Testing the Potential Energy Production of Wind and Solar Farms at High Altitude

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1 Abstract

Power output of a wind turbine and solar cells was measured at high altitude (a maximum of 340 m), and pressure and temperature were measured to determine their usefulness in estimating altitude. In order to perform these experiments, a weather balloon was filled with helium and used to lift a payload containing instruments to collect the necessary data. The assumed relationships between pressure and altitude as well as temperature and altitude were confirmed. Additionally, it was determined that there was little significant increase in power generated from solar cells at high altitude. Due to difficulties measuring wind speed at high altitude, however, it remains to be determined whether wind farms at high altitude are an efficient way of generating electricity.

2 Introduction

2.1 Background

2.1.1 Atmosphere

The Earth's atmosphere is critical to the survival of humans as well as other living things. This is because it is made up of various layers of gasses that absorb ultraviolet radiation as well as help maintain a moderate environment by regulating the Earth's temperature [1].

The atmosphere is composed primarily of the gasses nitrogen, oxygen, argon, and carbon dioxide. The concentration of these gasses is

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lower at higher altitude and higher at a lower altitude. Additionally, the Earth's atmosphere is essentially in hydrostatic equilibrium, meaning the upwards force of air due to pressure gradients is equal to the force of gravity. Since air is assumed to work like an ideal gas, that upward force of air is caused by higher pressure molecules attempting to move into areas of lower pressure. However, gravity keeps the atmosphere stratified; its force keeps those molecules from equalizing the atmosphere and causes the air to be denser at lower altitudes. Denser air results in a higher barometric pressure. As pressure decreases, temperature also decreases because the fewer molecules there are, the less kinetic energy the space contains. This is demonstrated by the Ideal Gas Law $PV = nRT$ (where P is pressure, V is volume, n is amount of gas measured in moles, R is the gas constant, and T is temperature). Thus, as altitude increases, pressure and temperature both decrease [2].

These principles clarify what we know about the atmosphere and why it is a critical component of life on Earth. The two primary benefits of our atmosphere are the absorption of UV rays and the heating of the Earth via the greenhouse effect. Oxygen and ozone gasses, primarily, absorb almost all wavelengths of light shorter than 300nm, making this harmful radiation unable to reach the Earth. The greenhouse effect is essentially the atmosphere's ability to trap heat trying to escape the Earth. When light hits the Earth it is absorbed and reemitted as infrared radiation (due to the properties of the Earth's surface). Greenhouse gasses, such as water vapor and carbon dioxide, absorb this infrared radiation and reemit it back to the Earth, thus continuing to heat both the air and the Earth's surface. This prevents heat from the Sun from escaping and allows the Earth to maintain livable temperature conditions. The great value of the atmosphere makes it of interest to study and continue to investigate [3].

2.1.2 Renewable Energy

In recent years there has been a drive towards renewable energy due to the environmental crisis we are now facing. One potential source of energy that has begun to be used is wind power. However, to date most turbines that tap into this source of energy have been land-based, which some argue is not the most efficient way of harnessing this energy. The wind at low altitude is subject to surface friction, which slows it down considerably. However, the wind higher up in the atmosphere is considerably stronger since it is not subject to as much friction. Theoretically, this would yield a higher amount of energy than the current models [4] [5].

Another potential source of energy is solar energy. This raises a similar question as to whether it would be more efficient to produce solar energy at higher altitudes, closer to the sun and thus not subject to the filtering effects of the atmospheric gasses. Theoretically, at high enough altitudes it would be significantly easier to harness solar energy. But for both of these energy sources, it is unclear whether the advantage gained of producing energy at a high altitude is worth the costs of sending a balloon up to the sky.

2.2 Theory

2.2.1 Balloon Liftoff

For both experiments, it was necessary to perform tests at varying altitude. In order to do this, a weather balloon was filled with helium and sent up to an altitude of approximately 1000 ft. The balloon was tethered to the reel and maintained its maximum altitude for a while, then was reeled back down.

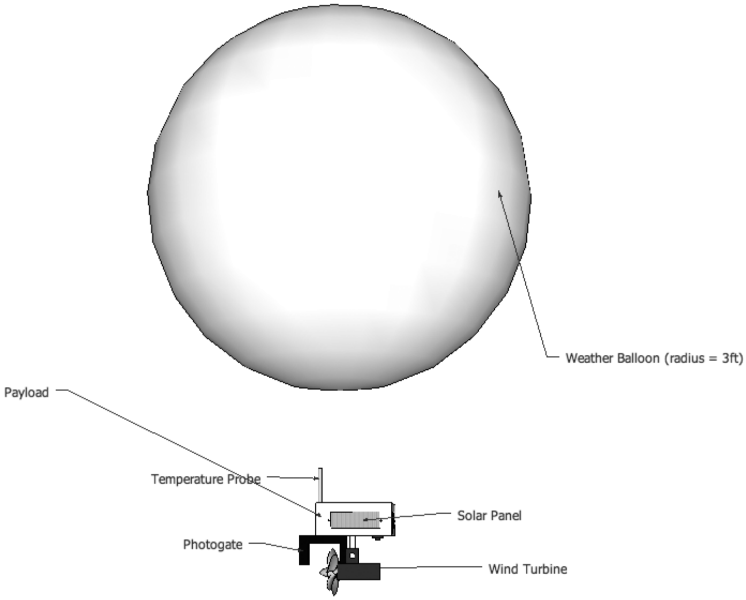

Figure 1: *Overall Setup of the Experiment. A weather balloon with a radius of approximately 0.9 meters lifts the payload 1,000+ ft. into the atmosphere. The outside of the payload includes a temperature probe, photogate, four solar panels wired in series, and wind turbine. The temperature probe is used to measure the outside temperature. The photogate is used to measure the rotation of the wind turbine. The solar panels are used to measure solar energy in the atmosphere. The wind turbine is used to measure wind power in the atmosphere.*

A payload was attached to the balloon to hold the apparatus (see Appendix B) needed to perform the various experiments. The maximum payload weight had to be determined, as well as the force that would need to be applied by the reel in order to anchor the balloon and bring it back down to Earth.

In order to compute the buoyant mass (the maximum load that can be lifted) of the weather balloon ensemble, the volume of helium contained by the balloon must first be determined [6] [7].

$$r = 3\text{ft} = 0.914\text{ m}$$
$$V = \tfrac{4}{3}\pi r^3$$
$$V = 3.2\text{ m}^3$$

And from the volume, the buoyant mass can be calculated (ρ_{he} = density of helium at 20°C and 1atm).

$$BuoyantMass = (\rho_{air} - \rho_{he}) \cdot V$$
$$BuoyantMass = (1.21\ \mathrm{kg/m^3} - 0.16\ \mathrm{kg/m^3}) \cdot 3.2\ \mathrm{m^3}$$
$$BuoyantMass = 3.36\ \mathrm{kg}$$

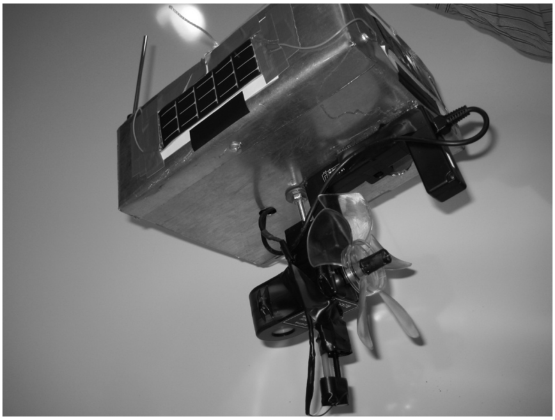

Figure 2: *Underside of the constructed payload. Wind turbine and photogate are mounted to the bottom of the aluminum box to measure wind power and wind speed.*

From this value, the mass of the weather balloon (0.20 kg) is subtracted, which gives a maximum mass of 3.16 kg for the payload. However, the payload ended up being 1.63 kg, allowing for the apparatus to maintain some net buoyancy. The net buoyancy (after attaching the payload) was:

$$NetBuoyancy = (BuoyantMass - M_{balloon} - M_{payload}) \cdot g$$
$$NetBuoyancy = (3.36\ \mathrm{kg} - 0.2\ \mathrm{kg} - 1.63\ \mathrm{kg}) \cdot 9.83\ \mathrm{m/s^2}$$
$$NetBuoyancy = 15.0\ \mathrm{N}$$

However, if the reel used to anchor the balloon is locked, the balloon's ascent is blocked, and by Newton's Third Law the net force applied on the balloon is transferred to the reel, making the net force on the reel 15.0 N when the reel is locked. Similarly, the same 15.0 N of force is required by the reel system in order to pull the balloon down at a constant velocity.

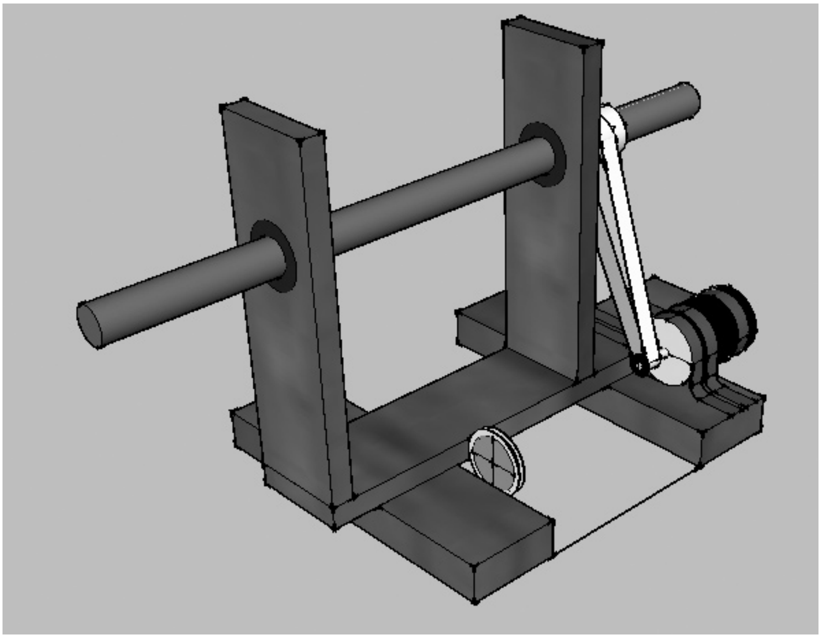

Figure 3: *Sketchup of reel system. Rope (not shown) wraps around main shaft and attaches to balloon. Motor turns shaft to unspool rope and let balloon rise or to reel balloon back down.*

2.2.2 Pressure and Temperature

Pressure and temperature data were taken to estimate altitude above sea level. The section of atmosphere within which the experiment was conducted is called the troposphere. Inside the troposphere, according to the U.S. Standard Atmosphere Model, pressure and temperature both decrease as altitude increases. Up to the roof of the troposphere, 11 km above sea level, the equation $T = T_0 \cdot (1 - h/44329\ m)$, where T_0 is equal to the absolute temperature at sea level, 288.15 K, can be used to find the temperature in Kelvin. The pressure in Pascals ($\frac{N}{m^2}$) can be determined by the equation $P = P_0 \cdot (1 - h/44329\ m)^{5.255876}$, where P_0 is equal to the standard air pressure at sea level, 101.325 kPa [8].

To prove this relationship existed, a brief experiment was conducted where pressure data was taken at three known altitudes. One data point was taken at 167 ft. above sea level (50.90 m), another at 63 ft.

above sea level (19.20 m), and the final one at sea level. This confirmed the theory that pressure decreases as altitude increases (see Figure 4).

In order to collect data on pressure and temperature, a barometer and a temperature probe were placed on the payload to read data to the LabQuest. Data was collected during ascent and descent of the balloon to estimate altitude.

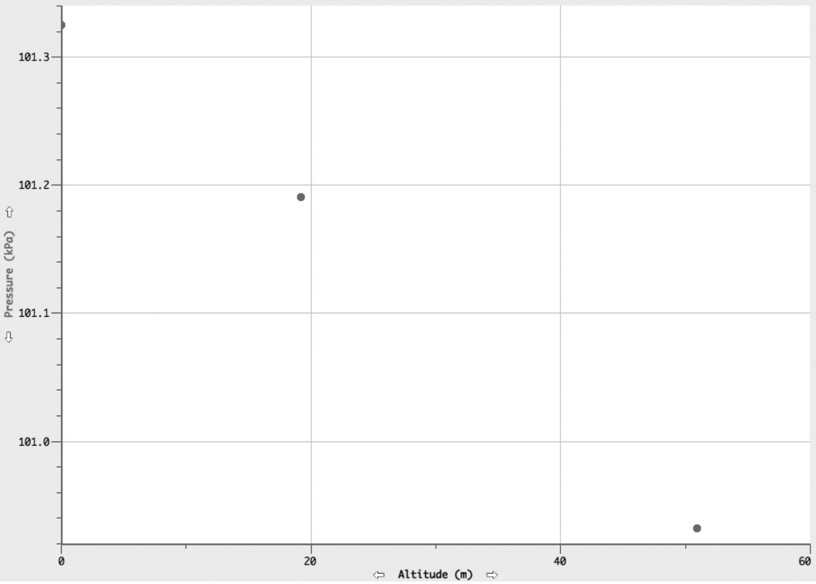

Figure 4: *Graph of pressure vs. altitude. Although the calculated values of pressure differ slightly from the actual measured values (as expected at such low altitudes), there is a marked decrease in the measured atmospheric pressure from 19.20 m to 50.90 m. That is consistent with the equation and NASA's model.*

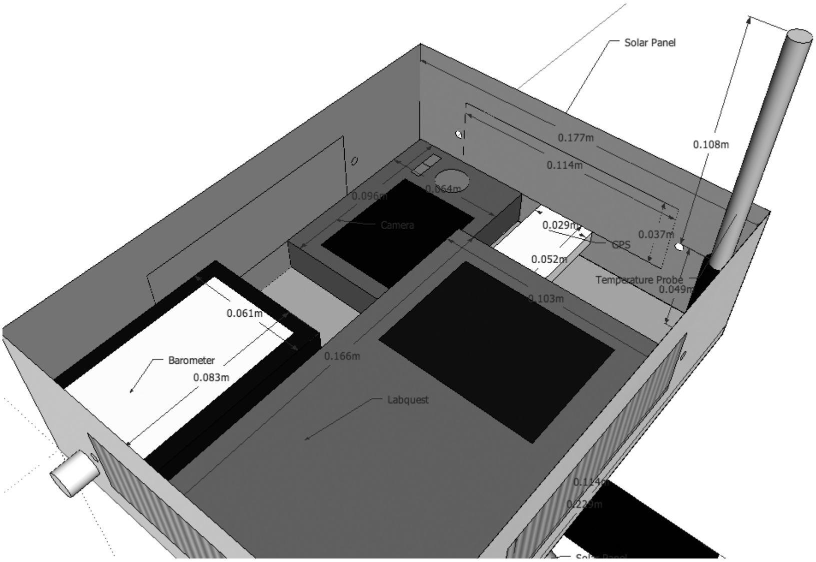

Figure 5: *Interior of the payload. The there is a camera, LabQuest, GPS, and barometer. The camera lens is sticking through a hole in the bottom of the payload. The camera is shooting a time-lapse video, taking a photo every second. The barometer is measuring the atmospheric pressure and is protruding from the side of the payload. The GPS is used to find the longitude and latitude of the payload. The temperature probe is protruding from the lid of the payload and is measuring the outside temperature. The LabQuest is recording the data of the devices connected to it: barometer, solar panels, the wind turbine, the GPS, the temperature probe, and the photogate.*

2.2.3 Wind and Solar Energy

The experiment performed with the on-board wind turbine during the weather balloon's flight sought to verify the validity of the claim that turbines at higher altitudes yielded energy more efficiently by comparing the wind speed to the power outputted by the wind turbine and graphing the windspeed against the altitude.

The wind turbine was attached to the bottom of the payload (see Figure 7) and its power output was measured. The fan of the turbine turned a generator that completed a circuit with a 10 Ω resistor. The voltage drop across the resistor was measured to find the power dissipated using the equation $P = \frac{V^2}{R}$.

The windspeed was measured using a photogate measuring the motion of the wind turbine blades. Since the photogate gave a reading in terms of linear velocity, an equation to relate the linear velocity reading of the photogate and the windspeed was found by doing in-house testing of the photogate at known windspeeds. After a natural logarithm curve was fitted to the resulting points (see Figure 6), it was found that velocity measured by the photogate = 0.52 · ln(1.43 · *windspeed*). This formula would then allow us to directly plot windspeed against power output of the wind turbine.

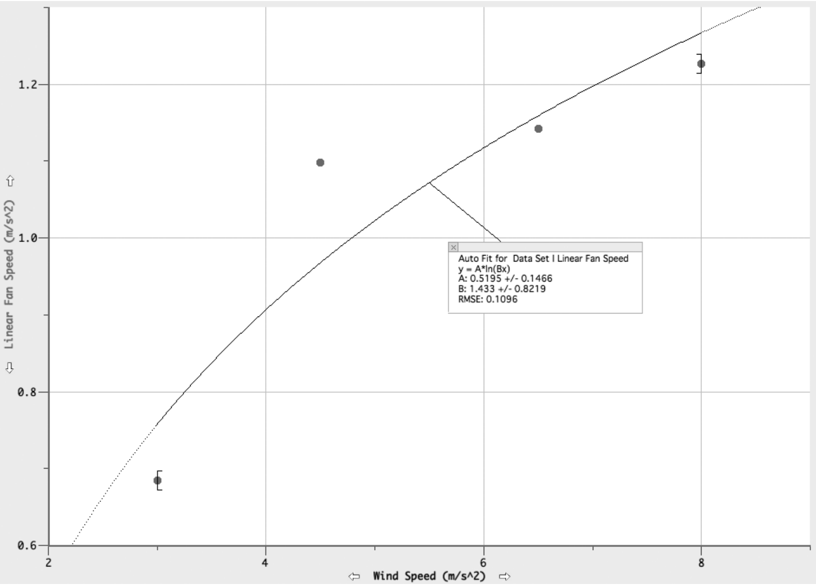

Figure 6: *Graph of linear wind turbine blade speed vs. windspeed. Windspeed was measured using altimeter, and wind was generated using fans at various settings. The fans were then placed at the same distance from the wind turbine in order to determine the linear speed reading of the photogate at each wind speed. The relationship between the windspeed and linear speed is logarithmic because the more power the wind turbine generates, the more load on it, meaning the turbine grows increasingly difficult to spin faster.*

The experiment performed with the solar panels was designed to investigate whether a change in altitude made a significant difference in the power output of the solar panels. The solar cells were attached on the outer walls of the payload (see Figure 7) in order to receive sunlight regardless of the relative position of the sun. The cells were connected in series to a 10 Ω resistor and, as with the wind turbine, the voltage drop across the resistor was measured in order to find the power dissipated.

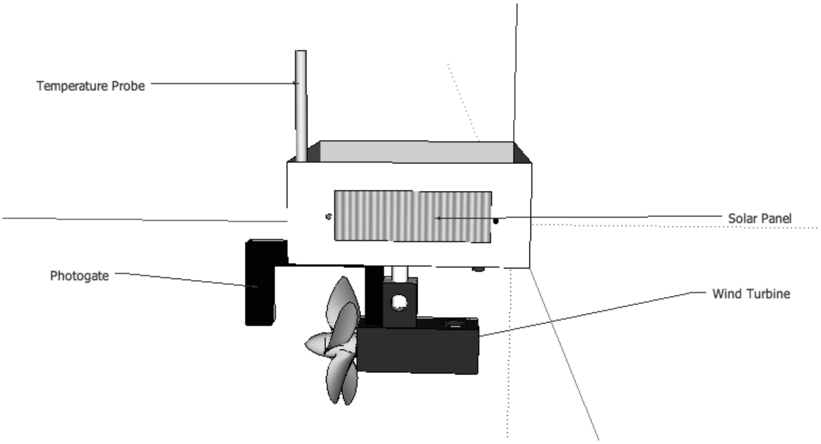

Figure 7: *A closer view of the payload. Payload is a 0.177 m x 0.076 m x 0.229 m aluminum box with a lid and measuring devices mounted to the outside of the box. Outside of the payload are a temperature probe, photogate, four solar panels wired in series, and wind turbine. Temperature probe is used to measure the outside temperature. The photogate is used to measure the rotation of the wind turbine. Solar Panels are used to measure solar energy in the atmosphere. The wind turbine is used to measure wind power in the atmosphere.*

3 Results and Error

3.1 Pressure and Temperature

The data gathered for pressure during the ascent of the balloon somewhat resembled what we expected. As the altitude rose, the pressure dropped faster and faster. As a result, the data fit an exponential curve $\text{Pressure} = 101.1 - 0.03 \cdot e^{0.016 \cdot Altitude}$. However, the NASA model for atmospheric pressure is far more linear at such low altitudes. It shows pressure decreasing fairly constantly as the altitude increases. This discrepancy is likely due to the capability of the barometer. In order for it to accurately measure the pressure at a certain altitude, it must maintain that altitude for a long period of time, so it was unable to accurately gauge the pressure levels during the balloon's ascent. However, when the balloon was able to sit at a certain altitude, the barometer was able to accurately measure the pressure, providing a consistent pressure reading at 282 m (the range finder's maximum distance where the balloon was suspended for a short period of time). The balloon was then allowed to rise further and the minimum pressure reading corresponded to an altitude of 340 m (in accordance with the NASA model). [9]

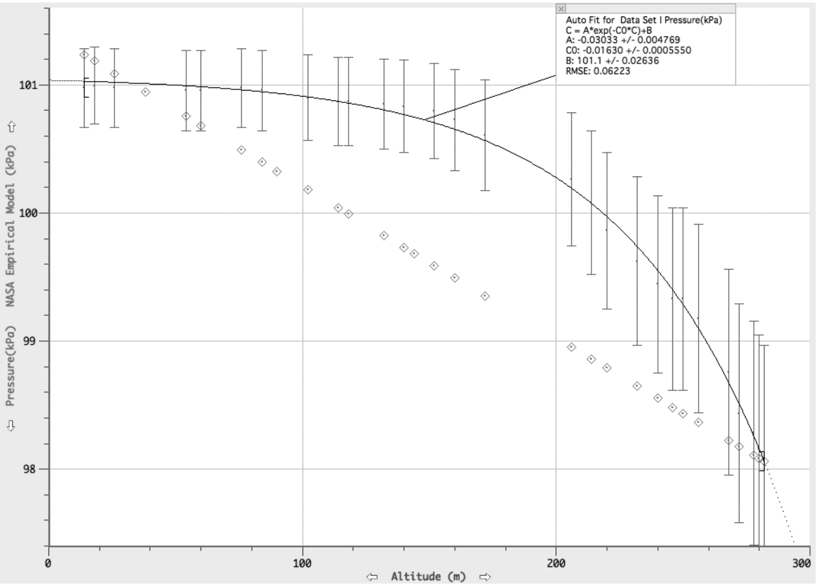

Figure 8: *Altitude (m) vs. pressure (kPa) graph displaying change in pressure as the weather balloon ascended into the atmosphere. Raw data with curve fit. Error bars were calculated by the square root of 101.35 minus the pressure in order to obtain error of the change in pressure. The ground pressure of the launch was assumed to be 101.35 kPa. Altitude was measured from the ground with a rangefinder. Time of rangefinder and LabQuest were aligned and the corresponding data matched. NASA model for pressure is also graphed for comparison.*

The data gathered for temperature during the ascent of the balloon was more sporadic than expected. For low altitudes it is assumed that temperature decreases fairly constantly (similarly to pressure) as altitude increases. While the overall trend of the data demonstrated that relationship, the data varies from this trend a lot. This is likely due to the temperature sensor, which, like the barometer, needs time to provide an accurate reading. As a result, our temperature data could not help us accurately estimate the altitude of the balloon.

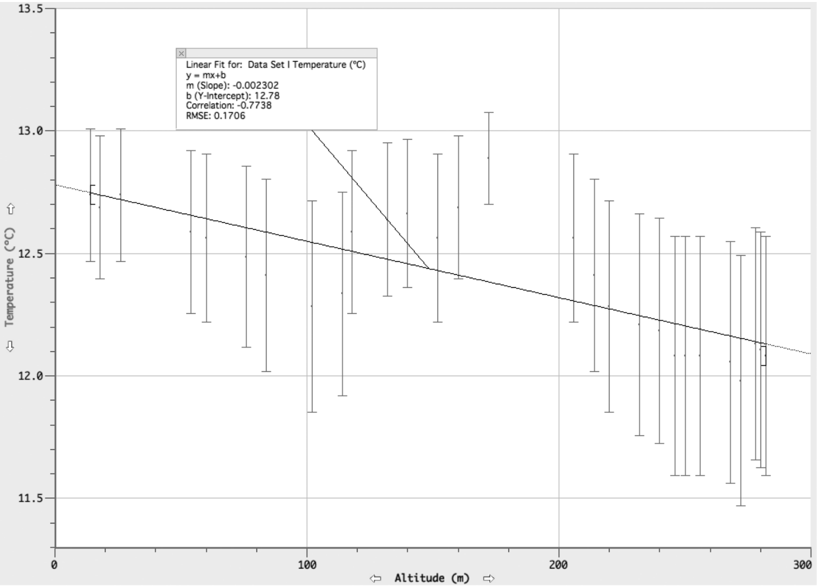

Figure 9: *Altitude (m) vs. temperature (°C) graph displaying change in temperature as weather balloon ascended into the atmosphere. Raw data with curve fit. Error bars were calculated by the square root of 13.03° C minus the temperature in order to obtain error of the change in temperature. The ground pressure of the launch was measured to be 13.03° C. It is important to remember that the temperature probe takes approximately 10 minutes to find accurate temperature. Altitude was measured from the ground with a rangefinder. Time of rangefinder and LabQuest were aligned and the corresponding data matched.*

3.2 Wind and Solar Energy

The data gathered from the wind turbine was fairly inconclusive for two reasons. First, there was insignificant wind on the day of the experiment, and second, the photogate was unable to take data at high altitudes. Because of the lack of wind, the power generated by the wind turbine was under 15 mW at all altitudes. There was some rise in power with a rise in altitude, but because it was such a small rise it is unclear whether a small gust of wind could have caused a spike in the data. It is assumed that windspeed increases at higher altitudes, but as it was a still day, there was little evidence of this. Additionally, the method of measuring windspeed (using the photogate data) was rendered useless. This is thought to be because at high altitudes the sunlight interfered with the laser mechanism of the photogate, resulting in no photogate data during the period of highest altitude.

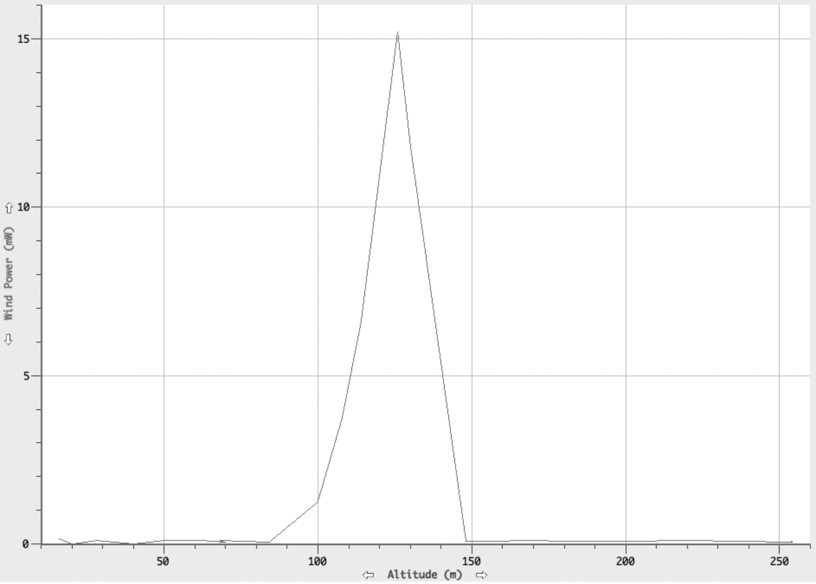

Figure 10: *Altitude (m) vs. wind power (mW) graph displaying wind power produced as the weather balloon ascended into the atmosphere. Wind power was calculated with the wind turbine voltage data and with the equation* $P = V^2/R$*. Resistance was 10 Ω. As the power produced was too small to be displayed in Watts, it was converted to milliWatts. Altitude was measured from the ground with a rangefinder. Time of rangefinder and LabQuest were aligned and the corresponding data matched.*

The data gathered from the solar panels was fairly straightforward. When the panels were out of direct sunlight, shaded by buildings and trees, the power output was fairly minimal. However, as soon as the solar panels received direct sunlight, the power output clearly increased.

As predicted, the closer the solar panels got to the sun, the more power they produced; however, this change was minimal.

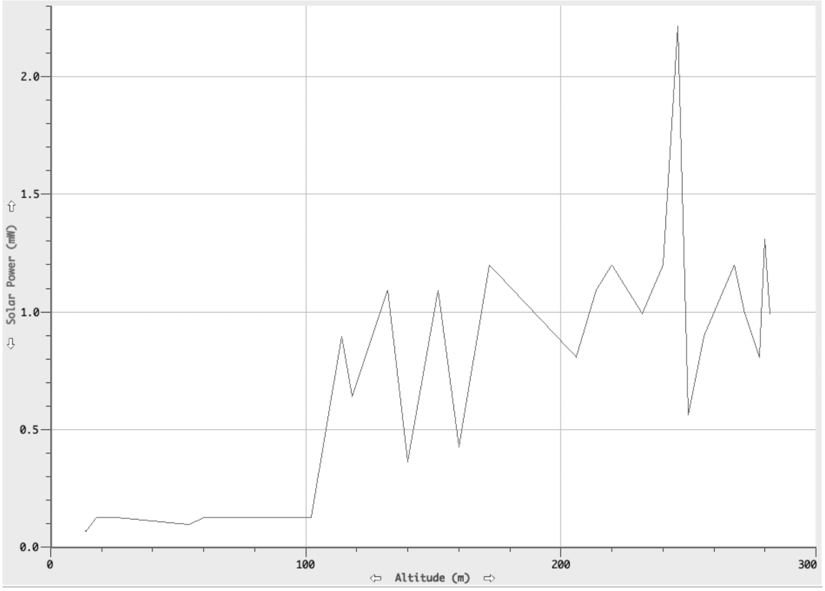

Figure 11: *Altitude (m) vs. solar power (mW) graph displaying solar power produced as the weather balloon ascended into the atmosphere. Solar power was calculated with the solar cell voltage data and with the equation* $P = V^2/R$*. Resistance was 10* Ω*. As the power produced was too small to be displayed in Watts, it was converted to milliWatts. Altitude was measured from the ground with a rangefinder. Time of rangefinder and LabQuest were aligned and the corresponding data matched.*

3.3 Error

There were many sources of error in the experiment, though mostly due to the equipment used. For the temperature and pressure experiments, accurate measurements could not be taken because the instruments required time to collect accurate data. The solar energy experiment did not have any visible errors; however, the wind turbine experiment was filled with them. First, the wind was not consistent enough to provide a strong clear voltage reading, so there were many sporadic data points.

Second, the windspeed was not possible to measure due to sunlight interfering with the photogate.

4 Conclusion

Both experiments, the atmosphere experiment and energy experiment, had a success and a failure. Both failures were due to an unforeseen or inevitable problem. Despite the failures there is still much to be learned. Each experiment was able to provide insight, whether into the understanding of Earth's atmosphere or the discovery of more efficient ways to harness renewable energy. The atmosphere experiments evidenced the variation of pressure and temperature as altitude changes. They also proved the difficulty of accurately measuring air temperature due to the many variables that play a role, including how the sun or wind affects the temperature probe. The solar energy experiment proved to us that getting closer to the sun is not the most efficient way of getting electricity. Nevertheless, this insight can drive new ideas on how to maximize the time solar panels are exposed to the sun or to better their ability to harness all of the light they absorb. The wind energy experiment proved fairly inconclusive due to the lack of wind during the experiment. While it is very plausible that more energy can be produced using a wind farm at high altitudes, what was learned is that on calm days there is minimal benefit to be gained, thus it may not be worth spending the energy to lift a wind farm into the sky in order to gain a small benefit in energy produced. This insight can also drive people to look to new solutions to better utilize renewable energy sources. Hopefully researchers in both fields, atmosphere and renewable energy, can continue to better understand their respective areas of study, because knowing more about the atmosphere, what we need in order to survive, and energy, what we want in order to live, can benefit society and hasten its progress. ●

5 Citations

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6 Appendices

6.1 Appendix A: Experiment Protocol Sheet

6.1.1 In the morning (at least an hour before beginning of experiment):

1) Plug in LabQuest to ensure that it is fully charged for the experiment

2) Hook up barometer, surface temperature sensor, and both voltage probes respectively connected to solar cell circuit and wind turbine to LabQuest channel ports

3) Hook up photogate installed on wind turbine to LabQuest digital port

4) Hook up GPS Sensor to LabQuest USB port

5) Verify that all components are in place for experiment

6) Verify that the data collection for each component is set correctly

6.1.2 In the afternoon (directly before beginning of experiment):

1) Install reel (with rope) at launch site and bring out gondola

2) Verify that GPS is properly set up (must display latitude and longitude on LabQuest display)

3) Attach both carabiners attached respectively to rope and gondola onto the weather balloon's metal ring

4) Start data collection on LabQuest, start video on camera, and place lid on gondola

5) Rapidly let out the rope in order to quickly maximize balloon's height, measure height of balloon with rangefinder every minute

6) Once balloon is at maximum height, slowly reel back in balloon

6.2 Appendix B: Equipment Specification Sheet

6.2.1 Vernier LabQuest

Handheld device that records various types of data in experiments with variable components and devices that can be attached at preference. Settings can be adjusted to specification and is able to run multiple collections simultaneously. It can either be attached to a computer and run with logger pro or use its own built-in system. In all the brain of the operation that collects all data and presents it in data tables and graphs.

Instructions: Completely recharge batteries. Turn on LabQuest. Plug in GPS to top port. Plug in photogate, surface temp. probe, barometer, voltage probe from solar cells, and voltage probe from wind turbine. Set collection to one data point per second. Click "collect data." Click "stop collecting" when retrieved/ done with collection.

6.2.2 Global Positioning System

Vernier GPS sensor collects real time latitude, longitude, and altitude. Connects to LabQuest and displays coordinates.

Instructions: Plug in to USB port on top right (make sure in all the way). Data collection begins when "collect data" hit.

6.2.3 Solar Panel (x4)

A solar panel takes the energy from light and converts it into electricity; specifically the photons of light hit the semiconducting material on the cells and cause the electrons to come loose from their atoms and travel, creating direct current. Four of these panels are attached in series with a resistor at the end of the circuit, which causes a voltage drop across it. A voltage drop sensor is attached on each side and the drop is recorded in the LabQuest.

Instructions: Attach four solar panels to each side of the payload. Connect the solar panels in series. Attach a 10 Ω resistor to circuit. Attach voltage probe leads on each side of the resistor. Attach the probe to LabQuest. Data collection begins when "collect data" hit.

6.2.4 Wind Turbine

A wind turbine simply converts wind into electricity. The rotating blades are attached to a magnet with a coil on top and under it. When the blades rotate the magnet rotates and current is created in the coils. A resistor is attached to the coil circuit, which induces a voltage drop across it and the voltage drop sensor is attached there.

Instructions: Attach photogate to wind turbine (make sure blades trigger beam). Attach a 10 Ω resistor to wind turbine circuit. Attach voltage probe on each side of resistor. Attach the probe to LabQuest. Install wind turbine at the bottom of payload with bolts and screw. Data collection begins when "collect data" hit.

6.2.5 Photogate

Vernier photogate can be used for many experiments, but in this case it serves to calculate the period of the rotating turbine. A laser is passed in between the gate and when it is blocked the LabQuest records a data point as long as the blades are in direct path of laser.

Instructions: See wind turbine for attachment. Connect port to LabQuest. Data collection begins when "collect data" hit.

6.2.6 Surface Temperature Probe

Vernier temperature probe that works in liquids and air and takes temperatures in a range of -40° to 135° C. Just expose tip to area of choice and record on LabQuest.

Instructions: Attach probe facing up in any corner of payload. Plug into LabQuest. Data collection begins when "collect data" hit.

6.2.7 Camera

Basic digital camera that takes a picture when trigger is pressed, with settings to take multiple pictures over a time lapse.

Instructions: Completely recharge batteries. Turn camera on. Set to take a picture once a second. Place lens in hole facing down. Hit "start" before lid closed. Hit "stop" when payload recovered.

6.2.8 RangeFinder

Rangefinder measures distance from an observer to a target.

Instructions: Turn on rangefinder. Set to appropriate measurement system. Scan sky and once payload in view, record reading.

6.2.9 Barometer

Vernier barometer is designed for weather experiments and has a range of 0.8 to 1.05 atm. Plug in and expose the white tip and data will be collected.

Instructions: Insert white tip of barometer in hole for sensor. Make sure majority of it is exposed to the outside. Connect to LabQuest port. Data collection begins when "collect data" hit.

6.3 Appendix C: Atmosphere Data

6.3.1 NASA Empirical Model vs. Exponential Model of Atmosphere

Layer of Atmosphere	**Standard Model Pressure**	**NASA Empirical Model Pressure**	**Difference**
Troposphere (5.5 km)	50.505 kPa	50.600 kPa	0.095 kPa
Lower Stratosphere (18 km)	7.503 kPa	7.570 kPa	0.067 kPa
Upper Stratosphere (50 km)	0.0759 kPa	0.0849 kPa	0.090 kPa

6.3.2 Atmosphere Composition

Gas	**Volume**
Nitrogen (N2)	780,840 ppmv (78.084%)
Oxygen (O2)	209,460 ppmv (20.946%)
Argon (Ar)	9,340 ppmv (0.9340%)
Carbon dioxide (CO2)	387 ppmv (0.0387%)
Neon (Ne)	18.18 ppmv (0.001818%)
Helium (He)	5.24 ppmv (0.000524%)
Methane (CH4)	1.79 ppmv (0.000179%)
Krypton (Kr)	1.14 ppmv (0.000114%)
Hydrogen (H2)	0.55 ppmv (0.000055%)
Nitrous oxide (N2O)	0.3 ppmv (0.00003%)
Xenon (Xe)	0.09 ppmv (9·10-6%)
Ozone (O3)	0.0 to 0.07 ppmv (0% to 7·10-6%)
Nitrogen dioxide (NO2)	0.02 ppmv (2·10-6%)
Iodine (I)	0.01 ppmv (1·10-6%)
Carbon monoxide (CO)	0.1 ppmv (0.00001%)
Water vapor (H2O)	~0.40% over full atmosphere, typically 1%-4% at surface

6.4 Appendix D: Menlo

Figure 12: *Menlo from above.*