

Optimization of Union College's Hybrid Microgrid to Meet All Load

Caitlin McMahon

ECE 498: Capstone Project

Professor Dosiek

Fall 2019

Report Summary

A microgrid is a small scale electric grid that generates some or all of the power used to meet its load and has the ability to disconnect from the main grid. Union College currently has a microgrid that meets 70 percent of the campus' load. It is made up of a cogeneration plant that uses natural gas from National Grid, as well as solar photovoltaic panels and wind turbines, which are renewable energy sources. The goal of this project is to determine the least cost energy mix that meets 100 percent of the campus' load. In Union's case, to minimize cost, energy should be generated on-site using solar and wind power, and potentially storage. Renewable energy sources will be used because they are environmentally friendly, and already make up part of the microgrid. The issue with solar and wind power is that they are variable based on time of day, time of year, and the weather. This needs to be addressed in the planning of Union's microgrid energy mix and capacity. The simulation needs to test worst case conditions on peak load days to ensure that the energy mix can meet load. Different options for sizes of photovoltaic panels, wind turbines and batteries will be inputs to the optimization.

Optimizing microgrid design is a widely researched topic. After considering various possibilities, this project will use Simulink software to model Union's microgrid. MATLAB will be used to call the information from the Simulink model and use it in linear programming optimization. The output of the MATLAB code will be a suggested energy mix, which will update the Simulink model. The simulation will be run again and then those values will be used in the MATLAB code. This will be done repeatedly until the optimal number, size and type of wind turbines, photovoltaic panels, and possibly batteries is found that meets load at a minimum cost.

Table of Contents

Report Summary	1
Table of Contents	2
Table of Figures and Tables	3
Introduction	4
Background	5
Implications of Renewable Energy and Microgrids on Society	5
Previous Work	9
Design Requirements	11
Simulation Design Requirements	11
Scenario Design Requirements	12
Add PV panels and wind turbines to meet load	13
Add PV panels, wind turbines and storage to meet load	13
Design Alternatives	15
Optimization Process	15
Optimization Function	16
Solar PV Panel Choices	17
Wind Turbine Choices	17
Storage Choices	19
Load and Power Data	20
Proposed Design	20
Optimization Software	20
Objective Function	21
Equipment	21
Load, Weather, Power Data	21
Carbon Tax	22
Preliminary Design	23
Schedule	26
References	27

Table of Figures and Tables

Fig. 1. Functional decomposition	15
Table 1. Goals for specifications	16
Table 2. Options for PV Panels	19
Table 3. Options for Wind Turbines	20
Table 4. Options for Batteries	21
Fig. 2. Pseudo code for optimization	25
Fig. 3. Union's Microgrid, modeled in Simulink	26
Fig. 4. Preliminary MATLAB code for Optimization	27

Introduction

The electric grid is traditionally a large scale, bulk energy system. Power plants generate power which is sent over transmission lines at high voltages to distribution substations and then to customers at low voltages. Fossil fuels are used to generate the majority of our electricity, however they are depleting in supply and have negative environmental effects. This is leading to a rise in the importance of cleaner, renewable generation, such as wind and solar power. There are many challenges associated with the integration of renewables, specifically the variability in power output due to time of day, time of year, and the weather. This is called intermittency. For example, solar photovoltaic (PV) panels cannot produce power overnight or when there is cloud cover. Similarly, wind turbines cannot produce power when there is a lack of wind speed to turn the turbines. This is often addressed by adding storage. These systems can also be more expensive than conventional systems [1]. Hence, adding renewable, clean sources to an electric grid requires advanced planning based on weather, load and cost analysis.

Along with the increase in renewable generation, microgrids are becoming a trend in the energy sector. A microgrid is a localized energy grid [2]. Microgrids can use power from the grid, from their local generation, or from a combination of both. Typically, microgrids generate power from renewable sources, whether it be for environmental reasons, or because this is a cost effective way to generate power on a small scale. Microgrids can also use more traditional methods of generation such as diesel or natural gas. A system composed of both conventional and renewable resources is called a hybrid system [3]. Control mechanisms for microgrids are often based on minimizing cost while still maintaining reliability. Hence, when there is a problem on the main grid, a microgrid can disconnect and operate on its own, providing increased reliability [4]. This control capability is useful for many communities, especially hospitals, jails, and college campuses.

Union College's microgrid currently meets about 70 percent of the load. The college's goal is to meet 100 percent of its load so that the microgrid can operate entirely on its own, but remain connected to the grid for reliability purposes. The hybrid system is made up of a cogeneration plant which provides most of the power, as well as solar photovoltaic (PV) panels and wind turbines. This paper seeks to find the least cost combination of energy resources to add to the current microgrid to meet all of the campus' load.

This report will first introduce background information including how renewable energy and microgrids affect different aspects of society. Then previous work for the optimization of microgrid design will be discussed. The design requirements for Union's microgrid and the optimization software will be described, then alternatives will be explored. This will lead into the discussion of the selected methodology for this project. In this section, two simulation scenarios will be described in depth, as well as how the optimization will be performed. The overall objective of this project is to determine the optimal amount of solar, wind, and possibly storage to add to the microgrid to meet the campus' load on all days of the year.

Background

Implications of Renewable Energy and Microgrids on Society

For most of our recent history, the electric grid has remained the same large scale system. As the grid is altered with distributed generation (DG), renewable energy, and microgrids, the energy market becomes more complex and affects energy prices. This reflects on our society as a whole. Microgrids offer many benefits such as increased grid reliability and efficiency, and decreased carbon emissions [5]. This is a great advantage compared to fossil fuels, which have been shown to have a negative impact on the

environment. Hence, government goals such as NYS Governor Cuomo's Green New Deal have been announced to help the environment. The deal raises the 2030 renewable energy generation goal from 50 to 70 percent of the electric grid through additional wind and solar resources [6]. As more customers are buying into DG and microgrids, control schemes are being created, incentives and policies are being implemented, and regulatory agencies and utilities are being educated, making implementation easier as time goes on [5].

Microgrids also offer safety benefits, especially for sites that rely on surety of power. For example, hospitals benefit greatly from having a well-designed, reliable microgrid. When there are issues on the main grid, the microgrid can disconnect and enter islanding mode. This allows the hospital to keep its power on and therefore keep its patients alive. This same idea is useful for jails, where a power outage could result in unlocking of jail cells and create safety risks for the security workers and inmates. Facilities like these are often prioritized by utilities during outages, but a reliable microgrid ensures constant supply of power.

The downside to renewable energy, as previously mentioned, is intermittency. As we move towards higher penetration of renewable energy, a lack of proper planning and load analysis could result in the grid's inability to meet demand under some circumstances without proper backup [7]. More simply, the lights could go out. This illustrates the importance of in depth analysis of renewable energy and the weather at the location of installation. In this case, designing the additions to Union's microgrid clearly requires consideration of load and weather patterns. Making sure the combination of wind and solar energy can supply sufficient power, even on the worst case days, will be a design requirement for the project.

Another important aspect of this analysis is the differences in a hybrid system with and without storage. Adding storage to a highly renewable energy based microgrid may have interesting effects on system reliability and cost. One study noted that placing storage close to generation can increase the voltage consistency on the grid [8]. This is a benefit of having storage in a microgrid, since all devices are closely located by definition. Furthermore, this “co-location” results in lower costs because of less hardware components and labor, as well as government initiatives for “solar plus storage” [9]. Policies encourage this because storage smooths the variability in the solar generation. Simulating adding storage to Union’s microgrid will therefore be one scenario, with the same requirement of minimizing cost while meeting all load. Comparing net costs including the purchase of all additions, maintenance, operation, and any resulting tax breaks and incentives with and without storage will be interesting.

Storage also has a downside. A possible negative effect of batteries is that they may not actually improve carbon emissions on a large scale without an official carbon tax [10]. This is because batteries charge when energy is cheap, which is often overnight. During this time, some fossil fuel plants are still operating at a percentage of their maximum output to avoid ramping restrictions. Hence, there is the possibility that batteries store some amount of energy generated from fossil fuels, which does not improve the carbon emissions of the energy system [10]. However, this microgrid could be designed so that the storage unit only charges when there is excess generation of renewable energy. This would improve carbon emissions in Union’s case. Rather than relying on natural gas from the cogeneration plant when solar and wind cannot supply enough power to meet demand, storage could supply the excess power that came from renewable sources. Another aspect of storage that is worth considering is their life cycle and resulting effect on the environment. When the typical double-A battery “runs out” or dies, we throw it out. The same will have to happen with large scale batteries. All batteries have different life cycles, and as the technologies develop, life cycles are often increasing. However, adding storage to a microgrid at this

point may still have a negative environmental impact since it cannot be recycled, and chemical waste does not align with the greener, sustainable aspects of a microgrid. This will be considered in the design requirements section as well.

Microgrid design tools like the ones discussed in the section below, and the one I am seeking to develop, can help advance the implementation of renewable energy in microgrids. Another advantage of developing systems like these is that policy makers and government officials who were not previously aware of the science behind the electric grid can see how systems work optimally. Those who create incentives for renewable energy can also explore the most cost effective systems [11]. This will all result in better planning and hence benefits for electricity customers. Another research paper discusses the impact that renewable energy and microgrids have on politics and policies. It claims that changes to the power sector are crucial to combat climate change, and power electronics “will be a key element in the energy policies of nations” [12].

Lastly, ethics are always necessary to discuss for any project. As for this paper, there are few ethical implications. There are no obvious ways in which the findings of this paper could be used in a bad way, and no harm can come from the actual installation of more wind turbines and solar panels on campus as long as it is done by professionals who know the proper techniques. The only apparent ethical issue with renewable energy is potential increased costs without incentives to lower energy costs. On a large scale, if more energy comes from renewable energy, or if there is ever a carbon tax implemented, the cost of energy could increase. This could negatively affect people with low incomes. However this is only applicable on a large scale, since on a small scale, the customer(s) would be purchasing the system themselves, knowing the associated costs. Furthermore, a microgrid usually results in decreased costs. Since minimizing cost is the basis of this project, this ethical concern is being considered.

Previous Work

Due to all of the reasons discussed in the sections above, there are various research papers discussing approaches to optimizing the design of microgrids. One study developed a model called Regional Renewable Electricity Economic Optimization Model (RREEOM) which simulates a renewable power based grid with the goal of obtaining the combination of generation and storage to minimize cost while reliably supplying the load [13]. This study provides valuable information to my project, however it is focused on a large regional electric grid rather than a microgrid. It was found that generating two to three times the electricity needed to meet electrical load was the least cost option, depending on the circumstances and initial conditions of weather and load. I will consider this by not constraining the system to a maximum number of PV or turbines. However, depending on the results, I may have to include this due to limited space for these additions. The same study also showed that higher storage actually increased system costs with the technologies available. My project will analyze both cases, with and without storage. Another conclusion from the study is that combining different types of renewable energy provided more stability on the grid [13]. Although since this study was based on a large scale with widely diverse generation sources at diverse locations, these findings have a limited, but still insightful, implication to a microgrid study.

HOMER is a tool developed by NREL that optimizes microgrid design and sizing. HOMER takes multiple inputs including the cost and capacity of generation sources, the location of the grid, and the load profile. Then it tests different combinations of resources and produces various options and prices [11]. Various studies utilize this tool [14-17]. One research paper tested a system with only PV, with only wind turbines, then with PV, turbines and batteries. HOMER determined the least cost, most reliable energy mix was the combined hybrid system [15]. A similar study on the design of a microgrid for a water

treatment plant recommended a solar-wind hybrid over a solely wind based system [17]. Clearly, a more diverse combinations of resources is better than just one type of energy source. The water treatment plant study utilized HOMER software because it was determined to be the best for their microgrid application. Other programs considered were EnergyPlan, which is a deterministic model and not suitable for this problem, and H2RES, which was not selected due to inability to simulate grid connection. Since Union needs to remain grid connected, H2RES cannot be utilized for my simulation either. HOMER is not a free tool, but will hopefully be used as a comparison to what my model and optimization process will produce.

A model of a microgrid based on wind, PV, and battery combinations was created by Ramos and Ramos [18]. Their research demonstrates how solar and wind can complement each other, since wind is often stronger at night and during the winter months, whereas solar can provide more energy during the day and the summer months. A higher ratio of wind to solar was optimal, while higher reliance on PV resulted in higher system costs. This is due to geographical factors and the weather. However, in Schenectady, the location and weather factors are different and need to be studied. Therefore, my design will include location specific wind and solar irradiance data.

An optimization of a residential energy supply (RES) system used linear programming and modeled the grid using only equations [1]. This is a limited approach because it only offers optimization of PV, a solar thermal collector, and a heat pump. Furthermore, the entire modeling and optimization process has application limitations due to broad assumptions. However the derivation of the objective function, or the function which will be optimized, is helpful to my project and will be further discussed in the design alternatives section.

REMix is another software developed to determine a “Renewable Energy Mix for Sustainable Electricity Supply” [19]. This tool considers a much larger scale than a microgrid - it investigates energy mixes for various countries in Europe and North Africa. One interesting topic this paper makes note of is the effect of politics on the energy sector, which in turn affects all users of electricity. Since renewable energy and storage technologies are newer and more expensive, if policy makers do not incentivize programs to encourage implementation of these environmentally friendly sources, they may not be implemented. The REMix model takes into account the availability and cost of renewable energy, transmission, and storage to determine the size and locations of equipment which makes up a power system that minimizes cost. Since my project will not have any transmission lines and is a much smaller scale than an entire country, some aspects of the design of this software are not relevant. However, this model also uses linear programming as the method of optimization, which illustrates to me that linear programming is sufficient for my needs.

Design Requirements

The purpose of this project is to determine the optimal energy mix for Union’s microgrid in order to meet 100 percent of the load at a minimum cost. Since this project simulates the options that could possibly be implemented, there are two subsections of design requirements: one for the simulation itself, and one for the scenarios which may be actually implemented.

Simulation Design Requirements

The simulation must have a practical run time of less than ten minutes, which constrains the size of the code. The optimization must consider the peak and average load day. The peak day is one worst case day for the microgrid because the system will have to supply the most power. For solar and wind, the

optimization must also consider the days with the lowest irradiance and wind speed, respectively, to make sure enough power can be generated to meet all load even under these worst case conditions. There must be the following parameters for each scenario: total cost of additions, total cost of maintenance for a one year period, total energy produced and consumed, any government incentives or tax breaks. The optimization must minimize the cost function while meeting all load.

Scenario Design Requirements

Based on the literature review above, a scenario with PVs and wind turbines should be analyzed, as well as a combined system with PVs, turbines, and storage. This creates the two scenarios which will be explored in this paper. Each scenario needs to be able to meet all of Union's load throughout the entire year, or else it cannot be considered optimal. Currently the microgrid can supply up to 70 percent of the campus' load, which peaks at approximately 2.4MW. The cogeneration plant supplies most of the load, peaking at 1.8MW, with solar panels providing about 6.3kW and the wind turbine providing less than 1.2kW. Hence, to reach 100 percent of the campus' load, there needs to be at least 592.5kW of added power generation, or approximately 0.6MW. Based on [13], the microgrid may require more than this to reliably meet load, due to the variability in power supply from PVs and turbines. The simulation will reveal how much extra power needs to be added above 0.6MW.

Another design requirement is the cost limitation. When Union added the cogeneration plant, a grant of \$12 million total was awarded for the project [19]. For the purposes of this paper, it will be assumed that a similar grant amount could be awarded. Hence, the scenario's net cost must be less than \$12 million in order for the college to consider implementing it.

Equipment and grid design are other important considerations for this project. The scenario needs to have the option to remain grid tied for emergencies. The equipment needed for each scenario must be easily available on the market, and meet all of the relevant standards for the respective piece of equipment. Along with these requirements, the two scenarios must meet additional specific requirements:

1. Add PV panels and wind turbines to meet load

This scenario requires space availability for wind turbines and PV panels. The results of the optimization must be analyzed closely to determine if the amount of PV panels and turbines could realistically be installed on campus. Because of solar and wind intermittency, there must be a control scheme implemented to determine when to use the cogeneration plant's power. The cogenerator should remain at least slightly on at all times to avoid ramping up and ramping down which is expensive, in terms of money and energy. The control scheme should use the minimum amount of power from the cogenerator as possible to avoid this while using the maximum amount of wind and solar power to meet load. When there is not enough wind power due to lack of wind, and not enough solar due to lack of sun, the cogenerator should increase its output to match the load. This is similar to two research papers which both developed a control scheme to limit PV power output only when the diesel generator is at its lowest and demand is still being met [8, 13].

2. Add PV panels, wind turbines and storage to meet load

This scenario builds on the previous one by adding storage. This can help the college use more power generated on site, rather than buying gas from National Grid. Hence, this scenario has potential economic advantages, but the cost of the storage may limit the benefits [13]. The control scheme for this case will build upon the previously described one. When the minimum power output of the cogenerator plus the

maximum output of the solar panels and/or wind turbines supply more power than demanded, the excess power can be stored. This avoids curtailment, which is defined as limiting the output of renewable energy sources when there is less power demanded than how much power the source could produce [2]. When there is not enough solar and wind output plus the minimum cogenerator output to meet demand, the stored power should be used. If there is not enough stored power to compensate, the cogenerator should increase its output. This control scheme aims to maximize environmental friendliness by using renewable sources of energy plus storage as much as possible, while also minimizing cost by producing as much as possible onsite before buying more gas from the grid.

These requirements create a starting point of a basic, top view design of my project. It can be summarized by simulating different combinations of energy resources, then optimizing the mix based on its ability to meet load at a minimum cost. Fig. 1 below depicts this process.

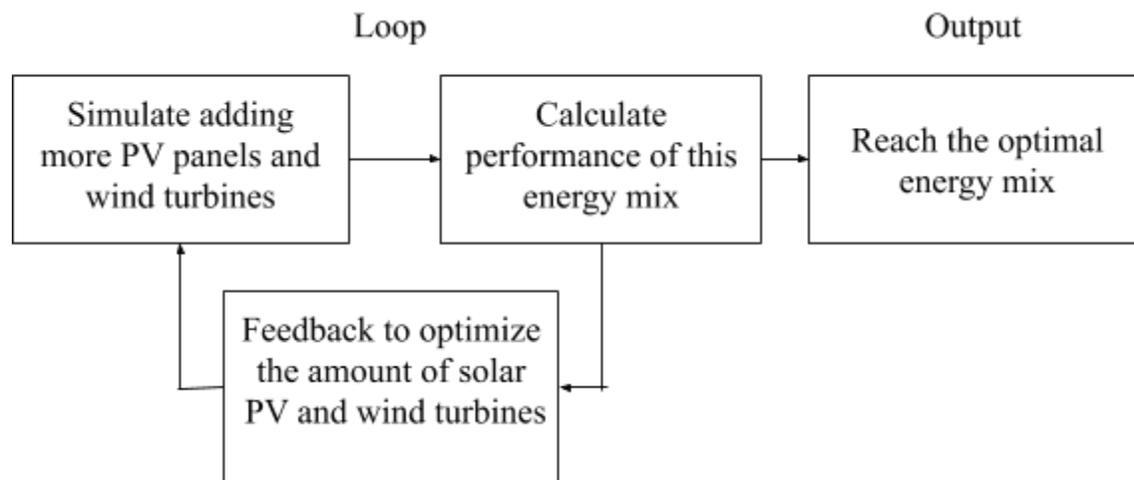


Fig. 1. Functional decomposition

Power produced in each iteration of the loop in Fig. 1 will be compared to load under worst case conditions on the peak day. Then, the optimization will update the ratio of PV panels and wind turbines to further minimize overall cost. This program will also run for the simulation of adding storage. The two optimal outputs will be compared.

A summary of the design requirements are tabulated below.

Category	Goal
Power	The additions to the microgrid must meet 100 percent of Union's load on every day of the year. At least 0.6MW of power generation needs to be added. Additional generation may be needed due to wind and solar being intermittent resources.
Cost	The net cost of the additions should be less than or equal to 12 million dollars. This is the grant amount that was used to install the cogeneration plant at Union so for simulation purposes, we will assume that we can win a similar grant to pursue these updates.
Control Schemes	The control schemes will be programmed into the scenarios to determine when to use which energy source to minimize the amount of gas drawn from the grid.
Usability of code	The code needs to run in under ten minutes.

Table 1. Goals for specifications

Design Alternatives

Optimization Process

To determine the optimal combination of energy resources to meet load, different proportions of solar and wind generation will be tested. Optimization processes can make this more efficient than testing

manually, and this has been done for many similar applications discussed above in the literature review. To optimize an objective function, many software programs could be utilized. In a review of current technologies available, there were over 75 programs listed and explored [7]. One of the programs mentioned was CYME, which I have access to through my internship at National Grid. However I do not have the ability to program an optimization such that energy resources are changed or added, I am only able to study what is currently there. On the system, Union is simply modeled as a load, so I would have to design the microgrid myself, making CYME no better than other alternatives.

I also considered Python Anaconda, PSCAD, MATLAB, and HOMER. A similar research project created a model of a renewable energy based grid consisting of a wind turbine and a solar panel on PSCAD [8]. To create the turbine, factors such as measured wind speed data, turbine and other mechanical efficiency factors, and electrical efficiencies were considered. To create the solar panel, an inverter modeled as a current source was used. For my own project, I would have to learn PSCAD or Python, however I have experience with MATLAB. The wind turbine and solar panels are modeled in a similar way in the Small Scale Microgrid model on MATLAB Simulink [21]. Furthermore, MATLAB has a toolbox of optimization abilities.

Optimization Function

Regardless of the software, there are various methods of optimization. Following similar grid design studies such as [1], a linear optimization approach is suitable. A subcategory of this is mixed integer linear optimization. This means some of the constraints are integers [22]. In this case, the number of solar panels and wind turbines are integer values. Quadratic optimization is another method, however it is for nonlinear applications and is therefore not necessary [23].

Solar PV Panel Choices

On the market, there are numerous types and sizes of solar panels. For this project, only a few options need to be considered that Union would potentially buy. The PV panels that Union currently uses will be one option. Without getting quotes from vendors, accurate costs of other panels are difficult to obtain. One alternative would be using data on the average price of a solar system in NYS. Options are listed below in Table 2.

Name	Suntech STP255S 20/Wdb	Average Price of 10kW solar system [25]
Information	PV panels on Union's Facilities building [24]	Without going through the process of getting quotes for specific panels, I will use the average price range
Cost	Waiting for information from the sustainability coordination, will be updated over winter break*	\$29,800, after federal investment tax credit (ITC) rebates \$20860
Rated Output	10.2kW for one 12.5kW two arrays combined	10kW
Annual Output	12.7MWh for one, 34 MWh total	-
\$/W	See above*	\$2.98

Table 2. Options for PV Panels

Wind Turbine Choices

There are also various options for wind turbines, shown below in Table 3.

Name	1.2kW Vertical Axis from Windspire [9]	Ramsond Atlas 3,000-Watt Wind Turbine Generator [26]	Excel 10 Bergey [27]
Information	Turbine that Union currently uses	Sold by Home Depot	Produces higher power
Cost	No longer available, 5kW is \$32,899.00	\$6098.40*	\$43,495 (turbine, tower, wiring kit)
Rated Output	5.1kW	3kW	10kW @ 12 m/s (27 mph) 8.9kW @ 11m/s (24.5 mph)
Annual Output	9400kWh @ 12.5 mph	2100kWh @ 12 mph	13800kWh @ 5 m/s (11 mph)
Standards Met	Emailed to inquire	GB/T 10760.1 GB/T 13981-2009 GB 17646 GB/T 19068.1 JB/T 10399-2004 JB/T 10402.1-2004 JB/T 10403-2004 JB/T 10405 2004 NY/T 1137-2006	AWEA Standard 9.1 - 2009 awarded by SWCC
\$/W	\$6.45	\$2.03	\$4.35

Table 3. Options for Wind Turbines

*Since the Ramsond Atlas turbine did not include mounting materials, the cost is approximated using pricing data from Bergey [27]. The additional materials were about 40 percent of the Bergey turbine's cost. So 40 percent of the Ramsond turbine was added to more realistically represent the total cost. One study on microgrid design references the Bergey wind turbine as being the best option after in depth research, which is why I chose to have this as an option [14].

Storage Choices

Since studies with similar goals of designing an optimal microgrid considered adding batteries as their source of storage, I will investigate the same thing [18]. In one study, a 4MWh Lithium Ion Phosphate battery was determined optimal for the microgrid after considering important characteristics of storage such as round trip efficiency, cycle life, safety, and environmental friendliness [8]. This is just one type of lithium ion battery which has increased safety but lower capacity, with 88 percent round trip efficiency, meaning only 12 percent of energy is lost during charge and discharge process. The size is too large for Union's microgrid, however it is worth analyzing a battery of the same type. Table 4 lists some options for battery choices. Note that many are generic options, not specific types ready for purchase. This is a limitation of the project at this point. However, this allows for greater variability in the sizing of storage, then based on the result I could find a battery of that size, get a quote, and analyze cost in greater detail.

Name	BWC Excel 10/S Turbine, include new VCS II Advanced Charge Controller [28]	Generic 1kWh battery [29]	Generic Lithium Ion battery [30]	Generic Lead Acid [30]
Information	Wind turbine off-grid battery charging	This is the data HOMER uses	Data from NREL study	Data from NREL study
Cost	\$43,495 including turbine, 18m tower, wiring kit	\$550 per unit	\$350/kWh	\$250/kWh
Ratings	10kW @ 12 m/s (27 mph) 8.9kW at 11m/s (24.5 mph) 13,800kWh at 5 m/s (11 mph)	1kWh	90% composite AC-AC round-trip efficiency	80% composite AC-AC round-trip efficiency

Table 4. Options for Batteries

Load and Power Data

The Simulink Microgrid model comes with example load data and solar irradiance data [21]. There is also data available through my internship with National Grid. However, this will only show the power that Union takes from the grid, which doesn't include the power that the cogeneration plant generates using the natural gas from National Grid or the small amounts of power generated from the on-campus solar PV panels and wind turbines. Union has data available on the power generated from the PV panels, although they are currently locked with a password. Eventually, I will get access and download that data. Union does not have data on wind power generated or wind speed, however there are sites nearby that provide wind speed data online that are accessible. One study designing a microgrid also utilized wind speeds from a location nearby and found that its accuracy was sufficient for preliminary designing needs [17].

Proposed Design

Optimization Software

MATLAB will be used for this project. I am already familiar with it, I have access to it on my personal computer, and it has a Small Scale Microgrid model I can work from as well as an optimization tool box with everything this project requires. There is a large amount of documentation of optimization processes on MATLAB as well as power system examples, including implementation of wind turbines. HOMER will likely be used in conjunction with this for comparison, however my design will be specific to Union's needs. Linear programming will be used for the minimization of the objective function.

Objective Function

In a microgrid design study, the objective function was the overall cost of the energy system [1]. I will follow the same idea, using MATLAB documentation as a reference for set-up [31]. Fig. 2 at the end of this section illustrate how this will be carried out. First I will explain other choices for my system. Specifically, what information is going to be input into the optimization.

Equipment

The objective function will be programmed to compare all options for the PV panels, wind turbines, and batteries. Then it will choose the type, size, and number of each that minimizes the cost functions along with the other variables. Hence, all of the information in Tables 2, 3, and 4 will be input into MATLAB. During winter term I will determine the best way to categorize each system so that the objective function can compare the options in each category.

Load, Weather, Power Data

The other crucial inputs into the optimization are data on load, weather, and power production. To choose the peak load day, I utilized an excel tool through National Grid called PI Datalink. I downloaded data for the maximum power that Union bought from the grid on each day in 2019, then filtered to find the day which had the highest overall value. I determined that May 18th was the day with the highest load in 2019. Although summer months usually have the peak day, Union is not in session then so this makes sense.

For solar power, I am currently using the data that is automatically in the Simulink Small Scale Microgrid model. Once I obtain a password to access Union's solar power data, I will use this data in the lookup

table to increase accuracy. One study shows that the placement and angle of the PV panel plays a role in power production [17]. Since my study does not include determining specific locations of the PV panels and wind turbines, average data can be used to simulate. To create the lowest solar irradiance day, I increased the shading factor block in the simulink model. This block is multiplied with the solar panel current. During hours 20h - 4h, the shading block makes sure there is no solar output [21]. During the day, there is partial shading during user specified hours.

For the wind data, I gathered 24h of wind speed (m/s) from a site in Albany. This is the closest obtainable wind speed information closest to the campus. The wind speed is an input to the wind turbine block in Simulink. The wind power is an output of the block, which is calculated based on parameters in the block. These can be changed to accurately reflect the exact wind turbine being used. However since I am simulating different options of turbines, I will leave those parameters as default for now. This can be altered at later stages of my project. To create the least windy day for the worst case conditions, I simply scaled down the wind speed data.

Carbon Tax

As a part of this project, I want to include something to reflect the environmental friendliness of any upgrades to the microgrid. In the future, carbon taxes may be implemented as a way to reward energy low carbon emissions and tax high carbon emissions. To calculate the carbon tax, a line in the code will use data from Wingas [32]. Their fact sheet states that 0.572 kg of CO₂ per kWh of electricity generated is produced by burning natural gas if transport, production and processing materials are considered. Using data from the NYISO's carbon tax proposal, I will calculate a carbon tax [33]. A tax of \$50/ton of CO₂ is proposed. Approximately 900 kg of CO₂ would need to be produced to be taxed \$50, equivalent to 1585 kWh for natural gas. This analysis will be at the end of my project and is not currently included in any

pseudocode. Since the carbon tax is directed at the large scale generation plants, and not small generators like within Union's microgrid, there will probably be a small effect. I still think it is worth investigating to learn how it will work.

Now that all of the design selections have been explained, Fig. 2 displays the pseudocode.

```

While system is not meeting load at least cost
  For peak day % check if scenario can produce enough power to meet load on peak day
    If the scenario's power produced < load
      Increase number of PV panels and/or turbines
    End
  End

  For lowest irradiance day, peak load % check if PV + wind turbines can produce enough
    If the scenario's power produced < load
      Increase number of PV panels and/or turbines
    End
  End

  For lowest wind day, peak load % check if PV + wind turbines can produce enough
    If the scenario's power produced < load
      Increase number of PV panels and/or turbines
    End
  End

  Total cost = construction cost + system cost + maintenance costs - tax breaks or rebates
  Optimize total cost with linear programming
  Update Simulink model with the new amounts and sizes of PV panels and wind turbines
End

```

Fig. 2. Pseudo code for optimization

Preliminary Design

Based off of the Small Scale Microgrid Model in Simulink, I have modelled what Union's microgrid is currently designed as in Fig. 3. I need to add the cogeneration plant and connect the wind turbine's power output to the grid through a converter. The wind turbine is connected to the three phase portion of the grid, while the PV panels and loads are connected on each single phase. The source on the far left models

National Grid. The yellow scope on the bottom left opens up a lower level which displays power and other variables. The red scenario box opens another lower level which contains the look up table blocks for the load data, solar data, and wind speed.

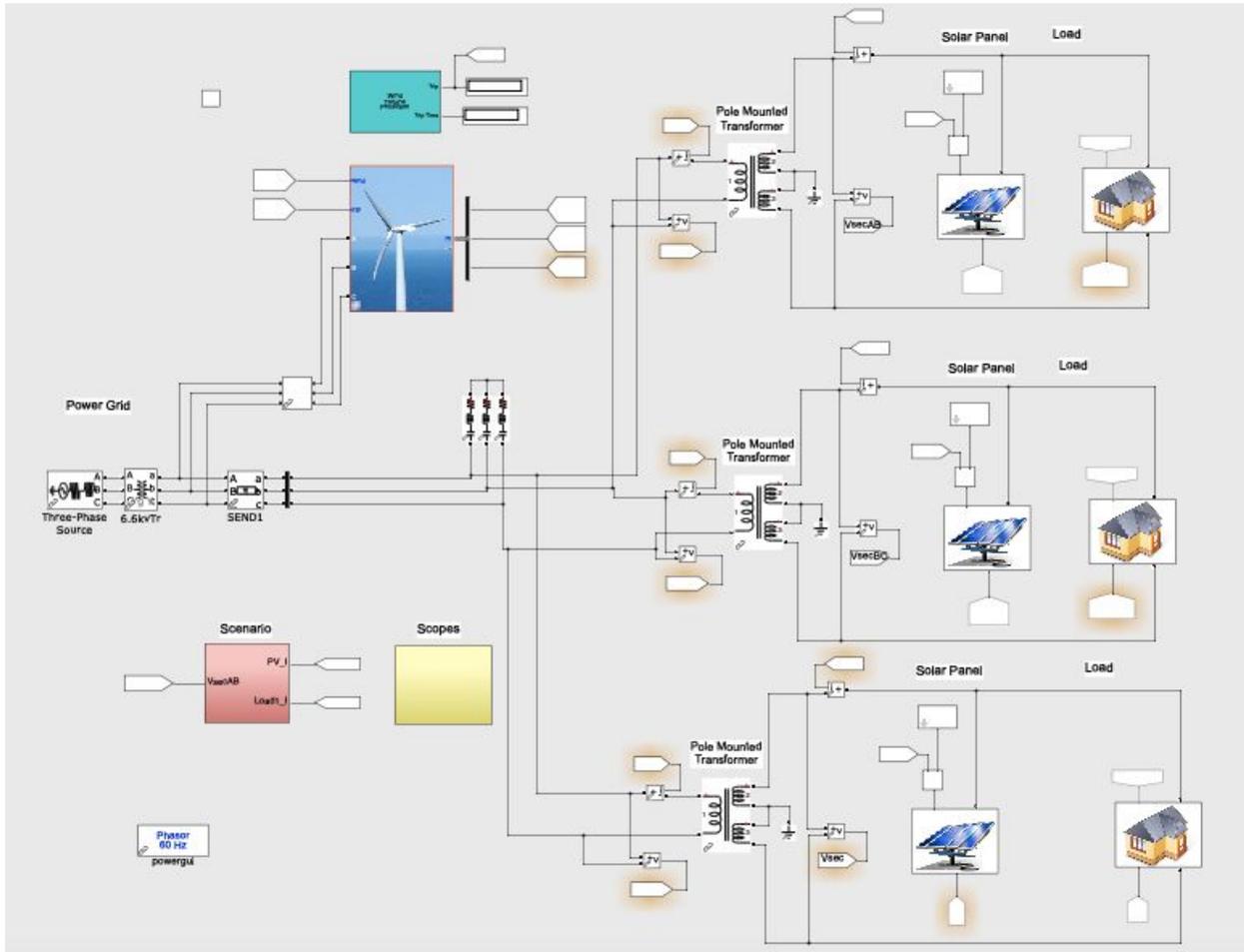


Fig. 3. Union's Microgrid, modeled in Simulink

Many of the variables in this model will be called into the MATLAB program to be parameters of the optimization function. For example, the total power will be used to determine if the scenario can meet load. Fig. 4 is the preliminary code for the optimization with the Simulink model.

```

energyprob = optimproblem; % create the optimization problem

solarPanels = optimvar('solar',2,'Type','integer'); % the number of panels is an integer, 2 options
windTurbines = optimvar('wind',2,'Type','integer'); % the number of turbines is an integer, 2 options

costPanel = [15000, 20860]; % cost for each solar system, $
powerPanel = [6300, 10000]; % size or power output for each solar system, Watts

costTurbine = [32899, 43495]; % cost for each turbine, $
powerTurbine = [5000, 10000]; % size or power output for each turbine, Watts

costSolar = costPanel*solarPanels; % number of solar panels times cost per panel
costWind = costTurbine*windTurbines; % number of wind turbines times cost per turbine

cost = costSolar + costWind;

energyprob.Objective = cost; % make the objective function the cost

totalPower = power_PV_AB + power_PV_BC + power_PV_CA + power_wind + power_cogen;
% these are the power variable in the Simulink model I have created

for partial_shading = high
    worstCaseSolar = totalPower;
    % total power when shading factor is high
    % control partial shading block in simulink from matlab and rerun simulation
end

for W_speed = low
    worstCaseWind = totalPower;
    % scale wind speed down and rerun simulation
end

energyprob.Constraints.conwcs = worstCaseSolar >= 250000; % simulate 2.5MW peak load
energyprob.Constraints.conwcw = worstCaseSolar >= 250000;
energyprob.Constraints.conc = cost <= 12000000; % cost less than $12 mil

[sol,fval] = solve(energyprob); % minimize using linear programming

```

Fig. 4. Preliminary MATLAB code for Optimization

There are some errors in the model which will be worked out during winter break and winter term. The code has not been run yet, but once the model is operational, I will begin working on the optimization of it.

Schedule

Week 1

- Add the cogeneration plant
- Fix the errors in the model so that it can operate

Week 2

- Work on a way to vary the amount and sizes of wind turbines and solar panels in the Simulink model through MATLAB
- Input the costs of the options for PV panels and wind turbines into variables in MATLAB

Week 3

- Debug the code and make sure it works with the Simulink model
- Work on optimizing the amount of wind and solar

Week 4

- Connect the battery
- Create a similar code but include cost and variables for the battery
- Work on optimizing the amount of wind, solar, storage

Week 5

- Utilize HOMER to see the optimal energy mix based on that software
- Continue troubleshooting and optimizing the energy mix
- Begin report: final design and implementation

Week 6

- Finish using HOMER and compare results
- Report: performance estimates and result, production schedule, cost analysis

Week 7

- Work out any unpredicted problems
- Report: user's manual, discussion conclusions and recommendations

Week 8

- Report: references, appendices

Weeks 9 and 10

- Revise report

References

- [1] C. Milan, C. Bojesen and M. Nielsen, "A cost optimization model for 100% renewable residential energy supply systems", *Energy*, vol. 48, no. 1, pp. 118-127, 2012. Available: 10.1016/j.energy.2012.05.034.
- [2] "Curtailment Fast Facts", *Caiso.com*, 2019. [Online]. Available: <https://www.caiso.com/Documents/CurtailmentFastFacts.pdf>. [Accessed: 22- Nov- 2019].
- [3] E. Silveira, T. de Oliveira and A. Junior, "Hybrid Energy Scenarios for Fernando de Noronha archipelago", *Energy Procedia*, vol. 75, pp. 2833-2838, 2015. Available: 10.1016/j.egypro.2015.07.564.
- [4] E. Alegria, T. Brown, E. Minear and R. Lasseter, "CERTS Microgrid Demonstration With Large-Scale Energy Storage and Renewable Generation", *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 937-943, 2014. Available: 10.1109/tsg.2013.2286575.
- [5] T. Mohn, "Campus microgrids: Opportunities and challenges", *IEEE*, vol. 2012, 2019. Available: 10.1109/PESGM.2012.6344610 [Accessed 22 November 2019].
- [6] "New York Gov. Launches 'Green New Deal' With Accelerated Clean Energy Targets", *Greentechmedia.com*, 2019. [Online]. Available: <https://www.greentechmedia.com/articles/read/new-york-cuomo-green-new-deal-clean-energy>. [Accessed: 22- Nov- 2019].

- [7] H. Ringkjøb, P. Haugan and I. Solbrekke, "A review of modelling tools for energy and electricity systems with large shares of variable renewables", *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 440-459, 2018. Available: 10.1016/j.rser.2018.08.002.
- [8] Q. Fu et al., "Microgrid Generation Capacity Design With Renewables and Energy Storage Addressing Power Quality and Surety", *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2019-2027, 2012. Available: 10.1109/tsg.2012.2223245.
- [9] "5kW Wind Turbine by Windspire", *Windspireenergy.com*, 2019. [Online]. Available: <https://www.windspireenergy.com/5kW-wind-turbine.htm>. [Accessed: 22- Nov- 2019].
- [10] E. Hittinger and I. Azevedo, "Bulk Energy Storage Increases United States Electricity System Emissions", *Environmental Science & Technology*, vol. 49, no. 5, pp. 3203-3210, 2015. Available: 10.1021/es505027p.
- [11] "The HOMER® Micropower Optimization Model", *Nrel.gov*, 2019. [Online]. Available: <https://www.nrel.gov/docs/fy05osti/37606.pdf>. [Accessed: 22- Nov- 2019].
- [12] B. Bose, "Global Warming: Energy, Environmental Pollution, and the Impact of Power Electronics", *IEEE Industrial Electronics Magazine*, vol. 4, no. 1, pp. 6-17, 2010. Available: 10.1109/mie.2010.935860.
- [13] C. Budischak, D. Sewell, H. Thomson, L. Mach, D. Veron and W. Kempton, "Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of

the time", *Journal of Power Sources*, vol. 225, pp. 60-74, 2013. Available:
10.1016/j.jpowsour.2012.09.054.

[14] R. Srivastava and V. Giri, "Optimization of Hybrid Renewable Resources using HOMER", *International Journal of Renewable Energy Research*, vol. 6, no. 1, 2016. [Accessed 22 November 2019].

[15] J. Lagorse, D. Paire and A. Miraoui, "Sizing optimization of a stand-alone street lighting system powered by a hybrid system using fuel cell, PV and battery", *Renewable Energy*, vol. 34, no. 3, pp. 683-691, 2009. Available: 10.1016/j.renene.2008.05.030.

[16] M. Chaichan, H. Kazem, A. Mahdy and A. Al-Waeely, "Optimal Sizing of a Hybrid System of Renewable Energy for Lighting Street in Salalah-Oman using Homer software", *International Journal of Scientific Engineering and Applied Science*, vol. 2, no. 5, 2016. [Accessed 22 November 2019].

[17] M. Soshinskaya, W. Crijns-Graus, J. van der Meer and J. Guerrero, "Application of a microgrid with renewables for a water treatment plant", *Applied Energy*, vol. 134, pp. 20-34, 2014. Available:
10.1016/j.apenergy.2014.07.097.

[18] J. Ramos and H. Ramos, "Sustainable application of renewable sources in water pumping systems: Optimized energy system configuration", *Energy Policy*, vol. 37, no. 2, pp. 633-643, 2009. Available:
10.1016/j.enpol.2008.10.006.

[19] Y. Scholz, "Renewable energy based electricity supply at low costs : development of the REMix model and application for Europe", *OPUS - Publication Server of the University of Stuttgart*, 2012.

[Accessed 22 November 2019].

[20] "Union's CoGen plant – A greener future", *Muse.union.edu*, 2015. [Online]. Available:

<https://muse.union.edu/garnetgoesgreen/2015/09/30/unions-cogen-plant-a-greener-future/>. [Accessed: 22-Nov- 2019].

[21] "Simplified Model of a Small Scale Micro-Grid- MATLAB & Simulink", *Mathworks.com*, 2019.

[Online]. Available:

<https://www.mathworks.com/help/physmod/sps/examples/simplified-model-of-a-small-scale-micro-grid.html#d117e28409>. [Accessed: 22- Nov- 2019].

[22] "Optimization Problem Types - Mixed-Integer and Constraint Programming", *solver*, 2019. [Online].

Available: <https://www.solver.com/integer-constraint-programming>. [Accessed: 22- Nov- 2019].

[23] "Problems Handled by Optimization Toolbox Functions- MATLAB & Simulink", *Mathworks.com*,

2019. [Online]. Available:

https://www.mathworks.com/help/optim/ug/problems-handled-by-optimization-toolbox-functions.html#tb_lminprobs. [Accessed: 22- Nov- 2019].

[24] "Lightgauge Data Monitoring", *Lg878.d.lighthousesolar.com*, 2019. [Online]. Available:

<http://lg878.d.lighthousesolar.com/index.html>. [Accessed: 22- Nov- 2019].

[25] L. Tarbi, "How Much Does a 10kW Solar Panel System Cost in 2019? | EnergySage", *Solar News*, 2019. [Online]. Available: <https://news.energysage.com/10kw-solar-systems-compare-prices-installers/>. [Accessed: 22- Nov- 2019].

[26] "Atlas 3,000-Watt Wind Turbine Generator", *Home Depot*, 2019. [Online]. Available: https://www.homedepot.com/p/Ramsond-Atlas-3-000-Watt-Wind-Turbine-Generator-LM3500/307565908?mtc=Shopping-B-F_D27E-G-D27E-27_31_CONTROL-Generic-NA-Feed-PLA-NA-NA-CONTROL_Nondoorbells&cm_mmc=Shopping-B-F_D27E-G-D27E-27_31_CONTROL-Generic-NA-Feed-PLA-NA-NA-CONTROL_Nondoorbells-71700000052998923-58700005105045162-92700048675636141&gclid=EAIaIQobChMI493YqYDt5QIVBpSzCh1Zdw_qEAQYASABEgLyIPD_BwE&gclsrc=aw.ds. [Accessed: 22- Nov- 2019].

[27] "Excel 10 - Bergey Windpower Co.", *Bergey Windpower Co.*, 2019. [Online]. Available: <http://www.bergey.com/products/grid-tied-turbines/excel-10/>. [Accessed: 22- Nov- 2019].

[28] "Excel 10 Off Grid - Bergey Windpower Co.", *Bergey Windpower Co.*, 2019. [Online]. Available: <http://www.bergey.com/products/off-grid-turbines/excel-10-off-grid/>. [Accessed: 22- Nov- 2019].

[29] "HOMER QuickStart", *Quickstart.homerenergy.com*, 2019. [Online]. Available: <http://quickstart.homerenergy.com/#/app/ee2e61bd-1bb7-47aa-ab2f-c39f78482fef/results/optimization>. [Accessed: 22- Nov- 2019].

[30] "COMPARATIVE STUDY OF TECHNOECONOMICS OF LITHIUM-ION AND LEAD-ACID BATTERIES IN MICROGRIDS IN SUB-SAHARAN AFRICA", *Nrel.gov*, 2019. [Online]. Available: <https://www.nrel.gov/docs/fy19osti/73238.pdf>. [Accessed: 22- Nov- 2019].

[31] "Mixed-Integer Linear Programming Basics: Problem-Based- MATLAB & Simulink", *Mathworks.com*, 2019. [Online]. Available: <https://www.mathworks.com/help/optim/ug/mixed-integer-linear-programming-basics-problem-based.html>. [Accessed: 22- Nov- 2019].

[32] "Natural gas is the most climate-friendly fossil fuel in electricity production", *Wingas.com*, 2019. [Online]. Available: https://www.wingas.com/fileadmin/Wingas/WINGAS-Studien/Energieversorgung_und_Energiewende_en.pdf. [Accessed: 22- Nov- 2019].

[33] "Understanding New York ISO's carbon pricing proposal", *ICF*, 2019. [Online]. Available: <https://www.icf.com/insights/energy/nyiso-carbon-price>. [Accessed: 22- Nov- 2019].