Small Scale Wind Energy for Hawaii

A SUBMITTAL TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI‘I AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE MASTER’S DEGREE OF GEOSCIENCE FOR PROFESSIONALS

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Master's of Geoscience for Professionals

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Abstract

Based on Hawaii’s and mankind’s need as a whole to switch to more renewable energy a study was performed near Kahala Beach on East Oahu. The prospect of integrating more small scale residential wind power and providing individuals a greater ability to convert to a higher percentage of renewable energy was of special interest. Harnessing more of the vastly underutilized wind resource on earth would be a powerful tool in the pursuit of clean energy. In this study a residential off-grid hybrid photovoltaic/wind turbine power system was deployed, and energy production was monitored over the course of one month. In addition, sensors were deployed to monitor wind speed, wind direction, and incident solar radiation. The amount of energy produced by the wind turbine was much smaller than expected and amounted to less than 15% of total energy production. This monitoring system was developed in a way to introduce pathways for a sustainable education program at the University of Hawaii, as well as the prospect of repeating the experiment at other island locations.
Small Scale Wind Energy for Hawaii

Table of Contents

Section 1: Introduction............................................................................................................6
Section 2: Wind Energy Explained........................................................................................7
Section 3: Wind Energy For Hawaii.........................................................................................8
Section 4: The Experiment.....................................................................................................11
Section 5: Methods................................................................................................................12
Section 6: Load.......................................................................................................................14
Section 7: The System............................................................................................................17
Section 8: Environmental Measurements.............................................................................19
Section 9: Physical Data Logging System............................................................................20
Section 10: Data Acquisition System.....................................................................................21
Section 11: Results................................................................................................................23
Section 12: Wind Energy Production.......................................................................................24
Section 13: Discussion............................................................................................................33
Section 14: What Can Be Done With This Power..................................................................35
Section 15: Understanding Power Production Storage And Use.........................................37
Section 16: Example Calculation............................................................................................38
Section 17: The Truth.............................................................................................................42
Section 18: Conclusion.........................................................................................................44
Special Thanks .....................................................................................................................46
Works Cited

List of Figures

Figure 1: Harvestable wind

Figure 2: Growth of wind power on the Island of Maui

Figure 3: Hawaii’s Electricity Production by Source

Figure 4: Severine Busquet of HNEI and Greg Ravizza of SOEST

Figure 5: Wind Turbine Installation

Figure 6: Data from June 16 used to illustrate load

Figure 7: June 16th Data load fluctuation with potential

Figure 8: Off Grid Hybrid Solar and Wind Schematic

Figure 9: AIR 40 Wind Turbine and Output

Figure 10: Wind Turbine and Anemometer Installation

Figure 11: Custom Data Logging System

Figure 12: Data collection points and direction of energy flow

Figure 13: Stacked line diagram, daily PV and wind energy production

Figure 14: Comparison of night time to day time wind energy production

Figure 15a: Wind direction data illustrating trade wind conditions associated with the most wind power production

Figure 15b: A 6-minute record illustrates short pulses of power production associated with wind gusts

Figure 16: AIR 40 Wind Turbine Power Curve

Figure 17: Comparison of measured wind speed to measured wind power generation
Figure 18: Comparison on of wind speed and wind turbine current production…………………………………………………………………..32

Figure 19: Igloo 40Qt Iceless cooler ........................................................................................................36

Figure 20: Tiny home located on the University of Hawaii, Waimanalo Ag. Campus…………………………………………………………………………………………………………45

List of Tables

Table 1: List of data logged by the data acquisition system.................................23

Table 2: Summary of quantities calculated from primary data .........................23

Table 3: July energy production by wind turbine, photovoltaic panel, load and power to and from battery.................................................................25

Table 4: Cooler load and PV current input by time..............................................41
Introduction

Earth’s wind energy is ultimately derived from solar energy. Therefore the amount of available wind energy is constrained to be a fraction of the total flux of solar energy to the Earth. In fact only a small fraction of all solar energy supplied to the Earth is transformed into wind energy (Miller et al 2011.) This transformation is illustrated schematically in Figure 1. Total Incoming solar radiation, approximately 175,000TW (Terawatts) at the top of Earth’s atmosphere, is calculated as the product of the solar constant (1367 (j/s)/m^2) and cross sectional area of the Earth. About 25% of this total energy flux can potentially contribute to useful wind energy. The remaining 75% is either reflected back into space or interacts with Earth’s surface. Of the ≈ 44,000 TW imparted to Earth’s atmosphere by the sun only 2% is transformed to wind power (≈900 TW) as air masses flow from regions of high pressure to low pressure. Not all this wind power is accessible to human use because some is too high to capture, and some of the low elevation boundary layer winds dissipate over the remote open ocean. Estimating these energy losses through atmosphere and accounting for mankind’s imperfect ability to harvest the wind constrains the total extractable wind power to be ≈ 68TW, globally. Although we tend to view the sun and the wind as limitless energy resources, the quantity of available power is finite, and is further limited by our extraction capabilities (Miller et al 2011.)
Wind Energy Explained

1. There is ≈ 175,000TW of solar radiation reaching the top of our atmosphere.

2. 45,000TW ≈ 25% of incoming solar radiation results in differential solar heating causing atmospheric pressure differences, setting air into motion.

3. 900TW ≈ 2% of differential solar heating comprises all wind power in the global atmosphere.

4. 450TW ≈ 50% of all wind power generated is dissipated in the atmospheric boundary layer.

5. 112TW ≈ 25% of Earth's surface is nonglaciated land thus this percent of wind energy is most accessible for extraction.

6. 68TW ≈ (60% maximum) available wind energy can be harvested by man due to inefficiencies in harvesting ability.

Although only a small fraction of incident solar energy is transformed to useful wind energy, there exists enough harvestable wind on earth to provide for all human energy consumption. In 2017 humans utilized the equivalent of 1375*10^7 tons of oil equivalent or, recasting annual human energy consumption as power, 18.33TW of energy (BP Statistical Review of World Energy 2017.) This rate of energy consumption is only about 25% of the rate of wind energy generation in Earth's atmosphere of 68 TW (Miller et al 2011.) In other words the amount of available wind power exceeds global human energy consumption by about a factor of four. This relationship demonstrates that wind energy constitutes a vast renewable energy source that is largely unexploited by humans.
Although there is more than three times the harvestable wind energy on earth than all current human energy requirements, what is possible in theory is not necessarily practical. The calculations performed by Miller et al. (2011) assumed large-scale wind turbine infrastructure distributed on Earth’s non-glaciated surfaces. Unfortunately wind resources are not equally distributed across the globe leaving some areas with little available wind energy. Wind resources are also intermittent and fluctuate seasonally. Furthermore, not all countries can afford large-scale wind turbine infrastructure and some cultures feel wind turbines are unsightly. For instance, large wind turbine construction has been contested on the island of Oahu Hawaii. Large wind turbines have also been responsible for numerous Hoary Bat deaths in Hawaii (Amlin, Afsheen 2016.) For Hawaii and the world to transition to green energy it will require multiple forms and scales of renewable energy.

Wind Energy For Hawaii

Wind power has been utilized in Hawaii already and will contribute some percentage of future green energy in Hawaii. Although there have been fluctuations in the amount of wind energy production in the past, and also in wind energy investment, there is an overall trend of increasing wind energy utilization. At the end of 2016 the island of Maui for example had approximately 37% renewable energy and 25% of that energy was from wind as seen in Figure 2 (Maui Electric 2017.) Oahu has had a fluctuating relationship with large-scale wind energy, as maintenance on existing wind infrastructure is not cost effective when oil prices
Another issue with large-scale wind turbines is that fluctuations in energy production can be problematic on small islands. Rural areas that are well suited for wind turbine locations often do not require vast amounts of energy like a city. Storing excess wind energy in a means that is easily utilized once the supply has decreased is a practical problem that has not yet been solved.

As household energy requirements fluctuate over time, an easier way to implement renewable wind energy may be on the residential scale. By installing a small-scale residential wind turbine, homeowners can increase the amount of renewable energy their home utilizes and also decrease their grid demand. As well as decreasing grid demand, residential wind energy similar to solar power production can leave homeowners more resilient to power outages.

Figure 2. Growth of wind power on the Island of Maui (Maui Electric, 2017)
In theory, residential wind energy can provide approximately 8% of the electricity consumed by an average Hawaii household. According to Hawaiian Electric, an average Hawaiian household uses less than 500kwh of electricity per month if they also utilize solar water heating (*Energy Tips 2017*). A first order estimate of wind energy production by a small commercial wind turbine suitable for residential use can produce 40kwh of electricity monthly. This estimate uses an inexpensive wind turbine (AIR 40) that makes approximately 40kwh of electricity per month at only 12-13.4 mph winds (*AIR 40 2013*). In theory, a Hawaiian household exposed to 13mph winds that utilizes less than 500kwh of electricity per month could easily produce 8% of their household energy with the use of just one small electricity-producing wind turbine. This first order assessment ignores many important details such as seasonal variations in wind, the role of wind gusts, and the influence of brief intervals of very low speed winds. Individuals in both first and third world countries have the option to create greener households through the availability of professional and salvage built small-scale residential wind turbines.

With small-scale residential wind turbines, Hawaii as a whole can get closer to its goal of being 100% green by 2045 (*Hawaii Clean Energy,* 2021). Looking at the seemingly obtainable household switch to 8% renewable energy, via wind production in applicable resource areas, what is the benefit to Hawaii as a whole? In Figure 3 we see that Hawaii utilizes fossil fuel combustion for 81% of its electricity production (*Hawaii.gov,* 2021). If we assume that half the Hawaiian population can take advantage of a moderate 12-13.4 mph wind which correlates to an 8% switch to
renewable energy than arguably we can say that Hawaii as a whole could see a 4% decrease in hydrocarbon usage for electricity. One must keep in mind that a homeowner on the Windward coast could see an approximate 10% switch to renewable energy from one small residential wind turbine so the 4% decrease in hydrocarbon use for electricity statewide is a conservative number. Even with a professional warrantied unit a vast majority of homeowners in Hawaii could theoretically make a minimum of an 8% switch to renewable energy at virtually zero long term cost due to monetary savings.

The Experiment

To test empirically what a small-scale residential hybrid system could power an experiment was set up approximately 1.5 blocks from Kahala Beach in East Oahu Hawaii. By logging data from both the conventional means of renewable energy (photo voltaic) and less abundant wind turbine energy, a direct comparison can be utilized to infer possible future use on the Hawaiian Islands. The small-scale residential solar power and wind turbine system was originally conceived of to power a tiny home in windward Oahu Hawaii on a University of Hawaii campus. The tiny home in the future will function as a UH sustainability education center so that students and public can see first hand an affordable, simple, off grid system. Ideally any individual interested in taking a hands on approach to decreasing their carbon footprint by producing their own renewable energy and simultaneously increase their resiliency to natural disasters can learn from this sustainability education
program. The energy produced could also easily be utilized to power an off grid aquaponics system to produce healthy local food as well.

![Figure 3. Hawaii’s Electricity Production by Source (Hawaii.gov hawaiicleanenergyinitiative.org)](image)

Methods

The off-grid power system and the complementary environmental monitoring equipment deployed in this study consist entirely of commercially available components. However, the data logging system was custom built for this effort under the direct supervision of Severine Busquet of HNEI. Dr. Busquet and Jonathan Kobayashi at HNEI also provided the software used for data logging (Figure 4.) The primary data logged in approximately one-second intervals consisted of wind speed, wind direction, solar irradiance, voltage at the solar charge controller, battery bank voltage, wind turbine amperage, amperage on the load side
of the charge controller, and the amperage flow between the battery and the charge controller.

Figure 4. Severine Busquet of HNEI and Greg Ravizza of SOEST

Figure 5. Wind Turbine Installation (Greg Ravizza and Karl Gerstnecker)
With the help of Greg Ravizza an AIR 40 brand wind turbine as seen in Figure 5 was installed at a height of approximately 30 feet. Along with the small scale residential wind turbine a 100W Photovoltaic panel was installed as well as an anemometer with a wind vane. All equipment was connected to an off grid battery bank comprised of 4, 12VDC deep cycle marine batteries wired in parallel. LED light strips on a rheostat were utilized as an easily adjustable battery load in order to discharge the battery bank to allow for constant charging.

**Load**

The use of 12VDC LED light tape yielded interesting results as a dump load. As seen in Figure 6 this nearly linear graph shows the battery charge from approximately dawn to mid afternoon. In this data, negative values represent charging. The X-axis of Figure 6 indicates power flow to and from the battery over a 24-hour period. Negative values indicate battery charging (typically daytime,) and positive values indicate battery discharge (typically nighttime.) The Y intercept corresponds to the situation where power production exactly matches power consumption, and the battery is neither charging nor discharging. Consequently the value of the Y-intercept closely approximates the power consumption by the load (approximately 16W.)

Throughout the day this relationship is not strictly linear as you can see by the M1 - 1.04 deviation. This deviation is due to the LED’s becoming brighter during battery charging, as there is greater potential across the battery bank from charging
voltages having to be higher than a battery at rest. This is even better seen in Figure 7 where as the potential at the batteries rise the LED’s have access to greater current and in turn become brighter and utilize more energy. LED brightness fluctuation created an unforeseen automatic dampening effect however, this was not a problem.

Figure 6. Data from June 16 are used to illustrate the power (Watts) balance for the off-grid system deployed. Power (wind + PV) produced (Y-axis) must be balanced by the nearly constant power consumption of the LED load (Y-intercept) and variable power consumption (charging <0) & release (discharging >0) of the batteries (X-axis). The 4% deviation from a -1 slope reflects the influence of battery voltage on the magnitude of the load drawn by the LEDs (See figure 7 below.)
Figure 7. June 16th Data. Load (Blue) climbs with Voltage (Red). This behavior of the LED load resulted in a systematically larger load during times of maximum power supply to the batteries (mid-day/peak sunlight), which is the underlying cause of the deviation of the slope in figure 6 from -1 and the variable power draw from the battery a zero power production.

Figure 8. Off Grid Hybrid Solar and Wind Schematic (Air 40) Altered by KDG.
The System

Displayed in Figure 8 is a general schematic for the hybrid solar and wind system. This schematic does not include the data logging set up; this is a mechanical schematic showing a basic hybrid solar and wind installation. Points of interest in this schematic are the wind turbine stop switch and the external charge controller for the solar panel. The wind turbine stop switch disconnects the turbine from the charging system but also essentially shorts out the wind turbine creating an internal braking situation within the wind turbine. The turbine components and wire gauge utilized are sufficient to withstand energy generation up to 49mph winds and a unit survival speed of 110mph winds (AIR 40 2013.) The wind turbine brake switch is useful during high winds to limit excessive rotational speeds that can wreak havoc on wind turbines. The external charge controllers utilized for solar panels are often programmable microprocessors allowing the operator to set maximum charge voltages as well as some providing a means to cycle loads based on system power available. The reason the solar panel output has an external charge controller is because solar panels are normally not “smart” in terms of how to operate. Without being connected to a power source to charge, solar panels are essentially able to turn off and be inert even when exposed to the sun. The power produced by solar panels is usually routed through a charge controller to prevent battery over charging. However, wind turbines while turning are usually always producing power unless the circuit is open which then allows the wind turbine to spin freely. Allowing a wind turbine to spin freely can create a situation where excessive rotational speeds can damage the turbine. Efficient wind turbines also contain trade
secret programming to allow the turbine to begin spinning and obtain a specific rotational kinetic energy before engaging the electric generating mechanism. Furthermore the more advanced wind turbines do not mechanically engage the generator but they instead utilize sophisticated sensors and electronics to electronically change their generation capabilities similar to alternators. Due to the threat of unit destruction from excessive wind speeds and the sophisticated electronics required to operate the electricity generation, efficient wind turbines often contain internal battery charge controllers.

Figure 9. AIR 40 Wind Turbine and Output (kWh) (Air 40 2013)

The AIR 40 was mounted utilizing galvanize pipe and a professional guy wire system similar to the mounting system seen in Figure 8. Instead of placing the base of the tower in the ground it was simply attached it to a vertical 6” x 6” post that was part of the framing for an existing outdoor shower. The shower pergola also provided a platform to reach the turbine and assisted in the installation and removal
of the turbine and tower. The pergola was also utilized to support the PV panel and irradiance sensor.

**Environmental Measurements**

An irradiance sensor to monitor incident solar energy and an anemometer to measure wind speed and direction (on loan from HNEI) were also deployed in conjunction with the power system. Ideally this data could be used to calculate the operating efficiency of the PV panel and the wind turbine. While the solar sensor performed as expected, the anemometer was not located such that it recorded the same wind field experienced by the wind turbine; this was observed when the wind turbine and anemometer would align themselves out of parallel with one another. Although the anemometer was close to the wind turbine and out of the trajectory of the wind that interacted with the wind turbine, the turbulence of the wind patterns in the area were apparent during lower wind speeds. However, during high winds the anemometer and wind turbine would yaw equally into the wind. Subsequently, the anemometer data was used to make a semi-quantitative assessment of turbine performance rather than a rigorous efficiency calculation.
Physical Data Logging System

Data logging system physical walkthrough: As seen in the upper right of Figure 11 all power inputs (photo voltaic (PV), wind turbine (WT), Battery) are
connected through switchable breakers. Breakers were utilized for safety and ease of switching as well as a means of connecting large gauge wire from the PV panel and WT to the data logging equipment. Shown in the top left, a standard programmable solar charge controller was utilized and also powered the dump load (LED lights.) In the center from left to right there is a step down DC power supply for the Analog to Digital converter. In the center there are 4 shunts that enable recording of PV input, WT input, Battery potential, and the combined dump load. There is also a power buss for the shunt circuit boards in the center to the left of the fuses for the power supply. The blue box in the center right is the Analog to Digital Converter. At the bottom from left to right there is a step down power supply for the Anemometer circuit board powered by an automotive USB/12vdc power outlet that also supplies power via USB to the Raspberry Pi (tiny data recording computer not shown.)

Data Acquisition System

Data logging equipment was designed and assembled to record numerous data points in the system digitally at approximately one-second intervals. The following system data was recorded: wind speed, wind direction, solar irradiance, voltage at the solar charge controller, battery bank voltage, wind turbine amperage, amperage on the load side of the charge controller and the amperage flow between the battery and the charge controller. The core of the data logging system was a Raspberry Pi 3 (RPi3) Model B Quad-Core computer. The Raspberry Pi received input from an (M-7017) 8-channel analog input module known as an analog-to-digital (A-D)
The A-D converter is limited to 8 separate data inputs. Three of these data streams were used for logging wind speed, wind direction and the solar irradiance sensor. Of the remaining 5 available data ports, 2 were used to monitor system voltage (battery and charge controller) and 3 were used to monitor current (Figure 11). Data collection points within the physical data for current measurements by the logging system are shown in Figure 12, which also shows energy flow direction. Bi-directional current flow such as that between the solar charge controller and the battery bank is recorded as positive and negative data (negative represents charging in this system.)
### Measured Quantities

<table>
<thead>
<tr>
<th>Measured Quantities</th>
<th>Units/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>Mph (miles per hour)</td>
</tr>
<tr>
<td>Wind direction</td>
<td>0 to 360° (North = 0°, East = 90°)</td>
</tr>
<tr>
<td>Solar Irradiance</td>
<td>Watts per square meter (w/m²)</td>
</tr>
<tr>
<td>Charge controller voltage (Vcc)</td>
<td>Volts</td>
</tr>
<tr>
<td>Battery voltage (Vbatt)</td>
<td>Volts</td>
</tr>
<tr>
<td>Wind turbine current (Iwt)</td>
<td>Amps (current flow from wind turbine)</td>
</tr>
<tr>
<td>Load current (Ild)</td>
<td>Amps (current flow to LEDs)</td>
</tr>
<tr>
<td>Charge controller (Icc)</td>
<td>Amps (current flow between battery &amp; charge controller; i&lt;0: charging battery)</td>
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</table>

Table 1. List of data logged by the data acquisition system. The complete set of eight inputs was logged at approximately one-second intervals.

### Calculated Quantities

<table>
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<th>Equation</th>
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<td>PV Panel Current (Ipv)</td>
<td>$I_{pv} = I_{ld} - I_{cc}$</td>
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<td>Based on current balance at charge controller</td>
<td>$(I_{cc} &lt; 0: battery charging)$</td>
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<tr>
<td>Battery Current (Ibatt)</td>
<td>$I_{batt} = I_{cc} - I_{wt}$</td>
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<tr>
<td>Based on current balance at battery bank</td>
<td>$(I_{batt} &lt; 0: battery charging)$</td>
</tr>
<tr>
<td>PV Panel Power (Ppv)</td>
<td>$P_{pv} = I_{pv} \times V_{cc}$</td>
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<tr>
<td>Wind Turbine Power (Pwt)</td>
<td>$P_{wt} = I_{wt} \times V_{batt}$</td>
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<td>Load Power (Pld)</td>
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<td>Battery Energy (Ebatt)</td>
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Table 2. Summary of quantities calculated from primary data.

### Results

The off-grid PV and wind turbine energy system was deployed from mid-June to mid-August. It is useful to describe the performance of the system on multiple time scales. Specifically, understanding the nature of the wind energy resource requires discussion of power production on very short time scales (minutes or seconds), while a comparison of the relative performance of the PV and wind energy
components requires a minimum integration of a full 24 hour day-night cycle. Although, a performance comparison over the full annual cycle is also desirable, practical considerations limited the duration of the testing period to approximately 2 summer months. The testing period ended with the arrival of Hurricane Lane when the wind turbine and PV panel were dismounted and placed indoors to avoid damage.

**Wind Energy Production**

The amount of energy produced by the wind turbine was disappointing. This project was motived by an expectation that wind energy production by the turbine would yield a respectable fraction of total household energy use (approximately 40 KWh.) For the entire month of July slightly less than 2 KWh of wind energy were produced. The percentages given below are based upon the daily energy production and consumption data for July (Table 3.) Daily wind energy production averaged 14% ± 5 % (1 S.D.) of total energy production, with a minimum of 5% and a maximum of 27% (Figure13.) PV and wind energy production show no correlation on a daily basis throughout July. Note that ideally this assessment could be made over a full annual cycle.
Table 3. July energy production by wind turbine (WT) and photovoltaic panel (PV.)
Load and power to and from the battery (neg. is charging) is also shown as well as the percentage of total daily energy that was produced by the wind turbine.

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Figure 13. Is a stacked line diagram of daily PV (blue area) and wind (red area) energy production throughout July. Note that PV energy production is consistently more than 4 times larger than wind energy production.

Importantly, nighttime wind energy production was small compared to daytime wind energy production. Over the course of July, night wind energy production averaged $22\% \pm 9\%$ (1 SD) of total daily wind energy production, with a maximum of $39\%$ and a minimum of $8\%$. Compared to total (PV & wind) energy production, nighttime wind energy production is only $3.4\% \pm 2.3\%$ of the 24hr total, with a maximum of $9.6\%$ and a minimum of $0.5\%$. Nighttime wind energy is of special interest because it contributes to meeting energy demand when PV energy production is zero. Significant nighttime power production by the wind turbine could also contribute to a reduction in the battery bank size required to meet specific demands and would also increase the overall resilience of the off-grid power system. The lesser contribution of night wind energy production is illustrated
by a comparison of nighttime vs. daytime wind energy production on a daily basis throughout July as seen in Figure 14. This is consistent with the common perception that winds tend to build following sunrise and become calmer at night. Qualitatively, examination of daily records indicates that most nighttime wind energy production occurs in the early part of the night and is correlated with the strength of daytime winds from earlier that day.

![Correlation of Day & Night Wind Energy Production](image)

Figure 14. Comparison of night time to day time wind energy production on a daily basis for the month of July.

At a given point wind speed and direction vary on multiple time scales and these natural variations contribute to highly variable wind energy generation. As expected, the wind energy resource is largely determined by the prevailing easterly trade winds (Figure 15a.) Although these winds are persistent in climatological
terms, at a given point they show large variations on short time scales (gusts) that are of great importance in assessing the small-scale wind resource. Figure 15b represents 6 minutes of data (≈ 360 lines of data corresponding to our 1 sample per second). Note that the one sampling per second frequency of data collection allows accurate measurement of wind power produced by these gusts. For example, a current peak of 0.005 decimal hours (18 seconds) duration produced by a gust of wind Figure 15b is defined by 18 separate measurements. Lower sampling rates; such as hourly measurements at meteorological stations likely lack the data resolution to accurately represent the wind resource on a smaller time scale.
Figure 15. (a.) Wind direction data from June 16 (24 hours of data) illustrating typical trade wind conditions that were associated with the most wind power production. (b.) A 6-minute record of wind turbine current production from the same day illustrates the short pulses of power production associated with wind gusts.

Technological limitations also contribute to the intermittent character of the wind resource. Although winds of any speed carry energy, there is a threshold
windspeed known as the *cut in speed*, below which a wind turbine cannot generate energy. Below the cut in wind speed no energy is produced because the wind is not sufficiently strong enough to overcome the inertia of the stationary turbine blades. For the Air 40 the cut in wind speed is 7 mph (Figure 16.)

![AIR Power Curves](image)

Figure 16. AIR 40 Wind Turbine Power Curve. The power generation as a function of wind speed for two different commercial (Primus) wind turbines. The red curve corresponds to the Air 40 deployed in this study.

This 7 mph cut in wind speed for energy production is a major factor that limited wind energy production at the deployment site on East Oahu. In spite of the mismatch in height between the anemometer and the wind turbine, it was possible to make a first order comparison of acquired wind speed data and wind turbine energy production. In contrast to Figure 16 the data acquired in this study display a
great deal of scatter; including no power generation during times of high wind speed as well as power production at lower than cut in wind speed (Figure 17.)

![June 23 Data](image)

Figure 17. Comparison of measured wind speed to measured wind power generation for June 23 (blue points) displays a similar trend to manufacturer specification but with a great deal of scatter. (Black squares based on Figure 16.)

Although we cannot be certain of the cause of the scatter, we suspect that it is the result of turbulence caused by nearby trees and structures creating large variations in wind speed and direction on small spatial scales. This was an aspect of wind energy production that we did not fully appreciate at the outset of the study.
Qualitatively, obstructions to the prevailing wind regime are analogous to clouds shading a PV system, but more difficult to visualize and anticipate.

Last, but perhaps most important is the location of turbine deployment. Figure 18. Shows that wind power production is a highly non-linear function of wind speed. Deployment at a different site, for example windward Oahu, with average wind speeds of 15 mph vs 10 mph, and in an area with less turbulence from structures and vegetation, would significantly increase wind power production.
In a wind regime with constant 15 mph winds, the wind turbine has the capacity to produce 2400 Wh of energy per day. The average amount generated over July was 57 Wh, corresponding to a capacity factor of between 2 and 3%. This is about one tenth the value typically associated with wind energy production.

**Discussion**

Hydro or Geothermal energy production requires very specific source terrain or temperature gradients that are not homogenously dispersed globally. Wind energy, although not perfectly homogeneously distributed globally, is the most readily attainable renewable energy resource. Wind energy can be harvested utilizing infrastructure that can be constructed from globally available salvage material (*Ahsan 2014*.) As our climate continues to change, the ability to easily produce renewable energy will become increasingly important.

Sea level rise will likely displace millions into areas with less grid infrastructure than the current highly populated coastal areas. It has been estimated that by the year 2100 approximately 2 billion people (an expected 1/5\(^{th}\) of the global population) we be displaced by rising sea level (*Friedlander 2017*.) Climate change refugees will be forced to seek higher ground. In many second and third world countries the inundation of areas by climate change refugees may cause massive utility grid infrastructure failures. Access to electricity can save lives in developing and over populated areas of the world. With human migration forced by sea level change, countless individuals would benefit from the ability to harvest
renewable energy. Electricity can provide refrigeration for food storage as well as certain medicines that require refrigeration. Water can also be desalinated, sterilized, and purified with electrically driven equipment. At a very basic level, electricity can be utilized to boil water thus sterilizing it and mitigating problems from water-borne illness in heavily populated areas.

Similarly to small-scale wind energy production being able to mitigate the hardships of an area inundated by a flood of refugees, the availability of renewable energy could also help with future extreme weather events. Small-scale wind energy could greatly improve a community’s resilience to natural disasters and their associated utility grid failures. One advantage of small-scale wind turbines is that they are easy to store in a safe area during storm events such as hurricanes. In an area like Puerto Rico that was continuously damaged in 2017 by large hurricanes, small-scale wind power and residential battery banks would have been hugely beneficial. These large storms are well forecasted often up to a week in advance. Individuals have plenty of time to take down small-scale wind turbines and store them safely. Immediately following a storm event off grid systems can be reassembled and can be immediately useful to survivors and emergency personnel. During long power outages especially during a flooding event like Hurricane Harvey in 2017, the ability to call for evacuation or listen to government direction can be the difference between life and death.
As seen in Table 3 there are significant challenges facing small scale residential wind power in urban environments. The significant impact of turbulence from nearby structure and vegetation could perhaps be overcome in future experiments by utilizing smaller wind turbines that have a lower cut in speed.

**What Can Be Done With This Power**

The easiest way to implement small-scale residential renewable energy is to keep it off grid. This approach mitigates permitting issues and eliminates the need to enter into net metering agreements with the local utility. However, care must be taken to ensure that off-grid systems conform to local electrical codes for safety. Off grid setups also ensure the benefit of owner resilience to power grid failures such as blackouts resulting from heat waves or storm damage. By converting part of your everyday energy demand to off grid power you are removing those corresponding loads from the grid thus contributing personally to greater sustainability and the resiliency of our society. For instance, powering a refrigerator, household lighting, or charging electronics daily from off grid power would both lessen grid demand and ensure that those items will continue to operate during grid failures. While renewable energy system sizing is always relevant to the amount of energy one wishes to utilize on a daily basis, in terms of resilience during power grid failure some individuals are more at risk than others. The elderly or individuals with special medical needs are at very high risk during power grid failures. This is where small-scale residential power production can be very beneficial. For instance, unused insulin containers need to be kept between 36°F and 46°F and in general if
insulin is not stored in the refrigerator it should at be stored as cool as possible (Kent 2014.)

The least energy intensive means of refrigeration is by being able to utilize DC power directly from a battery bank. There are now several companies making thermoelectric coolers that operate on 12VDC. These thermo electric coolers utilize Peltier modules for cooling and have no condenser like today’s conventional refrigerators thus require much less energy. As seen in Figure 19 Igloo’s Iceless 40Qt cooler can be utilized as a cooler or upright as a refrigerator and draws 4.5 to 6.5 amps 12VDC depending on outside ambient temperature etc. In terms of operating this thermo electric cooler from the system constructed for our experiment it is important to understand the basics of energy use and production.

Figure 19. Igloo 40Qt Iceless cooler 4.6 – 6.5A 12VDC
Understanding Power Production Storage And Use

Understanding power production, storage, and use is not complicated but it is often not common knowledge. For simplicity and cost, the system constructed for this project employed solar panels and wind turbines that produce 12VDC (12Volts Direct Current.) This means that the solar panels were factory built to produce 12VDC, as is the wind turbine. 12VDC batteries and accessories/appliances are often cheaper than other options because the automotive industry operates on 12VDC. Car batteries and nearly everything that has been made for the RV or trucking industry, as well as everything you plug into your car operates on 12VDC. Therefore, 12VDC was deemed most suitable for this study as opposed to also including an inverter to convert DC power to higher voltage AC power used in grid-connected residential systems.

Off-grid energy system design typically begins with considering the load, or power consumption requirements. Calculating an appliance’s load takes some understanding of how power requirements vary over time. For instance, a one-cup coffee maker requires a lot of energy but it only operates for about 25 seconds and it may only operate once or twice a day. Whereas a thermo electric cooler that can be utilized as a 12VDC refrigerator will operate all day and night because they lack a thermostat. Although nearly all electric appliances or their power supplies have a sticker displaying the electricity input, output, and load (seen as watts,) some simple math may be required to obtain needed information. If you have an appliance that only tells you the watts you can divide by the operating voltage to get the amperage...
required by the appliance (Watts/Volts =Amps.) Figuring out the amperage an appliance requires to operate is an effective means to estimate the battery storage requirements of an off-grid system.

Batteries are labeled by their Amp hour capacity some times labeled “RC” for Reserve Capacity rating in Amp hours. This is a convenient way of expressing the total amount of recoverable charge that can be stored in a battery. Simplistically speaking, ignoring the efficiency of discharge rates in certain batteries, a battery or battery bank that has 50 usable amp hours can run a 1-amp appliance for 50 hours, or a 50-amp appliance for 1 hour. Considering a thermoelectric cooler consumes 4.5 to 6.5amps at 12VDC, we can calculate how much energy this appliance will require over a given time period. A worse case scenario assumes that the thermoelectric cooler continuously consumes 6.5 amps.

**Example Calculation**

For simplicity, considering that we don’t know the wind turbine energy production from your wind resource without qualitative analysis of your unique area, lets assume only a constant *photovoltaic* power input. Lets assume 10 solid hours a day of good usable solar power meaning that our appliance will rely solely on the battery bank and no incoming power for 14 hours a night. This means that our battery bank being fully charged needs to be able to supply 6.5 amps x 14 hours meaning we need a battery bank that has at least 91 usable amp hours (Table 3.)
Note that I said 91 usable amp hours (91AH worth of charge in a type of battery that can safely supply 91AH) some batteries like the lithium ion batteries in your phone can be fully discharged without damaging the battery. The batteries in the power system constructed for this experiment were lead acid batteries. Lead acid batteries although affordable are not able to be fully discharged without damage, they are also much heavier than lithium ion batteries. A standard car battery is only meant to start your car and then an alternator running from the petroleum fired engine will recharge the battery while powering all electronics on the car. Therefore, a standard car battery is meant to deliver a huge amount of power (sometimes up to 800amps) while cranking the car for only a few seconds. Standard car batteries only have a usable range or cycle of about 10% to 20% of their entire reserve capacity. To power 12VDC items that require more energy there are 12VDC Deep Cycle batteries. Deep Cycle batteries are sometimes referred to as Marine batteries as they are very common on watercraft where it is important to have greater usable reserve battery capacity to operate radios, lights, bilge pumps etc. In general deep cycle batteries can be cycled to about 50% of their total reserve capacity without damaging the batteries, although only using 30% to 40% of their reserve capacity is better for their longevity.

Knowing that we need 91 usable Amp hours to sustain our thermoelectric cooler during a 14hr period, we can calculate whether the battery bank employed in this test study is large enough to operate this appliance. The battery bank constructed for this experiment is comprised of 4, 175amp hour batteries wired in
parallel. Wiring batteries in parallel does not alter the voltage, our battery bank remains 12VDC but it's as if the battery has 4 times the original amp hour capacity. 4 x 175 amp hours = 700amp hours total. Although we have 700 amp hours in reserve capacity in our battery bank these deep cycle batteries should only be cycled to 50% of their total reserve capacity. 700 amp hours / 2 = 350 *usable* amp hours, therefore we can definitely power our thermo electric cooler during 14 hours of darkness (91 amp hours.) If we take our usable reserve capacity 350amp hours divided by the 6.5amps that the cooler draws per hour this equates to 53.8 hours. Starting with the fully charged battery bank it could run the thermoelectric cooler for approximately 53 hours. With just this understanding you can see how an individual who requires insulin to be refrigerated would be resilient during a power outage for over two days even with no other power input.

In our battery bank example assuming a daily 14 hour period of no solar power input (evening, night, and dawn) drawing a total of 91 amp hours (Ah) from our battery bank we need to not only replace the 91Ah with solar power but we also need to continue to power the thermoelectric cooler during the day (Table 4.) We want to create a robust off grid system that is not discharging more than it is charging. You normally want to produce more energy than you consume to insure a fully charged and maintained battery bank. A solar charge controller will prevent battery over charging and solar panels can simply turn off or trickle charge batteries once fully charged. The wind turbine we utilized (the AIR 40) has an internal microprocessor to prevent overcharging a battery bank. However, in a typical
situation where a wind turbine is producing energy but it’s battery bank is full there is often a mechanism to utilize excess energy such as to heat water etc. The solar panel utilized in this experiment produced 100W at 12VDC so 100W/12V= 8.33 amps. For simplicity lets assume the solar panel is incredibly efficient and can actually produce 8 amps (just because the math says it can produce 8.33 this is FAR from the actual average output.) With the thermoelectric cooler constantly utilizing 6.5 amps its as if we only have a 1.5amp solar panel (8A-6.5A=1.5A to battery.) Therefore during the remaining 10 hours of daylight the system is only able to charge the battery 1.5A x 10hrs = 15Ahrs. In this situation although the cooler only consumes 6.5 amps and the solar panel can produce 8amps, if we look at the time we wish to draw off the battery (24 hours a day) and the conservative amount of time we will be producing power (10hrs,) this will result in a net battery drain. In this example the system would be drawn upon 156Ah per 24hr period and only producing 15Ah per 24-hour period. If you were in an area with a good wind resource the wind turbine could potentially make up for this loss. However, during our experiment the average daily wind turbine input during the entire month of July was approximately 4.8Ah, and only 8Ah max. Although the real time wind turbine current input was far from making up for our 141Ah daily deficit in our example, a turbine deployed in a better wind regime should show vastly more current input.

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<td>PV Amperage 8Amps 12VDC</td>
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Table 4. Cooler load and PV current input by time.
For simplicity we will only consider solar power input in our example. In this situation we know we need to produce at least 156Ah of renewable energy per day. Keeping with the example convention that we only have 10 hours of sunlight per day and that our 100W solar panels could produce 8amps or 80Ah per day (8A x 10hrs daylight = 80Ah) we can calculate how many more solar panels are needed. With 156Ah required by the thermoelectric cooler divided by 80Ah of energy produced by each solar panel daily this equals approximately 2, 100W solar panels (156Ah / 80Ah = 1.95 panels.) Assuming the thermoelectric cooler will always consume its maximum load and that our solar panels can produce energy for 10 hours per day and at 8 amps each per hour, in this example calculation we can assume that two solar panels will run our thermoelectric cooler indefinitely with our current battery bank. The solar charge controller utilized in this experiment can handle up to 20Amps 12VDC so an additional 8.33A solar panel can easily be added to the system without changing any infrastructure. We also know that if there was no energy produced at all from our solar panels we could still sustain our thermoelectric fridge from our battery bank for approximately 53.8 hours without damaging our batteries. Note that this example simulation does not take into account for cloudy days and other solar panel inefficiencies.

The Truth

Due to tree shading at different times of the day and true efficiency factors the average daily July PV panel input was only 30.3Ah. (Table 3) Although the example simulation may be easier for educational purposes our 30.3Ah average
reflects a true approximate 15% efficiency factor for the 100W solar panel. Output from a 100W solar panel for 24 hours should equal 2400W hours or 200Ah (2400Wh/12V=200Ah) of output. However, knowing that there is nightfall as well as clouds and efficiency limitations of the solar panel, assuming a 15% efficiency factor 200Ah x 15%=30Ah which matches our actual 24hr amp hour findings. Therefore in reality the required number of 100W solar panels needed to produce 156Ah minimum to maintain the 24-7 use of our thermo electric cooler is 156Ah/30.3Ah = 5.2 solar panels. With 6 solar panels on this system the solar charge controller should be upgraded to handle the maximum instantaneous amperage of the solar panel array regardless of efficiency factor, for safety.

While the collected data may be dismaying to those looking to power a portion of their lives from renewable energies keep in mind that many of your daily energy uses can be replaced with just one 100W solar panel and 2 of these same deep cycle batteries. Utilizing this exact same solar panel and two of the exact same batteries I was able to comfortably live off grid for 7 months powering a 400 lumen light when needed as well as a fan for 8 hours a night, a small rice cooker for 20mins a day, a one cup coffee maker, charge a laptop and two phones (one acting as a wireless hotspot.) On very cloudy months, some days I had to forego the coffee. This was a great qualitative experiment that left me wanting for very little and happy that individuals the world over could live on renewable energy somewhat easily. However, beings that solar panels cannot be constructed from scratch, wind power seemed to be a more globally obtainable resource.
The example calculation shows the simulated benefit of small-scale wind energy production. We had to assume only 10 hours a day for energy production whereas wind energy can be harnessed at any time in a 24-hour period. The ability to produce energy at night when solar panels have been rendered useless is a hugely powerful tool in one's ability to move towards green energy. The wind turbine utilized in this experiment the Air 40 can produce 16Amps therefore during a strong breeze its as if you gained two operational solar panels even if the strong breeze is at night or during cloudy or stormy periods. Unfortunately in reality due to our substandard deployment location (turbulence from nearby trees and structures) we did not achieve results assimilating the AIR 40 to the output of two 100W solar panels. In reality as seen in Figure 13. and in Table 3. PV power production averaged more than 4 times greater than wind turbine power production for the entire month of July.

**Conclusion**

Although the results of the experiment yielded dismal results in terms of small-scale residential wind power production in urbanized neighborhoods. One can reasonably expect that better results would be obtained if the experiment were performed from elevated or windward coastal homes. Prior to data collection the impact of turbulence in the wind resource at 30’ in elevation in a neighborhood setting was not understood. At the deployment location on East Oahu the turbine had a nearly direct line of sight to the ocean overlooking a vacant lot. However, the turbulence created by neighborhood structures and vegetation caused the turbine
to regularly yaw out of the wind resource during operation. This experiment helps to paint a clearer picture of where small-scale wind energy can be implemented successfully. However, future experiments utilizing smaller wind turbines that have lower cut in speeds may yield more desirable results. The data logging equipment constructed can provide a great deal more data for other similar projects in various areas. Ultimately the off grid (solar and wind) tiny home on the Waimanalo Ag. Campus will hopefully be utilized as a tool to facilitate place-based experiential learning about sustainability.

Figure 20. Tiny home located on the University of Hawaii, Waimanalo Ag. Campus. The hybrid solar and wind turbine set up is planned for installation at this location in a way that is accessible to those interested in learning how to implement their own renewable energy. Ideally, this pipeline between the School of Ocean Earth Science and Technology (SOEST) and the College of Tropical Agriculture and Human Resources (CTHAR) will allow forward thinking, environmentally conscious students of diverse backgrounds to collaborate between departments and continue hands on science for the future.
Special Thanks

To my **Girlfriend**: My best friend, who is always there for me.

To my **dog Jack**: Mans best friend who has put up with nearly 7 years of college.

To my **Parents and Family**: Who took the time to teach me the skills required perceiver through life.

To my **Grandpa Goose**: An electrician by trade who passed away during the completion of this paper, who may have enjoyed reading it, and who finally agreed that I am no longer in “diaper school.”

To **Greg Ravizza and his Family**: For expertly helping advise my Master's Degree and allowing me to install my data logging equipment on their property.
Works Cited

Why limiting global warming to 2 degrees Celsius is so important (2017, August 23) retrieved 17 October 2017 from https://phys.org/news/2017-08-limiting-global-degrees-celsius-important.html


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Hawaii’s Electricity Production by Source (Source EIA) https://data.hawaii.gov/dataset/Hawaii’s-Electricity-Production-by-Source-Source-E/it4ckd85


