Sustainable Engineering Internship 2021
Final Report

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Assignment 1 - The Power of Wind

1.1 Background

The Shoals Marine Laboratory (SML) operated a 7.5 kW Bergey wind turbine from the summer of 2007 until the spring of 2019 when the turbine experienced an internal electrical failure. The unit was replaced on June 18th, 2021 with a 10 kW version and an upgraded VCSII battery charge controller. Wind power contributes significantly to SML's green energy grid because it has the capability of providing power at night, and during stormy weather when the island's photovoltaic systems are less effective. In general, wind is a more efficient power source than solar. Compared to photovoltaic panels, wind turbines release less carbon dioxide to the atmosphere, consume less energy, and produce more energy overall.

1.1.1 Site Characteristics

Shoals Marine Laboratory is located on Appledore Island, a 95-acre island approximately 10 km off the New Hampshire and Maine border coast. According to IOSN3 White Island measurements, the mean annual speed is 7.0 m/s at 13.7 m AMSL and 7.7 m/s at 13.7 m AMSL for October through April (Carpenter, 2003).

1.2 Purpose

The purpose of this assignment is to confirm that the turbine is operating as expected for the BWC Excel 10 model. Under the direction of Professor Martin Wosnik from the Department of Mechanical Engineering at the University of New Hampshire, interns were asked to quantify the energy output of the new wind turbine and compare the data with theoretical outputs suggested by the manufacturer. The analysis will provide a greater understanding of the contribution of wind energy toward SML's net energy production and point to possible recommendations for improving wind energy storage and utilization efficiency through existing equipment or future upgrades.

1.3 Scope

The interns will examine the actual power output of the Excel 10 turbine in comparison to the AWEA rated power output displayed on the spec sheet. Graphing wind speed versus power output can determine if the turbine is meeting its intended specifications. Once the turbine's efficiency is confirmed, the interns will be able to quantify the percentage of wind energy to total energy production on the island and propose additional upgrades to transition Shoals to almost fully renewable and self-sustaining.

1.3.1 Turbine Specifications

Table 1: Turbine Specifications (Bergey Windpower Co., 2020)

AWEA Rated Power	8.9 kW at 11 m/s (24.5 mph)
AWEA Rated Annual Energy	13,800 kWh at 5 m/s (11 mph)
Max. Design Wind Speed	60 m/s (134 mph)
Type	3 Blade Upwind
Tower Height	25 m (~ 80 ft)
Rotor Diameter	7 m (23 ft)
Generator	Permanent Magnet Alternator
Output Form	3 Phase AC, Variable Frequency

1.4 Methods

1.4.1 Power Law for Wind Variation with Elevation z

Since wind speed increases with height above the ground, it is necessary to interpolate wind measurements for accuracy. As a result, the wind speed from SML's Radar Tower anemometer was adjusted to account for the elevation difference between the anemometer and the turbine hub to accurately convey the wind velocity at the elevation of the turbine. The relationship of increasing speed and power to increasing elevation is commonly referred to as the one-seventh power law ($\alpha = \frac{1}{7}$).

$$\frac{U_{hub}}{U_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^{\alpha} \text{where } \alpha = \frac{1}{7}$$

The radar tower height(Z_{ref})is 54.0 meters above mean sea level (AMSL), whereas the turbine's height (Z_{hub})is 36.4 meters AMSL.

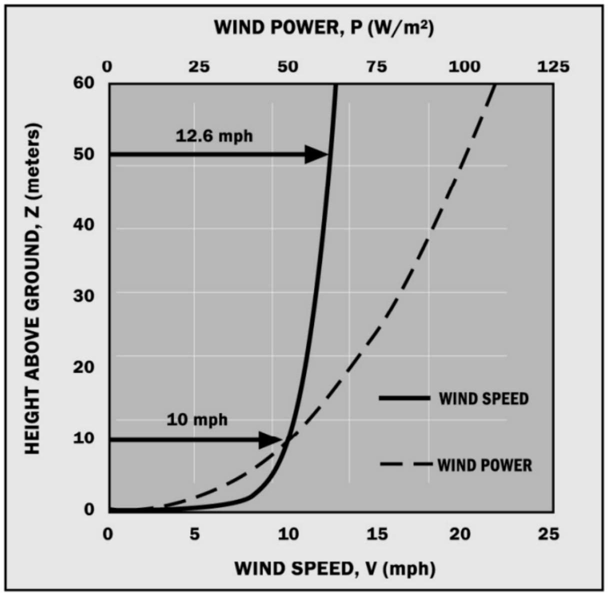

Figure 1: Typical Wind Shear Profile (Carpenter, 2003)

1.4.2 Wind Speed at Hub Height

The equation is then adjusted to ascertain the wind speed at the turbine (Wosnik, 2021). This equation was utilized to properly adjust all of the wind velocity readings from the radar tower (U_{ref}) for the wind turbine hub (U_{hub}).

$$U_{hub} = \left(\frac{Z_{hub}}{Z_{ref}}\right)^{\frac{1}{7}} \times U_{ref}$$

1.4.3 Power Equation

The power equation is used to determine the theoretical maximum amount of power contained in the wind at a given wind speed for a turbine with a defined rotor area. The value obtained with this equation is used to determine the efficiency of a turbine with the actual power it produces.

$$P = \frac{1}{2} \times \rho \times A \times U^3 \times C_p \text{ where } A = \frac{\pi}{4} \times D^2 \text{and } \rho = \text{ air density} = 1.225 \text{ kg/m}^3$$

1.4.4 Coefficient of Power Equation

The amount of power generated by wind turbines depends on the density, velocity, and volume of air, as well as the swept area of wind turbine blades and blade design. Due to generator inefficiencies, friction, and blade design, wind turbines can only convert a maximum of 59.3% of the kinetic energy into mechanical energy, known as the Betz limit (Le Gourieres, 1982). Therefore, the coefficient of power is used to determine the efficiency of the turbine's power production relative to the maximum power available in the wind, where $C_{p\,(max)} = 0.59$.

$$Cp_{actual} = \frac{P_{turbine}}{P_{wind}} = \frac{P_{actual}}{\frac{1}{2} \times \rho_{air} \times A_{turbine} \times U^3}$$

$$\text{Percent Change} = \frac{Cp_{actual} - Cp_{theoretical}}{Cp_{theoretical}} \times 100$$

1.4.5 Total Energy Generation

To provide an analysis of the contribution wind energy is making toward SML's net energy production, interns divided the wind turbine generation by the island's total grid generation. Data was extracted directly from SML's dashboard.

$$Total\ Island\ Grid\ Generation\ (kWh) = solar + wind + generators$$

$$Contribution\ of\ Wind\ Energy = \frac{Wind\ turbine\ generation\ (kWh)}{Island\ total\ energy\ generation\ (kWh)} \times 100$$

1.4.6 Data Acquisition

The island engineers noticed data noise when the turbine was not rotating yet generation was still being reported by the AcuDC. The noise is variable based on how much solar is being produced. 0.29 kW was the maximum value of noise recorded with the new turbine and has been subtracted from all of the data before being uploaded to the dashboard (Sustainable SML, 2021). While 0.29 kW was used as an estimated offset for power generation, it may vary substantially with fluctuating wind speeds. Interns analyzed the offset by manually subtracting the power output displayed by the VCSII charge controller from the output recorded on the AcuDC. As a result, interns developed a graphic comparing the offset to the power displayed on the VCSII charge controller in section 1.5.3.

1.5 Results and Analysis

1.5.1 Theoretical Power Output

The graphed power curve below shows the logistic growth rate between power output and average wind speed at the hub of the wind turbine. Around 12,500 W, the curve reaches its maximum output. The curve was corrected to a sea-level air density of 1.225 $\frac{kg}{m^3}$.

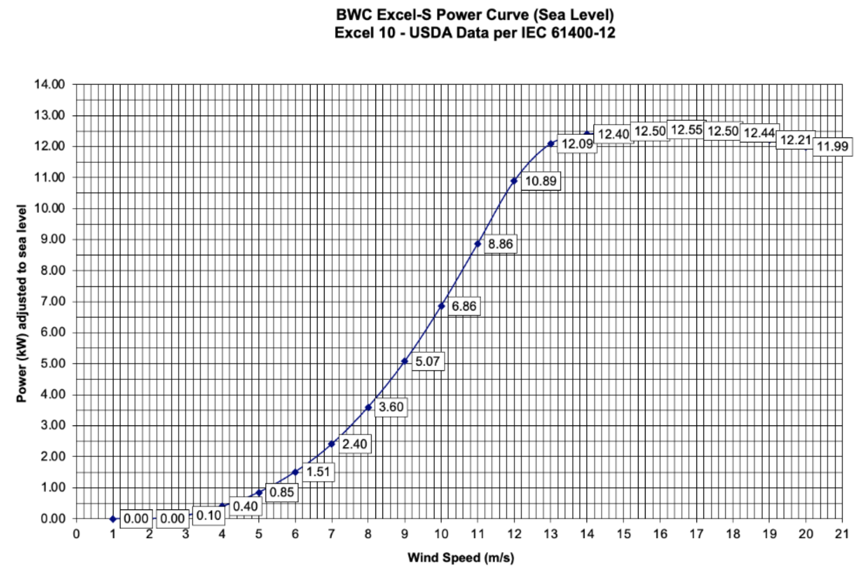

Figure 2: Theoretical Power Curve of Bergey Excel 10 (Bergey Windpower Co., 2020)

1.5.2 Weibull Performance Calculations

Wind Speed Bin (m/s)	Power (kW)	Wind Probability (f)	Net kW @ V
1	0.00	3.81%	0.000
2	0.00	7.18%	0.000
3	0.10	9.78%	0.010
4	0.40	11.38%	0.046
5	0.85	11.95%	0.102
6	1.51	11.58%	0.175
7	2.40	10.50%	0.252
8	3.60	8.97%	0.323
9	5.07	7.25%	0.368
10	6.86	5.58%	0.382
11	8.86	4.08%	0.362
12	10.88	2.85%	0.310
13	12.09	1.90%	0.230
14	12.39	1.21%	0.150
15	12.49	0.74%	0.092
16	12.55	0.43%	0.054
17	12.50	0.24%	0.030
18	12.44	0.13%	0.016
19	12.21	0.07%	0.008
20	11.99	0.03%	0.004
2011, BWC	Totals:	99.65%	2.913

Table 2: Weibull Performance Calculations (Bergey Windpower Co., 2020)

Wind speed probability is calculated as a Weibull curve defined by the average wind speed and a shape factor, K. To facilitate piecewise integration for the theoretical model, the wind speed range is broken down into bins of 1 m/s. For each wind speed bin, instantaneous wind turbine power is multiplied by the Weibull wind speed probability. This cross product is the contribution to average turbine power output contributed by wind speeds in that bin. The sum of these contributions is the average power output of the turbine on a continuous, 24 hour, basis (Carpenter, 2003). The wind turbine's power output was calculated using Bergey's Wind CAD performance model and the following parameters: Weibull K factor of 2, wind shear exponent of 0.250, and a turbulence factor of 0.0% (Bergey Windpower Co., 2020).

1.5.3 Wind Turbine Power Offset

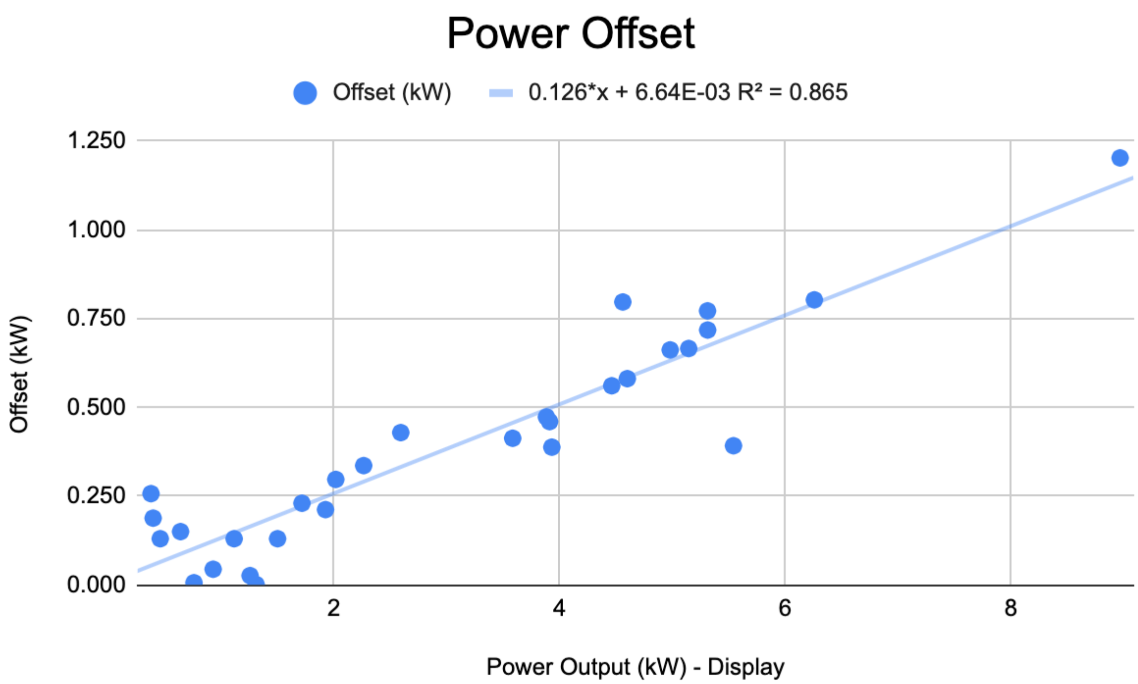

Figure 3: Power Offset

The data points graphed above were collected randomly, from varying wind speeds and days. Data was collected by taking a photo of both the AcuDC and VCSII displays at the same time. By plotting the data, it is clear the linear trendline portrays a positive correlation between increasing power output and offset. The 0.29 kW value previously used no longer seems reliable when there is a minimum offset of 0.001 kW and a maximum offset of 1.203 kW observed. Interns recommend offsetting the data from the AcuDC as a linear function of the power output illustrated by the following equation: *0.126x + 0.00664*. With an R^2 of 0.865, the equation provides a strong estimate for the correction factor at a given power output. However, there are limited data points for higher wind speeds and higher power outputs, and data points should continue to be gathered to generate a more accurate equation. Refer to the Appendix for all collected data points.

1.5.4 Actual vs. Theoretical Power Output

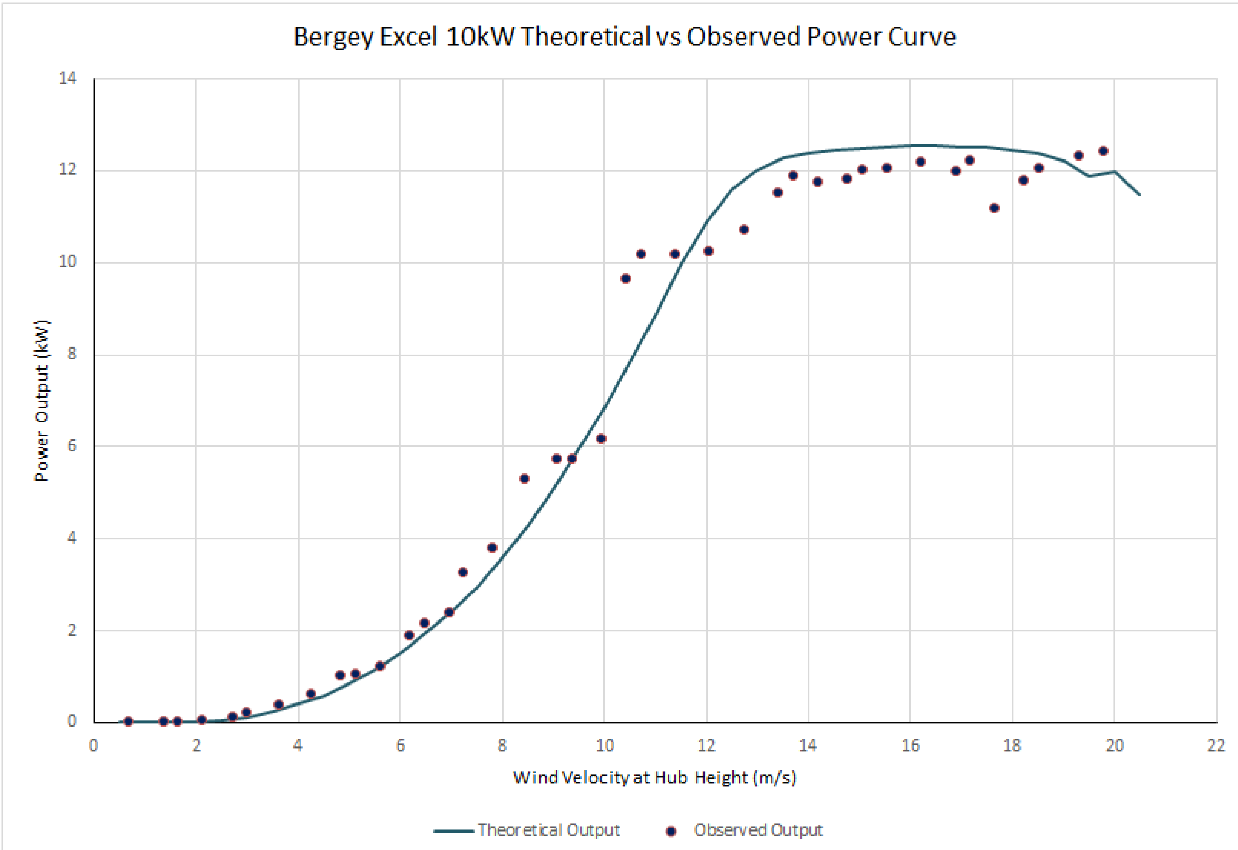

Figure 4: Actual and Theoretical Power Curve of Bergey Excel 10, Pre-Offset

Extracting the data from Sustainable SML's dashboard, interns collected the wind speed from the radar tower and its actual power output (Sustainable SML, 2021). The wind speed was then adjusted to account for the decreased elevation at the wind turbine, utilizing the equation referenced in 1.4.2. The actual power output and wind speed were then graphed in conjunction with Bergey's theoretical power curve to display the efficiency and similarities of the actual output. As witnessed in Figure 4, it becomes apparent that the actual power curve is highly correlated to the theoretical power curve, excluding some minor outliers. Before the variable offset was discovered, interns had happily reported that the new turbine was performing with an average Cp of 0.24; 14.3% higher than the theoretical Cp of 0.21. However, after their discovery, the following figure was procured.

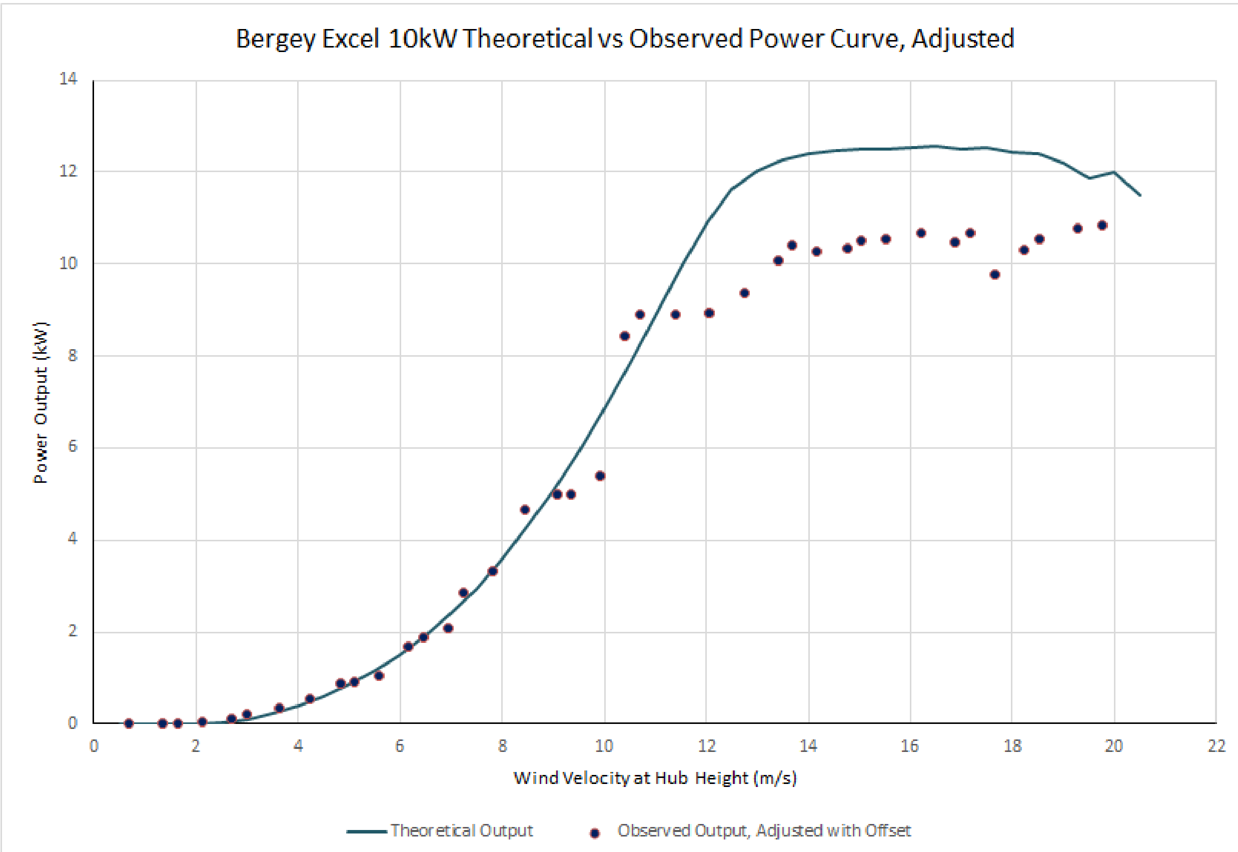

Figure 5: Actual and Theoretical Power Curve of Bergey Excel 10, Adjusted with Offset

With the power outputs adjusted, the new actual power curve closely matches the theoretical curve for the first 11 m/s of power output, then remains about 2 kW below the rated output. However, the average Cp of the adjusted output is 0.21, the same as the theoretical Cp, when analyzed from the cut-in speed (2.5 m/s) and higher. Interns are unsure as to why the Cp values are the same when the actual output clearly does not match the theoretical output, however. The maximum output hovers around 10.5 kW, lower than the 12.5 kW suggested by the theoretical, but on par with the 10 kW rating of the turbine itself. Refer to the Appendix for all data points and the magnitude of their adjustment.

1.5.5 Total Grid Generation

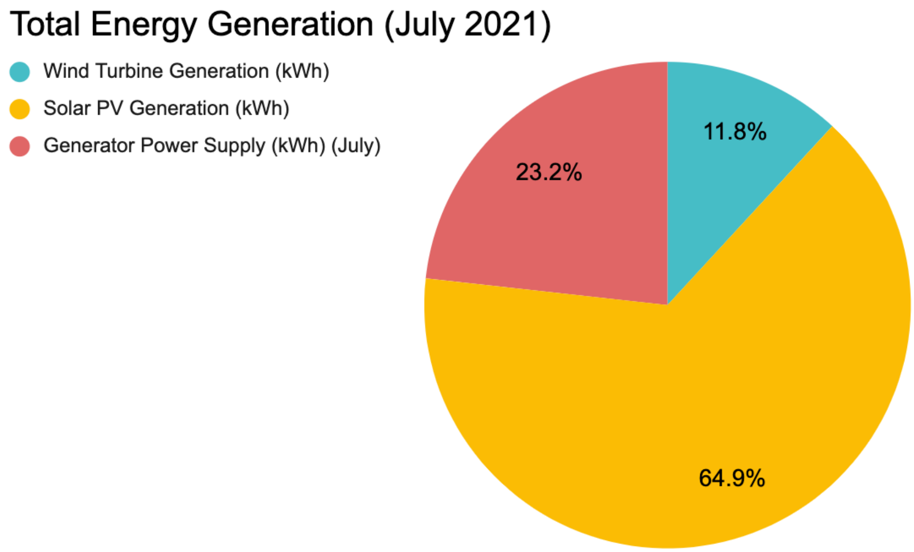

Figure 6: Total Energy Generation (July 2021)

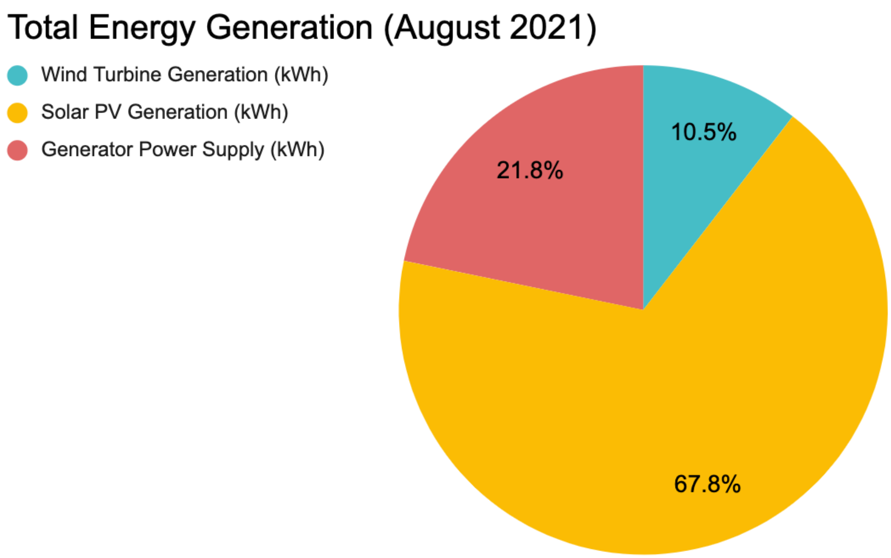

Figure 7: Total Energy Generation (August 2021)

Wind turbine generation for July and August was 1456.57 kWh and 895.62 kWh, respectively. This was adapted from the equation referenced in section 1.4.5. SML's Bergey Excel 10 kW rated wind turbine feeds power into the ECB grid when the wind velocity is at least 2.5 m/s. At night, this is the island's only source of green energy.

1.6 Conclusions and Recommendations

Prior to the offset adaptation, interns suspected that the average power coefficient for the island's turbine was 24% compared to the 21% coefficient suggested for the theoretical model. As a result, the initial analysis valued the turbine to be 14.3% more efficient than the expected output. After adjusting the power offset to account for wind noise and differing values from the VCSII charge controller and the AcuDC display, interns determined that this initial coefficient of power and efficiency standards were incorrect and suggested better than average outputs. After adjustment, the Cp value was 0.21 and the maximum power output was 10.5 kW, compared to the initial 12.5 kW and 0.24 value that the interns initially proposed. The new Cp value is equivalent to the suggested Cp value of 0.21. Regardless, these values still indicate that the turbine is working up to code and producing more than enough for its 10 kW capacity.

It is important to note that this sample size was extracted from the date of installation on June 16th, 2021 to early August and may not correlate to long-term trends. These rudimentary results may have been a result of above average wind conditions from a particularly cold, and turbulent, summer (National Data Buoy Center, 1996). Interns recommend that the 2022 SEI cohort further monitor these outputs over a longer duration to determine its sustained capabilities and confirm the Cp and actual power curve realized this summer.

Overall, wind turbine generation contributed around 11.8% to the island's total energy generation in July and 10.5% in August. Green energy still contributed 76.2% to the grid despite poor weather conditions, while the generator's power supply leveled at 23.8%.

As a result of the Excel 10 turbine operating as anticipated, interns recommend continued maintenance and what's already being done, such as taking down the blades in the winter season to sustain longevity. BWC Excel wind turbines and blades boast a five-year warranty after the date of installation. During that period, Bergey will repair or replace, at its discretion, defective components or assemblies (Bergey Windpower Co., 2020). After completion of the 5-year warranty, interns recommend upgrading the existing equipment to Excel 15 or the newest turbine available.

To improve SML's accurate data collection there are a few things that may be done. One solution is to install a PS TAB (third party software) on the VCSII charge controller to accurately read the power output at varying wind speeds and output it into a format the dashboard could easily read. However, this would cost upwards of $1300 and is not the best solution. The interns recommend that future SEI interns collect more offset data, solidify the linear trendline, and apply the equation to data read from the AcuDC before being displayed on the dashboard.

In 1.6.1, interns will go into further detail outlining recommendations to avoid “free spin”.

1.6.1 Discoveries

On SML’s island grid, solar power serves as the main driver for energy production, whereas the wind turbine acts as a supplemental source of energy. However, on days with excess wind and sun, the VCSII seems to confuse the solar charge controllers when the battery reaches approximately 56 V and prompts the solar charge controllers to essentially ‘back off.’ After speaking with Bergey Windpower technicians, the interns deduced that the ultimate charge on the batteries is 56.4 V, with an equalization charge of 62 V. Considering the maximum power output of SML’s turbine is 56.39 V (Sustainable SML, 2021), the Excel 10 model is right on track - as evidenced by the results above.

Nevertheless, once the battery voltage reaches 56.4 V, the turbine keeps “free spinning” without being under any load or generating any power. In this case, the VCSII acts as the load, and when the batteries are full, the VCSII opens a contactor and allows the turbine to “free spin.” Without loading the alternator or drawing current from the wind, the turbine continues to spin at a much faster rate. Even though the turbine is still producing power, nothing is happening with that power. And while the excess wind does not overcharge the batteries, it will wear out the turbine in the long term. This can lead to mechanical degradation of the turbine’s longevity and quality.

While a diversion load for the turbine is not directly available, the same thing can be done by putting a load on the batteries so they are never all the way full. This allows the turbine to push the current and keep the amount of time it is “free spinning” to a minimum. Tyler Garzo, SML’s IT Specialist, suggested a non-complex baseline load, such as a bitcoin miner, to be installed on the island which can be activated or deactivated automatically depending on daily wind and sun projections.

A Bergey technician also recommended adjusting the float voltage through the user configuration file by modifying the set parameters in the SD card; for example, from 56.4 V to 54.5 V. If this is done, it was strongly recommended to save the original parameters by copying the SD card first. When the batteries are full and there is wind and solar available, it was advised to let the turbine ‘top off’ the batteries, instead of the solar, as is currently being done. This would prevent any damage from “free spinning” and would be beneficial to the turbine long-term. However, because the solar output is more reliable at SML, it should remain as the driver for battery recharge with the turbine treated as secondary generation. Furthermore, interns suggest analyzing the output of the solar charge controllers and the battery monitors and communicating with Schneider Electric if a change is deemed necessary.

1.8 References

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Le Gourieres, D. (1982). Description and performances of vertical axis windmills. *Wind Power Plants*, 121–147. https://doi.org/10.1016/b978-0-08-029966-2.50011-0

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Assignment 2 - Green Energy - How Much?

2.1 Background

SML currently maintains three independent green grids that combined include 232 photovoltaic panels with 92 kilowatts of capacity, one 10 kW wind turbine, and 470 kilowatt-hours of battery storage (Balkin et. al., 2017). The main island grid supplies power for the majority of the infrastructure on Appledore Island with 65.5 kW of rated capacity between the PV panels and the turbine.

The K-House grid powers the saltwater pump which then supplies water to the sea tables, saltwater spigots and faucets, the reverse osmosis unit, and the fire hoses. The K-House grid is the result of a donation of a Mobile Renewable Energy Unit from a Cornell alumnus and includes 100 solar panels and 16 lithium ion batteries that store 76.4 kWh. These batteries are utilized solely by the saltwater pump and are completely independent of the other two grids. There is an unknown amount of energy generated by the solar panels and stored in the batteries that are not utilized and could offset demands on other parts of the island. At maximum capacity, the K-House solar panels can produce 29.4 kW.

The absorbent glass mat battery storage at the Radar Tower is outdated, and therefore, supplies inadequate power. As a result, the tower is always buying from the main grid during the summer, and data indicates it has gotten significantly worse: 77 kWh in July 2019, 175 kWh in July 2020, and 252 kWh in July 2021. Data indicates average battery voltage has stayed the same over the past 3 summers, implying a potential set point issue. During the winter, the tower operates independently from the main grid and has about three days worth of charge available to operate just the tower. When operating efficiently, the tower grid, made up of PVs on Dorms 2 and 3, can produce 7.5 kW and power the PK Lab and Dorm 2 and 3 when operational (Sustainable SML, 2021).

The rated capacity is the maximum capacity that PV panels can produce. This value is determined when they are initially fabricated and depreciates over time. It is liable to change due to variables such as temperature, the time of day, and the global horizontal irradiance available from the sun. Thus, the grids do not often reach their maximum output and instead rely on diesel generation to keep up with demand.

During periods when stored energy is depleted, SML operates a 27 kW diesel generator to provide power to its island campus. Planning is underway to integrate the currently independent green energy grids to increase the percentage of SML’s electricity production using green technologies. An analysis is needed to determine the current ratio of green energy to diesel-powered energy sources, and determine what additional infrastructure will be required to consistently reach 95 to 100% green energy utilization rates.

2.1.1 Green Grid Schematic

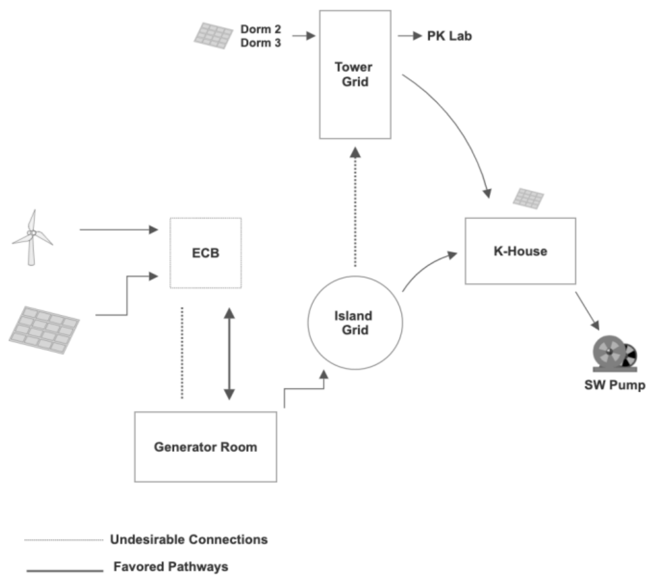

Figure 8: SML's Green Grid Connections

2.1.2 SML Electrical System Diagram

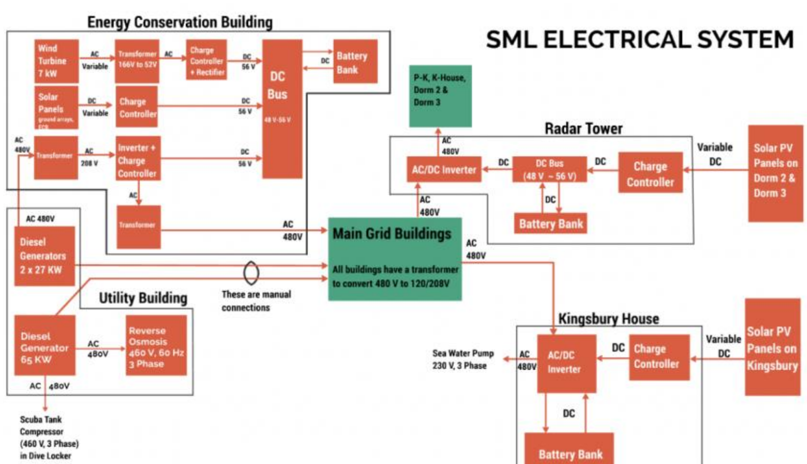

Figure 9: SML's Electrical System Diagram

It is important to note that Figure 8 displays the 7 kW turbine versus the updated 10 kW turbine. Regardless, it does not change the rest of the schematic, which shows how the island grids are currently wired.

2.2 Purpose

Shoals Marine Laboratory intends to transition to 95 to 100% green energy utilization rates through intelligent re-routing and communication of the island's green grids, as well as necessary upgrades made to the island's battery banks. While there is still substantial dependence on diesel generation through the night when photovoltaics are inactive, interns will assess different solutions to reduce the overall usage of fossil fuels to less than 5%. Ultimately, Shoals strives to serve as a model for other communities nationwide to make the switch to a fully renewable and sustainable lifestyle.

2.3 Scope

Using data from SML's dashboard, interns will calculate the percentage of energy production that originates from green sources on Appledore Island. Interns will propose a combination of photovoltaic, wind, and battery installations that would reduce overall electrical production from fossil fuels to less than 5%. Additionally, interns will work closely with Professor Wosnik's research team and their adapted green energy model to predict certain outputs when the battery load is below 68% or above 76%. After it was realized that the model would not be completed within a usable timeframe, interns shifted their focus onto the current energy provided by the generators to size the new battery system.

2.4 Methods

2.4.1 Ratio of Green Energy to Diesel-Powered Energy Sources

To improve the current percentage of renewable generation on Appledore, it is necessary to calculate how much the island is currently reliant on the diesel-powered generators. Solar generation, wind turbine, and generator production data was compiled from the dashboard for July and thus far in August and analyzed as follows. Only the impact of the new turbine was considered during this period. The turbine output was calculated using the same two equations highlighted in Section 1.4.5.

$$\begin{aligned} &Total\ Island\ Green\ Generation \\ &\qquad = ECB\ solar + K - house\ solar + Tower\ solar\ + Wind\ contribution \end{aligned}$$

$$Contribution\ of\ Green\ Energy\ = \frac{Green\ grid\ generation\ (kWh)}{Island\ total\ energy\ generation\ (kWh)} \times 100$$

$$Contribution\ of\ Diesel\ Generators\ = \frac{Diesel\ generation\ (kWh)}{Island\ total\ energy\ generation\ (kWh)} \times 100$$

2.4.2 Additional Battery Storage Locations

Interns provided an estimate of the physical space available to store additional batteries. The radar tower and the basement of the K-house were the two locations considered based on their current usage of battery storage and proximity to current grids. The tower batteries are very old and hold minimal charge, making them ripe for replacement. The K-house batteries are lithium ion instead of the absorbent glass mat that the rest of the island uses and thus do not communicate as well. Interns measured the physical space available in these two locations, assuming the current batteries are removed and estimated the amount of Absolyte GNB batteries that could be installed.

2.4.3 Additional Battery Storage Needed

To calculate the battery storage required to reduce the generator use, the daily generator energy supplied was downloaded from the dashboard for the 2021 season. The average and standard deviation of the data set was calculated, after removing the days which had zero generator energy supply as that would skew the statistics towards zero, providing an underestimate. The generator supply followed a normal distribution, and thus the following statistical analyses could be applied. The average generator energy supplied represents the usable battery capacity that is needed to reduce diesel generation by 50%. The average plus one standard deviation represents 84% of diesel generation and the average plus two standard deviations represents 95%. To obtain the required installed battery capacity, usable battery capacity values were multiplied by 100/32 to account for the 32% depth of discharge in the current system use settings.

2.4.4 Estimating Underutilized Solar Energy

Currently, there is wasted PV production due to limited battery capacity. The total wasted energy is the sum of the difference between the ideal and real PV output of both the ECB grid's and K-House's panels. The pyranometer is no longer installed on the island, so interns used the average of two days of 2019 SEI data as an estimate for the ECB panels, at 80.6 kWh (Hall et. al., 2019). By examining the real K-House panel outputs on a sunny day, it is clear there is a section missing, which may be approximated as the missing one-third of the total parabola, or half of the real output. According to the dashboard, daily K-House outputs maxed out at 94 kWh in a day this season. Half of 94 kWh is 46 kWh, so interns chose 40 kWh of excess from the K-House panels to be safe. In total, 120.6 kWh of excess solar energy will be realized by increasing the battery capacity and connecting the grids.

2.4.5 Additional PV Capacity Needed

After increasing the battery storage, the green sources on Appledore must be able to fill the top 32% on an average sunny day. In scenarios where the necessary usable battery storage increase exceeded the value of extra PV energy gained, the additional capacity of PVs to be installed was calculated with the following equation.

$$PV\ Capacity\ = \frac{kWh\ of\ Generation\ Needed}{Hours\ of\ Peak\ Sunlight} * \frac{1}{System\ Efficiency}$$

The usable battery capacity was used for this equation, rather than the installed battery capacity because the PVs will only ever need to fill the usable top 32% of the bank.

The value chosen for system efficiency was 0.6 after consulting with Lee Consavage of Seacoast Engineers, who provided interns with this value based on his years of experience in energy systems, as well as documentation supporting this value for PV-battery systems (Consavage, 2021 and Schimpe, et. al., 2017). The value chosen for hours of peak sunlight was 8.5 after also consulting with Lee and confirming close estimates based on the island current panels and ideal outputs (see Appendix).

2.5 Results and Analysis

2.5.1 Ratio of Green Energy to Diesel-Powered Energy Sources

Interns calculated the percentage of green energy and diesel generation on the island using the data available on the SML dashboard. The results of the analysis are shown below in Table 3.

Table 3: Green and diesel-generated energy for July and August 2021

Month	Green Energy Generation (kWh)	Diesel Generator Production (kWh)	Total Island Energy Production (kWh)	Green Energy Percentage	Diesel Generator Percentage
July	9178	2858	12036	76.25%	23.75%
August 1-23rd	6691	1862	8553	78.23%	21.77%

2.5.2 Additional Battery Storage Locations

The radar tower currently has a very old Absolyte Battery bank made up of twelve batteries in two stacks of six. The current dimensions of the bank are 80 in width x 56 in height x 24 in depth. The number of batteries available to fit is based on the dimensions of the current batteries, the Absolyte GP 90G15, and may need to be altered slightly if different batteries are to be used. After taking measurements of the available space, interns made the following recommendations:

Remove the old Absolyte batteries and replace them with two columns of batteries stacked eight high. The wooden shelf above the current batteries would need to be removed. A third stack of eight batteries may be placed as well, but it would rest on top of where the generators used to be located, and interns are concerned with the integrity of the concrete. According to the Absolyte manual and 2012 IBC, an S_{DS} value of at least 0.51 is required for above-grade battery stacks of eight high (Absolyte GP, 2015). Instead of the third stack, or in addition to, more batteries may be placed on the back wall, below the "Network Control Panel Base North" where a sparsely populated workbench currently resides. There is room for another eight batteries here, stacked in columns of four. In summary, the twelve old batteries should be replaced with sixteen new batteries, as well as an additional eight batteries either in a third stack or on the back wall under the network control panel. Thus, the capacity of battery storage in the radar tower will be increased by 100%. However, because the current capacity of the radar tower batteries is so low, the effective capacity increase will be even higher. Furthermore, interns recommend that the Outback electrical equipment in the tower is replaced with Schneider equipment to match the rest on the island and increase ease of use.

The Kingsbury House, or K-House, currently sports a 76.4 kWh Lithium battery bank that supports the saltwater pump. While these batteries were only installed in 2017 and are likely still in good condition, they are not as useful as the Absolyte batteries because they are intended to be drained from full to empty, a practice not utilized on the island. The current battery setup is arranged in five steel boxes with dimensions of 36 in width x 36 in height x 25 in depth. The number of batteries available to fit is based on the dimensions of the current batteries, the Absolyte GP 90G15, and may need to be altered slightly if different batteries are to be used. After taking measurements of the available space, interns made the following recommendations:

Remove the current lithium batteries and replace them with new Absolyte batteries. There is enough space beneath the current electrical equipment to stack batteries four high, and enough lateral space to accommodate approximately nine stacks (~30 ft). With this space, 36 Absolyte batteries may be installed, and up to 72 batteries may be installed if the opposite wall is utilized as well. This installation would result in a massive increase in battery storage, between 270 and 540 kWh, where green energy generated during the day may be stored and utilized at night. However, if the electrical equipment required to get the lithium batteries to send or receive energy from Absolyte batteries exists, and the island engineers do not mind complicating the system, the current lithium batteries should remain. 36 Absolyte batteries should be installed on the opposite wall, adding about 346 kWh to the total battery storage when including the lithium batteries.

2.5.3 Battery Capacity Needed

After following the methods in section 2.4.3, interns provided the necessary battery capacity for the island to reduce its diesel generator reliance. The results of this analysis are shown below in Table 4.

Table 4: Analysis of reducing diesel generator usage at SML based on the 2021 season

Generator Use 2021	**Average**	**One SD**	**Two SD**	**Max Value**
Generator Reduction %	50%	84%	97.5%	100%
Approximate Renewable %	88.70%	96.38%	99.44%	100%
Usable Battery Capacity Needed (kWh)	85.03	118.91	152.79	235.34
Installed Battery Capacity Needed (kWh)	265.73	371.60	477.46	735.44
# Batteries Added	36	48	64	100

2.5.4 PV Capacity Needed

For scenarios in which the usable battery capacity increase suggested is greater than the excess available solar resource, additional capacity of PVs to be installed is suggested. These are necessary so that the increased battery capacity can be filled on a sunny day. The options, labeled by approximate island renewable energy contribution, are displayed in Table 5 below.

Table 5: Approximate renewable energy reliance scenarios

Approximate Renewable %	**88.70%**	**96.38%**	**99.44%**	**100%**
Remaining Gen. Needed (kWh)	0.0	0.0	32.2	114.8
PV Capacity Needed (kW)	0.0	0.0	6.7	23.9

2.6 Conclusions and Recommendations

Interns provided four options for reducing the diesel generator reliance on Appledore and suggest option #2, one standard deviation, over any other choice. With this option, SML will operate at about 96% renewable energy reliance while only having to install new batteries. The two more extreme options would involve many more batteries and additional PV to be installed, drastically increasing cost. When adding batteries, the tower batteries should be replaced first, per the recommendations of section 2.5.2, followed by adding storage capacity to the basement of K-House. In the future, engineers may want to install more PV capacity. Interns recommend replacing and recycling the panels on Dorms 2 and 3 first, as they are the oldest on the island and not performing as they once were. The mountings and wiring may be reutilized with newer, higher-rated panels. Recommendations and calculations were given with the following assumptions or conditions:

1. Any electrical losses due to wiring or transfer between battery banks were ignored.
2. Battery capacity to be added refers to net storage additions. So, if lithium batteries are replaced, the equivalent value of their current usable drawdown must be added.
3. Lithium and Absolyte batteries (non-lithium) can cooperate.
4. Recommendations for space and number of batteries were made using the size and storage of the current installed Absolyte model, GP 90G15.
5. Current depth of discharge, 32%, was used for calculations.
6. Generator energy supplied per day was based on summer 2021 values, and may be an overestimate due to the rainy July experienced.
7. Values are preliminary calculated estimates and should be confirmed by at least one model, either Dr. Martin Wosnik's or Revision's before implementation.

2.7 References

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Assignment 3 - Reverse Osmosis and the Well

3.1 Background

Shoals Marine Laboratory's primary freshwater source is a dug well that relies on rainfall for replenishment. In 2019 SML purchased and installed a new reverse osmosis unit (RO) that desalinates seawater to generate potable water. The new RO was sized to operate using excess green energy sources and produces water at a slower rate than the unit it replaced. Freshwater is a limited resource for most island communities, but reverse osmosis has high electrical demands compared to other water treatment technologies.

3.2 Purpose

The purpose of this assignment is to understand the best practices for running the new reverse osmosis system based on available green energy and the machine's settings that allow for the most potable water to be produced. In addition, the interns will look at the RO production and its relationship with total gallons drawn from the well, the water level of the well, and total island water consumption to determine how the RO use is affecting these variables. Additionally, interns will compare the electrical consumption of these two water production systems.

3.3 Scope

Interns will help Shoals Marine Laboratory quantify the relationships between reverse osmosis and well water production and electrical use. By documenting daily inland water use, daily RO water production, and daily volume of well water treated, interns will be able to display noticeable trends and relationships of the RO and well. In addition, interns will monitor daily well level and rainfall data and generate a graphic highlighting these relationships. Ultimately, the interns will propose recommendations for sustainable water treatment best practices using existing equipment on the island.

3.3.1 Reverse Osmosis Model Specifications

Table 6: Lifestream Water Purification Make and Model

Rated Power	480 V / 60 Hz / 3 Phase
Product Output at 25 °C	2600 gallons per day
Max. Product	1.80 GPM
Min. Rejection Rate	99.7%

Feed Flow	12 GPM
Feed Pressure	Min. 2 psi / Max. 50 psi
Max. Feed Salinity	36,000 PPM

3.4 Methods

3.4.1 Daily Inland Water Use

Extracting values from the monthly drinking water reports provided by Michael Rosen, interns averaged total gallons pumped and average flow from May 2018 to July 2021.

$$\frac{\Sigma\ (Daily\ Gallons\ Pumped)}{Days\ of\ the\ month} = Average\ daily\ inland\ water\ use$$

3.4.2 Daily RO Water Production

Interns obtained daily reverse osmosis water production from the RO logbook, updated by the island engineers whenever the machine runs.

$$\Sigma\ (Daily\ RO\ Water\ Production)\ =\ Monthly\ RO\ Water\ Production$$

$$\%\ of\ Total\ Water\ Produced\ by\ RO\ =\ \frac{Total\ RO\ Generation}{Total\ Water\ Use} \times 100$$

3.4.3 Daily Volume of Well Water Treated

$$\Sigma\ (Daily\ Well\ Water\ Production)\ =\ Monthly\ Well\ Water\ Production$$

$$\%\ of\ Total\ Water\ Treated\ from\ Well\ =\ 1 - \%\ of\ Total\ Water\ Produced\ by\ RO$$

3.4.4 Energy Consumption of the RO and Well Pump

One of the variables the interns analyzed is how the energy demands of the RO and the well pump compare in terms of kWh/gal of potable water produced. To make this comparison, interns collected well pump power draw with the Fluke meter for one day and contrasted it to the power draw data that the SEI 2019 interns collected from the RO when run at various VFD and pressures. After consulting with a Lifestream technician, who suggested the ideal RO run settings are 600 to 650 psi and 54 to 60 Hz, which is higher than previous interns had analyzed, interns collected additional RO run data at these new settings. Increasing pressure increases the power draw.

To compare the energy consumption, it needs to be displayed in the same units. To get the well pump and RO data in kWh/gal, the following equation was used.

$$\frac{Power\ draw\ (kW)}{Flow\ (gal/min)} * 1\ hr/60\ min = kWh/gal$$

Since both methods of potable water production require chlorination and thus the running of the chlorine pump, the electrical demand of this pump was not included.

3.5 Results and Analysis

3.5.1 Daily Inland Water Use

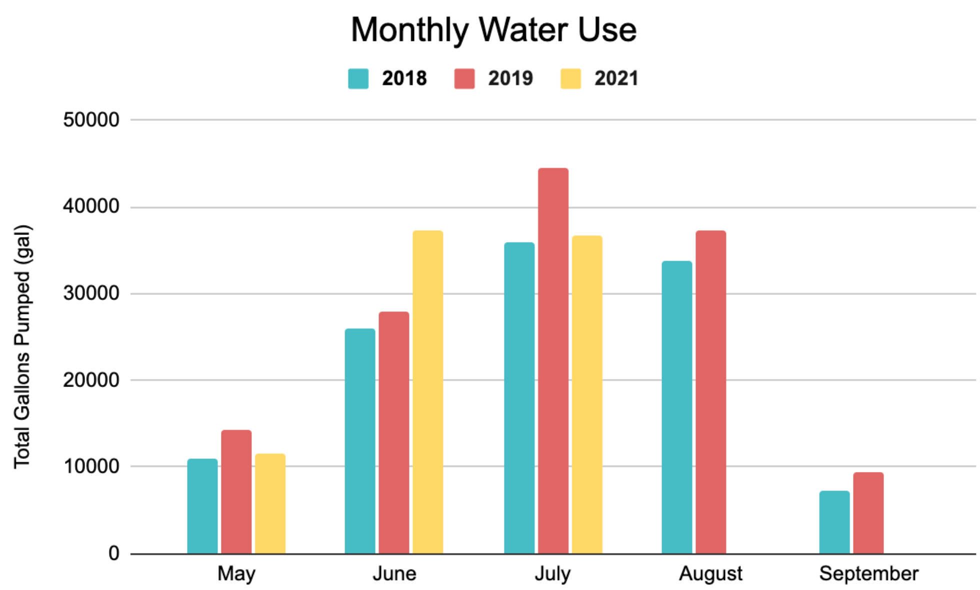

Figure 10: Average Water Use by Month

Daily water use at SML is heavily dependent on the number of residents on the island. Due to COVID-19, SML had to significantly reduce the number of students together at one time and the number of classes available for the 2021 season. As a result, interns assumed there would be a significant decline in water production for 2021. According to the figure above, however, this does not appear to be the case. Average water production for the 2021 summer season is as follows: 11,574 gallons for May, 37,191 gallons for June, and 36,755 gallons for July. Compared to 2019, May had 22.3% less water use, June had 33.3% more, and July had 17.5% less. As a result, there aren't any discernible trends in daily inland water usage. The average daily island water use for the 2021 season was 1245 gal/day, from June 1st to August 22nd.

3.5.2 Daily RO Water Production

The new reverse osmosis machine by Lifestream Watersystems Inc. was first run this summer on June 16, 2021. As a result, interns were only able to collect a full month's worth of data for the RO in July. Regardless, the RO produced 14,448 gallons in June and 15,240 gallons in July due to the average runtime per day being 7.0 hours in June and 4.1 hours in July. This may have been because island engineers did not want the membranes to foul by not running them enough. This led to a similar percentage of total water produced by the RO, at 39% in June and 41% in July.

3.5.3 Daily Volume of Well Water Treated

The total volume of well water treated was 22,743 gallons for June and 21,515 gallons for July, and is graphed in conjunction with the RO produced for those days. For the first six days, the RO was not yet installed. The percentage of total water treated from the well was 61% and 59% for June and July.

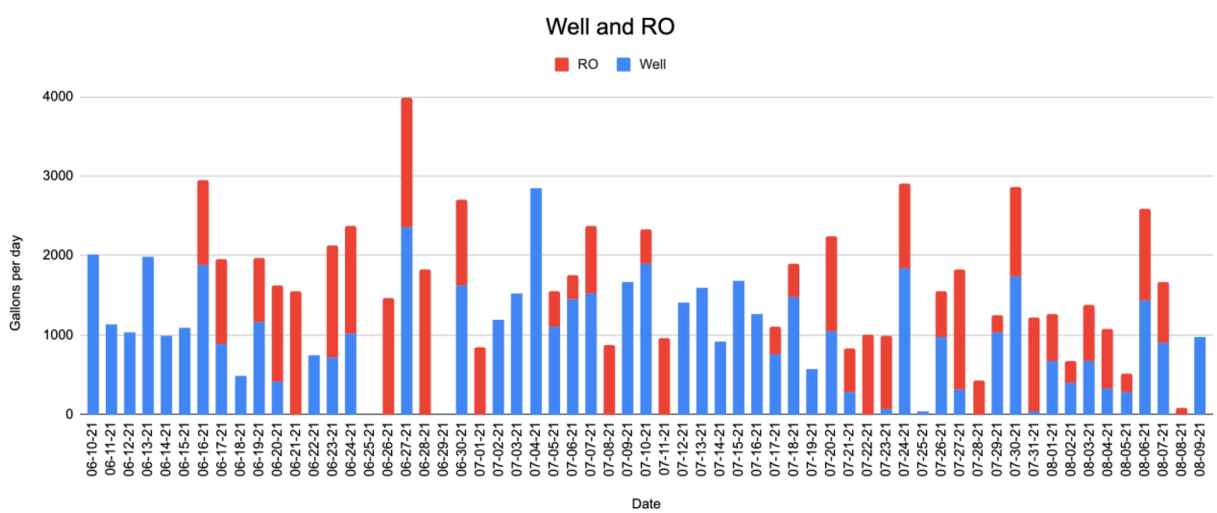

Figure 11: Gallons Produced from Well vs. RO

As demonstrated in the figure above and values from 3.5.2 and 3.5.3, the daily volume of well water treated surpassed the daily RO water production.

3.5.4 Energy Consumption of Water Production via Well

Figure 11 shows the power draw of the well pump that is pumping water from the well into the cistern to be chlorinated, in kW. The pump only triggers when the water level in the cistern reaches a certain drawdown level, activating the pump for half an hour and drawing 1.05 kW, equivalent to 0.5025 kWh of energy.

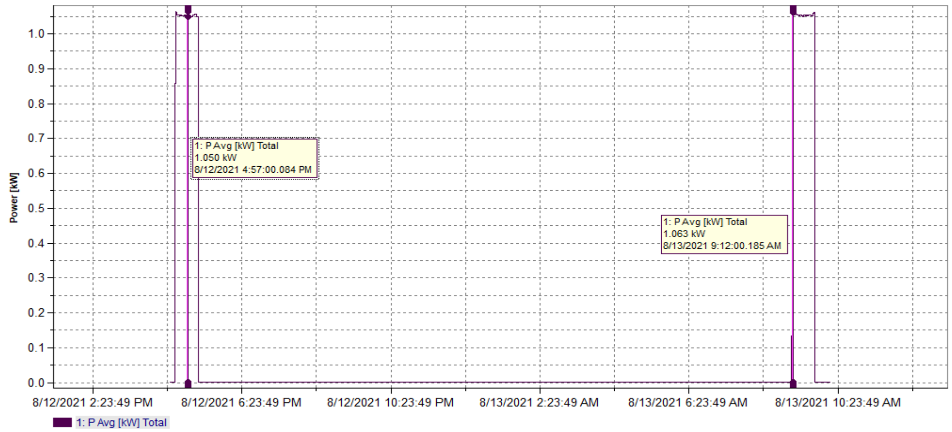

Figure 12: Power Demand of Well Pump

The figure above shows the power demand of the well pump when activated. When idle, it draws no power. The flow from the well pump is approximately 17.6 gal/min, from data previously collected by the 2018 SEI interns (Shactman et. al., 2018), which results in a calculated energy use of 0.99 Wh/gal.

3.5.5 Energy Consumption of Water Production via RO

Below, Table 7 shows the power requirements of the RO system as it produces fresh water from ocean water in various settings.

Table 7: Power Requirements of RO System, 2019 Data

Data from 07/11/2019										
VFD	Pressure (psi)	Product Flow Rate (gal/min)	Active Power (kW)	Number of hours RO can run off excess	Product Volume (gal)	Ideal VFD	Ideal Pressure	Hours to run	Total Energy Usage (kWh)	Time (hours)
54.1	715	4	4.9	7.551	720.00	54.1	715	3.0	14.7	3
54.1	670	3.6	4.65	7.957	648.00	-	-	-	-	
54.1	600	3.1	4.28	8.645	558.00	-	-	-	-	Excess Energy (kWh)
54.1	550	2.9	4.04	9.158	522.00	-	-	-	-	37
54.1	500	2.4	3.81	9.711	432.00	-	-	-	-	
54.1	450	1.9	3.54	10.452	342.00	-	-	-	-	MAX product volume (gal)
51.1	600	3.1	3.95	9.367	558.00	-	-	-	-	720.00
51.1	550	2.5	3.69	10.027	450.00	-	-	-	-	
51.1	500	2.2	3.48	10.632	396.00	-	-	-	-	
48.1	600	2.8	3.6	10.278	504.00	-	-	-	-	
48.1	550	2.4	3.4	10.882	432.00	-	-	-	-	
48.1	500	2	3.17	11.672	360.00	-	-	-	-	
45.1	600	2.9	3.5	10.571	522.00	-	-	-	-	
45.1	550	2.5	3.3	11.212	450.00	-	-	-	-	
45.1	500	2.1	3.09	11.974	378.00	-	-	-	-	
42.1	600	3	3.37	10.979	540.00	-	-	-	-	
42.1	550	2.7	3.14	11.783	486.00	-	-	-	-	
42.1	500	2.1	2.96	12.500	378.00	-	-	-	-	
38.5	600	2.5	2.93	12.628	450.00	-	-	-	-	
38.5	550	2	2.71	13.653	360.00	-	-	-	-	
38.5	500	1.6	2.52	14.683	288.00	-	-	-	-	

The flow of potable water varies at different settings of the RO. Based on the data collected by the 2019 SEIs, the product flow and power draw increased with higher VFD and HP settings. Interestingly, according to the 2019 data, the most energy-efficient product water production is at settings of 42.1 VFD and 600 psi. At these settings, the RO produces water at 18.7 Wh/gal.

While this information is very useful for estimating total RO electrical use and water production, Lifestream suggested that the RO is run at 54 Hz to 60 Hz. This is to prevent the buildup of marine growth and to keep the membranes from clogging. While the 2019 SEIs collected data at 54.1 Hz, additional data was required for 60 Hz. Using the Fluke meter, interns collected power draw readings by the RO, whose results are shown below in Table 8. Between the data collected and Lifesteram's suggestions, the RO should be run between 54 and 60 Hz and between 600 and 650 psi. At these settings, the RO produces water between 21 and 26 Wh/gal. The operating parameters and resulting data are shown below in Table 8.

Table 8: Power Requirements of RO System, 2021 Data

Date	VFD (Hz)	Pressure (psi)	Active Power (kW)	Product Flow Rate (gal/min)	Energy Use/Gal (Wh/gal)
8/2/2021	54	610	4.23	3.2	22.0
8/3/2021	54	610	4.2	3	23.3
8/4/2021	60	650	4.65	3	25.8
8/4/2021	46	600	3.65	3	20.3

Something observed by the interns is that when the RO runs over a period of time, the power draw slightly decreases over time. This is shown below in Figure 13. This indicates that when the RO is run, it should be done so over a longer period of time to maximize its efficiency. While the power draw only decreases by about 0.1 kW in the following example, any efficiency gain is a positive discovery.

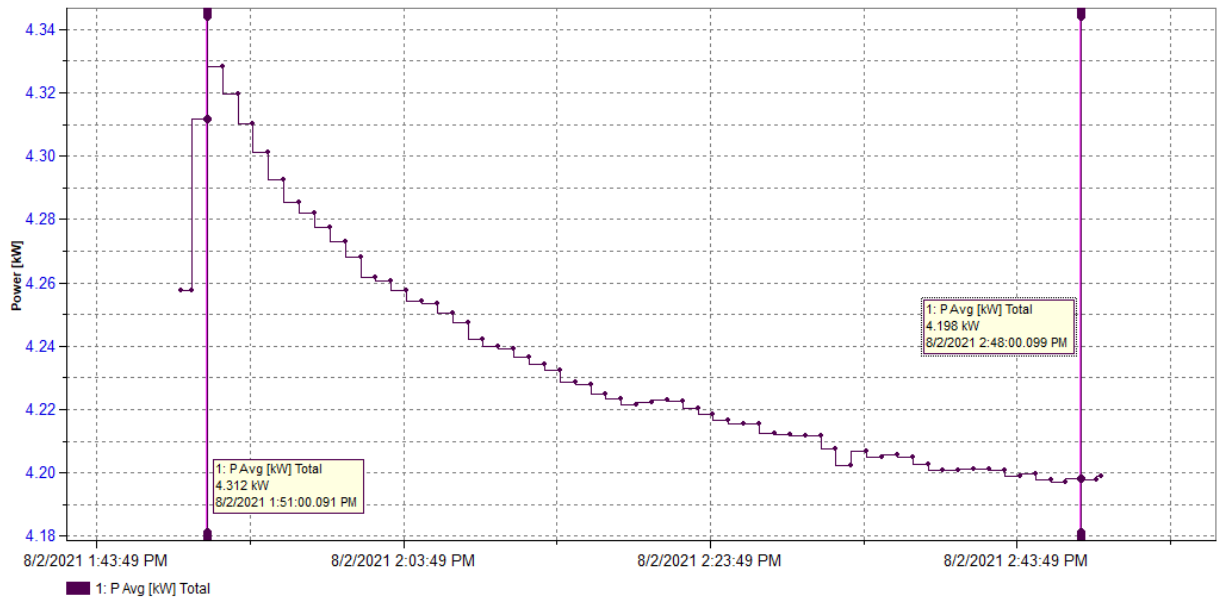

Figure 13: RO Power Draw at 54 Hz and 610 PSI

Based on the manufacturers recommendations and the observed power draw, interns recommend the following parameters to run the RO.

Table 9: Recommended VFD and pressure settings for the RO and the resulting power used

Recommended Reverse Osmosis Run Settings					
	VFD (Hz)	Pressure (psi)	Active Power (kW)	Product Flow Rate (gal/min)	Energy Use/Gal (Wh/gal)
Min	54	600	4.28	3	23.8
Max	60	650	4.65	3	25.8

It is clear from an energy perspective that utilizing the well water and pump to produce potable water for the island is the more sustainable option. However, on particularly dry summers there are concerns that the well will run dry, and thus severe water limitations are enacted. In situations like these, having the RO as a backup water source is extremely useful, especially considering that there is a surplus of green energy on clear sunny days. If the maximum battery capacity is to be increased, as discussed in Assignment 2, this surplus of green energy will dissipate, but the storage increases should allow for the RO to run if there is a stretch of sunny days expected in the forecast.

3.5.6 Daily Well Level and Rainfall

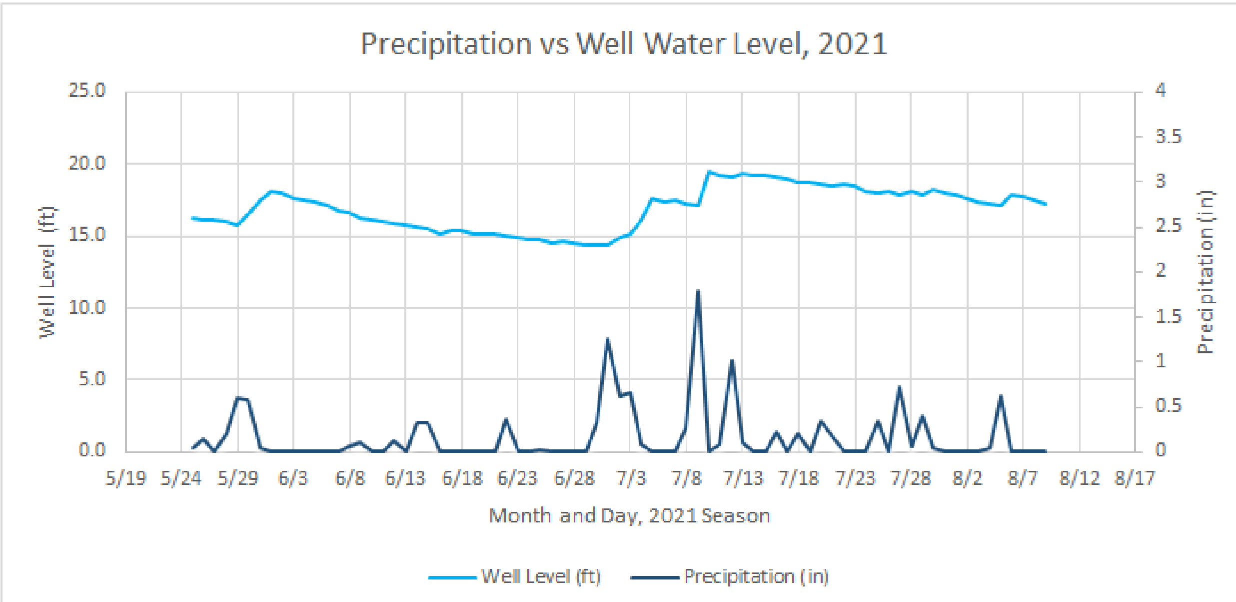

Figure 14: Daily Well Level and Rainfall Data for mid-May to early-August, 2021

Figure 14 demonstrates the impact of precipitation on the depth of the well. The sky blue line indicates the well level in feet, whereas the navy blue line shows the daily precipitation in inches. The values for the well depth and precipitation were compiled via SML's dashboard. Notice how days with large precipitation events, such as July 1st and July 9th, do not correlate to an immediate increase in the well water depth, with the well level lagging behind two to three days. This is due to the slow percolation of the rain into the groundwater table that eventually seeps into the well. On particularly dry summers, the well water level may take even longer to realize any increase from precipitation, as the parched vegetation and unsaturated soils absorb a higher proportion of the water falling on Appledore Island. Overall, it appears that in order to realize a noticeable well level increase, at least one inch of precipitation must fall over a two-day period.

3.5.7 Relationships

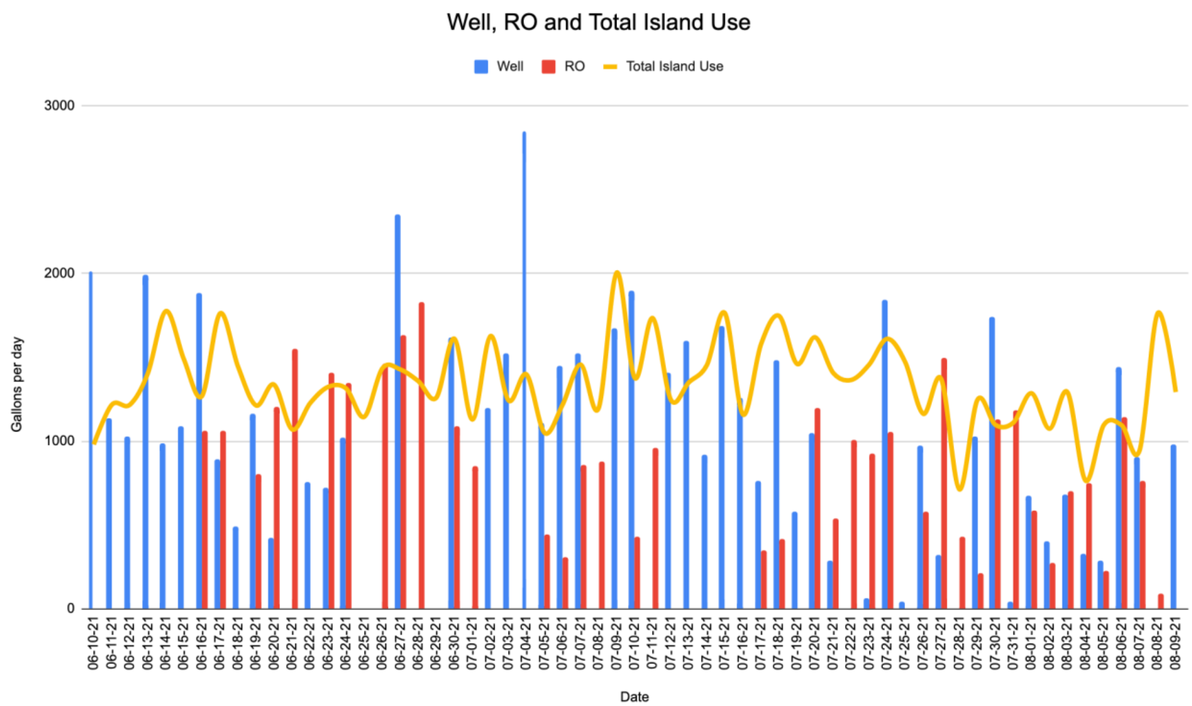

Figure 15: Relationship of Well, RO, and Total Island Use

Figure 15 reveals the correlation of the well water treated, RO water produced, and total island usage from June to August 2021. While total island usage is assumed to show the capacity of water for each day, that is not necessarily the case - as evidenced by the spikes in well water treated. That data shows the well water pumped into the cistern to be treated and the total island use is pumped out of the pressure tank. As a result, the water may not be used the same day as it is treated. There is a specific anomaly to point out on July 4, 2021. Although island engineers are unsure of why well water treated is so high that day, interns suspect it is due to pressure cleaning or excess water usage due to the holiday. July 9, 2021 corresponds with the highest island water consumption day, so perhaps engineers were prepping the pressure tank for the expected water use.

3.6 Conclusions and Recommendations

3.6.1 Best Practices for Sustainable Water Treatment

Clean water is a limited resource, especially in remote island communities. The 2021 SEI interns took this into account when evaluating efficiency, pointing out trends, and considering best practices for sustainable water treatment. It was determined that if the RO were run at 3 gal/min for 7 hours per day, it could provide enough potable water for the entire island's use for the summer, at about 32 kWh/day. This estimate is based on the island's average daily water use, but it is not recommended to use the RO to generate all of the island's potable water, 1245 gal/day if the well has enough water. The well generates water at a significantly cheaper electrical use, 0.99 Wh/gal compared to over 21 Wh/gal. Interns recommend utilizing the well at the beginning of the season when it is relatively full. If deemed necessary to supplement the water supply in July or August, the RO can be switched on and run at the parameters outlined above. Currently, it is recommended to utilize the RO based on the predicted renewable energy input for the day, as suggested by the 2019 interns, because this renewable energy generation would otherwise be wasted. If the battery bank size is increased, however, the green energy will no longer be wasted and instead be utilized instead of the generators at night. Given this scenario, the battery banks would need to increase by a further 32 kWh, corresponding to an increased PV capacity by an additional 7 kW, calculated by the same method as in section 2.4.3.

To lengthen the lifespan of the new purification system, interns recommend increasing the frequency of the cycles to between 54 and 60 Hz and 600 and 650 psi to promote the health of the membranes and prevent clogging. Additionally, frequent backflushing of the various membranes and filters will keep the membranes free of biofoul and working efficiently. Finally, interns recommend that at the end of each day of use a freshwater flush is implemented, to kill any marine microorganisms that may be stuck in the membranes and cause clogging.

Various factors affect the island's total water demand at any given time; such as the amount of precipitation filling up the wells, the current population on Appledore, and infrequent events like pressure washing. To promote SML's water conservation mission, interns recommend following the suggested protocols such as biweekly navy showers, the "yellow mellow" rule, and turning off running water when not in use. Additionally, interns recommend frequent monitoring of the property to check for bursts, clogged pipes, or leaks in the system. Periodic metering of the facility's water will also assure the equipment is running correctly and being maintained properly (Environmental Protection Agency, 2021). Lastly, interns suggest resuming the rainwater recovery system and redirecting it to irrigate the landscape, fill non-compostable toilets, and supply water to the well.

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Assignment 4 - Refrigeration Upgrade Evaluation

4.1 Background

Shoals Marine Laboratory's commercial kitchen is equipped with a walk-in refrigerator and freezer for food storage. Based on data and recommendations from the 2018 and 2019 Sustainable Engineering Interns, SML upgraded its 35+ year old refrigeration system with new compressors, condensers, evaporators, piping, doors, and insulation to improve its overall energy consumption and efficiency.

The specifications of the new walk-in refrigerator and freezer are as follows.

VOLTAGE		SYSTEM REFRIGERANT			RATING		SUCTION TEMP	AMBIENT TEMP	CAPACITY	
208-230/3/60		**R407A**			**0.8Hp**		**23.9 ºF**	**95 ºF**	**8778 BTUH**	
FANS			COMPRESSOR				CIRCUIT TOTAL			
QTY	POWER	FLA/FAN	TYPE	QTY	RLA	LRA	AMPS	WATTS	MCA†	MOP‡
1	**130W**	**0.5**	**ZB07KAE-TF5-118**		**5.2**	**37.8**	**5.7**		**7**	**15**
LIQUID	**3/8 in**	SOUND	**-**		REC CAPACITY	**11 lb**			APPROVALS	
SUCTION	**5/8 in**	WEIGHT	**167 lb**		REF CHARGE	**2 lb**				

Figure 16: Walk-in Refrigerator Specifications (Goguen, 2019)

VOLTAGE		SYSTEM REFRIGERANT			RATING		SUCTION TEMP	AMBIENT TEMP	CAPACITY	
208-230/3/60		**R407A**			**2Hp**		**-20.2 ºF**	**95 ºF**	**6803 BTUH**	
FANS			COMPRESSOR				CIRCUIT TOTAL			
QTY	POWER	FLA/FAN	TYPE	QTY	RLA	LRA	AMPS	WATTS	MCA†	MOP‡
1	**130W**	**0.5**	**ZF07KAE-TF5-118**		**8.6**	**58**	**9.1**		**11.2**	**20**
LIQUID	**3/8 in**	SOUND	**-**		REC CAPACITY	**14 lb**			APPROVALS	
SUCTION	**7/8 in**	WEIGHT	**290 lb**		REF CHARGE	**3 lb**				

Figure 17: Walk-in Freezer Specifications (Goguen, 2019)

4.2 Purpose

The original walk refrigerator and freezer were installed in the 1970s. In the fall of 2019, a new refrigeration system was implemented to improve power consumption for the grid. The 2019 Sustainable Engineering Interns were then tasked with determining the system's power usage and comparing it with 2018 data. The purpose of this year's project is to make further comparisons to quantify the efficiency increases of the new equipment.

4.3 Scope

Interns will work with SML staff and Unitil representative Justin Ulrich to set up metering to monitor the energy usage of the new refrigeration systems as well as document those findings and compare them with the 2018 and 2019 SEI refrigeration data. Interns will also calculate the energy used by the refrigeration systems as a percentage of SML's total energy consumption, and document any efficiency increases realized through the installation of the new equipment.

4.4 Methods

4.4.1 Data Collection

Ross Hansen utilized a Fluke 173x Power Monitor to collect data on the various refrigeration system components. To directly compare to data collected in years past, power draw was collected for each of the following pieces of the system: refrigeration fans, refrigeration compressor, freezer fans, and the freezer compressor. Each piece was recorded for a week, from 6/21/2021 through 7/22/2021, to ensure a comprehensive overview and inclusion of the various refrigeration cycles.

4.4.2 Data Extraction

The data was compiled onto a USB flash drive that was attached to the Fluke meter and needed to be extracted before it could be analyzed. After downloading the Fluke instrument software on one of SML’s computers, Justin Ulrich from Unitil guided the interns in navigating the software and reading the data. Justin explained the basics of electrical circuitry and wiring and the Fluke outputs to better understand the data.

4.4.3 Data Analysis

The two types of currents are direct current, DC, and alternating current, AC.

For a DC current, watts are directly related to voltage times amperes.

$$W = V \times A$$

The energy consumption of a machine, regardless of current, is calculated by multiplying wattage over the time interval that it is drawing power.

$$E = W \times t$$

For an AC current, the relationship between watts, volts, and amps is a little more complicated. The refrigeration system acts as a three-phase AC motor, meaning that three AC wires carry an alternating current that fluctuates as a sinusoidal wave. As a result of this alternating wave, there are inherent inefficiencies in AC power distribution. Voltage times amperes equal VAs instead of watts. VAs, or volt-amps, represents the apparent power that must be delivered by the electrical cable for the appliance to draw its active power, or watts. The reactive power required, or VARs is necessary for the true power to be applied, but does not do any of the work. They are caused by the necessary shift in current and waveforms, and, in essence, represent system inefficiencies. VAs, Watts, and VARs are related by a right triangle, illustrated below in Figure 18. Thus, VAs can be calculated using the Pythagorean theorem when both watts and VARs are known.

$$VA = V \times A \qquad VA = \sqrt{W^2 + VAR^2}$$

The following diagram visualizes the physical relationship between VAs, Watts, and VARs.

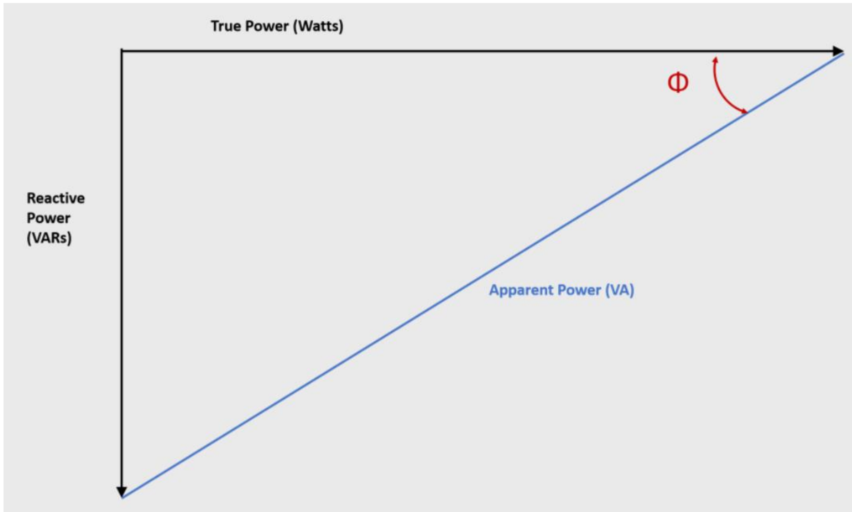


Figure 18: Relationship between watts, VAs, and VARs (Fluke, 2019)

The Fluke Meter records both the reactive power, VARs, and active power, watts, of the device it is measuring. With these two attributes, the apparent power, VAs, may be calculated. By comparing VAs and watts from before the refrigeration system upgrades to after, interns were able to quantify energy savings.

4.4.4 Temperature Verification

At its core, refrigeration involves removing heat from objects that are placed inside it. Thus, the higher the ambient temperature, or the temperature of the room outside of the system, the more heat that the refrigerator needs to remove (Saidur et. al., 2002). By comparing the average ambient temperatures during the weeks that the data was recorded between 2018, 2019, and 2021, the interns could determine if the machinery was more efficient or simply working harder due to hotter weather.

4.4.5 Total Energy Consumption

To obtain an estimate of the total refrigeration system relative to the total island load, interns compiled the usage data on SML's dashboard to calculate total island energy usage for July 2021. Then, by multiplying the refrigeration system's power draw by 24 hours per day and 31 days per month, and dividing by total energy use, the energy used by the refrigeration system as a percentage of total island energy consumption was calculated.

$$Total\ Island\ Grid\ Consumption\ = Main\ grid\ usage\ +\ tower\ grid\ usage\ +\ k - house\ consumption$$

$$\%\ of\ Total\ Island\ Energy\ Consumption\ = \frac{System's\ power\ draw\ \times 24\ hours/day\ \times 31\ days/month}{Total\ energy\ use} \times 100$$

4.5 Results and Analysis

4.5.1 RMS Power Graph

Below is an example of how the fridge compressor works and draws power as it attempts to self-regulate the temperature inside. When the fridge is opened, the temperature increases, and spikes in the power follow, as seen below in Figure 19.

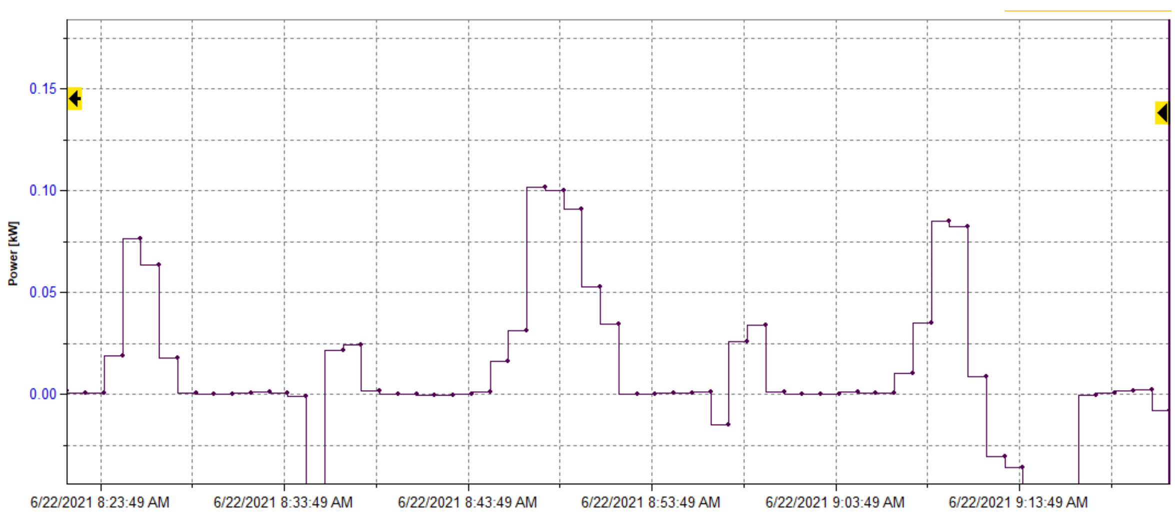


Figure 19: 2021 Graph of Power Supply to the Fridge Compressor (1-hour)

Based on the 2019 SEI analysis, the power average over 1 hour reached 1.922 kW. As demonstrated in the figure above, the power seldom reached 0.10 kW in 2021.

4.5.2 Fluke Meter Data 2021

The data for the entire system from 2021 is tabulated below, showing an active power draw of 0.518 kW, which translates to about 87 kWh of energy use over one week.

Table 10: 2021 System Energy Use

System Active Power, kW	**System Apparent Power, kVA**	**System Energy Use, kWh/Week**
0.518	0.946	87.024

4.5.3 Comparison of Active Power Savings

The active power, measured in kW, from each year is displayed below in Table 11. The largest source of active power savings was from the fridge fans, which required 458 fewer watts in 2021 than in 2018. Figure 20 below highlights the savings by the system, clearly showing that the fridge components headlined the power savings. As a combined system, the improvements made to the refrigeration system reduced the active power draw by 66.1%.

Table 11 shows the active power draw of each of the system components from 2018-2021 and the total and percent change.

Table 11: Active Power

Active Power, kW						
		2018	**2019**	**2021**	**Delta**	**% Change**
Fridge	**Compressor**	0.464	0.208	0.152	-0.312	67.3%
	Fans	0.529	0.351	0.071	-0.458	86.6%
	Total	0.993	0.559	0.223	-0.770	77.6%
Freezer	**Compressor**	0.453	0.438	0.230	-0.223	49.2%
	Fans	0.080	0.053	0.065	-0.015	18.8%

	Total	0.533	0.491	0.295	-0.238	44.7%
System	**Total**	1.526	1.050	0.518	-1.008	66.1%

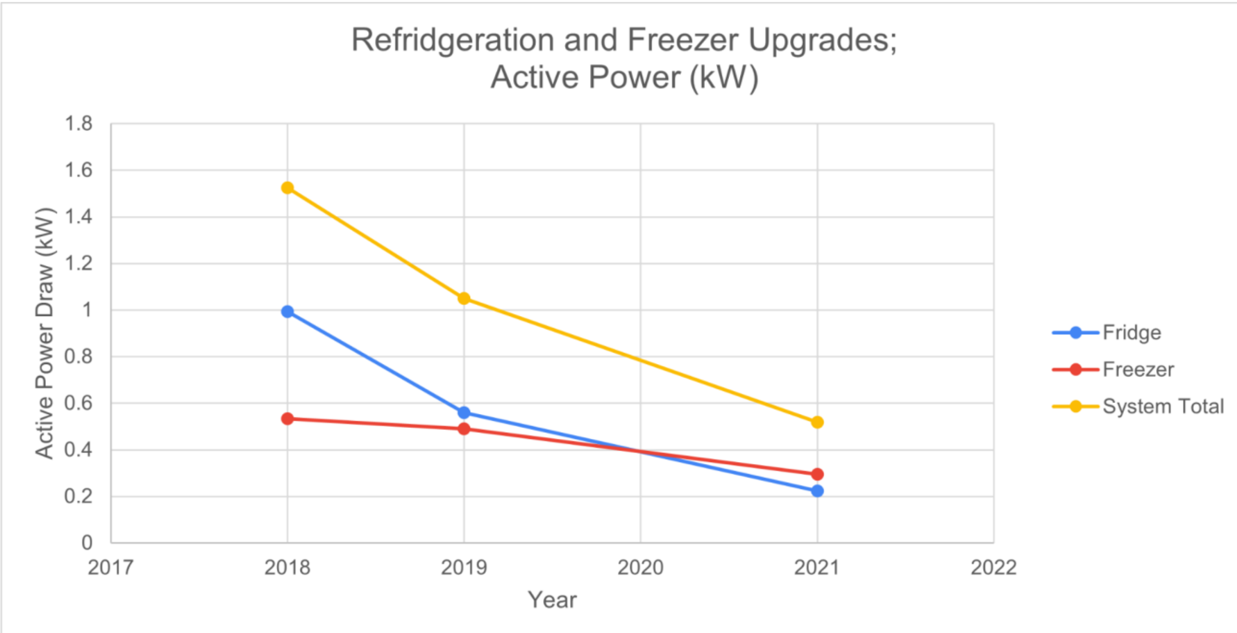


Figure 20: Active Power Change of Fridge, Freezer, and Combined System

4.5.4 Comparison of Apparent Power Savings

The apparent power, measured in kVA, from each year is displayed below in Table 12. The largest source of apparent power savings was also from the fridge fans, which required 424 fewer VAs in 2021 than in 2019. Figure 21 below highlights the savings by the system, demonstrating that the kVA savings were evenly realized by the two systems. The 2018 data provided by previous interns did not include enough information to calculate kVAs. As a combined system, the improvements made to the refrigeration system reduced the apparent power by 48%.

Table 12 shows the apparent power draw of each of the system components from 2019 and 2021 and total and percent change.

Table 12: Apparent Power

Apparent Power, kVA						
		2018	**2019**	**2021**	**Delta**	**% Change**
Fridge	**Compressor**	--	0.282	0.260	-0.022	7.9%
	Fans	--	0.533	0.109	-0.424	79.5%
	Total	--	0.815	0.369	-0.446	54.7%
Freezer	**Compressor**	--	0.604	0.447	-0.157	26.0%
	Fans	--	0.403	0.131	-0.271	67.4%
	Total	--	1.007	0.578	-0.429	42.6%
System	**Total**	--	1.822	0.947	-0.875	48.0%

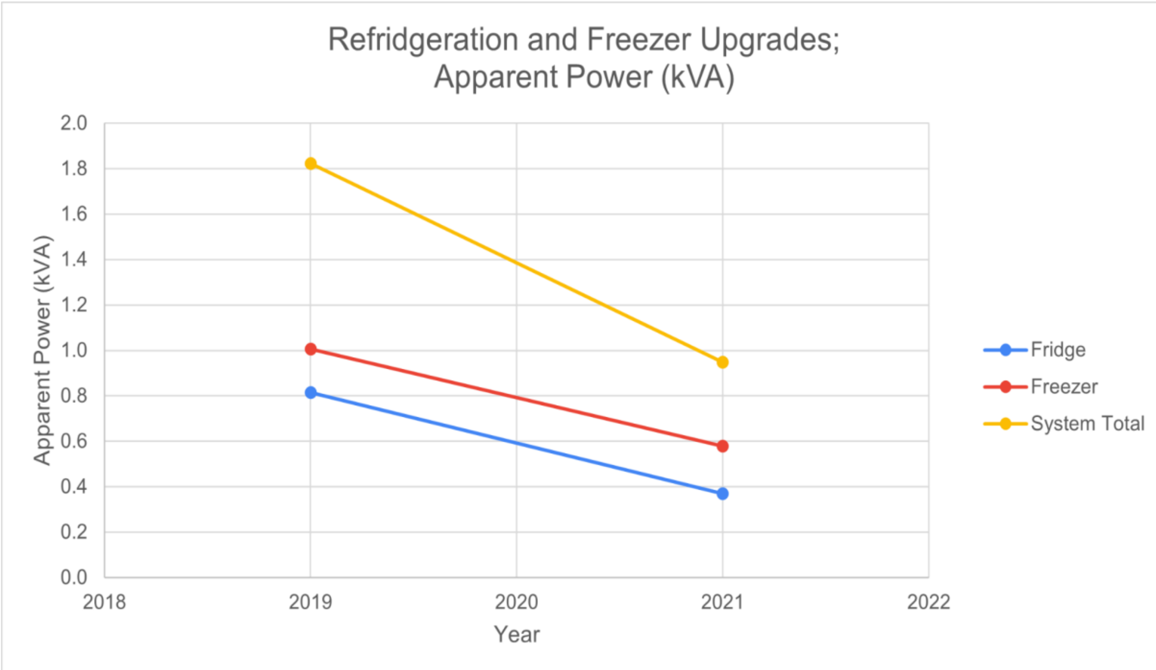


Figure 21: Apparent Power Change of Fridge, Freezer, and Combined System

4.5.5 Comparison of Power Savings with Respect to Temperature

The ambient temperature was considered for the monitoring period of each system component for each year. When the ambient temperature is higher, the cooling system must work harder to remove the excess heat (Saidur et. al., 2002). Table 13, on the next page, shows both active and apparent power use as well as ambient temperature, demonstrating that even when temperatures are hotter, the system is still drawing less power.

Table 13: Active, Apparent Power, and Ambient Temp for each Component's Monitoring Period

Component	Year	Ambient Temp (°F)	kW	kVA
Fridge Fans	**2018**	63.3	0.529	--
	2019	--	0.351	0.533
	2021	68.7	0.071	0.109
	Total Change	+5.4	-0.458	-0.424
Fridge Compressor	**2018**	59.2	0.464	--
	2019	--	0.208	0.282
	2021	66.4	0.152	0.260
	Total Change	+7.2	-0.312	-0.022
Freezer Fans	**2018**	64.6	0.080	--
	2019	59.9	0.053	0.403
	2021	64.3	0.065	0.131
	Total Change	-0.3	-0.015	-0.271
Freezer Compressor	**2018**	61.3	0.453	--
	2019	55.1	0.438	0.604
	2021	63.4	0.230	0.447
	Total Change	+2.1	-0.223	-0.157

4.5.6 Total Energy Consumption

The total island energy consumption for July 2021 was 10,476.5 kWh. With a total refrigeration system draw of 0.518 kW, the system would have used 384.4 kWh. Thus, the upgraded refrigeration system represents approximately 3.7% of the total island energy usage.

4.6 Conclusions and Recommendations

The improvements made to the refrigeration and freezer units in the kitchen resulted in drastic power savings and efficiency increases. The apparent and active power requirements for the system as a whole decreased by 48% and 66.1%, respectively. The results are further supported by analyzing the ambient temperature. The temperature was hotter in 2021 than it was in 2018 or 2019 for most of the components, and the power draw was still lower. Something else to consider is the number of people on the island in the summers analyzed. 2021 supported much fewer residents than a usual year and may explain in part some of the efficiency increases shown by the system due to fewer fridge or freezer openings. However, the kitchen staff still prepared large complex meals, only varying the volume of ingredients withdrawn. This may have led to slightly less time spent open or fewer openings, but the high reduction in active and apparent energy draw makes interns confident that the system upgrades contributed significantly. To confirm this, 2022 SEIs may reexamine the refrigeration power draw and compare it to 2021, assuming maximum capacity in 2022.

While the refrigeration system is much more efficient than it once was, there are still ways it may be improved. One is installing strip curtains on both the freezer and the fridge doors to prevent the cold air from escaping. Another method is to reduce the ambient air temperature by cooling the kitchen. If the kitchen temperature is lower, then less heat will need to be removed from the items placed in the refrigeration system, although more energy is spent on cooling the space itself.

4.7 References

Goguen, T. (2019, February 6). General Walk-In Freezer Load Calculation. *Refrigeration Trenton Products, Granite State Plumbing and Heating.*

Saidur, R., Masjuki, H. H., & Choudhury, I. A. (2002). Role of ambient temperature, door opening, thermostat setting position and their combined effect on refrigerator-freezer energy consumption. *Energy Conversion and Management*, *43*(6), 845–854. https://doi.org/10.1016/s0196-8904(01)00069-3

What is power factor? How to calculate power factor formula. Fluke. (2019, May 16). https://www.fluke.com/en-us/learn/blog/power-quality/power-factor-formula.

Future Project Suggestions

Anaerobic Digestion to Sustain Kitchen's Needs

Maclane Keohane, SML's Island Engineer, is interested in the direct utilization of biogas from anaerobic digestion of sewage, food processing, and other wastes to provide an energy source for cooking and hot water production on Appledore Island. He suggests picking a few polyethylene cans around the island (particularly, HDPE) and creating an inlet pipe for food waste as well as an outlet pipe for fertilizer liquid. Ideally, there would be a gas valve on the top that can lead to another container or inflatable housing that can direct gas to Kiggins Commons and provide a dependable energy source for the kitchen.

People Powered Electricity Generation in New Gym

Amidst the stagnant lifestyle brought upon by Covid-19, SML took this as an opportunity to renovate their existing warehouse space and turn it into a micro-gym, decked out in brand new equipment graciously donated by a Cornell alumnus. This modest, but functional, gym comprises TRX bands, dumbbells, a bench, yoga mats, resistance bands, as well as an elliptical and rower machine. Interns believe this space cannot only serve as a place for good sweats and stress relief but also as a source for energy generation to SML's main grid. Stationary bikes, steppers, and ellipticals create resistance, and through this movement, electricity can be produced. By removing the internal resistance of a machine and giving it an external load, it can provide energy to a DC generator. These machines can then be wired to a central unit containing an inverter that converts the DC power generated to an AC. Essentially, the inverter can connect to SML's electrical system and ultimately feed the ECB grid. Although the energy output from a single exercise machine is quite minimal, interns believe this experiment can reap great benefits regarding education about sustainability and wellness to students, employees, and visitors alike.

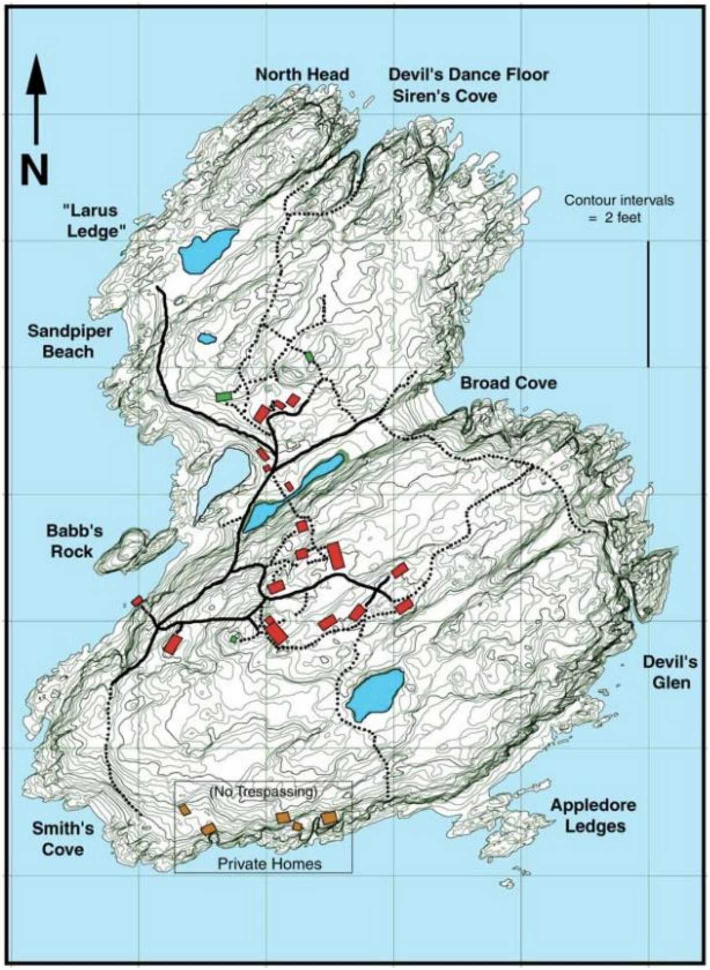
Continued Monitoring of Wind Turbine Power Output

Interns recommend continued maintenance and monitoring of the new 10 kW Bergey turbine to ascertain an adjusted power offset equation and a corrected coefficient of power value. Additionally, interns suggest considering the installation of a non-complex baseline load or PS TAB for the VCSII charge controller to further understand power output at varying wind speeds.

Improved Grid Connectivity through Wosnik Model

The 2022 SEI cohort should work closely with Professor Martin Wosnik's model to determine the minimum battery storage capacity and additional infrastructure needed to reach 95-100% green energy utilization rates. The model should be adjusted to account for varying external factors and variables such as precipitation, cloud coverage, and gull excrement, etc.

Appendix



Appendix 1: Site Specifications (Carpenter, 2003)

Corrected to a sea level air density of 1.225 kg/m^3					Category A	Category B	Combined
Bin No.	**Hub Height Wind Speed**	**Power Output**	**Cp**	**1-minute samples**	**Standard Uncertainty, Si**	**Standard Uncertainty, Ui**	**Standard Uncertainty, Ci**
	m/s	*Watts*			*Watts*	*Watts*	*Watts*
1	0.5	-12		158			
2	1.0	-12		224	0.1	0.9	0.9
3	1.5	-11		309	0.3	0.9	1.0
4	2.0	0		391	0.9	2.9	3.0
5	2.5	39	0.11	375	2.1	10.9	11.1
6	3.0	102	0.16	661	3.0	20.2	20.4
7	3.5	229	0.23	818	3.4	43.8	43.9
8	4.0	399	0.26	1060	3.2	65.4	65.4
9	4.5	596	0.28	1213	3.0	84.5	84.6
10	5.0	848	0.29	1235	3.7	116.9	117.0
11	5.5	1,151	0.29	1279	4.7	152.6	152.6
12	6.0	1,510	0.30	1250	5.4	195.2	195.3
13	6.5	1,938	0.30	1401	6.0	248.5	248.6
14	7.0	2,403	0.30	1355	7.1	293.3	293.4
15	7.5	2,949	0.30	1014	9.9	362.8	362.9
16	8.0	3,602	0.30	885	12.7	452.4	452.6
17	8.5	4,306	0.30	687	16.8	523.1	523.3
18	9.0	5,071	0.30	736	18.0	604.1	604.4
19	9.5	5,960	0.29	668	19.7	725.9	726.1
20	10.0	6,856	0.29	707	21.4	790.8	791.0
21	10.5	7,849	0.29	650	26.2	912.1	912.5
22	11.0	8,863	0.28	599	28.0	994.0	994.4
23	11.5	9,928	0.28	635	24.3	1098.6	1098.9
24	12.0	10,885	0.27	606	24.8	1105.8	1106.1
25	12.5	11,619	0.25	504	21.7	1044.8	1045.0
26	13.0	12,019	0.23	432	15.0	968.6	968.7
27	13.5	12,276	0.21	337	13.3	906.1	906.2
28	14.0	12,395	0.19	333	7.4	906.0	906.1
29	14.5	12,449	0.17	292	7.2	904.5	904.6
30	15.0	12,495	0.16	279	3.3	907.5	907.5
31	15.5	12,508	0.14	231	10.3	907.4	907.4
32	16.0	12,546	0.13	187	5.4	911.0	911.0
33	16.5	12,555	0.12	165	8.5	910.7	910.8
34	17.0	12,503	0.11	125	24.4	908.8	909.1
35	17.5	12,528	0.10	138	17.8	909.2	909.4
36	18.0	12,442	0.09	98	36.2	908.2	908.9
37	18.5	12,396	0.08	94	36.8	901.0	901.7
38	19.0	12,208	0.08	57	65.2	916.2	918.5
39	19.5	11,878	0.07	39	83.4	960.0	963.6
40	20.0	11,989	0.06	18	130.0	882.0	891.5
41	20.5	11,495	0.06	15	124.6	1066.4	1073.7

Appendix 2: Tabulated Power Curve (Bergey Windpower Co, 2021)

Wind Speed at Turbine (m/s)	Power (kW)	Cp (actual)	Offset Applied (kW)	Adj Power (kW)	Cp (adj)
0.68	0.011	0	0.008	0.003	0.00
1.35	0.018	0.31	0.009	0.009	0.16
1.64	0.033	0.32	0.011	0.022	0.21
2.12	0.062	0.28	0.014	0.048	0.21
2.70	0.134	0.29	0.024	0.110	0.24
2.99	0.231	0.37	0.036	0.196	0.31
3.62	0.412	0.37	0.059	0.353	0.32
4.24	0.613	0.34	0.084	0.529	0.29
4.82	1.020	0.39	0.135	0.885	0.33
5.11	1.068	0.34	0.141	0.927	0.29
5.59	1.218	0.30	0.160	1.058	0.26
6.17	1.914	0.35	0.248	1.667	0.30
6.46	2.177	0.34	0.281	1.896	0.30
6.94	2.393	0.30	0.308	2.084	0.26
7.23	3.260	0.37	0.417	2.843	0.32
7.81	3.820	0.34	0.488	3.332	0.30
8.44	5.326	0.38	0.678	4.649	0.33
9.07	5.728	0.33	0.728	5.000	0.28
9.36	5.728	0.30	0.728	5.000	0.26
9.93	6.186	0.27	0.786	5.400	0.23
10.42	9.667	0.36	1.225	8.443	0.32
10.71	10.181	0.35	1.289	8.891	0.31
11.38	10.191	0.29	1.291	8.900	0.26
12.06	10.247	0.25	1.298	8.949	0.22
12.06	10.247	0.25	1.298	8.949	0.22
12.74	10.717	0.22	1.357	9.360	0.19
13.41	11.521	0.20	1.458	10.063	0.18
13.70	11.903	0.20	1.506	10.396	0.17
14.18	11.768	0.18	1.489	10.279	0.15
14.76	11.841	0.16	1.499	10.342	0.14
15.05	12.031	0.15	1.523	10.508	0.13
15.53	12.077	0.14	1.528	10.549	0.12
16.20	12.208	0.12	1.545	10.663	0.11
16.88	12.002	0.11	1.519	10.483	0.09
17.17	12.224	0.10	1.547	10.677	0.09
17.65	11.190	0.09	1.417	9.774	0.08
18.23	11.784	0.08	1.491	10.293	0.07
18.52	12.055	0.08	1.526	10.529	0.07
19.29	12.319	0.07	1.559	10.761	0.06
19.77	12.425	0.07	1.572	10.853	0.06

Appendix 3: Tabulated Actual Turbine Outputs, Pre and Post Adjustment

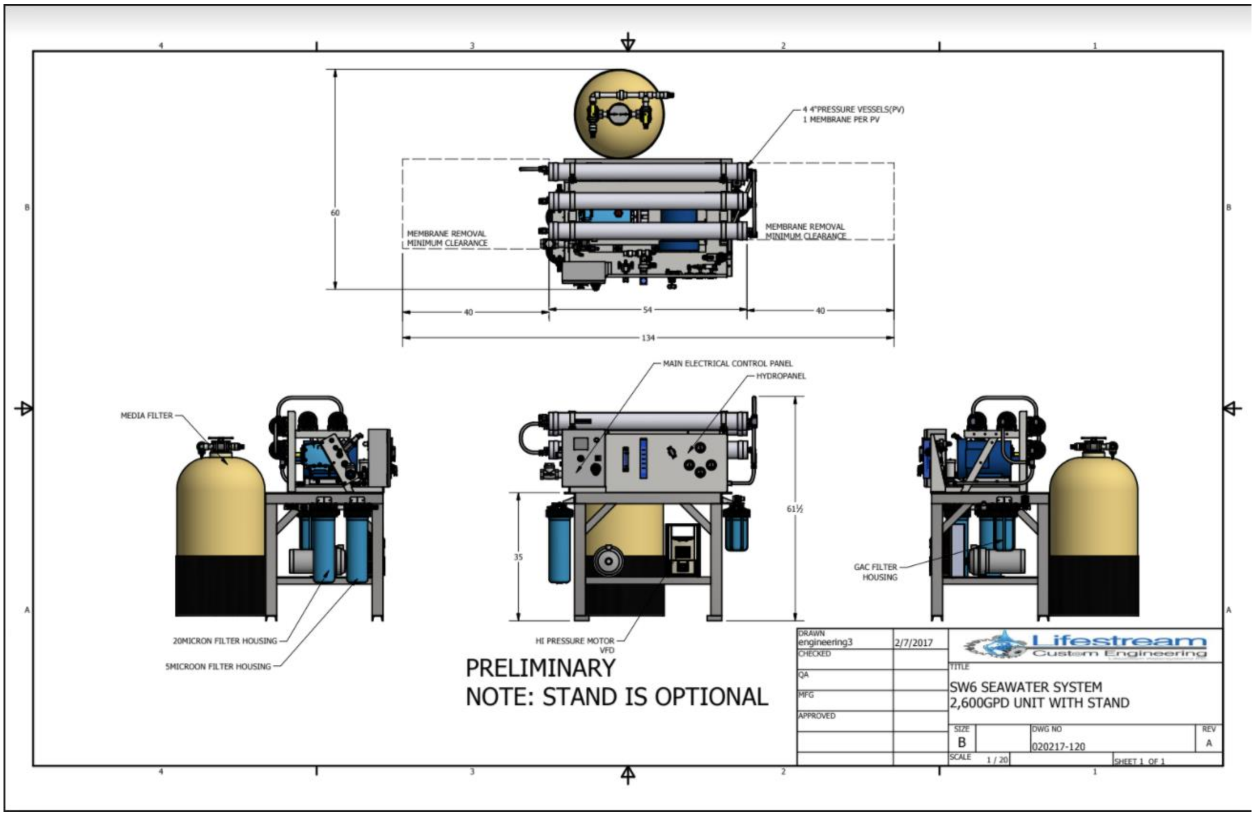
Power - AcuDC (kW)	Power - VCSII (kW)	Offset (kW)
1.311	1.310	0.001
5.145	4.479	0.666
1.257	1.231	0.026
3.932	3.544	0.388
3.585	3.172	0.413
1.501	1.371	0.130
4.601	4.020	0.581
4.561	3.764	0.797
6.259	5.456	0.803
0.379	0.122	0.257
3.884	3.411	0.473
3.912	3.452	0.460
4.463	3.902	0.561
5.312	4.540	0.772
4.981	4.319	0.662
5.313	4.595	0.718
0.760	0.754	0.006
0.461	0.331	0.130
0.398	0.210	0.188
0.641	0.491	0.150
0.930	0.886	0.044
2.593	2.164	0.429
1.116	0.986	0.130
1.717	1.487	0.230

1.926	1.714	0.212
2.264	1.928	0.336
2.017	1.720	0.297
5.542	5.150	0.392
8.969	7.766	1.203

Appendix 4: Raw AcuDC and VCSII Offset Data

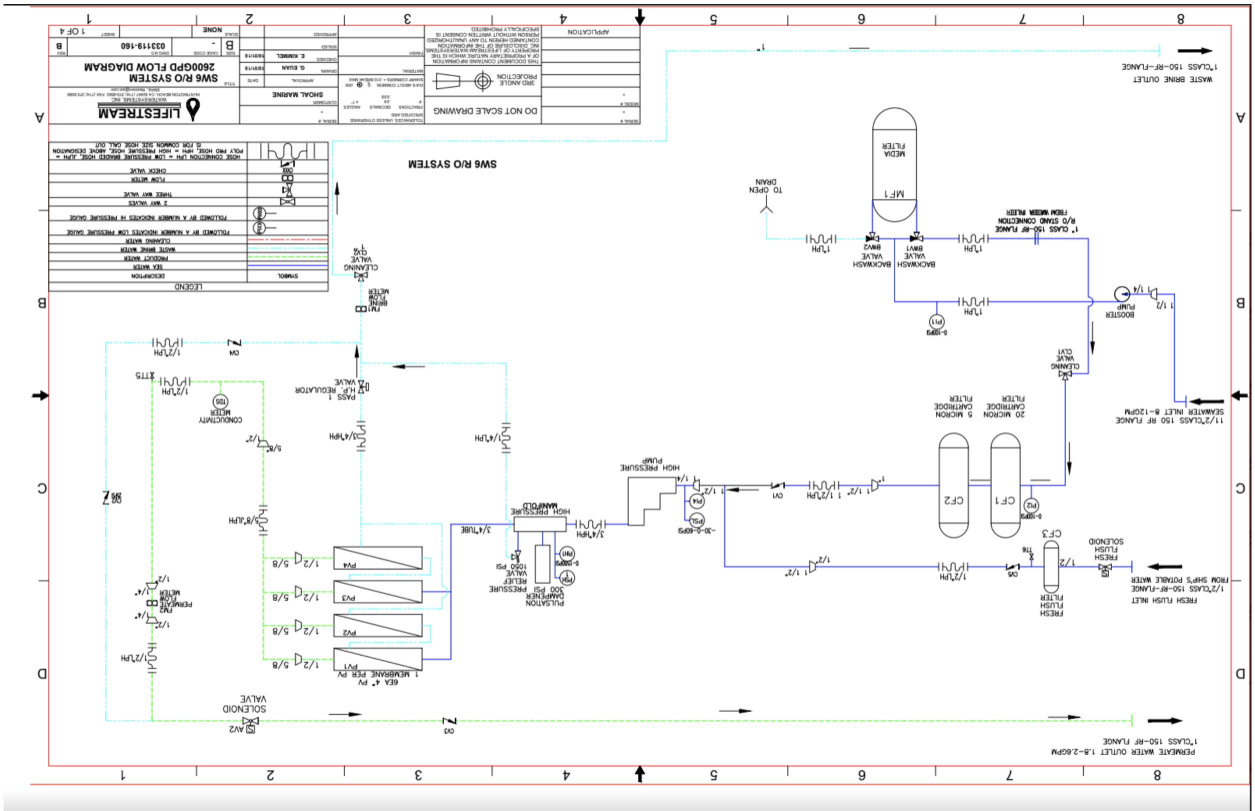
PV Sizing Equation vs Island Values					
Grid	Ideal Solar Output/Day (kWh)	Efficiency	Hours Peak Sunlight	Calc. PV to Generate Ideal Output (kW)	Installed PV (kW)
ECB	306	0.6	8.5	60	55.5
K-House	140	0.6	8.5	27.5	29.4

Appendix 5: Section 2.4.5 Equation Corroboration



Appendix 6: SW6 Seawater System 26,000 GPD Unit With Stand

(Lifestream Watersystems Inc, 2021)



Appendix 7: SW6 R/O System (Lifestream Watersystems Inc, 2021)