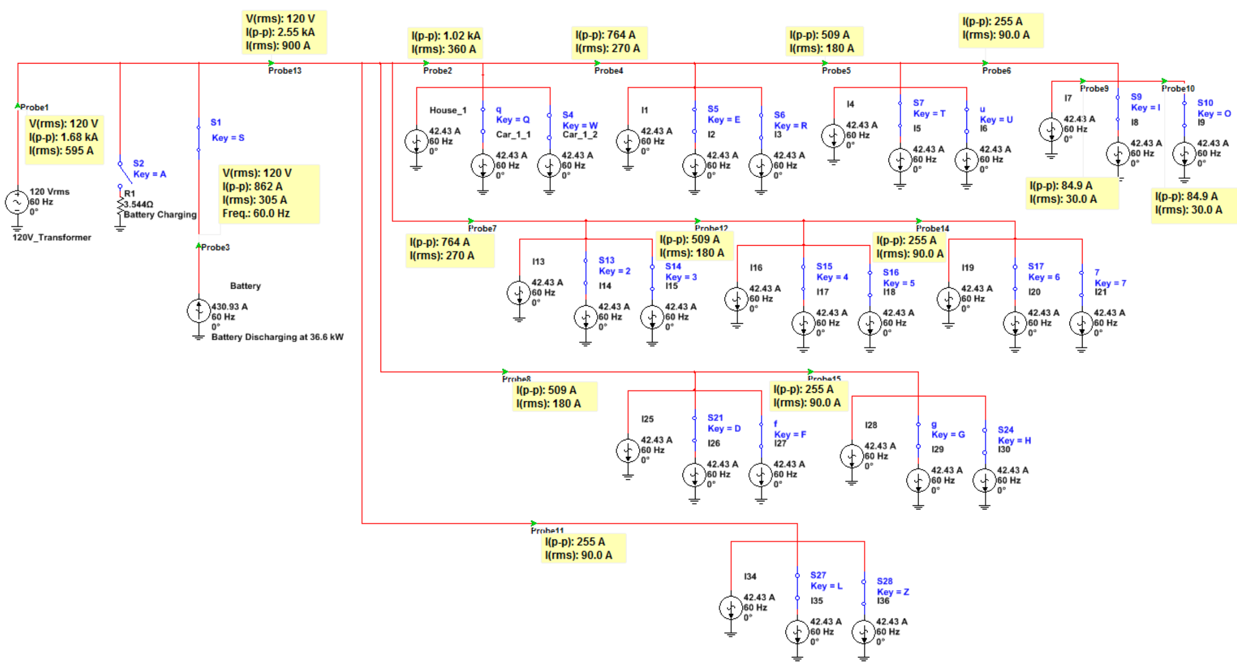

Figure 69: All cars charging at peak current draw, battery discharging

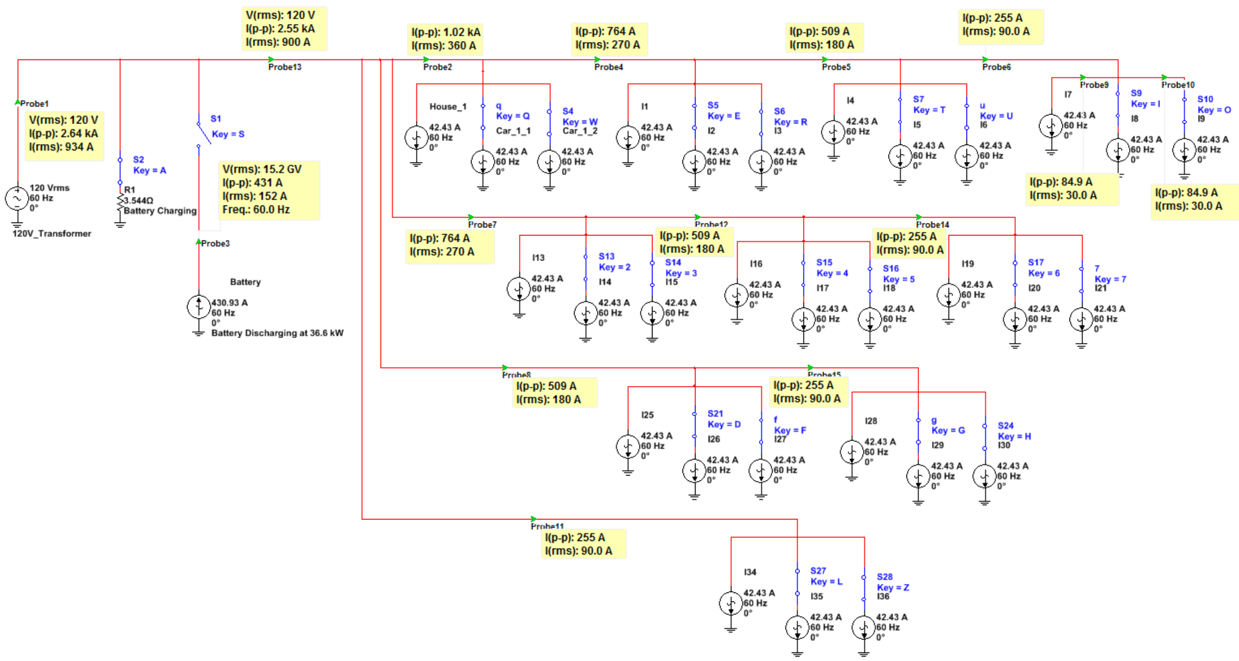

Figure 70: All cars charging at peak current draw, battery charging

These model results show that a transformer supporting ten houses, each charging two electric vehicles simultaneously, has a current draw of 900 A after the battery. When discharging, the battery supplies a current of 305 A to decrease the demand on the transformer. While charging, the battery draws a current of approximately 34 A in order to charge the battery over a nine hour period.

Our assumption on present-day power demand estimates that the typical house at peak hours draws a peak current of 30 A at once, meaning each transformer line supports approximately 300 A at once. In order to maintain line life, we set a cautionary limit of 350 A drawn from the line and saw how many cars could charge in this scenario. The following figures display our results.

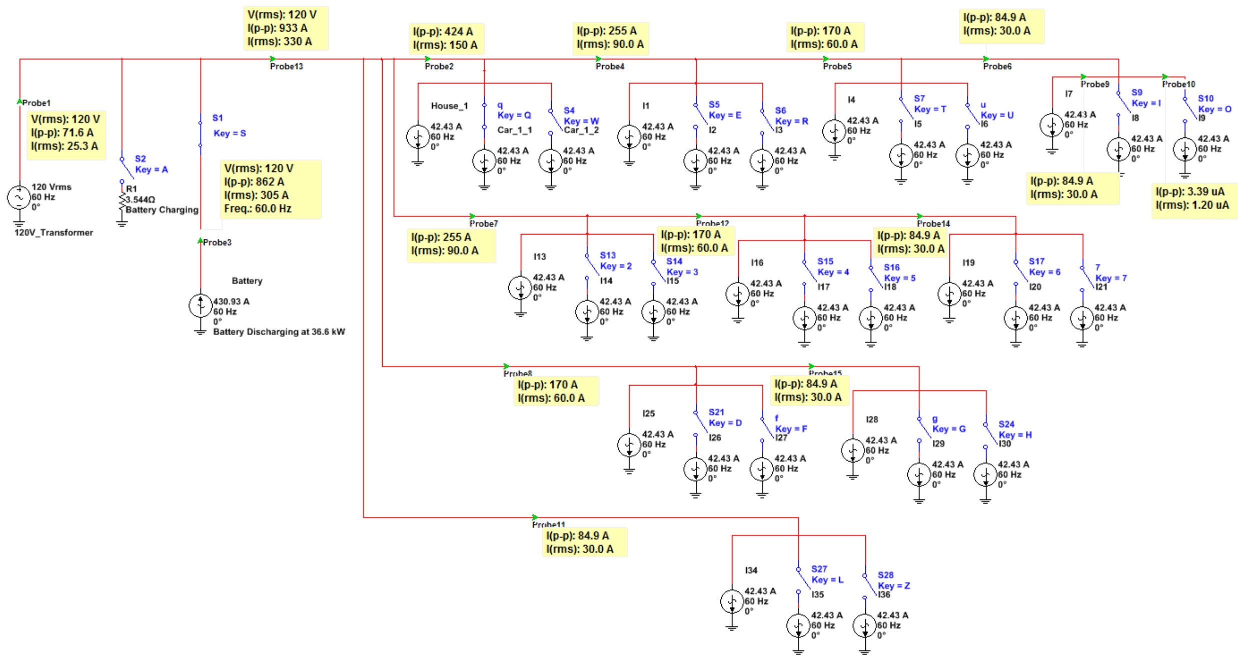

Figure 71: One car charging at peak current draw, battery charging

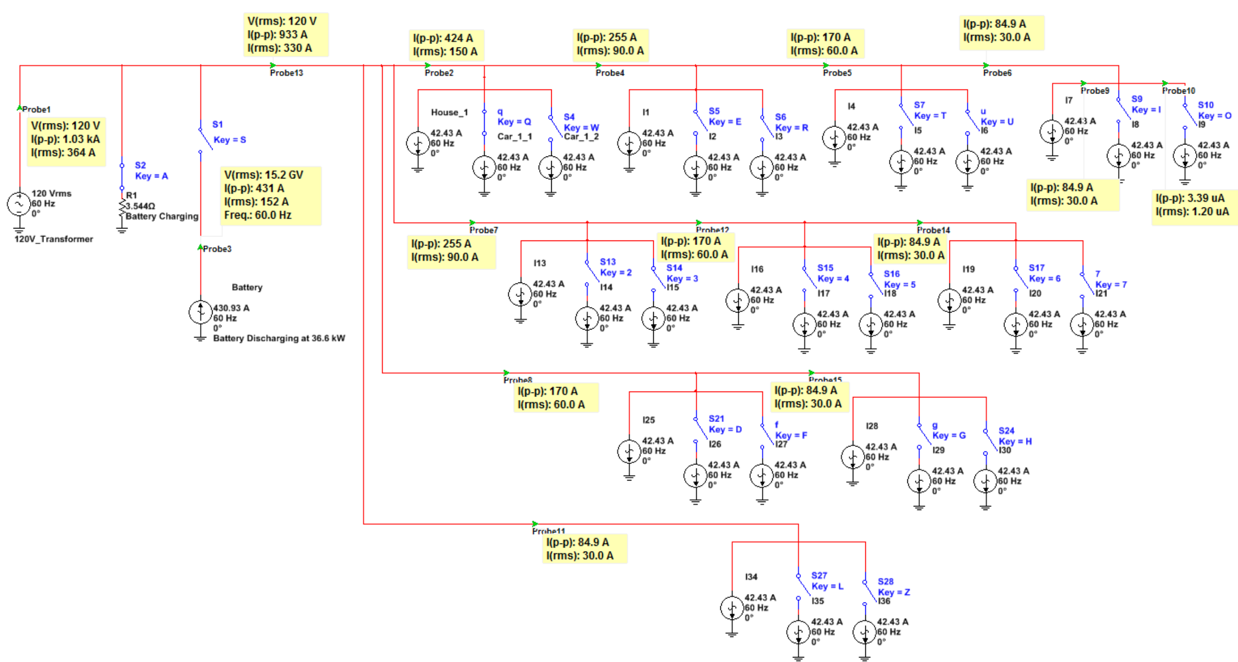

Figure 72: One car charging at peak current draw, battery discharging

The simulations show that the line after the battery can support no more than one car charging out of twenty during peak hours. While the battery is discharging, the transformer needs to supply only 25.3 A to keep up with demand. While the battery is charging, however, the transformer must supply 364 A. From these results we can conclude that no more than one car may charge at a time during peak household consumption hours and only while the battery is discharging.

The following two figures shows the results of the same simulation during a low household power consumption. Each house is modeled now as a 10 A current draw.

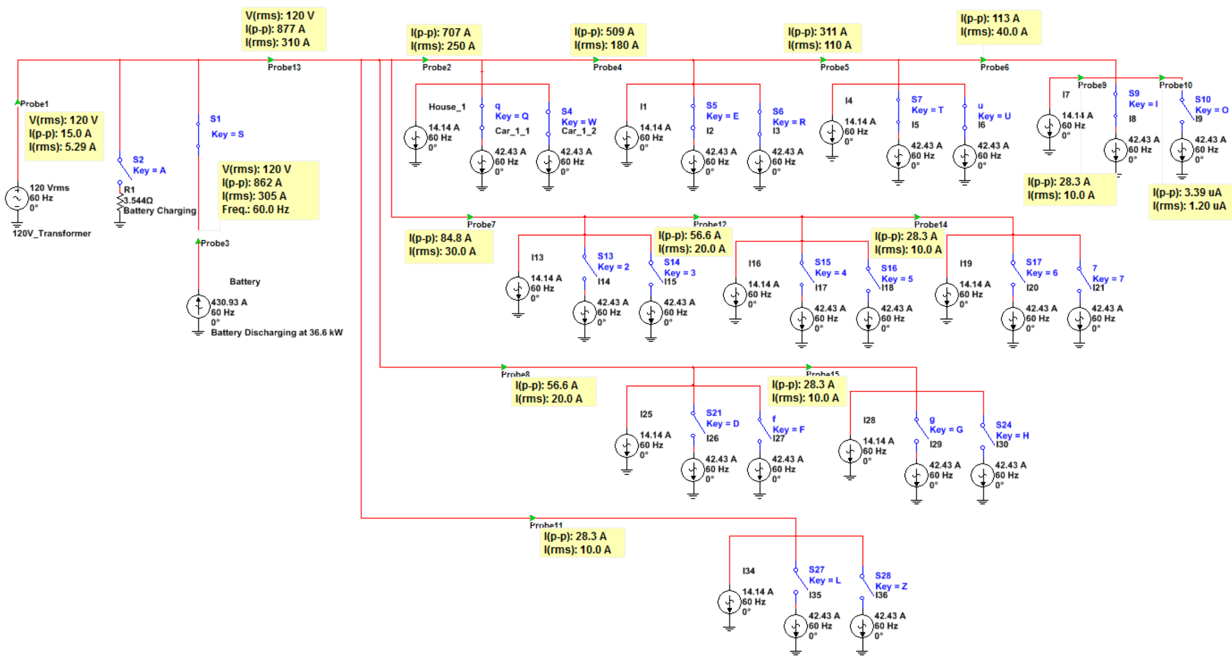

Figure 73: Seven cars charging at 10 A house current draw, battery discharging

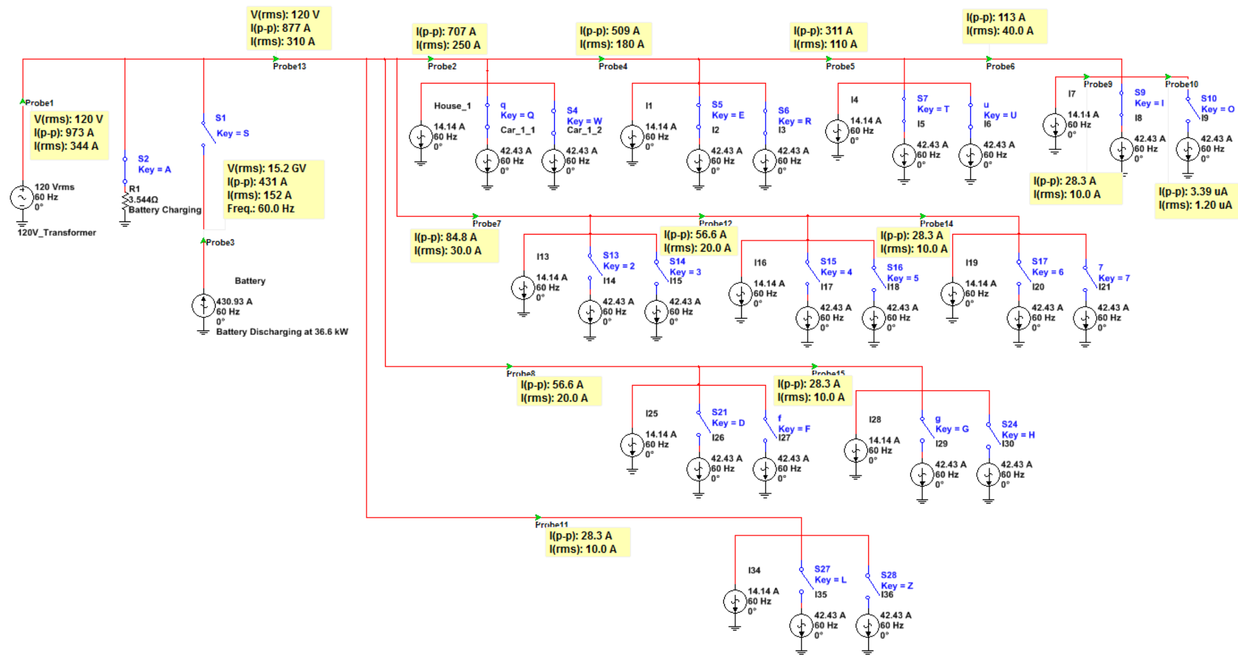

Figure 74: Seven cars charging at 10 A house current draw, battery charging

Under these conditions, the line after the battery can safely support seven cars charging simultaneously, supplying 310 A to the customers. While the battery is charging, the transformer must supply only 5.29 A to keep up with demand. While the battery is charging, the transformer must supply 344A, which is only slightly under our cautionary limit of 350 A.

In order to design this system so that it can support a worst-case scenario at the year 2040, we calculated the projected household current draw based on the 0.9% annual increase in energy consumption. The projected current draw was found using the following equation:

Equation 10: Projected peak current draw in year 2040

$$I \ = 30 * 1.009^{25}$$

where

I = the projected peak current draw for a home in 2040

The projected current peak current draw in 2040 is calculated to be 37.53 A $_{rms}$. Supporting a twenty car simultaneously charging during peak hours requires a line with an ampacity that can support approximately 100 A per connected house as well as the current needed to charge the battery. Assuming a battery that is charging over nine hours and drawing 34 A at any given time, the new transformer line must have an ampacity of at least 1034 A.

We consulted the standard American ACSR conductors to find the appropriate lines available that could support this magnitude of current.

ALUMINIUM CONDUCTORS STEEL REINFORCED **ACSR**

ASTM B 232/B 232M **TABLE 8 (contd.)** **AMERICAN SIZES**

Code Name	Nominal Area			No./Nominal diameter of wires		Approximate Overall Diameter	Approximate Weight	Nominal Breaking Load	Nominal DC Resistance at 20° C	Current Rating (*)
	Aluminium	Steel	Total	Aluminium	Steel					
	mm2	mm2	mm2	No./mm	No./mm	mm	kg/km	KN	ohm/km	A
Ruddy	455.50	31.67	487.17	45/3.59	7/2.40	28.74	1507.3	104.53	0.0634	656
Canary	456.28	59.15	515.43	54/3.28	7/3.28	29.52	1723.1	134.33	0.0633	660
Catbird	484.61	13.46	498.07	36/4.14	1/4.14	28.98	1434.4	86.74	0.0593	679
Rail	483.84	33.54	517.38	45/3.70	7/2.47	29.61	1598.1	110.76	0.0597	680
Cardinal	484.53	62.81	547.34	54/3.38	7/3.38	30.42	1825.9	142.34	0.0596	685
Tanager	522.79	14.52	537.31	36/4.30	1/4.30	30.10	1553.5	93.85	0.0550	710
Orotlan	523.87	36.31	560.18	45/3.85	7/2.57	30.81	1730.5	118.32	0.0551	713
Curlew	522.51	67.73	590.24	54/3.51	7/3.51	31.59	1977.6	153.90	0.0553	716
Bluejay	565.49	38.90	604.39	45/4.00	7/2.66	31.98	1866.0	127.66	0.0511	745
Finch $	565.03	71.57	636.60	54/3.65	19/2.19	32.85	2127.8	164.58	0.0514	748
Bunting	605.76	41.88	647.64	45/4.14	7/2.76	33.12	1996.9	136.55	0.0477	776
Grackle $	602.79	76.89	679.68	54/3.77	19/2.27	33.97	2278.1	176.59	0.0481	777
Skylark	646.02	17.95	663.97	36/4.78	1/4.78	33.46	1913.6	115.65	0.0445	804
Bittern	644.40	44.66	689.06	45/4.27	7/2.85	34.17	2130.8	145.89	0.0448	805
Pheasant $	645.08	81.71	726.79	54/3.90	19/2.34	35.10	2431.4	183.26	0.0450	808
Dipper	684.24	47.20	731.44	45/4.40	7/2.93	35.19	2263.2	154.79	0.0422	834
Martin $	685.39	86.67	772.06	54/4.02	19/2.41	36.17	2581.7	194.82	0.0423	838
Bobolink	725.27	50.14	775.41	45/4.53	7/3.02	36.24	2397.2	164.13	0.0398	862
Plover $	726.92	91.78	818.70	54/4.14	19/2.48	37.24	2734.9	206.39	0.0399	866
Nuthatch	764.20	52.83	817.03	45/4.65	7/3.10	37.20	2529.6	171.25	0.0378	888
Parrot $	766.06	97.03	863.09	54/4.25	19/2.55	38.25	2883.7	217.51	0.0379	892
Lapwing	807.53	55.60	863.13	45/4.78	7/3.18	38.22	2663.5	180.14	0.0358	916
Falcon $	806.23	102.43	908.66	54/4.36	19/2.62	39.26	3038.5	229.52	0.0360	919
Chukar $	903.18	73.54	976.72	84/3.70	19/2.22	40.70	3083.1	217.51	0.0321	976
Bluebird $	1092.84	88.84	1181.68	84/4.07	19/2.44	44.76	3731.9	256.65	0.0266	1083
Kiwi $	1099.76	47.52	1147.28	72/4.41	7/2.94	44.10	3423.9	215.28	0.0264	1083
Thrasher $	1171.42	63.94	1235.36	76/4.43	19/2.07	45.79	3754.2	243.75	0.0248	1122

Figure 75: Standard American ACSR Sizes and specifications. [68]

The three standard ACSR sizes that could potentially support this current draw are the Bluebird and Kiwi, each with an ampacity of 1083 A, and the Thrasher which has an ampacity of 1122 A.

Figure 76 below shows the S-curve for EV proliferation after the implementation of the micro-grid storage solution. This figure resembles Figure 68 in the previous section. It can be seen that the micro-grid solution can accommodate for about 600% EV proliferation before reaching the feeder maximum of 12MVA, proving the validity of this solution.

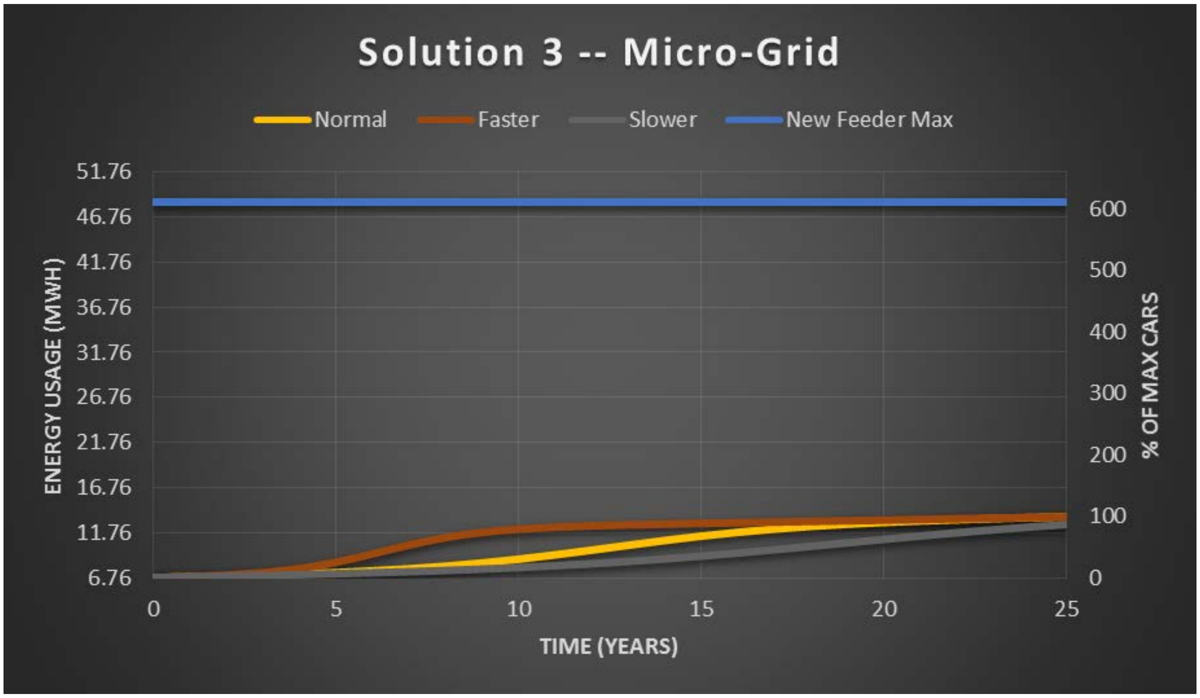

Figure 76: Solution 3 – Micro-Grid

5.4 Predicted Costs of Implementation (Solutions 2 and 3)

The main expense in either of these two solutions is that of the energy storage. While considerations such as building and installation costs must be taken to account in the actual construction of the battery units, the variable that is most pertinent to affordability is the cost of storage per kilowatt-hour. The price per kilowatt hour for lithium ion battery has decreased exponentially over the past decade and is projected to continue as companies continue to research and develop more efficient and energy dense batteries for usage in consumer electronics. A decrease in cost is also essential for the commercialization and acceptance of electric vehicles, which depend on a less expensive, more energy dense battery to lower the overall consumer cost. For this reason, the cost of energy storage for each solution is dependent on the date at which contracting and construction would take place.

In order to calculate when the battery storage would have to be installed to achieve reliable load leveling we calculated the projected electrical energy consumption on the example feeder provided. This calculation takes into account the projected increase in consumption of 0.9% per year, the increase of consumption due to the acceptance of electrical vehicles between 2015 and 2040, and the approximated subscribed power limit on our example feeder. These assumptions were also used in calculating the total energy consumption based both the summer average energy consumption and the maximum energy consumption derived from the day in the data set that experienced the most energy usage. The calculations were performed in Excel using the normal, fast, and slow acceptance rates with projected EV saturation midpoints at 12.5 years, 6.25 years, and 18.75 years, respectively. Table 32 below lists the years at which the feeder would reach the subscribed power limit and would therefore require battery installation to handle reliable EV charging as well as the cost of lithium ion battery storage per kilowatt-hour. Table 33 below shows the same information but for the Feeder Max.

Table 33: Subscription Max

Subscription Max		
Proliferation Rate	**Year**	**Cost/kWh**
Normal	2021	$240
Faster	2018	$290
Slower	2024	$210

Table 34: Feeder Max

Feeder Max		
Proliferation Rate	**Year**	**Cost/kWh**
Normal	2027	$180
Faster	2021	$240
Slower	2033	$115

To estimate the cost of the feeder storage solution, it is necessary to price out both limits we are trying to mitigate, Subscription and Feeder Max. These occur at 7.33 and 12.86 years respectively. Since it will take time to install the batteries, the price per kWh will be chosen a year in advance of when the solution is needed. The first price estimate will be to avoid the Subscription Max. In 2021, the average cost per kWh will be approximately $240/kWh. Since the batteries must be a total of 63MWh, this will cost $15,120,000 in 2014 US Dollars. The second price estimate is to avoid the feeder limit of 12 MVA. In 2027, the average cost per kWh will be approximately $180/kWh. The price of these batteries will be $11,340,000 in 2014 US Dollars. Although this does not take into account the cost to build a structure to house the batteries or connect them to the grid, these costs are small compared to the cost of the batteries. A building that is 8 feet tall (an average floor height) would require the area of the building to be 627 square feet. The size of this structure is smaller than a house and doesn't have the same requirements, such as plumbing and sewer. Unfortunately, the price of building materials and labor varies too greatly with the general economy. This greatly increases the range of possible costs, all of which are still magnitudes lower than the batteries. Table 34 below lists the cost estimation for creating the feeder battery solution if purchased at the subscription max and the feeder max.

Table 35: Lithium Ion Feeder Storage Cost Estimation per kWh using Normal Proliferation Rate

Lithium Ion Storage Feeder Cost Estimation per kWh using Normal Proliferation Rate		
	Subscription Max	**Feeder Max**
Cost per battery	$5,040,000	$3,478,000
Total cost of solution	$15,120,000	$11,340,000

Table 36 below describes current cost estimates for feeder elements needed to implement the solution for the normal proliferation of EVs.

Table 36: Solution 2 Cost

Solution 2 Line Costs					
	Base Cost ($)	**Distance (ft.)**	**Net weight (lbs.) per 1000 ft.**	**Total kvar**	**Total Cost ($)**
Line A (Sparrow) [39]	$248/100 lb. (CWT) * [40]	20,000	91.3	N/A	$4,528.48
Line B – New (Oriole) [39]	$247/100 lb.	16,000	527.1	N/A	$20,830.99
Line C (Raven) [39]	$235/100 lb.	40,000	145.3	N/A	$13,658.20
Line D (Penguin) [39]	$229/100 lb.	16,000	230.8	N/A	$8,456.52
Line E (Waxwing) [39]	$270/100 lb.	20,000	365.2	N/A	$19,760.80
13.8kV Transformer & AC/DC Inverter System [42]	$1,000,000	N/A	N/A	N/A	$1,250,000 **
Capacitors [43]	$10/kvar	N/A	N/A	8,960	$89,600
				Estimated Total Cost:	$ 1,447,586.99

* CWT (hundredweight) – a unit of measurement for weight equal to 100 lbs.
** Total cost is 25 to 30 percent higher (includes taxes, transportation, special features and testing, etc.)

As well as the solution for fast proliferation, a financing option may be considered including investor payback and other taxes. For the purpose of adding labor costs in a simplified way, the Estimated Total Cost listed in Table 35 shall be rounded to $2M. Using the CRF referenced in section 2.8, using an aggregate interest rate of 17% for the FCR, and assuming a 20 year payback period, the AFCs for construction and installation to meet subscription max and feeder max would be:

$$\boldsymbol{Subscription\ Max}\ AFC = (\$2{,}000{,}000 + \$15{,}120{,}000)\ \times\ 17\% = \$\mathbf{2,910,400}/\boldsymbol{yr}$$

$$\boldsymbol{Feeder\ Max}\ AFC = (\$2{,}000{,}000 +\ \$11{,}340{,}000)\ \times\ 17\% = \$\mathbf{2,267,800}/\boldsymbol{yr}$$

These price projections are made in 2014 dollars. Future fluctuations or fruitions in the United States and global economies and faster or slower advancement in battery technology may cause discrepancies from these projections.

The cost of the micro-grid battery solution is found in a similar method to the feeder storage battery, however the limits are found using the slow proliferation rate. The subscription max is projected to be reached at 9.94 years and the feeder max is projected to be reached at 18.66 years. The costs of lithium ion storage is projected to be approximately $210/kWh at 9.96 years and approximately $115/kWh at 18.66 years. In 2014 dollars, the cost of the storage for the complete solution at these two years is projected to be approximately $13,230,000 and $7,245,000, respectively. Table 37 below lists the cost estimation for creating the micro-grid battery solution if purchased at the subscription max and the feeder max.

Table 37: Micro-Grid Lithium Ion Storage Cost Estimation per kWh using Slow Proliferation Rate

Micro-Grid Lithium Ion Storage Cost Estimation per kWh using Slow Proliferation Rate		
	Subscription Max	**Feeder Max**
Cost per battery	$22,050	$12,075
Cost per battery unit	$66,150	$36,225
Total cost of solution	$13,230,000	$7,245,000

Unlike the previous solution, the micro-grid solution does not require construction or replacement of overhead lines from the substation. Constructing new lines between the pole transformers, the batteries, and the houses they serve is necessary, however, yet it is unfeasible to make a firm estimation due to variables such as the distance between houses and the battery placement, the number of houses connected in series, the cost of labor for such a task, etc. A various number of lines can be used depending on the configuration of houses connect to the battery; no matter which line is chosen, the line must have an ampacity such that it can support 100A per house.

Using a total cost estimation for new cable, labor costs, and other associated expenses of $2,000,000, the CRF referenced in section 2.8, using an aggregate interest rate of 17% for the FCR, and assuming a 20 year payback period, the AFCs for construction and installation to meet subscription max and feeder max would be:

$$\boldsymbol{Subscription\ Max}\ AFC = (\$2{,}000{,}000 + \$13{,}230{,}000) \times 17\% = \$\mathbf{2,589,100}/\boldsymbol{yr}$$

$$\boldsymbol{Feeder\ Max}\ AFC = (\$2{,}000{,}000 + \$7{,}245{,}000) \times 17\% = \$\mathbf{1,571,650}/\boldsymbol{yr}$$

These price projections are made in 2014 dollars. Future fluctuations or fruitions in the United States and global economies and faster or slower advancement in battery technology may cause discrepancies from these projections.

In designing and preparing for a worst-case scenario, no matter which battery solution is selected if one is chosen, contracting and construction on battery storage should be scheduled based on the maximum projected energy consumption, though this also limits time in allowing the market to reach a state of more dedicated commercialization and competitive pricing. A more accurate timeline as to when battery construction should take place can be achieved by a census of electrical vehicle ownership over time to accurately gauge how urgently battery storage is needed. If both electrical vehicle growth and the increase in electrical consumption are both smaller than our researched and established projections then battery installation can be delayed, improving the odds of lithium ion grid battery commercialization and availability.

6 Recommendations & Conclusions

6.1 Solution 1 Conclusion

The solution explored for fast proliferation of EVs would be a long term, predictable, and easily installed solution by using existing technologies and simply updating the distribution system. Though costly to buy and install, the suggested plan for Solution 1 would create the needed room for EV growth without hazard for the time duration of 25 years in this study. Comparatively, the overall price for this solution was calculated to be much less than the total for the other solutions listed; however, the potential for energy savings would be considered non-existent, thereby forcing the utility to raise their subscription limit to whatever is needed. This solution also allows for existing transformers and other distribution system parts to continue to be used until they have outlived their usefulness. Additionally, future electrical devices will have improved on power efficiency (LED lighting, etc.), becoming less expensive and more widely used.

6.2 Recommendations Based on Projected Conditions

The fundamental process of energy storage for load shifting entails charging the battery primarily during off-peak hours to minimize cost. The power would be rectified from AC to DC, and then stored in the battery unit. The power would then be inverted back to AC and then used during peak hours to supplement the power draw on the feeder. Given the selected solution of lithium ion energy storage using batteries to mitigate load shifting, our team has formulated two possible methods of storage: mass, centralized storage that could serve a large section of customers, such as those on a single feeder, and micro-grid storage that would serve a collective of about ten buildings.

6.2.1 Solution 2 Recommendations

A mass energy storage unit would realistically be able to serve a single feeder by storing a large amount of energy during off-peak hours and then distributing that energy during peak hours. While this solution would mitigate the issue of power generator or subscription limits, it does not directly solve the issue of distribution line stress. For this solution, an additional feeder line which is connected from the battery to each house on the feeder would have to be installed so that power discharged from by the battery unit does not cause the power lines to experience premature wear by coupling with generated or subscribed power that is normally distributed to the customers. Furthermore, batteries of such an immense size would require a large amount of construction to properly house them.

6.2.2 Solution 3 Recommendations

A micro-grid storage system would involve a collective of approximately ten houses that each share a battery unit as opposed to all of the customers on an entire feeder. While this method would require more construction of batteries and housing units, the overall size of each battery would be much smaller and housing construction could be simplified by utilizing recycled materials such as storage containers. Construction of a new complimentary feeder line for the battery storage would not be needed, though the installation of short power lines to connect the batteries to their respective houses or new, higher ampacity lines from the pole transformers would be needed to handle the increase in current draw. We recommend a line size that can handle 100 A per house plus 34 additional amps to support battery charging. The specific sizes we suggest are the Bluebird and Kiwi, each with an ampacity of 1083 A, and the Thrasher which has an ampacity of 1122 A.

This solution also allows for simple integration of point-source generation by way of renewable energy sources such as solar or wind generation. Because these sources generate a DC voltage signal, they can be regulated and stored directly by the battery without the need for rectification, which further reduces the cost over time to charge the battery for peak time usage. We recommend exploring these options to further drive the cost of charging the batteries over time down and reduce the amount of required power needed by the transformer to support both ten houses charging electric vehicles simultaneously and charging the grid battery.

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8 Appendix

8.1 Basic Transformer Information

The electrical distribution system must provide usable electricity to residential, commercial, and industrial users, which includes using transformers to lower the voltage to user levels. The two transformers most frequently used in a residential area are the substation transformer and the pole transformer. There are several different types of transformers, providing variation in use preference and functionality; however, all transformers have fundamental parts in common.

Figure 77 below shows a generic picture of the inside of a transformer [44].The function of a transformer in the distribution system is to change voltage levels from high to low, indicating that the higher voltage goes in the primary terminals, is transformed through the core windings, and exits the secondary terminals [44].Although the voltage is different going out, power is conserved.

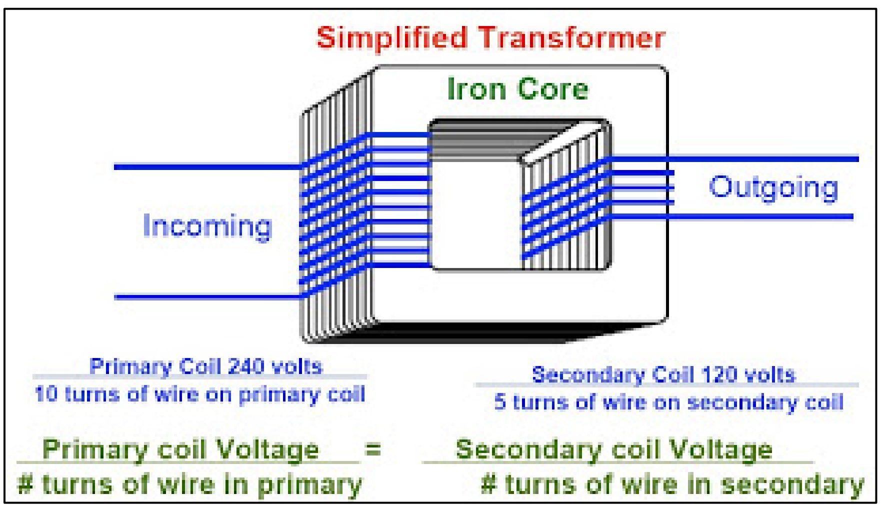


Figure 77: Transformer Basic Operation [44]

Figure 78 below displays one simplified version of an oil filled transformer [45].Liquid-filled transformers are often preferred over dry-type transformers in distribution systems because they have proven to be more efficient, longer lasting, and are able to withstand greater overloading [46].Some drawbacks to liquid-filled transformers are that they require more frequent maintenance, are prone to spills, and are more flammable [46].Further, dry-type transformers are widely used indoors, while liquid-filled transformers are better suited outdoors [46].

It can be seen in figure below that the transformer radiates heat, which is a crucial part of transformer design. In the mineral oil filled transformer below, heat is radiated through a convection motion through tubes [45].Other cooling designs include any combination of radiators, cooling fans, and flow control with an oil pump.

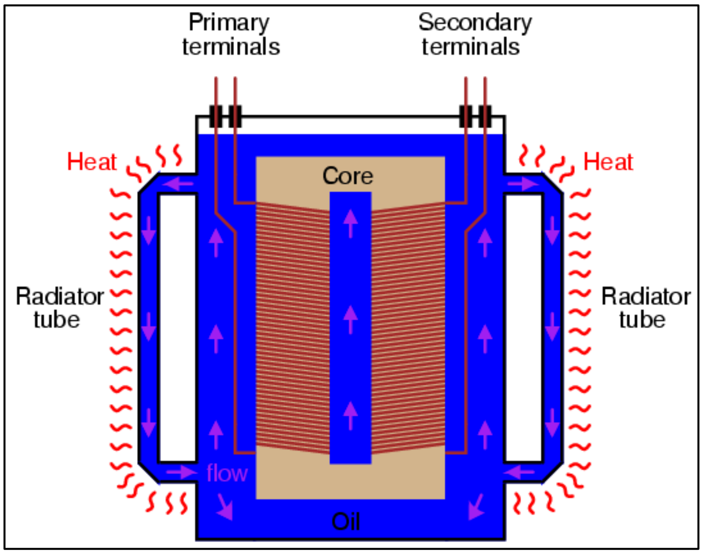


Figure 78: Distribution Transformer Cross-Section [47]

The representation of an ideal transformer may be portrayed in Figure 79 below. The idealized transformer model shows the primary and secondary voltages, the primary and secondary currents with directions, the number of turns for the primary and secondary side of the transformer, and the load on the secondary side. The polarity dots at the top of each coil also show current direction, and may change location in different drawings [48].

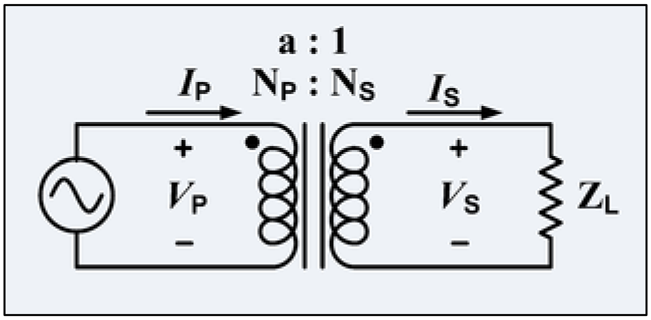


Figure 79: Ideal Transformer Model [48]

The behavior of an ideal transformer may be summarized with the equation set below. The relationships described by the ideal transformer equations easily explain how electrical properties are transferred from the primary side to the secondary side. It is usually acceptable to use the ideal models for transformers due to the usual efficiency of around 98% [49].

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} = \sqrt{\frac{Z_1}{Z_2}}$$

Equation 1: Ideal Transformer Equations [49]

All transformers work only with alternating current due to the properties shown in Figure 80 below [49].The primary and secondary sides are not physically connected; however, current is induced in the secondary side due to the magnetic flux created by the primary current [50].As shown in the ideal transformer equations above, the induced current and voltage level of the secondary depends on the turns-ratio between the primary windings and secondary windings.

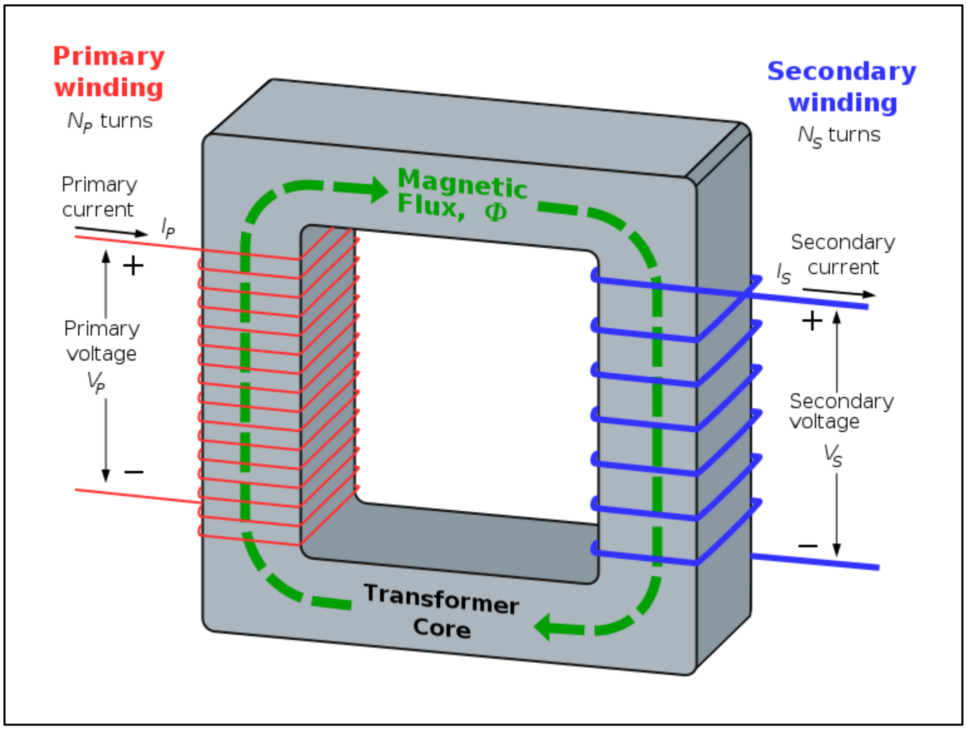


Figure 80: Magnetic Property of Transformers [50]

This project is concerned mainly with the power transformer governing the feeder, and how the transformer cools itself will have an effect on how much heat (and current) the transformer can tolerate. The power transformer for the feeder was considered to be an oil immersed transformer, and thus lending to four possible cooling methods [51].The majority of the losses in the transformer will be in the form of heat losses, which makes cooling methods noteworthy [51].

The first cooling method, Oil Natural Air Natural (ONAN), has been previously mentioned in this section and may be exemplified in the figure below. The principles of convection allow the oil to flow through radiators on the sides of the transformer, relying on ambient temperature to cool the unit [51].

Oil Natural Air Forced (ONAF) is a second cooling method, displayed in Figure 81 below. This method uses the ONAN method of radiators in conjunction with fans blowing on the radiators, thereby accelerating the cooling by lowering the ambient temperature and allowing for better dissipation and circulation [51].

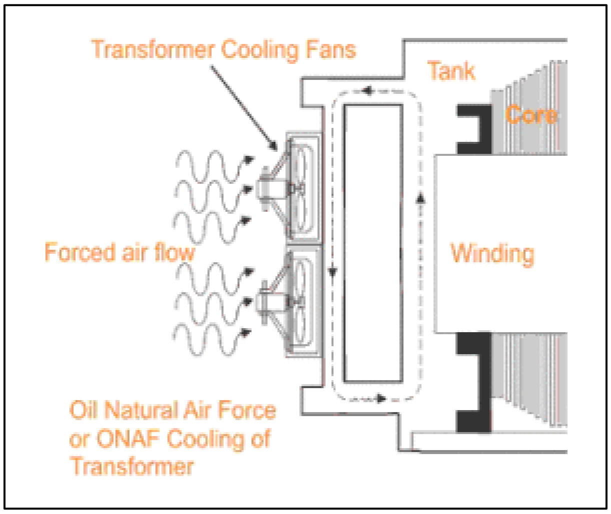


Figure 81: ONAF Cooling Method [52]

Oil Forced Air Forced (OFAF) is a third cooling method, displayed in Figure 82 below. OFAF utilizes radiators for heat exchange and also cooling fans for greater heat dissipation, but also involves a pump to circulate the oil from the transformer casing to the cooling chamber, thereby accelerating the natural process of convection. This method allows for an even greater cooling pace than ONAN or ONAF by speeding up the pace of oil circulation [51].

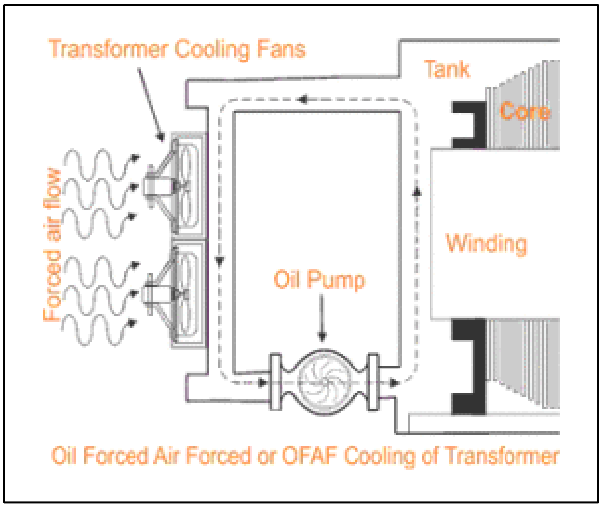


Figure 82: OFAF Cooling Method [52]

Oil Forced Water Forced (OFWF) is a fourth cooling method displayed in Figure 83 below, and the final method discussed here. The OFWF method utilizes an oil pump and radiators similar to that of the OFAF method; however, the radiators are immersed in water pumped through the cooling chamber, due to the lower ambient temperature of water compared to air [51].The water is additionally cooled separately, not shown in the figure below [51].The addition of a water cooler accelerates the cooling of the oil even further, providing more overheating protection. Though there are a few other cooling methods used in industry, they all involve variations of aforementioned methods, and are above the scope of this project.

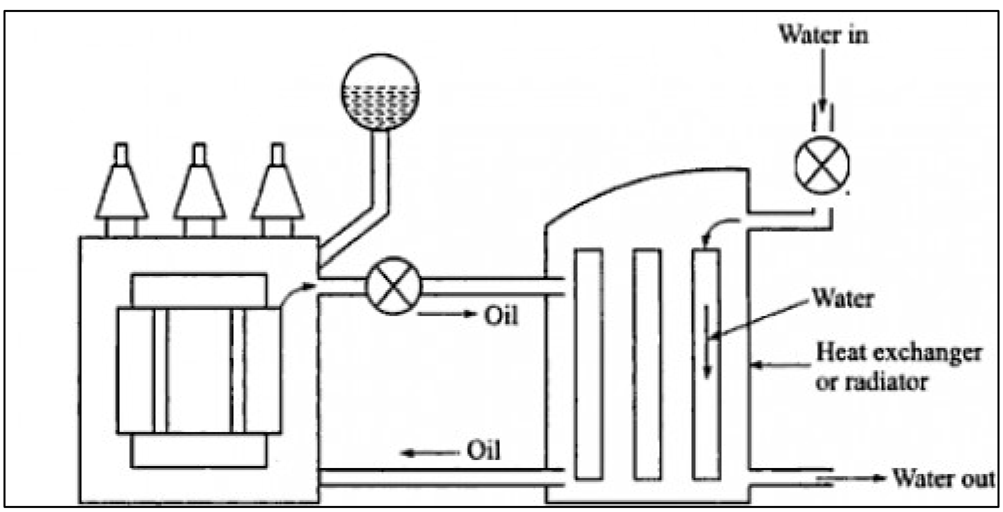


Figure 83: OFWF Cooling Method [53]

8.2 IEEE Std. C57.91-1995Supporting Material

Table 38: Temperature Variable Definitions [33]

C	is the thermal capacity of the transformer, Watt-hours/°C
EXP	is 2.71828 (base of natural logarithm)
I_R	is rated current
K	is the ratio of load L to rated load, per unit
L	is the load under consideration, kilovoltamperes or amperes
m	is an empirically derived exponent used to calculate the variation of $\Delta\Theta_H$ with changes in load. The value of m has been selected for each mode of cooling to approximately account for effects of changes in resistance and off viscosity with changes in load.
n	is an empirically derived exponent used to calculate the variation of $\Delta\Theta_{TO}$ with changes in load. The value of n has been selected for each mode of cooling to approximately account for effects of change in resistance with change in load.
$P_{T,R}$	is the total loss at rated load, watts
R	is the ratio of load loss at rated load to no-load loss on the tap position to be studied
t	is the duration of load, hours
Θ	is temperature, °C
Θ_A	is the average ambient temperature during the load cycle to be studied, °C
$\Theta_{A,R}$	is the average ambient temperature at rated load, °C
Θ_H	is the winding hottest-spot temperature, °C
$\Theta_{H,R}$	is the winding hottest-spot temperature at rated load on the tap position to be studied, °C
$\Theta_{H,U}$	is the ultimate winding hottest-spot temperature for load L, °C
Θ_{TO}	is the top-oil temperature, °C
$\Delta\Theta_H$	is the winding hottest-spot rise over top-oil temperature. °C
$\Delta\Theta_{H,i}$	is the initial winding hottest-spot rise over top-oil temperature for t = O, °C
$\Delta\Theta_{H,R}$	is the winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied, °C.
$\Delta\Theta_{H,U}$	is the ultimate winding hottest-spot rise over top-oil temperature for load L, °C
$\Delta\Theta_{H/A,R}$	is the winding hot spot rise over ambient at rated load on the tap position to be studied, °C
$\Delta\Theta_{TO}$	is the top-oil rise over ambient temperature, °C
$\Delta\Theta_{TO,R}$	is the top-oil rise over ambient temperature at rated load on the tap position to be studied, °C
$\Delta\Theta_{TO,i}$	is the initial top-oil rise over ambient temperature for $t = 0$, °C
$\Delta\Theta_{TO,U}$	is the ultimate top-oil rise over ambient temperature for load L, °C
τ_{TO}	is the oil time constant of transformer for any load L and for any specific temperature differential between the ultimate top-oil rise and the initial top-oil rise
$\tau_{TO,R}$	is the time constant for rated load beginning with initial top-oil temperature rise of 0 °C, hours
τ_W	is the winding time constant at hot spot location, hours

Subscripts:

A	is ambient
R	is rated
U	is ultimate
i	initial
H	is winding hottest-spot
TO	is top oil
W	is winding
I	is over

Table 39: Temperature Calculation Equations [33]

Equation #	Symbolic Equation
1	$\Theta_H = \Theta_A + \Delta\Theta_{TO} + \Delta\Theta_H$
2	$\Theta_{TO} = \Theta_A + \Delta\Theta_{TO}$
3	$\Delta\Theta_{TO} = (\Delta\Theta_{TO,U} - \Delta\Theta_{TO,i})\left(1 - \exp^{-\frac{1}{\tau_{TO}}}\right) + \Delta\Theta_{TO,i}$
4	$\Delta\Theta_{TO,i} = \Delta\Theta_{TO,R}\left[\frac{(K_i^2 R + 1)}{(R+1)}\right]^n$
5	$\Delta\Theta_{TO,U} = \Delta\Theta_{TO,R}\left[\frac{(K_U^2 R + 1)}{(R+1)}\right]^n$
6	$C = 0.06(\text{weight of core and coil assembly in pounds}) + 0.04\,(\text{weight of tank and fittings in pounds}) + 1.33\,(\text{gallons of oil})$
7	$\tau_{TO,R} = \frac{C\Delta\Theta_{TO,R}}{P_{T,R}}$
8	$\tau_{TO} = \tau_{TO,R}\frac{\left(\frac{\Delta\Theta_{TO,U}}{\Delta\Theta_{TO,R}}\right) - \left(\frac{\Delta\Theta_{TO,i}}{\Delta\Theta_{TO,R}}\right)}{\left(\frac{\Delta\Theta_{TO,U}}{\Delta\Theta_{TO,R}}\right)^{\frac{1}{n}} - \left(\frac{\Delta\Theta_{TO,i}}{\Delta\Theta_{TO,R}}\right)^{\frac{1}{n}}}$
9	$\Delta\Theta_H = (\Delta\Theta_{H,U} - \Delta\Theta_{H,i})\left(1 - \exp^{-\frac{t}{\tau_w}}\right) + \Delta\Theta_{H,i}$

10	$\Delta\Theta_{H,\,i} = \Delta\Theta_{H,\,R}K_i^{2m}$
11	$\Delta\Theta_{H,\,U} = \Delta\Theta_{H,\,R}K_u^{2m}$
12	$\Delta\Theta_{H,\,R} = \Delta\Theta_{H/A,\,R} - \Delta\Theta_{TO,\,R}$

8.3 Transformer Specifications

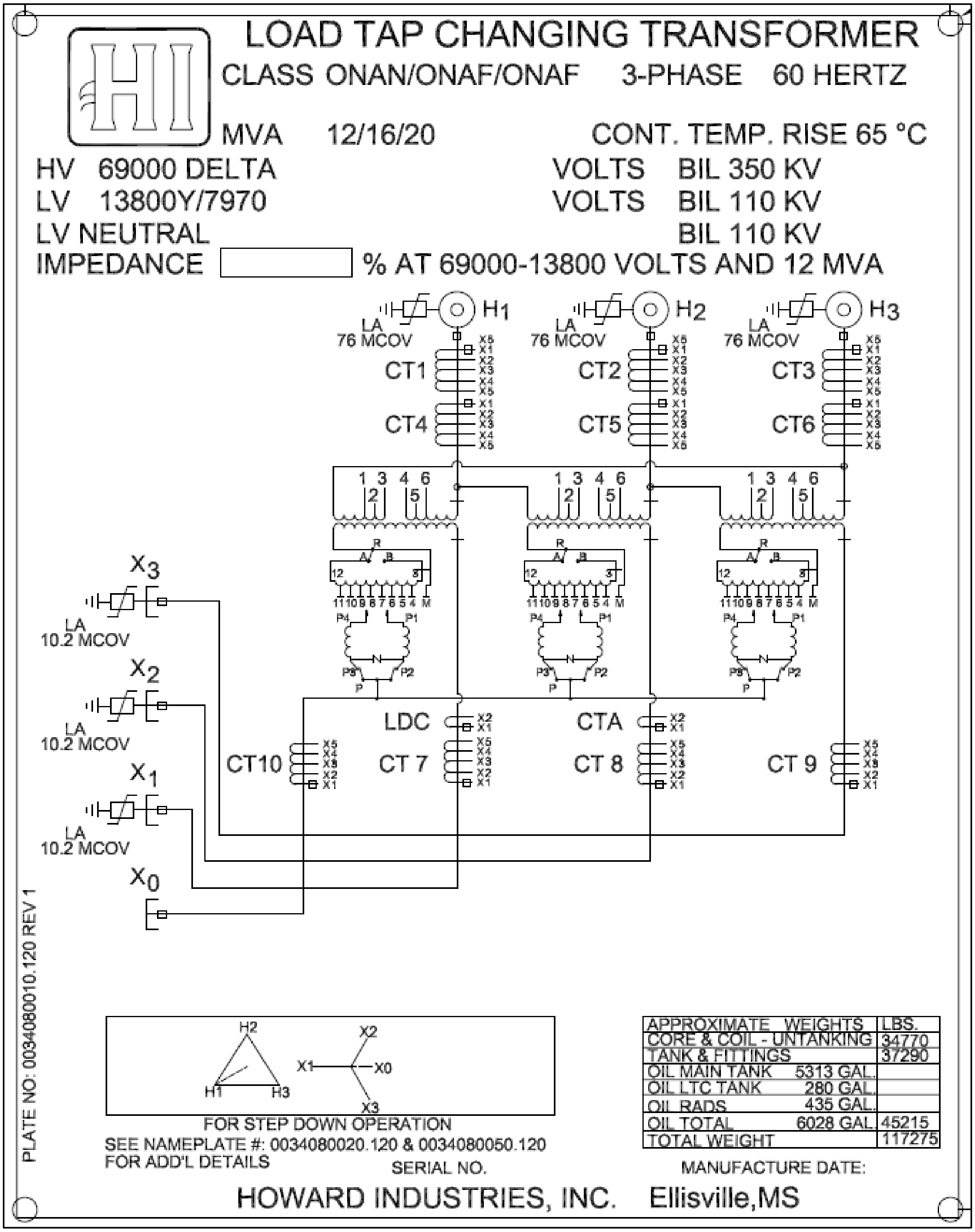
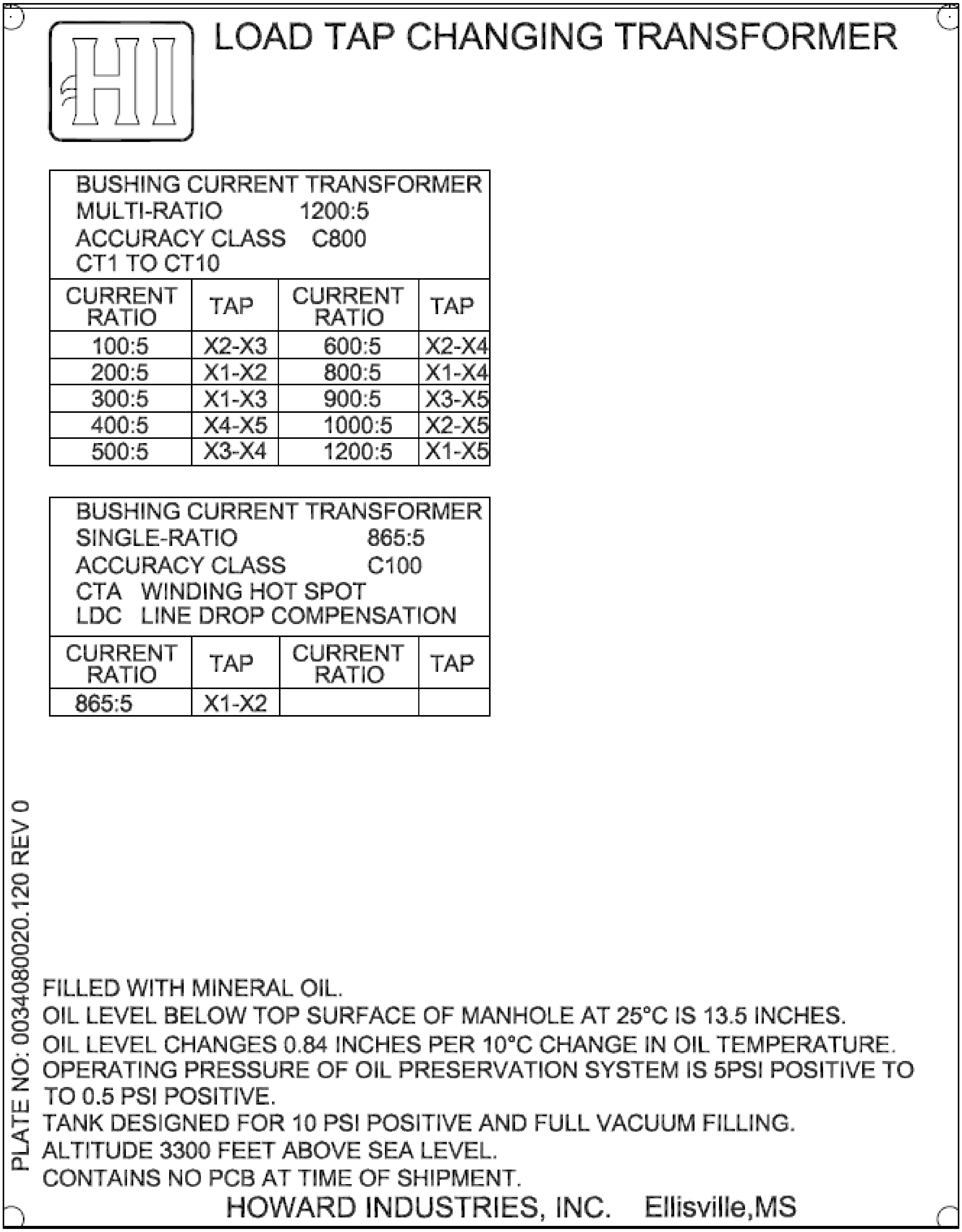


Figure 84: Transformer Specification 1



LOAD TAP CHANGING TRANSFORMER

BUSHING CURRENT TRANSFORMER
MULTI-RATIO 1200:5
ACCURACY CLASS C800
CT1 TO CT10

CURRENT RATIO	TAP	CURRENT RATIO	TAP
100:5	X2-X3	600:5	X2-X4
200:5	X1-X2	800:5	X1-X4
300:5	X1-X3	900:5	X3-X5
400:5	X4-X5	1000:5	X2-X5
500:5	X3-X4	1200:5	X1-X5

BUSHING CURRENT TRANSFORMER
SINGLE-RATIO 865:5
ACCURACY CLASS C100
CTA WINDING HOT SPOT
LDC LINE DROP COMPENSATION

CURRENT RATIO	TAP	CURRENT RATIO	TAP
865:5	X1-X2		

PLATE NO: 0034080020.120 REV 0

FILLED WITH MINERAL OIL.
OIL LEVEL BELOW TOP SURFACE OF MANHOLE AT 25°C IS 13.5 INCHES.
OIL LEVEL CHANGES 0.84 INCHES PER 10°C CHANGE IN OIL TEMPERATURE.
OPERATING PRESSURE OF OIL PRESERVATION SYSTEM IS 5PSI POSITIVE TO TO 0.5 PSI POSITIVE.
TANK DESIGNED FOR 10 PSI POSITIVE AND FULL VACUUM FILLING.
ALTITUDE 3300 FEET ABOVE SEA LEVEL.
CONTAINS NO PCB AT TIME OF SHIPMENT.
HOWARD INDUSTRIES, INC. Ellisville,MS

Figure 85: Transformer Specifications 2

8.4 EV Models

8.4.1 Tesla Model S

The Tesla Model S was Tesla Motor's second vehicle when it was introduced in 2012. The Model S is a full-sized, luxury lift back (similar to a hatchback). It is currently the top selling plug-in electric vehicle and has won many awards including being named Motor Trend Car of the Year back in 2013 [54] [55]. It has the largest range of any electric vehicle on the market at 240 miles. It is one of the few fully electric vehicles to have all-wheel drive. The Model S has the most expansive charging capabilities of any electric vehicle with (home) dual chargers that can charge the battery in 4 hours as well as superchargers on the road designed for long distance travel that can charge half the battery in 20 minutes [56]. Tesla offers models with 70 and 90 kWh batteries. For our research, we looked at the base 70-kWh model [21].

Figure 86: Tesla Model S [57]

8.4.2 Nissan Leaf

The Nissan Leaf became Nissan’s first electric vehicle to hit the open market back in late 2010 after previous attempts dating back to 1997 had been unsuccessful [58]. The Leaf is a compact, hatchback vehicle with front wheel drive. As of December 2015, it was the world’s all-time best selling highway-capably electric vehicle with over 200,000 vehicles sold, with more than 90,000 of those sold in the United States [59]. Its most recent iterations have ranges of 84 miles (24 kWh battery) and 107 miles (30 kWh battery). These are among the top for electric vehicles that are not manufactured by Tesla. It has home charging capabilities that allow it to be fully charged within 5 hours. While Nissan does not have their own road chargers like Tesla, companies like ChargePoint offer road-charging access to other electric vehicles including the Leaf [60]. As stated above, Nissan currently offers two models of the Leaf, one with a 24 kWh battery and the second with a 30 kWh battery. For our research, we looked at the 24 kWh battery model [22].

Figure 87: Nissan Leaf [61]

8.4.3 Chevrolet Volt

When Chevrolet unveiled the concept for the Volt in 2007, they became the first major car manufacturer to publicly show a plug-in hybrid vehicle [62]. The first generation of the Volt was officially released in late 2010-early 2011 and has since sold over 100,000 units worldwide, including about 85,000 in the United States, and became the all-time best-selling plug-in hybrid vehicle as of October 2015 [63]. It has since won many awards including the North American Car of the Year back in 2011 [64]. The Volt differs from the previous two cars mentioned in that it is a plug-in hybrid, not a fully electric car. Despite the difference, the Volt does operate as a fully electric vehicle until the battery drops below a certain threshold, but because of its hybrid nature, its pure electric range is only 53 miles, plus another 420 miles from the gas engine. To supplement normal charging, the Volt also incorporates regenerative braking, which is energy normally lost during braking is turned into kinetic energy for immediate or late use, which is found in other hybrid vehicles [23].

Figure 88: Chevrolet Volt [65]

8.4.4 Destination Charging

To improve the customer experience, Tesla has partnered with many hotels, restaurants, shopping centers, etc. allowing its users to charge their car from almost anywhere. This allows customers to get the most out of their Tesla and allow them to charge their vehicle whenever they go out. There are hundreds of locations across the country that offer this service. To entice companies to install these chargers at their place of business, Tesla will install two wall chargers free of charge assuming they are visible or convenient location on the property [66].

8.4.5 Superchargers

Superchargers are free connectors designed by Tesla that charge the vehicle in minutes instead of hours. They work by placing multiple Tesla chargers in parallel so that they deliver 120 kW of DC directly to the battery. They were created to allow people to use their Tesla's on long trips where they may need to charge their vehicle before reaching their destination. They are strategically placed along routes between major cities conveniently located near restaurants, shopping centers, and Wi-Fi hot spots. They are capable of charging 120 kW, which equates to 170 EPA rated miles in as little as 30 minutes and can provide a full charge in about 75 minutes. As of 2016, there are 595 Supercharger stations with 3465 Superchargers across the world. Figure 89 and Figure 90 below illustrate the difference between regular EV chargers and the supercharger, and the charging profile of the supercharger, respectively. [56]

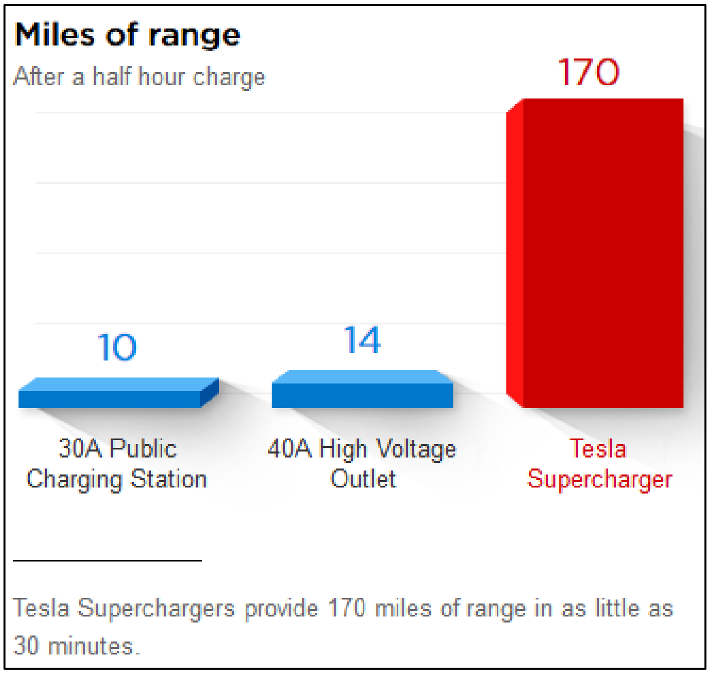


Figure 89: Tesla Supercharger vs. Other Chargers [56]

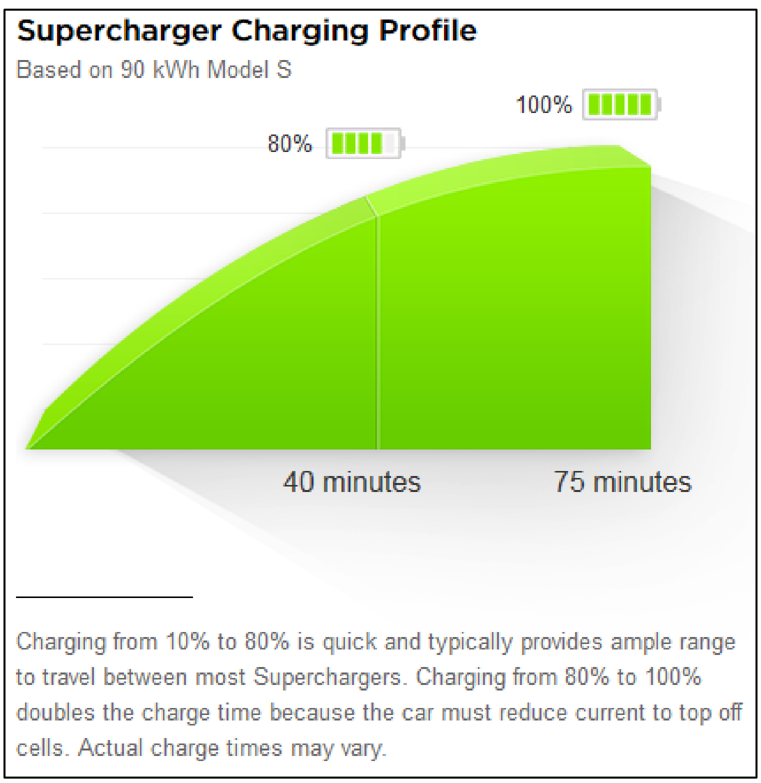


Figure 90: Tesla Supercharger Charging Profile [56]

8.5 PowerWorld Figure Key

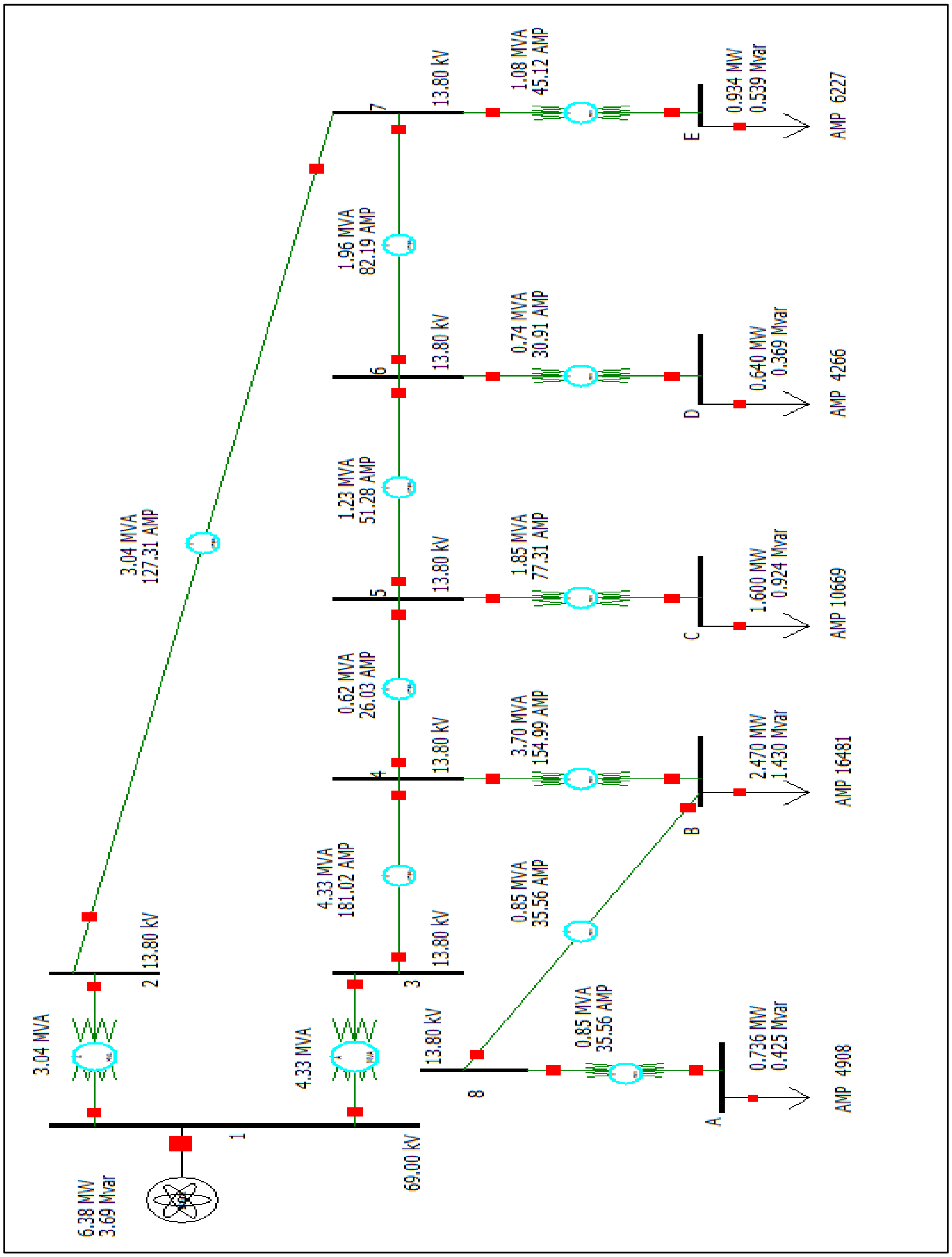
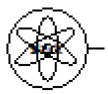
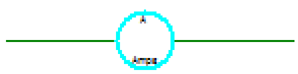
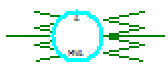
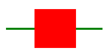
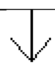


Table 40: PowerWorld Map Key

	Energy Generation Source. In this case, the generation source is represented by nuclear energy.
	Distribution feeder line. The blue circle represents an Ammeter.
	Transformer. The blue circle represents an Ammeter.
	Circuit Breaker built into the lines. Can be used to shut off current flow.
	Bus Bar. This element works as a node, or point of connection.
	Load Element. The load may be represented in MVA

8.6 PSPICE Code

```
*EV 400V Charger Prototype

Vac 1 0 SIN(0 340 60)          ;240Vrms
R1 1 2 100m

Lp 2 0 .212                    ;Transformer
Ls 3 0 1.55
K Lp Ls .99

.SUBCKT DIOSN 101 102
DX 101 102 DIO
.MODEL DIO D(RS=1m BV=10k)
Cs 103 102 1u IC=0
Rs 101 103 100
.ENDS

X1 3 4 DIOSN                   ;Rectifier
X2 0 4 DIOSN
X3 6 3 DIOSN
X4 6 0 DIOSN

;Cap 4 6 100m IC=0
Vb 5 10 400                    ;Battery Voltage
Rb 4 5 1
Lb 10 6 100m IC=0

.TRAN 2 2 .5 50m UIC
.PROBE
.END
```

8.7 Battery Storage Calculation

The following lists the calculations performed in order to find the necessary requirements of the feeder and micro-grid storage solutions.

Feeder Calculations:

Total Displacement Needed	38 MWh	
Total Battery Capacity Needed = Displacement / (Round trip efficiency x Depth of discharge)		
	= 38 MWh/(0.9x0.9x0.75	
	62.5514403 3	MWh
Rounded ->	63 MWh	
Batteries needed per unit	=63/24 [MWh]	
	2.625	
Rounded ->	3 Batteries per unit	
Discharge time per battery	=7 hours/3 batteries	
	2.33333333 3	hours per battery
Total power from unit	=(38 MWh/(0.9*0.9))/7 hours	
	6.70194003 5	MW
Useful power from unit	= 38 MWh/7 Hours	
	5.42857142 9	MW
Power Losses	1.27336860 7	MW
Total energy in each battery	=63 MWh / 3 batteries	
	21	MWh per battery
Total revolving energy in each battery	= 21 MWh *0.75	
	15.75	MWh
Size of Battery Unit	=88 ft^3/MWh * 63 MWh	

	5544 ft^3
Weight of battery unit	=14770 lbs /1 MWh * 63 MWh
	930510 lbs

Micro-Grid Calculations

Total Displacement Needed	38 MWh
Total Battery Capacity Needed	63 MWh
# of Units needed per feeder	200 Units
Displacement needed per unit	=38 MWh / 200 units
	190 kWh
Total Batery Capacity per unit	=63 MHw / 200 units
	315 kWh
Batteries needed per unit	4 hours max per battery over 7 hours. 2 batteries, 3.5 hours each
	2 Batteries per unit
Discharge time per battery	3.5 Hours
Total power from unit	= (190 kWh/(0.9*0.9))/7 Hours
	33.5097 kW
Useful power from unit	=190 kWh / 7 hours
	27.14286 kW
Power Losses	6.366843 kW
Total energy in each battery	=315 kWh / 2 batteries
	157.5 kWh
Total revolving energy in each battery	= 157.5 kWh * 0.75
	118.125 kWh
Size of Battery Unit	=88 ft^3/1 MWh * 1MWH/1000 kWh * 315

	kwh	
	27.72	ft^3
Weight of battery unit	=14.8 lbs/1 Kwh * 315 kWh	
	4662	lbs

9 Executive Summary

This Major Qualifying Project shall study an electrical power distribution system feeder in conjunction with a predicted EV proliferation. Through data analysis, suggestions and conclusions shall be made to allow full power delivery while mitigating the negative effects of the additional load from the EV proliferation. As the electric distribution feeder supplies an increasing load due to EV proliferation, changes shall need to be implemented to improve distribution system function and lifespan. Through further analysis and prediction, a suggested timeline to make distribution system improvements shall be made. Recommendations and conclusions shall then be made to mitigate brownouts and blackouts over the projected twenty-five-year span, from 2015 to 2040. A fast, nominal, and slow proliferation of EVs was investigated, and a solution was conceived for each scenario.

The Table below describes the basic assumptions for the project. Using the data assumptions, loading could be accurately predicted and modeled.

Table 1: Data Assumptions – Peak Demand

Data Assumptions	
Midpoint for Normal EV Proliferation:	12.5 Years
Midpoint for Faster EV Proliferation:	6.25 Years
Midpoint for Slower EV Proliferation:	18.75 Years
Initial Number of EVs (in Holden):	40 EVs
Total Number of EVs: *	4000 EVs
Average Daily Commute (in Miles):	30 Miles (as of July 2015)
Average EV kWh/100 Miles:	~32 kWh/100 Miles
Average Daily Charge (in kWh):	9.6 kWh
Average Cars per Household:	~2.00
Number of Households in Test Region:	2000 Homes
Total Number of Homes:	7500 Homes
MWh Subscription Total:	30 MWh
MWh Subscription of Test Region:	8 MWh
MVA Feeder Maximum:	12 MVA
Total Energy Added to Grid from EVs: *	38.4 MWh
Phase Angle (Power Factor):	30
Peak/Off Peak Hours: **	Peak: 8 AM – 9 PM (13 Hours) Off Peak: 9 PM – 8 AM (11 Hours)
Peak-Off Peak % for Evenly Distributed Load:	Peak: ~62% Off Peak: ~38%
Peak Hours (Work/Home):	Work: 8 AM – 3 PM (7 Hours) Home: 3 PM – 9 PM (6 Hours)

*Extreme worst-case scenario if everyone in test region has an EV

**Monday through Friday only excluding holidays; weekends and holidays are always off peak hours

The Equation below describes the proliferation curve, or S-curve, that allowed for a realistic assumption of the proliferation of EVs over time. Through time, it was assumed that the addition of EVs will cause a rise in power demand in the form of this linear model.

Equation 1: Modified Logistic Function

$$X(t) = \frac{X_S}{1 + \left(\frac{X_S}{X_0} - 1\right) e^{-at}}$$

Where,

a = the proliferation rate (unitless)

$\mathbf{X_S}$ = the curve's maximum value (Percent of Total EVs)

$\mathbf{X_0}$ = the initial value of the curve (Percent of Total EVs)

t = time (in years)

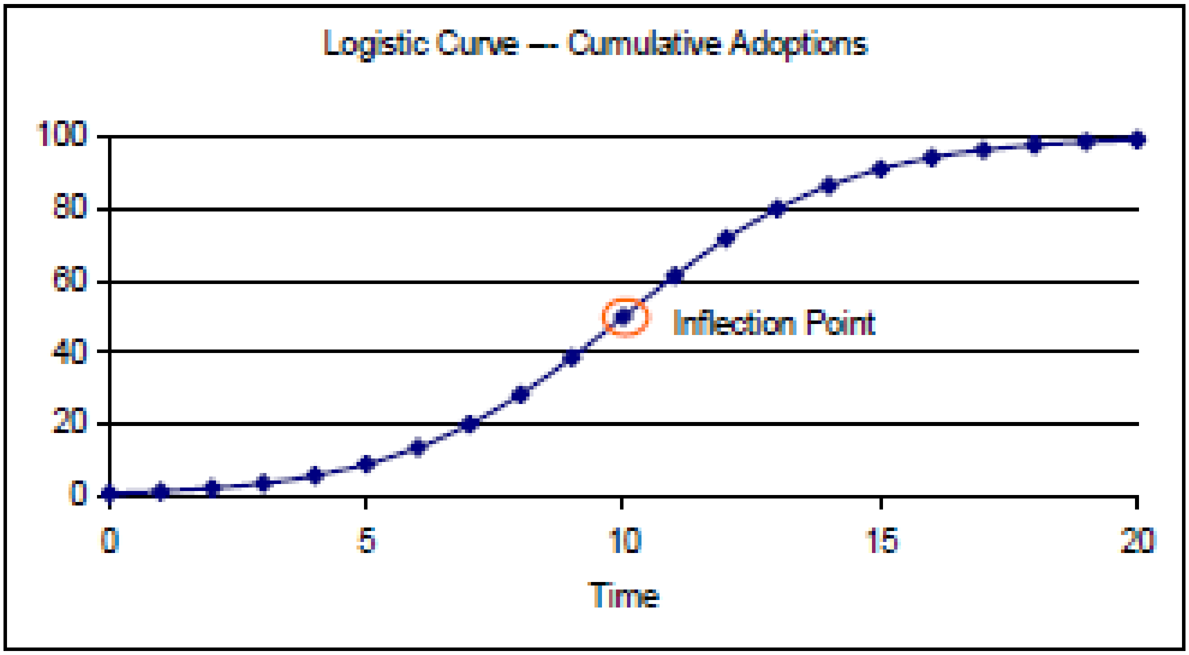


Figure 1 – Logistic Function Used to Model EV Proliferation

Figure 2 below describes the physical layout of the sample feeder tested. Figure 2 shows the lumped loading for one-line diagram purposes, as well as the percentages of the total load that each lumped load represents. Two substations are also tied to the feeder as shown, implying two transformers providing power to the feeders.

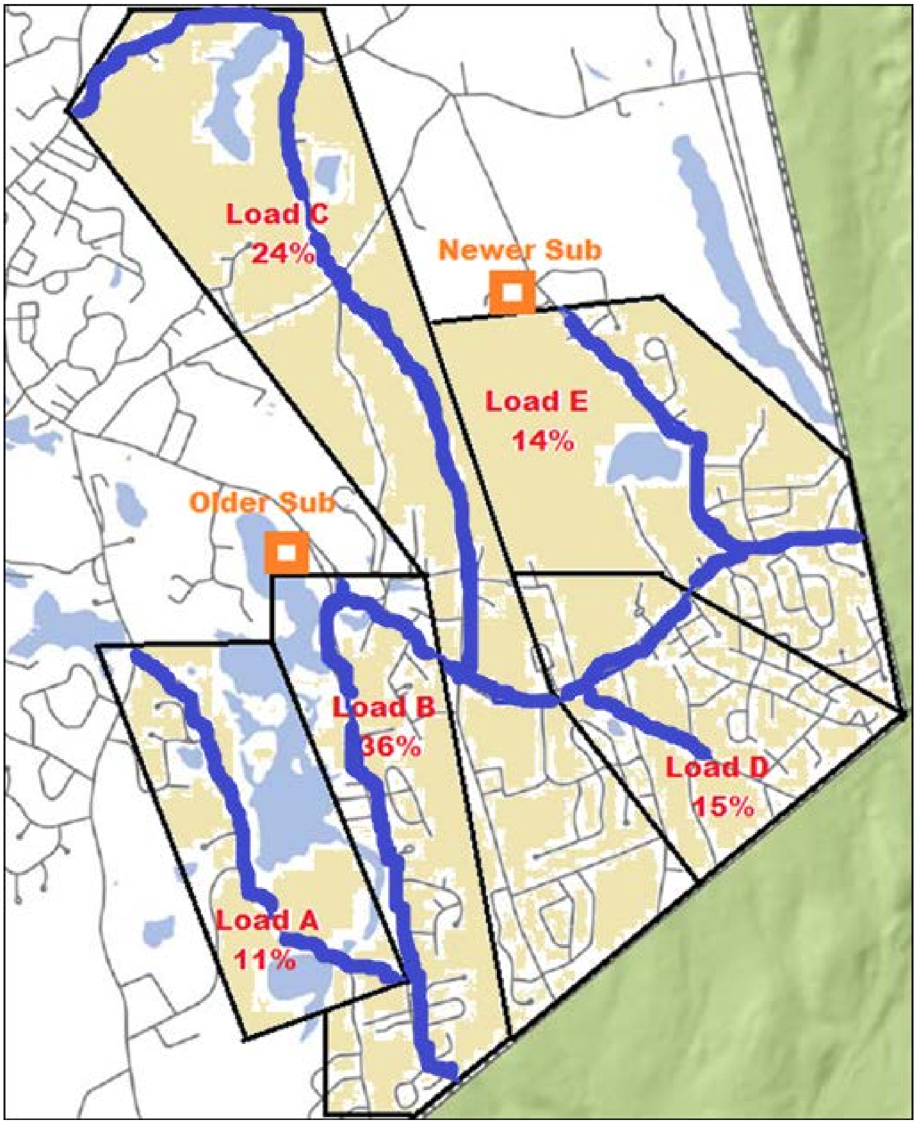


Figure 2: Annotated GIS Map of the Sample Feeder

Figure 3 below shows the proliferation curves of three possible proliferation scenarios with the addition of a realistic annual energy increase of 0.09% every year to the S-curve models. Figure 3 below shows the model that was primarily used for load analysis and future predictions about what the loading would look like over time on the test feeder.

The Table below describes when the current subscription maximum of 8MW and the feeder maximum of 12MVA would be reached on each S-curve proliferation scenario. With the time limits predicted for each proliferation scenario, solutions may now be envisioned for each scenario.

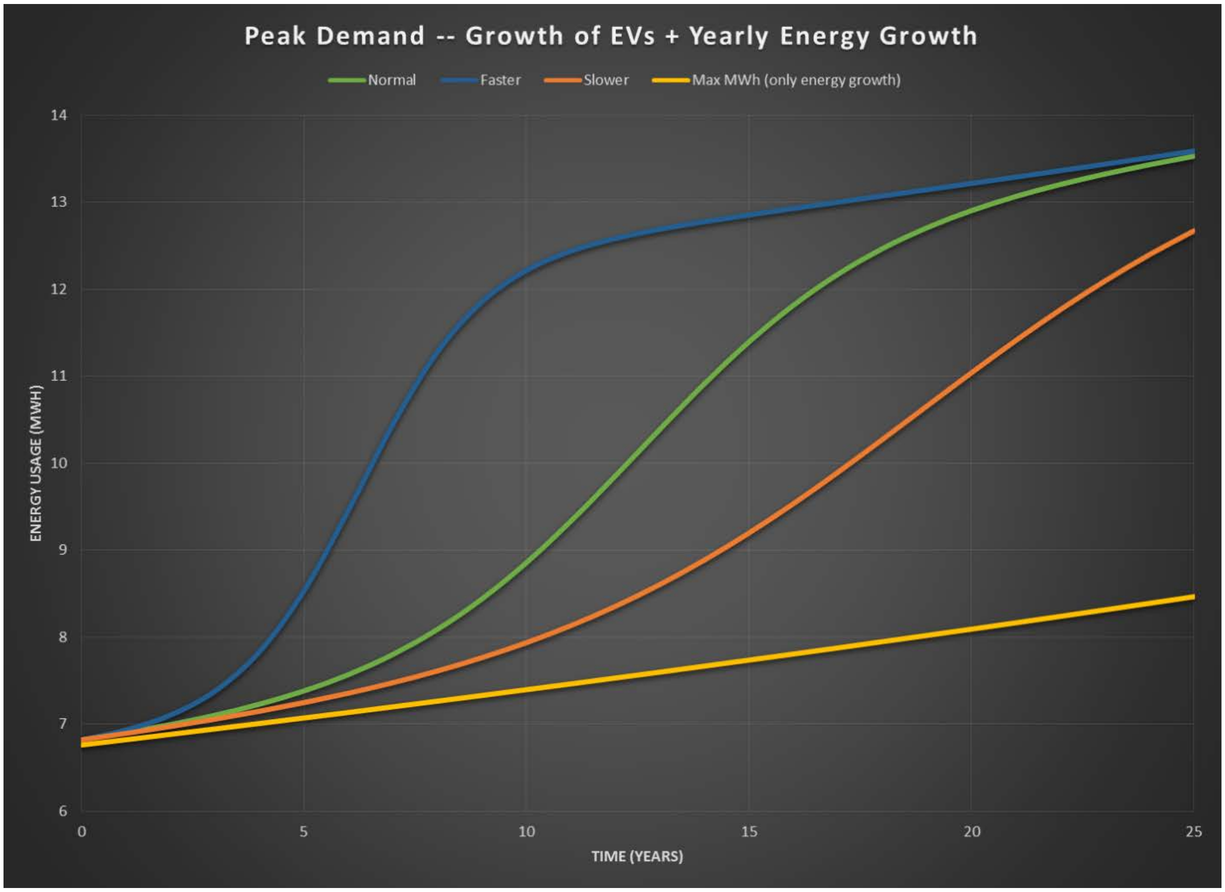


Figure 3 – S-curve Scenarios with Added Predicted Energy Growth

Table 2 – Time to Reach Maximums on the Feeder

Curve	***Subscription Max (Years)***	***Feeder Max (Years)***
Normal	7.33	12.86
Faster	3.93	6.94
Slower	9.94	18.66

For the solution regarding a fast proliferation S-curve, the solution to split the feeder into two separate feeders was proposed. Figure 4 below displays the proposed new feeder lines. Though the figure shows two substations, the old feeder consists of the two existing transformers from both substations, while the new feeder consists of a new transformer at the newer substation.

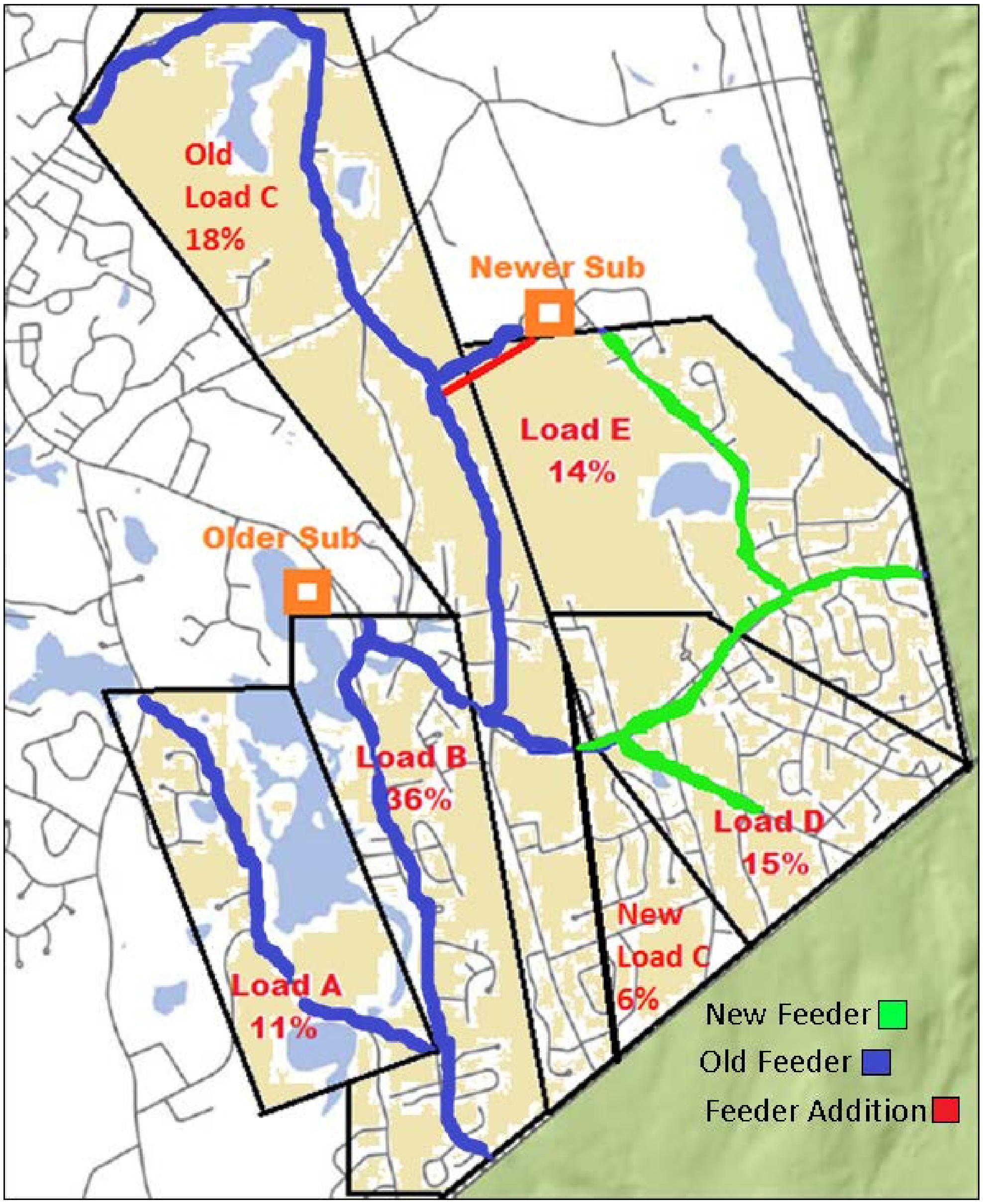


Figure 4 – Split Feeder Solution for Fast Proliferation

The estimated cost of splitting the feeder in two as proposed was estimated to be $2M, including parts and labor. The option for investor financing included a total fixed cost rate of 17%, which includes the capital recovery factor, taxes, fixed maintenance, and insurance. The resulting yearly fixed payment for a 20 year span is listed below as the annual fixed cost (AFC).

$$AFC = \$2{,}000{,}000 \times 17\% = \$\mathbf{340{,}000}/\boldsymbol{yr}$$

The solution regarding the proliferation of EVs at a normal rate, reaching the maximum proliferation after 25 years, included battery storage for the whole feeder. Battery storage may be considered for a normal EV proliferation due to the lowering cost of battery storage. The feeder would remain as it were structurally with the addition of lithium battery storage with enough energy capacity to be discharging during the peak hours and charging during the off-peak hours. The effect of this method would be a leveled load curve, flattening the daily demand. The Table below outlines the feeder storage solution.

Table 3: Feeder Storage Solution

Feeder Storage	
Total unit capacity needed	63 MWh
Number of batteries per unit	3 Batteries
Discharge time per battery	2.333 Hours
Total power from unit	6.70 MW
Useful power from unit	5.43 MW
Power losses	1.27 MW
Total energy in each battery	21 MWh
Revolving energy in each battery	15.75 MWh
Size of unit	5544 ft^3
Weight of unit	930510 lbs.

Figure 5 below shows a one-line diagram of the feeder storage solution with the battery working at the peak hour of the highest demand day, maximizing the EV proliferation and the years covered by this project. In this scenario, when the feeder is topped out, the demand can be seen to be below the subscription maximum of 8MW, which would be well in the range of normal operation, and thus proving the validity of this solution.

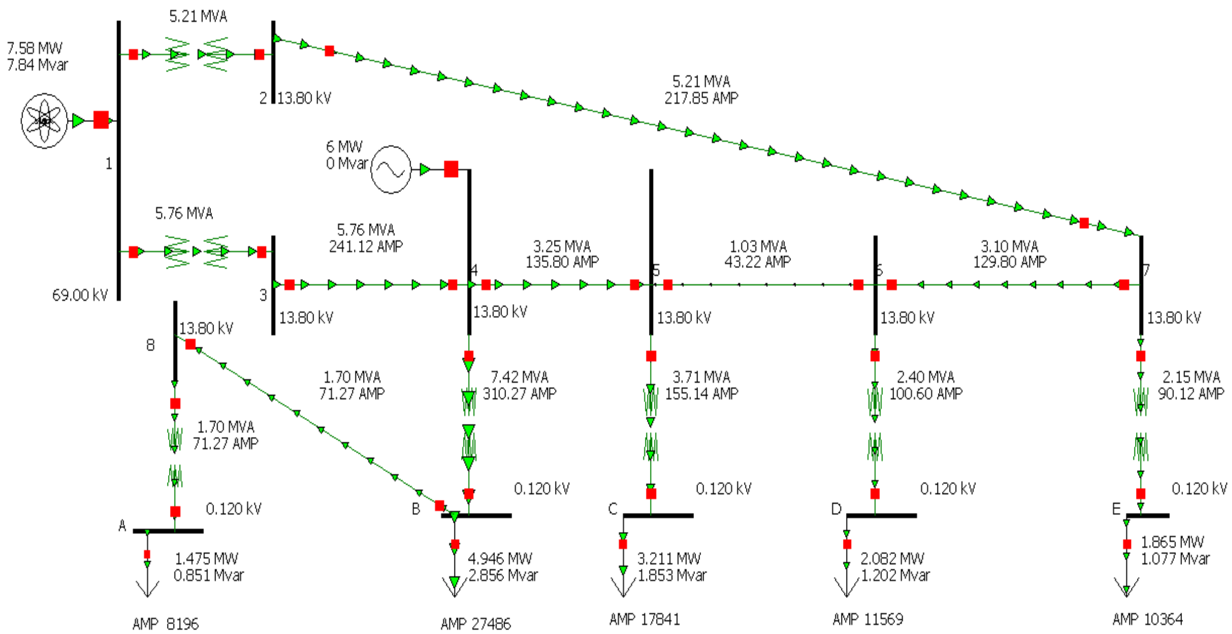


Figure 5: PowerWorld model – Peak Power Demand with the Feeder Battery Connected

The solution for the slow proliferation of EVs allows for the most time to act on a solution, allowing for the progressive solution including micro-grid battery storage. Ideally, each 8 to 10 houses connected to the same pole transformer would have its own storage battery, taking the load off the feeder lines while simultaneously conserving energy coming from the substations. The Table below outlines the micro-grid storage solution.

Table 4: Micro-Grid Storage Solution

Micro-Grid Storage	
Battery units needed per 10 houses per feeder	200 units
Number of batteries per unit	2 Batteries
Total unit capacity needed	315 kWh
Discharge time per battery	3.5 Hours
Total power from unit	33.51 kW
Useful power from unit	27.14 kW
Power losses	6.367 KW
Total energy in each battery	157.5 kWh
Revolving energy in each battery	118.125 kWh
Size of unit	27.72 ft^3
Weight of unit	4662 lbs.

Figure 6 below helps to describe the physical layout of the micro-grid solution. The maximum number of EVs for 10 houses would be 20 EVs, so 2 EVs per house, plus the normal power use at peak hours; therefor, 3 loads per house at a total of about 90A per house at peak load.

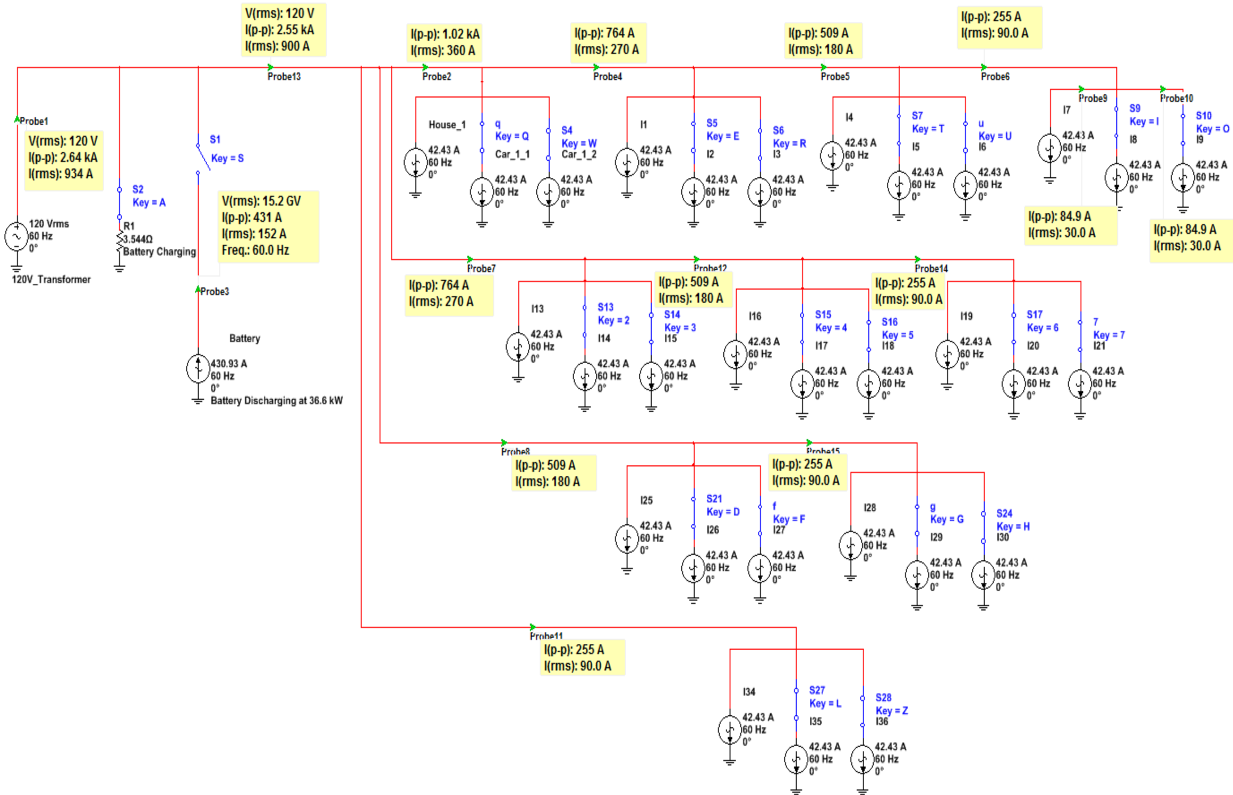


Figure 6: All cars charging at peak current draw, battery charging

The estimated annual fixed cost for the feeder storage and micro-grid storage solution as proposed was estimated in the following costs below. It may at first seem curious as to how the feeder storage could be more than the micro-grid storage solution when the cost of installing a similar amount of kWh for each solution should likewise be similar. Due to the number of years allowed before action is necessary for the micro-grid storage option, prices for storage are predicted to drop enough to make such a difference. Either way, the cost of splitting the feeder in the first solution was a fraction of the price annually. The main benefit to a storage option would be the ability to level loading, allow for renewable energy to be efficiently used in conjunction with the storage, and ultimately lowering utility subscription responsibility.

$$\boldsymbol{Feeder\ Storage}\ AFC = (\$2{,}000{,}000 + \$11{,}340{,}000) \times 17\% = \$\mathbf{2{,}267{,}800}/\boldsymbol{yr}$$

$$\boldsymbol{Micro-Grid\ Storage}\ \ AFC = (\$2{,}000{,}000 + \$7{,}245{,}000) \times 17\% = \$\mathbf{1{,}571{,}650}/\boldsymbol{yr}$$

The proliferation of EVs as described in this report could be summarized as a likely event motivated by the volatility of the petroleum energy market and overall cost. Petroleum is a finite element, and the overall cost of EVs should eventually drop due to developing battery technology and a motor assembly with several less parts and required maintenance than a combustion vehicle. As described above, proliferation may be modeled by the S-curve in addition to projected annual electrical energy demand growth, and simulated to find the limits of the test feeder. Each proliferation speed led to a different solution that would be possible in the time leading up to the feeder limits. Each solution had specific advantages and disadvantages associated with the solution, and largely depended on the time allowed before action must be taken. The solutions presented were recommended for each proliferation timeline, specifically designed to assist a utility company in deciding a course of action given their circumstantial experience with EV proliferation. It is the hope of this project to provide insights to the possibilities involved to solve the electrical distribution problem associated with the rapid growth of EV ownership.