Behind-the-Meter Solar Garden Load Following / Zero Injection Controls

EE465 – Senior Design II
Senior Design Project
Final Design Report

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Executive Summary

This report presents the concept of a behind-the-meter solar garden, which is a utility scale solar photovoltaic plant located on the distribution side of a transmission to distribution transformer. There are two main advantages to installing generation systems at the distribution level. The first is the ability to avoid the long and expensive generation queue process that is required at the transmission level, which generally requires comprehensive interconnection studies and permits that significantly increase the cost of a project. Additionally, Missouri River Energy Services is an organization of 61 member municipalities that own and operate their own distribution grids but do not own nor operate any transmission grids. Thus, if they desire to install their own generation system, it must be at the distribution level because that is all they operate. In addition to decreasing reliance on the transmission system and inherently decreasing the amount of energy that must be purchased, distributed generation systems also allow for voltage support. Thus, the distribution system becomes more stable and load tap changers do not need to be relied on as heavily for voltage regulation. As a result, both the municipality and their customers benefit because the life expectancy of the load tap changers increases, and the household voltages do not fluctuate as much.

However, one of the main challenges associated with installing generation facilities at the distribution level is that they are generally not allowed to inject power into the transmission grid. Thus, in situations where the generation exceeds the power demand of the distribution system, the excess power has nowhere else to go and backfeeds the transmission grid. As a result, an effective control scheme is needed to limit the power injection of the behind-the-meter solar garden such that it does not exceed the distribution system load.

In this project, a small scale version of a behind-the-meter solar garden was designed and built in the SDSU Microgrid Laboratory as a proof-of-concept system. The designed system was tested and verified over a wide range of load conditions to ensure that it is capable of limiting power injection even during extreme circumstances. Additionally, the voltage support provided by the solar garden was investigated and compared to how a load tap changer would accomplish the same level of support.

The economic implications of a full scale behind-the-meter solar garden at a potential installment location were also considered. Historical load data at the given location and sample solar output data from a comparable location were used to determine the power generation of the speculative system throughout the year. The savings from energy purchases, capacity charges, and demand charges were all considered, in addition to initial installation and annual operations and maintenance costs. The optimal size for the speculative solar garden was determined and various economic metrics were calculated. Further, the tool that was created for the economic analysis was intended to be easily applicable to other locations. Thus, the costs, rates, load consumption, and solar output are all input variables. As a result, the tool will be capable of facilitating decisions regarding the economics of installing a behind-the-meter solar garden.

Project Motivation and Justification

Recently, there has been a considerable emphasis on renewable resources in the power and energy field. Solar in particular has been growing at a rapid rate due to integration costs decreasing steadily over the last several years. For instance, over the last ten years, the costs associated with installing a utility scale solar system have decreased by 80% [1]. Thus, Missouri River Energy Services (MRES) is looking to take advantage of these reduced costs by incorporating more solar into their generation fleet and increasing the renewable options for its members. However, the process for adding a new generation facility into the transmission system is long and expensive. Thus, MRES is looking to add solar generation at the distribution level, which would provide an economic benefit as well as allow for a faster approval process. A solution to this is to make it a behind-the-meter solar garden. In this case, the meter is a wholesale meter at a given municipal substation, likely at or near a larger power transformer.

By putting the solar garden on the distribution side, the generation queue process can be avoided. This will allow MRES to help supply one of their member municipalities with its own clean energy, which would benefit the environment as well as reduce the amount of power purchased from transmission. Ideally, the solar garden will have enough generation capacity to be able to provide power for the entire municipal load. Thus, there is the possibility that the output could be greater than the load on the distribution side of the transformer. This is a concern since distribution level generating resources cannot be allowed to inject power back out onto the transmission grid. Thus, an effective control scheme must be developed in order to control the output of the inverter while still maximizing installed capacity.

Brief Project Description

It is necessary that the solar garden output is controlled in an industry-standard way to not inject power onto the transmission system. The control scheme must detect when the load is less than the output of the solar garden and adjust the output of the inverter to be less than the load. The control scheme must also monitor changes in the load to ensure that the solar output does not increase too rapidly and overshoot the load given a sudden load increase.

The ability of the solar garden to effectively regulate voltage will also be investigated. Currently, voltage regulation at most MRES member locations is done with a load tap changer (LTC) on the transformer. However, when generation resources are located closer to the load that they serve, the voltage drop across the transmission line serving the load is decreased. This will be the case for a solar garden installment, as all of the power that is generated by the solar garden will go to serve a nearby load. Thus, less power is needed from the transmission system and the voltage at the solar garden installment will be increased. As a result, the solar garden could provide voltage support for the system and decrease the reliance on LTC's. This would then lead to less wear and tear on the LTC's which operate with mechanical components that are prone to breakdown through use.

An economic analysis will be performed in order to determine the best value and optimal size for the solar garden in a given location. This analysis will consider the revenue from and cost of additional solar capacity beyond the 1st percentile load of that area. The primary revenue of the solar garden is from the energy that it generates. Additionally, the solar garden leads to decreased capacity and demand charges for the municipality, which will also be considered as revenue. Capacity charges are required to ensure power security for the municipality, as they have the right to consume as much instantaneous power from the transmission utility as they have purchased in capacity. Further, demand charges are based on the highest instantaneous power consumption seen at a location during a certain time period, typically on a monthly basis. Thus, when the municipality has its own generation resources, the capacity and demand charges are inherently decreased. However, the added cost of additional solar capacity must also be considered. Thus, the analysis will focus on optimizing the size of the solar garden based on these considerations in order to meet the desired outcomes.

Background

Project Status and Key Terminology

MRES is an organization of 61 member municipalities that own and operate their own electric distribution systems. The organization is governed by a 13-member board of directors who are elected by and from the ranks of its member representatives.

MRES is dedicated to supplying its members with reliable, cost-effective, long-term energy and energy services in a fiscally responsible and environmentally sensitive manner. MRES is an extension of its members, and through joint action, members will remain competitive while enhancing their relationships with their customers.

With ongoing changes in the industry, and a stronger desire for clean energy options by its customers, MRES is investigating renewable generation options. Of those options, behind-the-meter solar gardens have some appealing characteristics. These installations are competitively priced and can contribute to the need for valuable capacity. As for the aspect of installing them behind-the-meter (wholesale meter at a given municipal substation, likely at or near a larger power transformer), this is an effective way to expedite the studies, get approvals, and start construction. This installation location can also be effective in avoiding expensive transmission related costs since the generation is installed on the distribution system near the customer's load.

Current State of The Art

Traditionally, MRES members do not have their own generation systems and rely entirely on the transmission system to provide for the power needs of their distribution network. Additionally, the main adopters of utility scale PV generation facilities have either been private developers, such as NextEra Energy, or utilities that own and operate their own transmission systems, such as Xcel Energy. While PV generation at the transmission level is attractive due to the ability to implement extremely large systems, it does not provide the opportunity for distribution only utilities, such as MRES members, to participate. If MRES members implement their own PV generation facilities within their distribution network, they could decrease their reliance on the transmission system and provide their customers with locally generated clean energy. Additionally, the power system as a whole benefits from generating resources being located closer to the loads that they serve as the line losses are significantly reduced. For instance, the United States Energy Information Agency estimates that transmission line power losses equal approximately 5% of the total electricity transmitted in the United States [2]. These losses could be avoided entirely if sufficient generation resources were in place on the distribution system. However, due to market rules and regulations, distribution level generation systems are not permitted to inject power back onto the transmission grid.

The issue of active power curtailment is present not only for municipal utilities, but also for some residential customers who have solar panels installed at their home. In many areas of the United States and throughout the world, either net metering is not permitted or there are specific regulations set by the utility that prohibit customers from injecting power back onto the grid. Thus, these systems can be used as a small scale analogy to the problem that municipal utilities face. The output power from these systems can be controlled in a variety of ways. The most inefficient and least attractive option is to apply additional loading on the inverter when the generated power is close to exceeding the load power draw. This is not desirable because it requires high power load resistors, which incur additional costs and create significant heat within a small area. Another option is to disconnect the inverter when the power generation exceeds the load and reconnect when the load is increased. This is another inefficient option since the power generation potential of the solar is significantly decreased. Alternatively, a battery could be installed within the system to harness the excess PV generation when the load falls below the PV output. However, the high cost of batteries makes them unrealistic from an economic perspective, particularly when they would only be charged during the short time of excess generation. Additionally, batteries are still largely inefficient and take up a lot a space within a site. The final and most practical option to control power injection into the grid is the use of an inverter with active power limitation capabilities. For these inverters, the active power output can be limited via external signals, serial communication, or ethernet [3]. This option is the most desirable because it maximizes the output potential of the solar generation while not exceeding the load.

Additionally, LTC's are traditionally used to regulate the voltage levels of MRES member systems. LTC's operate by adjusting the tap position of a transformer, typically on the transmission (high voltage) side, effectively adjusting the turns ratio of the transformer. Thus, in cases where the voltage on the distribution (low voltage) side is below the desired level, the tap position can be moved down to boost the voltage back into the correct range. On the other hand, when the voltage is too high, the tap position can be moved up. These devices are typically used to help offset the effects of voltage drop across the transmission line that feeds the distribution network by decreasing the tap position in response. However, if the MRES member had their own generating resource located on the distribution network, the current travelling through the transmission line feeding the network would be decreased. Thus, voltage regulation would be provided by the generating resource and the LTC would not need not to be relied on as heavily, prolonging its life expectancy.

Scope of Project

<u>In Scope</u>

The scope of this project will include:

1. The development of a control system for a behind-the-meter solar garden.
    a. The solar garden output power will not exceed the distribution system load.
    b. The effectiveness of voltage regulation using the solar garden will be investigated.
2. A prototype will be constructed in the South Dakota State University (SDSU) Microgrid Lab to model the system being proposed.
    a. The designed system will be tested and verified.
3. An economic analysis will be completed to investigate the most effective size of the solar garden to maximize the economic benefit to the municipality.
    a. MRES will provide sufficient load data and price information as required.

<u>Out of Scope</u>

The scope of this project does not include:

1. Implementation of the designed system in a full scale solar garden.
2. The design of interconnection infrastructure associated with a full scale solar garden.
    a. Power transformer design to achieve the appropriate voltage step from the inverter output to the distribution level.

Objectives, Requirements, and Specifications

There are many requirements and specifications that must be adhered to throughout this project in order to achieve the overall objectives.

1. Objective: Develop an automated control scheme for the behind-the-meter solar garden.

    1.1. Requirement: Injecting active power into the transmission system should be avoided outside of hard criteria, but the response should not be sporadic.
        1.1.1. Specification: Limit active power injection within Southwest Power Pool (SPP) market rules and regulations.
        1.1.2. Specification: The power factor of the solar garden output shall be at least 0.95, leading or lagging.

    1.2. Requirement: Investigate the effectiveness of voltage regulation as a result of the solar garden.
        1.2.1. Specification: Normal system voltage operating range of 1 - 1.05 p.u. with a target voltage 1.03 p.u.
        1.2.2. Specification: The power factor of the solar garden output is permitted to fall outside of the range specified in 1.1.2 when regulating voltage.
        1.2.3. Specification: Remain within the guidelines outlined in the IEEE Standard 1547 [4].

    1.3. Requirement: The designed system must be verified over a variety of solar generation levels and behind-the-meter load conditions.
        1.3.1. Specification: Ensure that active power is effectively curtailed in cases when the solar generation exceeds the load.

2. Objective: Perform economic analysis on the optimal sizing of the solar garden with respect to the behind-the-meter load.

    2.1. Requirement: Optimize the size of the solar garden based on solar and load data.
        2.1.1. Specification: Sample data from a 1 MW solar garden will be used to predict the speculative solar garden output.
        2.1.2. Specification: Detailed load data at a potential installment location will be used to determine the effective utilization of installed solar capacity.
        2.1.3. Specification: Wholesale price data will be used to determine the cost savings associated with the solar garden.

Constraints

The customer has required that the project adhere to the following constraints:

- The control scheme must be validated based on available hardware setup and simulation tools, according to the specifications and design criteria.
- A Schweitzer Engineering Laboratories (SEL) Real Time Automation Controller (RTAC) will be used as the main system monitor.
- Modbus will be used as the communications protocol for inverter control.
- The system prototype must be built with available materials and stay within $1000 for additional materials.
    - Available materials include what is already in the SDSU Microgrid Lab. MRES also has an available power meter that can be borrowed and returned at the conclusion of the project.
    - If extenuating circumstances arise, SDSU and MRES will coordinate on the purchase of required items.
- Non-disclosure agreements (NDAs) will not be needed, so long as the location associated with any load data received from MRES is not made public.

Design and Design Procedure

The proposed solution to the problem can be divided into two sections, hardware implementation and economic analysis.

Hardware Implementation

The design requires a significant amount of communication design, including communication between the RTAC and the SEL power meters, as well as communication between the Fronius inverter and the smart meter. Also, the design includes configuring the settings of the SEL power meters, RTAC, and the Fronius inverter to accomplish a zero injection control system that is capable of remote monitoring.

One-Line Diagram of System

The one-line diagram, Fig. 1, shows the design of the system to meet the specifications and requirements. Items within the dashed box are a part of the designed solar garden, while items outside of the box are already present in the existing system.

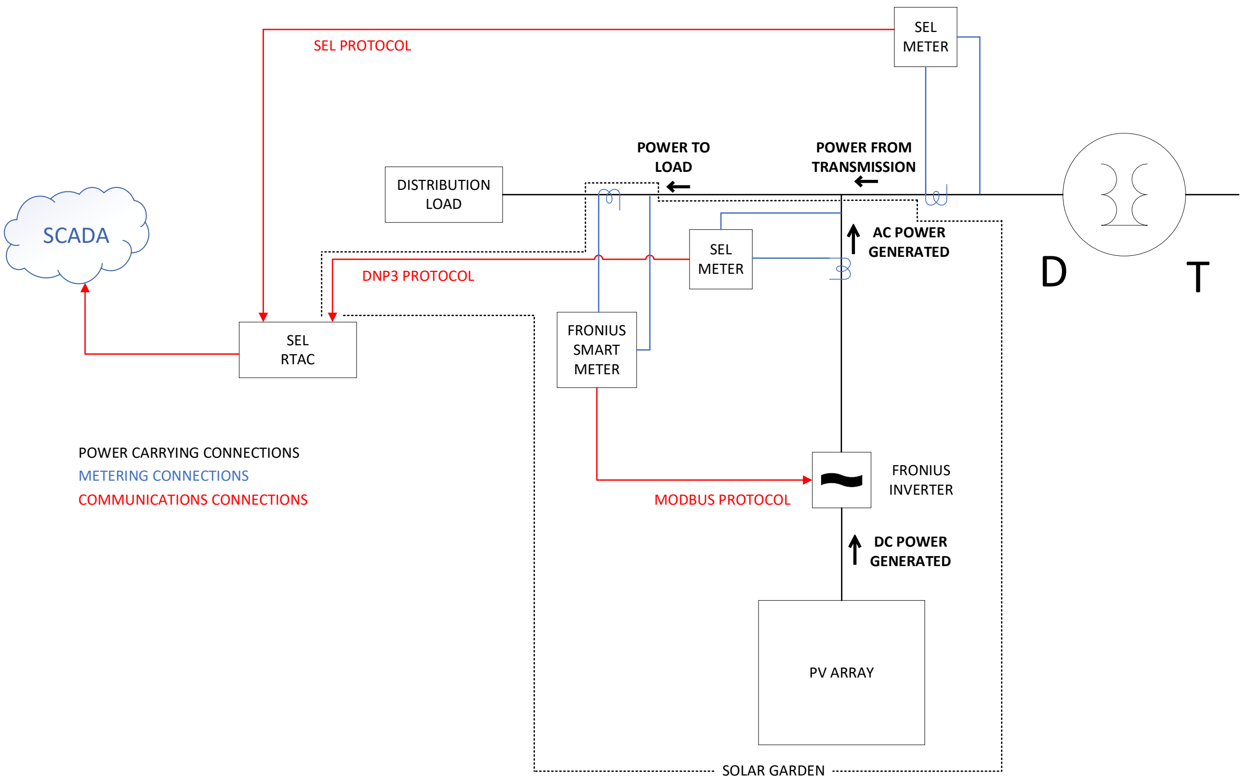

Figure 1: One-Line Diagram

Below is a description of each component in the system, and the effect it has on the overall functionality.

Power Transformer

The power transformer is assumed to be present and is not a part of the system design. In a full scale system, the transformer steps down the voltage from transmission level to distribution level in order to service the load.

Distribution Load
The load of the member municipality, which will be simulated with a variable three-phase load bank within the SDSU Microgrid Lab, Fig. 2. This is the load that the power output from the solar garden shall not exceed.

Figure 2: Variable Three-Phase Load Bank

Fronius Inverter
The inverters currently installed in the SDSU Microgrid Lab are SMA Sunny Boy 5000's. These are inverters are not able to curtail their power output and are no longer supported by SMA. Additionally, the SMA Sunny Boy 5000 is a single phase inverter and thus three of them are required to create a three-phase output. However, a single three-phase inverter is preferred over three separate single-phase inverters to simplify the system wiring and communication, as well as be similar to an actual utility scale system, which would most likely use three-phase inverters. Thus, the Fronius Symo 10.0-3 three-phase grid-tied inverter was chosen for the design. The Fronius Symo 10.0-3 is rated at 10 kW and 208 V (line-to-line), while the smallest three-phase inverter that is available from SMA is 33 kW, which exceeds the PV power that is available in the SDSU Microgrid Lab. Additionally, the Fronius inverter is able to support both the Transmission Control Protocol (TCP) and Remote Terminal Unit (RTU) variations of Modbus while current versions of the SMA inverters only support the TCP variation, giving them less flexibility. The design team was also able to contact Fronius directly and spoke with a representative who provided more insight and relevant documentation in addition to what was located on the Fronius website. On the other hand, when the team tried to contact SMA, the representative did not know what the Modbus communication protocol was and transferred to someone else who did not answer. Thus, the Fronius Symo 10.0-3 was selected as the inverter to be used in the designed small scale system, Fig. 3.

Figure 3: Fronius Symo 10.0-3

Fronius Smart Meter and Current Transformers

The Fronius Smart Meter, Fig. 4, is a vital part of the solar garden control scheme as it measures the power consumption of the distribution load and sends that value to the inverter via Modbus communication. The inverter was programmed so that it uses the measured power consumption of the load as its maximum power setpoint. Thus, the inverter is able to constantly adjust its power output such that it does not exceed the load power consumption. The inverter could also be programmed such that there is a defined amount of power injection to the transmission system allowed, either as a percentage of the nameplate value or as a certain power amount. However, for the designed system, which is to abide by the SPP market rules and regulations, the maximum injection was set to zero. Thus, the system only injects power onto the transmission grid during times of an instantaneous decrease in load power and the injection only lasts for a short amount of time.

Figure 4: Fronius Smart Meter

The Fronius Smart Meter is rated for a line-to-line voltage input of up to 276 V. Thus, voltage transformers were not needed. However, the smart meter required a special type of current transformer, manufactured by Continental Control Systems, that converts the line current to a voltage through the use of an internal terminating resistor. A line current of 27.8 A was expected, given a 10 kVA and 208 V line-to-line system (1). Thus, the ACTL-0750-050 Opt C0.6 current transformer was selected since it is rated for 50 A, Fig. 5. The next size down is only rated for 20A and thus would become overloaded when the system is operated at full capacity.

$$I_{line} = \frac{S_{three-phase}}{\sqrt{3}V_{ll}} = \frac{10kVA}{\sqrt{3}*208V} = 27.8A \quad (1)$$

Figure 5: ACTL-0750-050 Opt C0.6 Current Transformer

<u>Photovoltaic Array</u>

The Fronius Symo 10.0-3 has two separate maximum power point trackers (MPPT's). Thus, there are two separate DC inputs on the inverter, which allows for the simultaneous use of two PV strings without having to directly tie the strings together. The two MPPT's, denoted as MPPT1 and MPPT2, are rated for 25 A and 16.5 A, respectively. Additionally, each MPPT is rated for a DC input voltage of 200 V to 600 V. Further, there were three existing PV strings already configured in the SDSU Microgrid Lab, listed below.

String 1: Evergreen (364 V and 11.27 A at Maximum Power)
String 2: Sunpower A (328 V and 17.46 A at Maximum Power)
String 3: Sunpower B (328 V and 11.64 A at Maximum Power)

Thus, existing strings 2 and 3 (Sunpower A and B), were used with MPPT1 and MPPT2, respectively. As result, the total plant PV power was 9.54 kW (2). This configuration also falls within the recommended PV power range for the Fronius Symo 10.0-3, which is from 8 to 13 kW.

$$P_{PV} = P_{MPPT1} + P_{MPPT2} = 328\,V * 17.46\,A + 328\,V * 11.64\,A = 9.54\,kW \quad (2)$$

<u>SEL Power Meters and Current Transformers</u>

Two SEL-735 power meters were used in the design, Fig. 6. The meter that monitors the solar garden output will provide MRES with the ability to monitor the solar garden and record relevant data. The second meter is located on the distribution side of the transformer because it is assumed that there is already a similar meter installed in this location of the prospective solar garden site. This is because the member municipality purchases energy from the transmission utility. Thus, a revenue grade meter, such as the SEL-735, is needed to keep track of how much energy the municipality has purchased.

Figure 6: SEL-735 Power Meters

The SEL-735 is rated for a maximum input voltage and current of 300 V (line-to-neutral) and 22 A, respectively. Thus, voltage transformers were not needed since the voltage of the system (120 V line-to-neutral) was below the maximum rating. However, current transformers were needed because the current would be 27.8 A if the system operates at full capacity (1), which exceeds the maximum current rating of the SEL-735. In addition to the maximum current rating of the SEL-735, the minimum current for revenue grade metering must also be taken into consideration when sizing the current transformers such that the maximum primary current rating did not greatly exceed the maximum current expected (1). Additionally, the current transformer hole size must be taken into consideration as the cam-lock fitting used in the SDSU Microgrid Lab have a diameter of 1 inch. Thus, three viable options for three-phase current transformers were found, shown in Table 1. The GE 3P40-101 was selected because it was the most accurate and the project had sufficient funding thanks to the grant received from GridEd. Further, the GE 3P40-101 only required 3 loops through the current transformer opening to achieve a desirable current ratio, Fig. 7.

Table 1: SEL-735 Current Transformer Options

Model	**GE 3P3-600**	**GE 3P56-151**	**GE 3P40-101**
Price	$159.60	$187.74	$380.95
Accuracy	±2%	±1%	±0.6%
Current Ratio	60:5 A	150:5 A	100:5 A
Hole Diameter	0.97″	2.13″	1.75″
Number of Loops Through Hole	2	5	3
Effective Ratio	30:5 A	30:5 A	33.33:5 A
Maximum Burden	2.0 VA	2.5 VA	2.5 VA

Figure 7: GE 3P40-101 Current Transformer

The SEL-735's were then programmed to align with the unity voltage ratio and 33.33 to 5 A current ratio.

<u>Real Time Automation Controller</u>

A SEL-3530 RTAC, Fig. 8, was used as the main system monitor and was also assumed to a part of the existing system at the potential installment location. The RTAC serves as the communications hub and sends useful data to the Supervisory Control and Data Acquisition (SCADA) system of the MRES member municipality.

Figure 8: SEL-3530 RTAC

The RTAC receives the power readings from the two SEL-735 meters via communications utilizing the SEL and DNP3 protocols. The SEL protocol was used with the meter monitoring the power coming from transmission, while the DNP3 protocol was used with the meter monitoring the power generated from the solar garden. Since the solar garden may not be located right next to the transmission / distribution substation, the SEL protocol cannot be used with the meter measuring its output. This is because the SEL protocol utilizes RS-232 serial, which can only be transmitted up to 50 feet. Over 50 feet, the signal is likely to be corrupted and/or cause equipment damage due to interference and induced voltage [5]. Thus, the DNP3 protocol was used instead, which utilizes an ethernet connection and is capable of being transmitted up to 328 feet over a copper line or up to 75 miles over a fiber optic line if transceivers are used to establish a fiber optic link [6]. On the other hand, the meter that measures the power coming from transmission and the RTAC were anticipated to be installed within the same control enclosure and thus would be close enough to utilize the SEL protocol. Based on the power readings from each meter, the power being delivered to the load can be calculated within the RTAC (3).

$$P_{Load} = P_{Solar\ Garden} + P_{Transmission} \tag{3}$$

<u>Supervisory Control and Data Acquisition</u>
A SCADA system was also assumed to be present in the existing system at the potential installment location. SCADA systems are crucial in the operations of the power grid as they allow for monitoring, data logging, control, etc. throughout the network. Although SCADA was not a part of the designed system, its functionality was simulated by accessing the RTAC data through its web interface, Fig. 9, similar to how the SCADA system would communicate and retrieve data.

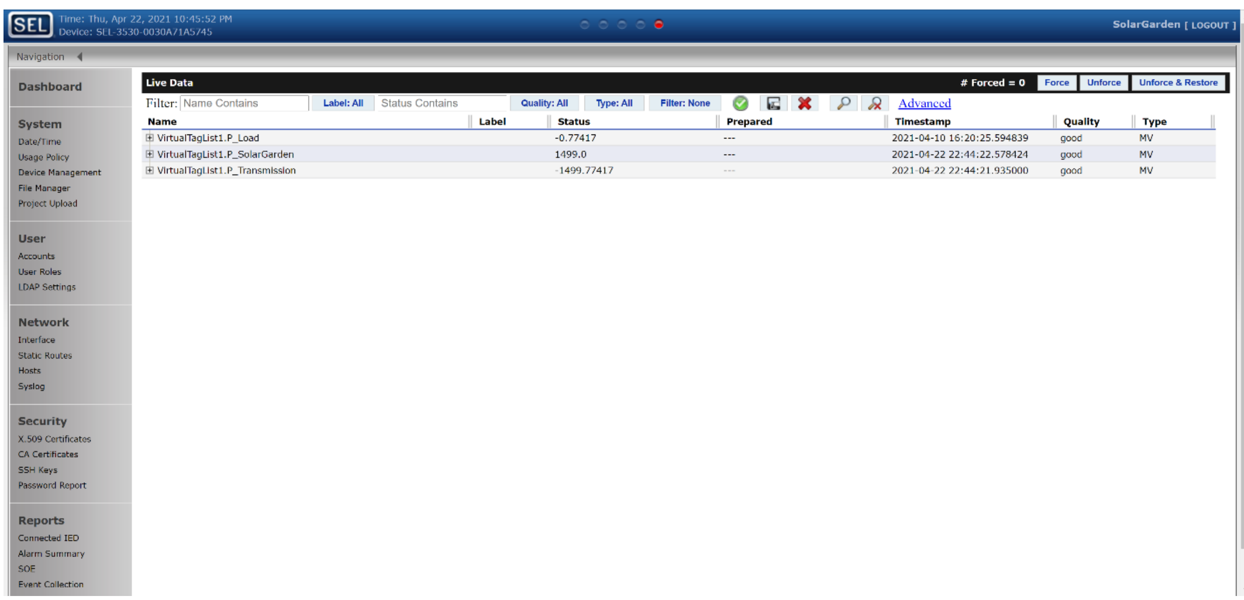

Figure 9: RTAC Web Interface

Economic Analysis

A tool was created to give a reasonable understanding of the economics involved with the installation of a solar garden. There is a comparison of two substations within the city of interest, which will be referred to as Sub A and Sub B. Each substation was treated independently, and the analysis was completed for both. Thus, it could be seen which location would be better suited for a solar garden in financial terms, and it will show the return on initial investment. The tool takes into account several input variables, such as discount rate, capacity and demand charge rates, and installation and annual operating costs.

Data was received from the SCADA systems of MRES members to complete this economic analysis. This included multiple years of half-hourly load data for the entire city load, multiple years of load data split between the two main circuits that run through the city, a single month of half-hourly load data for the specific substations in the city, and one year of the solar output data from the Pierre 1 MW solar garden. Additionally, MRES provided one year of hourly-averaged real time pricing data from the Southwest Power Pool (SPP) and a table detailing the specific time that a demand charge was incurred each month. 2019 was the year of focus for the analysis and was assumed to be indicative of a typical year.

The analysis was based on yearly amounts, but the substation load data given only had a month worth of data. Thus, a year's worth of substation load data had to be extrapolated from the given month of data. To do this, the load data split between the two main city circuits were used, as both substations of interest were on the same circuit. However, the system has normally open lines that could be closed to redistribute load as needed. There were a few times during 2019 where this happened, causing the two circuits to redistribute their load for a brief time, thus resulting in load values that do not include the same substations they normally do. To correct this, the load values of circuit data from the exact same time frame in 2018 were used to replace these jumps. In these cases, the 2018 load value was multiplied by the ratio of the total energy consumption of the city in 2019 to the total energy consumption of the city in 2018 to account for the increase in overall system loading between 2018 and 2019.

The month of substation load data was compared to the same month of the manipulated circuit data. The percentage of the substation load to the circuit load was found for each data point in the month. Then, the percentage value for each half-hour increment was averaged together. For example, every occurrence of 1:30 AM in that month had its percentages averaged. Those average percentages were multiplied by the year of manipulated circuit load data to give the extrapolated substation data for a full year. By averaging the percentages of each half-hour of the day, it gives a more detailed and precise estimate of load values since it accounts for variation throughout each day. Thus, Specification 2.1.2 was met as detailed load data from the potential installment location was used. This was all performed using equations in Microsoft Excel and macros in Visual Basic.

The year of output data from the Pierre 1 MW solar garden was used to represent the solar output of the new solar garden and thus Specification 2.1.1 was met. The city of the potential solar garden is similar to Pierre geographically and thus the irradiance at the location would be similar to the irradiance at the Pierre 1 MW solar garden. System Advisor Model (SAM) was used to confirm that the average solar irradiance in the city of interest is within 3% of the average solar irradiance in Pierre. Other factors, such as tilt angle, were assumed to have the same parameters as Pierre for this analysis. Therefore, the solar data from the Pierre 1 MW location was scaled linearly to represent the various installment sizes of interest.

The year worth of real time pricing data given was hourly-averaged numbers in dollars per MWh. Since all the other data used in the analysis had half-hour granularity, the hourly-averaged pricing data was duplicated on the half-hours to account for this.

The scaled solar output was compared to the extrapolated substation load for the whole year, and if the solar ever exceeded the load, it would be curtailed down to what the load was at that time. Then, the solar output values were multiplied by the real time price at that time to determine the energy purchase savings and thus Specification 2.1.3 was met. These were added together for the entire year, and that sum represents the amount of money that the city saves from energy purchases as a result of the solar garden.

There are two primary costs that go into the analysis, install cost and yearly operation and maintenance cost. These cost rates were both simply multiplied by the desired size of the solar garden. All the rates used in this tool are input variables that can be changed at any time. This way, the tool can be used for multiple MRES locations and future rate scenarios.

There were also two additional avoided costs that are factored in, cost of new entry (CONE) and load demand charges. The CONE refers to amount of capacity that needs purchased. By implementing a solar garden, it will reduce the amount of capacity that needs purchased. However, only a certain percentage of the nameplate rating of a solar installation can count towards the capacity requirement as a result of variability in solar resources. That percentage is also an input variable for the tool and was set to 50%. For example, a 2 MW solar garden can in this case reduce the capacity requirement of the city by 1 MW. Thus, 1 MW worth of capacity charges can be avoided and also contribute to the revenue of the solar garden. The demand charge is based on the highest load value within the transmission zone each month. Using the times provided by MRES for when this charge occurs, the output of the solar garden at those times was multiplied by the demand charge rate, also an input. These were added up for all twelve months to show how much money would be saved by having the solar garden in place.

This tool provides many output values. An important output is the yearly net cash flow that considers the savings of not purchasing energy from the grid due to the generated solar output, the CONE charge, the demand charge, and the cost of the operation and maintenance. There is also the number of years until the solar garden makes back the money it took to install it and how many years until it pays back at a discount rate, taking into account net present value. The discount rate was applied to give a sense of how the solar garden compares to alternative investment options that would potentially yield the discount rate. Another output is the annual percent return that the yearly net flow gives based on the installation cost. The tool also shows the net present value year by year of the investment at the specified discount rate out to thirty years.

Using all the calculations of the tool, a macro was created to generate graphs to compare an undersized, oversized, and correctly sized solar installation. The 'right size' was determined to be just higher than the 1st percentile load of each substation, which ended up being about 5 MW. 3 and 7 MW were used for the undersized and oversized values, respectively. The user may adjust any input variables and then start the macro. The macro will then input each of the three install sizes and grab certain outputs to place them in a table. Graphs are then generated from this new table.

Due to the use of multiple input variables, this tool can be used with ease to make any necessary adjustments to see how it will impact the solar garden financially. The most common variable to be adjusted is the size of solar garden to see what size makes the most financial sense. While there is room for more precision and more factors that go into the economics of this type of project, this provides a good understanding of what to expect for cash flow when looking to install a solar garden in a given location.

Validation of Specifications / Results and Analysis

The validation of specifications in accordance with the design requirements can be divided into two sections, hardware implementation and economic analysis.

Hardware Implementation

Per Specification 1.2.3, the designed system must comply with IEEE Standard 1547, which outlines the requirements for the interconnection of distributed generation resources. The post important feature required by IEEE 1547 is that the inverter must have anti-islanding protection. Thus, if there is a grid failure, the inverter must shut down immediately in response so that it does not create an island of energized equipment and lead to a dangerous situation for line workers. The inverter that was chosen for the design, the Fronius Symo 10.0-3, is compliant with IEEE 1547 and thus Specification 1.2.3 has been met.

Per Specification 1.3.1, the designed system must ensure that active power is effectively curtailed in cases where the solar generation exceeds the load. Additionally, per Specification 1.1.1, the designed system must limit any active power injection within SPP market rules and regulations. However, it was found that SPP does not have any hard criteria for how much power injection is allowed. According to them, some power injection is tolerable as long as the system is actively trying to mitigate the injection rather than just letting the injection happen in hopes of the load increasing. Thus, the system was tested over a wide variety of solar irradiance and load conditions, including sudden decreases in load to observe how quickly the system responds. The solar garden power generation, load power consumption, and power factor were observed, Fig. 10. It can be seen that upon startup, the solar garden matched the power consumption of the load exactly and there was no injection onto the transmission grid. Then, upon a sudden increase in load power consumption, the output power of the solar garden increased to match the load power consumption without overshooting or causing unnecessary power injection. Further, the effects a variable solar irradiance could be seen when the load power demand exceeded the amount of power that the solar garden was capable of producing at the given time. Thus, when the load power consumption was first decreased, the solar garden output was unaffected because it was already outputting the maximum amount of power it was capable of at that time. Then, upon the next decrease in load power consumption, the solar garden reacted within two seconds by decreasing its output power to below the load consumption and returning steadily to match the load. Thus, Specification 1.3.1 was met as the solar garden was able to effectively curtail its output power in cases where the generation was capable of exceeding the load. Additionally, Specification 1.1.1 was met as the system reacted very quickly to sudden decreases in load power consumption to avoid prolonged power injection. Further, Specification 1.1.2 was met as the solar garden output maintained a unity power factor at all times, which was well above the minimum value of 0.95.

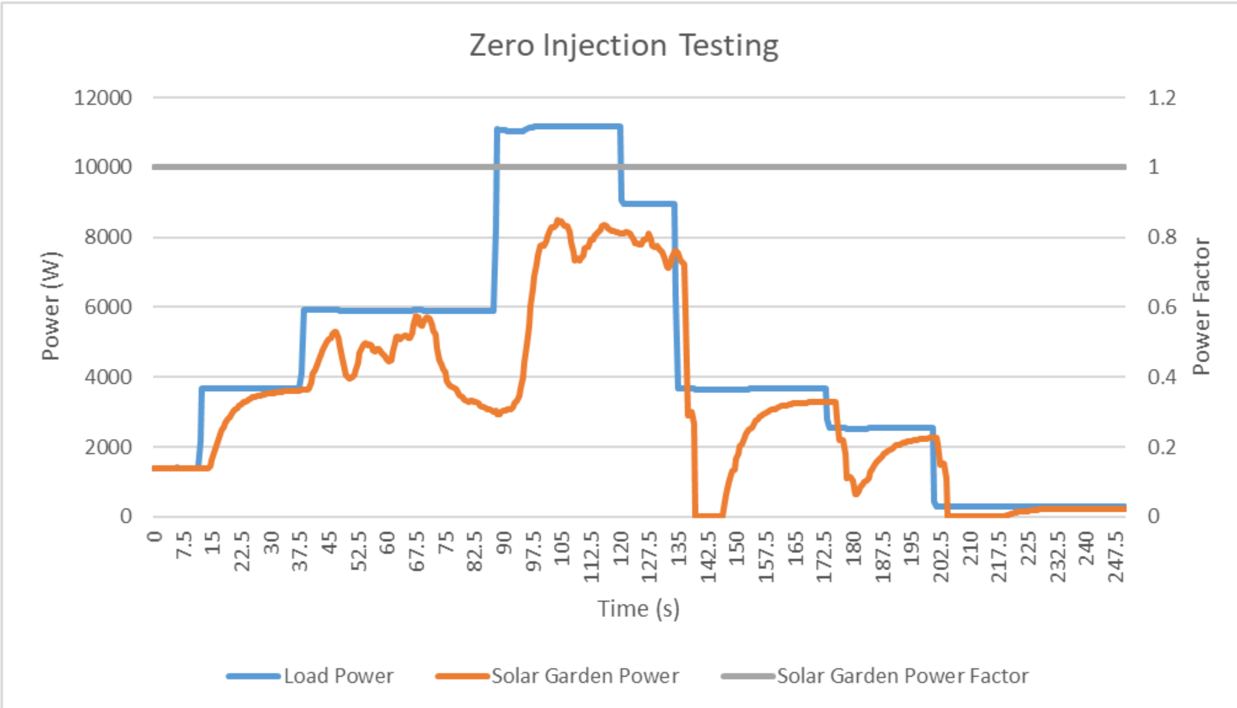

Figure 10: Zero Injecting Testing

Per Specification 1.2.1, the normal system voltage is between 1 and 1.05 p.u. However, when the system is connected directly to the utility grid within the SDSU Microgrid Laboratory, the voltage is fixed, and the effective line resistance as seen from the cabinet terminals is not able to be adjusted. Thus, the OPAL-RT and a three-phase power amplifier were used to simulate a grid interconnection point with a specified line resistance. The power amplifier works by taking an 'image' of the voltage desired at the input and replicating the waveform at the output as a high power version. Additionally, the power amplifier has built in current measuring, which can be sent to the OPAL-RT as an input. Thus, the grid voltage can be set within the OPAL-RT as a function of the current draw from the grid, (4), simulating the Thevenin Equivalent of a non-ideal interconnection point, Fig. 11.

$$V_g = V_{thev} - I_g R \tag{4}$$

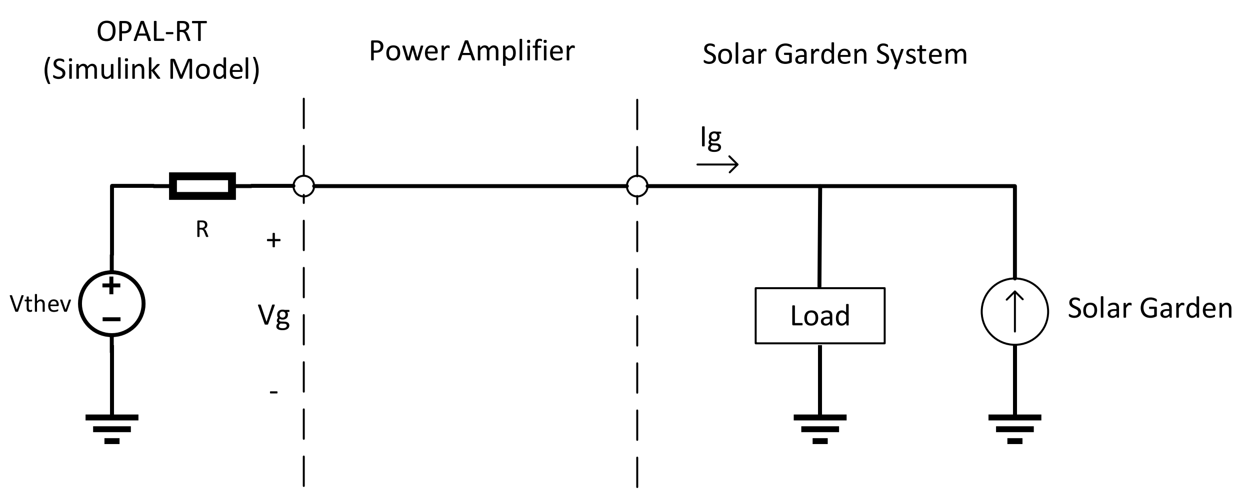

Figure 11: Schematic of Voltage Regulation Test Setup

The three-phase power amplifier is capable of outputting 2 kVA per phase, for a total of 6 kVA. Thus, the load to be used during testing must be well below 6 kVA so as to not overload the amplifier. As a result, a constant 4 kW load was used for the voltage regulation testing. Further, to ensure that the power generation of the solar garden could not exceed the load, the Sunpower A PV string was disconnected from the system and only the Sunpower B PV string was used. Thus, the solar garden would only be capable of outputting a maximum of 3.8 kVA, which would ensure that no power could be injected backwards into the power amplifiers and cause damage. Although the zero injection system had been shown to inject no power when at a constant load power consumption, this safety measure was put in place anyway to protect against sudden and unexpected decreases in load which would likely cause a brief period of injection. These sudden changes could be the result of a malfunction within the load bank, an accidental load bank adjustment, etc. Further, 1.05 p.u. was set as the system Thevenin voltage such that if there were no current draw, the grid voltage would be at the high end of the acceptable range. Finally, the interconnection resistance was set to 0.95 ohms. The Simulink model of the test system utilizes OPAL-RT I/O blocks to receive the current measurements from the amplifier and to send the calculated grid voltage to the amplifier, Fig. 12.

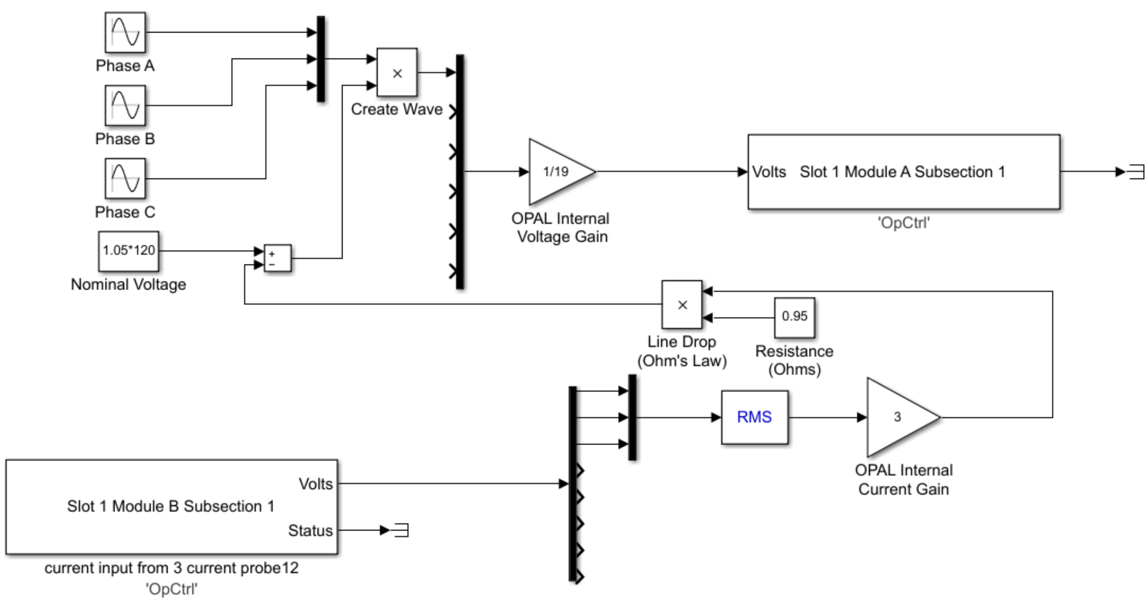

Figure 12: Simulink Model of Simulated Grid Interconnection

The system was then operated without the solar garden enabled. Thus, the entire load power consumption was served by the simulated grid. The system voltages were observed and recorded in Table 2. Then the system was operated with the solar garden enabled. Thus, most of the load power consumption was served by the solar garden while the rest was provided by the simulated grid. The system voltages were again observed and recorded in Table 2. As expected, the voltage levels were improved when the solar garden was in place versus when it was not. Further, the voltages were within the specified range of 1 to 1.05 p.u. when the solar garden was in place and thus Specification 1.2.1 was met. Finally, the solar garden possessed a unity power factor throughout the test and thus the added power factor tolerance provided by Specification 1.2.2 was not required.

Table 2: System Voltages With and Without Solar Garden

	V_A (V)	V_A (p.u.)	V_B (V)	V_B (p.u.)	V_C (V)	V_C (p.u.)
Without Solar Garden (V)	110.06	0.92	113.54	0.95	113.64	0.95
3.8 kW Solar Garden (V)	120.16	1.00	123.17	1.03	123.60	1.03

Additionally, the voltage regulation of each phase was calculated, (5), and recorded in Table 3. The level of voltage regulation with the solar garden in place is equivalent to the LTC setting required to attain the same voltage level had a solar garden not been put in place. Thus, it was shown that the system voltage can be supported through the addition of a solar garden and LTC's may not need to be used as heavily. This is beneficial from an operations and maintenance perspective, as the wear and tear on the mechanical components within LTC's could be reduced, prolonging their life.

$$\%\,Voltage\ Regulation = \frac{V_{with\ solar\ garden} - V_{without\ solar\ garden}}{V_{without\ solar\ garden}} * 100\% \quad (5)$$

Table 3: Voltage Regulation of Solar Garden

	Phase A	Phase B	Phase C
Voltage Regulation (%)	9.18	8.48	8.76

Economic Analysis

There are many factors that go into the analysis. Therefore, during the analysis, most of the input variables were kept constant, unless a specific comparison was being made such as different installment sizes. The base input variables for the analysis are shown in Table 3.

Table 3: Base input variables for economic analysis

Solar Capacity %	Discount Rate	Capacity Charge ($/MW-yr)	Size of Solar Installment	Install Cost ($/W)	O&M Cost ($/kW-yr)	Demand Charge ($/kW-month)
50%	3%	54,000	5 MW	0.93	16.70	6.70

One important comparison was to see which of the two substations would be the better location for the solar garden. By incrementing the size of the solar installment from 1 MW up to 15 MW and keeping the rest of the variables constant, the yearly net cash flow was noted for each substation at each size and compared, Fig. 13.

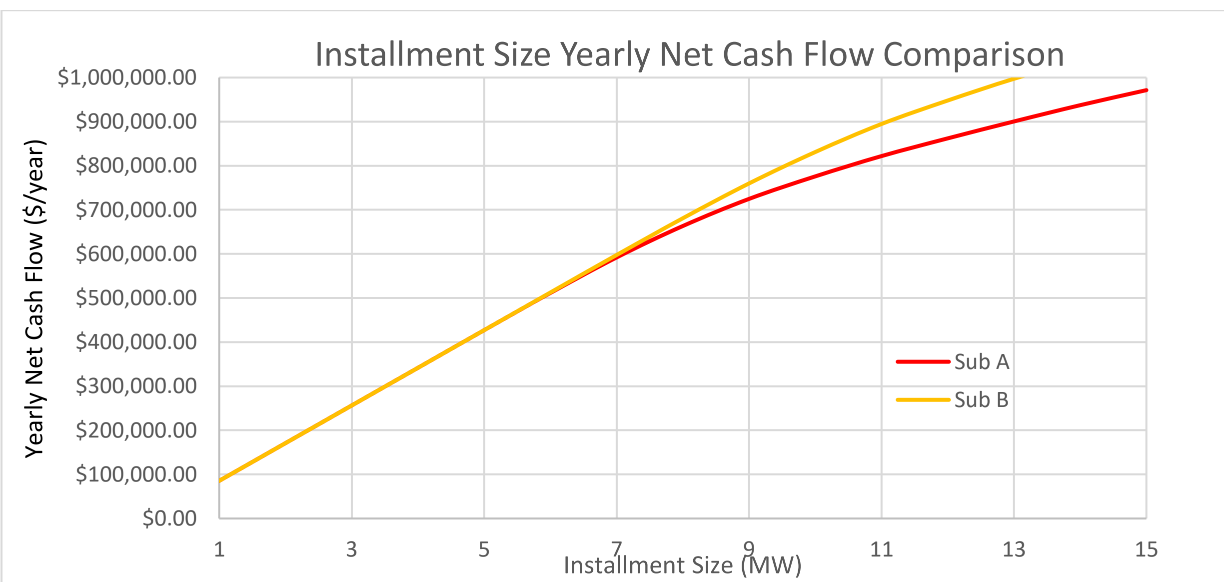

Figure 13: Installment Size Yearly Net Cash Flow Comparison

It can be seen that the two substations have the same cash flow until the installment size approaches 7 MW. From then on, Sub B proves to be the better fit for the solar garden. Sub B yields a higher cash flow at the larger installation values for the same installation cost as Sub A due to the differences in loading between the two substations. However, the advantage of Sub B does not become extremely dramatic until the solar garden is very oversized for the location. Additionally, there are other factors beyond the scope of this economic analysis that may take higher priority in the decision of placing the solar garden at one location versus the other, such as land acquisition, site layout and grading, etc. However, from a strictly economic perspective, Sub B holds a slight advantage over Sub A. The rest of the analysis just looked at Sub A because the differences in the two locations were negligible below 7 MW.

The 'right size' of the solar garden was determined to be 5 MW, which was just higher than the 1st percentile load of the substation. This size was found because the power was curtailed very few times throughout the year and thus the system produced a high rate of return while maximizing installment size. Comparisons were made between the correct size, undersized, and oversized solar garden. The sizes used were 3, 5, and 7 MW. A macro was used to obtain notable output values for each size of solar garden and were recorded in Table 4.

Table 4: Output values for a given solar installment size

Output	Solar Installation Size		
	3 MW	5 MW	7 MW
Yearly Net Flow	$256,247.26	$427,058.47	$591,973.90
Install Cost	-$2,790,000.00	-$4,650,000.00	-$6,510,000.00
Payback Years at Discount Rate	13.4	13.4	13.5
Years to Pay it Back	10.9	10.9	11.0
Annual % Return	9.18%	9.18%	9.09%
Money Lost to Solar Curtailment	$0.00	$20.30	$5,936.38

The amount the solar garden must curtail does not become a problem until it starts to be oversized for the location. Only about $20 is lost for the whole year due to curtailment when the solar garden is sized correctly at 5 MW. Thus, the annual percent return is constant until curtailment occurs and begins to decrease as the solar garden becomes oversized. The years it will take to make the money back shows to be consistently around 11 years for the given parameters. That understandably jumps up when considering net present value at the discount rate of 3%. This was because the solar garden was now being compared to other investment opportunities that would yield a return of 3%. The install cost, Fig. 14, will likely play a large role in determining what size of solar installation will ultimately be put in as the MRES member may only be willing to invest a certain amount.

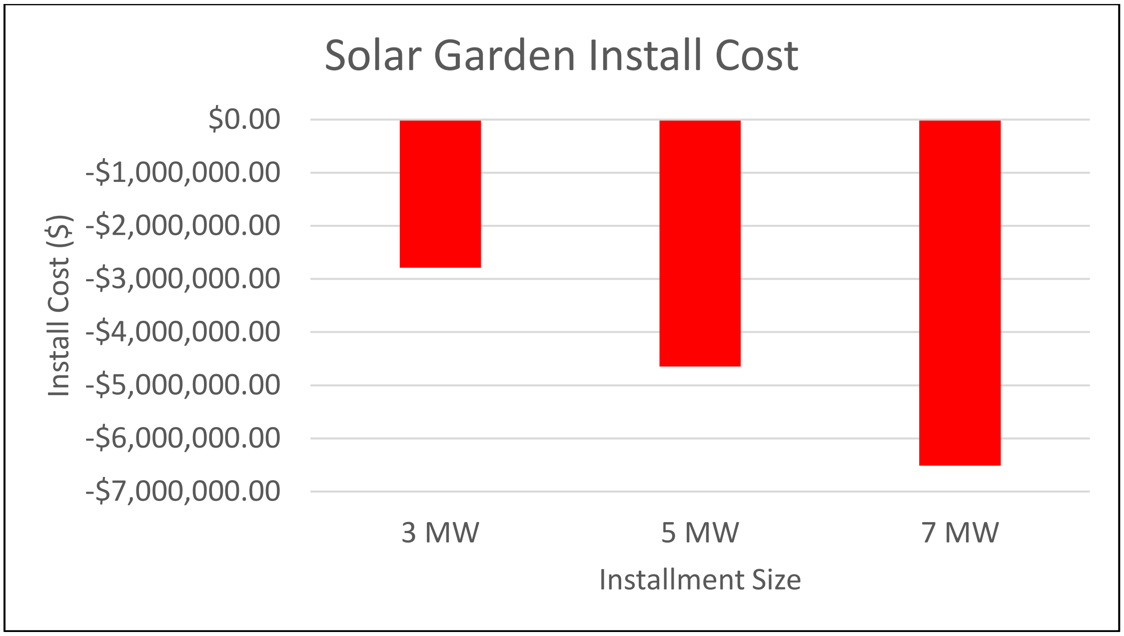

Figure 14: Install Cost Comparison

MRES indicated that the demand charge savings may or may not be applicable, depending on the location of interest. Thus, a comparison was made between using the demand charge as before and removing it from the analysis, Fig. 15. As expected, there was a noticeable difference that the demand charge makes on the amount of money that would be coming in every year from the solar garden.

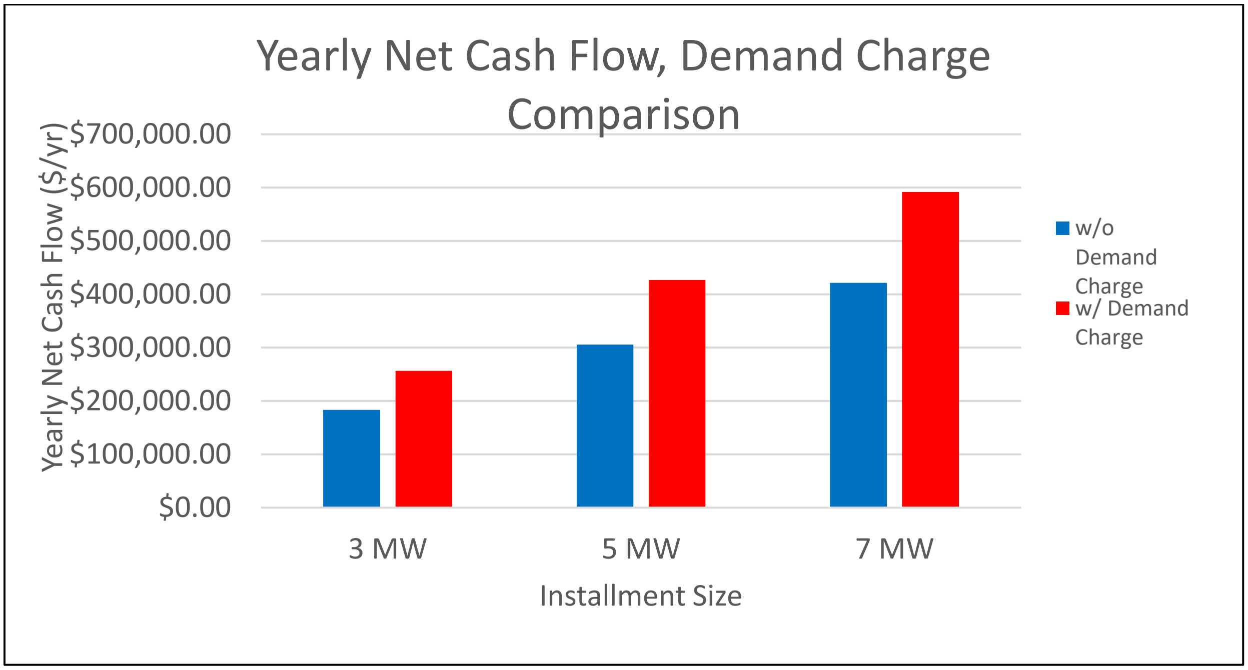

Figure 15: Yearly Net Cash Flow With and Without Considering Demand Charge

Conclusions

The small scale implementation of a solar garden within the SDSU Microgrid Laboratory served as a satisfactory proof-of-concept for a utility scale version. As expected, the control system was able to effectively curtail the power injection of the solar garden such that the generation did not exceed the load except for a brief time of sudden load decrease. Additionally, the solar garden was found to provide voltage support, which could prolong the life of LTC's. Finally, the small scale system could easily be scaled up to the utility level by combining multiple Fronius Symo string inverters together.

The economic analysis provided a tool that can be used to make any necessary adjustments and see what kind of outputs the solar garden will likely yield. The two substations ended up yielding results with negligible differences, and the solar garden should not be oversized for the location as it is not as efficient due to the curtailing of power.

Overall, a zero-injection solar garden installment was found to be feasible from an implementation perspective as well as an economic perspective. A solar garden would be an excellent opportunity for MRES to help its members generate their own clean energy while avoiding the long and expensive generation queue process. Additionally, the overall power system benefits tremendously by having generation resources located closer to the loads that they serve as line losses are significantly reduced. Finally, a solar garden was found to be an attractive investment opportunity, especially in locations that are subject to demand charges.

Future Work

The next steps in the development of a behind-the-meter solar garden would be to pitch the idea to MRES members using the small scale version as a proof-of-concept. Then, work can begin on the design of the full scale version of appropriate size for the location. There is much work that is yet to be done in regard to a full scale solar garden that was out of scope for this project. For instance, power transformers and circuits breakers would be needed to support the connection to actual distribution grid. Additionally, site grading, layout, and land acquisition are important aspects to consider in a full scale system that are heavily location dependent.

The economic analysis could get into finer detail to give more precise results. There are other factors and charges that can be considered into the outputs. If a full year was used for the substation load data rather than a month, extrapolation would not have been necessary making everything more precise. This tool can be used in the future and any adjustments could be made to the inputs. It could also be used for a different location or city as long as there is half-hourly load data for the substation of interest. It would also be beneficial to consider a situation where a loan is required to finance the project. Thus, the loan amount, term, and interest rate could be factored in as inputs.

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