SHOALS MARINE LABORATORY

2007 ENGINEERING INTERNSHIP

INTEGRATED ISLAND ENGINEERING SYSTEMS FOR SUSTAINABILITY

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TABLE OF CONTENTS

INTRODUCTION

The island community of Shoals Marine Laboratory (SML) offers an ideal setting for the implementation of sustainable practices and technology. The island systems are small in scale, the demands on the systems are predictable, and the consequences of altering these systems are readily observed. Nevertheless, the successful maintenance and operation of such systems hinges upon careful monitoring and data collection. These tasks formed the basis of the 2007 Saquish Sustainable Engineering Internship.

From July 16th to August 12th, 2007, six interns from Cornell University, the University of New Hampshire, and Olin College of Engineering participated in the Sustainable Engineering Internship at SML. Essentially, the goals of the internship were to collect data about the island systems and to use this data to evaluate performance and guide future developments. Specifically, the interns examined the operation of four systems: saltwater, freshwater, solar power and wind power. Additionally, the interns examined the operation of the reverse osmosis unit and collected baseline data on various aspects of SML's operation. Finally, an inventory of the greenhouse gas emissions of SML was conducted. Each of these projects was completed with extensive assistance from Ross Hansen, the Operations Manager; the island engineers; and visiting experts and professionals within each field of interest. Collectively, the results of these projects form a detailed illustration of SML's operation.

The following report details the data collection processes, results, and implications of each project. Over the course of the internship, many challenges arose; these included elusive historical data records, fluctuating water quality, power controls programming issues, and meddlesome seagulls. These challenges expanded the original scope of the project and provided further insight into system performance. Furthermore, they inspired potential projects for future Sustainable Engineering Interns. It is the aim of the interns that the findings and recommendations presented here will be useful in improving the operation of Shoals Marine Laboratory.

BASELINE DATA COLLECTION

BACKGROUND

Baseline data collection of the major systems is essential for monitoring the overall performance of SML and for yearly reference. It is desirable to collect baseline data intensively to determine daily trends. The major systems are the wastewater, freshwater, saltwater, and power generation systems.

The wastewater system at Appledore Island consists of primary treatment with two settling tanks and one chlorination tank. Prior to the final discharge out of the system, the wastewater is de-chlorinated with sodium metabisulfate.

The freshwater system consists of a 20-foot well and a reverse osmosis (R/O) system. The R/O system is used towards the end of the season as the well level decreases and as the water demand increases with a greater island population. The disinfection treatment for the well comprises two filters followed by chlorination. The R/O system has a series of filters with chlorination by the same pump as the well. Water from both sources is stored in a cistern and piped to a steel pressure tank for delivery to campus.

The saltwater system consists of a pump which delivers saltwater to the island's toilets, sea tables, and various hoses and spigots.

The power generation system consists mainly of two 65-kW Caterpillar generators and one 30-kW Detroit Diesel generator. The PV array and the wind turbine are not tied into the main grid. Instead, they are used to charge a GNB battery bank which then powers University of New Hampshire's AIRMAP equipment and Dorm 3.

OBJECTIVE

The objective is to provide SML operators with performance data for the wastewater, freshwater, and saltwater systems as well as generator fuel usage and population data.

DATA COLLECTION

Baseline data were collected from the systems every two hours from 6:00 AM to 10:00 PM from July 18, 2007 to August 7, 2007. Readings were taken for the freshwater system from a flow meter located between the steel pressure tank and the distribution manifold. In addition, the level of the chlorine tank was measured. For the wastewater system, the number of times the Equalizer and Batch pumps ran was recorded, with 575 gallons being moved with each run. This information was then used to determine the amount of wastewater discharged. For the saltwater system, readings were taken at the saltwater pump for intake pressure, discharge pressure, and flow rate. To determine diesel fuel usage, the level of fuel in the day tank was recorded. Peak daily and overnight population data were also gathered through the assistance of the SML office.

RESULTS AND DISCUSSION

Wastewater System

During the collection period, the number of discharges ranged from 2 to 6 per day (1150 to 3450 gallons/day), where a day spans from 6:00 AM on that day to 6:00 AM on the next. The average discharge per day was about 2000 gallons.

Note in Figure 1 that the batch reactors are functioning properly, with each taking on approximately the same load; during the data collection period, Batch 1 pumped 34 times and Batch 2 pumped 35 times.

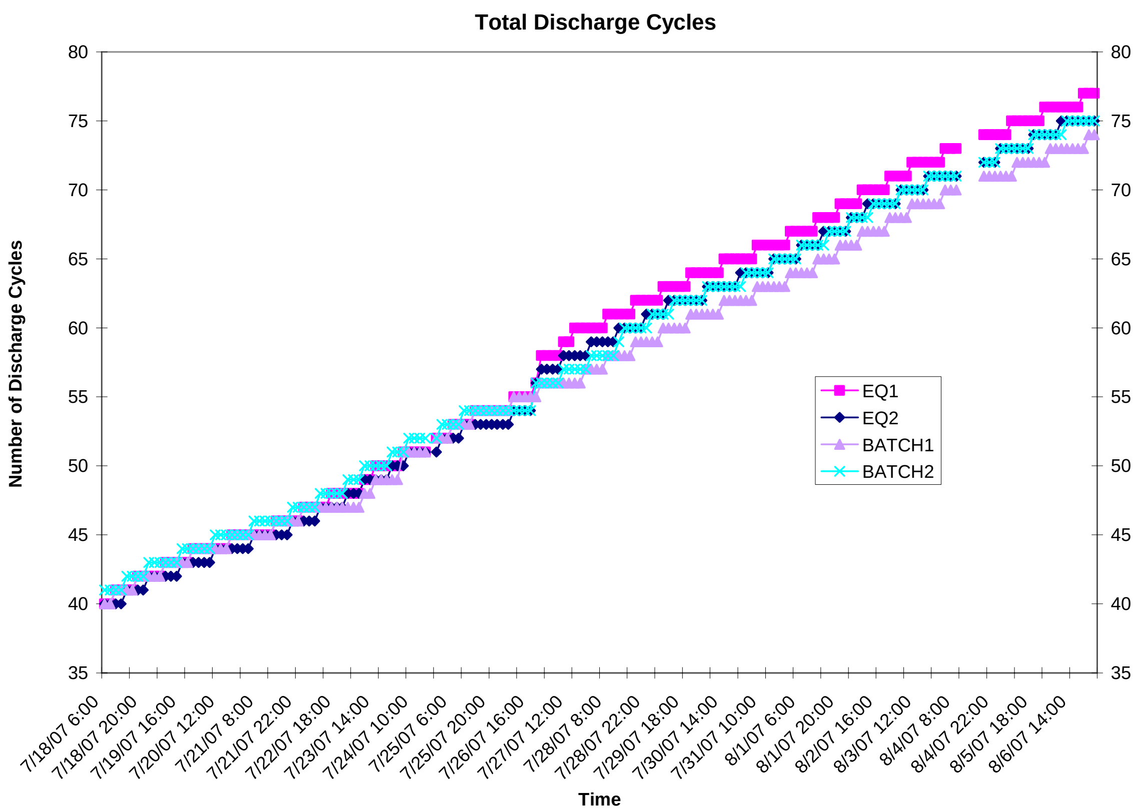

Figure 1. Total discharge cycles (July 18, 2007 to August 7, 2007).

Comparing the total number of cycles of the two batch reactors with the number of cycles of the corresponding equalizer pumps, there is no significant discrepancy between the numbers of pump cycles. This is desirable because after an equalizer pump runs, a batch pump is expected to run after the 30-minute contact time. At most, there is a difference of 2 cycles, which can be accounted for if the cycle was recorded while both of the batches were in the 30-minute process of being chlorinated. The difference could also be explained by tests the island engineers ran to check the pumps. Refer to the Digital Appendix for the corresponding charts.

By looking at the total average discharge cycles over the data collection period for the Batch 1 and Batch 2 Reactors, it can be seen that peak runs occur 6:00AM to 8:00AM, 10:00AM to 12:00PM, 4:00PM to 6:00PM and 8:00PM to 10:00PM (Figure 2).

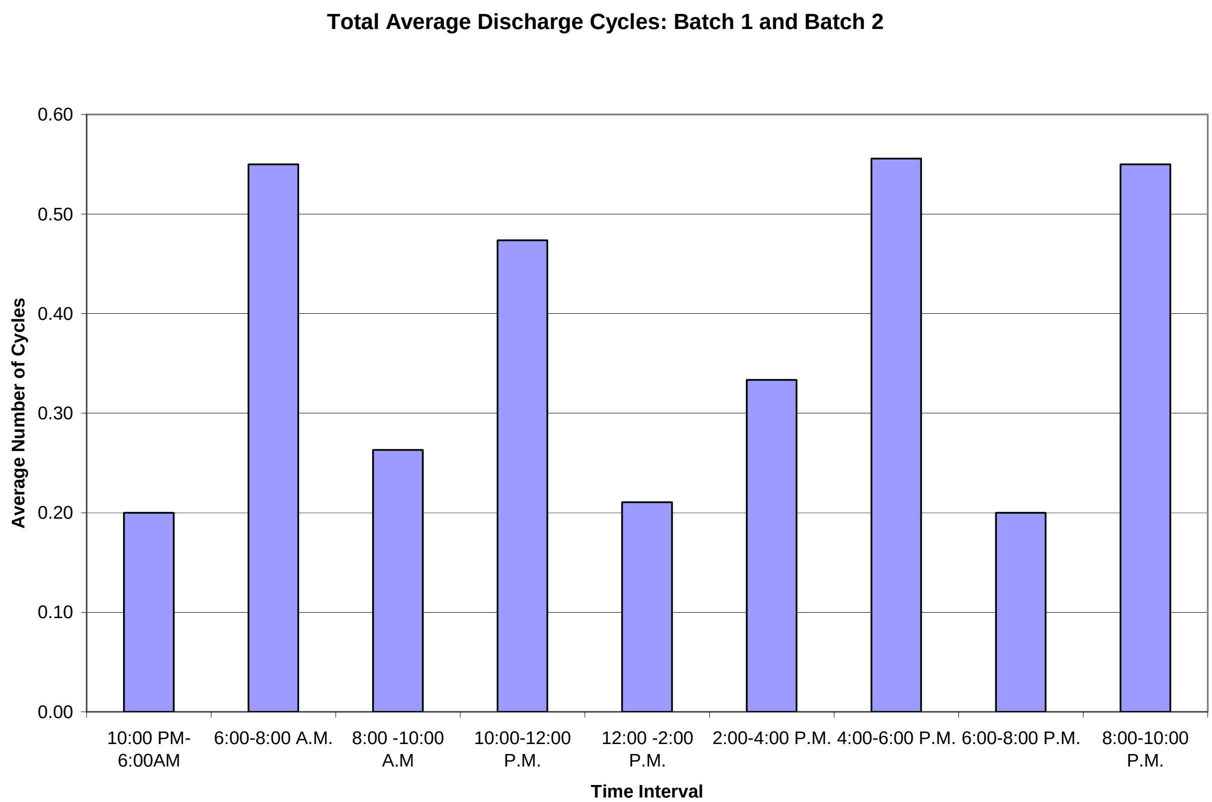

Figure 2. Total average discharge cycles (Batch 1 and Batch 2).

Showers most likely contribute to the morning and evening peaks. The morning, afternoon, and evening peaks occurring at meal times are probably attributable to wastewater from the kitchen and increased toilet use. The afternoon peak is not as great as the morning and evening peaks, which suggest that showers have a greater impact on freshwater consumption than the washing of kitchenware. However, the 4:00 PM to 6:00 PM peak cannot be explained by either showers or kitchen use, thus making it difficult to make definite conclusions about the apparent surges of wastewater generation.

Freshwater System

Freshwater use was fairly constant throughout the data collection period, ranging from 1100 gallons per day to 1800 gallons per day. The range can be attributed to increased shower use with an increase in island population. The average rate of consumption over the collection period was found to be approximately 1500 gallons per day.

As seen in Figure 3, peak water use occurs in the mornings from 6:00 AM to 8:00AM. This coincides with morning showers and bathroom facility use. After this peak, the rate of water usage decreases. The water usage then increases and holds steady from 4:00 PM to 10:00 PM. The increase in water usage could be contributed to kitchen water use in addition to people washing after a day in the field. The 8:00PM to 10:00PM peak could be attributed to shower usage, but because the rate is similar to the 4:00PM to 6:00PM and 6:00PM to 8:00 PM rates, no definite conclusions can be made. The minimum flow rate occurs, as expected, 10:00 PM to 6:00 AM, during sleeping hours. The average daily per-capita freshwater consumption rate followed a similar trend as the average daily consumption with peak use and minimum use occurring during the same intervals (see Digital Appendix).

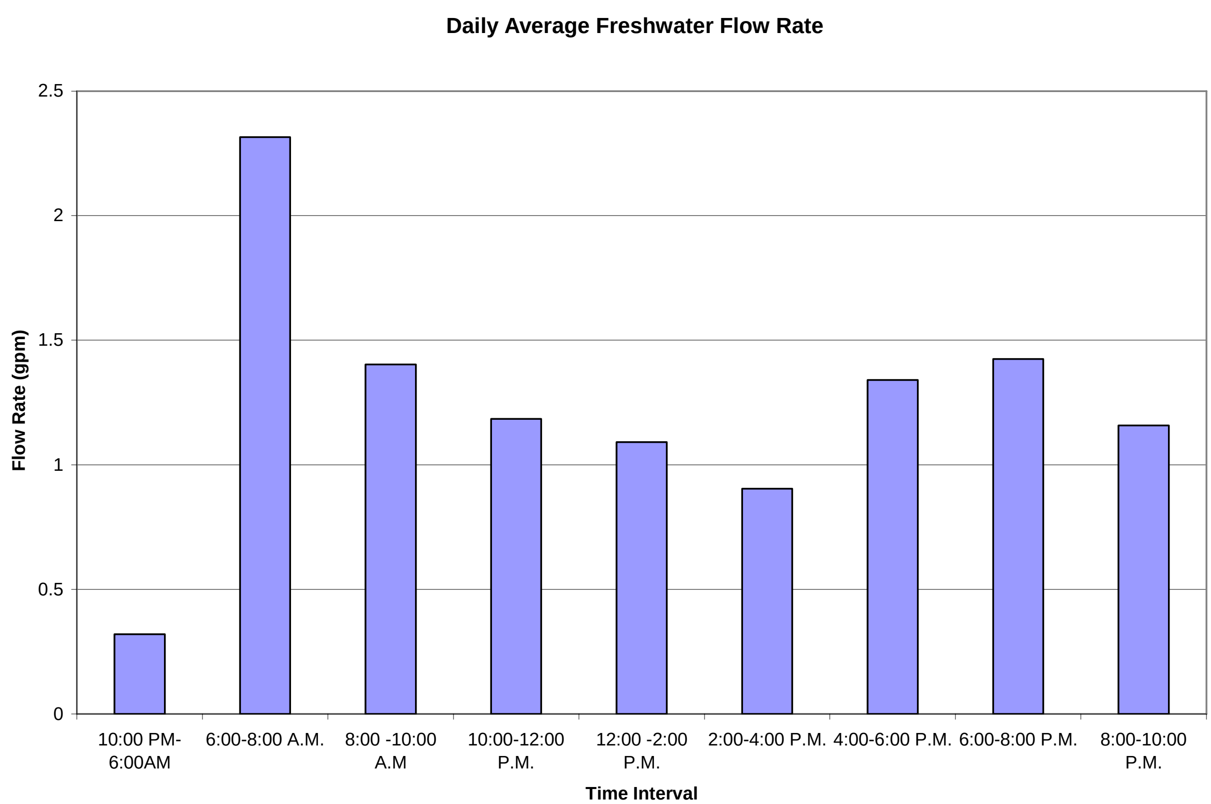

Figure 3: Average daily freshwater flow rate (July 18, 2007 to August 7, 2007).

Table 1 shows historical data for freshwater consumption. Data from 2001 to 2006 were obtained from the 2006 interns' data. Note that complete data was not available for every year. The average rate of freshwater consumption for 2007 was found to be 1.24 gpm and the per-capita rate to be 0.014 gpm. Note that the average rate is lower than in 2006, but the average per-capita rate is a higher. However, looking at the available data, average freshwater consumption has been fairly steady over the years.

Table 1. Freshwater consumption historical data.

Freshwater Consumption		
Year	Average (gpm)	Average per capita (gpm)
2001	1.19	
2002	1.13	0.014
2003		
2004	1.06	
2005	1.19	0.015
2006	1.27	0.012
2007	1.24	0.014

The chlorination system for the freshwater system uses a pump that delivers chlorine to the water either in the cistern if the well pump is on or as the water goes to the pressure tank if the R/O system is on. The frequency and rate of chlorine injection at different time intervals were determined by measuring the level of the chlorine tank.

Over the data collection period while the well pump was on, July 18th to July 25th, the levels of the chlorine tank were analyzed to determine the behavior of the pump. (Note that data from this time period were chosen because when the freshwater system was switched to the R/O system, the R/O unit was only run during the day; thus, this data would not be representative of the chlorine pump's behavior.) It can be seen in Figure 4 that the chlorine pump was on most often during specific time intervals. The highest frequency of chorine injection was during the 10:00 PM to 6:00 AM interval. The chlorine pump running during the night means that after a day of using water, the pumps are activated at night to refill the tanks. Note that during this time, the chlorine pump did not run once from 6:00 AM to 10:00 AM, most likely because enough water was already in the pressure tank. Also note that the frequency increases after 10:00 AM. This could occur because of high water use during the morning with showers and cleaning in the kitchens.

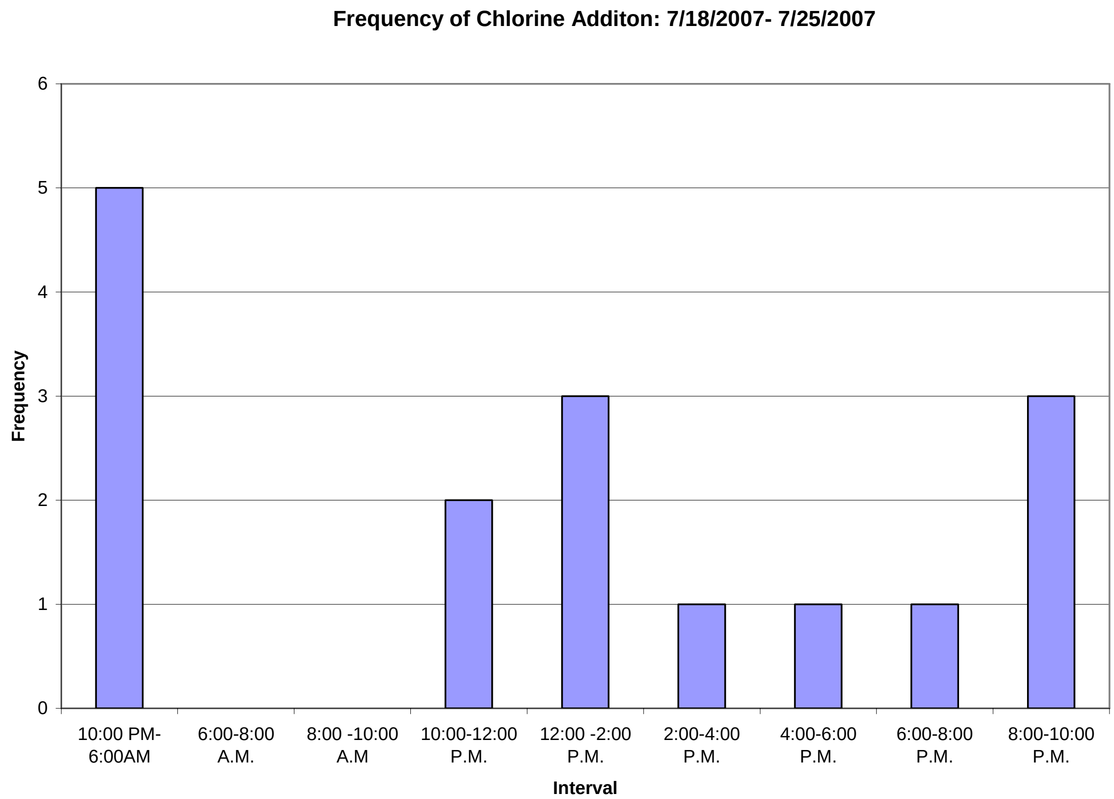

Figure 4. Frequency of addition of chlorine to the freshwater system from 7/18/2007 to 7/25/2007.

The average rate of chlorine addition while the well pump was on further supports the observation that the chlorine pump delivers most of the chlorine during the night (see Figure 5).

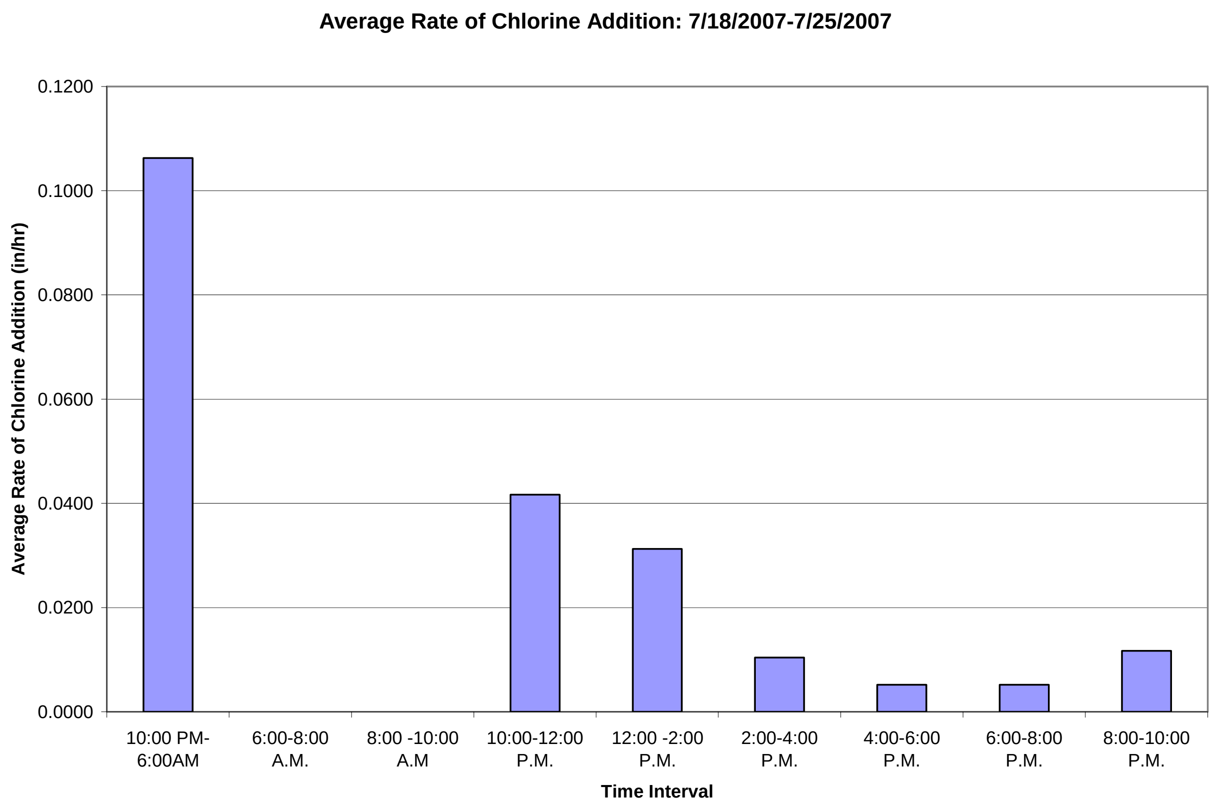

Figure 5. Average rate of chlorine addition to the freshwater (from July 18 to July 25).

Saltwater System

Refer to Saltwater Section for data and results for the saltwater pump baseline data.

Power Generation System: Diesel Fuel Consumption

Over the data collection period, there was a steady increase in fuel consumption (see Figure 6). This can be attributed to the gradual increase in the number of people on the island (see Digital Appendix for population data).

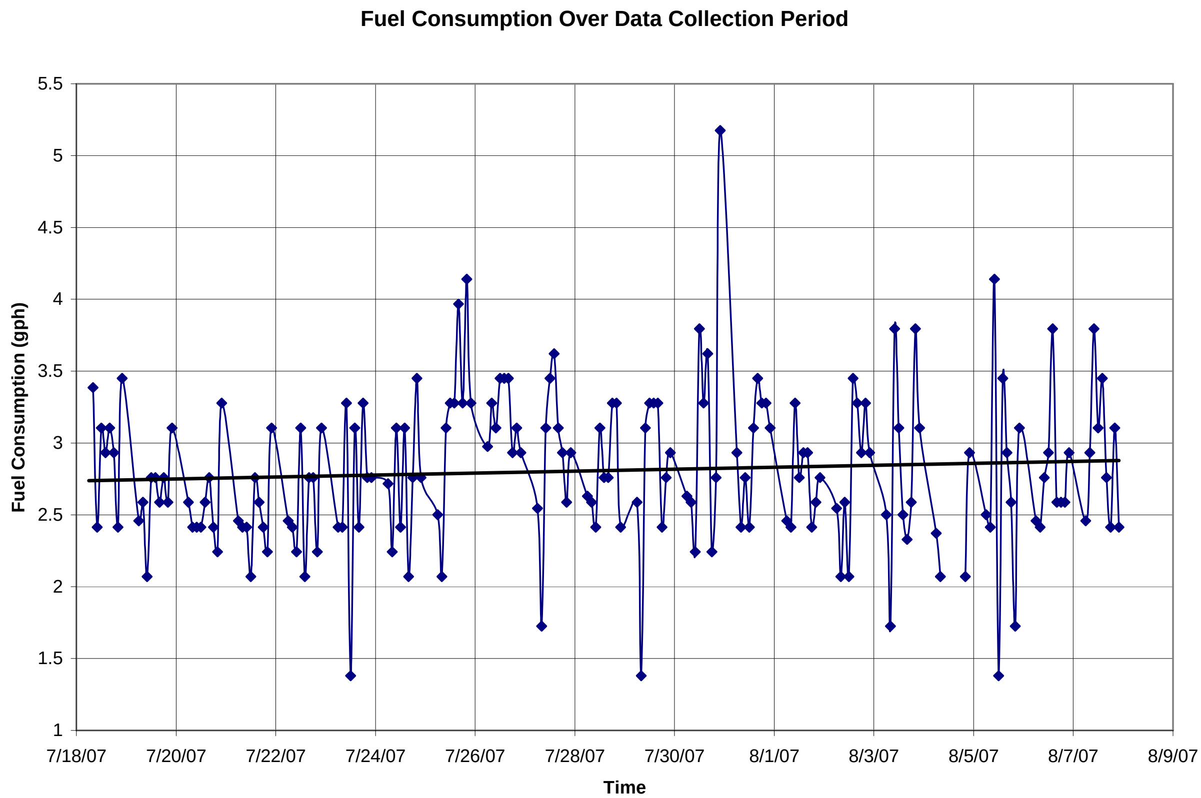

Figure 6. Diesel fuel consumption (gph) from July 18 to August 7, 2007.

Note in Figure 6 and Figure 7 that while the fuel consumption has an increasing trend, the per capita fuel consumption has a decreasing trend. Most of the load on the generators is independent from the number of people on the island. While more people would increase power consumption, this would essentially be a few more lights and electrical outlets being used. There is a fairly constant load from the various pumps and appliances (i.e. kitchen dishwasher and water heaters) that is not significantly affected by the addition of twenty or thirty people. Over the course of the collection period, the population of the island slowly increased. The decrease in the per-capita consumption of fuel could be attributed to a steady use of fuel being distributed over a greater number of people.

Alternatively, in light of the 2006 interns' fuel data[1], it is evident that using a higher fraction of the generators' capacity increases their efficiency.

[1] See fuel efficiency plot in "Electrical – Generator.xls" spreadsheet from 2006.

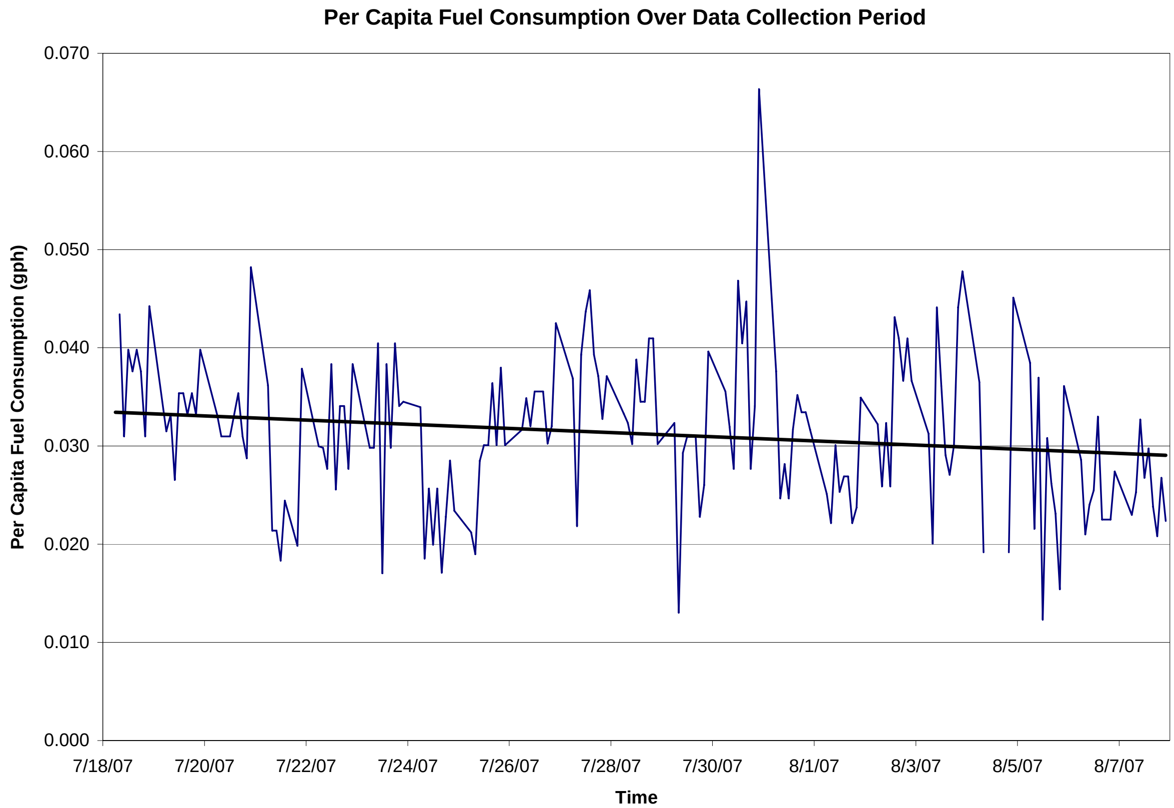

Figure 7. Per capita fuel consumption from July 18 to August 7, 2007.

As seen in Figure 8. Average daily fuel consumption rate From July 18 to August 7, 2007., the fuel consumption increases starting during the 8:00 AM to 10:00 AM interval and decreases during the 10:00 PM to 6:00 AM interval. The increase in fuel consumption after 8:00 AM can be attributed to people beginning to use lights, electronics, and lab equipment as well as to overall island startup. The increase during the 12:00 PM to 2:00 PM interval could be because of kitchen cleaning. The increase after 8:00 PM is most likely because of lights and outlets being used. The higher level of consumption between 10:00 PM to 6:00 AM could be attributed to people who are still awake and using electricity during the beginning of the interval and to lights that remain on during the night. The decrease in fuel consumption during the 6:00 AM to 8:00 AM interval could be attributed to the fact that people are just beginning to wake up. Overall, however, there appears to be a fairly constant rate of fuel consumption from 8:00 AM to 10:00 PM.

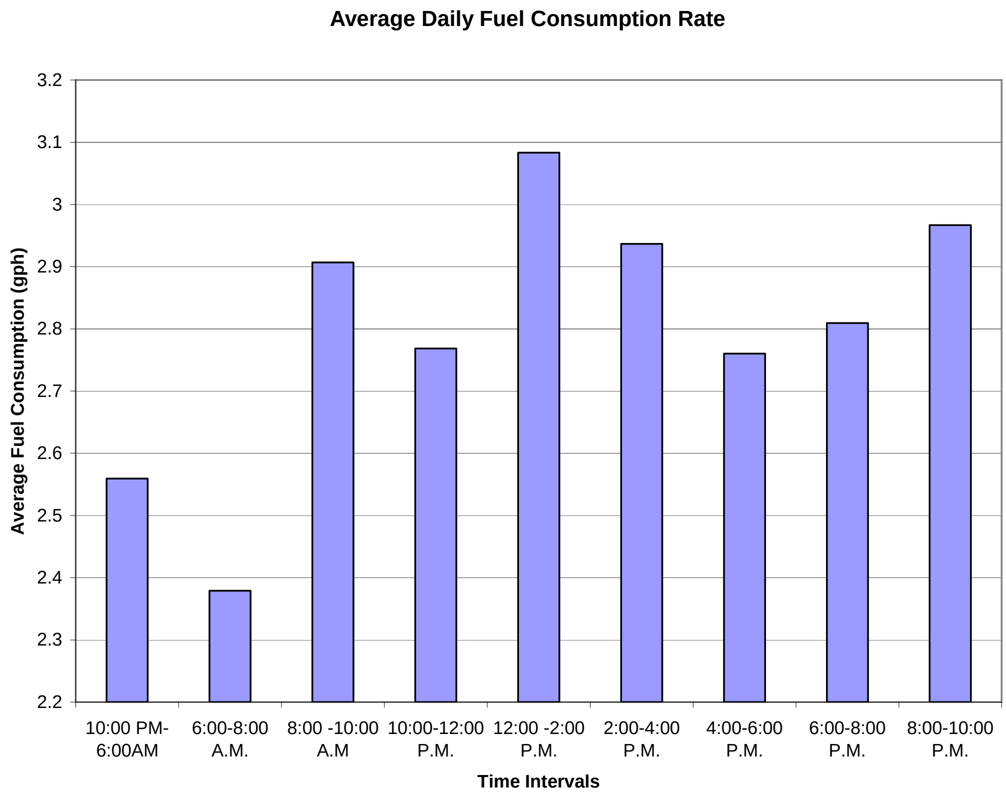

Figure 8. Average daily fuel consumption rate From July 18 to August 7, 2007.

Note in Figure 9 that the per-capita average fuel consumption peaks between 8:00 PM and 10:00 PM, coinciding with the time when the most lights and electronics are likely to be used.

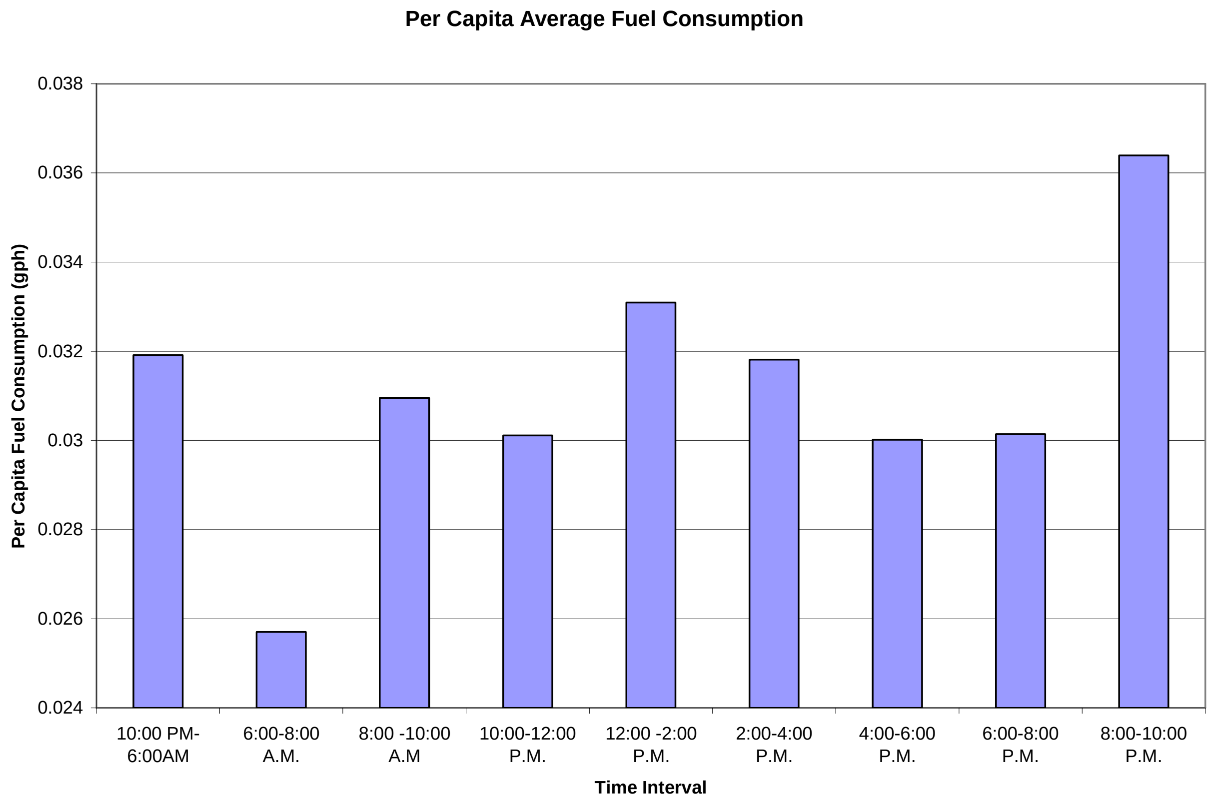

Figure 9. Per-capita average rate of fuel consumption rate from July 18th to August 7th, 2007.

Table 2 shows the historical data for fuel consumption. The values for 2001 to 2006 were obtained from the 2006 interns' data. Note that data were not available for every year. The average rate of diesel fuel consumption over the collection period was found to be 2.80 gpm and the average per-capita rate of consumption was 0.031 gph. The average rate of fuel consumption is slightly lower than in 2006, while the average per-capita rate is slightly higher. Overall, the rate of diesel fuel consumption has been fairly steady, but since 2005 there has been a slight downward trend for rate of diesel fuel consumption.

Table 2. Diesel fuel consumption historical data.

Diesel Fuel Consumption		
Year	**Average (gph)**	**Average per capita (gph)**
2001	3.12	
2002	2.86	0.037
2003		
2004	2.83	
2005	3.11	0.041
2006	2.83	0.027
2007	2.80	0.031

SALTWATER SYSTEM

BACKGROUND

Shoals Marine Laboratory requires saltwater for lab sea tables, toilets, fire hoses, and numerous saltwater spigots on campus. Last year, the saltwater delivery system lacked the capacity to operate multiple toilets and saltwater spigots simultaneously without noticeable flow losses at the sea tables. To ensure adequate flow through the sea tables during operation of other saltwater systems, the 2006 engineering interns recommended the installation of an additional 2" parallel line from the saltwater intake pump to Kiggins Commons. This addition was intended to increase the cross-sectional pipe area and decrease the hydraulic head loss in the system, allowing the pump to operate with higher flow rates and improved pump efficiency.

OBJECTIVE

Per the 2006 interns' recommendation, an additional 2" parallel saltwater line was implemented; the effect of this change on flow rate was not quantified at the time of installation. It is of interest to island operators to determine the increase in flow rate, if any, associated with the parallel saltwater line installation. Further pump capacity information is also desired to determine the feasibility of installing additional saltwater sea tables without disturbing flow to the rest of campus.

SCHEMATIC

A schematic of the saltwater system intake, delivery paths, and discharge routes is presented below in Figure 10. Saltwater intake and delivery system.

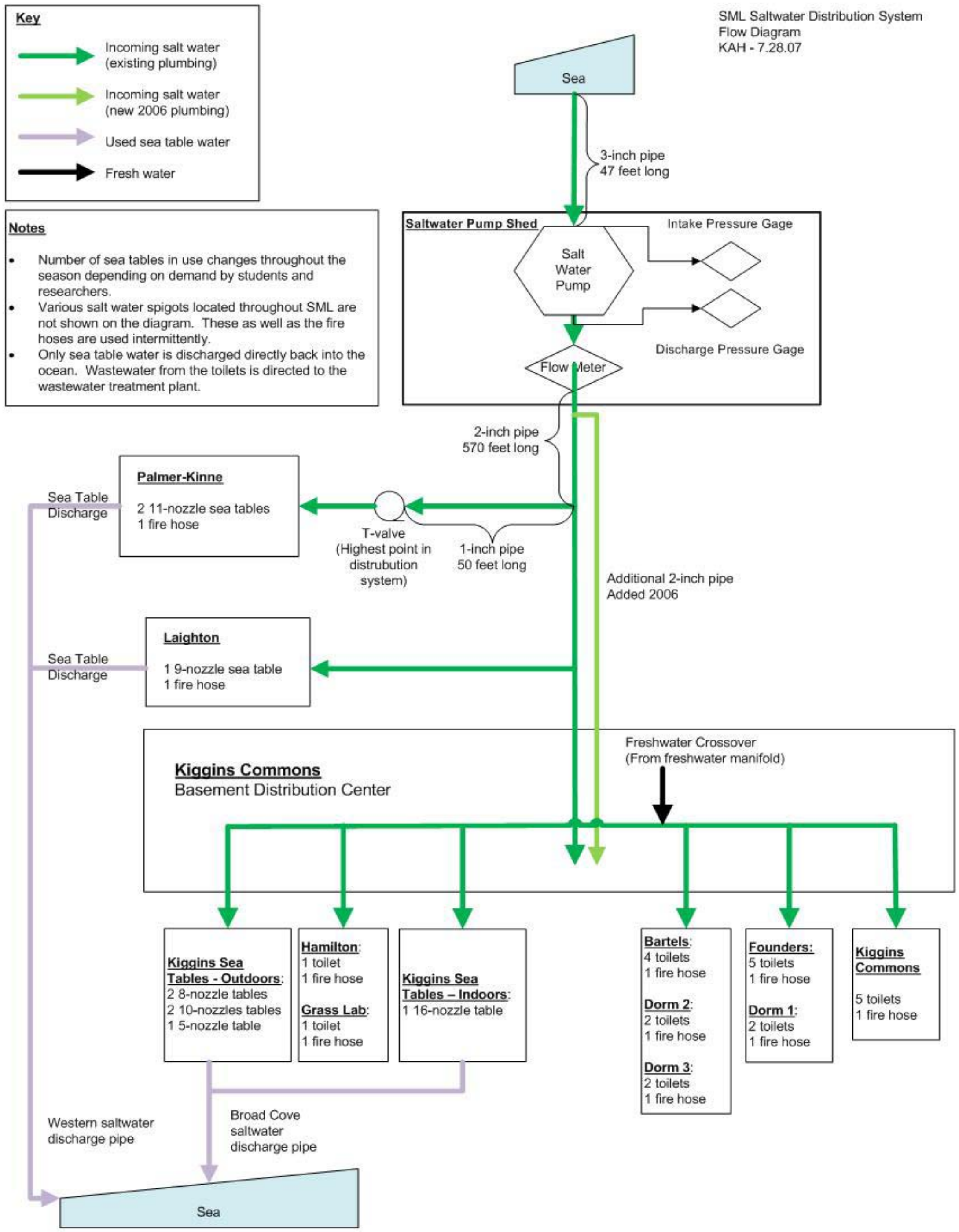

Figure 10. Saltwater intake and delivery system.

DATA COLLECTION

This summer, sea tables in the Palmer-Kinne Lab, Laighton Hall, and Kiggins Commons were operated at varying flow rates. To determine the expected increase in flow rate to campus, inflow and discharge data for the saltwater system were collected for comparison with 2006 data. Pump intake pressure in units of inches of Hg, pump discharge pressure in units of psi, and volumetric flow rate in units of gpm were recorded from gauges at the saltwater pump house every two hours from 6:00 AM to 10:00 PM daily from July 18th through August 7th; these records are available in the Digital Appendix.

It must be noted that several blockages of the saltwater system occurred during the data collection period. The saltwater intake pipe was replaced at approximately 3:00 PM on July 19th and again at 12:30 PM on August 1st by island engineers. On August 5th, a loss of flow was noticed at approximately 9:00 AM; the intake check valve was serviced at approximately 10:30 AM.

Discharge flow rates were calculated by measuring the time to fill a five-gallon bucket at each of the two saltwater outfalls; these measurements were conducted at 6:00 AM on both July 19th and July 20th and at 2:00 PM on July 24th. Measurements were taken twice at an early hour to reduce the likelihood of saltwater demand from campus toilets. This information allows comparison of the saltwater inflow and outflow rates to verify continuity in the system and is available in the Digital Appendix.

The saltwater pump test conducted by engineering interns in 2006 to determine maximum flow rate with a single 2" line was repeated on the afternoon of July 30th to determine maximum flow rate with the additional 2" line. This test included measurements of saltwater pump intake pressure, discharge pressure, and flow rate when valves at the pump shed and at Palmer-Kinne Lab were opened to the atmosphere to achieve maximum flow. The measurements were repeated with only the Palmer-Kinne Lab valve opened to achieve flow of 60 gpm; experimental results are available in the Digital Appendix.

RESULTS AND DISCUSSION

Average bi-hourly pump intake and discharge pressure measurements for 2006 and 2007 are presented below in Figure 11. For graphical purposes, the intake pressures, measured in units of inches of Hg, were converted to units of psi relative to atmospheric pressure. The diagram indicates substantially reduced intake pressure losses in 2007; the 2006 engineering intern report remarked that intake restrictions may have caused the large intake pressure losses noted that year. Note that 2006 intake pressure data fall below -14.7 psi and are therefore highly suspect.

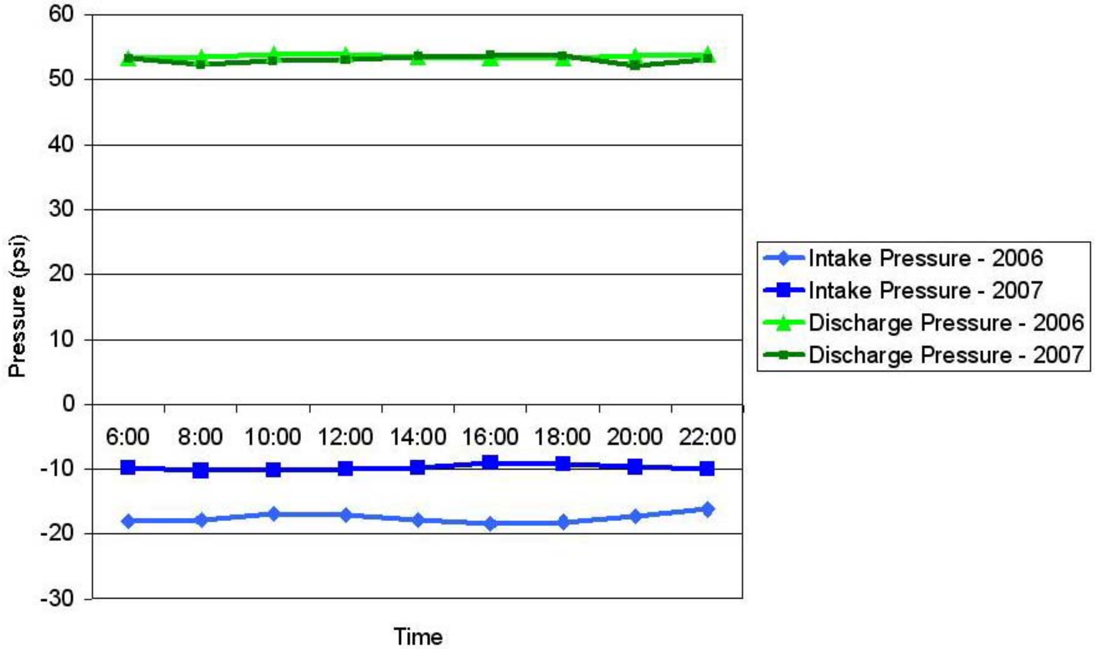

Figure 11. Average bi-hourly saltwater pump intake and discharge pressures for 2006 and 2007.

Average bi-hourly pump discharge pressure changed little from 2006 to 2007; this trend is indicative of the intake pump capacity to readily handle increased flow rates associated with the additional saltwater line, as presented below in Figure 12.

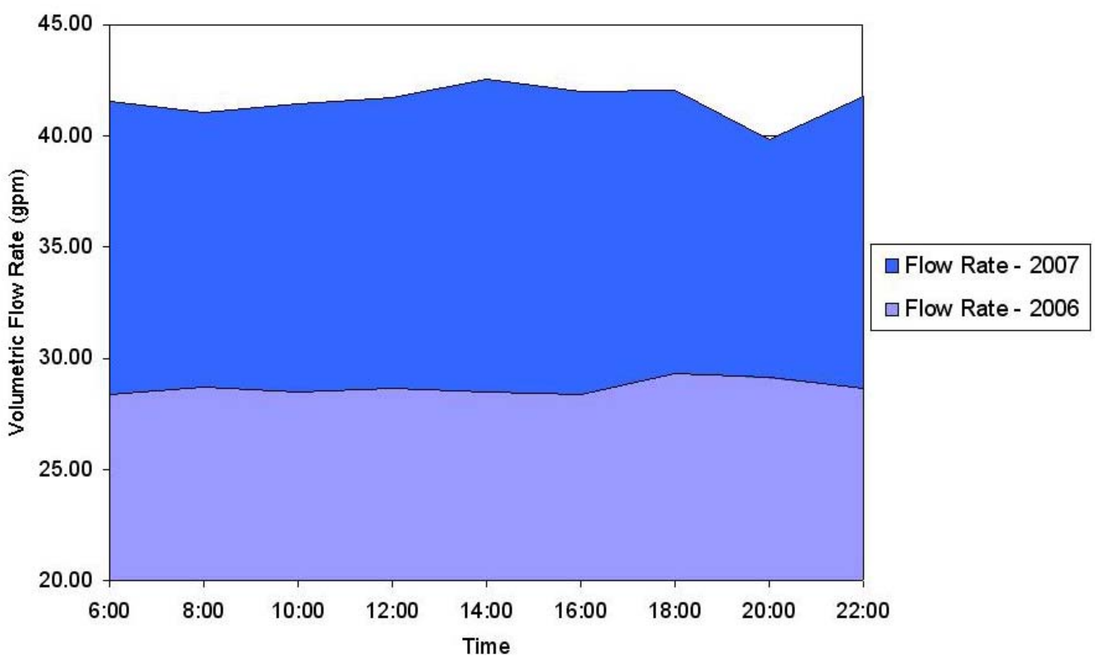

Figure 12. Average bi-hourly saltwater pump volumetric flow rates for 2006 and 2007.

For visualization of the tidal effect on intake pressure, a plot of water level and intake pressure versus time is presented below in Figure 13. Tidal data collected at Fort Point, New Castle, NH were corrected for tidal time differences to approximate the surface height history at Gosport Harbor; these data are available in the Digital Appendix.

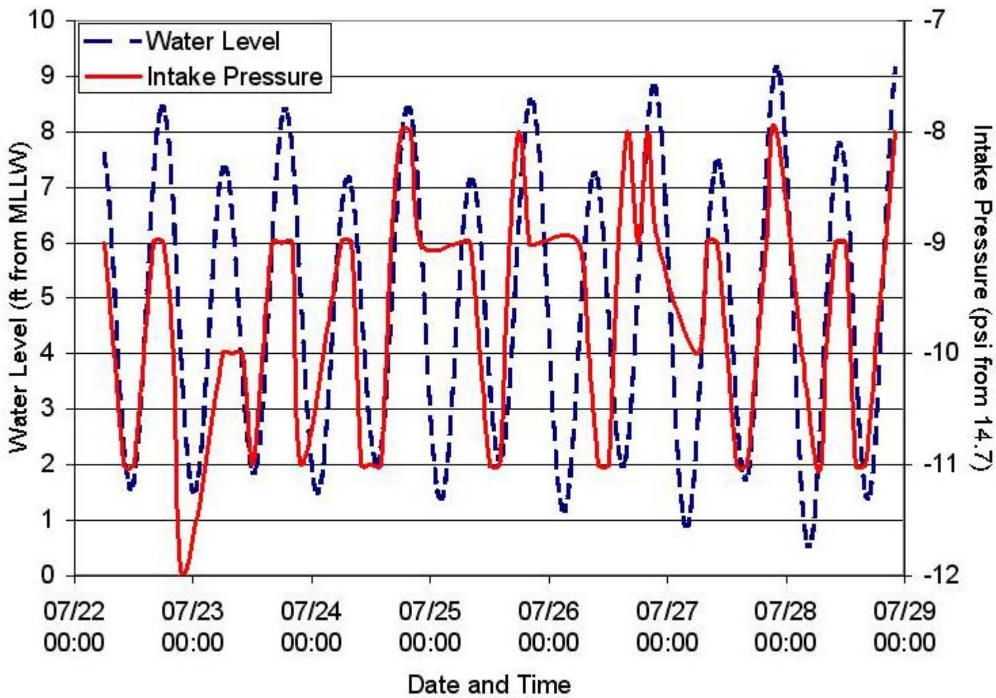

Figure 13. Tidal stage and bi-hourly intake pressure correlation.

Average daily flow rates remained substantially greater during the first week of measurement in 2007 than the maximum average daily flow rate of the entire 2006 data collection period. Although flow rates decreased substantially due to decreased saltwater demand after the first week of the 2007 measurement period, the early data strongly indicate increases of roughly 10 gpm in peak delivery capacity.

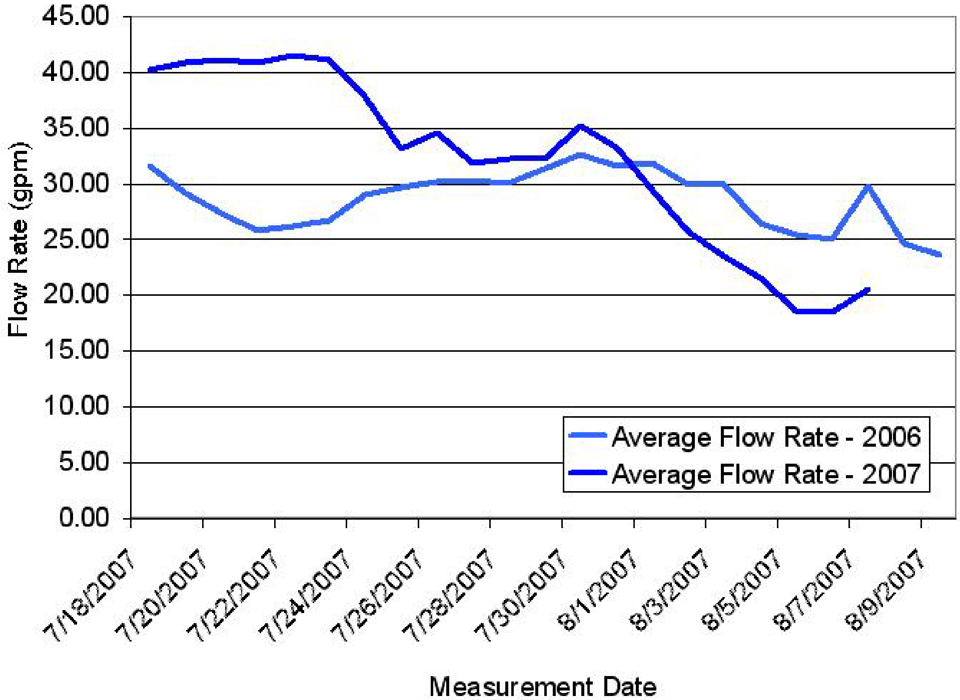

Figure 14. Average daily saltwater pump volumetric flow rates for 2006 and 2007.

Saltwater intake and discharge data are presented below in Figure 15, which shows saltwater losses to toilet and hose demand to be roughly one to four gallons per minute. These losses are within the expected range of toilet and hose demands, indicating a saltwater delivery system free of significant leakage, aside from a sea table leak noted on July 20th; the corresponding saltwater discharge data were discarded. Interestingly, and contrary to anticipated results, saltwater demand from campus toilets and hoses were greater on the morning of July 19th than during the afternoon of July 24th.

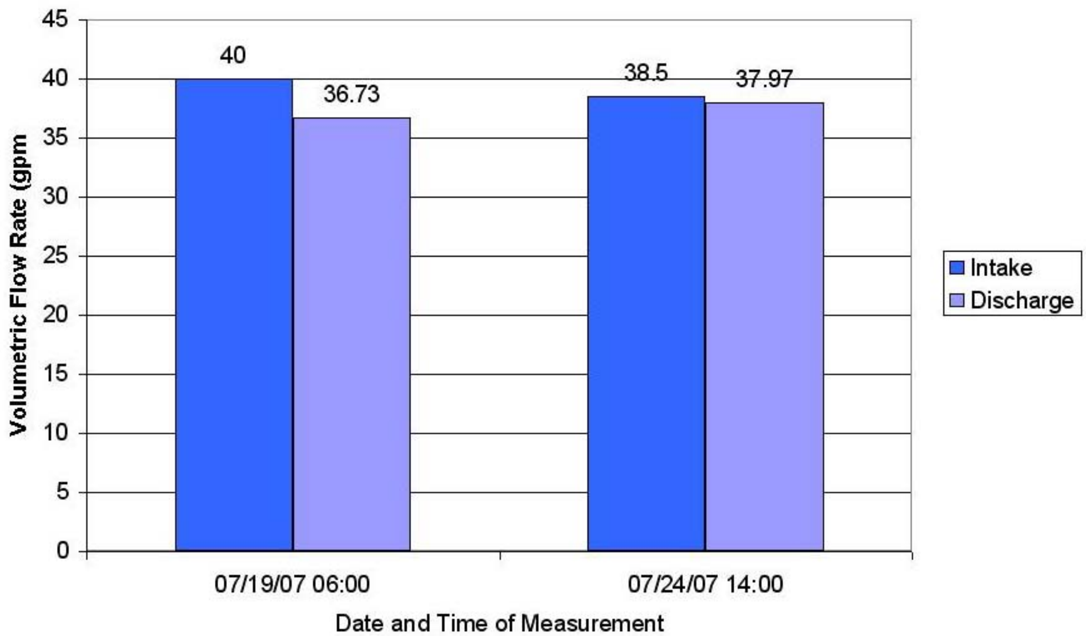

Figure 15. Intake and discharge flow rates for saltwater system continuity tests.

The saltwater intake pump is a Gould 3656 with a 6.25" impeller driven by a 7.5-HP electric motor. Saltwater intake pump performance data were compared with the factory pump curve to approximate the efficiency of the saltwater intake system and to determine the feasibility of adding additional saltwater sea tables without diminishing flow. The pump curve and experimental pump performance data indicate the potential for continued increases in flow rate with small decreases in total dynamic head, as shown by 2006 and 2007 maximum flow data presented below in Figure 16.

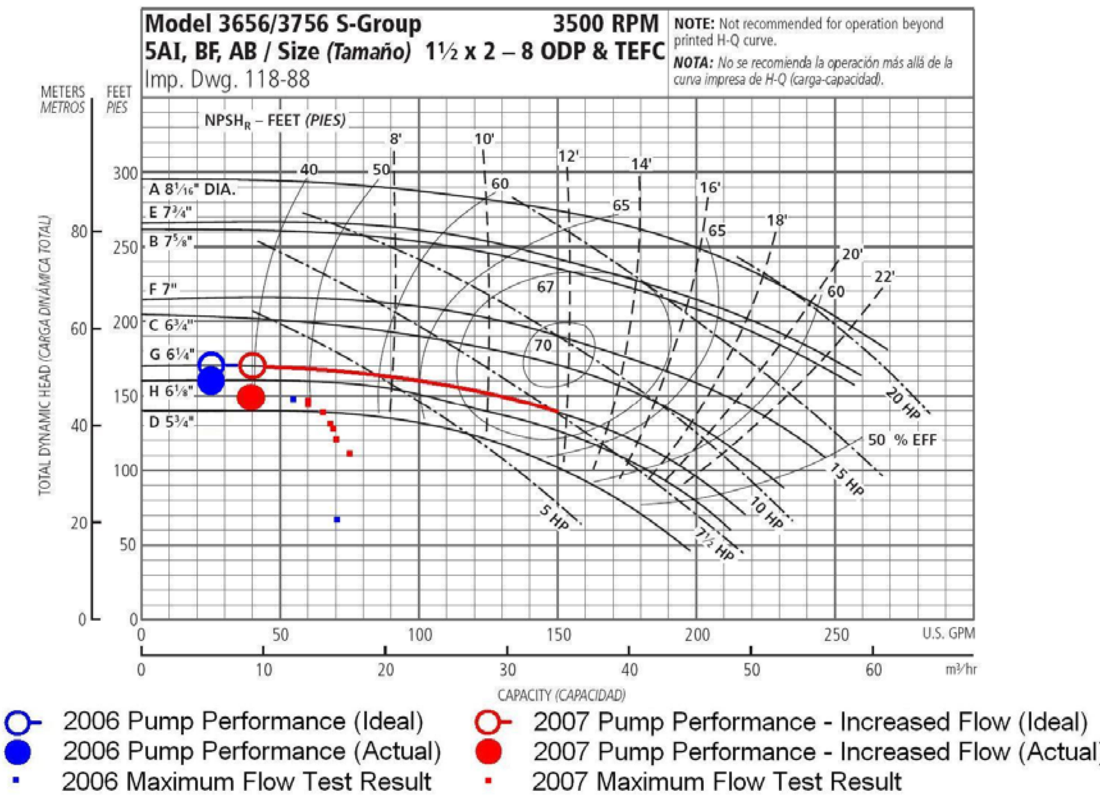

Figure 16. Saltwater intake pump manufacturer performance curve; modified to indicate ideal, typical, and maximum 2006 and 2007 pump performance. Adapted from pump curve available at http://www.goulds.com/pdf/36-3756S.pdf.

With normal operation of sea tables at Palmer-Kinne Lab, Laighton Hall, and Kiggins Commons and mid-day saltwater demand from campus toilets and hoses, saltwater flow rates typically ranged from 35 gpm to 45 gpm; this range of typical flow rates is noticeably greater than the range of typical flow rates from 2006 data. From the experimental data, it appears the addition of a second saltwater line from the intake pump to Kiggins Commons has allowed an increase in typical saltwater flow rate from approximately 29 gpm to 41 gpm with total dynamic head falling slightly from 163 ft to 145 ft. According to the factory pump curve, the increased flow rate has improved the pump efficiency from approximately 30% to roughly 40%.

The 2006 and 2007 maximum flow rate test results are imprecise because in both cases the flow meter operated above its calibrated range. However, 2007 maximum flow measurements were visually estimated during the test and point to maximum flow rates approaching 75 gpm. Total dynamic head calculations for the 2006 and 2007 maximum flow tests were approximately 69 ft and 111 ft, respectively. Together, these results confirm that the additional 2" saltwater line has significantly improved the saltwater delivery system's capacity to sustain increased flow.

RECOMMENDATIONS

Installation of additional saltwater tables at low elevations may further increase both the flow rate and the efficiency of the pump. Additional flow demands totaling approximately 15 gpm will be easily tolerated by the existing saltwater system. To ensure adequate flow at Palmer-Kinne Lab without requiring additional piping, it is recommended that total flow be maintained under 60 gpm and that all additional sea tables be installed at relatively low elevations, such as Laighton Hall and Kiggins Commons. Sea tables installed at Kiggins Commons were observed to have flow rates typically below 2 gpm, indicating the potential for at least five additional sea tables of similar size without diminishing flow to Palmer-Kinne Lab. If new sea table demand totals more than 15 gpm, especially at high elevations such as Palmer-Kinne Lab, an increase in delivery capacity is recommended. In this case, a third 2" parallel saltwater line between the intake pump and Kiggins Commons distribution point or the location of new sea table installation is recommended.

On July 19th, August 1st, and August 5th, the submerged saltwater intake required service. Blockage of the single saltwater intake causes widespread loss of saltwater specimens in sea tables, renders saltwater toilets inoperable, and greatly increases the risk of thermal damage to pump equipment. Divers are required during each cleaning and replacement, which may take several hours. To reduce saltwater system downtime and allow for increased repair time, a dual-intake arrangement is recommended for immediate transition from the restricted intake to a separate, parallel, and unrestricted intake of similar construction and location. Algal growth on the standby intake may be prevented using a positive-draft arrangement, as proposed on the conceptual schematic in Figure 17. Positive draft in the standby intake is accomplished by diverting a small fraction of pump discharge flow via a small-diameter pipe to the standby intake, upstream of the check valve.

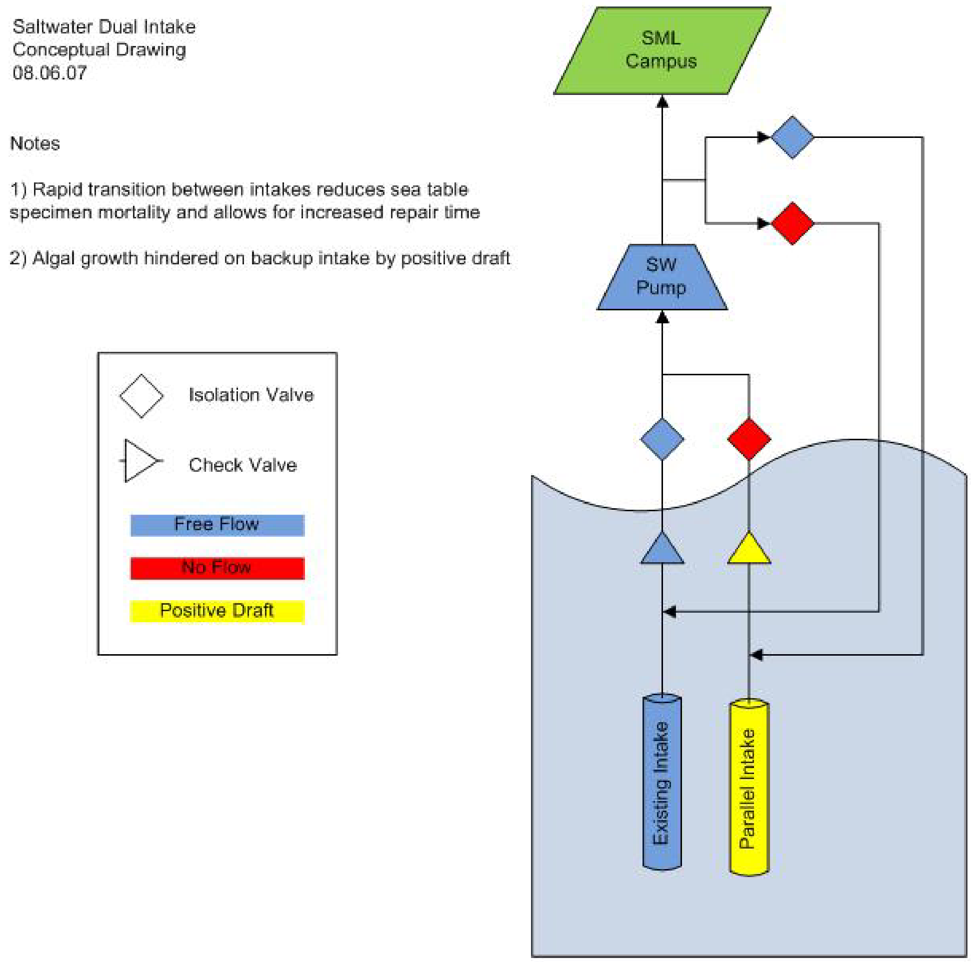

Figure 17. Saltwater dual intake conceptual design.

REVERSE OSMOSIS UNIT

BACKGROUND

A saltwater-fed Lifestream reverse osmosis (R/O) unit with a capacity of 8,000 gallons per day has been used since 1994 to produce freshwater at SML during periods of high demand and insufficient groundwater. The R/O unit is supplied by a one-horsepower electric saltwater intake pump separate from the SML campus saltwater delivery system. High-pressure filtered saltwater is applied to selectively-permeable membranes which block salt particles and allow freshwater molecules to pass. The resulting highly-purified water is then stored in a cistern for campus use.

OBJECTIVE

It is of interest to SML operators to determine the cost per gallon of freshwater produced with the reverse osmosis unit.

DATA COLLECTION

The R/O unit was not used in 2006 and required small repairs before restoration to full service on July 24th of this season; after seasonal start-up, the R/O unit was operated daily for several hours. Records of saltwater flow rate, freshwater flow rate, and operating hours, among many other performance data, were made by island engineers at each daily start-up and shut-down. These records were reviewed for average freshwater production rates from July 24th to August 7th.

The Lifestream reverse osmosis unit was donated by Cornell alumni and installed by volunteers; as such, the capital expenses associated with the purchase, transportation, installation of the unit were determined to be zero. For calculation of repair and routine maintenance expenses, records of business transactions between SML and Lifestream dating from 1994 to present were received in summary from Cornell University and Lifestream. The island operations manager provided estimates for seasonal start-up and shut-down expenses. Operating at typical production rates, electrical demands by the R/O unit were measured directly for one hour on August 1st using a power meter installed by Paul Krell of Unitil, a local utility company. Reverse osmosis unit operational records, a summary of business transactions, and power meter data are available in the Digital Appendix.

As electrical demands from campus increase with SML population throughout each season, a 30-kW diesel generator used during early weeks is retired and replaced with one of two 65-kW diesel generators. Generator performance data such as unit in service, power output, total daily energy production, and fuel consumption were recorded twice daily in operation logs. To better gauge fuel consumption, day tank levels were recorded in two-hour intervals from 6:00 AM until 10:00 PM daily from July 18th through August 7th and island engineers were asked to record time, start level, and finish level at each refill. Although generator operation logs dating back to 2001 were available, only records for the 2007 season were used to calculate fuel efficiencies of the three generators. Nighttime and daytime island population figures were recorded each day from July 18th to August 7th; portions of these data were used to examine per-capita electric consumption trends before and after seasonal start-up of the R/O unit. Generator performance data, fuel consumption measurements, island population records, and fuel cost records are available in the Digital Appendix.

CALCULATION METHODS

The cost per gallon of freshwater produced using a reverse osmosis unit is a function of the capital cost of the installed unit, expected lifespan of the machine, membrane replacement costs and service intervals, seasonal operation constraints, start-up and shut-down labor expenses, costs and frequencies of unplanned repairs, electrical inputs to the unit and its intake pump, and cost per unit of electricity.

The R/O unit purchase and installation were made possible by a generous donation from Cornell alumni and labor by volunteers; as such, capital cost of the installed R/O unit was determined to be zero to SML. Expected lifespan of the R/O unit was disregarded for the purposes of this calculation because the initial expense is effectively zero and makes no contribution to the unit cost of water produced over the life of the machine. Membrane replacement costs and all other non-seasonal repair and maintenance expenses were summed and divided by the number of years in service to calculate an average yearly expense for major or non-routine services. This figure was summed with the estimated costs of seasonal start-up and shut-down procedures to calculate an average annual maintenance and repair cost for the reverse osmosis unit.

Prior to installation of the power meter on August 1st, electrical demand by the R/O unit was estimated by determining from 2007 generator performance logs and island population records the average per-capita daily electric energy consumption before and after seasonal start-up of the R/O unit on July 24th. After start-up of the R/O unit, the figure for average per-capita electric demand without R/O unit operation was used with daily population data to determine an estimate for total daily electricity demand based solely on island population. For each day of the measurement period, this population-based estimate was subtracted from actual total electric energy production and then divided by the duration of service to arrive at an estimate of daily average electric demand by the R/O machine in units of kW. These figures varied widely from negative to unreasonably high power demand values; outlying results equal to or less than -20 kW and greater than 30 kW were discarded. Remaining estimates were used to estimate an average electric demand by the R/O machine in units of kW. Calculations were performed separately for each generator in service during R/O unit operation; this method is hereafter referred to as the "method of averages."

Generator operating costs associated with R/O unit operation are limited to fuel costs per kilowatt-hour; all other generator capital, maintenance, and repair expenses occurred and will continue to occur on an hourly basis, regardless of R/O unit service. This approach to generator operating cost calculation was discussed with the island operations manager. As such, average fuel efficiency figures in units of kWh/gal were calculated for each of the three generators from generator operating logs and fuel oil day tank refill records from 2007. The cost per gallon of fuel from a delivery on August 5th was used to calculate an average cost per kilowatt-hour delivered to the R/O unit with the aforementioned expense exemptions; this calculation was combined with estimated power consumption to approximate the fuel cost per hour of R/O unit operation.

To better gauge power consumption by the R/O unit, a power meter was installed from 11:17 AM to 12:17 PM on August 1st by Paul Krell from Unitil. A more direct calculation of the fuel cost per hour of R/O unit operation was achieved by the product of the generator fuel cost per kilowatt-hour and average power consumption measured directly on August 1st. This approach, hereafter referred to as the "power meter method," does not rely on averages of estimated R/O unit electric demand, which are subject on many levels to errors in measurement and recordkeeping.

The average yearly R/O unit maintenance and repair total outlined above must be treated as a base cost per season regardless of freshwater production. As such, the contribution of this base cost to the final cost per gallon of freshwater is reduced with each gallon produced during the season. Fuel cost per hour of R/O unit operation was coupled with the average freshwater production rate to determine a fuel cost per gallon of freshwater produced; this figure was calculated by the method of averages for each generator and by the power meter method for average generator performance. Summing the freshwater fuel cost per gallon with the production-dependent maintenance and repair contribution per gallon represents the estimated cost per gallon for a given freshwater production total.

RESULTS AND DISCUSSION

According to Cornell business records, maintenance and repair costs from the time of R/O unit purchase in May of 1994 to present total $19,785.95; new membranes were purchased in 2003 for an additional $8,439.45. According to a representative of Lifestream, seasonal membrane cleaning and storage amounts to roughly an additional $1,100 per year. Seasonal start-up and shut-down labor costs were estimated by the island operations manager at $600 per year.

Power demands from the R/O unit were estimated at approximately 29.0 kW and 11.4 kW by the method of averages for Generators 1 and 2 in service, respectively. The power meter directly measured average apparent power at 10.30 kVA and active power at 7.75 kW. At the time of power meter installation, the representative from Unitil explained that apparent power is a figure useful for sizing of generator capacity and that active power is the appropriate figure to use for power consumed directly by the R/O unit. Fuel cost estimates for the R/O unit according to each method of calculation are available in the Digital Appendix and presented below in Figure 18.

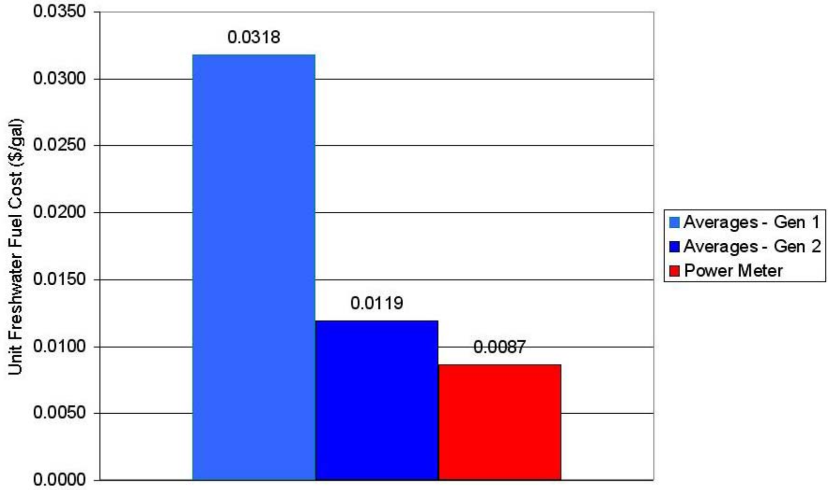

Figure 18. Estimated and calculated fuel cost per unit freshwater.

Using the method of averages, various population and generator usage anomalies caused the freshwater fuel cost per gallon to be significantly greater for Generator 1 than that calculated with Generator 2 in service. However, the estimated freshwater fuel cost with Generator 2 in service agrees well with the freshwater fuel cost derived from direct power measurement, as shown in the diagram.

The freshwater unit cost using each method of calculation decreases sharply during the first several thousand gallons of production, as shown below in Figure 19. For diagram clarity, the unit costs are presented after production of 5,000 gallons; the relatively enormous costs per gallon at production totals lower than 5,000 gallons require a graph scale inappropriate for closer inspection of long-term production costs.

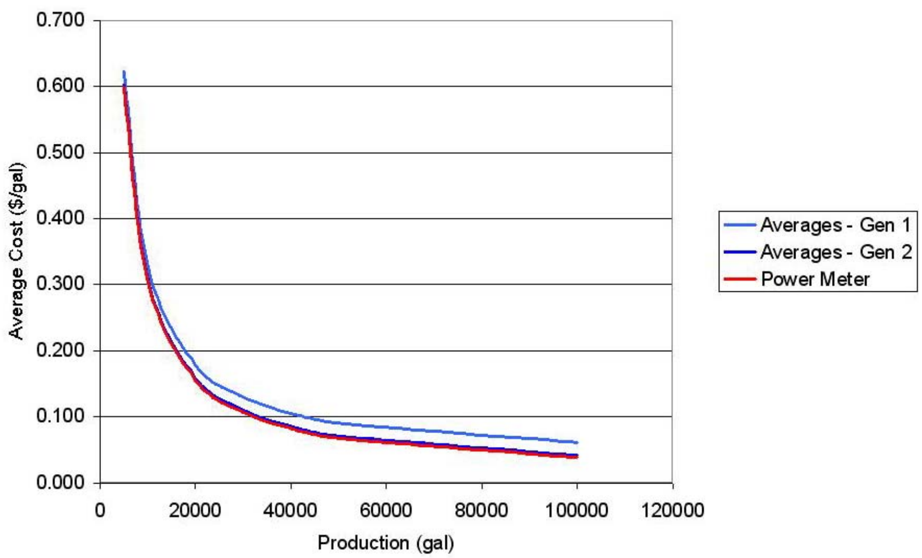

Figure 19. Freshwater unit cost versus total seasonal production.

On average, the R/O unit was operated for 6.44 hours per day at a rate of 4.45 gallons per minute for a total average production of roughly 1720 gallons per day. To better visualize the decreasing cost per gallon throughout a typical production season, freshwater unit costs calculated using the methods of averages and direct power measurement are presented below in Figure 20. As in the above diagram, the chart below depicts the rapidly decreasing unit cost of freshwater; again, unit costs calculated using the method of averages with Generator 2 in service agree well with unit costs calculated using direct power measurement.

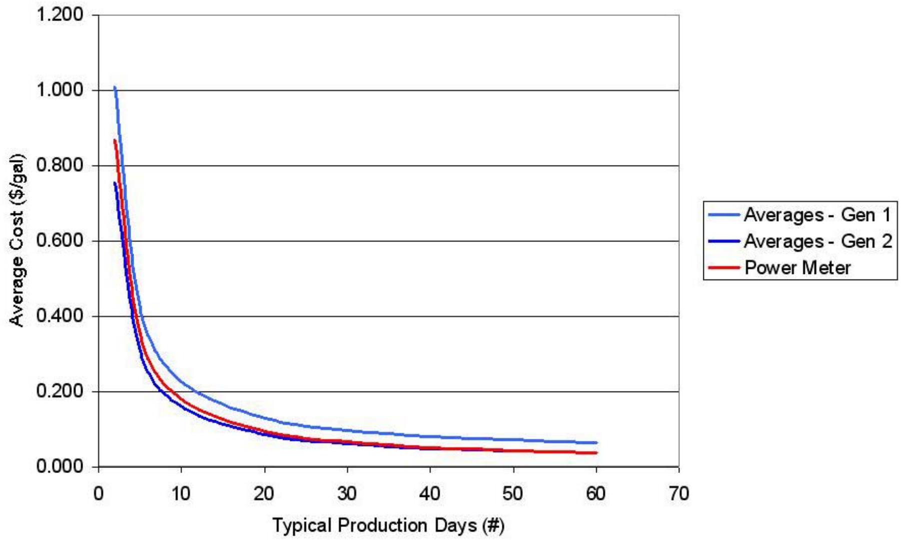

Figure 20. Freshwater unit cost versus total typical production days

A breakdown of annual maintenance, repair, and fuel costs for the average freshwater unit cost over seasons, defined as 15, 30, or 45 days of 6.44 operating hours per day, is shown below in Figure 21. This diagram indicates that non-routine maintenance, membrane replacement, and annual membrane services constitute the majority of costs per gallon throughout a typical season. It is uncertain as to whether SML or a donor purchases replacement membranes; for the purposes of the diagram, it is assumed that SML is the buyer, as indicated in Cornell business records with Lifestream.

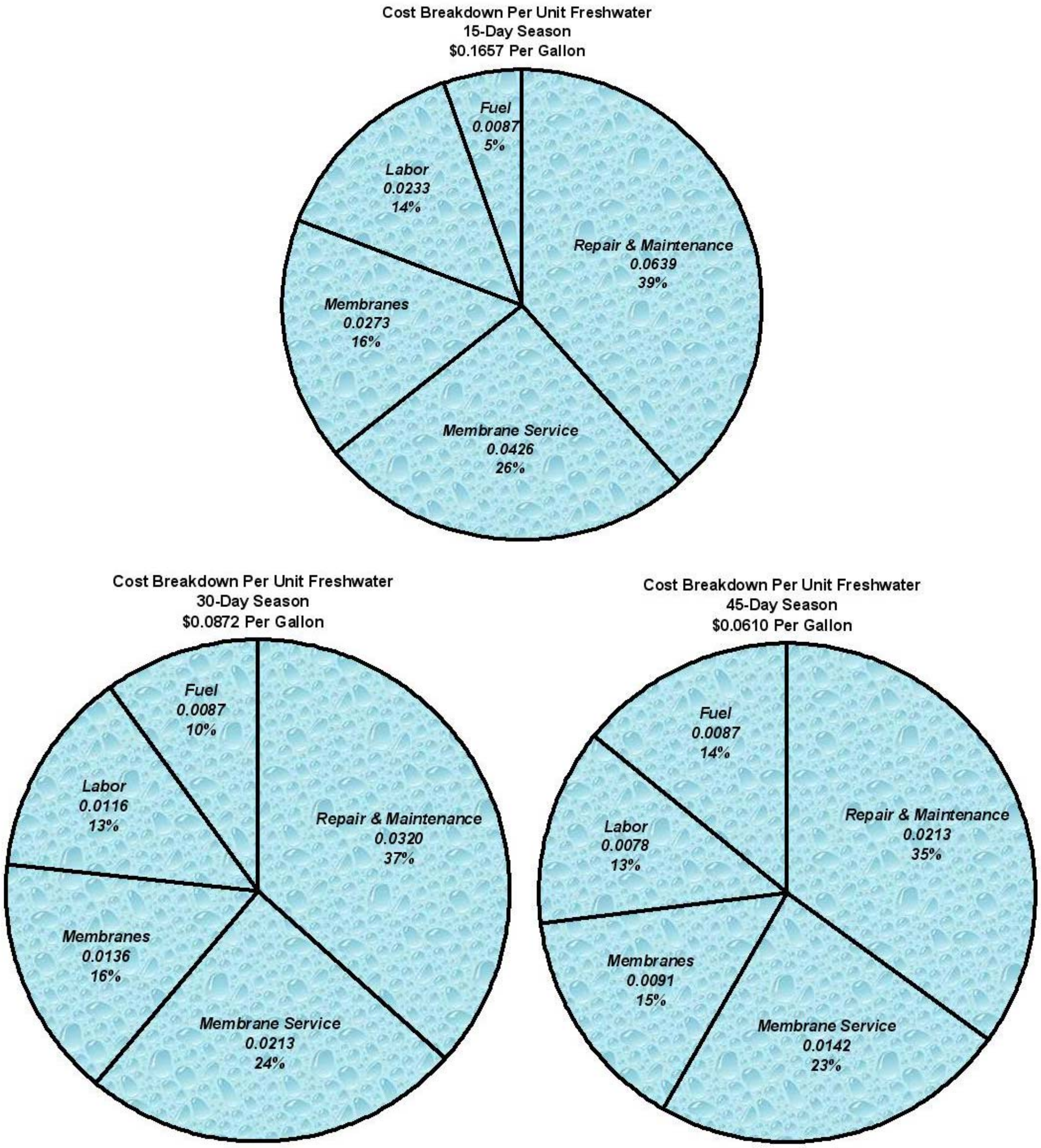

Figure 21. Freshwater unit cost breakdowns for 15-, 30-, and 45-day seasons

FRESHWATER SYSTEM

BACKGROUND

Freshwater at SML is sourced primarily from a 20-foot well under the influence of surface water and secondarily from a saltwater-fed reverse osmosis (R/O) unit during times of peak demand or reduced rainfall. A simple manually-monitored chlorination system treats all freshwater at SML; measurements of pH, temperature, turbidity, and chlorine levels are performed daily to verify compliance with State of Maine regulations.

Though chlorine levels throughout the freshwater delivery system tend to meet State of Maine requirements for safety, the existing chlorine injection system leads to unpleasant fluctuations of chlorine levels in drinking water at SML. These fluctuations negatively impact the taste and smell of the water, and unnecessary over-chlorination wastes money. At present, the island engineers manually adjust the speed and stroke of the chlorine pump when they notice excessively high or low chlorine levels; however, these changes can take up to a day to have an effect.

Jennifer Perry, a town engineer from Exeter, New Hampshire was consulted in the analysis of this system. This correspondence can be found in Appendix C.

OBJECTIVE

The objective is to examine the present condition of the chlorine injection system in order to explain and remedy the chlorine fluctuation problem.

SYSTEM OVERVIEW

In the freshwater system, the well and the R/O unit cannot be used simultaneously. When the well is in use, water flow is controlled by a float switch in the cistern. When the water level in the cistern becomes too low, the float switch activates the well pump, which draws water from the well. Simultaneously, the float switch activates the chlorine pump, which injects chlorine into the well water after it passes through the primary filter. The chlorinated water then travels through another filter outside the cistern shed before entering the cistern. The chlorinated water sits in the cistern until the pressure switch in the steel tank is activated by low water levels. The cistern pump then forces the water into the steel tank where it is eventually distributed throughout the system. This process provides the well water with a long contact time as well as additional mixing (through the second filter and the cistern pump) for thorough distribution of chlorine.

The R/O unit uses a completely different chlorination scheme. When the R/O unit is running, filtered water is poured at a constant rate into the cistern. The water waits there, un-chlorinated, until the pressure switch in the steel tank calls for more water. As the water travels between the cistern and the steel tank, chlorine is injected into the pipe. As the R/O water has a lower organic content than well water, it requires a lower contact time for disinfection. The diagram below illustrates the chlorination strategy for both water sources.

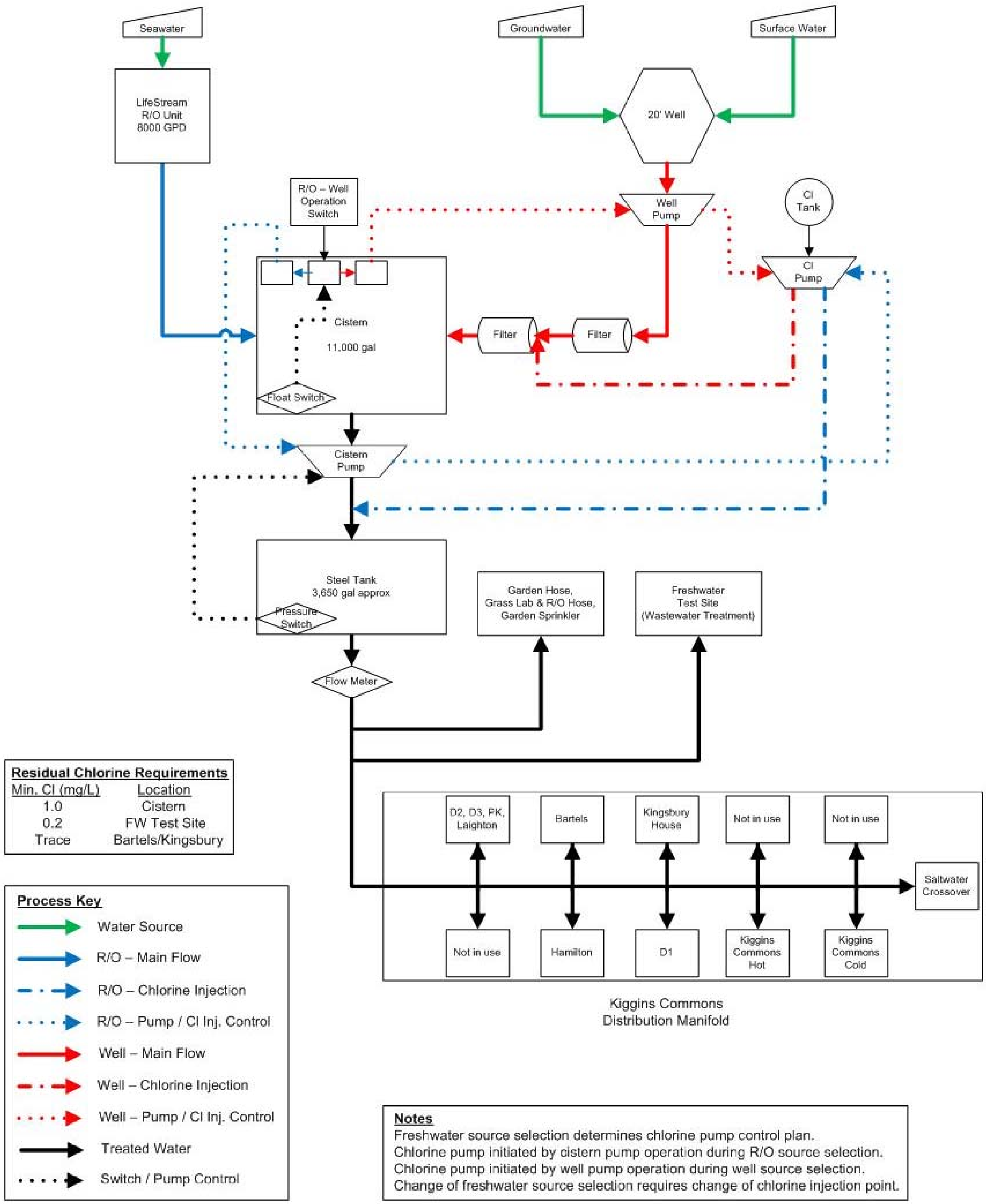

Figure 22. Freshwater system schematic.

DATA COLLECTION

Characterization of Chlorine Residual Fluctuations

Close monitoring of the freshwater system was necessary to determine the nature and cause of the chlorine level fluctuations. The pH, temperature, turbidity, and chlorine demand of the well water were measured twice daily from July 22nd to July 26th. The R/O water was measured once daily from July 27th to July 30th. The pH and temperature were measured with a Beckman pH/Temp meter and the turbidity was measured using an Orbeco-Hellige portable turbidimeter. See the Digital Appendix for full results.

The chlorine demand for the well water was measured by adding 0.25 mL of 6% Clorox (the same chlorine ordinarily used for disinfection) to 6L of un-chlorinated well water, which was obtained from the spigot over the cistern. The theoretical total chlorine concentration was calculated to be 2.5 ppm:

0.25 mL * 60,000 mg/L * (1L/1000 mL) = 15 mg Cl
15 mg / 6L = 2.5 mg/L = 2.5 ppm (for dilute aqueous solutions)

After ten minutes of contact time, the free chlorine of the water was measured using a HACH pocket colorimeter and a DPD free chlorine reagent. The free (or residual) chlorine is defined as the quantity of chlorine which has not reacted with organic materials and is, therefore, still available for disinfection. By contrast, the total chlorine includes both reacted and un-reacted chlorine in the water. Chlorine demand is defined as the difference between the total chlorine and the free chlorine. In order to meet Maine regulations, there must always be a chlorine residual in drinking water to ensure complete disinfection.

When calculating the chlorine demand of the R/O water, which was obtained directly from the cistern, the test was modified in order to directly measure the total concentration of chlorine after a total chlorine reagent was made available. Approximately 0.2 mL of chlorine was added to 6 L of water to ensure that the total concentration was about 2 ppm, below the 2.2 ppm upper detection limit of the instrument. The demand was calculated in the same way as for the well water, using the measured total concentration rather than the theoretical value.

Measuring the chlorine demand in this way presented several problems. Often, the total chlorine concentration as measured by the test equipment differed from the calculated concentration. The measured value was close to the calculated value only twice out of seven times in which the test was performed. It is unknown whether this discrepancy resulted from the inherent error associated with measuring such small quantities of chlorine or from inconsistencies in mixing the solution properly. Furthermore, when testing the R/O water, the free chlorine concentration reading was sometimes higher than the total chlorine concentration as measured by the colorimeter. Some of the inconsistencies fall within the tolerance of the colorimeter, which is 0.02 mg/L at 25°C.[2] Extending the contact time to 20 minutes sometimes improved the reading, indicating that the original contact time may have been insufficient for full neutralization. However, even with these corrections, the colorimeter results for the total concentration were not consistent. Therefore, all of the chlorine demand values are highly suspect and should be analyzed with this in mind.

A chlorine profile of the freshwater distribution system was conducted by measuring the residual chlorine concentration at the cistern, the wastewater plant, Kiggins, and Bartels on July 20th and July 25th. The wastewater plant measurements were taken to be indicative of the chlorine concentration in the steel tank. Therefore, there is some error associated with these measurements due to stagnant water in the pipe between the steel tank and the wastewater plant. The concentrations were then compared to Maine regulations. See the Digital Appendix for full results, including pH, turbidity, and temperature.

Water Quality Trends

A YSI 556 Handheld Multi-Probe Meter was used to gather detailed water quality data every five minutes from the well and the R/O unit. A short, preliminary investigation was conducted at the well from July 24th to July 27th. On July 27th, the meter was moved to the cistern to gather data on the R/O water quality. The results from this test indicated that the oxidation-reduction potential (ORP) of the well water fluctuated daily while all of the other parameters (dissolved oxygen, conductivity, pH, and temperature) remained constant. On the other hand, all of the parameters remained relatively constant for the R/O water. Therefore, the YSI meter was deployed in the well again from July 28th to August 3rd. It is important to note that the well was not in use during this second test and it rained on July 28th.

Pump Performance

On July 20th, extensive testing was performed on the LMI P151-392 chlorine pump. Using a graduated cylinder, the amount of chlorine injected at various speeds and strokes was measured. These results were compared to the manufacturing specifications of the pump. To determine the precision of the pump, every stroke was measured at 25 strokes/min for 4 minutes and at 50 strokes/min for 2 minutes. The amounts injected by these two tests for the same stroke should have been approximately the same.

The height of the well was also monitored every two hours from 8:00 AM to 8:00 PM on August 1st to August 3rd. As depicted in Figure 23, a string with a weight was used to monitor small variations. This data were used to determine any relationship between the height of the well, the tides, and the barometric pressure. The tidal data for Portland, ME, were obtained from NOAA and then corrected to more accurately reflect the tides at Gosport Harbor, which are 59 minutes ahead of the tides in Portland. The barometric pressure was obtained from the AIRMAP website.

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2 "HACH Pocket Colorimeter Analysis System Instruction Manual" <http://www.hach.com/fmmimghach?/CODE%3A4676088387%7C1>

A well water flow rate test was performed on July 20th and July 30th to determine whether the flow rate was constant. The well was not in use at the time the second test was completed. The flow rate was measured by timing how long it took to fill a 5-gallon bucket averaged over three trials. The pipe was opened at the end of the filter closest to the chlorine injection point.

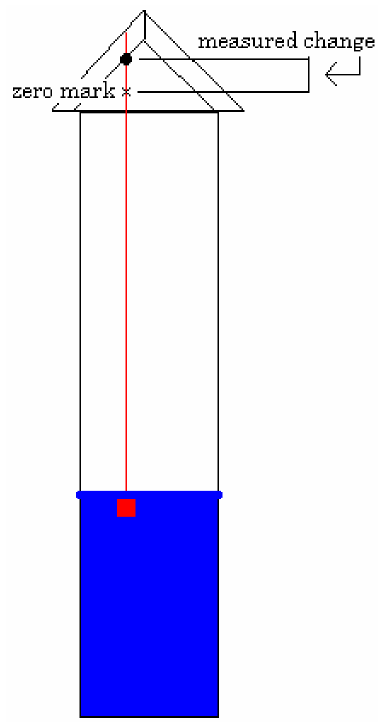

Figure 23. Well height test diagram. A weight tied to a string was used to measure small changes in the well height.

RESULTS AND DISCUSSION

Characterization of Chlorine Residual Fluctuations

Chlorine levels are affected by a wide number of variables including, but not limited to, contact time, flow rate, pH, temperature, and ORP. In turn, these variables are affected by water usage, the height of the well, and time since the last rainfall. It is clear from close observation that the chlorine levels are fluctuating due to some combination of these variables; however, it is difficult to pin down the exact cause.

Chlorine disinfects water by reacting with organics (such as bacteria) in the water, rendering them harmless. Well water has a higher organic concentration and therefore exhibits a higher chlorine demand. However, this demand can vary from 0.7 ppm to 1.4 ppm, making it difficult to predict. For comparison, the R/O water quality remains fairly constant, as expected considering the high-grade filters used in that process. As a result, the chlorine demand is much more consistent in the R/O water. Due to the problems in collecting chlorine demand data, the results of those tests were inconclusive and will not be discussed further. See Appendix C for results.

Contact time refers to the length of time the water is in contact with chlorine before entering the distribution system. The longer the contact time, the lower the organic content of the water will be as a result of disinfection. In addition, the chlorine disinfection rate is impacted by the temperature and pH of the water – a high temperature and a low pH will speed up the process. At SML, the well water has an average contact time of 600 minutes (a high estimate), which is well above the required 18 min by the State of Maine for 1 log inactivation of Giardia cysts in water with a pH of 6 and a temperature below 15 degrees Celsius.[3]

The actual contact time differs from this estimate of 600 minutes; it is regulated by the water usage rate. As seen in Figure 24, the residual chlorine concentration clearly follows the trends in water usage. As water usage increases, the contact time decreases between the chlorine injection point and the distribution system. Less time for disinfection causes the chlorine concentrations to remain high. Sharp spikes in water usage as groups arrive and depart make an especially significant impact on this trend.

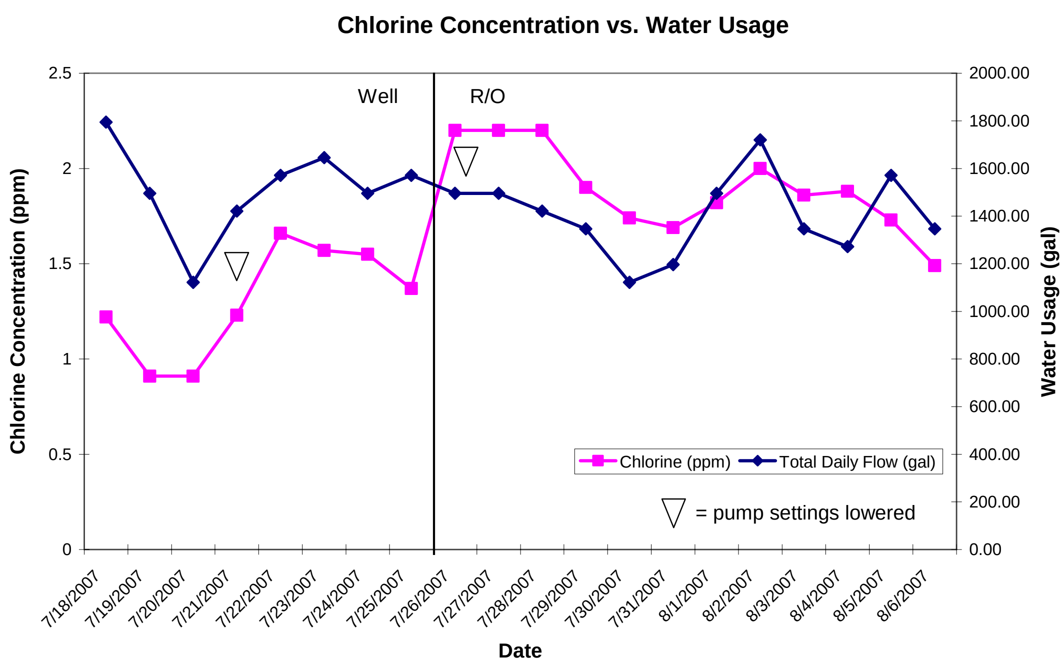

Figure 24. Chlorine concentration vs. daily water usage. The chlorine concentration follows the fluctuations of water usage, indicating that contact time is an especially important parameter to consider.

[3] "State of Maine Drinking Water Program: Contact Time Tables" <http://www.maine.gov/dhhs/eng/water/forms/rules/ct_tables.pdf>

Water usage is not the only parameter affecting the behavior of the chlorine residual fluctuations. The chlorine concentration is highest immediately after the transition to R/O water when the island engineers were still determining the proper chlorine dosage settings and clearing the system of well water. Since the colorimeter was not calibrated to measure concentrations above 2.2ppm, it is unclear what the exact chlorine concentration was at that time. The island engineers also occasionally adjust the chlorine pump settings if there is a spike or dip in concentration. Depending on the situation, this would amplify or diminish the impact of water usage, with up to a day of lag time. In Figure 24, the triangles symbolize instances when the island engineers noted lowering the pump settings. In the first instance, there was a delay of one day, but the lower water usage trend was amplified. In the second instance, the data are difficult to analyze since the chlorine concentration was at the maximum of the colorimeter. However, it does appear to have diminished the effect of spikes in water usage. This change in response behavior can be attributed to the R/O unit requiring a lower contact time in general and therefore being less affected by changes in water usage.

Table 1. Chlorine Residual Profile

Location	7/20 Test	7/25 Test	Maine Regulation
Cistern	0.78	1.69	1
Wastewater Plant	0.81	1.54	
Kiggins	0.08	0.62	0.2
Bartels	0.05	0.11	trace

Since the chlorine levels decrease as contact time increases, it makes sense to expect that the chlorine levels decrease depending on how far the water is distributed. Therefore, there are mandated levels of chlorine residual that must be met at certain points in the system. This summer, two chlorine profiles were conducted five days apart to determine if those regulations were being met (Table 1). On July 20th, the chlorine levels were slightly low and the wastewater plant chlorine residual was higher than the cistern. This can be attributed to an error by the colorimeter, which has a tolerance of 0.02ppm. While the drop between the wastewater plant and Kiggins is reasonable, it is unusual to have such a low drop between the cistern and the wastewater plant, considering the long contact time.[4] As the freshwater consumption increases, the water also sits in the pipes for shorter periods of time. While this has little effect on the safety of the water, it may contribute to the chlorine fluctuations noticed in different parts of the island, especially in Kiggins.

Water Quality Trends

The data from the YSI meter show an unusual trend. As seen in Figure 25, while the temperature (11 degrees Celsius), pH (5), conductivity (0.2 mS/cm), and dissolved oxygen (0.5 mg/L) levels of the well water remained constant, the ORP fluctuated wildly. Oxidation-reduction potential is, most broadly, a measurement of the water disinfection potential. A

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[4] "Modeling Chlorine Dissipation in Distribution Systems" University of Central Florida. <http://www.research.cecs.ucf.edu/drinkingWater/Students/Arevalo/Modeling_chlorine_dissipation_in_DS_Jorge_Arevalo_ACE04.pdf>

positive ORP indicates a tendency towards oxidation, chemical reactions that involve losing electrons, while a negative ORP indicates the opposite. ORP can be measured within an accuracy of +/- 25 mV. With a minimum of -170 mV, maximum of 189 mV, and average daily fluctuation of 130 mV, these results cannot be purely due to instrument error. The ORP values present in the SML well lie in the no-man's land between ionized water (below -200 mV) and ordinary tap water (above 200 mV). The addition of chlorine to water is an oxidation-reduction (redox) reaction so ORP is usually used to determine the effectiveness of chlorine that has already been added to the water. In swimming pool and spa applications, it is considered to be a better measurement than chlorine concentration because it accounts for the effect of changes in pH on the chlorine levels. Therefore, it is unexpected to see these sorts of fluctuations before any chlorine has been added.

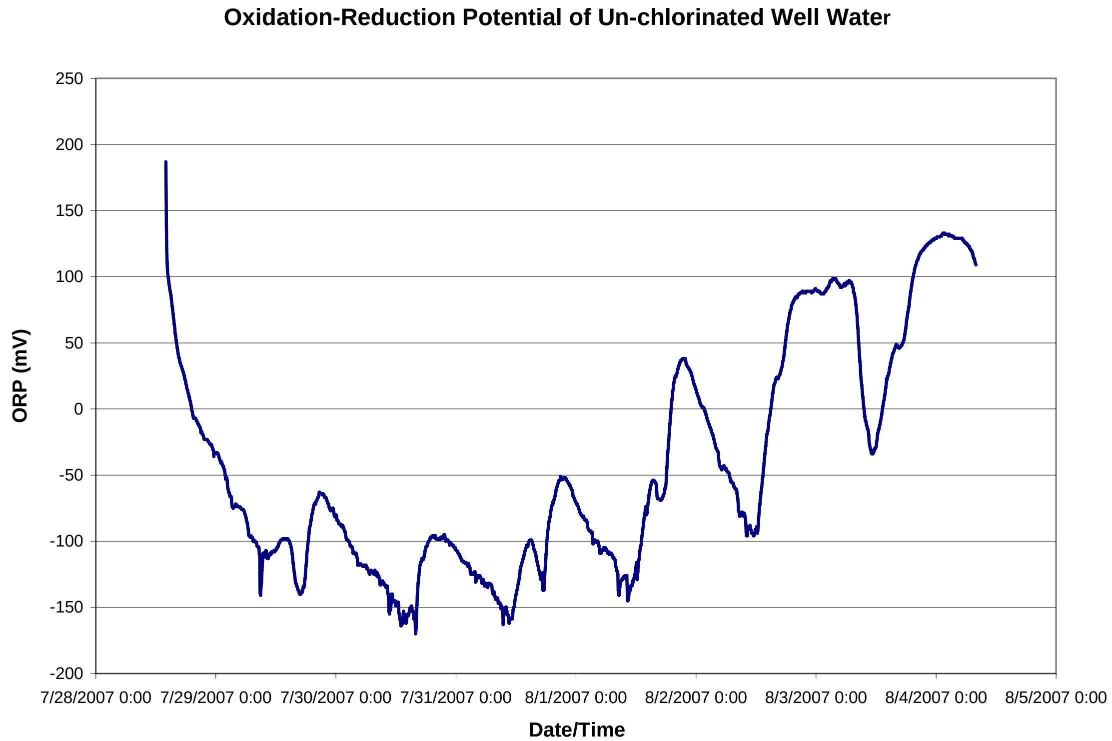

Figure 25. Oxidation-reduction potential (ORP) of un-chlorinated well water. The well was not in use when this sample was taken. The water had a pH of 5 and was 11 degrees Celsius. The peak in the beginning of the data can be attributed to calibration.

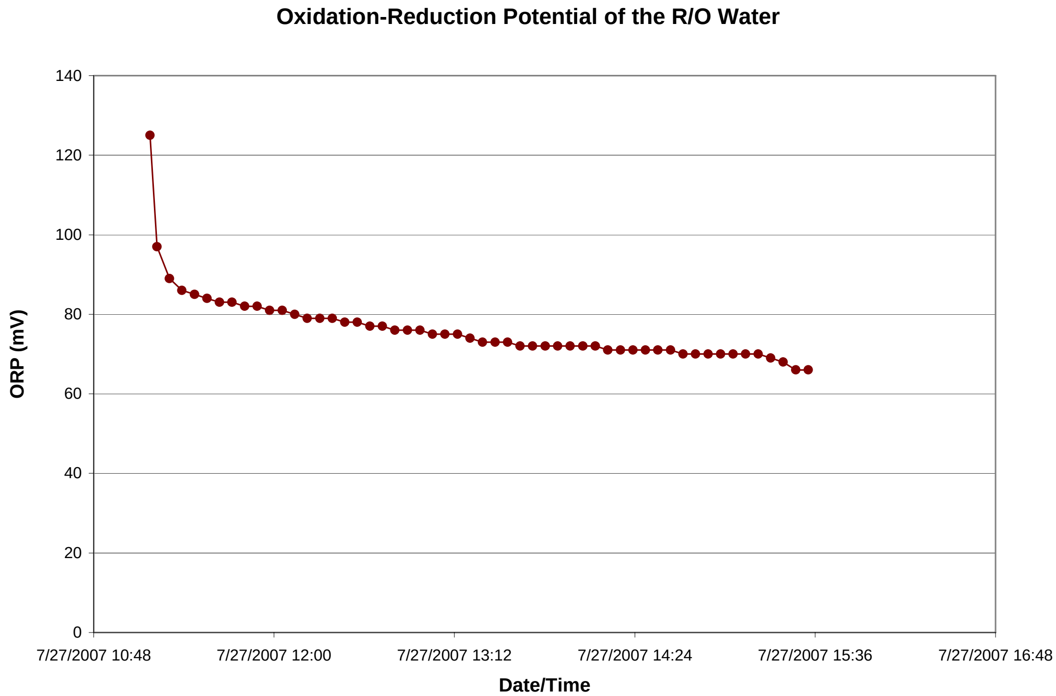

Figure 26. Oxidation-reduction potential of the R/O water. In contrast to the well water, the ORP of the R/O water is relatively constant. The initial spike is due to calibration errors.

In contrast to the well water data, the R/O water data exhibit a relatively constant ORP (Figure 26). The initial spike is due to calibration errors as the probe adjusts to the new test. While the ORP value does degrade slightly over time, it is within the error of the measurement. Due to this sort of behavior, ORP is usually interpreted in ranges, rather than point values.[5]

Many possibilities were considered in attempting to determine the cause of the well water ORP fluctuation. Since it occurs in a daily cycle, one theory was that algae were growing in the well. However, this was disproved by the fact that the dissolved oxygen remains constant. Another theory was that the SML well was exhibiting artesian behavior and the tides were regulating the fluctuation. In artesian wells, the height of the water changes according to the tides and barometric pressure. It was hypothesized that a fluctuating well height could impact contaminant levels. However, as displayed in Figure 27, any correlations between the ORP and the tides appear to be coincidental since both have diurnal cycles. Further possibilities that were not tested include specific contaminants such as ammonia or nitrite. If such contaminants exist, their fluctuation over the course of a day could cause ORP and chlorine levels to fluctuate as well.[6]

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[5] "Understanding Oxidation Reduction Potential (ORP) Systems" by Lori McPherson Walchem. Corporation *Association of Water Technologies Analyst Magazine* <http://www.awt.org/members/publications/analyst/2002/spring/orp.htm>

[6] "Automated Chlorination Control System – The Orlando Eagle Eye" by Roy A Pelletier and David S. Sloan. *Florida Water Resources Journal, June 2000*. <http://www.fwrj.com/articles3/0006.pdf>

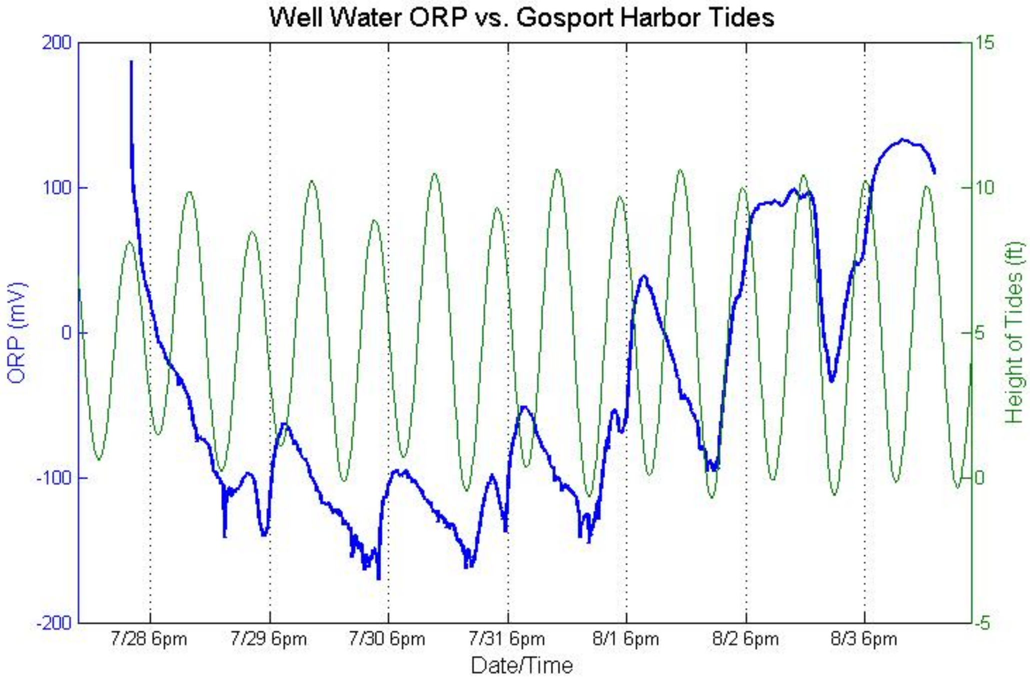

Figure 27. Well water ORP vs. Gosport Harbor tides. The ORP fluctuation is not regulated by the tides, despite the fact that both operate on a diurnal cycle.

Pump Performance

Currently, the island engineers are forced to adjust the chlorine pump speed and stroke manually as they notice the residual chlorine levels fluctuate. Since there is some delay in the system, it can take up to a day for these changes to take effect. However, since the chlorine pump is running at the bottom 30% its operating range, there is not much room for adjustment. After extensive testing, it is clear that the chlorine pump is not performing properly. While speed settings function according to specifications, the stroke settings are doubly problematic. The range of stroke sizes on the current SML pump only corresponds to the 60-90% range of a properly-functioning pump. In addition, the observed stroke volume does not correspond to the manufacturer's specifications at any stroke settings (Figure 28). This issue probably amplifies the effect of other important variables such as water usage. When water usage increases, the chlorine pump operates more frequently and over-chlorinates the water.

Having established that the chlorine pump was operating poorly, the only other pump that could impact the chlorine concentrations was the well pump. In order to test for artesian behavior, the well height was monitored for several days while the well was not in use. While no correlations were made to the tides or barometric pressure, a fluctuating well height could change the total head on the well pump and impact the flow rate. It is well known that the height of the well does change significantly over the course of a season. The best way to test this theory would be to install a flow meter and monitor the flow rate over the course of a season in order to correlate it with well height.

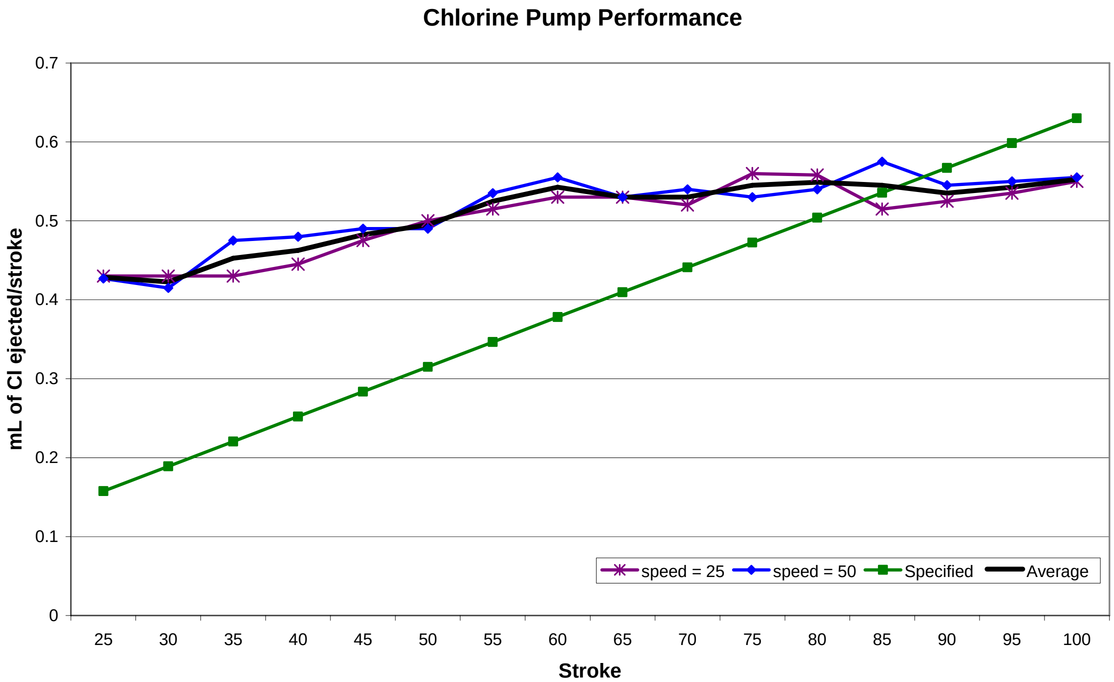

Figure 28. Chlorine pump performance.

Two flow rate tests were conducted to determine the consistency of the well pump output. Each test consisted of three trials to calculate the average gallons/minute. As described in Table 2, there was a significant difference in the flow rate between the two tests. While the well was not in use during the second test, this should not have impacted the flow rate. In addition, the well height was approximately equal at about 12.5 ft between the two tests. This preliminary data suggest that the well pump output is not constant. However, more extensive testing should be conducted to determine the extent of the fluctuations.

Table 2. Average Flow Rate of Well Pump

Date	Avg. Flow of 3 Trials (gal/min)
7/20/07	4.3
7/30/07	5.3

RECOMMENDATIONS

The well system and the R/O system are essentially two freshwater systems in parallel. This configuration complicates the implementation of a solution that can be easily applied to both systems.

The first step—and in some ways the most important one—is to purchase a new chlorine pump. The pump is currently being operated on its lowest settings, especially when the R/O unit is in use. This is clearly not because the pump is oversized but because it is operating inefficiently. The pump is approximately six years old while the typical warranty only lasts for 2 years. It would be best to purchase a new pump that has a digital input for potentially shifting to automated control. LMI's B71 pump is an industry standard with both manual and digital inputs to control the stroke rate. (See Appendix C for specifications sheet.)

The best option for responding to the fluctuating chlorine demand is to purchase and install an automated chlorine analyzer/controller. This would require little effort to maintain constant chlorine residual concentrations and save chlorine by preventing over-chlorination. However, these controllers can be expensive and would be difficult to implement across both systems. Therefore, it would be best for a controller to only regulate the well water, which has more frequent chlorine demand fluctuations. At present, all available chlorine controllers are based on one of three parameters: chlorine concentration, ORP, or water flow rate. Both concentration and ORP controllers would be able to react most directly to fluctuations in chlorine demand; however these controllers would require the installation of a recirculation system. The easiest system to implement here would be a proportional flow controller, which adjusts the chlorine injection rate according to the water flow. As the data show, there is some change in the water flow rate, although the full extent of the fluctuations has not been properly documented. It would be best to install a flow meter to record these fluctuations the next time the well is in use. Research indicates that a Seametrics MJE-Series controller would be a good choice and is compatible with LMI pumps (see Appendix C for resources). The MJE-Series controller injects a certain number of strokes per a certain number of gallons. This meter provides the bare minimum of features, but would serve the island's purpose far better than the more complicated controllers on the market.

SOLAR POWER SYSTEM

BACKGROUND

A number of Mobil Solar Energy Corporation 285-Watt photovoltaic (PV) panels were donated to SML by Cornell trustee emeritus Dick Aubrecht '66, Ph.D. '70. Eight were to be installed on the roof of Dorm 3 during SML's 2007 operating season, with plans to evaluate their effectiveness in powering Dorm 3 and the UNH AIRMAP equipment in conjunction with the wind turbine. The installation began on July 23th, 2007, and final wiring was completed on July 24th. In the first week of August 2007 it was decided to bring eight more PV panels of the same type to SML for installation in the fall of 2007 or spring of 2008. Information was requested regarding the installation of these panels and their integration into the current system.

OBJECTIVE

As of July 2007, Appledore Island's renewable energy system was still not thoroughly tested or understood. The addition of Dorm 3's PV array prompted a push to evaluate both the performance of the PV and of the system as a whole. Detailed observations of the solar array's power output were to be performed by the engineering interns. Special attention was given to the problem of gull pucky accumulation on the panels, and how this accumulation might affect output. Proper performance of the battery-charging system was also thoroughly investigated to protect the reliability and longevity of the large battery bank that the system depends on during periods of low sun and/or wind resources.

SYSTEM OVERVIEW

Eight PV panels were installed on the roof of Dorm 3 in two rows of four panels each. The array was wired to consist of four strings, each with two panels. A string of two panels in series has an open-circuit voltage (V_{oc}) of 106 V, which falls within the allowable voltage range for the OutBack MX60 charge controller. The strings were wired to each other in parallel to increase the output of the array while keeping voltage the same. Two weatherproof rooftop fuse boxes were used to combine the strings into the parallel configuration. The consolidated roof wiring was routed through a 1" PVC conduit down off the roof and into a DC disconnect box on the outside wall of the building. From this DC disconnect box the electricity flows to the bottom floor of the radar tower, where it is routed through an OutBack Power Systems MX60 charge controller. The MX60 steps the array voltage down to charge the 48-V battery bank. The battery bank consists of twelve GNB Absolyte IIP lead acid batteries. Each battery consists of six 2-V cells in series to produce 12 V nominally. The 12-V batteries are connected in strings of four to produce 48 V, the desired battery bank voltage. Three such strings are connected in parallel to increase battery capacity without changing the bank voltage. The total capacity of the battery bank is 1824 Ah or 88 kWh. Figure 29 shows the PV system in its current configuration.

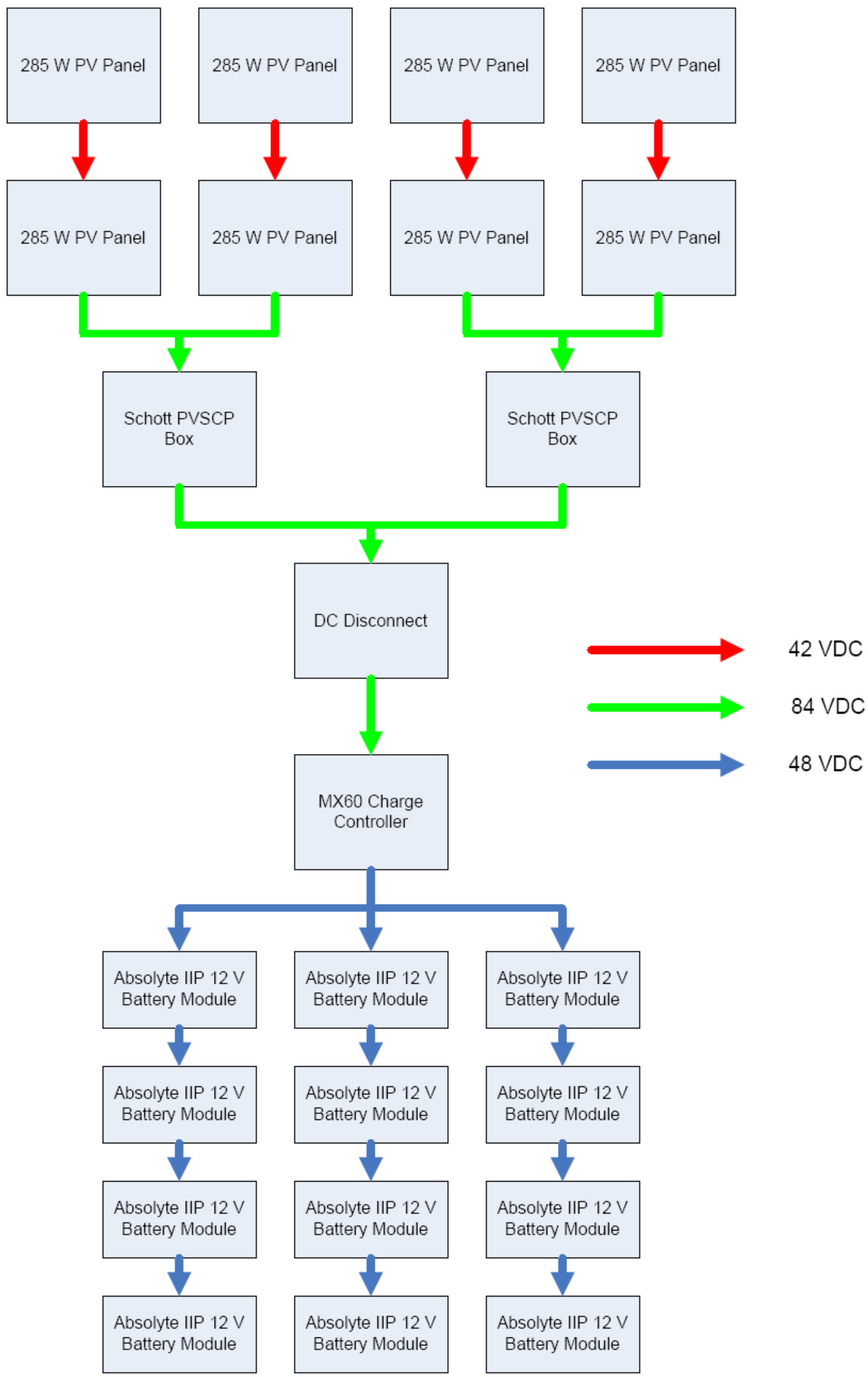

Figure 29. PV system configuration.

DATA COLLECTION

Once the array was installed and operational, data collection began in two-hour intervals from 8:00 AM to 6:00 PM. Light conditions on the roof were measured with a Watt Stopper FX-200 Illuminometer. This meter measures light levels in lux, which is not an immediately useful unit because PV cells are rated using the light density unit W/m^2. However, it was still possible to compare general light levels over the course of a day and from one day to the next. The temperature of the panels was measured using a Fluke 179 digital multimeter with a thermocouple attachment. The thermocouple was placed against the bottom of the array's upper right panel to measure the temperature. It was assumed that the temperatures of the other panels were similar. After the temperature and light conditions were measured, the power output of the panels was recorded. These data were found on the digital readout of the MX60 charge controller. PV voltage, PV current, battery voltage, battery charge current, PV wattage, and kilowatt-hours were recorded. General weather conditions were also noted. Total kWh production and peak wattage were recorded at the end of each day, also from the MX60 readout. Data were recorded in this manner from July 24th through August 1st. For August 1st and later, the power output data were collected every minute and uploaded onto the internet automatically using AIRMAP monitoring equipment, where it could be subsequently downloaded and analyzed. The online feed, labeled "Turbine Data" on AIRMAP's website, consists of all the data that can be logged from the MX60 charge controller as well as the three OutBack FX3048T inverters. These data include most of the parameters recorded manually as described above, plus several additional parameters that give additional insight to the operation of the PV system. Due to technical difficulties, the solar data that "Turbine Data" provides is available only from August 1st, 2007 to the present.

To supplement the manual and automated PV measurements, AIRMAP's pyranometer data were also collected. The pyranometer data provide radiation measurements for Appledore Island once every minute of the day, and they are available for every day that the solar array was functioning. These measurements are given in W/m^2 instead of lux, so they are not directly comparable with the previous manual measurements. However, they are very useful for finding average values of sunlight each day and for studying the effect of sunlight intensity on PV array output. The pyranometer is located on top of the radar tower and is mounted horizontally. As such, its measurements do not perfectly represent the conditions at the PV array, which rests on the south-facing pitch of Dorm 3's roof. Nonetheless, the relationship between sunlight intensity and PV output was clearly documented (Figure 30).

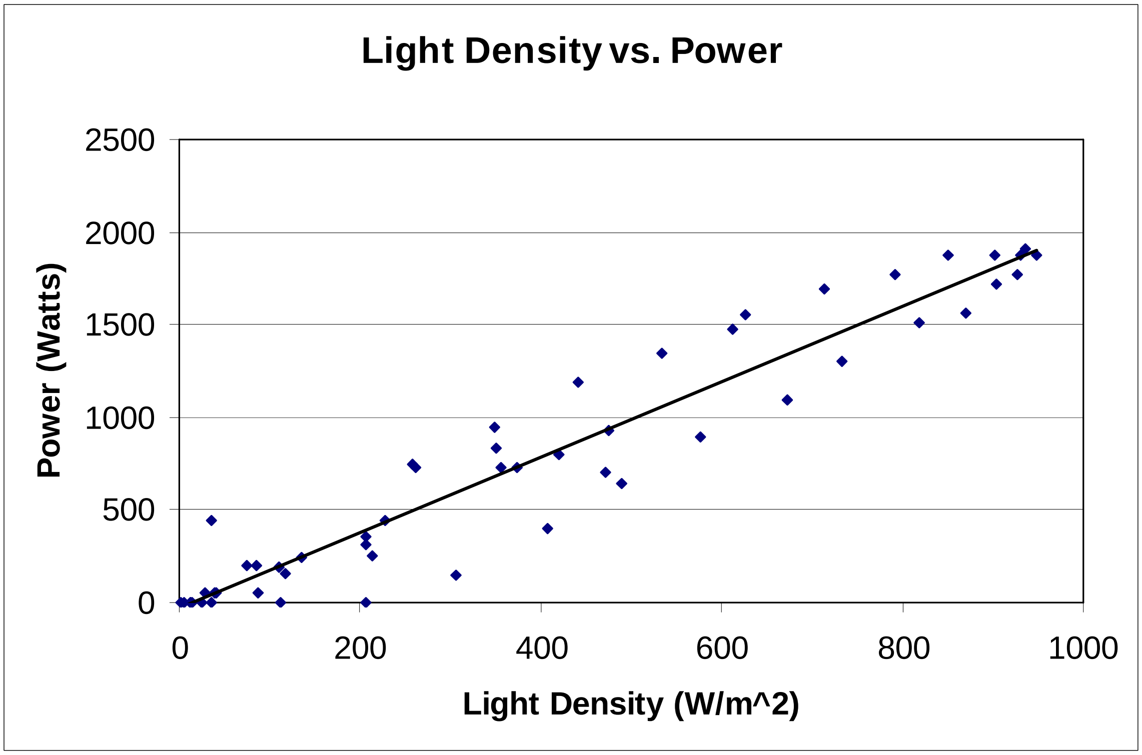

Figure 30. Sunlight intensity vs. PV output.

One of the principle obstacles to effective solar power on Appledore Island is the risk that gull pucky can accumulate on PV panels and reduce their output. It was unknown how severe this problem would be, but it became a priority in the interns' PV work. During the first three days of data collection, there were no gull countermeasures installed. Gull pucky was cleaned from the panels before each reading in order to obtain good baseline data. If a power reading was taken with some gull pucky left on the panels (overnight accumulation, for example), the panels were cleaned and the output re-measured immediately afterwards as a comparison to the dirty panels. On the morning of July 27th, fishing line was strung around and over the solar array at a height of one foot to act as a gull deterrent. This allowed the interns to reduce the frequency of panel cleanings. Beginning on the evening of July 28, the interns ceased cleaning the solar panels altogether. Gull pucky was allowed to accumulate for one full week to evaluate the effectiveness of the gull deterrent over a more reasonable time period between cleanings. At the end of the week, the PV output was measured with the week's accumulation of pucky . The panels were then cleaned and the output re-measured.

RESULTS AND DISCUSSION

The interns collected much useful data on the operation and output of the PV array. Between roughly 10:00 AM and 2:00 PM on a sunny day, the array regularly produced 1700 W to 1900 W. Output peaked at over 2000 W for brief periods. In less ideal weather, output was mixed. The array could still produce more than 1000 W on a foggy day if the sun was partly burning through the clouds. Output was limited to less than 1000 W in very foggy or cloudy conditions, but the array could still produce hundreds of watts for much of the day. Output was never less than 100 W except in the early morning or late evening, or during extremely bad weather. In terms of total power produced, sunny weather regularly resulted in more than 13 kWh generated in a day. The highest recorded measurement was 15.2 kWh per day, while the lowest recorded was 5.9 kWh. The average total output for the measurement period (about a week and a half) was about 12.5 kWh per day, though in a cloudy week the average output could conceivably be less than 10 kWh per day. See Figure 31 for power output profiles on a sunny and cloudy day.

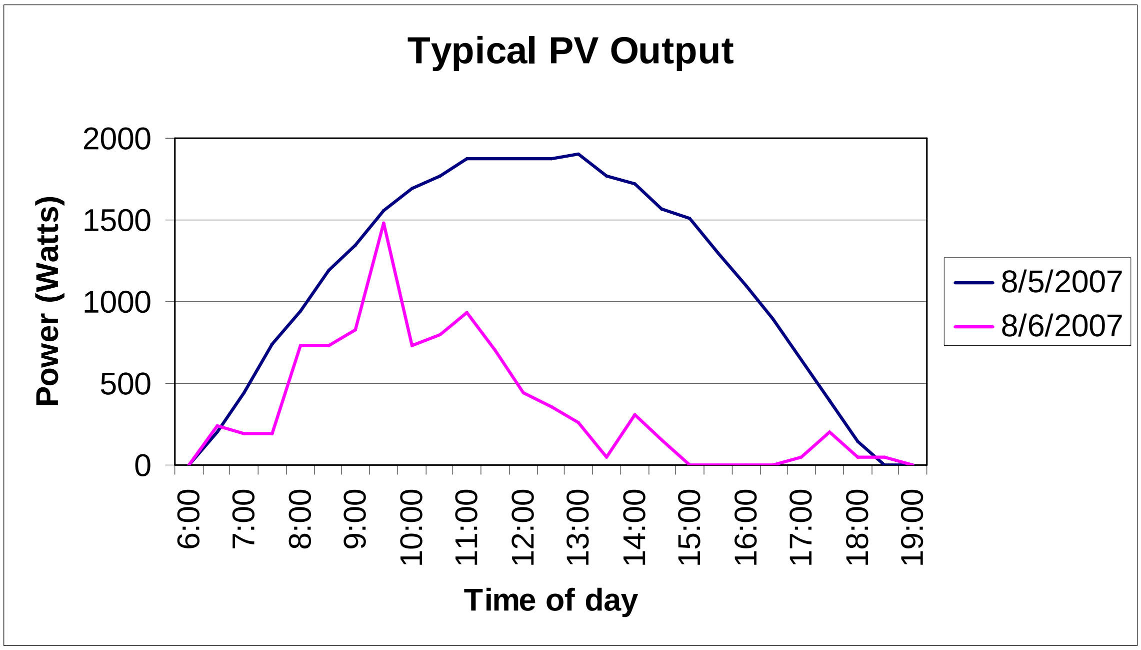

Figure 31. Output Profiles: 8/5/2007 was sunny while 8/6/2007 was cloudy.

On August 5 the array produced 15.2 kWh. On August 6 only 5.9 kWh were produced.

The effect of gull pucky accumulation on the PV array's output was a major concern for the interns, but reliable data in this area were difficult to obtain. Before the gull deterrent was installed, the effect of overnight pucky accumulation was measured twice. In both cases, the array produced approximately 150 more watts after the pucky was cleaned from all eight panels. However, since these results were obtained around 8:00 AM on sunny days, it is likely that light intensity was steadily increasing during the "before and after" measurements. Luminosity measurements with the FX-200 confirmed this suspicion. As a result, it is unclear how much of an affect the pucky was having on panel output.

After the first week of letting gull pucky accumulate with the fishing line deterrent installed, the interns noted that a relatively small amount of pucky was present despite the long period without cleaning the panels. A similar test as the one described above was performed in the early afternoon, a time when the solar energy available should be relatively strong and constant. After the panels were cleaned, they produced approximately 50 more watts total. However, the reading on the MX60 (where these data were obtained) was fluctuating considerably at the time of recording, showing a lower output as often as a higher one. Also, AIRMAP pyranometer data show an increase in light density from 825.32 W/m^2 when the panels were dirty to 847.43 W/m^2 after the panels were cleaned. These factors introduced enough uncertainty into the test that it was considered inconclusive by the interns. While more data would be desirable as far as gull pucky is concerned, the lack of a convincing trend either way indicates that the issue is probably not as serious as originally thought. With the gull deterrent installed, weekly or even bi-weekly cleanings are probably sufficient to maintain adequate PV output.

There was one incident of a gull becoming entangled in the fishing line of the gull deterrent. The bird was injured enough that it had to be put down. Suggested ways to eliminate this problem will be discussed in the Recommendations section.

RECOMMENDATIONS

During the time that the panels were evaluated, they proved to have consistently high power output. Although the Bergey wind turbine is capable of producing higher peak outputs, the solar panels are a much more reliable source of green power in the summer months when SML needs power needs are greatest. For this reason, it is recommended that SML continue to expand its use of PV panels wherever possible.

In regards to the eight panels being installed in the near future, installation should be a simple procedure. The OutBack MX60 charge controller currently used is designed to handle a maximum of 60 amps of constant current. Since adding another eight panels to the array will put the maximum current over this limit, an additional MX60 charge controller will need to be purchased. It is important to wire only one solar array to each MX60 charger to ensure that the charge controllers do not conlict with one another as they operate. However, as long as the arrays are wired correctly, the arrays and charge controllers are scalable and the new system can be added to the existing system.

When Abigail Krich initially helped size the PV array for SML, she included Table 3. Abigail Krich's dorm 3 load estimations. in her report as an estimate of the loads being placed on the system and the appropriate battery bank sizing for such a system. This table was adjusted in an attempt to more accurately reflect the loads in Dorm 3. The updated table, Table 4, has all the same sources of loads, but the wattage for the specific loads as well as the average hourly usage per day has been adjusted in accordance with what the interns witnessed in their dorms. It is important to consider that these figures are estimates and highly dependent on the number of people that occupy the dorm as well as individual usage patterns. The tables shows that the majority of the load comes from the outlets in each room, and these loads could fluctuate wildly if laptops, iPods, cell phones, and radios are heavily used. However, it is still useful to have Table 4 when determining how extensively the available green power can be used.

Table 3. Abigail Krich's dorm 3 load estimations.

Load	**Wattage**	**Number of Loads**	**Average Hours Use Per Day**	**Wh Per Day**
Overhead Lights	16	21	6	2016
Task Lights	10	20	2	400
Plug Loads	20	20	6	2400
Water Heater	1500	0	7	0
Outdoor Lights	25	2	12	600
			Total AC Wh/day	5,416
			Max W	986

Table 4. Interns' dorm 3 load estimations.

Load	**Wattage**	**Number of Loads**	**Average Hours Use Per Day**	**Wh Per Day**
Bathroom Lights	25	2	2	100
Overhead Lights	14	13	4	728
Outdoor Lights	14	2	12	336
Task Lights	14	20	2	560
Plug Loads	40	20	4	3200
Water Heater	1500	0	7	0
			Total AC Wh/day	4,924
			Max W	1340

After comparing the average daily output of the PV array and the estimated power demand of a typical dorm found in Table 4, it is advisable to expand the reach of the renewable energy system and connect more buildings to the battery bank instead of the diesel generator grid. As shown in the Results and Discussion section, the average daily output was 12.5 kWh with a more conservative output expectancy of 8.3 kWh. The estimated power use of a fully occupied Dorm 3 is only 4.9 kWh so the PV array is producing a surplus of power. The additional eight-panel array should provide a similar output since the hardware is exactly the same. This means the 16-panel array should produce at least 16.6 kWh on an average day, which is enough power to run Dorms 1, 2, and 3 without needing any extra power from the grid, assuming Dorm 3 is representative of the other two dorms.

One of the future goals for the PV project must be to reduce the likelihood of a gull becoming entangled in the gull deterrent fishing lines. This occurred once during the interns' stay. The interns believe that two factors contributed to this incident. First, the gull deterrent was secured in a temporary way while its effectiveness was being evaluated. The posts to which the fishing line was tied were attached to the roof and panels with woodworking clamps. It was observed that the posts could move if enough force was put on the fishing line, making the line less taut. It may be easier for a gull to become ensnared in a loose line than a tight one. If the gull deterrent was secured in a more permanent fashion (as is the eventual goal), a gull impact would be less likely to loosen the lines and cause entanglement. Second, it is difficult for the gulls to see the fishing line. While the "surprise factor" in encountering a line is presumably a good deterrent, the interns initially sought to avoid gull impacts by wrapping small pieces of aluminum foil around several of the lines. The shininess makes the lines more visible to gulls, and may also be disconcerting enough to ward them off. Much of the original aluminum foil fell off the fishing lines, so the interns recommend that it be replaced with something similarly visible but more secure.

WIND POWER SYSTEM

BACKGROUND

A 7.5-kW Bergey wind turbine was installed at SML in the summer of 2007. Its primary purpose is to power the University of New Hampshire's AIRMAP system, which collects air quality and meteorological data. The data are analyzed to make air quality, meteorological, and climate change predictions by assessing the effects of downwind emissions from urban areas. With the installation of the wind turbine, the AIRMAP system will be able to collect data during the off-season when the diesel generators are turned off. During the winter months, there will more power available from the wind turbine as the wind speeds are typically much greater than in the summer months.

SYSTEM OVERVIEW

Figure 32 is an overview of the wind turbine system. The wild alternating current generated by the wind turbine goes through a transformer, which steps down the voltage from 200 to 50 volts. It then passes through the Bergey charge controller and charges the Absolyte IIP battery bank, which is also charged by the eight newly-installed solar panels. The power from the battery bank is then used for the AIRMAP instrumentation and to power Dorm 3.

OBJECTIVE

The objective is to monitor the power output of the wind turbine in order to ascertain the effectiveness and efficiency of the system and to determine the feasibility of using more wind power in the future.

DATA COLLECTION

A power meter was installed at the Bergey transformer by Paul Krell from Unitil Corporation. It recorded readings of the wild AC current produced by the wind turbine from August 1st-8th in five-minute intervals.

Data for wind speed in one-minute intervals were made available by AIRMAP, which has an anemometer installed at approximately the same altitude as the wind turbine.[7] The time stamp (UTC) of the wind speed data was adjusted for the purposes of comparing these data to other data.

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[7] AIRMAP Meteorological Data: http://soot.sr.unh.edu/airmap/rawdata/

There are four main criteria associated with power output, real power, reactive power, apparent power, and the power factor. Real power is the power actually produced after resistance from resistors and circuits is accounted for. Reactive power is associated with inductors and capacitors that drop voltages and currents. Apparent power is the vector sum of real power and reactive power; it is the ideal power output without any losses. The power factor is a measure of real power to apparent power. The greater the power factor, the less energy has been lost through resistance.[8]

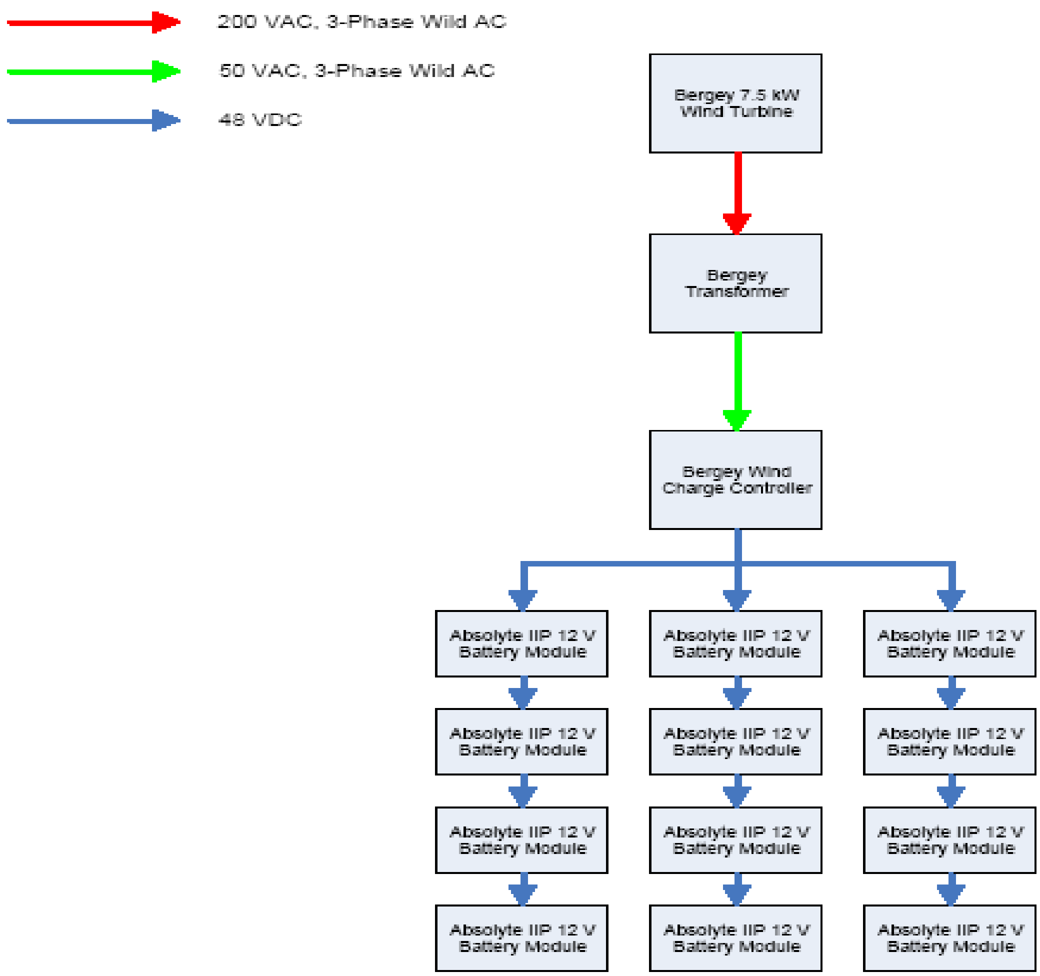


Figure 32. Overview of the wind power system.

[8] http://www.allaboutcircuits.com/vol_2/chpt_11/2.html

RESULTS AND DISCUSSION

Over the course of the data collection period, there was great variance in wind speeds and in the corresponding power output. Figure 33 and Figure 34 show the power output of the wind turbine and the wind speeds, respectively, from August 1st at 3:00 PM to August 8th at 3:00 PM. Note how the graphs correlate and in particular how the data agree with the manufacturer's specifications that wind speeds over 6 m/s are needed for an appreciable power output. Figure 35 is a plot of wind speed and power output on the same axis and emphasizes the correlation between the two. Note that the turbine appears to be working as it should and note the peak power output of 8 kW with a wind speed of 15.7 m/s from a storm.

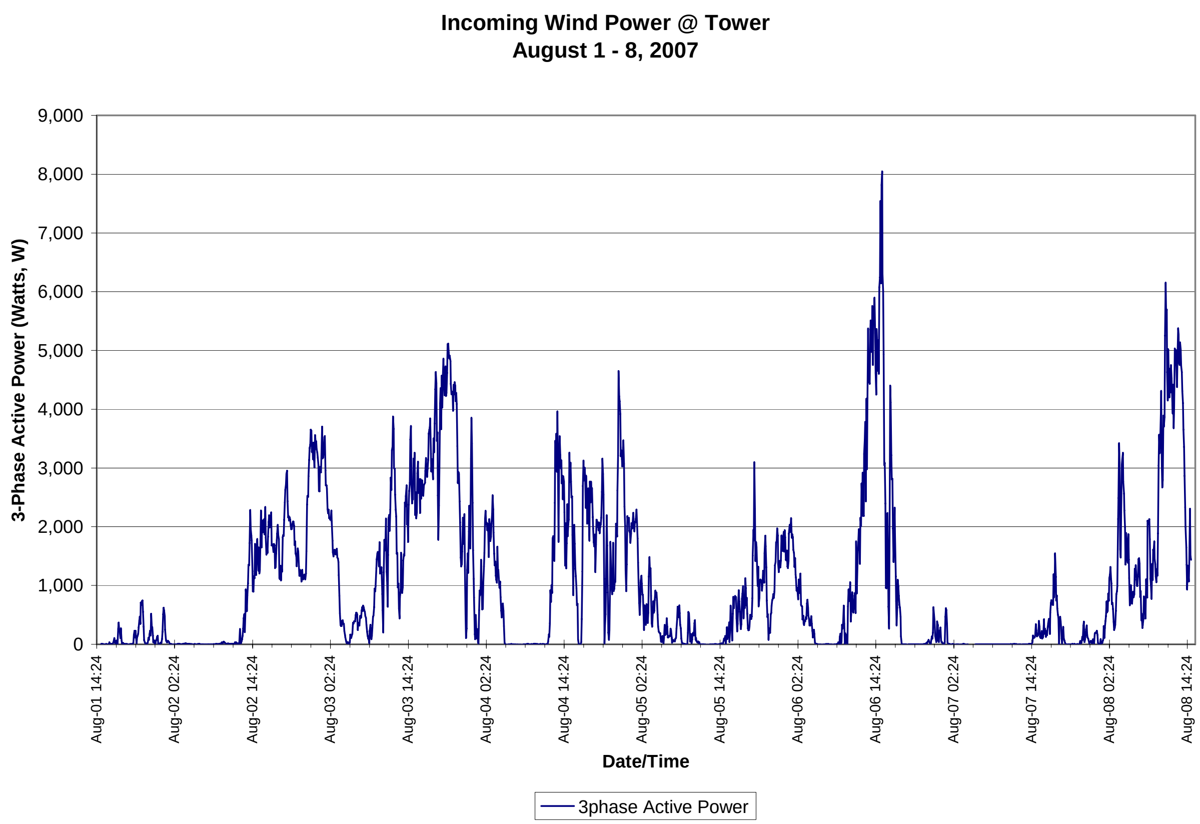


Figure 33. True power output of the wind turbine.

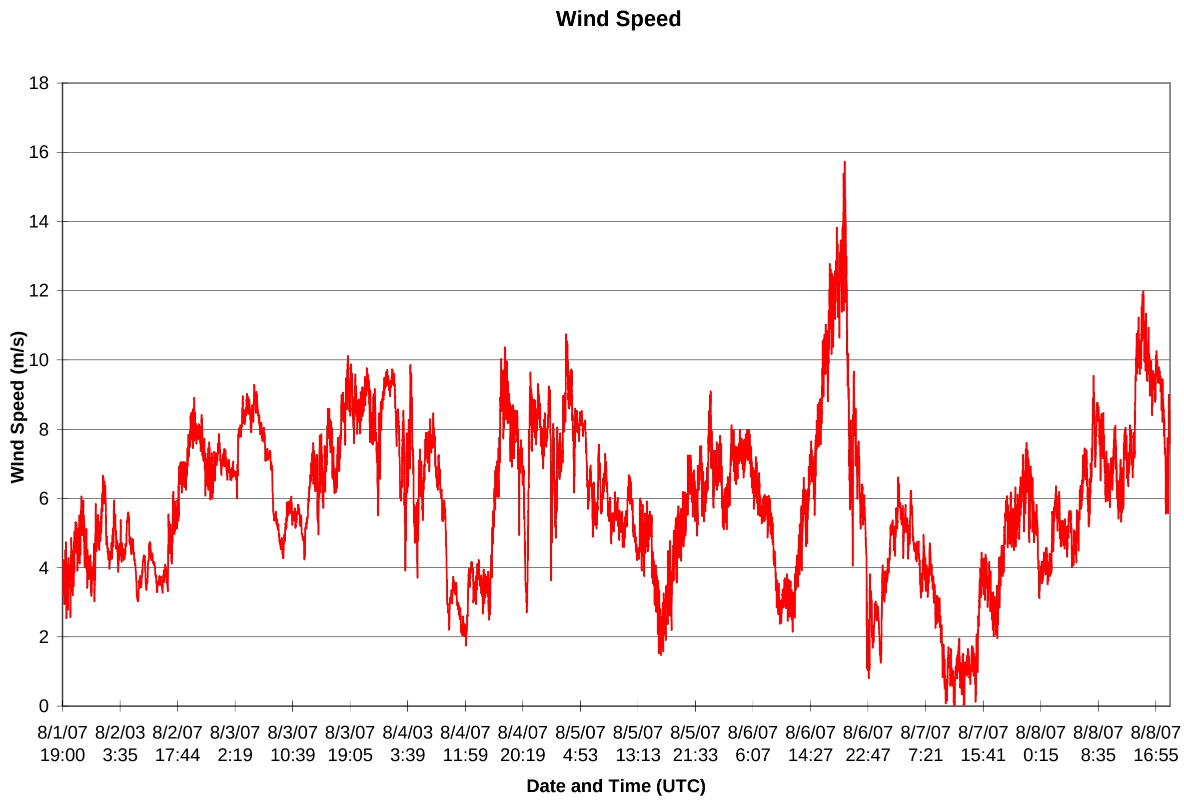


Figure 34. Daily wind speed.

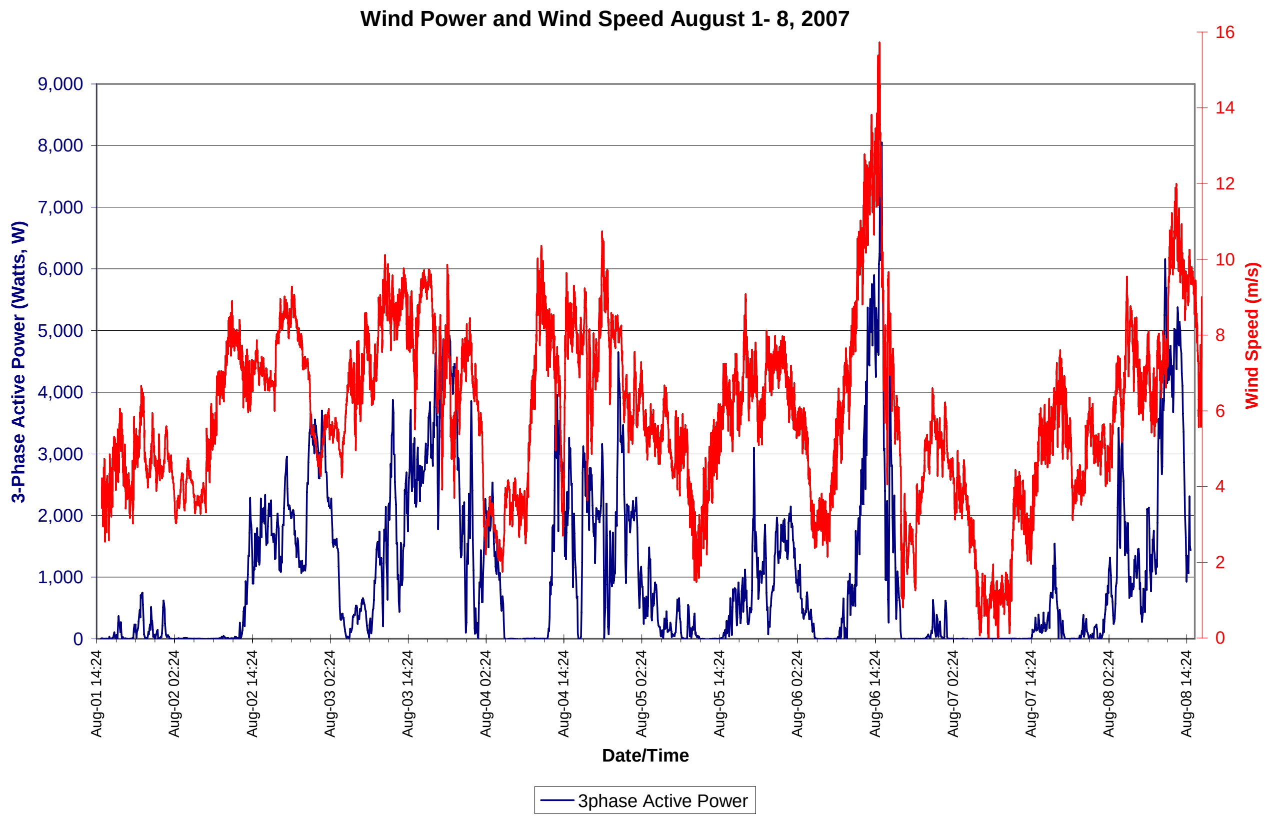


Figure 35. Correlation between wind power and wind speed.

Figure 36 shows the probability of different wind speeds from August 1st to 8th. When determining the probabilities, it was assumed that a speed of 3 m/s, for example, would correspond to any speed greater than or equal to 3 m/s, but less than 4 m/s. The most probable wind speed over the week was between 3 m/s and 7 m/s.

The collection period was fairly representative of a typical summer week with days of varying weather conditions. The average real power output during the week was about 1 kW with an average daily output of 24.75 kWh (refer to Table 5). The average wind speed was 5.93 m/s, barely at the speed required for an appreciable power output.

The AIRMAP equipment requires 1.8 kW of constant power with surges of 3.6 kW every two hours. As seen in Table 5, on August 8th, the average wind speed was 7.5 m/s with an average real power output of approximately 2 kW. Because the wind speeds are considerably lower in the summer than in the winter when they approach speeds greatly higher than 8 m/s, it is feasible to run the equipment on power generated by the wind turbine throughout the winter. The high wind speeds on the days that the turbine is producing power will be able to charge the batteries to compensate for the days with low power output.

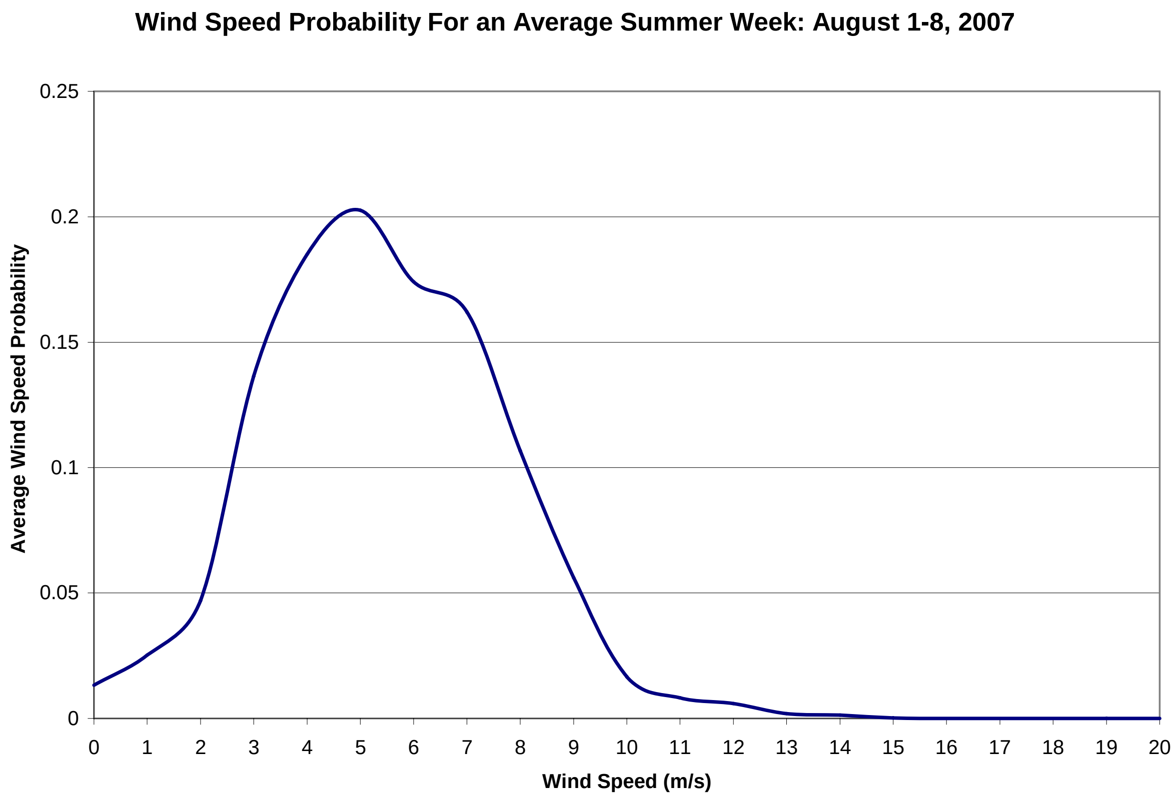


Figure 36. Average probability of different wind speeds.

Table 5. Daily and weekly average wind and power data for the wind turbine.

Date	Average. Wind Speed (m/s)	Average Real Power Output (W)	Real Power Output (kWH)	Average Apparent Power Output (V-A)	Average Power Factor
8/1/2007	4.62	106.01	2.54	206.43	0.51
8/2/2007	5.92	837.44	20.10	995.60	0.84
8/3/2007	7.37	2079.33	49.90	2324.90	0.89
8/4/2007	6.21	1266.55	30.40	1449.41	0.87
8/5/2007	5.75	621.41	14.91	741.70	0.84
8/6/2007	6.22	1250.36	30.01	1402.73	0.89
8/7/2007	3.76	101.29	2.43	171.91	0.59
8/8/2007	7.56	1990.16	47.76	2217.60	0.90
Average	5.93	1031.57	24.76	1188.78	0.79

Figure 37 compares the average power factor of the wind turbine with the average wind speed for each day during the week of data collection. Note that the efficiency of the system increases significantly as the wind speed increases above 6 m/s and then seems to level off. The system is about 90% efficient as the wind speed approaches 7.5 m/s.

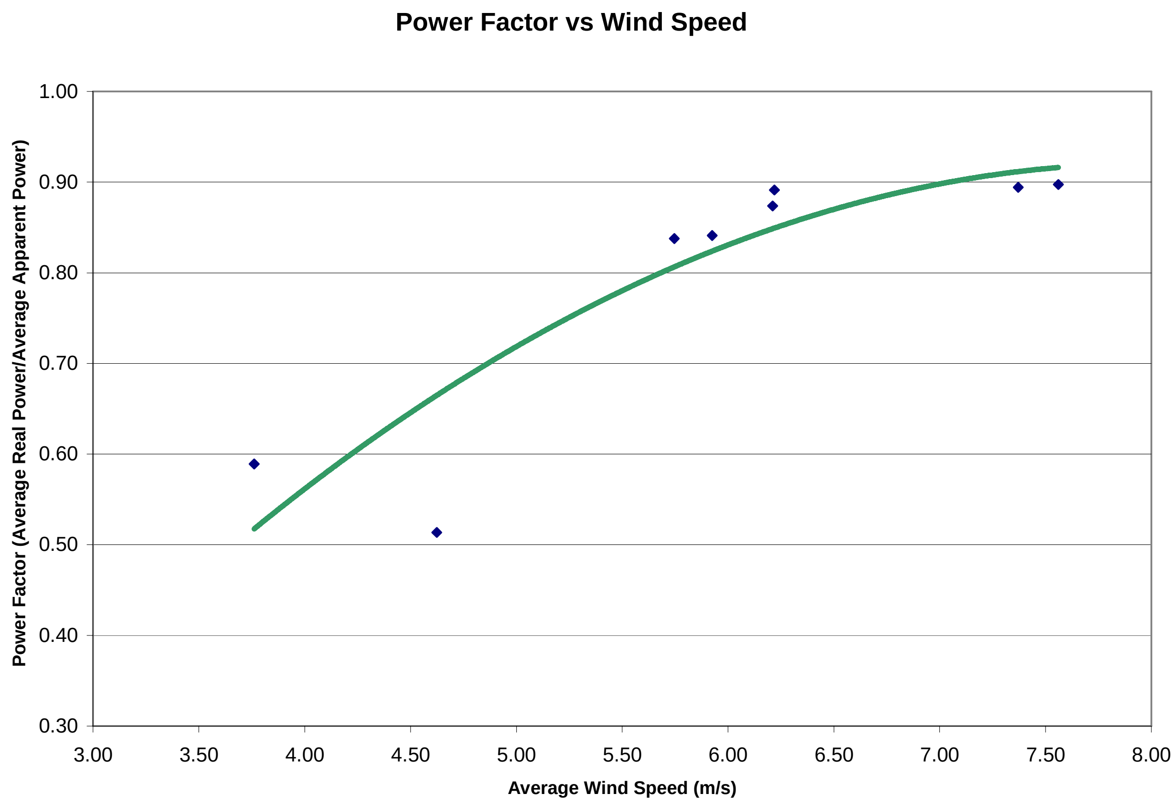


Figure 37. Daily average power factor of power output at average wind speeds from August 1-8, 2007.

On August 6th, 2007, a storm with winds around 15.7 m/s produced a peak of 8 kW of power generation. Manufacturer's specifications indicate that at that speed, the power output should be 6.14 kW. Figure 38 is a plot of power output over a range of wind speeds provided for the wind turbine. Figure 39 is the plot of power output at the corresponding wind speeds over the course of the day on August 6th. Note how the general trends of the two graphs are fairly similar. The power output increases with increasing wind until output hits the maximum and then drops after leveling off. The trendline for August 6th shows that the power output is about 0.5 kW lower than expected and that the trend is more gradual than expected, with a higher output at speeds above 14 m/s. There are also points where the output was much greater than expected, suggesting that the wind turbine has the potential to produce an output significantly greater than specified.

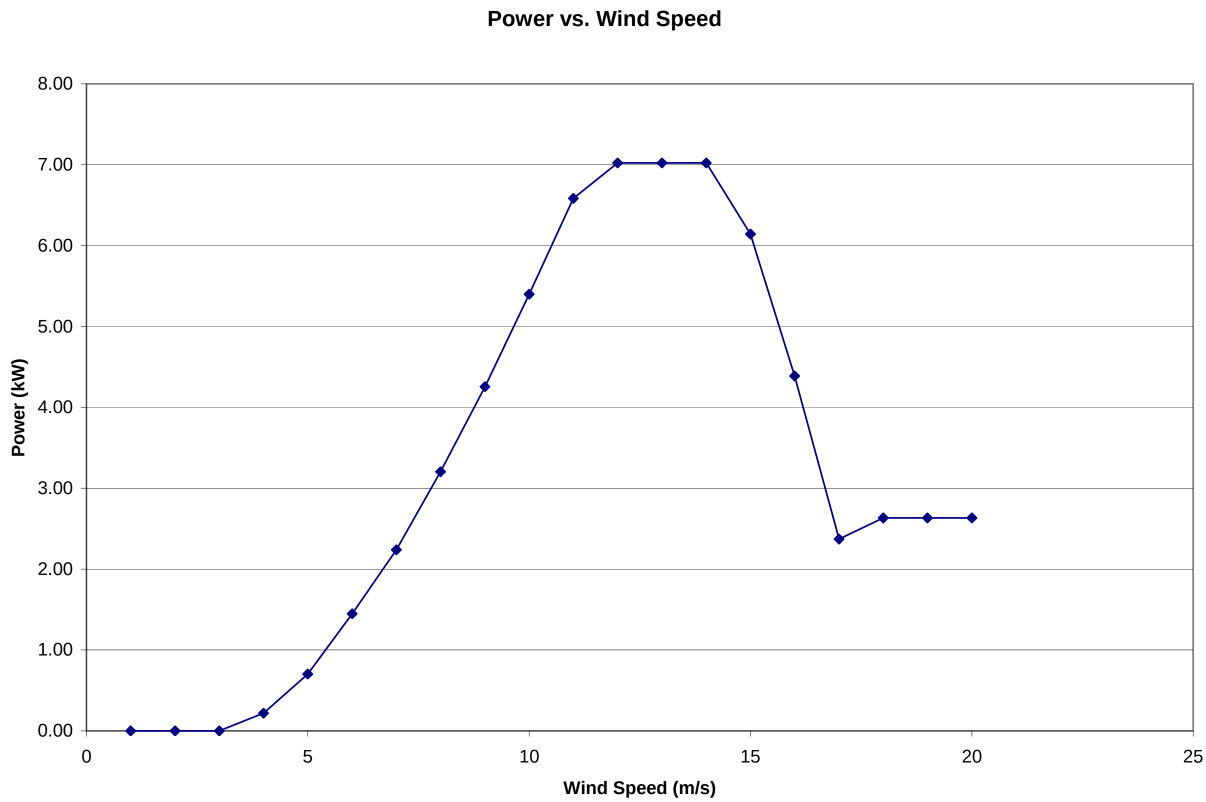


Figure 38. Expected power output at various wind speeds.

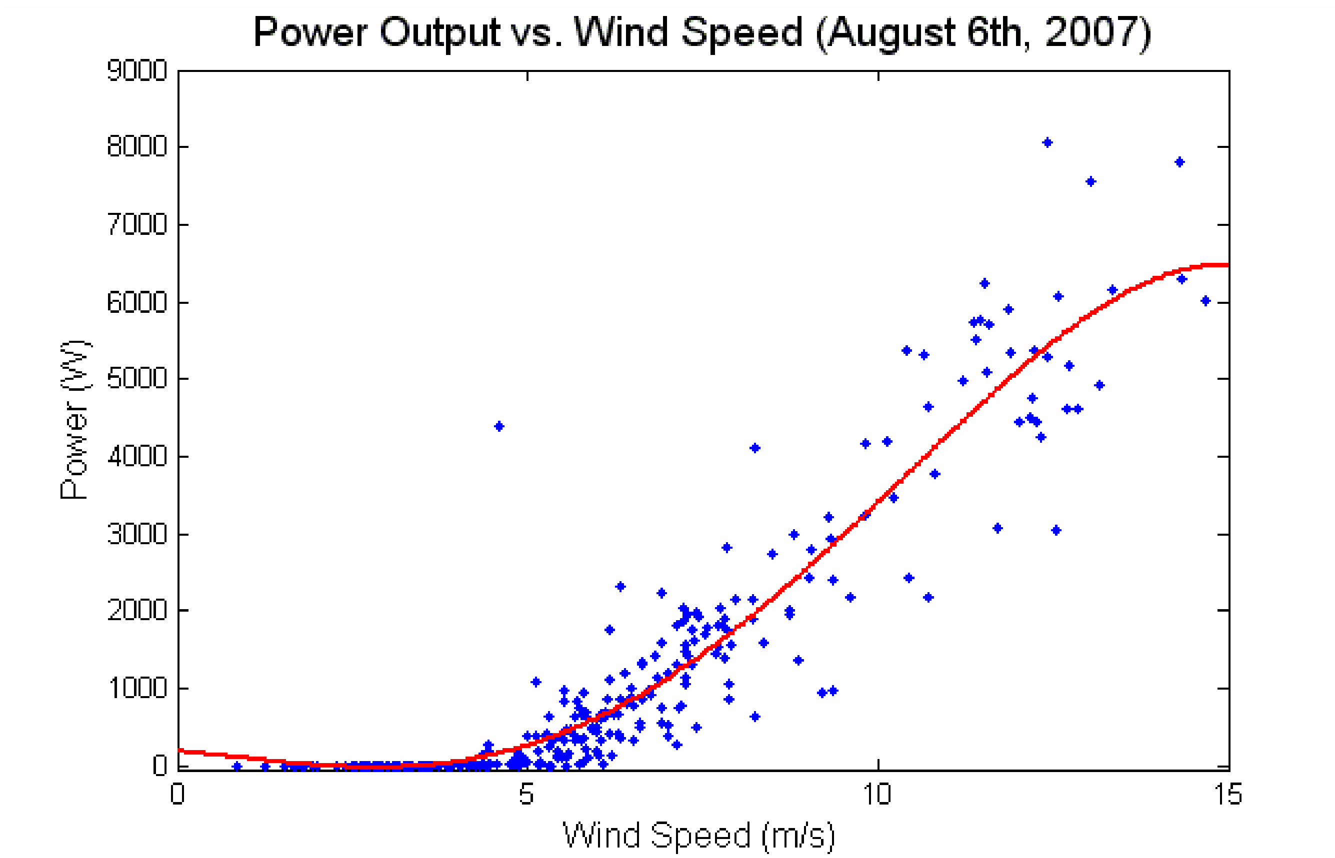


Figure 39. Power output at corresponding wind speeds: August 6, 2007.

RECOMMENDATIONS

Data about the performance of the wind turbine was limited. Without the assistance of Unitil, no power data would have been attained. To determine the feasibility of using wind power in the future on Appledore Island, instruments to measure the power output of the Bergey wind turbine are desperately needed.

Simply purchasing a larger wind turbine will not necessarily increase green energy production. Successful implementation of wind power will be limited by the size of the battery bank because the power output of the wind turbine is so inconsistent. Overall, more data must be collected before any conclusions are made.

INTEGRATED GREEN POWER SYSTEM

BACKGROUND

This report has addressed the power outputs of the wind turbine and PV array, but there has been no mention of how the two systems tie together to make one comprehensive green power system. Initial designs of the green power system had the two alternative energy sources and their battery banks as separate entities, but later in the design phase it was decided to integrate the two. Both systems use the same type of battery and inverters, so tying the two together was simple. In addition, the wind power is able to supplement the PV power on windy but cloudy days, and the opposite happens on sunny but windless days. This integration also allows for a larger battery bank which provides more energy storage to make up for days when sources of alternative power are minimal.

OBJECTIVE

The objective is to determine the optimal settings for the operation of the integrated green power system. The interns worked with GNB, the battery manufacturer, and OutBack, the controller and inverter manufacturer, to ensure that everything was set to provide SML with the best power output and battery life.

SYSTEM OVERVIEW

The overall system is comprised of the wind turbine system, the PV system, and a backup generator system. A simplified version of the system's one-line diagram can be found in Figure 40. When the batteries are receiving adequate power from the wind turbine and PV array, they continue to power any loads on the system. Any excess power is used to either charge the batteries or, if they are full, the power is dumped to three large diversion loads. When there is more demand than available power, the batteries will make up for this excess demand by discharging. However, if the batteries get too low, the generator has to turn on to power the loads and bring the batteries back up to an acceptable voltage. This recharging by diesel generator is possible only during normal SML operation months. In the winter the batteries and any equipment they power will shut down until the batteries are charged to an acceptable voltage. The regulation of this system is done by three controllers: the OutBack Mate controls the generator power; the OutBack MX60 controls the PV power and the diversion loads; and the Bergey Wind Controller controls the wind turbine. Figure 41 shows in more detail how the system is controlled.

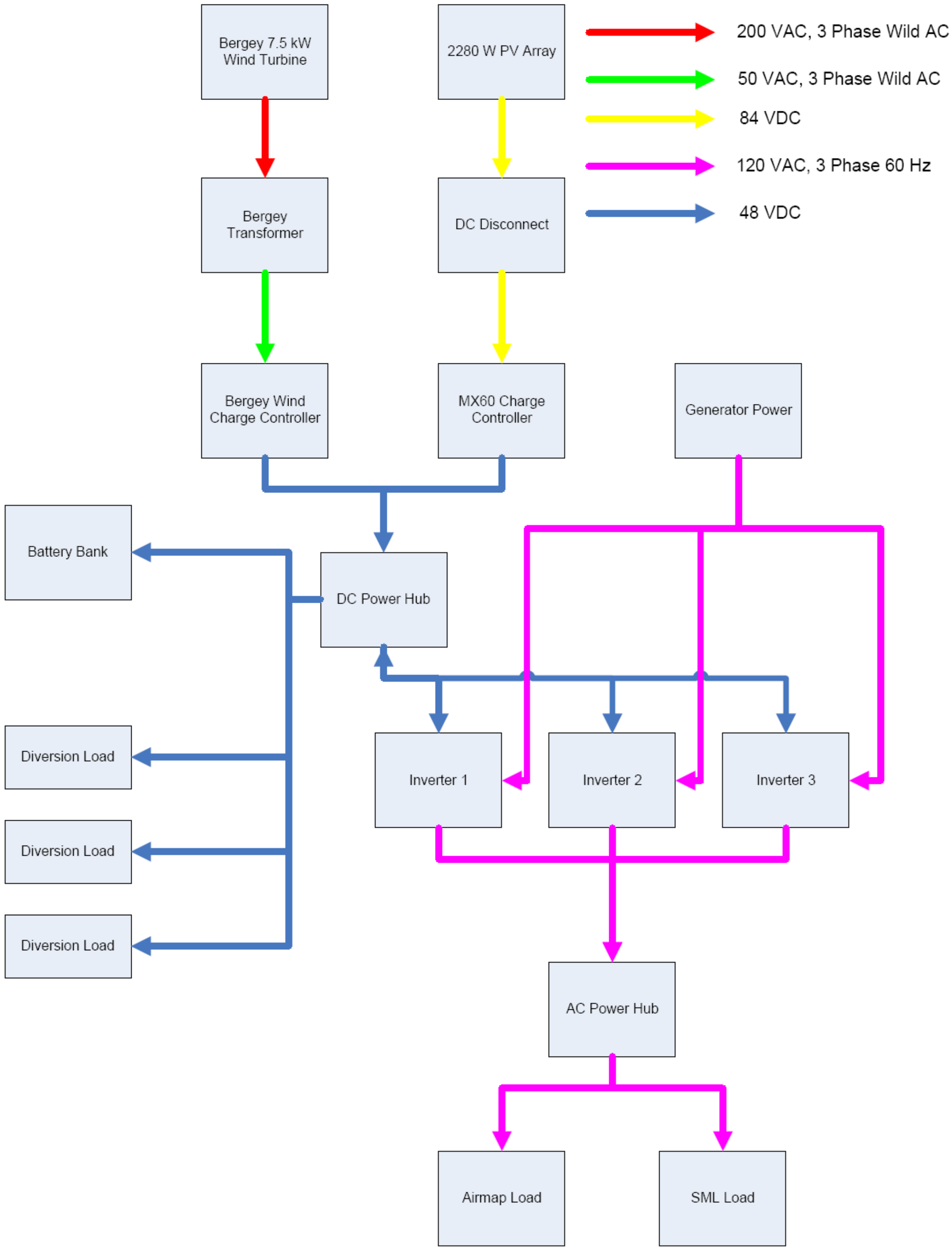


Figure 40. Integrated Green Power System Diagram

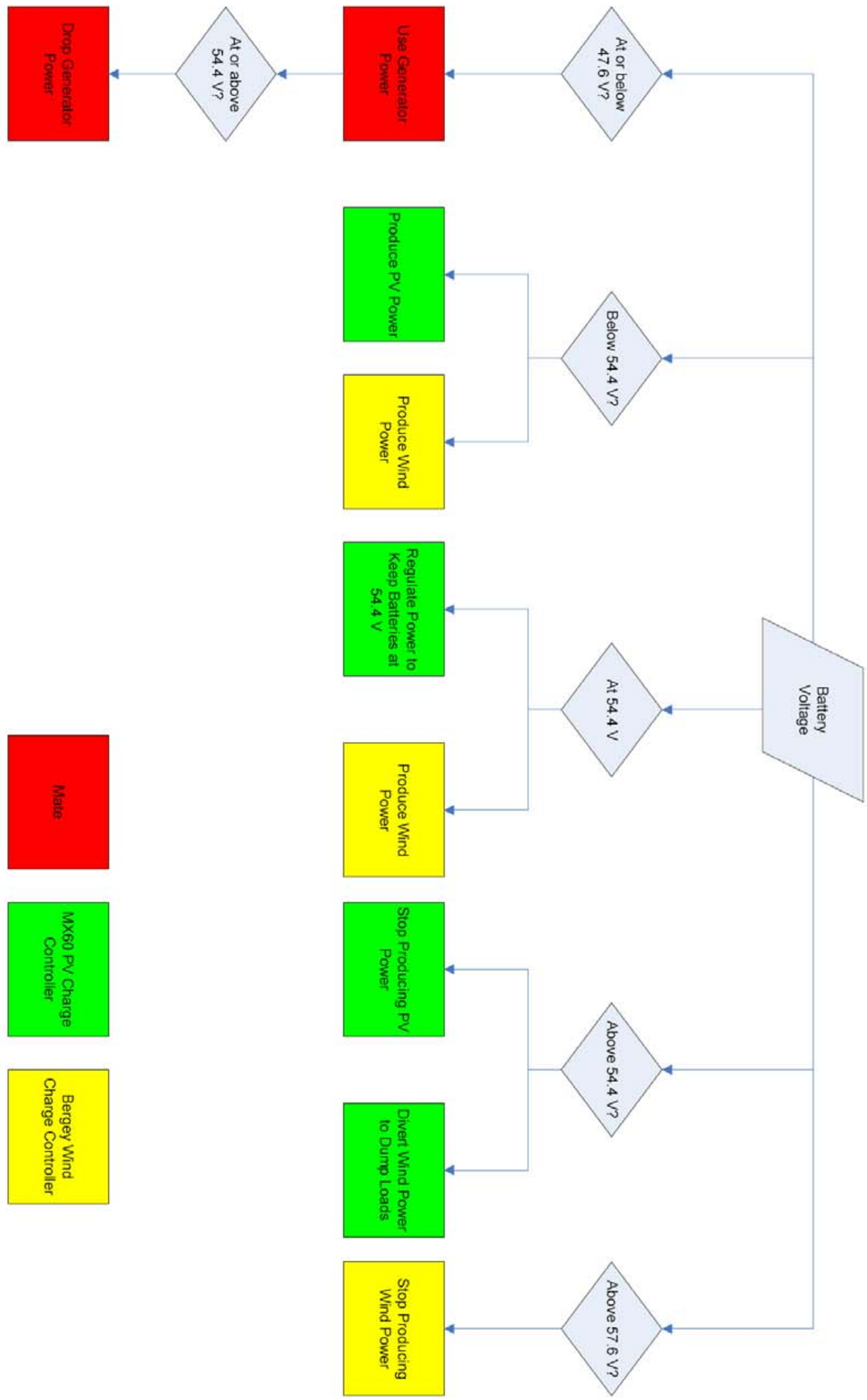


Figure 41. System controller decision tree.

The battery power is distributed by three OutBack FX3048T inverters that are configured for three-phase power. At maximum output, the three-inverter system can supply 9.0 kW of power continuously if the load is perfectly balanced on the three inverters, as each individual inverter can provide only 3.0 kW of power. As described in the PV system configuration, the battery bank consists of 12 batteries with a total output of 1824 Ah or 88 kWh.

DEFINITION OF SETTINGS

To ensure that the batteries are being used properly there are multiple settings which need to be adjusted in the OutBack Mate, OutBack MX60, and Bergey controllers. Although the definition of these settings could be looked up in the appropriate manual, they are also defined below for ease of use.

OutBack FX3048T Inverter Settings (Controlled Through OutBack Mate)

These are the settings that the inverters use when charging the batteries using an AC source. In the case of SML, the AC source is the diesel generator.

- **Absorb Setpoint**: This is the voltage that the batteries will be brought up to when the inverters are using generator power to charge the batteries. The Absorb Setpoint is the highest charge the batteries will reach during normal use.
- **Absorb Time Limit**: This is the amount of time that the generator will keep the batteries at the Absorb voltage.
- **Refloat Setpoint**: If the generator power was turned on manually using the Mate, the generator power will turn back on when the batteries fall to this voltage.
- **Float Setpoint**: This is the voltage that the batteries will be brought up to after reaching the Refloat Setpoint, as long as the generator power was turned on manually. The Float Setpoint is the voltage at which the batteries would prefer to stay at for the duration of their life.
- **Float Time Limit**: This is the amount of time that the generators will keep the batteries at the Float Setpoint.
- **Equalize Setpoint**: If, according to Section 13 of the Absolyte Installation and Operating Manual, the batteries need to be equalized, this is the voltage that the batteries will be brought up to during an equalize procedure. Typically, a battery bank needs to be equalized if the voltage between individual battery cells starts to vary.
- **Equalize Time Limit**: This is the amount of time that the generators will keep the batteries at the Equalize Setpoint, which can also be found in Section 13 of the Absolyte Installation and Operating Manual.

OutBack Mate Settings

The OutBack Mate has an advanced feature by the name of high battery transfer, or HBX mode. This feature is used when a power system is typically able to handle the loads placed on it through the use of alternative energy, but may need occasionally recharging by an AC source such as a generator. This is the type of green power system SML is using, since the PV and wind power typically charge the battery. While SML is open, the generators are accessible to charge the batteries if they fall below an acceptable voltage.

- **HBX-Use Grid Setpoint**: If the batteries fall to this voltage, the HBX feature will use the generator to charge the battery bank.
- **HBX-Use Grid Delay**: This is the amount of time the batteries must stay at or below the HBX-Use Grid Setpoint before generator power is used.
- **HBX-Drop Grid Setpoint**: This is the voltage that the batteries will be brought up to by the generator.
- **HBX-Drop Grid Delay**: This is the amount of time the batteries must stay at the HBX-Drop Grid Setpoint before generator power is dropped.

OutBack MX60 Charge Controller Settings

These are the power settings that the MX60 controller uses when determining how much power to provide the batteries from the PV array. The MX60 internally regulates the power being supplied to the batteries based on the current voltage of the battery and the settings below. If the batteries are full and power is not needed, the MX60 will decrease power to zero even if there is power available.

- **Absorb**: This is the maximum voltage that the battery bank will be charged to during normal operation.
- **Float**: This is the voltage that the MX60 will try to keep the batteries at whenever possible.
- **Diversion Relative Volts**: The MX60 controls the dump loads that have been installed in the system to make sure the batteries are not overcharged. As shown in Figure 41 if the voltage is at its maximum allowable value and the wind turbine is still providing power, this excess power is routed to the diversion (or dump) loads. The Diversion Relative Volts is the maximum allowable value for the difference between the battery voltage and the Absorb voltage. If the difference between these two values is higher than the Diversion Relative Volts value, the diversion loads will be utilized.
- **Diversion HYST**: This is the value that the voltage must fall from the time the dump loads were turned on in order for the diversion loads to be turned back off.
- **Diversion Hold Time**: This is the amount of time the voltage must stay above its maximum allowable value before the diversion loads turn on.
- **Diversion Delay Time**: This is the amount of time the voltage must be at the Diversion HYST value before the dump loads are turned off.
- **Battery Equalize**: This is the same equalization setting as in the OutBack Mate.

- **Battery Equalize Time**: This is the same equalization setting as in the OutBack Mate.
- **Absorb Time Limit**: This is the amount of time the MX60 will try to keep the battery bank at its absorb voltage.

Bergey Wind Controller Settings

The Bergey Wind Controller regulates the amount of power that is coming from the wind turbine into the green power system.

- **Potentiometer**: This potentiometer regulates the amount of power the wind turbine provides depending on the current voltage of the battery bank. Once the battery bank voltage reaches this limit, the controller cuts off all power to the green system.

OPTIMAL SETTINGS

Typically, the absorb voltage is associated with the battery voltage at full charge. The float voltage is the voltage that the battery operates best at, and the equalize voltage is either at or above the absorb voltage according to manufacturer specifications. However, David Plante, the engineer at Seacoast Consulting Engineers, LLC, who helped design the green power system, did considerable research on these batteries and found this was not the case for the Absolyte IIP batteries SML is using. For the SML system David advised that the Absorb and Float voltages both be set to the same value of 54.4 V, which is within the normal float value range given by Absolyte. Since the HBX-Use Grid setting is just an automated charge setting, this should also be set to 54.4 V. The Refloat Setpoint will rarely be used since the AC input will rarely be in manual mode, so its setting was left at 52 V. This could be adjusted in the future if the manual AC input became more important. To ensure that the generators are being used as little as possible, any time delay settings were set to minimal values. However, the HBX-Drop Grid Delay might need to be lengthened in the future. Currently, the observed battery voltage decreases rapidly once the generator power is turned off, so a longer delay might be necessary to allow the batteries to hold at their float voltage.

The HBX-Use Grid set point is currently at 47.6 V, which is approximately a 62% state of discharge. This point was chosen by the engineers at Seacoast Consulting Engineers, LLC, based upon the demand on the system and the lifetime of the batteries. The batteries rated for a 20-year life at float voltage by their manufacturer, but the life can also decrease depending on the number of charging cycles that the batteries go through. Lee Consavage modeled the green power system at SML and determined that the system will go through fewer than 100 charging cycles per year, equating to 2000 cycles in their lifetime. GNB states that at 60% state of discharge the battery life is approximately 2000 cycles so this discharge setting is appropriate for the SML system. It would be possible to increase the number of cycles the battery bank could go through by decreasing the state of discharge per cycle but the batteries would still be limited to 20 years of life.

GNB employee Ken Isabel gave some general recommendations for battery care and maintenance. He confirmed that the current voltage set points for battery charging (recharging the battery bank to 54.4 V once it is drawn down to 47.6 V) are reasonable. He was not concerned with the battery bank being discharged lower than 47.6 V (or 1.98 V per cell) as long as it did not remain there for too long. He was more concerned that the battery be charged high enough on a regular basis, which the system should do if it is working properly. Ken recommended performing an equalizing charge, per Section 13 of the Absolyte IIP Installation and Operating Instructions, about once a year, and possibly more than once a year if cell voltages are observed to be out of balance. Individual cell voltages can be measured with a standard multimeter, though specific safety precautions were not discussed. If cell voltages are distributed across a range of more than one or two hundredths of a volt, the battery bank should be equalized.

Any time there is excess green power available, it goes towards charging the batteries. As the batteries fill, there are a couple ways to regulate the charge and make sure they are not overcharged. The MX60 regulates this internally, depending on the absorb and float voltages. The Bergey Wind Charge Controller regulates the power coming from the wind turbine via a potentiometer. Theoretically, it would be possible to set this potentiometer so that once the battery voltage gets too high the controller cuts off all power; in actuality it is much more difficult. It is difficult to determine the exact value the potentiometer is being set at because of the discrepancy between the digital readout and the measured voltage. In addition, the Bergey controller seems to prematurely regulate power. Instead of waiting until the batteries reach the determined maximum voltage to regulate power, the Bergey controller starts to regulate it as the batteries approach the maximum value, wasting power. Fortunately, the MX60 has an auxiliary option that allows it to divert power to dump loads. Thus it is possible to set the Bergey controller's potentiometer to a value much higher than it should be and control the maximum battery voltage through the MX60. This allows all possible green power to be captured and used instead of being turned into heat inside one of the controllers. Since the batteries do best when floating at 54.4 V, it was decided to set 54.5 V as the maximum allowable voltage before diverting power to the dump loads. This was done by setting the Diversion Relative volts to 0.1 V. To make sure the dump loads weren't randomly switched on and off due to a quickly varying voltage, the Diversion Hold Time was set at 10 seconds. This means the battery readout must read 54.5 V for 10 seconds before the MX60 will divert the load. As the battery discharges, it is desirable to redirect the load back to charging the batteries as soon as possible. For this reason, the Diversion Hysteresis is set to 0.2 V and the Diversion Delay Time is set to 10 seconds. With these settings, once the battery voltage drops to 54.3 V for 10 seconds, the green power will be redirected from the dump loads to the battery bank. Currently, the potentiometer is set at 2.4 V per cell, or 57.6 V for the total battery bank. It has yet to be determined whether this setting is high enough to allow uninterrupted flow of power from the wind turbine.

RECOMMENDATIONS

As mentioned in the System Configuration section, the green power system is capable of distributing up to 9.0 kW of power, with a maximum of 3.0 kW on each inverter. If loads are not distributed evenly via the hardwiring of the island's power grid, the capabilities of the green system will be lowered. Using AIRMAP's "Turbine Data" from August 1st, 2007 to August 7th, 2007, it was discovered that, on average, Inverter #1 carries 84% of the load on the system while Inverter #2 carries 5% and Inverter #3 carries 10%. Currently, this does not present a problem because the loads on the green system are much lower than its 9.0-kW limit. However, if Dorms 1 and 2 were also added to the system, the margin for error would be much smaller. Table 4 of the Solar Power System section shows that the peak load from one of the dorms is approximately 1.34 kW, so with all three dorms on the system this would be 4.02 kW of power needed from the inverters. AIRMAP staff has indicated that their equipment uses 1.8 kW typically with surges to 3.6 kW every 2 hours. They also run an air conditioner in the summer months which uses 1.2 kW to 1.8 kW. Including the air conditioner, these loads go above the 9.0 kW of power available from the three inverters. For this reason it is recommended to balance the loads on the system as much as possible. If the additional dorms are put on the green power system, it is also advisable to add another inverter to the system to increase the cushion between maximum available power and the maximum load.

Although a significant effort was put into configuring the controllers correctly, it is also suggested to continue monitoring and testing the system to make sure it is working properly. It was discovered that after the diesel generator charges the battery bank to 54.4 V and turns off, the battery voltage drops almost immediately to 52.0 V. It may be necessary to tweak the HBX-Drop Grid Setpoint and HBX-Drop Grid Delay so that the battery bank holds its charge more effectively. The Bergey Wind Controller's potentiometer settings may also need to be tweaked to ensure the wind turbine is still providing all available power to the battery bank as the voltage approaches 54.4 V instead of regulating the power prematurely.

CARBON FOOTPRINT

BACKGROUND

The "Carbon Footprint" of a community comprises all the greenhouse gas (GHG) emissions generated by the community's activities. Important greenhouses gases resulting from human activities are the following: carbon dioxide, which is generated during the burning of fuel and other materials; methane, which results from the production and transport of various fuel sources, agricultural activity, and the decay of landfill waste; nitrous oxide, which results from agricultural and industrial processes and fuel combustion; and fluorinated gases, which come from a variety of industrial processes. The World Business Council for Sustainable Development and the World Resource Institute have established accounting methods for three different scopes of GHG emissions. These scopes of GHG measurement allow for the completion of a greenhouse gas inventory for a community such as SML.

OBJECTIVE

A greenhouse gas inventory for SML has never been conducted. Such an inventory is essential to improving the GHG management of the lab and reducing its contribution to global warming.

DATA COLLECTION AND CALCULATION METHODS

The first step in estimating the carbon footprint was demarcating the boundaries of the analysis. The organizational boundary was defined as the island itself and the boats going to and from the island. That is, any Shoals facilities and activities beyond the dock in Portsmouth were not considered in the analysis. Thus, commuter traffic and air travel of SML residents were not considered in the analysis.

SML was assessed in manner similar to that defined by Clean Air-Cool Planet (CA-CP) for college campuses. By this method, the operational boundaries of the community are defined for three different scopes. For Shoals, these boundaries were set as follows:

- **Scope 1**: Includes on-campus stationary sources and transportation. For SML, this was defined as the following:
  - No. 2 fuel oil (diesel)
    - Generators
    - Backhoe
    - Tractor
    - Gators (2)
    - R/V Heiser
    - R/V Kingsbury (prior to 2007)

- Propane
  - Hot water tanks
  - Kitchen
- Unleaded gasoline: trucks (2)
- B5 biodiesel: R/V Kingsbury (2007 only)
- Refrigerants

- **Scope 2**: Includes all purchased electricity and steam. For SML, these quantities are zero.
- **Scope 3**: Includes all other indirect sources of greenhouse gases. For SML, Scope 3 included the following:
  - Solid waste
  - Wastewater

Evaluation of Scope 3 emissions was limited to readily quantifiable GHG emission sources for SML. Other indirect sources, such as food and office supplies, also contribute to a campus's carbon footprint. Due to time and feasibility constraints, the GHG emissions associated with these sources were not evaluated quantitatively.

Estimating the carbon footprint required searching for information about fuel usage and waste disposal from a variety of places and people. Table 6. Data time spans and sources.documents the source of information for each set of data.

The data were entered into the Greenhouse Gas Emissions Inventory Calculator provided by the Clean Air-Cool Planet website.[9] This calculator estimates the greenhouse gas emissions in equivalent weight of carbon dioxide gas for each year of data.

[9] http://www.cleanair-coolplanet.org/toolkit/content/view/43/124/, Version 5

Table 6. Data time spans and sources.

Information	Years	Source and Assumptions
Stationary diesel	2001 - 2002	Historical data from CD given to interns ("SML Facility Spreadsheet" Excel files)
	2003	No records
	2004 - 2006	Ross Hansen's records for generators
Diesel for Shoals boats	2004 - 2006	Captain's logs for R/V Heiser and R/V Kingsbury; 2004 Heiser data incomplete
Diesel for backhoe, tractor, and gator	N/A	Excluded from analysis due to relatively small magnitude and high uncertainty
Propane	2001 – 2006	Rymes Propane & Oils, Inc.; assumed to be yearly number of gallons delivered
	2007	Interns recorded number of fuel runs; assumed 25 100-pound tanks were filled on each fuel run
Unleaded gasoline	Yearly estimate	Ross Hansen
Solid waste	Yearly estimate	Ross Hansen and Solid Waste Management; landfill methane is flared but not used for power generation
Refrigerant	2004-2006	Ross Hansen. According to Ross, it has not been necessary to add refrigerant to the island refrigerators.
Island population	2001 – 2005	"SML Facility Spreadsheets." However, years 2002, 2004, and 2005 contain identical data, so the numbers are questionable.
	2006 – 2007	Exact data were available for the periods during which the 2006 and 2007 interns were present. Data for the rest of the season were not available and were too difficult to estimate.

Solid Waste Quantification

The footprint calculator requires annual weight of solid waste produced on campus. SML's solid waste goes to Turnkey Landfill in Rochester, New Hampshire. This landfill captures and flares methane but co-generation has not yet been implemented.

The characteristics of the waste and the dumpster, provided by the waste management facility, are as follows:

Table 7. Solid waste characteristics.

Density	200	lbs/yd^3
Dumpster size	10	yd^3
Weight per dumpster load	2000	Lbs
	1	short ton

According to the figures provided by Ross, the solid waste pickup rate varies throughout the season as shown in Table 8. Solid waste collection rates.

Table 8. Solid waste collection rates.

Time Period	Weeks	Collection Rate	Total Collections*	Weight (short tons)
Mid-April to mid-June	8	every 2 weeks	4	4
Mid-June to end of August	10	every week	10	10
September to first week of October	5	every 2 weeks	3	3
Total	23			**17**

*For the 5 week period from September to October, total collections were rounded up from 2.5 to 3 to be conservative in GHG emission estimates.

Thus, approximately 17 short tons of solid waste are generated by SML each season. This figure was used for all years examined in the carbon footprint analysis.

Wastewater Carbon Footprint

As SML's wastewater treatment differs slightly from conventional municipal wastewater treatment, the carbon footprint of the wastewater was examined separately. Currently, SML treats its wastewater via a primary treatment system in which solids settle out of the wastewater as it passes through two settling tanks in series. The water undergoes no secondary treatment, or degradation of biological matter—a fact essential to the carbon footprint calculation.

There are two greenhouse gases associated with wastewater: nitrous oxide (N_2O) and methane (CH_4). The following equation estimates the N_2O emissions associated with a population's wastewater[10]:

$$\text{lbs. } N_2O \text{ released/yr.} = \text{person-days / yr.} * 0.0006 \text{ lbs. } N_2O \text{ / person-day}$$

As this equation is based on the typical nitrogen content of human waste and has no dependence on treatment method, it was deemed a suitable estimation of N_2O emissions.

There are several different equations for calculating methane emissions; the appropriate equation depends on the method of secondary treatment. To be conservative, any methane reductions associated with secondary treatment were eliminated from these equations, yielding the following estimate of methane emissions[11]:

$$CH_4 \text{ emissions} = \text{total person-days/yr.} * 0.066 \text{ lbs. } CH_4 \text{ / person-day}$$

This equation represents the maximum methane-producing capacity of the wastewater.

Calculating GHG emissions from wastewater requires data about the number of "person-days" for the season. This figure is obtained by summing the daily population data. Unfortunately, reliable population data for the past several years does not exist; the few years of historical data are questionable in that many years' data are identical. Consequently, it was difficult to estimate the GHG emissions for a given year. Instead, an estimate of 8400 person-days per year was assumed based on the available population data. Equations 1 and 2 were then applied to calculate yearly methane and nitrous oxide emissions.

Converting these CH_4 and N_2O emissions to equivalent metric tons of carbon dioxide is essential to the evaluation of SML's overall footprint. Each GHG has an associated "Global Warming Potential" (GWP) which characterizes its radiative effect relative to carbon dioxide. The Intergovernmental Panel on Climate Change (IPCC) has defined the GWP's of these gases as follows[12]:

Table 9. Global warming potentials of selected greenhouse gases.

Greenhouse Gas	**100-Year GWP***
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296

*GWP vary depending on the time horizon; 100-year values, used here, are typical for GHG inventories.

[10] Dautremont-Smith, Julian. "Guidelines for College-Level Greenhouse Gas Emissions Inventories: Version 1." 2002. http://www.nwf.org/campusEcology/pdfs/inventories.pdf. Accessed August 6, 2007.

[11] Ibid.

[12] Albritton, D.L., and L. G. Meira Filho. 2001: Observed Climate Variability and Change. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

In other words, one ton of methane has the same atmospheric warming effect as 23 tons of carbon dioxide. Thus, the calculated CH_4 and N_2O emissions are converted to equivalent masses of CO_2 by multiplying by factors of 23 and 296, respectively. This conversion was necessary only for the wastewater calculations; the Inventory Calculator provided by CA-CP performs this conversion automatically for all other data.

These calculation methods yield the following results for GHG emissions from wastewater:

Table 10. Estimated annual GHG emissions from wastewater.

Gas	**Annual Emissions (metric tons)**	**Equivalent CO_2 Emissions (MT eCO_2)**
CH_4	0.25	5.8
N_2O	0.0023	0.7
Total eCO_2		**7**

Input Data

All the data collected for the GHG inventory are displayed in the following table.

Table 11. Input data for inventory calculator.

	Generator Diesel	**Kingsbury Diesel**	**Heiser Diesel**	**Unleaded Gasoline[1]**	**Propane[2]**	**Refrigerant**	**Solid Waste[3]**	
Year	**Gallons**	**Gallons**	**Gallons**	**Gallons**	**Gallons**	**Pounds**	**Shorts tons**	**Generator operation days**
2001	10759				2303			175
2002					2471			174
2003					2479			162
2004	10576	1420	606.49[4]	400	1583	0	17	174
2005	10245	2007	1378.56	400	2282	0	17	169
2006	8609	1250	2053.3	400	1358	0	17	161
2007					1307	0	17	

[1]Estimate only; assumed to be relatively constant from year to year.
[2]Indicates amount of propane purchased each year, which may differ from the actual amount used because propane is stored between seasons.
[3]Estimate only; assumed to be relatively constant from year to year.
[4]As a portion of the captain's logs are missing, this figure is incomplete.

Compilation of the data reveals that complete data sets exist for years 2005 and 2006 only; the remaining years lack certain data for various reasons. While missing data could be estimated based on existing data, such estimations are of limited use in investigating trends in GHG emissions over the years. Consequently, GHG inventories were completed for 2005 and 2006 only.

These data were entered into the CA-CP GHG Inventory Calculator. The calculator uses emissions factors for each GHG source to convert the input data to equivalent metric tons of carbon dioxide emissions, abbreviated MT eCO_2, for each emission source. Determining these emissions factors involves examining the chemistry of combustion reactions, the efficiencies of energy production processes, and many other factors unique to each GHG source. Details about the tabulation of emissions factors can be found via the "Reference" tab of the CA-CP Inventory Calculator. Refer to the Digital Appendix for the original input and results spreadsheets used in the calculator program.

RESULTS AND DISCUSSION

The GHG emissions for 2005 and 2006 are displayed in the accompanying figures.

Table 12. GHG emissions for 2005 and 2006, MT eCO_2.

		GHG Emissions, MT eCO_2			
Scope	**Source**	**2005**	**2006**	**Average**	**Change**
1	Stationary Diesel	103	87	95	-16
	Propane	13	8	10	-5
	Gas Fleet	4	4	4	0
	Diesel Fleet	34	33	34	-1
2	None	0	0	0	0
3	Solid Waste	4	4	4	0
	Wastewater	7	7	7	0
TOTAL EMISSIONS		**165**	**142**	154	**-23**

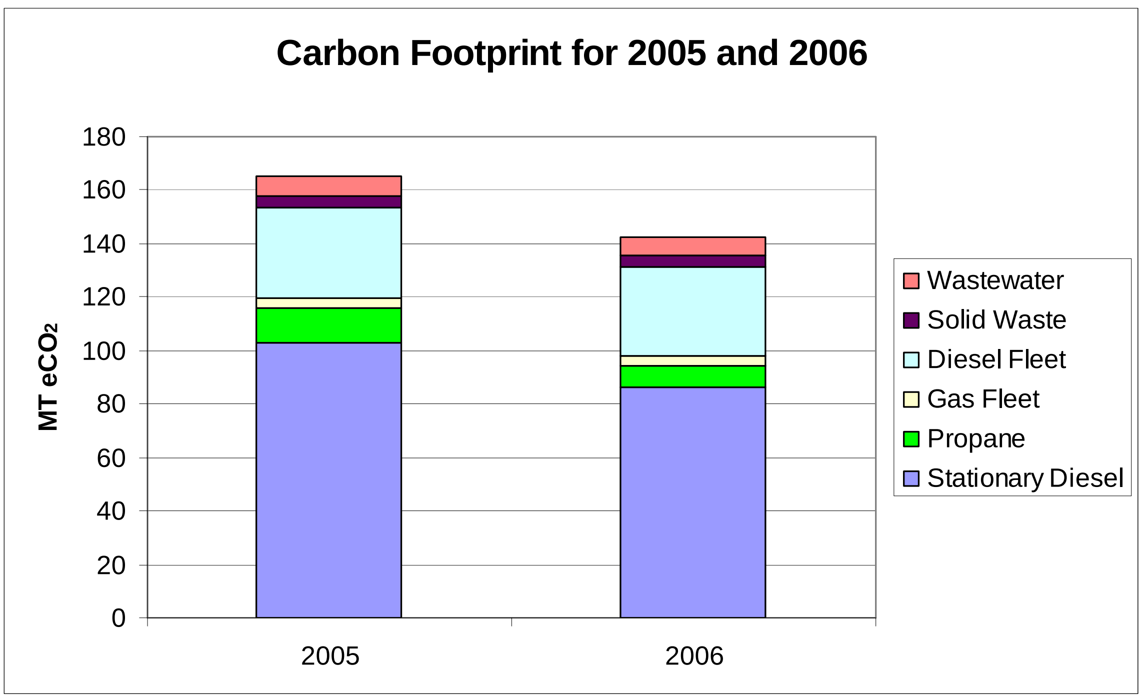


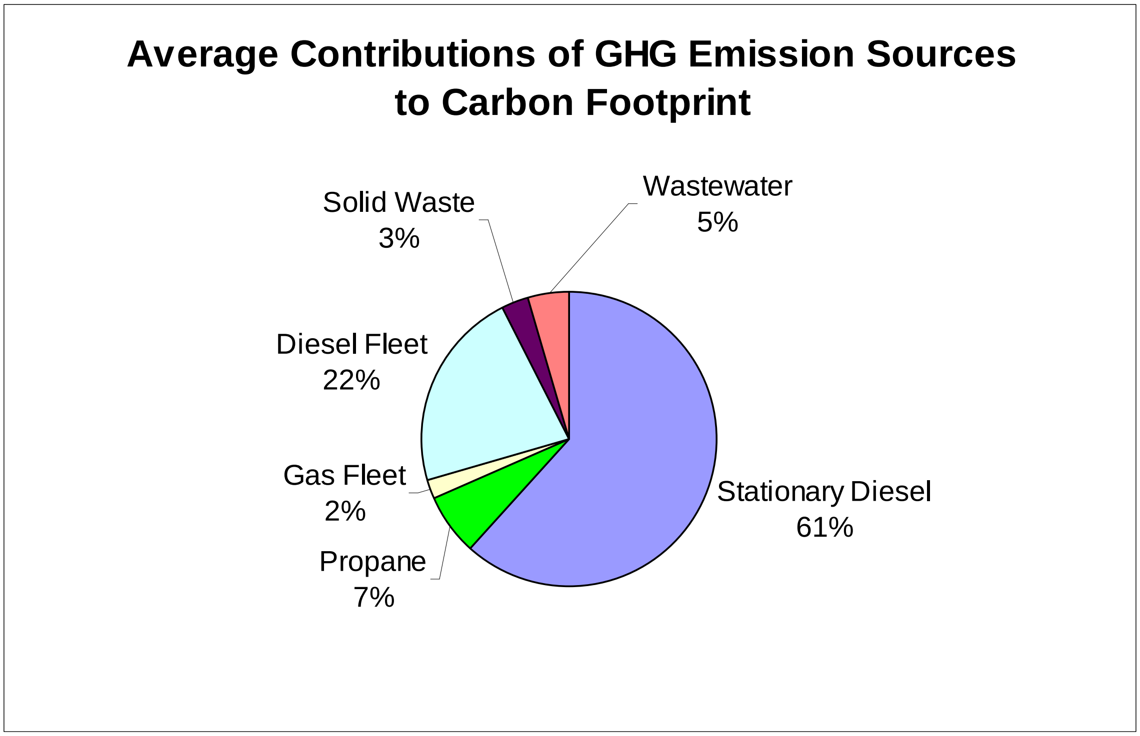
Figure 42. GHG emissions for 2005 and 2006.

The results indicate a 14% decrease in the carbon footprint of SML between 2005 and 2006. As the graph illustrates, this decrease is largely attributable to decreases in stationary diesel and propane consumption. As mentioned previously, the yearly propane data may not reflect actual propane consumption for a given year due to storage between seasons. Thus, the results are inconclusive regarding the contribution of propane consumption changes to the carbon footprint from 2005 to 2006.

A change in the consumption of stationary diesel—that is, diesel used in the generators—was responsible for a 16 MT eCO_2 decrease between 2005 and 2006. The decrease in diesel consumption is partially attributable to an eight-day decrease in the operational time of the generators from 2005 to 2006. Historical data also suggest that the daily fuel consumption rate decreased from 61 gal/day to 53 gal/day. Thus, both shorter operational season and lower fuel consumption rates were responsible for a 16-MT eCO_2 reduction from 2005 to 2006.

With only two years' worth of activity data, it is difficult to formulate conclusions about the trends in SML's footprint over the years. Furthermore, it is impossible to determine whether the current trends will continue into the future. It is apparent, however, that diesel consumption rates are the driving force behind considerable changes in GHG emissions between 2005 and 2006. The carbon footprint for 2007 will depend largely upon diesel consumption.

It is of interest to the management of SML's carbon emissions to examine the relative contribution of each emission source to the overall footprint. To this end, the 2005 and 2006 results were averaged; the averaged results are shown below:



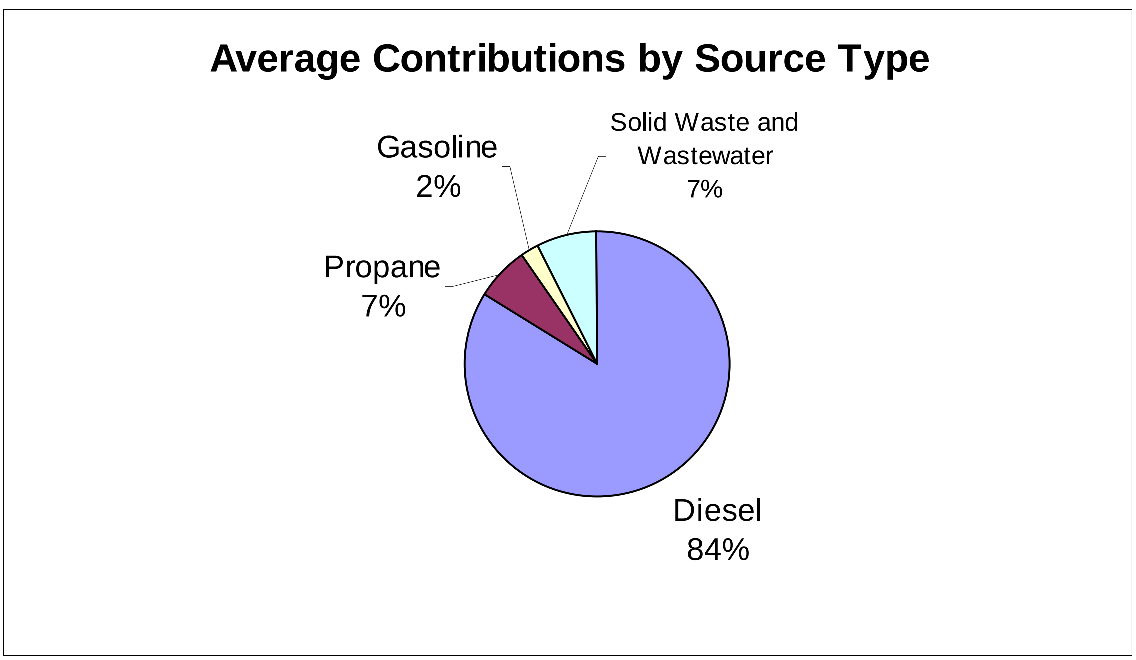


Figure 43. Average carbon footprint based on 2005 and 2006 data. Upper diagram shows each source individually; lower diagram groups emission sources by type.

As the figure shows, diesel—as generator fuel, vehicle fuel, and boat fuel—is responsible for 84% of SML's GHG emissions. Thus, SML's reliance on diesel is the driving force in the carbon footprint.

While three greenhouse gases—carbon dioxide, methane, and nitrous oxide—are emitted by SML, their individual contributions to the overall carbon footprint are significantly different. Divided by gas, SML's average emissions are as shown:

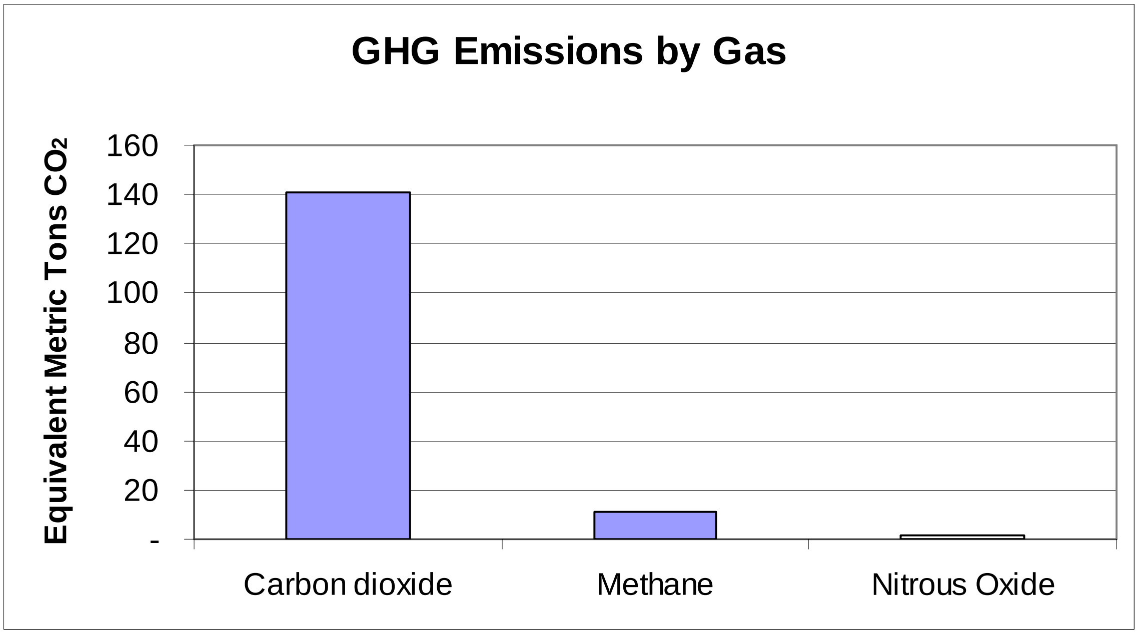


Figure 44. Average GHG emissions by gas.

The contributions of methane and nitrous oxide emissions compared to that of carbon dioxide are relatively small. Furthermore, 93% of methane emissions are attributable to solid waste and wastewater. Nitrous oxide emissions from SML are practically negligible.

MANAGING SML'S CARBON EMISSIONS

The management of carbon emissions is essential to SML's mission to exemplify sustainability. Reducing the Lab's carbon footprint requires a combination of new technology and improved conservation techniques. During the 2007 season, many changes were made to SML's operation, including the installation of alternative energy systems and the adoption of biodiesel in SML vessels. The following section details the effects of these developments on the overall carbon footprint.

Effect of Alternative Energy Sources on Footprint

During the 2007 season, SML installed two renewable energy systems: a wind turbine and a photovoltaic system. As these systems relieve the generators of a portion of their load, they reduce the overall carbon footprint of the island.

To quantify the effects of these new energy systems, a rough estimate of their yearly energy production is required. Since these systems are new, data about their performance are limited. Additionally, existing data are highly erratic, as the systems are constantly being adjusted. Thus, it is possible only to estimate the implications of the renewable energy systems for the carbon footprint.

PV Emissions Savings

According to calculations performed by Abigail Krich in 2006, the PV panels should provide approximately 7 kWh of power per day. Thus, using the following assumptions[13], the emissions savings associated with the PV array are estimated as shown:

> Daily PV power generation = 7 kWh/day
> Length of season = 165 days
> Energy content of diesel = 0.14 MMBtu/gal
> Emissions factor for diesel = 0.010 MT eCO_2/gal

$$\text{carbon savings} = \frac{\frac{7\text{ kWh}}{\text{day}} \times \frac{165\text{ days}}{\text{year}} \times \frac{3.412\times10^{-3}\text{MMBtu}}{\text{kWh}} \times \frac{0.010\text{ MT eCO}_2}{\text{gal}}}{\frac{0.14\text{ MMBtu}}{\text{gal}}}$$

$$\text{carbon savings} = 0.28\frac{\text{MT eCO}_2}{\text{year}}$$

With an overall yearly carbon footprint on the order of 150 MT eCO_2, an emissions savings of 0.28 MT CO_2 is negligible. Even the proposed doubling on size of the PV array later in the 2007 season will have minimal consequences for the carbon footprint. Thus, small scale PV generation is not an effective strategy for managing SML's emissions.

Wind Turbine Emissions Savings

Wind turbine power generation is highly variable over the course of a year. Unlike the PV panels, which only produce appreciable power during the spring and summer, the wind turbine is most productive during the winter. However, the AIRMAP equipment powered by the turbine has never been operated during the winter before; that is, winter wind power does not replace an existing power generation. Thus, using wind power in the winter does not reduce carbon emissions.

Quantifying the carbon savings associated with the spring and summer operation of the wind turbine is difficult. The power produced by the turbine is highly variable depending on the day's wind speed. The specifications for the wind turbine suggest a daily power generation of about 58 kWh given average wind speeds at SML. However, considering on the week's worth of data which was collected from August 1st to August 8th, the daily average power output is likely to be much lower at approximately 24 kWh. To be conservative, this figure is used for carbon emissions calculations.

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13 Energy contents and emissions factors for diesel and other fuels are found in the "EF_Stationary" worksheet of the CA-CP Inventory Calculator.

Using the same calculation procedure used for the PV power system, the wind system produces the following carbon savings:

$$\text{carbon savings} = \frac{\frac{24\text{ kWh}}{\text{day}} \times \frac{165\text{ days}}{\text{year}} \times \frac{3.412\times10^{-3}\text{MMBtu}}{\text{kWh}} \times \frac{0.010\text{ MT eCO}_2}{\text{gal}}}{\frac{0.14\text{ MMBtu}}{\text{gal}}}$$

$$\text{carbon savings} = 0.97\,\frac{\text{MT eCO}_2}{\text{year}}$$

As for the PV power system, the carbon savings associated with the wind power system are also minimal. Wind energy is not an effective means of significantly reducing SML's carbon footprint.

Effects of Biodiesel on Carbon Footprint

This year, SML began using B5 biodiesel in the R/V Kingsbury. Pure biodiesel (B100) reduces carbon emissions by 78% over petroleum diesel.[14] Thus, the carbon emissions associated with a biodiesel blend are calculated as follows:

$$\text{biodiesel emissions} = \text{petroleum diesel emissions} \times 0.78 \times \text{fraction biodiesel}$$

The typical biodiesel mixtures reduce carbon emissions by the following factors:

Table 13. Percent reduction in GHG emissions for various biodiesel blends.

Biodiesel Blend	% GHG Reduction
B5	3.9%
B20	16%
B100	78%

If biodiesel were used in both the R/V Kingsbury and the R/V Heiser, SML's carbon footprint would be altered as shown in Figure 45. Effects of biodiesel use in SML boats.

14 Sheehan, John, Vince Camobreco, James Duffield, Michael Graboski, and Housein Shapouri (National Renewable Energy Laboratory). "Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus" (1998), 18.

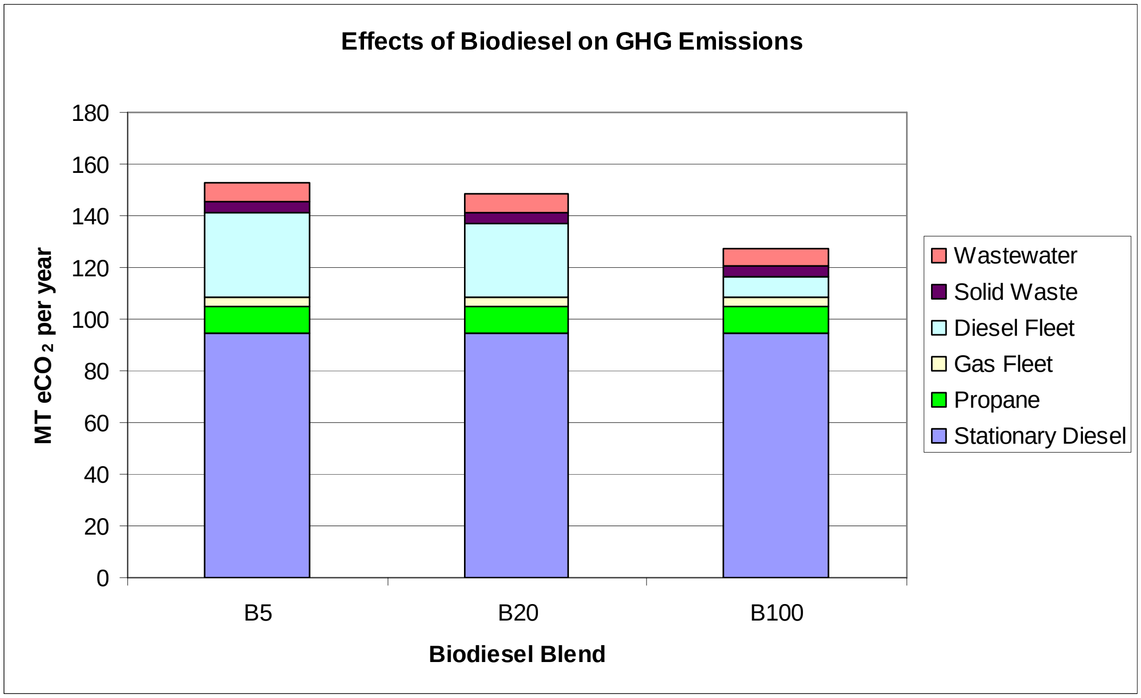

Figure 45. Effects of biodiesel use in SML boats.

As shown, using B100 exclusively in SML's boats would significantly reduce the GHG emissions, rendering the diesel fleet emissions similar in magnitude to propane emissions. However, there are several problems associated with using B100, including gelling during cold temperatures and warranty implications. Currently, B100 does not appear to be a viable alternative. However, B20 can be used with relatively few complications. Switching to B20 biodiesel for both vessels would save 4 MT eCO_2 per year.

Effect of Landfill Co-generation Project on Footprint

Solid waste contributes to an institution's GHG emissions by releasing methane and carbon dioxide as it sits in the landfill. Many landfills—including Turnkey Landfill, which receives SML's waste—practice gas flaring, in which the gas is captured and burned to relieve pressure and control odor. In the near future, the landfill gas may also be used for electrical generation, providing power for the University of New Hampshire. This change will affect the quantities of greenhouse gases released by SML into the atmosphere.

Based on the current solid waste production rate of 17 short tons per year, the CA-CP GHG Inventory Calculator indicates that the change in landfill gas management will decrease annual GHG emissions from 4 MT eCO_2 to 2 MT eCO_2. Since only 3% of SML's emissions result from solid waste, this effect of this change on the overall footprint is practically negligible.

Summary of GHG Reductions

Overall, the aforementioned changes to SML's operation affect the carbon footprint as follows:

Table 14. Carbon savings associated with various operational changes.

Improvement	Yearly GHG Emissions Reduction (MT eCO_2)
Photovoltaic power	0.28
Wind power	0.96
Landfill gas power generation	2
B20 boat fuel	4
Total Reductions	**7.2**

These savings constitute 5% of the total average carbon footprint of the island. While these savings are relatively small, it is important to remember that significant reductions in carbon emissions would require drastic changes in SML's operation.

Validity of Carbon Footprint as an Evaluation Tool

As the results indicate, PV power, wind power, and landfill gas power do not significantly reduce the carbon footprint of SML. However, this is not to suggest that such projects are not worthwhile endeavors. SML strives to be an example of the effective implementation of renewable energy systems. Demonstrations of the viability of alternative energy systems are essential to increasing public awareness of such technologies and decreasing SML's dependence on traditional fuel sources. While the carbon footprint analysis provides valuable insight into the distribution of SML's GHG emissions, it is not the ultimate evaluation tool for the island systems. Rather, the carbon footprint analysis should be used as a guide for the island's future developments.

RECOMMENDATIONS

Significantly reducing SML's carbon footprint is a serious challenge. As the results indicate, most of SML's emissions originate from diesel consumption. While alternative power sources, such as photovoltaics and wind energy, decrease SML's dependence on diesel, they cannot supply more than a small fraction of the load. Thus, a combination of conservation measures and new technology is necessary should SML desire to reduce its carbon footprint. These recommendations are discussed below.

Changes in Food Purchasing

The carbon emissions associated with producing and transporting SML's food were beyond the scope of this project; thus, quantitative recommendations in this area are difficult to make. Nevertheless, there are several ways in which changes in SML's food purchasing decisions could reduce the overall carbon footprint.

In general, the farther food items must travel to reach their ultimate destination, the more carbon emissions they produce. These emissions result from the extra fuel required to transport the food long distances. It is in the interest to SML's carbon management to purchase as much locally-produced food as possible. While pineapple makes for a tasty and attractive breakfast, it is not the best choice for a sustainable carbon management scheme. Furthermore, food with as little unnecessary packaging as possible requires less energy to produce and is therefore a good choice for reducing carbon emissions.

As previously mentioned, it is difficult to quantify the effects of these food purchasing decisions; furthermore, the decisions are limited by cost and convenience. Nevertheless, any efforts to reduce the carbon footprint associated with food purchases contribute to SML's mission to demonstrate sustainable living.

Conservation Education

Any efforts to reduce the energy consumption at SML will reduce fuel consumption and, therefore, carbon emissions. At present, SML implements many energy conservation strategies; compact fluorescent light bulbs are used throughout the dorms, and residents are encouraged not to waste energy. It is essential that SML continue educating residents about the importance of reducing their energy consumption. Students should be encouraged not to leave computers and chargers plugged in when not in use; these devices have phantom loads which greatly increase the overall power demand. Additionally, all students should be reminded to take "navy showers" to reduce the energy costs associated with water heating. To this end, posters in the bathrooms explaining proper shower protocol were installed in Kiggins Commons at the beginning of August.

Historical Record-Keeping

The greatest challenge in conducting the greenhouse gas emissions inventory was obtaining accurate historical records. While some data can be reasonably estimated, these approximations are of limited use in accurate comparisons across years. Should SML wish to continue monitoring its GHG emissions, it is essential to improve record-keeping practices. Improvement is necessary in the following areas:

1. **Population.** Hamilton provided daily and nightly population numbers upon request. However, the office does not keep records of daily population data for future reference. Population data are useful for per-capita analyses of emissions as well as for estimating emissions. Therefore, it would be helpful if the office kept a daily population log for the entire season.
2. **Diesel fleet.** As the diesel vehicles are refueled by different individuals as necessary, it is difficult to obtain an accurate estimate of their fuel consumption. SML staff should record the amount of fuel added to each vehicle each time it is refilled during the season. Such records would be simple to maintain and informative regarding the distribution of diesel consumption.
3. **Gasoline fleet.** Fuel consumed by SML's gasoline-powered vehicles was estimated for this analysis. As for the diesel fleet, it would be useful to keep track of the refueling of gasoline powered vehicles as well.
4. **Propane.** Precise data for propane delivered to SML were available from the propane provider. However, such data may not reflect actual propane usage due

to storage considerations. More exact propane usage records would provide a more accurate estimate of SML's carbon footprint.

CONSERVATION PROJECTS

BACKGROUND

Since heating water is such an energy-intensive process, ways to improve the hot water system at SML were researched. Water conservation is an easy way to reduce energy consumption in this area, but there are practical limits to hot water conservation.

Residents of SML need to have hot water available for their allotted number of showers per week. In the spring and fall months, weather conditions on Appledore Island are colder, so having hot water available in the residents' dorms is also important.

Hot water is also necessary for proper cleaning and sanitation of dining utensils and kitchen equipment. SML currently uses a low-temperature dishwashing machine, but this machine still requires a water temperature of 120°F for proper cleaning and recommends using water at 140°F. The heater in Kiggins Commons that provides hot water for this dishwasher currently heats it to 150°F.

OBJECTIVE

In light of these restraints on conservation, other ways of reducing energy demand in the hot water system were researched. The main objective of this research was to find ways to reduce energy consumption without significantly affecting the quality of life on the island. This reduction in energy consumption would allow SML to operate with a smaller carbon footprint and, in some cases, reduce the operating budget of the island.

DATA COLLECTION

Questionnaires were placed in multiple bathrooms at SML to determine the amount of hot water being used in the facilities. See Appendix H and the Digital Appendix for the original survey sheets.

To obtain a rough estimate of hot water usage in the kitchen, the kitchen staff was asked to mark a piece of paper every time they used the dish washing machine throughout a period of one day. The day was divided into two-hour intervals from 6:00 AM to 10:00 PM in order to determine times of peak hot water usage. On August 1st, 2007 the dishwasher was run 87 times, using 147.9 gallons of hot water. As expected, the dishwasher runs most frequently around meal times: 8:00 AM to 10:00 AM, 12:00 PM to 2:00 PM, and 6:00 PM to 8:00 PM. These data suggest that a minimum of approximately 150 gallons of hot water is used in the kitchen each day when the hot water faucet demand is also included. The exact number of dishwashing cycles during each time period can be found in Appendix H and the Digital Appendix.

A similar survey was used in Bartels to estimate the amount of hot water being used for staff showers. Staff members were requested to report each time they showered and the approximate length of the shower. The day was divided into two hour intervals from 4:00 AM to 2:00 AM the following day. For analytical purposes, the 12:00 AM to 2:00 AM time period was grouped with the previous day. If shower length was not specified, the length was estimated at 5 minutes long. The showers in Bartels have low-flow shower heads which use 2.5 gallons of water per minute. Since showers use a mixture of hot and cold water, the hot water usage was estimated at 2 gallons per minute. After a week, the average hot water use per day was 49 gallons, with the maximum of 84 gallons one day and a minimum of 12 gallons another. The raw data for this survey can be found in Appendix H. These data probably suggest slightly lower hot water use than what is actually consumed. One of the staff members transferred to a new position before this survey was done, and there were a couple staff members living off the island for at least one of the days of data collection. Nevertheless, an average of 49 gallons per day is a reasonable estimate for future water heating projects.

The last set of data collected was hot water usage in the clothes washer. Originally, this test was supposed to take place in Bartels to compliment the shower data collected, but the washing machine in Bartels was broken during the week of testing. Since the Kingsbury House is the only other facility used at SML to wash staff clothing, the questionnaire was placed there. The staff was asked to report every time they used the warm or hot water cycles each day. At the end of the week, there were no reported clothes washing cycles that used warm or hot water. These results are probably accurate because most of the staff reported that the hot water cycle is rarely or never used on Appledore Island.

Although the methods used to determine hot water usage on the island were simple, they were useful in at least showing the scale of water usage in different areas. For a more accurate usage estimate, flow meters could be installed in all areas using hot water; however, this would be very costly and time consuming and was outside the scope of the current project.

RECOMMENDATIONS

Drain-Water Heat Recovery System

Since the kitchen consume a significant amount of water, increasing the efficiency of the heating system in Kiggins Commons would be an easy way to save considerable amounts of energy. The two water heaters currently being used are relatively new propane heaters, so simply replacing the appliances will not improve performance significantly. However, a drain-water heat recovery system would compliment the current system extremely well and allow for significant increases in system efficiency. According to the U.S. Department of Energy, drain water carries with it 80 to 90% of the energy that was used to heat it in the first place[15]. By installing a drain-water heat recovery system it is possible to recover some of this lost heat and use it to preheat the water entering the heater. This is done by building a

15 http://www.eere.energy.gov/consumer/your_home/water_heating/index.cfm/mytopic=13040

simple heat exchanger around the drain pipe that carries the hot water. As the hot drain water flows down the pipe, the incoming cold water flows through a coil wrapped around the drain pipe. Heat is transferred from the warm wastewater to the incoming cold water, which is then fully heated to 150°F.

A drain-water heat recovery system is an attractive option for SML for several reasons. As stated in the Data Collection section, the kitchen uses at least 150 gallons of hot water each day. This water is extremely hot because of the requirements of the dish washer, so losing 80 to 90% of this energy is significant. The majority of the waste water flows through one drain pipe, so Kiggins Commons would require only one heat recovery system, which is good considering the costliness of such systems. Lastly, using this heat recovery system in an area where hot water use is consistently high allows for significant savings in energy and the quickest return on investment for the hardware purchased.

RenewABILITY Energy, Inc., builds and sells a drain-water heat recovery system that is advertised to reduce heating costs by 25 to 40% in residential settings and up to 80% in commercial settings. Their PowerPipe is made out of copper and is a counter-flow heat exchanger system that has a low pressure drop for the incoming cold water. The company sells many different versions of the PowerPipe, ranging from 30" to 72" long for 2" to 4" drain pipes. Larger PowerPipes are more expensive but are also more efficient, so any increase in initial cost will be offset by the fuel savings over the PowerPipe's 50 year life expectancy.[16]

The dishwashing machine uses a 2" drain pipe so the PowerPipe would also need to be 2" in diameter. Due to the location of the drain pipe in the crawl space underneath the kitchen, the heat recovery system will probably be limited to the 30" PowerPipe for 2" diameter drain pipes. This model costs $407 and is rated at 31.7% efficiency. The longer models are more expensive but are also more efficient so if the plumber felt a larger model could be used, this would be to SML's benefit.

When determining how much space was available for the drain-water heat recovery system it was discovered that during times of low hot water usage, the hot water in the storage tanks heats the cold water for a great distance along the pipes. Knowing this as well as the fact that the PowerPipe will provide its greatest returns with the coldest possible inlet water, it is advised to take the cold inlet water from as close as possible to the main inlet valve in Kiggins Commons. This will allow the maximum heat transfer from the drain water to take place.

To predict the savings in Kiggins Commons, some basic calculations were done. It was estimated that the drain water would be at a temperature of 125°F and the inlet water would be at 60°F. A 30" PowerPipe for a 2" diameter drain pipe has an efficiency of 31.7%, so at this efficiency the inlet water would be preheated by the PowerPipe to a new inlet temperature of 80.6°F. This would mean that instead of the water heater raising the temperature from 60°F to 150°F, it would only have to raise it from 80.6°F to 150°F. This is approximately a 23% savings in the amount of energy needed to heat the hot water. In the

[16] http://www.power-pipe.us/

cooler months, the inlet water temperature will be lower than 60°F, meaning that the difference between the original inlet water temperature and the preheated inlet water temperature would be greater. This would further increase energy savings.

Since SML receives donated propane, calculating a return on investment for this project is a challenge. The price of the PowerPipe cannot be compared with the savings in fuel costs since the fuel is currently free. However, the price of the PowerPipe can be offset by other factors. Fuel is heavy and relatively dangerous to transport to Appledore Island, and the process is slow and work-intensive. Having to transport fewer containers of propane to and from Appledore Island means less time and fewer dollars spent by SML. Also, the savings in fuel usage are one of many ways to reduce the carbon footprint of the island and increase the sustainable management of the facilities, which is the overarching goal of this program.

Solar Water Heating

Another way to reduce energy consumption is by installing a solar water heating system that either aids or completely replaces existing hot water heaters. There are several types of solar water heaters available, but because of the freezing temperatures that are possible on Appledore, SML is limited to two: the drain-down system and the closed-loop system. Both systems are actually closed-loop active systems, but they differ slightly in operation. In closed-loop active systems, a heat transfer fluid is pumped in a closed loop between the solar collectors on the roof and the hot water tank in the house. A heat exchanger transfers heat from the collectors to the heat transfer fluid, which is then pumped to the hot water tank to heat the potable water though a heat exchanger inside the tank. With the drain-down system, water is used as the heat transfer fluid. Since the water can freeze, the drain-down system uses gravity to pull the heat transfer fluid down into a tank when there is no heat available in the solar collectors. The drain-down system can also be used if the water in the tank is getting too hot. In a closed loop system, the heat transfer fluid is a type of antifreeze, so it doesn't need to be drained when there is no heat available. Instead, the antifreeze just stays in the lines and the pump turns off when there is no heat available in the solar collectors.[17]

There are also two types of solar collectors for typical solar water heating applications: flat plate collectors and evacuated tube collectors. Flat plate collectors are insulated boxes that have a dark absorber plate inside of them. These collectors are typically the cheaper option, but they have a lower output than the evacuated tube collectors, especially in the winter months.[18] The evacuated tube collectors are made of two concentric tubes. The inner tube is the collector and is coated in a material that allows radiation to enter but not escape easily. The space between the inner and outer tubes is evacuated to eliminate conductive and convective heat loss. This makes evacuated tubes well-insulated and efficient.[19]

Solar water heaters are capable of heating water to high temperatures, so overheating water in the storage tank is a concern. It is possible to construct the system such that the solar water heating system burns off any excess energy through a heat sink when maximum allowable temperatures are exceeded. Since this burned-off energy is wasted, it is much better to make sure that the water being heated will be used. For this reason it is important to carefully choose the best building in which to install a solar water heater. If a facility's hot water is rarely used, it is not an appropriate candidate for solar hot water heating. Any returns on such a system would be minimal due to the low demand. In addition, the water would be brought up to its maximum temperature relatively quickly, and any remaining energy available that day would be lost to the heat sink instead of used for heating. Table 15 is a list of all the buildings at SML with water heaters and their associated type, size, and energy consumption. The majority of the hot water systems on Appledore have small tanks in buildings with little hot water demand. The only use of hot water in these buildings is in the bathroom sinks. However, Kiggins Commons, Bartels, and Founders all have larger systems in which a solar system would be more beneficial.

[17] http://www.solardirect.com/swh/aet/aet.htm
[18] http://www.energyworksllc.com/hotwater.html
[19] http://www.eere.energy.gov/buildings/info/components/waterheating/solarhot.html

Table 15. Water Heater Inventory on Appledore Island

Building	Water Heater Type	Tank Size (gallon)	Energy Consumption
Kiggins Commons	Propane Storage Tank	82	156,000 BTU/H
Kiggins Commons	Propane Storage Tank	75	76,000 BTU/H
Dorm 1	Electric Storage Tank	6	2000 Watt
Dorm 2	Electric Storage Tank	6	1500 Watt
Dorm 3	Electric Storage Tank	6	1500 Watt
Bartels	Propane Storage Tank	40	34,000 BTU/H
Founders	Electric Storage Tank	40	4500 Watt
Palmer-Kinne	Electric Storage Tank	6	1500 Watt
Kingsbury House	Propane On Demand	No Tank	117 BTU/H Max 28 BTU/H Min
Laighton	Electric Storage Tank	10	2000 Watt
Hamilton	Electric Storage Tank	2.75	1500 Watt
Grass Lab	Propane Storage Tank	30	30,000 BTU/H

Installation of a solar hot water heating system in Bartels would be a good way to introduce solar hot water heating to the island and investigate the feasibility of using solar systems for other buildings such as Kiggins Commons. Hot water demand in Bartels is large enough to ensure the solar water heating system is being put to good use, yet not so large that the system may not perform as necessary. Providing water at 150°F in Kiggins Commons is very important for SML operations due to the fact that the kitchen staff needs to clean their supplies three times daily. However, if hot water is not available in Bartels, there is always the option of using the showering facilities in Kiggins Commons. Another reason Bartels would be a good location for researching a solar water heating system is the constant feedback that is available. The SML staff is housed in Bartels from the time the island is opened to the time the island is closed, so they will experience the wide range of conditions in which the system will operate. Staff feedback over this time period will be much more useful than feedback from students, who are on the island only for a few weeks at a time.

Energyworks, LLC, was contacted to design and price a solar water heating system that would be able to replace the current water heating system in Bartels. Energyworks is company based in Maine that specializes in renewable and energy-efficient energy systems. They are experienced with PV and solar water heating systems and designed and installed the largest solar array in Maine as of January 2007. Phil Coupe, a co-owner of the company, recommended a closed-loop system. It would use either a 30- or 44-evacuated tube collector array made by Apricus[20] to heat the water, which would be stored in a Stiebel Eltron 80-gallon, dual coil storage tank[21]. Energyworks produces the pump station that controls the whole system. This design provides between 60 and 80 gallons of hot water per day, depending on the weather, and ties in a backup propane source to ensure there is always hot water available. Total cost is estimated at $8500 to $9500, including installation. It would be possible to save between $300 and $700 by switching from evacuated tube collectors to flat plate collectors, but evacuated tubes are more efficient. Also, any future system for a high-demand building like Kiggins Commons would most likely use evacuated tubes, so testing them on a smaller scale first would be a great research project.

Water Conservation

Residential Buildings

The sinks in the dorms have separate hot and cold water faucets, making it difficult to use the hot water. The surveys placed in each dorm revealed that many people felt the hot water was too hot to use.[22] Dorm faucets, which are currently old and leaky, should be changed to a mixing model to allow for better temperature regulation. Additionally, since the current faucets are old and leak when not closed properly, new valves would reduce the amount of freshwater that is wasted through negligence.

The survey also showed that many people need the hot water after a day out in the field. The original proposal to discontinue using the hot water in the dorms was altered in favor of using a timer. The timer would control when the hot water heaters turned on, thereby conserving energy that would normally be used to heat unused water. As many of the residential buildings are unoccupied during most of the day, it is recommended to use the timers in these buildings as well as in the dorms. During the colder months of the season, when there is a greater demand for hot water throughout the entire day, the timer could simply be turned off.

Showers

Showers are large consumers of freshwater and energy. The current showerheads could also be replaced for more efficient, aerating shower heads that deliver the same shower quality while using much less water. Another recommendation is to install self-closing shower valves which would require the user to pull a chain or push a button continuously for flow.

A final suggestion to conserve water with showering is to install a re-circulating shower. This shower system takes the used water, filters and sanitizes it, and uses it for soaping up. Freshwater would then be used for rinsing. This system would save a great deal of water, especially during longer-than-recommended showers, when the only extra water used is for rinsing. For a summary of water conservation methods, refer to the following table.

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[20] www.apricus.com

[21] www.stiebel-eltron-usa.com

[22] For the original surveys, see Appendix H.

Table 2. Measures to conserve water and energy.

RECOMMENDED MEASURES FOR FRESHWATER CONSERVATION		
Problem	**Recommendations**	**Examples**
Some of the older faucets leak; the water coming from the hot valve is often too hot to use.	Replace separate hot/cold faucet with one mixing faucet	EPA WaterSense faucet
The energy used to continuously heat the six-gallon hot water heaters in the dorms is wasted as the water is not used except for mornings and evenings	Install a timer which would turn on the heaters 6-8 am and 9-11 pm	Intermatic 24 Hour Timer ($30-$35)
Showers are one of the biggest uses of freshwater on the island	Replace with more efficient aerating shower heads that would give comparable shower quality using less water	Prismere showerhead- 1.5GPM- $10.99 Real Goods- 1.2 GPM-$12- pause button so temperature adjustment can be preserved
	Self-closing shower valves	Self-closing shower valve
	Re-circulating Showers	Quench Showers
	Ensure that every person staying on the island knows what a "navy shower" is and the importance of conserving water.	design and hang posters in the bathrooms; this was done in the beginning of August
Top-loading washers on the island are in the last stages of their life; The washers can use up to forty gallons of freshwater.	Replace top-loading washers with efficient front-loading washers. Front-loading washers use about less water and less detergent. Clothes also have a lower water content, making them easier to dry.	Washers chosen by MEF (Modified Energy Factor - higher the number, higher the efficiency) and Water Factor (calculated by water used per cubic foot) See energystar.gov for efficient washing machines.
	Encourage residents to use cold water for the rinse cycle of the wash, which would save extra energy needed to heat up the water.	

FUTURE PROJECTS

In the course of completing the projects discussed in this report, many ideas for potential future projects for the Sustainable Engineering Internship emerged:

SOLAR HOT WATER HEATING

Using solar power for water heating would save energy and reduce SML's dependence on propane. Solar thermal technology is well-developed, simple, and affordable. Solar hot water heating would be of limited use in the dormitories, but supplementary solar hot water systems for Kiggins Commons and Bartels are worth investigating. It is also important for sizing purposes to obtain better hot water usage data through the use of flowmeters.

ALTERNATIVE FRESHWATER SYSTEMS

There are many low-energy, water-saving methods for obtaining freshwater that have yet to be investigated for application at SML:

Greywater Recycling

While the technology for recycling grey-water to produce potable water is still developing, recycled greywater can readily be used for irrigation and flush toilets. Doing so would save energy by reducing the need for the R/O unit and the long-distance pumping of water; and it would also produce less wastewater.

Solar Distillation

Solar distillation systems convert saltwater to freshwater via sun-driven evaporation and condensation. A solar distillation system could be useful for producing water for irrigation, toilets, and perhaps showers and drinking.

Rainwater Collection

Rainwater collection systems are simple to implement, requiring little more than a large basin to catch precipitation. Due to contamination, such a system would be applied primarily for irrigation, but other applications could be explored as well.

CONTINUED WIND AND PV MONITORING

The inaugural seasons of the PV and wind power projects saw much in the way of adjustment as proper operation was established. Monitoring these systems in their second season is critical to evaluating and optimizing their performance in the future. Additionally, determining the power losses in the lines between the wind turbine and the tower as well as between the PV panels and the tower is important for determining the limits of the distance between the energy source and the battery bank.

CARBON FOOTPRINT WITH EXPANDED SCOPE

The boundaries of the carbon footprint project were limited and did not include food, office supplies, or off-island transportation. It is of interest to investigate the emissions associated with these activities as well to construct a more complete greenhouse gas inventory.

BIODIESEL

SML is highly dependent on petroleum diesel, but the use of biodiesel is currently limited. Using biodiesel for SML's power generation would greatly decrease petroleum consumption and greenhouse gas emissions. However, investigation of biodiesel use raises several questions:

- How can biodiesel be used in low-temperature settings? There are several ways to keep biodiesel from gelling, including the use of additives or some type of fuel heating system. Would gelling over the winter months negatively affect the fuel before use in the spring?
- Can biodiesel withstand long periods of stagnation without producing considerable amounts of sediment? There are several additives that can be used to reduce sediment in biodiesel while it is sitting in storage tanks. Does the fuel degrade enough in a year to render it unusable?
- Is there an economically-feasible way of transporting biodiesel to the island? The vendor SML uses to transport diesel fuel to the island charges an additional fee for shipping fuel purchased through another company. Are there any other vendors in the area that can be used so that reducing GHG emissions is not so costly?
- Is it possible to run high-percentage biodiesel fuel in the generators without voiding their warranties? Caterpillar does not currently support the use of biodiesel in its generators. Are there any companies that do? Can SML work with industry to test alternative fuel use in its machines?

GENERATORS

It has been observed that diesel generator efficiency improves as the load approaches maximum generator capacity. SML currently operates its 65-kW generators at relatively inefficient, low levels, wasting fuel and increasing the risk of wet-stacking in the exhaust system. Using a combination of smaller generators to satisfy changing electric demand may lead to fuel efficiency increases and reduction of wet-stacking risk.

COMPOSTING TOILETS

SML's overboard wastewater discharge permit expires in 2009. Thus, it is worthwhile to investigate alternative methods of waste disposal. Composting toilets use little to no water and require little maintenance.

HYDROGEN

Hydrogen could be a better way to store energy produced by the integrated green power system. This hydrogen could then be combusted or used in fuel cells instead of using batteries as a power supply.

CONCLUSION

The Sustainable Engineering Internship has made, and will continue to make, tremendous strides for Appledore Island's efficiency, long-term sustainability, and quality of life. This is evidenced even in the first year of the program, which resulted in significant increases in the capacity of the saltwater system and was useful in identifying wastewater leaks. The second year of the program built on these foundations to provide serious recommendations for the freshwater chlorination system as well as determine the cost efficiency of the reverse osmosis unit. With the installation of solar panels and a wind turbine, SML has even moved towards relying on greener energy.

While all of these projects have already made a significant impact on the island, the Carbon Footprint has the most implications. The Carbon Footprint could be considered a metric for evaluating the sustainability of the island. However, some caution must be used. The only parameter of the island that is truly reflected in the carbon footprint is gas consumption. Considering the island infrastructure's heavy reliance on pumps and motors, it will be extremely difficult to become carbon neutral. While this is an admirable long-term goal, it is not a very useful metric for evaluating the sustainability of the campus in general.

Rather than being guided by a quantitative desire to be carbon neutral, the island should seek to implement appropriate technology. Appropriate technology is not always as high-tech as solar panels, wind turbines, and composting toilets. Sometimes it is as simple as changing the sink faucets, buying a new pump, or using a smaller generator. Every change that SML makes is a point for sustainability.

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