Integration of Energy Storage and Solar to Increase Rural Electric Distribution Reliability through the Utilization of a Digital Twin

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Power systems engineers lack the capability of knowing the real time status of the system and its vulnerabilities. Digital twins are introduced as a solution for distribution system applications and security.A digital twin's ability to perform real time calculations and analyses make it a unique tool that can strengthen our understanding of the power grid, mitigate threats, and improve decision making. Investigating how digital twins' application in power systems can help improve its efficiency, reliability, and functionality. A digital twin is used in this thesis to model and show the impact of the addition of distributed devices to enhance the reliability of power systems in rural areas.

Utility customers expect the highest levels of reliability as many day-to-day activities involve loads requiring a constant energy supply. In urban areas, to ensure this reliability factor, many utilities use networked systems to add redundancy in the event of an outage. In rural areas, however, lower population densities and power system branches cause the reliability techniques used in urban areas to become less practical. Consequently, customers in rural areas experience more outages and longer outage times due to the distance between customers.

Current research focuses on the integration of distributed generation to support rural circuits. This thesis will explore the impact of also integrating distributed storage in rural systems at the edge of the grid. These models will evaluate how these feeders accommodate new devices and how they impact the reliability of the circuit. The creation of these system models will help create a foundation for the development of a digital twin, which can be useful for utility personnel. The addition of newer devices will provide the utility more data to not only train their digital twin and run more accurate studies, but also better monitor and understand what is occurring on the rural circuits to make more informed decisions.

Keywords: digital twin, distribution system, energy storage, peak shaving, PV, rural circuits.

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Preface

I would like to acknowledge everyone who played a role in my academic accomplishments. First, my parents, family, and friends, whom love and pushed me to go beyond what I thought I could do. My professors, especially my committee members, who provided me support through both my undergraduate and graduate research process. Finally, my internship team, who not only provided me industry experience, but also a different perspective, in what and why I pursued this topic.

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1.0 Introduction

Grid modernization is one of the largest focuses within the power industry. The drive to design a reliable grid infrastructure has been prevalent since the conception of the power grid. One of the biggest issues is that the current grid does not have the capacity to meet the demands of 21st century with the original construction. Newer technologies have enabled the push for grid modernization, such as digital twins. Digital twins can help revolutionize the power grid by increasing operators' understanding of the grid and their ability to simulate and predict theoretical scenarios based on real time data.

Most utilities are currently concerned with the grid's edge. Monitoring and predicting load behavior at specific points of the grid is difficult for most utilities. Not only is there low visibility of the grid's edge, but there are also a limited number of actions the utility can implement to impact those regions. The current power system mainly relies on the use of large, centralized generation facilities transmitting and delivering power to the loads through the transmission and distribution system. Although load-side renewable energy is becoming more common, it is still within the minority of the generation profile [3]. To help increase edge-of-grid reliability, especially in rural areas, the use of energy storage and distributed solar generation is proposed.

Distributed solar coupled with storage devices can support the utility throughout rural areas of the grid and can decrease the duration and frequency of outages for downstream customers. Although energy storage has a limited generation capacity, it can provide utilities with additional time to repair the system by strategically supplying supplemental energy to that portion of the system. On site solar energy provides an alternative generation source when sunlight is available to not only preserve the battery, but also charge it during peak generation hours to prolong supply throughout an outage. The improved resiliency in these areas also minimizes the impact on downstream customers by providing an alternative source to disconnected feeders. With time and increased implementation of these devices, rural system reliability will increase. Energy storage systems and distributed generation can also be used to help peak shave throughout typical operating times to reduce the demand on the distribution system.

As costs continue to decrease for solar and storage devices, it is becoming more affordable to consider them as solutions to large-scale issues within the distribution network. Not only is energy storage becoming more affordable and common, grid-connected solar is also a rapidly growing energy source due to its economic and environmental benefits [15]. Many utilities recognize that the use of distributed generation can help improve power flow, minimizes losses, enhance voltages and loadability, and upgrade their network [15]. The use of digital twins can benefit the anticipated integration of distributed generation and storage. By having a real time model of these rural circuits, more information can be provided to the utilities to get a better understanding of what is occurring in their systems, where different vulnerabilities or issues may lie, and know how to control the different devices that are going to be added to the grid to best improve the performance of their system.

This thesis will start by providing background on digital twins, explaining how they work and how they can improve different areas within power systems. This thesis will then address the problems rural circuits typically face and provide background on the purpose of distributed energy devices. Existing studies will help establish a connection between rural circuits and distributed devices to help signify the benefits of solving issues with the implementation of this newer technology. Through implementation of a basic form of a digital twin, distributed storage and solar are modeled on a rural circuit, which is considered one of the worst performing parts of the distribution network. The creation of two different circuit models act as the foundation of developing a digital twin, where the model provides information on how integrating new devices will affect these modeled circuits. This twin can then be further developed for future advancements. This thesis provides an analysis of how the proposed solution of creating a digital model of rural circuits and integrating solar and energy storage will help demonstrate the positive impact distributed devices has on the distribution system. There will be a focus on the impact energy storage can have on reliability and how different levels of penetration can provide support to the grid and its loads, regardless of capacity and quantity. At the same time, this thesis will also identify gaps existing in current research, vulnerabilities of using digital twins and these new integrated technologies, and areas for further investigation to enhance our understanding of distributed energy devices as an advanced grid solution.

2.0 Digital Twins in Power Systems

What is a digital twin? A digital twin is the virtual representation of a physical system that can be used for real time prediction, optimization, monitoring, control, and decision making [26]. The concept of digital twins was proposed by Michael Grieves in wanting to map characteristic attributes of a physical system in a virtual space [14]. They are seen as a form of cyber-physical systems, which are embedded systems that integrate physical assets with cyber components and capabilities with an emphasis on real time capabilities [6]. A digital twin uses data from the physical model to create an exact virtual replica in order to complete analyses, test changes, and monitor both the equipment and the security of the system.

Why are digital twins unique? The use of a digital twin has enabled the ability to perform real time analysis on the modeled system and produce results more efficiently [36]. Digital twins store a database of information regarding the different devices, how they communicate, and the data that is being sent between the sensors [37]. In order to maintain system resiliency, it is imperative to constantly update and monitor the twin to override the old, obsolete data [4]. Maintaining current data also increases its ability to detect and self-diagnose issues and minimizes the need for human intervention when problems arise [9].

The integration of digital twins is also vital to processing big data in short periods of time [32]. By using a method that conducts its analysis under simulated, near real conditions, the computation time decreases and is more efficient. This also opens the door for testing new devices, trying new methods, and analyzing new technologies with high volumes of data [32]. In some scenarios, these simulations with big data can run faster than real time, allowing multiple simulations to run concurrently, which increases the analysis performance of the system [9].

How have digital twins evolved? The evolution of technology has enabled the development of digital twins. The increased data generation, preprocessing, and management has created a way to organize and use the data. Further development of internet of things (IoT) technologies and the internet has increased the opportunity for real time analysis [26]. IoT is meant to bridge the digital and physical world together with data collection, deep analysis, and real time control [13]. The digital twins rely on the use of real time data and high-volume data collection provided by the IoT technologies, while digital twins provide the visual aspects with a user-friendly interface.

Since their conception, the uses, capabilities, and understanding of digital twins have evolved. Researchers have divided this evolution into four parts that built upon one another: pre-digital twin, digital twin, adaptive digital twin, and intelligent digital twin as seen in Table 1 [9]. The pre-digital twin was mainly focused on the physics-based simulation. All the physical system models and computations are available, however, there is no communication between the modeled and physical system. For the digital twin, there was the addition of real time communication between the virtual model and physical model. In the adaptive digital twin, the focus moved to the user interface that can easily communicate what is going on in the system through a visual human interface so the operator can make informed decisions. Finally, the intelligent digital twin incorporated machine learning to find patterns and make autonomous decisions. The progress and changed features are seen in Table 1 where italicized features are supported, and unitalicized features are not supported. Most industries are currently using the adaptive digital twin and working to implement machine learning to reach the intelligent digital twin.

2.1 Digital Twin Applications

Applying digital twins to power distribution systems can help improve operations and management of the power grid by increasing reliability, reducing outages, and monitoring fluctuations in the market [36]. The energy sector has seen an increase in usage and demand as well as a shift in power flow that can cause strain on legacy Supervisory Control and Data Acquisition (SCADA) systems. Implementation and integration of newer technology can help relieve this stress on the system [9]. Power distribution systems require constant monitoring, high efficiency, high reliability, and a fast recovery time [4]. While SCADA systems handle

Table 1: Digital Twin Evolution [9]

Level 1: Pre - Digital Twin	**Level 2: Digital Twin**
Physics – Based Simulation	*Physics – Based Simulation*
Physical System	*Physical System*
Adaptive GUI	Adaptive GUI
Machine Learning	Machine Learning
Level 3: Adaptive Digital Twin	**Level 4: Intelligent Digital Twin**
Physics – Based Simulation	*Physics – Based Simulation*
Physical System	*Physical System*
Adaptive GUI	*Adaptive GUI*
Machine Learning	*Machine Learning*

the acquisition of data and use it for supervisory control of large electrical networks, a digital twin creates a digital representation of the physical system by acquiring data from the actual physical system and uses it for its digital mapping. This provides operators with not only more information about the system, but it also increases their control over the system.

The following are more specific areas, or potential areas of growth, within the utility that can further benefit from digital twins and where some form may already exist.

Distribution System Modeling: Digital twins are especially useful for a utility trying to decrease the number of models that are used throughout the company [37]. Typically, each division has their own model of the power system and it may not be the same relative to other departments. Establishing a digital twin can help standardize the model to ensure the calculation's accuracy [37]. Digitization of energy systems also increases monitoring and control by finding anomalies, exploring different behaviors, and recalibrating the system [24]. Modeling the distribution system with the integration of distributed energy resources and online measurement increases system situational awareness, stability, flexibility, and power quality [22]. There are also improvements in the assessment of supply, state estimation, and monitoring voltage in the system [22]. Exact digital twins can be used for power flow optimization [6].

Distributed Energy Management Systems: There is a proposition to integrate the use of digital twins into distributed energy management systems due to its ability to create and edit the virtual system easily and form the virtual models to replicate the physical one [31]. Traditional networks utilize a radial configuration, but the integration of distributed generation sources have created new networked configurations. Digital twins are proposed as a solution to model these changes and the change in power flow throughout the system. They can also help visualize the functioning of the system and show power flow, interconnections, and instantaneous values, which help with system management and analysis. The virtual space also allows operators access data from the sensors and control them remotely. Digital twins offer a higher fidelity for load models, which classically come from historical and forecasted data. The sensor measurements that are recorded in the virtual space more accurately represent the real-time activity of the given load.

Operation Centers: Power system operation centers want to increase their observability of the power system to increase situational awareness. Digital twin implementation makes this possible in addition to the ability to project future states, which is a powerful tool for the control centers. The purpose of control centers is to limit disturbances within the grid and have a reduced reaction time if anomalies occur before it causes more disruption [7]. Smart grids and other power systems have a high reliability on digital communication and networks [9]. The high volume of data within these signals require constant communication and monitoring to ensure the passing of accurate information for analysis. New data exchange is based on short, frequent messages between the control center and the field, or vice versa. With all the new sensor data that is available to the operators, a digital twin enables a method of quickly processing the high volume of data and providing real time assessments that are continuously updated [7].

Fault Diagnosis: Digital twins can also be used for design methodology, mathematical analysis, simulation, and experimentation for fault analysis [16]. Research shows that the digital model increases the system's ability to identify faults [16]. This ability to self-diagnose is important to decrease the system vulnerability [9]. In addition, by identifying potential issues, the system can learn how to self-adapt and heal to reduce operator intervention, increase the lifetime of the system, and increase the reliability for consumers. Fault diagnosis can also use deep transfer learning to autonomize fault detection. The proposed model in [33] can account for insufficient training data based on simulation results. They use deep transfer learning in areas that do not get sufficient data from traditional fault detection methods to increase its ability to identify potential faults, thus improving its accuracy in fault detection.

Battery Systems: Batteries are one of the most common forms of energy storage on the gird and are used to strengthen the distribution system. Battery management is important to know the performance of the system and ensure its safety and reliability [19]. IoT has made it possible to monitor the status and data within the battery system to create a digital twin that can help diagnose and make future predictions on its function, life, and performance. Accurate modeling can help with state of charge and state of health estimations [19]. These models help account for battery degradation, efficiency, and lifetime in system planning and update these values as needed based on current battery behavior.

Renewable Energy Generators: The Institute for Drive Systems and Power Electronics also advocates for the need of digital twins to model large generators in order to increase the reliability of renewable energy [10]. Creating models of renewable energy systems allows researchers to model the inconsistent, fluctuating generation and find solutions to compensate for demand discrepancies. In [10], the author proposes the use of a digital twin to create a multi-domain live simulation for wind and hydro power. This system has been partially constructed in the Generator Converter Lab at Leibniz University Hanover. With a physical, large generator lab, it has the potential to connect their experimental test bench with a digital representation for data acquisition and modeling [10].

2.2 Digital Twin Composition

The components within power systems digital twins are typically categorized into three layers or components. The first component is the *physical model* [28]. In power systems, this contains the smart meters, appliances, electric vehicles, measurement sensors, controllers, and many other devices [4], [32]. The sensors are meant to acquire voltage and current signals from the inverter and pass them to the controller [32].

There is also the *application layer*, or *virtual model* [28], where there is a virtual representation of the physical model in a software [36]. This is an interface where engineers can work on development, manage the physical infrastructure, and analyze real time data to be used for decision making [4]. The virtual layer also houses the data libraries for models, environment states, and optimization parameters [4].

Last, there is the *communication layer*, or *hybrid layer* [28], which is the connecting layer between the physical and virtual models and houses the communication protocols and transferring data [4]. This component is the link between the real and virtual space where data processing and decision making happens [36]. This can also be seen as a decision-making layer since this portion of the digital twin is where algorithms, mapping, and monitored data is found [4].

Figure 1 shows the connections between the three layers of the digital twin and how each of their components interact with one another in the transmission of data. The blue box surrounding the entire system represents the digital twin structure. Within it, there is the physical model shown in gray around the controller, power system components, and sensor blocks, communication layer shown in orange around the AI and ML training block, and the virtual model shown in yellow around the simulation model block.

Data is derived from devices within the physical system by data acquisition devices, such as sensors and phasor measurement units (PMUs). That information is collected and sent via communication networks to the virtual space in real time [36]. The virtual model will process the information and perform necessary analyses before sending the results (e.g. commands) back to the real (physical) space to be used for decision making or to create a closed loop control [36].

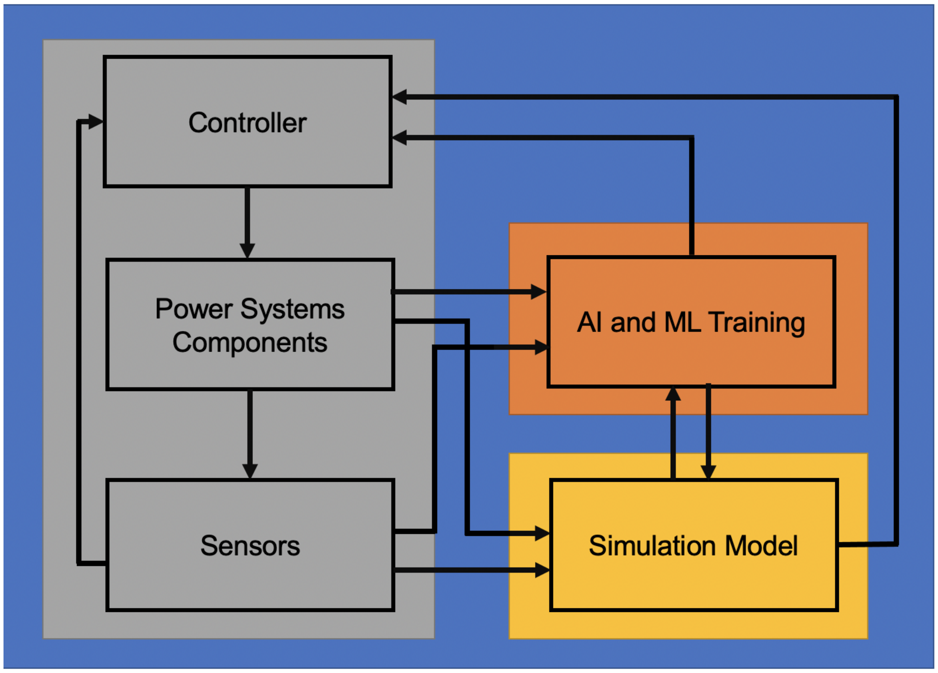

Figure 1: Digital Twin Composition

The digital twin can also act as an operator, which uses its decision-making control center to send packets of information and commands to the master terminal. The master terminal then communicates with the sensors of the physical environment to implement the given commands and return data back to the digital twin for further analysis and instructions [4].

2.3 How Do Digital Twins Work?

There are different modes of operations for a digital twin. The comparative operation is used when the theoretical model is considered an approximation to the actual power system [32]. Independent operations are used to calibrate the system and are able to disconnect while maintaining the characteristics of the grid to run simulations and experiments [32]. The runtime operation executes both systems simultaneously enabling comparisons and verifications [32].

The system learns its behaviors based on algorithms. Many times, when humans perform the analysis, there is a large list of rules that need to be followed [36]. The increased number of rules add to the complexity of the system and increase the number of interconnections, thus making it more difficult to memorize all of them. In a digital twin, these rules are digitized so the system knows what to follow and are easily updated. They can also adapt their tolerance and be modified as seen fit [24]. Constant monitoring of these rules allows the system to identify deviations from expected values and alert the operator if it is too large. A common goal is to computerize all the rules and allow the computer to work autonomously in decision making. Current implementations have the computer scanning through the rules; however, the operator is the one to make the final decision [36]. In power grid dispatch, there are a lot of rules that the operators are required to memorize and understand how to identify them. With increased complexity of the power grid due to newer devices, these rules are increasing and becoming more complex. Being able to digitize these rules will ensure all the rules are being followed.

Machine learning (ML) can also be used to improve the capabilities of the digital twin [29]. ML and artificial intelligence (AI) are studies of algorithms and models which efficiently perform tasks without being explicitly programmed [26]. Supervised learning helps in prediction (e.g. predict demand or cost) and inference (e.g. examine impact of features on response). Reinforcement learning helps in identifying the rules and policies based on data. All of these analyses are improved with more representative data and require efficient algorithms for mining big data [26].

Advances in AI and digital twins integrate to improve our understanding of the power system at a given instance [35]. Although smart power systems are able to monitor their status in real time while performing analyses with the given data, increased demand has called for further development in the current methods [35]. Using AI, the model can update synchronously with the physical system and develop a better understanding of devices, such as transformers and sensors, from around the system for analysis, such as fault analysis and life-time prediction. All these aspects can also improve the user experience and reduce costs [35].

ML can be used to analyze the security of the system (e.g. by identifying abnormal patterns). The training can be applied to the neural network to verify potential invalid inputs, for example due to faults or a security breach [36]. The beneficial part of using a digital twin is the constant access to information to update and retrain the ML algorithm with the most current available data. This can increase the security of the system by making the old data obsolete and invalidate the injected data.

3.0 Power Flow Challenges in Rural Circuits

Rural circuits are considered the weakest portion of the distribution network [34]. Rural distribution systems, by definition, are characterized by longer, radial feeders with fewer consumers per mile [12]. When looking in terms of reliability alone, it may appear as though those in rural areas are ”deprioritized” because their performance may not be as reliable as those in urban areas. Unfortunately, this is due to the population density as, in the event of large outages (such as those caused by storms), the priority is to recover power to as many customers as fast as possible, which can be most efficiently done by targeting urban areas first.

However, beyond residential homes, there are many facilities in rural areas that are essential to society. These areas typically require large loads for machinery, irrigation, and other typical electric loads on large scales [20]. When an outage occurs, this can cause productivity problems for these facilities. This not only impacts that farm or business but can also impact downstream consumers who will inevitably need the resources these industries produce. The integration of onsite or distributed energy resources is not common, thus there is still a high dependence on utilities for energy [20].

3.1 Adding Edge of Grid Devices

There is an increased interest for distribution systems to increase the number of newer smart devices into their network [23]. These devices can increase the visibility at the edge of the grid, which can be especially useful for rural circuits. The integration of sensing and measurement devices, automated devices, and other intelligent end devices will help distribution operators gain better understanding and control of rural circuits [23]. These devices will send data from the distribution system to operations within the utility to provide information, such as load consumption, that engineers can use to run studies and learn the behavior of their customers to provide ample support when needed. These devices monitor behavior of feeders such that outliers in behavior can be quickly identified, allowing the distribution network to actively respond to changes in a timely manner before larger problems arise. Some utilities even use the data they get from meters and sensors to predict the health of the devices throughout the system and to predict how much generation to purchase to meet the anticipated demand.

Another way to address customer needs with the integration of new devices is through the integration of distributed generation throughout the edge of the grid, specifically in rural areas. A promising candidate for this application is the combination of solar energy and battery storage due to their ability to support each other's weaknesses, as presented later in this thesis. Grid-connected photovoltaics (PV) is one of the fastest expanding renewable generation systems [5]. The integration of solar power on rural circuits converts the traditional rural, radial network into an active network [34]. Traditional distribution systems typically see one-directional power flow from the distribution source to the loads; however, integrating PV into the distribution network may create two-way power flow [5]. The integration of solar has some researchers concerned, as explained in a later section. By being aware of these concerns early on, mitigations can be made to try and minimize these negative impacts, such as through the implementation of battery storage along with the solar energy.

3.2 Control

To understand the impact of renewable energy and distributed generation within a rural circuit, one group created a comparison between two different utilities. In this case, one utility did not have any renewable energy, load management, or control while the other used supervisory control and data acquisition (SCADA) for load management and obtained power purchase agreements (PPAs) for renewable energy [20]. The team in [20] performed an evaluation that compared both system's behavior; it was seen that there was a significant difference in system losses and the team concluded that the utility with renewable energy had less loss throughout their system.

3.3 Voltage and Power Flow

A study in [34] uses a rural, poverty-stricken area on its network to see the impact on voltage regulation when installing solar power. Depending on the amount and location of solar installed, grid impacts will vary. It was found that increasing the overall solar output that is appended to the system will increase the feeder voltages. In addition, [34] was able to show that adding solar power to the loads further from the substation provided significant support to the overall system.

The addition of solar power at the loads would be beneficial for customers and residents in rural areas. This solar power will provide more localized generation in the event the main generation source becomes unavailable, and the introduction of solar creates a networked system rather than radial, which is typically more robust. Unfortunately, there are some concerns with the two-way power flow that may result when more solar is generated than required by the loads. When this occurs, there will be an excess of generation at the distribution side and the typical one-way power flow from the distribution substation to the loads will be violated [5]. This may cause issues with power quality, protection devices, and reliability.

Most of the impacts seen on the grid are located at network connection points such as overvoltage, fluctuation driven by the intermittency of solar power, and reverse power flow [5]. Although many researchers and engineers are aware of these potential issues, that has not slowed the implementation of solar power on the distribution system. Voltage stability and reverse power flow can be further rectified when a combination of solar power and battery energy storage systems is used, as proposed by researchers in [5]. Battery storage systems enhance solar systems by storing excess energy and discharging to smooth intermittency and help regulate voltages. This is referred to as the "Battery Energy Storage System allocation problem" where researchers investigate the ideal location and size of a battery to reduce power injection and absorption [5].

Implementing these distributed generation sources at sensitive busses, which would typically experience unstable voltages, can prevent voltage collapse through continuous power flow, as well as enhance loadability by minimizing reactive power losses [15]. Intermittent, non-dispatchable solar power is supported by the battery energy storage systems, transforming the variable renewable energy into a dispatchable source. Charging and discharging the battery when there is excess or insufficient solar energy creates a more constant output from this system. The mitigation of solar irregularity throughout the day and storing any excess energy can also improve residential peak shaving during the day, improving the load demand from the generation system [15].

4.0 Can We Use Digital Twins in Rural Circuits?

Digital twins offer the opportunity to expand the capabilities of researchers, analysts, and operators by integrating newer technologies with older implementations. Applying them to power systems, subsequent devices, and methodologies can improve how we use and understand their current states. There is currently a lack of measurement devices in the distribution network, so utility operators have no knowledge of what is occurring throughout their systems. Incorporating a digital twin requires measurement data to be collected to properly build the model, thus providing the operators more information about what is occurring in real time. They also help integrate machine learning and artificial intelligence to expand the operator's capabilities and autotomize the system. Security can also be improved and easily validated through the creation of digital twins of distribution systems.

This implementation can not only improve the visibility of rural circuits, but this two way communication will also allow operators to make informed decisions and potentially act prematurely rather than after an outage or failure occurs. In order to start accomplishing this, first a base model of rural circuits need to be constructed. This model will help build a foundations understanding of current behaviors. Once the existing system is developed, tests and changes can be made to see how the system would react. Incorporating newer devices will help depict theoretic future scenarios that can be easily manipulated and provide data will help bolster the system. For example, it is predicted that there will be an increase in energy storage and solar at the grid's edge, so these models can demonstrate how newly added devices will affect the system and how changing certain parameters can control these devices to support the rural distribution system in other ways.

With digital twins being a reasonably new implementation due to the other forms of technology it incorporates, it is important acknowledge there are still some challenges, known and unknown. First, there would need to be an accurate representation of the model and continuous calibration between the physical and digital systems to ensure an accurate analysis [24]. It is also important to not present all potential anomalies, only flagging and reporting those that are relevant and pressing. This should be learned by the system and developed using machine learning, however, the computer's interpretation may be unreliable. When analyzing a distribution circuit, it is important to prioritize the different warnings since some may be preventative, such as feeder that is close to overloading on a hot day but functions normally during typical conditions, or critical, such as a device failure or consistent overloading. Some other common challenges are application differences in time critical, safety, and mission critical services. There is also the need for interoperability, security, dependability, sustainability, reliability, and predictability [26]. The success of the digital twin is based on its two-way communication and ability to adapt to system changes, which may be hard to constantly update. Finally, the digital twin should be user friendly with a certain level of transparency so it can be easily used, evaluated, and monitored [26].

The use of digital twins as a method for increasing visibility at the edge of the grid is a promising solution. It is important to understand and recognise the benefits and potential concerns with this usage and preparing for all outcomes. The following sections explain some of the concerns in both of these areas and how they may be mitigated.

4.1 Digital Twin Vulnerabilities

When applied to digital twins, common attacks require different approaches to a solution or preventative measures due to the construction of the system. For example, a denial of service (DoS) attack is known for impairing a system by sending overwhelming amount of fictitious information packets and draining system resources. Due to the use of wireless connections, especially in smart grids, there is an increased vulnerability to this kind of threat [4]. As a countermeasure, if data is interrupted, the digital twin is deemed ineffective and the physical system will default to using SCADA for its measurements. Having these two systems integrated at the same time allows for a sense of redundancy in the acquired measurements, so the information going back to the utility can be verified. By having a data-monitored system, the available time stamps alert the operator as to when the attack occurred and which parts of the system were affected [9]. Another security threat is false data injection, which is more difficult to execute since the attacker would need to inject data that would align with a real-world solution to not alarm the system. This would require more knowledge of the current system settings and performance, which is hard to identify and accurately predict. In addition, to be effective, the data would have to be realistic to not set off any alerts to the operator, which takes further planning and personal analysis. This also applies to a man in the middle attack, where attacker intercepts transmitted and received data between two end-devices and may inject its own while the end devices assume they are communicating directly. This can be mitigated since the digital twin can identify unnatural changes in the data that is being received from the digital twin and compute the probability the data is true or not. Yet, well-crafted attacks may go unnoticed if proper security measures (e.g. authentication, authorization, encryption, etc.) are not applied.

With the increased use of IoT in power systems, there has been an increase in system vulnerabilities, especially due to the inability to track the security on so many devices [4]. For example, a security weakness in an IoT system is in regard to their end-devices (e.g. smart meters), which may not have computational resources to apply complex security measures [21]. These devices constrain the security of the system. To improve the security strength, these devices need to account for authentication and confidentiality when sending and receiving data [21]. Vulnerabilities can also be addressed via how the model of the system is set up and taking a whole system security approach to ensure the end-to-end security in the system. This would be executed by adding a security layer over the entire system that is able to validate the data integrity, as well as validate the physical systems operations and detect anomalies if present [21].

In using cloud technology for big data, there is the removal of the central control center, which can increase the number of attacks and make the system more vulnerable to coordinated attacks [28]. However, if these attacks are anticipated, using a digital twin in the cloud can allow the system to be tested and learn how to defend against them [28]. This was tested in [28] and was found to be able to correctly identify when an attack was occurring as well as identifying the compromised agents of the attack and isolating them from the healthy ones. Other digital twin cloud services, such as Azure, take extra precautions to decrease vulnerabilities within their systems to ensure users a certain level of security for their data [30]. Using the cloud technology, however, also raises some privacy concerns.

4.2 Distributed Device Concerns

Digital twins are not going to be the only area vulnerable to these potential threats. Battery storage devices alone face concerns regarding its physical and cyber protection. In some cases, these concerns are tied to one another like [17] demonstrates when expressing their concerns. [17] proposes that there are some susceptibilities battery energy storage systems are vulnerable to, specifically cyber threats, which may cause physical damage to these systems as well. One specific example that was used is the cybersecurity threat of manipulating the monitor outputs of these batteries. Through the manipulation of the state of charge reading, the storage controller may charge or discharge and non-optimal time frames, potentially accelerating battery degradation, or even putting unnecessary stress or strain on the distribution system. These small manipulations can cause dominoing affects on downstream devices.

There are also some areas that cause concern for solar panels. Although photovoltaics are one of the the most common forms of renewable distributed energy, there are many factors that can affect their performance. In order to function, these panels ideally require constant contact with the sunlight. With residing outdoors, these devices are subject to all weather conditions, which can leave the panels vulnerable. Bad weather not only blocks out sunlight, but wind and water can lead to deterioration and corrosion of the metal components[2]. In addition, flying debris can cause damage to the panels, decreasing its efficiency and increasing maintenance costs [2]. These poor weather affects may be obvious, however, there are instances where good weather is also unideal. Even though photovoltaics require sunlight to produce energy, they have an ideal operating temperature range. If this temperature grows too high, the panel's performance may change and the panel's energy production will decrease [2]. Unfortunately, this is a negative constant cycle. Solar panels are energy producers, using solar irradiation as its fuel. A byproduct of this power generation is heat that gets dispersed on the surface of the panel, thus heating up the device, slowly decreasing the efficiency and degrading the panels.

4.3 How to Mitigate These Issues

Creating a standard for smart grid cybersecurity and understanding potential vulnerabilities can help form a strong defense that can monitor and mitigate security threats [4]. A cybersecurity threat compromises the integrity of any system and threatens the main purposes and functions of the system [4]. The cybersecurity system is also becoming more complex with changes in infrastructure communication, control, smart meters, and PMUs [28]. By creating a replica of the physical system using digital twin, more accurate data representing complex physical processes can be obtained. This would hence enable investigating complex attacks via simulating the physical system and paves the road towards developing advanced secure protocols for detecting and identifying attacks in designing a resilient power system.

Not only are cyber standards being proposed, but also improving implementation standards for these new systems can help improve physical vulnerabilities. [27] proposes and uses a pilot test to demonstrate how arduous it is to commission a battery energy storage system with solar availability. This integration faced challenges around being able to seamlessly integrate with the existing distribution system, in this case, a system in Brazil was used. In order to execute this pilot, [27] indicated that the lack of national standards forced the team to turn to international standards to find the best guidance for integration. Through the use of standards from other areas, this team aims to build the foundation for their own national set of standards that work best for their country, ensuring there are properly trained technicians, regulatory studies, and adequate road maps to ensure a cohesive and properly functioning distribution network [27].

5.0 Implementation of Distributed Resources on a Rural Circuit

The goal of this thesis is to prepare a digital twin for rural circuits to get a better understanding of the impact of adding distributed generation within a provided rural circuit. The concept was derived from previous research in [34], evaluating the impact of solar on rural circuits, while trying to mitigate some of their concerns. The use of a digital twin, created by modeling different circuits in OpenDSS and driving changes via its COM interface in Python, allows the results to be comparable to what the existing system may expect. Through analyzing the behavior of isolated energy storage before adding other components, such as solar energy, we can have a better understanding of how the system adapts to energy storage and understand its own shortcomings that can be further developed. Then, the addition of solar is introduced to the system to see its impact on the overall power consumed by the system.

It is important to note there are some assumptions that are made due to the lack of these devices and measurements on the actual system. This model acts as a foundation that can be built upon for the development of a future, complete digital twin. In this case, the loads are assumed to follow a typical, duck load curve via OpenDSS's default values and the solar is assumed to generate energy based on OpenDSS's default behavior. The batteries are controlled based on parameters driven by the user. When real time load and solar data is available, the code has the capacity to change these default values with different datasets.

5.1 Implementation on Real Circuit

5.1.1 Model Construction

The following circuit demonstrates an existing sample rural circuit with realistic loading, device sizing, and distances. This circuit was provided by a utility who already created the base model for what already exists on their distribution system. The utility considers it to be poor performing, and thus, the proposed use of energy storage to help increase its reliability is simulated. Figure 2 provides a high-level overview of the circuit that is being used and manipulated and is plotted using the *Daisy Plot* feature in OpenDSS.

Figure 2: High Level Circuit Being Manipulated

The main node that was used as a parameter to search for was the connection node between a transformer and the existing load. Figure 3 shows a sample of how these components are connected and the bus that is being evaluated. Using these values and connected bus with OpenDSS's COM interface in Python, the code iterates through all the existing transformers and looks for ones that were attached directly to the load. When one is identified, energy meters, storage devices, and storage controllers were added to that branch. The devices that were implemented are the default components from OpenDSS.

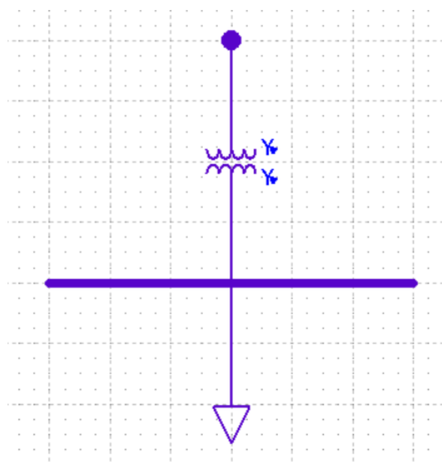

Figure 3: Realistic Circuit - Original Single Line of Loads

Once the ideal configuration was identified, an energy meter (circle with an M), storage device (battery), and storage controller (circle with a SC) are attached to these devices, as shown in Figure 4. The storage controller and energy meter attach to the transformer and the storage unit attaches to the active bus. Parameters of these new devices are dictated based on the existing devices. The storage controller is driven by default peak shaving capability, where its target values are 30% of the maximum and minimum of the original load curve for each individual load, calculated prior to adding the new components.

Even though the storage controller is not attached to the storage device, OpenDSS allows us to dictate the storage unit that each controller is meant to control, as shown by a dotted line. For this application, due to the nature of iterating through different busses, new storage controllers automatically pair with unassigned storage units. These pairings do not need to be explicitly written in the code and are matched by default. For the storage devices, it is assumed the power ratings are the same as the power of the existing load and their voltage base is the same as the attached bus.

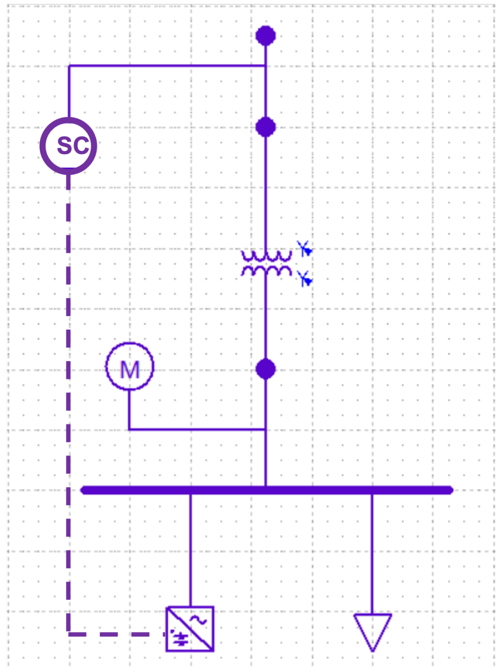

Figure 4: Realistic Circuit - Single Line of Newly Added Devices

5.1.2 Results (No Solar)

The initial results of adding battery storage to the same bus as the loads in the circuit are shown over a three-day period. Figure 5 demonstrates the meter data of the transformer (top) and the status of the battery storage (bottom) in all the meters and storage devices in the system. For this graph, and the subsequent graphs that have a similar configuration, each line on the graph represents a different meter and battery pair that resides on the system. These graphs represent the results of adding energy storage to every location where a load exists, where each storage unit is depicted with its own separate, individual line.

Figure 5 shows that the meter data is maintained within similar thresholds and is relatively flat. This is the 30% peak shaving that was implemented. Figure 5 also shows the behavior of the battery as it charges and discharges in the second graph. This shows that the battery discharges while peak shaving and then charges when the load is below the low threshold of its range. Unfortunately, the overall energy stored in the battery slowly de-

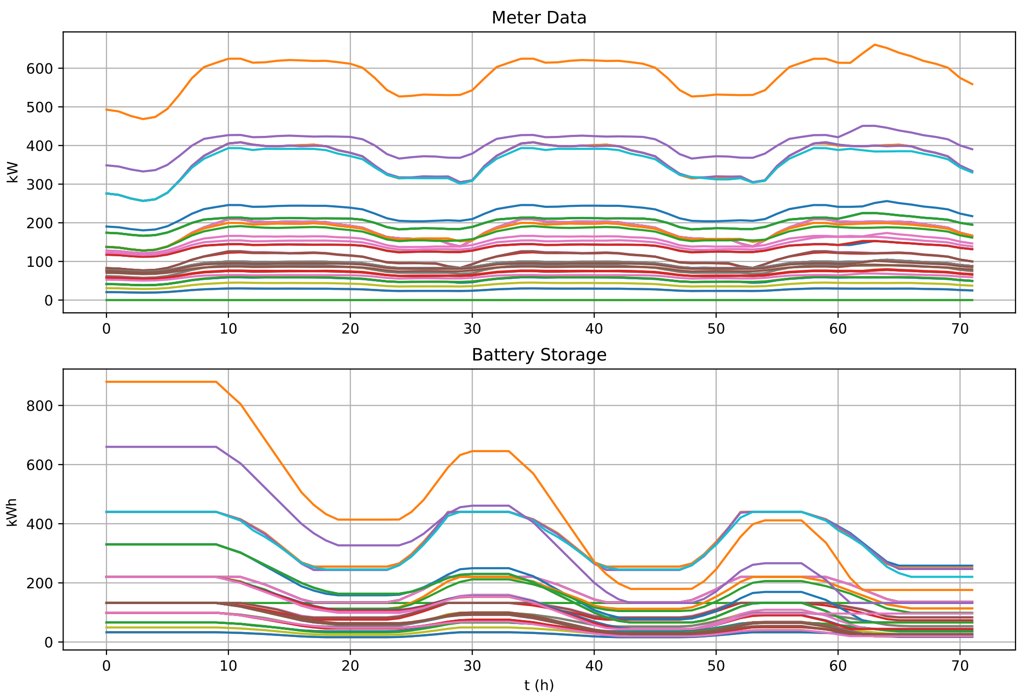

Figure 5: Realistic Circuit - 47 Meters and Storage Devices No Solar - 100% Penetration

creases over time. This signifies that at some point, there will not be sufficient energy to continue to peak shave. This slow decrease is due to the rate of charge and discharge that are set by the battery's parameters. This may be mitigated by the use of different settings for the rate of charge and discharge or the use of a more realistic load curve that is not the same every day, like the default daily curve used. Not only would batteries help support the solar panels as explained in [5] regarding the "Battery Energy Storage System allocation problem," but the use of solar may provide more support by decreasing the load curve, thus requiring the storage device to become active less frequently.

In addition, the entire system's load demand is plotted and compared. This value is read from the meter that sits at the substation of the circuit. Figure 6 shows that the overall peak of the system decreases with the integration of energy storage. This demonstrates that energy storage can provide support to the rural circuits. The integration of batteries, during a typical day, can help provide peak shaving and decrease the system demand and strain. Although there is an increase in the minimum load, that is not a concern because fluctuation in overall demand is minimized, thus requiring constant power, which is more ideal.

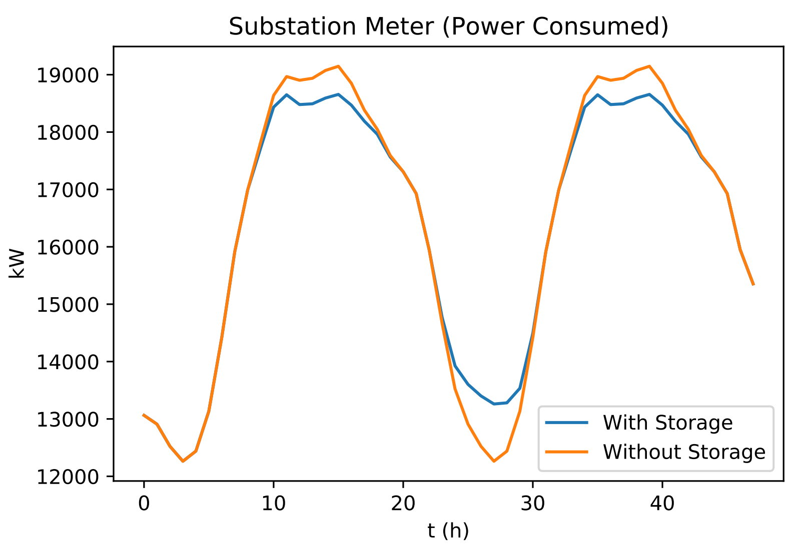

Figure 6: Realistic Circuit Substation Meter No Solar - 47 Storage Units

Adding energy storage can help decrease the overall demand seen at the substation, without interrupting the performance of the loads. As shown by the graph, the peak decreases by 2.56%, showing the relative effectiveness and impact of the addition of energy storage. The decrease in peaks shows that the batteries have the capacity to store, and potentially provide, a significant amount of energy to the grid that may be able to help with reliability issues, as presented in a future section. In addition, through varying the penetration levels to a more realistic amount, it can be seen that there is still a positive impact, as shown in a future section.

5.1.3 Results (Solar)

The integration of solar onto the system was also modeled. In this case, the use of the OpenDSS *Distribute* function places new *Generator* devices based on user defined parameters for the number of loads to skip and the total capacity of generation desired for the system. For this application, the skip value was 15 and total capacity was 2000kW. This generates a methodical, "random" placement of generation devices throughout the circuit. In order to change these generation devices to mimic solar panels, the model type parameter is changed from a "PQ generator" model to a "constant kW, kvar, but current limited" model, as recommended by the developer. The new behavior of the meters and storage devices can be seen in Figure 7. When comparing with Figure 5, there is a shift in the magnitude of the meter's curves and there are even some batteries that do not discharge due to there being excess solar providing the peak shaving.

The only unfortunate part with this method is the the solar panels are not placed at the same nodes as the batteries. This can be seen by the different battery statuses where some are fully charged for the entire time period and others do not change from those depicted in Figure 5. Thus, the result is there is no precise way of knowing how the proper placement of the batteries and solar panels work together to further support the system. Attempts were

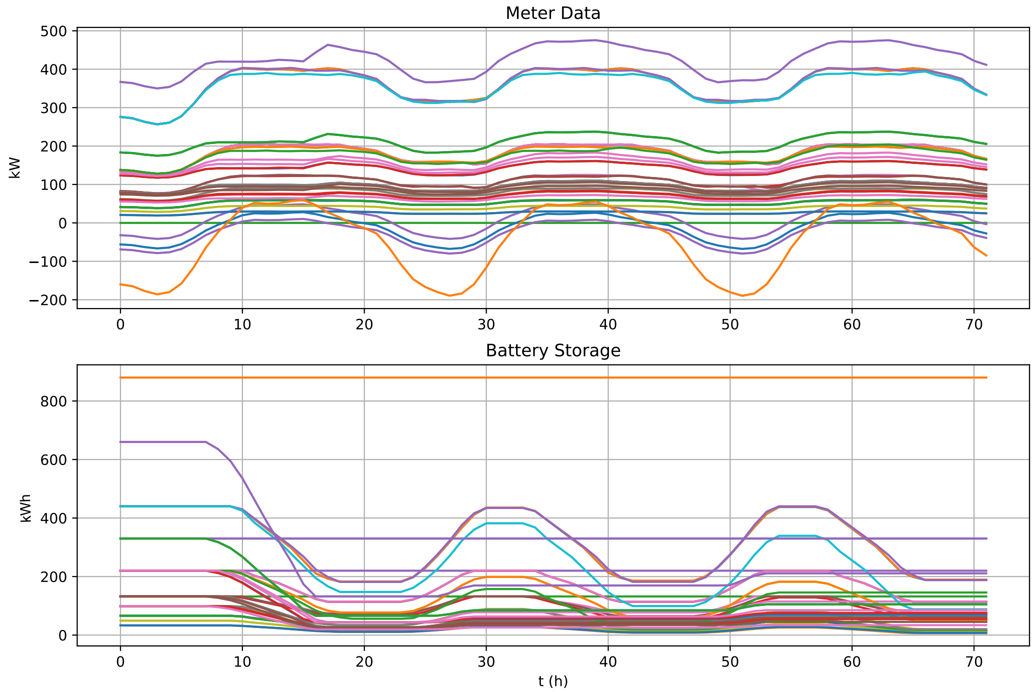

Figure 7: Realistic Circuit - 47 Meters and Storage Devices 2000kW Solar

made to manipulate the model in order to have this level of control, however, due to how the model was provided, this was unable to be completed. After communicating with the company, there was no way to verify the most accurate way of how their model was built, thus, a second circuit was used to verify these assumptions, and is shown in a future section.

Even without knowing exactly which areas overlap between the storage devices and solar panels, the observations from the substation meter, as seen in Figure 8, there is still a substantial decrease in energy demand. In this specific case, the decrease is seen to be 12.36%, which is significantly more than the percent difference shown in Figure 6 which was only 2.56%.

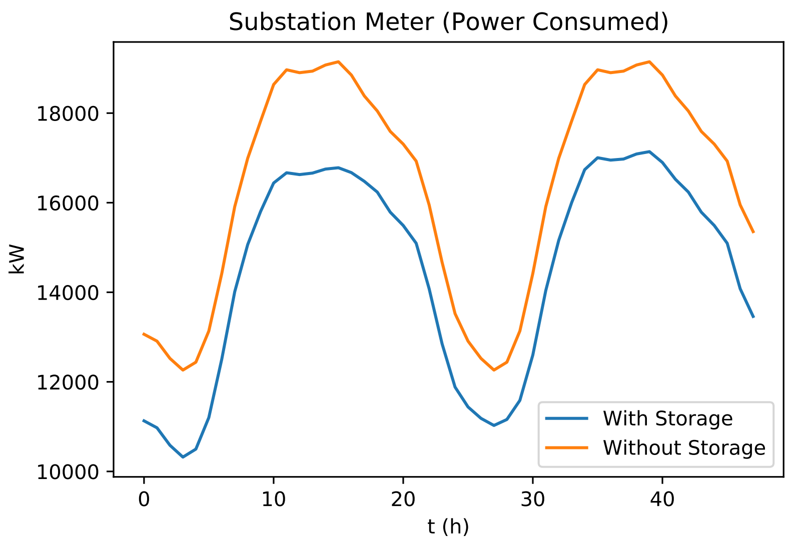

Figure 8: Realistic Circuit Substation Meter 2000kW Solar - 47 Storage Devices

5.2 Implementation on IEEE 37 Node Test Circuit

In order to test the functionality of adding battery storage and solar panels to different loads, the IEEE 37 Node System was chosen as comparison model since it is considered a standard system. In addition, there were a lot more certainties with the construction of the model and, since it is a smaller system, following specific connection points was easier than the realistic system with less manipulated parts. Figure 9 provides a high-level overview of the circuit that is being used and manipulated. The use of a IEEE Standard System is to verify that the results could be found on another system rather than an existing one in the distribution system.

The intention was to use the same code to do a one for one comparison with the realistic circuit. Unfortunately, due to the difference in construction, which will be shown later in this section, the code had to be modified to accommodate these changes. The construction of a second Python code to perform similar actions, in different ways, not only helped identify methods to help construct a more universal code, but it also allowed for the development of new implementations of the same processes to have the OpenDSS COM interface become less reliant on pre-built functions.

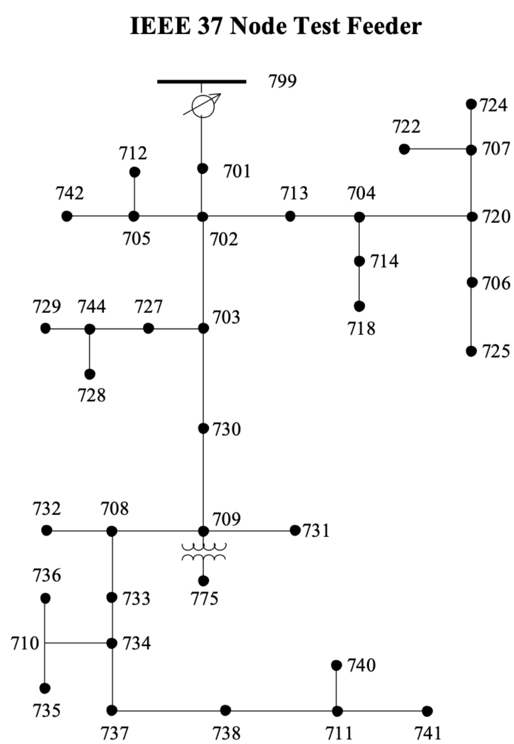

Figure 9: High Level Circuit Being Manipulated - 37 Node

5.2.1 Model Construction

Properly distributing devices throughout the system is the fundamental concept of the OpenDSS *Distribute* function. In order to figure out the accurate proportion of the newly added elements to the system, the proportion of the loads is used to make sure that all their sizes are comparable to what is seen on the busses. This is done by iterating through all the loads that exist in the system. Based on a user specified number that dictates the number of loads to skip, the code stops at each of those equally spaced loads in the order they are written in the code, to create both the storage devices and solar panels attached to those loads. As the program iterates through all the loads, when one of them is selected as one to be built upon, the code saves its power rating. These rating are summed up to find the total power and then the proportion is just the specific rating of that load over the total. The user will also indicate the total amount of battery storage and solar desired. The total power of these devices are divided among the newly placed generation and storage units proportional to the load it is being attached to.

Rather than using the OpenDSS storage controller, the storage units are driven by the Python COM interface based on user specified values for the batteriers. This choice was made due to the inability for the solution to converge. When using OpenDSS's storage controller, the solutions were not behaving as expected. By creating our own control scheme, it allows the user to have more power to change and manipulate the battery. It also puts less work on the compiling portion of OpenDSS to have more of the work occur within Python. This change was also beneficial for a future goal since it is the first step for future development in creating an artificially intelligent (AI) controller. More information and goals of this controller are mentioned in Future Work.

When looking at each branch of the system, the construction began as a load connected directly to the line, as shown in Figure 10. Once the loops of the code were executed, the final system was meant to look like the single line shown in Figure 11. It is important to note that in some cases there were multiple loads to a line. This caused issues when attaching the energy meter and the storage devices since only one meter could be attached to each line. Although we could have the meter monitor the multiple storage devices that could be added, it was found to be easier to skip the duplicate loads on the same bus so that when we monitor the storage device, its individual impact on the bus can be better identified rather than a combined contribution.

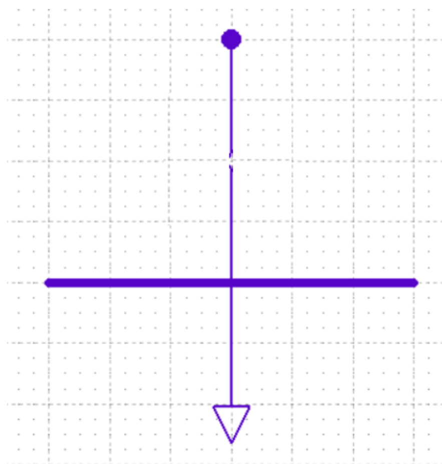

Figure 10: IEEE 37 Node - Original Single Line of Loads

5.2.2 Results (No Solar)

The first set of results is derived from looking at the impact of the battery storage alone. [34] has shown the impact of solar alone on their system, so it was important to make sure the storage system will behave as expected without other additions to the model. In this case, 2000 kW of storage was chosen as the base parameter with a skip value of 2. This meant that 7 storage units were added to random points in the system. Unlike the realistic system, this system is much smaller, thus less storage units will create a different level of impact.

Figure 12 shows the meter data (top) and status of the battery storage (bottom) for all the meters and storage in the system. It can be seen that after certain period of incline in the power read off the meter, it eventually plateaus to a relatively constant value before descending. Since the typical load curve was loaded in to represent the loads, it is easy to visualize the peak shaving that is occurring. In this specific case, like the controller that was

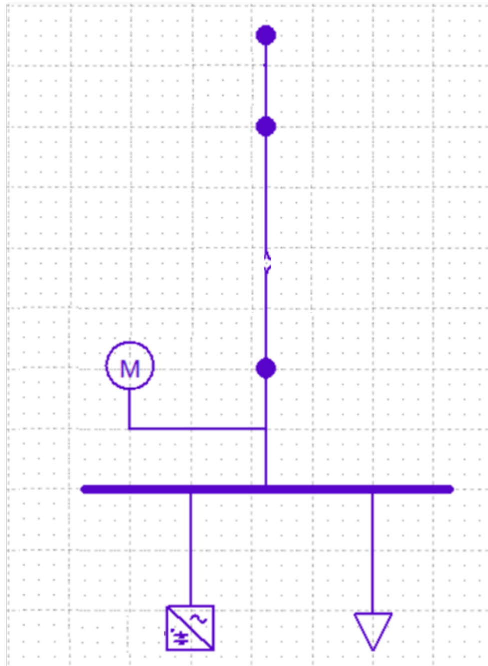

Figure 11: IEEE 37 Node - Single Line of Newly Added Devices

used in the realistic circuit, the battery was programmed to discharge when the load hits 70% of its peak, thus creating a 30% peak shave. On the other side, it can be seen that the valley of this system also plateaus a little higher than expected. During this period, rather than allowing the load to drop all the way to its minimum, the battery will charge.

In addition, the behavior of the entire circuit is plotted to demonstrate how this individual peak shaving of the loads through the use of batteries help support the system. With energy storage alone, the addition of 7 storage devices totaling 2000 kW, there is a 3.99% decrease in peak usage. Specifically, the consumption changes from approximately 2587kW to 2484kW. This can be seen in Figure 13.

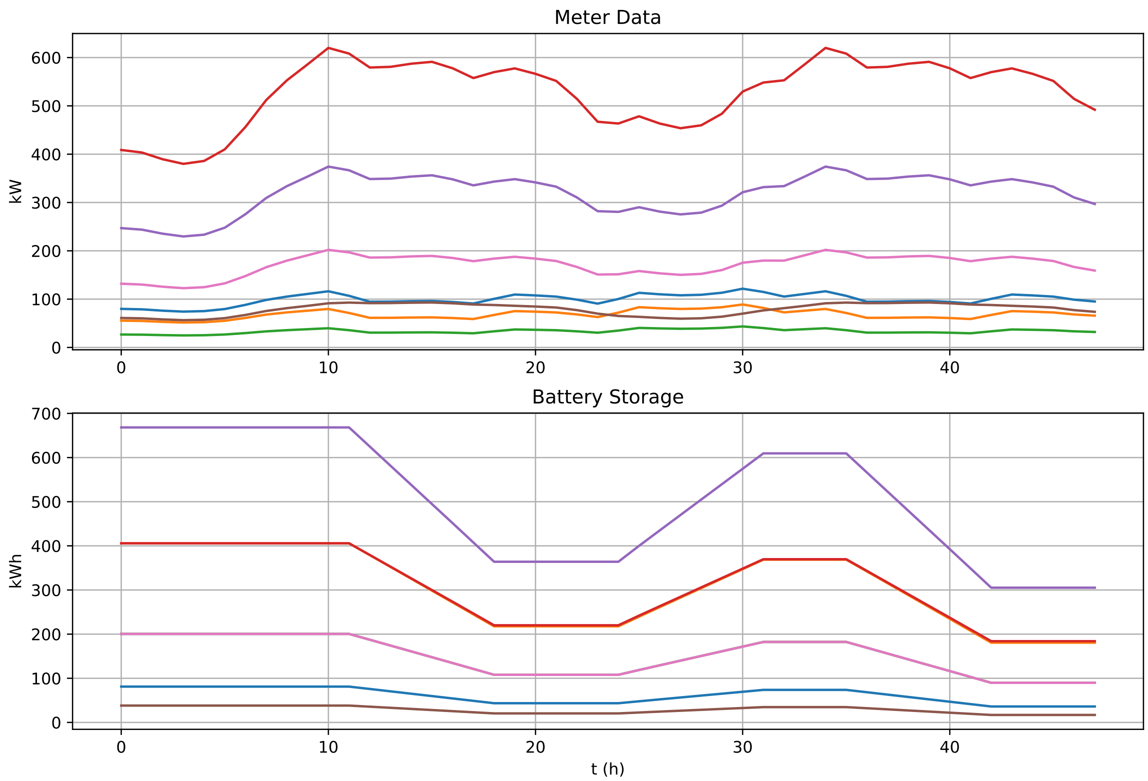

Figure 12: IEEE 37 Node - 7 Meters and Storage Devices No Solar

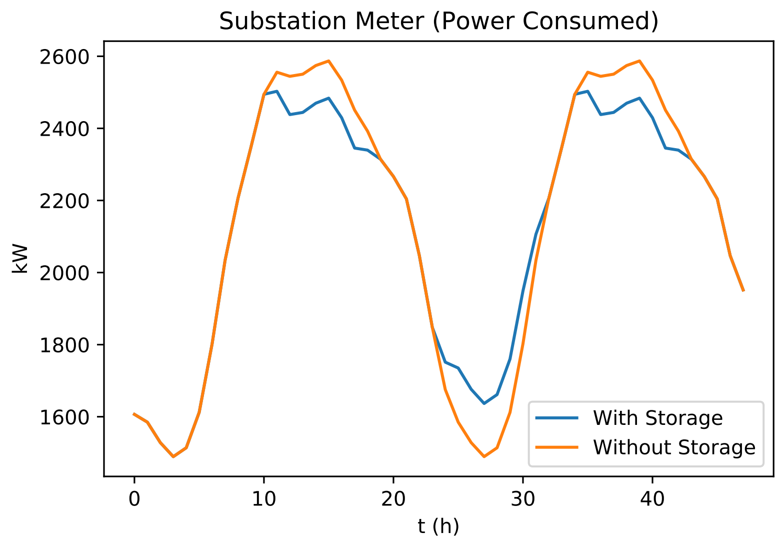

Figure 13: IEEE 37 Node Substation Meter No Solar - 7 Storage Units

5.2.3 Results (Solar)

Continued decrease in the system demand can be executed with the use of solar power as a method of providing an alternative, onsite source of energy for the circuit. In order to add this to our mode, using the same method of iterating through the loads for integrating, when the energy meters and battery storage devices are added to the system, solar panels are now added. These are created using the *Generator* in OpenDSS. These panels are similarly sized to the battery. The user is able to choose an overall total for how much solar power is added to the system and, based on the proportion of the load it is attaching itself to, the solar panel will also take that proportion of capacity. Using this method of distribution of solar panels, placement of all the new devices on the same bus can be ensured, thus the impacts can be more accurately traced.

Several total solar capacities are used to help show the different impacts that can be made. Starting with the smallest unit of measure, when only 10kW of solar generation is added throughout the circuit. The individual meter and battery graphs are shown in Figure 14. In addition, the substation meter is shown in Figure 15, which shows the shift in overall power consumption of the system. If comparing with the graphs of no solar, they appear to be very similar. There is a change in percent difference of 4.39% compared to no solar with 3.99%. Although this is not a large difference, it is still noticeable, and it is important to note that, for a large system, 10kW is not a lot of generation being added. Typically, one home sees an average of 2kWh of solar [18], so this would be equivalent to five loads adding panels to their home.

On the other end, if the solar system were to be approximately 100kW, there is a more substantial change in the meter and battery graphs as well as the overall system consumption. These outputs are shown in Figures 16 and 17 respectively. Although the overall shape of the curves are still similar, looking at the axes, the magnitude of power demand changes a lot more drastically for each individual meter as well as the system's meter.

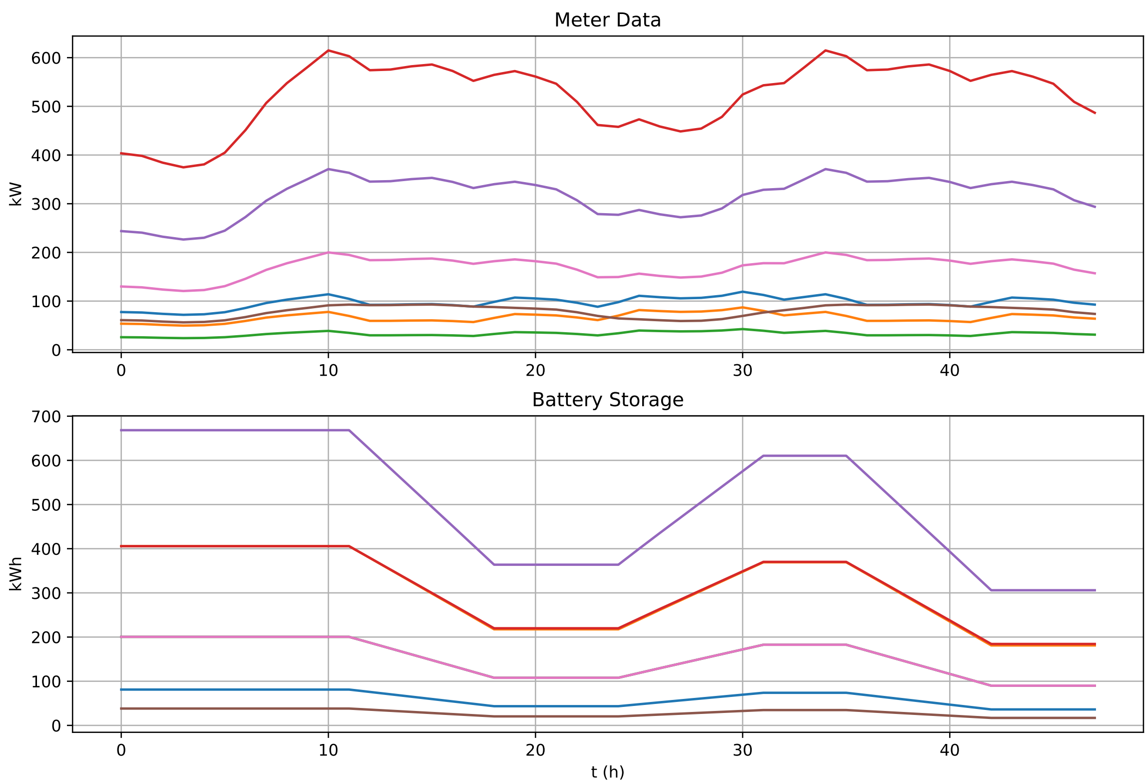

Figure 14: IEEE 37 Node - 7 Meters and Storage Devices 10kW Solar

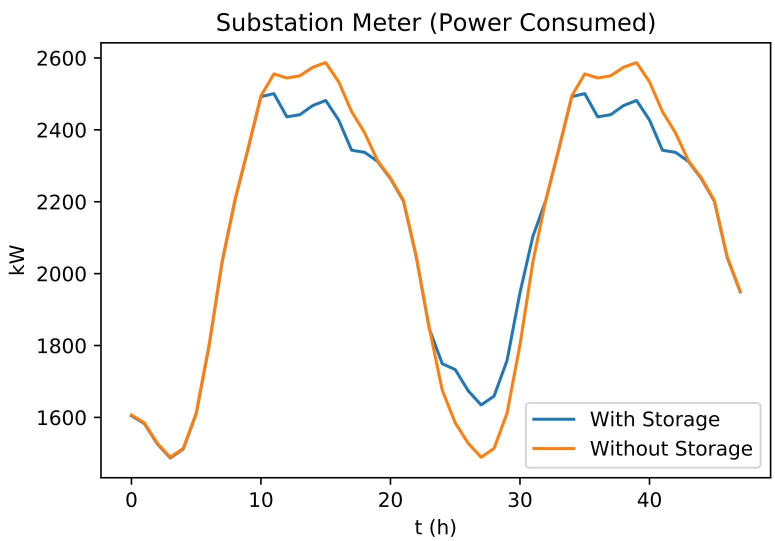

Figure 15: IEEE 37 Node Substation Meter 10kW Solar - 7 Storage Units

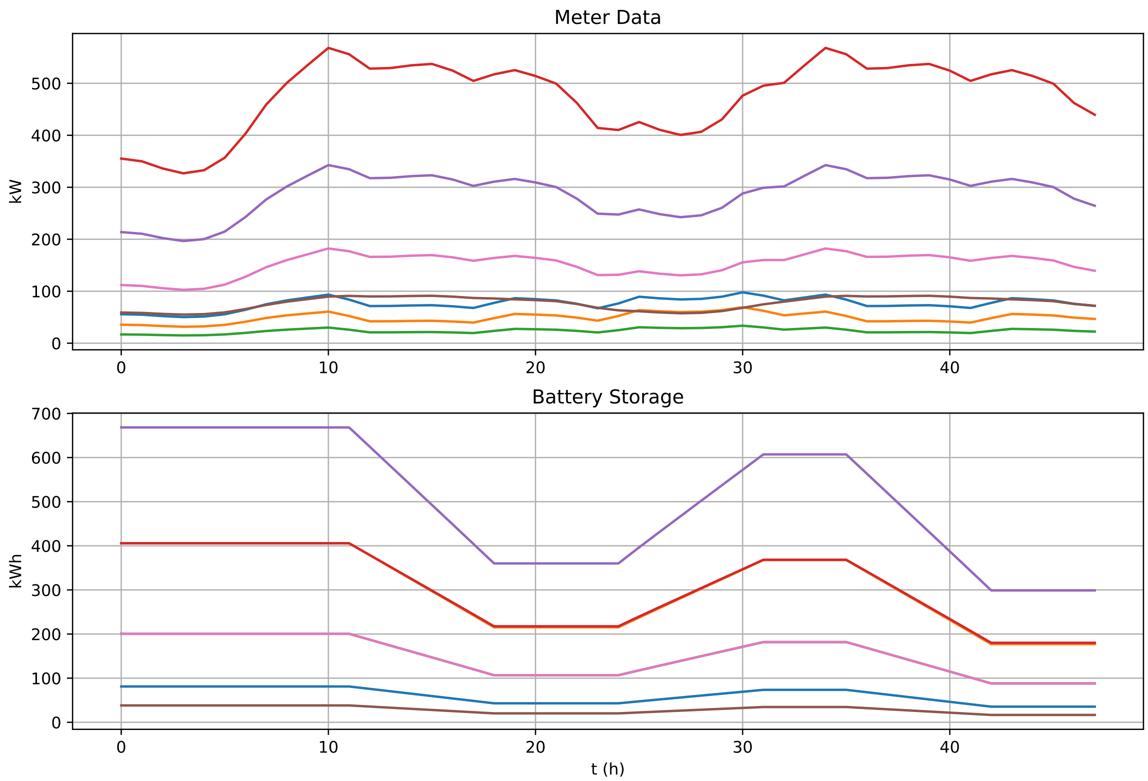

Figure 16: IEEE 37 Node - 7 Meters and Storage Devices 100kW Solar

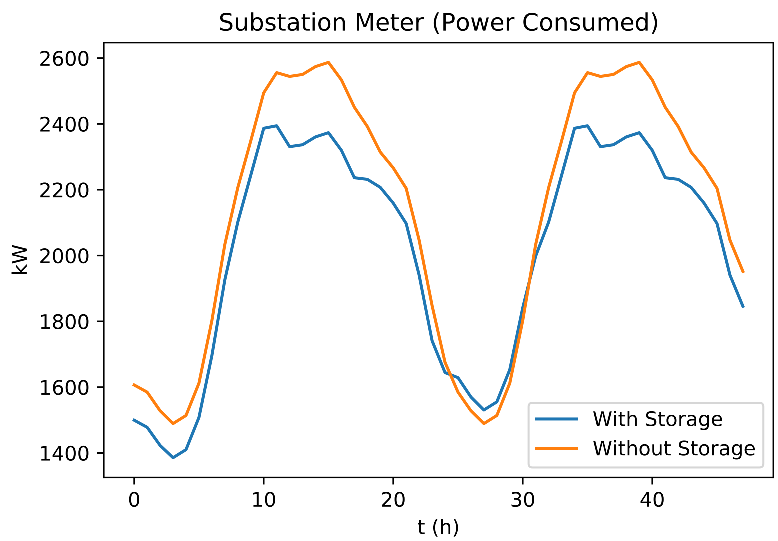

Figure 17: IEEE 37 Node Substation Meter 100kW Solar - 7 Storage Units

6.0 Impact of Distributed Resources on a Rural Circuit

Once newer devices are added to the system, there is a change in how the system behaves. Solar and battery storage integration provides a method to alter the power and voltages through the system. Several analyses are conducted to see how different quantities, sizes, and placements of these devices affect the system differently.

6.1 Varying Penetration Levels

To begin, the study analyzes different levels of energy storage penetration. This analysis is done on the real circuit implementation. The purpose of this section is to demonstrate how much of an impact, if any, varying levels of penetration provides. This section neglects the addition of solar to focus on the individual impact of the energy storage.

The benchmarking levels of penetration that are being compared are approximately 100%, 75%, 50%, and 25%. For this analysis, it is assumed that 100% penetration is where devices are placed at every possible location indicated by the code. This is accomplished by using the *random* function in Python to select the location of these storage units. The *random* function generates a value from 0 to 1 and if it within the ideal percentage range, the storage unit will be placed there. Due to the implementation of a randomized value, the number of storage units is not exactly at these percent divisions, but are close enough to see a general trend. In implementing these different levels, 47, 31, 19, and 12 storage units, respectively, are put into the system. The overall system load is compared to see how much peak shaving is supported through increasing numbers of devices.

The graphs of the different storage units in each level of penetration are shown in Figures 5, 18, 19, and 20. These figures follow the same trend as one another, demonstrating that they all behave independently of one another. The only difference is that there are different combinations of the original 47 storage unit graphs being shown. Please note that in Figure

20, it appears as though the batteries are not discharging over time. This is not the case; in this example, the largest battery discharges slower than the others because of its load curve. The depletion of the batteries is just a general trend and is more prominent than in the other implementations.

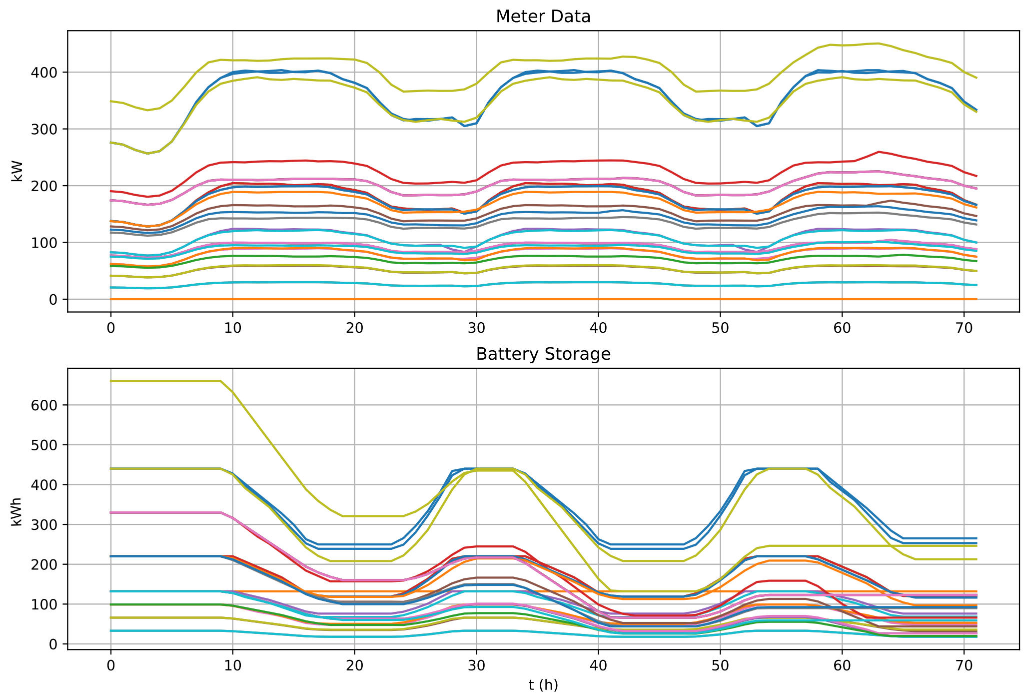

Figure 18: 75% Penetration, 31 Meters and Storage Devices No Solar

Although it can be assumed that 100% penetration would provide the most support, this analysis shows that even only 25% can create a positive impact on the system. Although the significance is less, it is a starting point for seeing how energy storage influences the

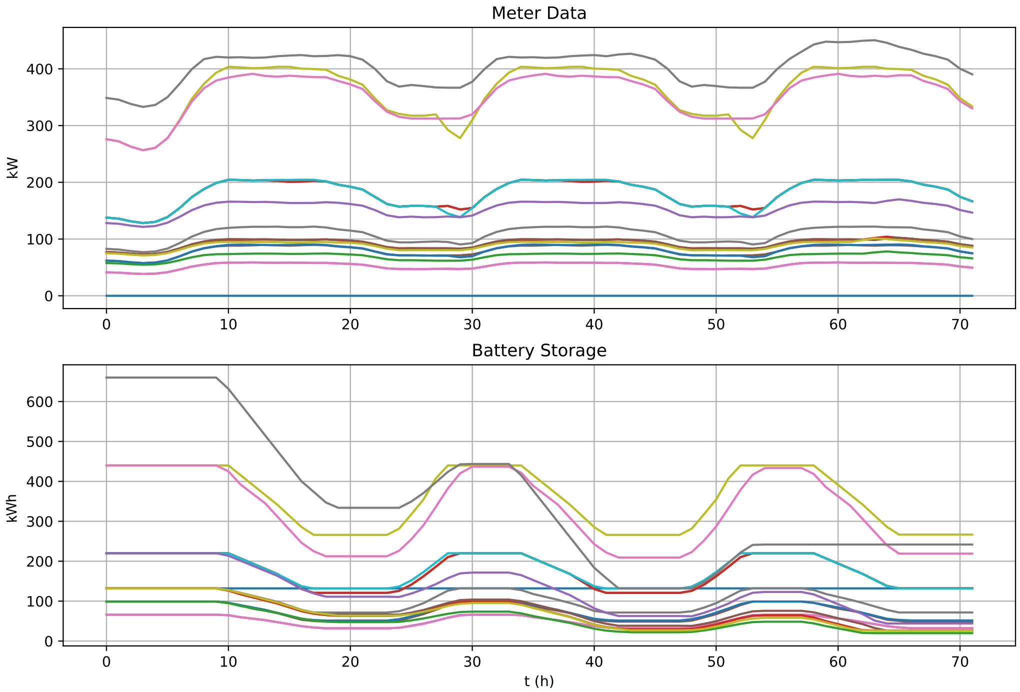

Figure 19: 50% Penetration, 19 Meters and Storage Devices No Solar

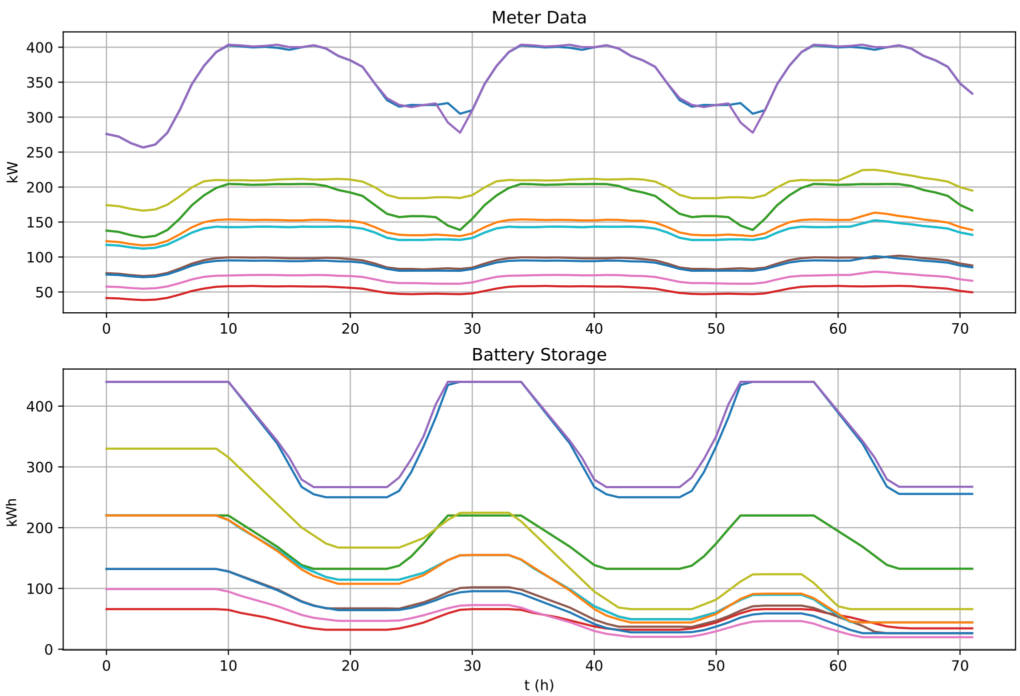

Figure 20: 25% Penetration, 12 Meters and Storage Devices No Solar

grid system, especially when comparing energy storage with electric vehicles. Figures 6, 21, 22, and 23 show the system graphs at different penetration levels. These penetration levels are shown at a substation level and compare a normal 48-hour load curve to a 48-hour load curve with the varying amounts of energy storage attached.

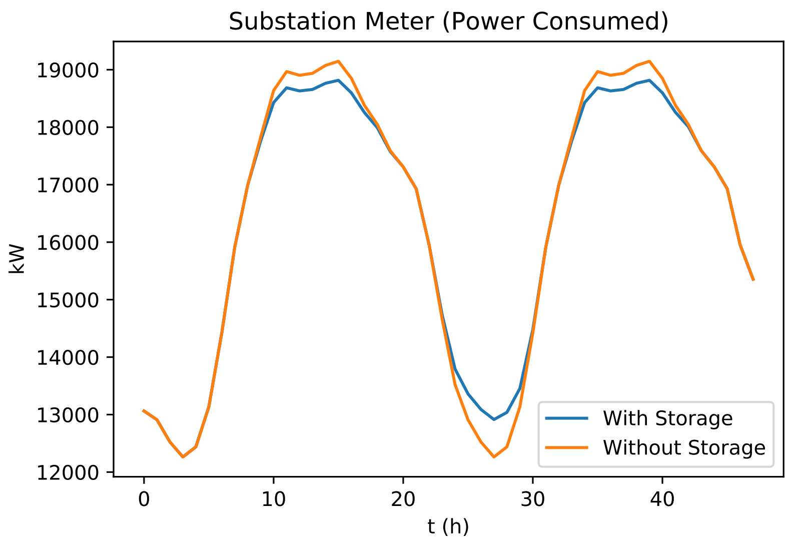

Figure 21: 75% Penetration System Load

The percent change in the peaks are then calculated and compared with one another to quantify the impact. These values are then compared in Table 2. It can be seen that even with a 25% penetration, or 12 storage units, there is a small impact. Even though it is less than a percent change, or even the small 2.5% change when using 100% penetration, it shows that improvement can be made by adding storage to the loads. In addition, the less than a percent change may not seem like a lot. However, it is important to remember this is read from a substation load. The power drawn here is typically in the megawatts, therefore 1% is still in the kilowatts of power.

One way to help increase the impact of energy storage on the circuit could be by adding storage at the utility level. This could open the opportunity of implementing larger sized batteries as well as increasing their number throughout the system. At this point, this is outside the scope of the thesis, but is being addressed as a future point of work.

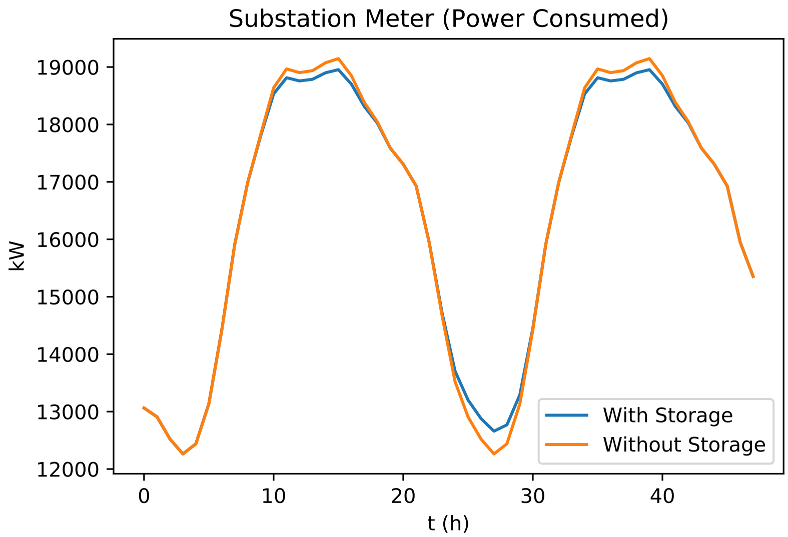

Figure 22: 50% Penetration System Load

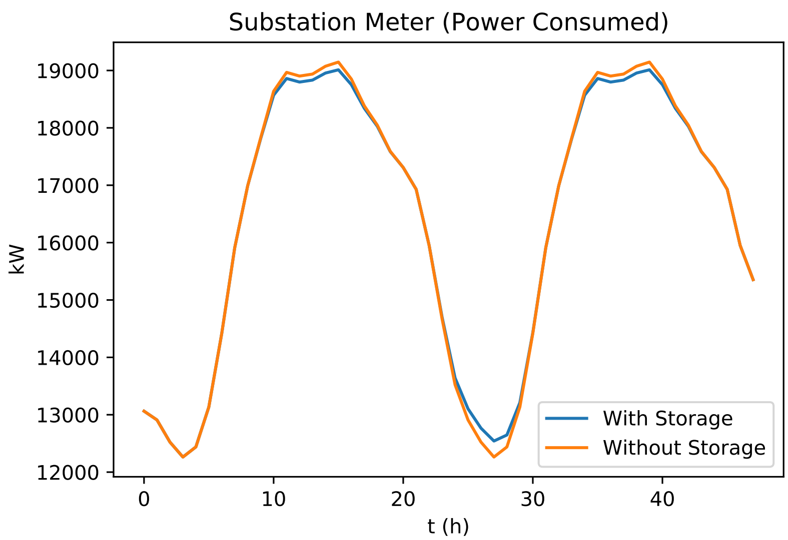

Figure 23: 25% Penetration System Load

Table 2: Variation in Penetration - Change in Peaks

Penetration %	**# of Storage Units**	**% Decrease**
100%	47	2.56%
75%	31	1.73%
50%	19	1.01%
25%	12	0.70%

6.2 Impact on Reliability

In order to show the impact on system reliability, the goal is to see how much capacity the batteries have and how long they can support the system given no generation support. In order to figure this out, the curve of one transformer and one battery device is used from each of the circuits. One random branch of the system is selected, like shown in Figure 4, where the storage unit is intended to support the connected load.

6.2.1 Real Circuit

When modeling the singular storage device of a device on the realistic circuit, as shown in Figure 24. Based on these graphs, it can be seen that the maximum amount of power that can be stored within the battery approximately 65kWh. Since the peak is similar to the battery, it can be seen that no solar resided on this bus. Given the meter data curve, focusing within the first 24 hours, the battery would take between 1 and 2 hours to discharge depending on the time of day and load. Due to the parameters given in this scenario, it just so happens that the size of the battery is approximately the same as the peak load, thus creating a short buffer time. If desired this time can be elongated by changing the size of the the batteries or adding solar to the bus. This time can also be expanded if the loads are shaved to critical loads or through the integration of solar power to add increased localized generation, but this is outside the scope of this work.

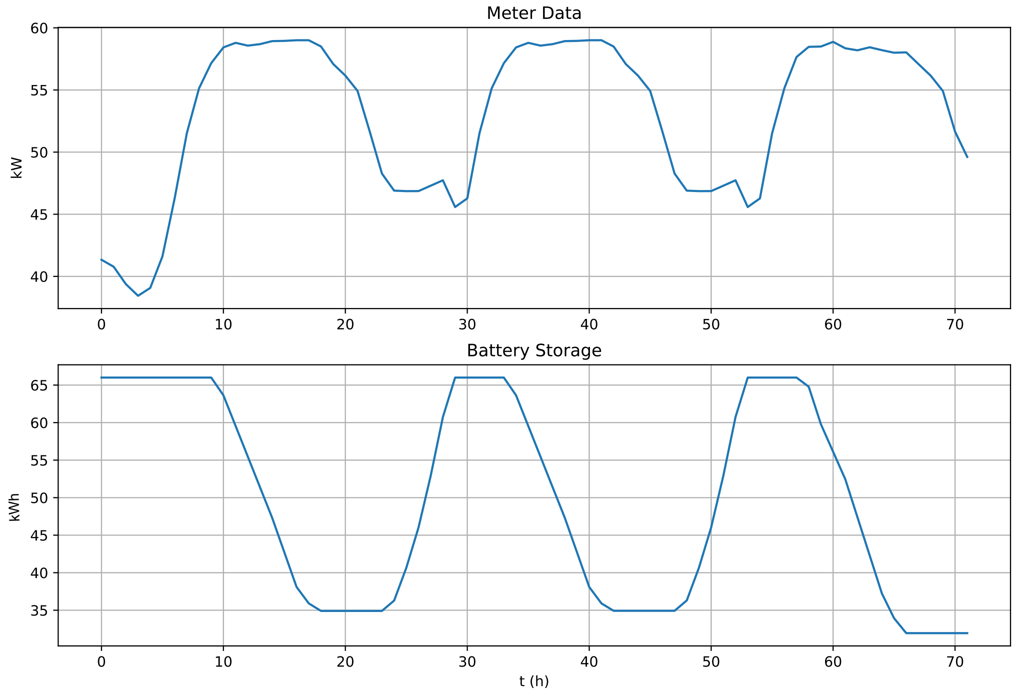

Figure 24: Realisitic Circuit - One Location of Storage Data

Although this may not seem significant, in the event of an outage, that is an additional hour gained to wait for repairs to be made. For rural circuits, this buffer time can be the difference between being suddenly out of power for hours or being able to prepare water, food, and other necessities to wait out an outage. Not only are rural circuits more vulnerable and suffer longer outage times, which can potentially be shortened as shown by batteries, but many customers also rely on well water and electric stoves. Being able to have an extra hour or so to properly prepare for an outage can add convenience and comfort to waiting out a storm.

6.2.2 IEEE 37 Node System

When extracting the data of only one meter from the IEEE 37 Node system, the battery's maximum storage can be seen to be 200kWh in Figure 25. The peak of the load is approximately 180kW, thus, the battery has the ability to provide power to the home for approximately 1-2 hours depending on at which point of the load curve and the current state of charge of the battery. The size of the battery and the load profile depends on the parameters chosen for the system. In this case, there is 100kW of solar power added to the system and 2000kW of battery storage.

To elongate this amount of time, as shown in a different configuration of Figure 26, the duration of battery life shifts from less than 2 hours at most to over 2 hours at any point in time given the battery is fully charged. In this scenario, where there is 500kW of solar power and 2000kW of storage, the maximum load is approximately 100kW while the maximum battery capacity is still 200kWh. In this scenario, even at the lowest point of charge for the battery, at approximately 100kWh, after a day of peak shaving, there would still be enough remaining storage to compensate for at least an hour's worth of load during an outage.

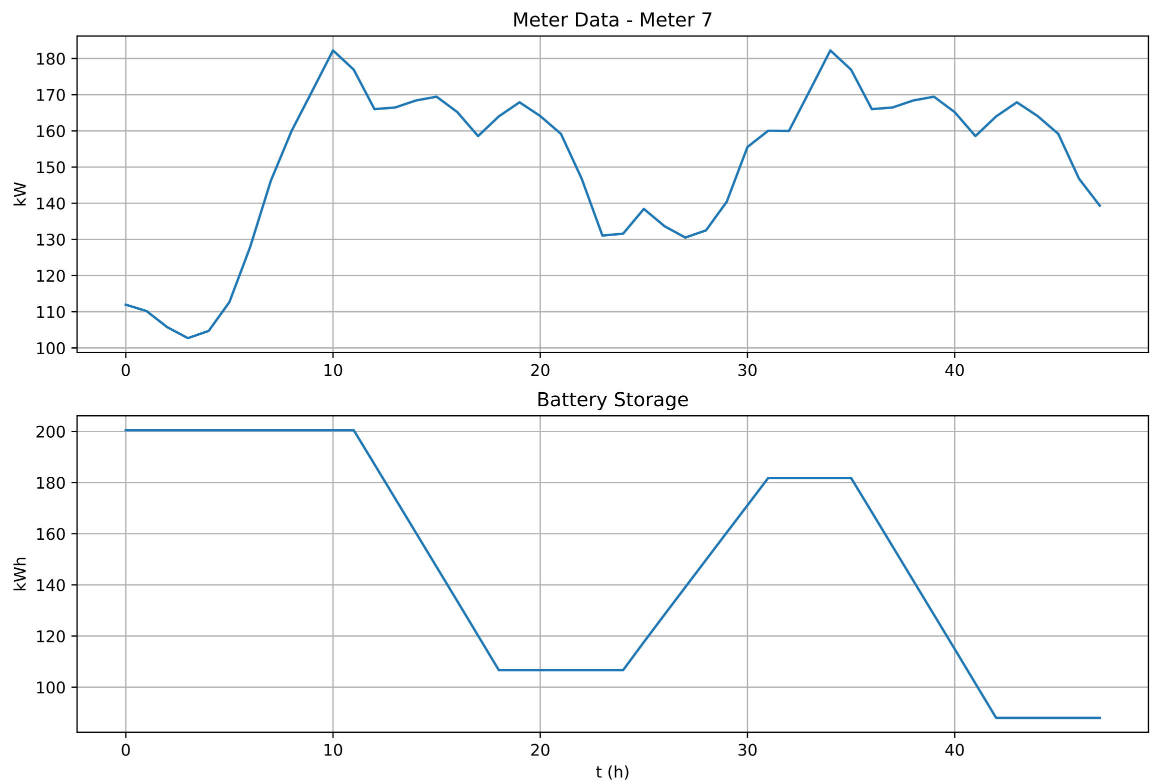

Figure 25: IEEE 37 Node System - One Location of Storage Data 100kW Solar

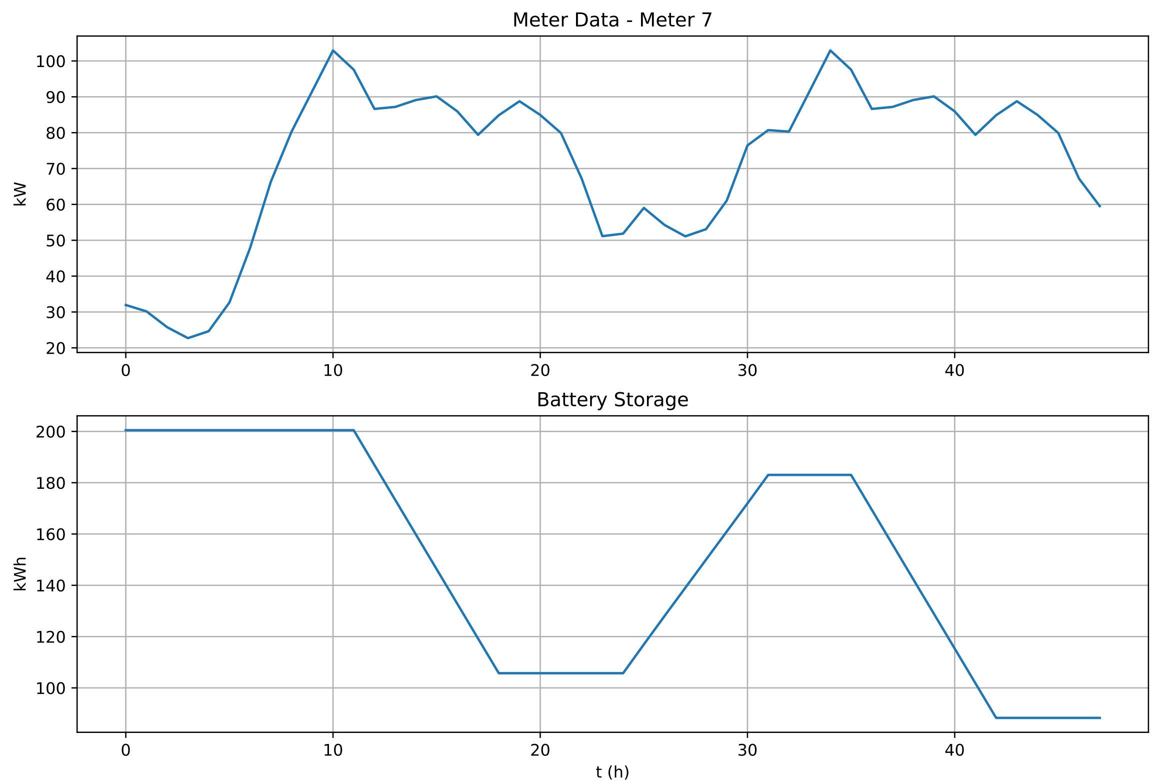

Figure 26: IEEE 37 Node System - One Location of Storage Data 500kW Solar

6.3 Optimization of Uniform Placement

In the previous portions of this thesis, an arbitrary *Skip* value was chosen. Rather than using a random value, some conditions and parameters are dictated to find the ideal *Skip* value in a user specified range. This value is meant to help build a foundational method to optimize placement of solar and battery storage devices. To begin this execution, the user is meant to provide values for the total desired kW of batteries they want on the system and desired kW of solar. These are done as user defined values since it is assumed that, in order to use this program, the user will know how much capacity they want to add, or are able to add. Based on those values, the code will iterate through a range of integers, in this case 1 through 5. Using a loop, the system is solved using the different *Skip* values.

Optimizing the entire system is done by evaluating the voltages throughout the system. By taking the measurements of the voltages from different nodes at different distances, the change in per unit voltages can be plotted. Figure 27 and Figure 28 plots the system voltages, which was used as the conditions for helping identify this *Skip* value. For Figure 27, each phase is in a different graph, and in Figure 28, they are overlaid to see how each phase compares to one another. A scatter plot is used to have a better visualization of each specific point that was being analyzed.

To maintain the integrity of the system, according to ANSI C84, the voltage should be within 10%, or +/- 5% of 1 p.u [1]. When choosing how to best add these devices, it can be seen that most of the instances have deviation outside the 10% bandwidth. This 10% range is based on ANSI C84's Range A for service. However, there is also a Range B, or +6%/-13% [1]. This range is meant to act as an additional buffer range that need to be satisfied, but is still viable for operating the grid. It is important to note that, even though this range is acceptable, it should still be minimized [1]. Thus, it is ideal to choose the least number of instances where the system is operating within this range and with the smallest amount of deviation. In Figures 27 and 28, these bandwidths are represented by the blue line for Range A and the red line for Range B.

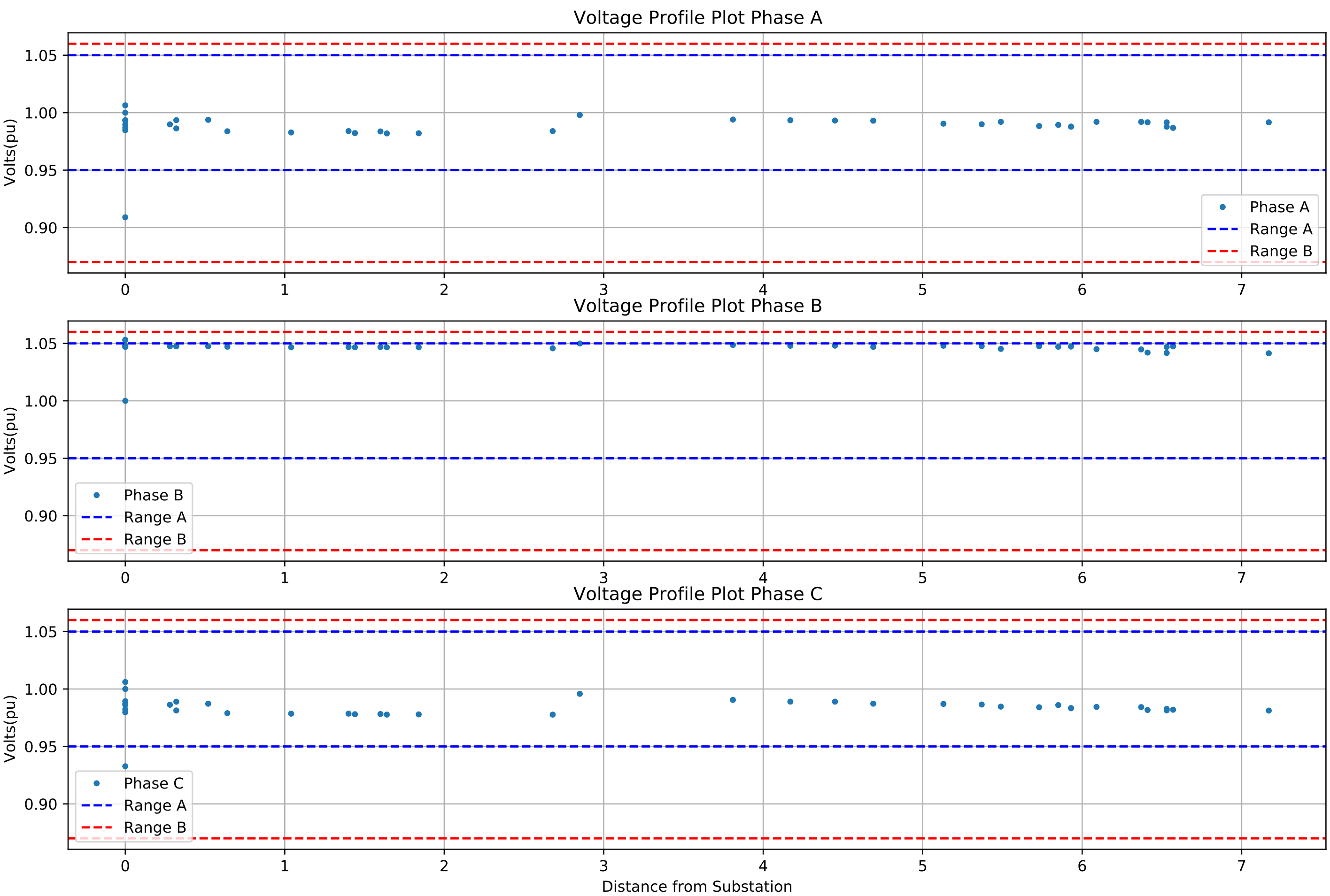

Figure 27: IEEE 37 Node System - Voltage Plot Separate

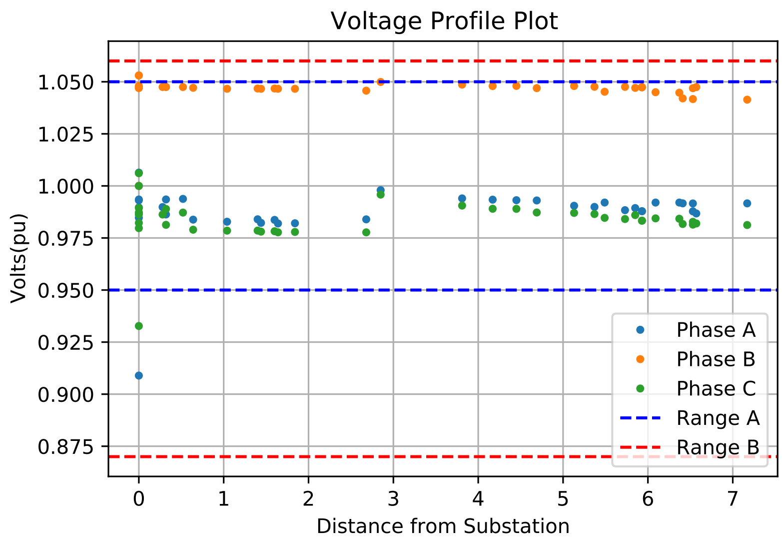

Figure 28: IEEE 37 Node System - Voltage Plot Overlapped

Based on these specifications, when plotting with different *Skip* values, the voltage of the system is analyzed. For each run, the code will output a count integer for each instance the voltage is outside the ideal 10% bandwidth and it will create a summation for a per unit voltage value to see how far the deviation from that bandwidth is. It will also check that, for the occurrences when the voltage is outside Range A, it strictly stays within Range B. If there is any moment this range is not satisfied, that *Skip* value is no longer viable.

To choose the best option for where to place the storage devices, first the count values are compared. Ideally, the smallest number of deviations is selected. In the case there are multiple *Skip* values that have the same number of deviations, of those multiple cases, the amount of voltage is deviation is compared and the smallest is selected. That values are computed by finding how far from the 10% bandwidth the voltage at that node is and, for all points, those differences are summed. If there are multiple instances where there are the same number of occurrences outside the bandwidth range and with the same summed deviation magnitude, the highest *Skip* value is chosen. When skipping more loads, there are less storage and solar devices being added, thus minimizing costs for purchase.

For the IEEE 37 Node System, the ideal *Skip* value within a 1 to 5 range would be 4. The use of this value in conjunction with 2000kWh of battery storage and 500kW of solar provides a system percent difference of 24.7%. Figure 29 then shows the resulting 5 Meters and Storage Devices and Figure 30 shows the overall system's power consumed.

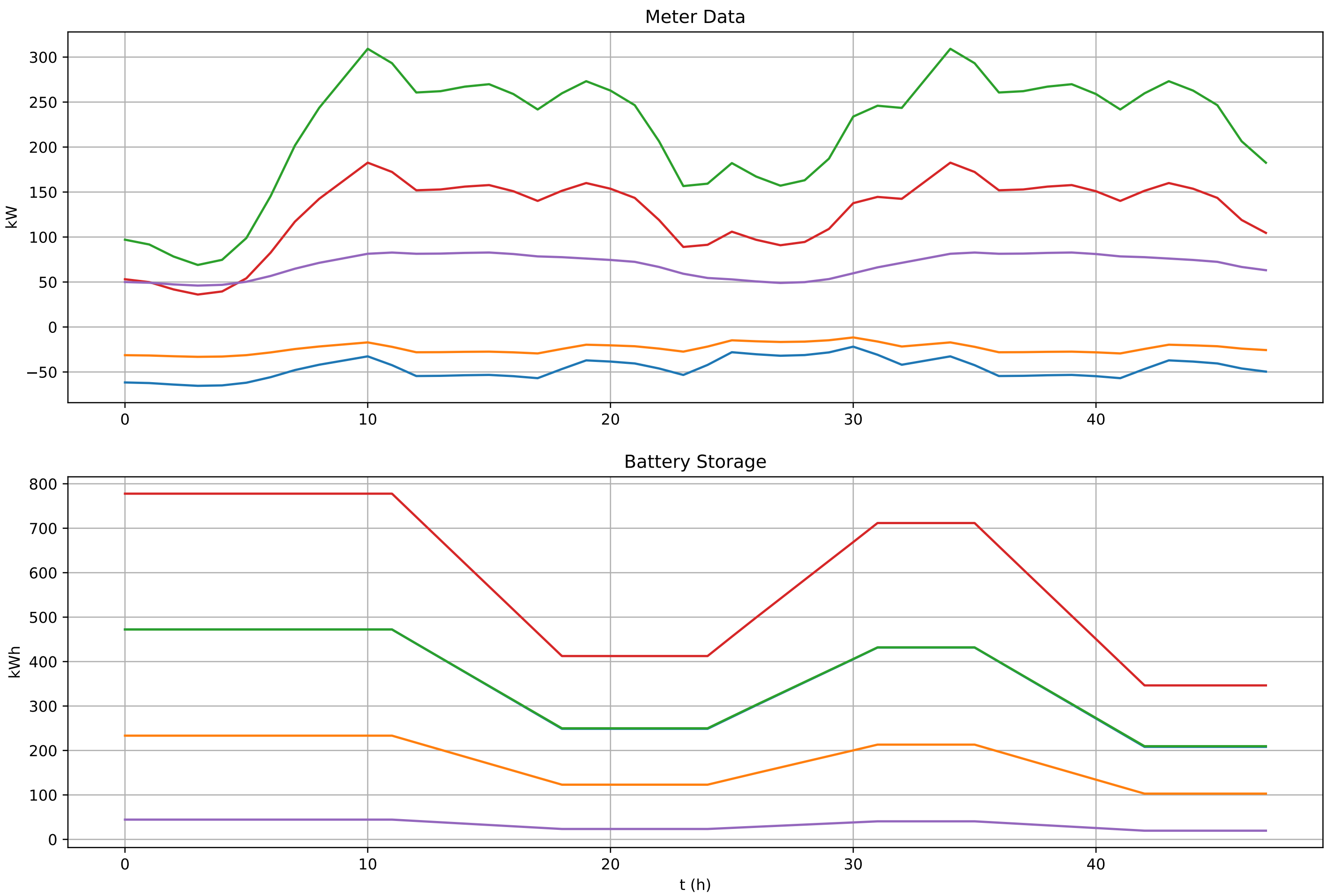

Figure 29: IEEE 37 Node System - Optimization 5 Meters and Storage Devices

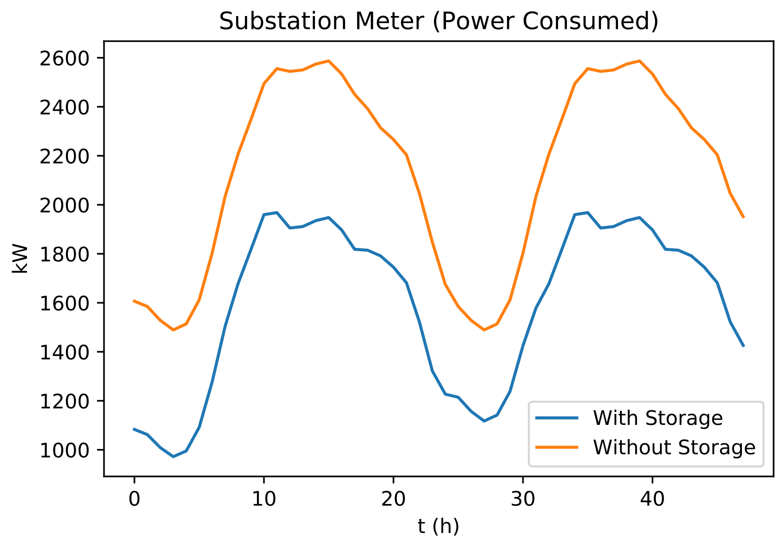

Figure 30: IEEE 37 Node System - Optimization Substation Meter

Due to the existence of some of the points still residing outside the 10% range, it is important to note that although this is allowed, these voltages cannot remain operating at this level. Additional devices, not added within the scope of this paper, will be needed to boost or lower the voltage into Range A, however, the voltages can occur at this range for a short period of time. There are methods utilities can add in order to help regulate these voltages within the system beyond the addition of these distributed devices.

For the long term and future work, it will be ideal to make comparisons for varying placement throughout all feeders in different combinations, however, for the scope of this thesis, the manipulations are only within the *Skip* value. In addition, another point of expansion would be within the location of where these devices are being placed.

7.0 Conclusions

Utilities and their part in distributing power to customers is a fundamental service that almost all parts of modern day life depend on. Unfortunately, most of the process in how this system is run and maintained is still very similar to how it functioned in its conception. In order to keep up with developments in other fields, increasing demands, and the desire to drive carbon emissions down, providing a digital twin of these circuits can prove insightful and helpful. To accomplish this, a rudimentary version of a digital twin for a rural circuit is constructed to see the effects of the addition of distributed solar and storage, which can be further built upon to create a complete digital twin of the system.

This work focuses on the rural portions of the distribution circuit as an area that faces many outages. Rural circuits need more support to operate at the same level of reliability as urban circuits since the same methods of redundancy cannot be used. By integrating distributed storage within the rural circuit, enhanced grid reliability can be achieved. Energy storage provides additional time in the event of an outage and can help peak shave the load demand. Although these devices still have some shortcomings, as they are still newer to the distribution system, their increased penetration in the grid shows they are going to be more common, so it is important to find ways to use them to the distribution system's advantage to support the grid and better service customers.

This work is still a primitive representation of the capabilities of energy storage and solar on rural circuits, it provides a foundation of its capabilities, and with further expansion and more data, more could be learned about storage devices and how they support the energy system. This foundation allows for significant expansion in not only demonstrating how current technologies can be used to support the rural system, but also begins the first steps in constructing a digital twin. Using these proposed, newly added devices and monitors, data can be used by the utility operators to make more informed decisions, model the impact of adding more devices at different locations, and help train any integrated matching learning algorithms, such as the one proposed for the controller. The construction of a digital twin increases the utilities understanding of what is occurring at the grid's edge, and use this information to better their service and reliability.

8.0 Future Work

As demonstrated through the work done in [34], the location of the connection between the distribution system and these distributed devices can significantly impact the performance of the system. For future work, it would be ideal if, beyond the quantity, the the location and size of these distributed storage devices can be optimized when connecting to a rural distribution system. These optimization points would be driven by the price and return on investment the solar and batteries will provide to the owner. Ideally, the least number of batteries would be implemented for the most amount of impact, measured in the amount saved in utility generation consumption, to have the owner save as much as possible in the long run, acting as an incentive to want to install these devices. With this growth, it would also be beneficial to integrate real data for the loads and the solar to create a more accurate representation of the system when creating a virtual model and trying to optimize their placement in the system.

The impact of adding energy storage in areas that are utility owned, rather than only focusing on adding storage at the loads, to provide increased support to the system should also be evaluated. This provides the opportunity to add batteries in more locations on a larger scale and help support multiple loads with one device. This integration of generation at the utility level will help them increase their customer reliability and continue selling energy, even during outages, thus increasing profits.

A large focus will also be on developing a functional digital twin that can work in real time. Due to constraints on manipulating an actual rural circuit for testing, this will be modeled on a smaller scale using the Electric Power Systems Lab located in Benedum Hall. Using this equipment, a digital twin can be developed for a home including battery storage and solar generation. Once the physical lab is built, a virtual model will be constructed and, through the use of meters and monitors, we can establish communication between the two systems, physical and virtual, to run different tests and simulations to show the model can provide the same results as a physical system. This connection with real data points will also make this a Live Digital twin, rather than one relying on old information, which is one of the purposes of using this modelling configuration.

Another goal is to expand and refine how the battery is set to behave, as shown with electric vehicles in [11], where different charging and discharging modes will influence the system differently. In the case of this work, the default operations that exist within the OpenDSS device are used; however, there are hopes to build a customized controller that may operate with different rules to have more effective control over the battery for their applications. Specifically, there is the intention of integrating an AI controller that will use predictive measures to learn the patterns in energy prices and weather patterns to best judge whether to charge or discharge. This can not only help maximize the use of solar when it is available, but also minimize spending costs on electricity.

This work could also build off of the efforts made by other groups such as [8] who are looking to decrease electric vehicle impact through smart charging. As their market share continues to increase, electric vehicles may eventually prove to be the primary source of distributed storage, decreasing the utility need for large scale investment. Although this is not a perfect solution and there may be other vulnerabilities, this method can help bolster grid reliability and customer satisfaction through a non-wire alternative to minimize the need for rewiring large sections of the distribution system at heavy expense. With the increased prevalence of electric vehicles projected to enter the system [25] and this work's demonstration of some support with more storage devices, the use of electric vehicles as storage devices to support the grid is more promising and may potentially further decrease the negative impact they have on the existing power system. This is another area this group hopes to explore as a less invasive solution utilizing current trends and vehicle-to-grid (V2G) technology.

These different goals with machine learning, the use of V2G, and wanting to better understand what is occurring at the grids edge will all help bolster, and will in return provide the needed data for, developing a digital twin. The use of additional monitors, sensors, and controls will not only allow utility operators to manipulate the rural circuits, but also provide a plethora of real time data to better train the models and make more informed decisions. These modes of communication, sensors, and use of machine learning may cause gaps in the network's security. Certain measures will need to be taken to ensure the system remains secure and is not vulnerable to hackers or other bad agents. Keeping the cybersecurity in mind, beyond the physical security, will help create a more robust an complete system. The creation of a complete digital twin for rural circuits should be a long term goal, even if real time communication is not feasible due to security reasons, however, these models will help utilities provide improved service to their customers.

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