Renewable Energy: Wind

Introduction

History

Like all other forms of renewable energy, wind energy has been in use for several millennia. The earliest records of its use date back as early as 5000 B.C., when simple sails were employed to transport boats along the Nile River. This form of transport proved to be no temporary phenomenon, as it was the primary method of boat transport well into the 1800's. The employment of rudimentary navigational techniques with it allowed humans to open worldwide trade routes, forever changing the face of the planet.

Figure 1: NEG Micon Turbine in Moorhead Minnesota (*DOE*)

However, transportation was not the only use for wind energy. As with hydropower, people invented ways to harness wind to replace the backbreaking work of grinding grain to make flour. This technological achievement dates back as least as early as 200 B.C. in Persia and the Middle East. Farmers in China were also irrigating the crops in their field by this time, using windmills to pump water from underground wells.

It is this latter technological advance that was the predominate image of wind energy in the U.S. until recently. Farmers in the Central and Western U.S. have used metal windmills to provide water for their crops and livestock for almost 150 years in these regions. As fossil fuels began to replace renewable forms of energy during the 1800's, this was the last presence for wind energy in the U.S. It survived mostly because wind energy was so plentiful in the region, and because most farms were remote enough to limit the availability of fossil fuels. It was not until the Rural Electrification Administration programs that started in the 1930's began to bring fossil fuel energy to these farms and ranches that wind energy for irrigation began to disappear.

Spurred by industrialization and such programs as the REA, the U.S. experienced an increased need for electricity during the 1940's. This led to experimentation with the use of wind energy to drive generators. At the time, it was believed that windmill designs needed to be very large to produce the vast sums of electricity that would be needed. As an example, a windmill was built in 1940 at Grandpa's Knob in Vermont that had blades that were 175 feet in diameter and weighed 8 tons each. This windmill was able to produce 1.2 megawatts of electricity, but at a cost of $1,000 per kilowatt, which was very expensive for the time.

The interest in windmills soon waned, as oil became plentiful following the end of World War II. Research that might have led to cheaper designs that produced the needed electricity went by the wayside, as the price of fossil fuels plummeted. It was not until the Oil Embargo of the early 1970's that work began again in earnest to develop such technology. Once again, interest was high while oil prices were high, but decreased when the price of a barrel of oil fell to all-time lows in the 1980's. Luckily, advances in technology had occurred that brought the price of producing electricity with windmills down. Currently, electricity can be produced at about 3-4 cents per kilowatt-hour with windmills under certain conditions, which is comparable to that produced from coal and natural gas.[1,2]

Windmill Basics

The idea behind generating electricity from wind is quite simple. Wind is the manifestation of the kinetic energy of air molecules in the atmosphere. In order to use this kinetic energy for other purposes, all that one has to do is to have the wind hit a surface that is allowed to move. This will cause the kinetic energy of the wind to be converted to the kinetic energy of the moving object. Anyone who has ever been outside on a very windy days understands these concepts. The hard part about generating electricity from wind is doing it cheaply. To do this, a more fundamental knowledge about wind energy is needed

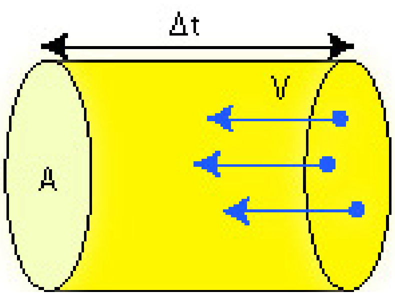


Figure 2: Diagram of wind tube

Let us imagine air that is moving through an area A with a velocity v as shown in Figure 2. From our section on energy, we know that the kinetic energy of an individual air molecule is given by the formula $1/2\ mv^2$. We want to consider a large system of air molecules, which means looking at a volume of particles. In a time Δt, the mass of the air that will flow through the area A is given by $m = \rho A v \Delta t$, where ρ is the density of the air. If we put these two formulae together, we get that the kinetic energy of the air that passes through an area A in a time Δt is given by the formula $1/2\ \rho A v^3 \Delta t$. Since the energy per unit time is equal to the power, we get that the power in the wind moving through the area A is given by

$$\mathbf{P = K.E./\Delta t = 1/2\ \rho\ A\ v^3}$$

While this is the power that is in the wind, this is not the power that you can get out of the wind. To understand why, consider how one would extract energy from the wind. As we stated above, this involves allowing the wind to hit an object and transfer its kinetic energy to the object. If the air that hits the object delivers all of its kinetic energy to the object, then the air comes to a complete standstill while the object begins to move. The problem with this is that the air that has just hit the object needs to get out of the way in order for more air that is behind to be able to hit the object. In other words, if you extracted all of the energy from the wind, you would begin piling up air in front of your object and thus cutting off the wind. Therefore, the air that hits your object must still have some kinetic energy in it in order for it to move out of the way to allow more air to hit it. In 1919, a German physicist by the name of Albert Betz[3] showed that the maximum amount of power that one can get from the wind is only 59% of that given by the formula above. In actuality, we will get less than this maximum amount. Therefore, we often write the formula for the power from a wind turbine as

$$\mathbf{P = 1/2\ C\rho\ A\ v^3}$$

where the factor C depends on the actual design of the windmill that you build. The factors that affect the constant C are many and complicated. If you wish to learn more about it, you might wish to visit the websites in the Additional Reading section at the end.

We should note that the formula for power depends on two other factors. The first of these is the area of the wind that is captured. This linear relationship shows that the bigger a windmill is, the more power it will be able to output. This is why a lot of commercial windfarms rely on large turbines. The formula also shows that the power depends greatly on windspeed. This is not a linear relationship between the two variables, but a very strong dependence to the third power. This means that the difference in power between wind moving at 1 meter/second and wind moving at 2 meters/second is a factor of $2^3 = 8$. Therefore, the amount of energy that one will get out of a windmill depends tremendously upon the windspeed, and it is vitally important that the windmill be placed in a location where winds are strong.

Wind Basics

What factors affect windspeed? To answer this, we need to remember some meteorology basics. The driving force behind wind is sunlight, as you have no doubt seen described many times before. Materials at the Earth's surface absorb some of the energy from the Sun that gets through the atmosphere. This causes the surface to increase its temperature above its surroundings, which results in heat transfer back into the atmosphere. Some of this heat is transferred by conduction; some of it, by radiation in the infrared region which gets absorbed by greenhouse gases. Both of these methods cause the air near the surface to increase its temperature, which results in it expanding. This expansion causes a net reduction in the density of the air, and it rises as it becomes more buoyant. Thus, just like the water in a teakettle before it boils, the air undergoes convection.

This, though, is not the wind that we feel. This is vertical air movement, and not the horizontal movement that we need to drive windmills. It is just the first part of the process of wind creation. The air that rises takes a great deal of mass with it. Without the weight of the air pressing down in this area, the air pressure is reduced. This makes the surrounding air that is not rising higher in air pressure. The resulting pressure difference causes the surrounding air to rush toward the lower air pressure, giving us surface winds. This part of the process is known as advection.

Latitudinal Effects and Hadley Cells

This process can happen on large or small scales, creating either large wind patterns that persist over hundreds and thousands of miles or small patterns of just a few miles.   What are some of the factors that affect it? One of the most obvious answers is latitude. As we discussed in the Solar Energy Activity, the closer the Sun's ray are to perpendicular when striking the Earth's surface, the higher the energy density of that sunlight. Since the Sun is more directly overhead near the equator throughout the year, the more energy it receives, and thus the hotter it gets. Thus, we expect to see a lot of warm air rising near the Equator. Conversely, we expect to see a lot of cold air descending near the poles.

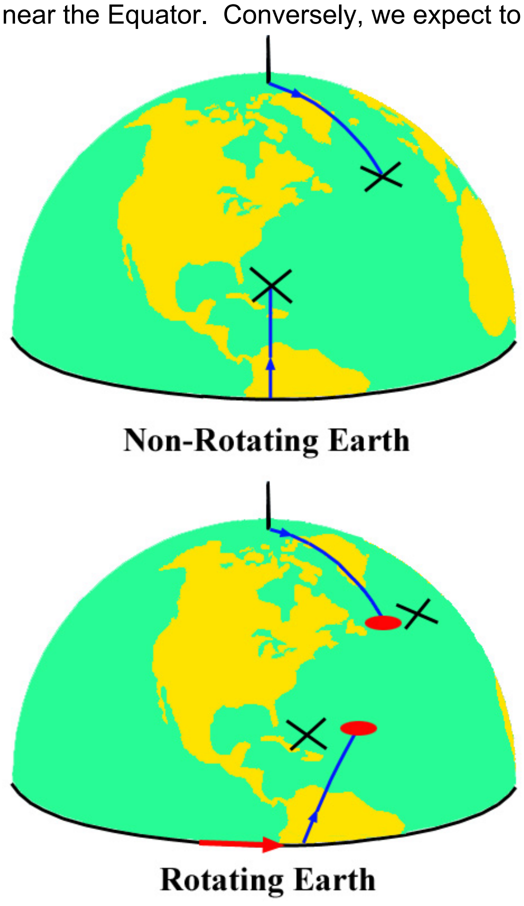


Figure 3: Coriolis Effect Diagram

If the Earth was not rotating, this latitudinal heating would result in two giant cells of air movement, rising near the Equator, moving in a straight line in the upper atmosphere directly to the poles, descending near the poles, and moving laterally from the poles to the Equator near the surface (See Figure 3). However, this does not occur because of the Coriolis effect, which causes this type of air cell to break up into three air cells in each hemisphere of the Earth. To understand how it does this, we have to consider what the airflow looks like from above the Earth.

In order for air to remain static with respect to the Earth over the equator, it must be moving at slightly more than 1000 miles per hour in the direction of the Earth's rotation. Air that is static over the poles, on the other hand, has zero velocity with respect to an observer in space. The velocity of static air as one moves from the poles to the equator is a slowly increasing value between these two extremes. As long as air is static over the Earth, everything looks okay.

Now, consider air that is near the equator moving toward the North Pole. As it moves to higher latitudes, it will be over a portion of the Earth that is moving slower than 1000 miles per hour in the direction of the Earth's rotation. The initial velocity it had in this direction is, therefore, going to cause it to move eastward relative to the ground (See

Figure 3). In essence, the air will appear to veer to the right as it heads poleward. Going to greater latitudes will only increase the curvature, as the Earth is moving slower in those locations. Eventually, the air will curve so much that it will start moving due east. Eventually, it will cool, contracting as it does and becoming denser. This will cause it to sink towards the Earth surface, where it will continue curving back toward the equator. From outer space, the air will not look as if it curved at all. Observers there will note that the air has two components of velocity (one poleward, one in the direction of rotation) and is actually moving at an angle relative to a line of longitude. It will just look like it tried to move in a straight line on a curved surface. It is only to an observer on Earth that thinks that the air is static over the equator that will image that the air is curving do to some "force". This is why the Coriolis effect is often misnamed the Coriolis force in some textbooks and online materials.

In a similar fashion, we can follow air that is leaving the North Pole and heading toward the equator. This air has no velocity in the direction of the Earth's rotation. As it goes to lower latitudes, it will be over land that does have velocity in this direction. Therefore, the air will appear to curve westward, or to the right, as it tries to proceed toward the equator. Eventually, it will warm as it picks up energy from the surface, expand, and then rise into the atmosphere. As it does, it continues to curve and head back to the North Pole, never reaching the equator. Because of its size and the speed of its rotation, the Earth forms three different "cells" of air circulation in each hemisphere. These cells are called Hadley cells, and they form the large-scale wind patterns that we see. They are driven by predominate low-pressure systems near the equator and high-pressure systems near the poles.

Other Factors

While these large-scale wind motions in the atmosphere drive a lot of weather patterns that we see, they are not solely responsible for surface winds. If they were, we could almost be assured that wind would always blow in the same direction all of the time. Surface winds can also be affected by disparities in the rates of heating of land and water. Near a beach, solar energy shines equally on both the water and the land surface. However, water has a heat capacity that is nearly 8 times that of soil and rock. This means that an equivalent amount of energy put into both water and soil will result in the soil increasing its temperature 8 times that of the water, i.e. the soil will get hotter than the water faster. The air that is over the land, therefore, will get hotter than the air that is over the water, and rise faster. This upward air movement over the land will create a local low pressure, and higher pressure air over the water will be forced in to replace it.

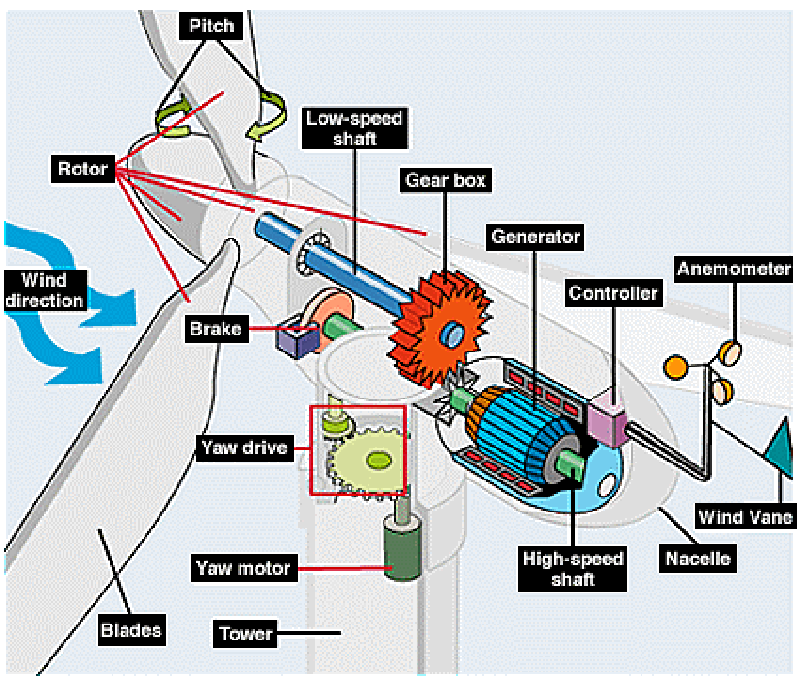


Figure 4: Diagram of a wind turbine (*DOE*)

At night, when the Sun has set, the process will be reversed. The soil will cool off faster than the water. After a while, the air that is over the land will be cooler than the air over the water. Now, the air over the water will become more buoyant and rise into the atmosphere. The air over the land will have a greater air pressure, and be pushed out towards the water by the pressure difference. If you have ever travelled to the seashore, you have probably experienced this phenomenon. During the middle of the day while the Sun is out, the wind will be blowing in from the ocean toward the beach. Around midnight or so, the wind will reverse and begin to blow out to sea.

Currents that are flowing in the water can modify this effect immensely. If cold water is being brought towards the surface of the ocean near the beach, this can cause the difference between in temperatures between the land and the water during the daytime to increase, and vice versa.

Mountains can also play a role in creating and modifying the wind. Their affect depends a great deal upon the number of them, their orientation, and their shape and height. For instance, a mountain chain can create a “wall” to airflow. This can block pressure systems from moving across them. If a high pressure system does force the wind over the mountains, the air can be “squeezed” as it passes over the mountains, resulting in high wind speeds in mountain passes and on the lee side of the range as it descends. Mountains can also generates wind, as when a shallow, cold air mass descends down a mountainside and produces strong winds. The reverse of this can also happen when heated air in a valley descends up the side of a mountain.

Additional Reading

It suffices to say that there are many factors that affect winds speed. To enumerate all of them would take some time. We recommend that you look at the links below in order to learn more about the wind and the generation of electricity from wind energy. The first link below goes to the U.S. Department of Energy’s Energy Efficiency and Renewable Energy division. This is the section of the DOE that researches and tests wind energy systems. The second link will give you to the Danish Wind Industry Association. They have a lot of background information about wind energy and wind systems. They also have some simulators that will help you to understand the factors involved in producing electricity from wind.

Department of Energy	**Topic**: Wind Energy **Summary**: Energy Efficiency and Renewable Energy division’s wind energy program homepage **Link**: http://www.eere.energy.gov/wind/

Danish Wind Industry Association	**Topic**: Wind Energy and Wind Turbines **Summary**: A compendium of information about wind, wind energy, and wind turbines **Link**: http://www.windpower.org/en/core.htm

References

1 http://www.eere.energy.gov/wind/history.html, September 9, 2003.
2 http://telosnet.com/wind/early.html, September 9, 2003.
3 http://www.windpower.org/en/stat/betzpro.htm, September 9, 2003

Activity

This week, we are going to study the relationship between barometric pressure and wind speed and direction. If you watch the weather forecast during the news, you will usually hear the meteorologist (or weather reporter, as the case may be) state what the air pressure is for the day and in what direction it is changing. As we have seen above, differences in air pressure are what causes air to move from one place to another. If the local air pressure is decreasing, then this means that the area is becoming a low-pressure area, and that wind will start blowing into the region. If the lowest air pressure in the region is at a location, then this is the place where air is ascending, which can result in precipitation as the air going up cools and increases relative humidity to 100%. If the air pressure is increasing, then the reverse of this can happen. If a location is a local high pressure, the result is usually cloudless, sunny days as air is descending from above where it has little moisture.

What we wish to investigate this week is how the wind speed and direction depend upon air pressure gradients at the surface of the Earth. From what we have stated above, one would logically expect that large pressure differences would result in higher wind speeds than small pressure differences. What is not so clear is the direction that the wind will blow under the influence of pressure gradients. We would expect that large-scale pressure system that operate high in the atmosphere would be affected by the Coriolis effect, and cause wind directions high above the surface to veer to the right in the Northern Hemisphere. What we are not sure of is whether the same thing will occur for small-scale systems that are occurring over rough terrain near the surface. We are going to look at weather patterns over several days to see if we see any pattern that might lead us to some understanding of how this will work.

In particular, we are going to plot wind speed and direction data on an isobaric map of the U.S. An isobar is a line of constant air pressure. This means that pressure gradients are along perpendicular lines to isobars. Where isobars are very close together on a map, the pressure gradient is largest; where they are the farthest apart, the gradient is smallest. Making an isobaric map is not a very detailed process. One merely plots out values of air pressure on a map and then connects points of equal pressure in a smooth way. If your instructor wishes for you to do this, you should skip item 2 below and use the data that you collect from each city make your isobars.

For this exercise, though, we are going to allow you to forego the process of making isobaric maps everyday. The University of Illinois's Weather 2010 website will provide us with these maps, which are produced every three hours on their website. What we are going to do is to trace the isobars from their website onto our clean map of the U.S. and then to plot wind speed and direction onto them to see the relationship between the variables.

Procedure:

1. Print out a copy of the map of the United States attached below.
2. Go to the Weather 2010 website and find the latest isobaric map. Trace the isobars onto your clean copy of the U.S. map.
3. Print out a copy of the U.S. city table for collecting wind speed and direction data.
4. From the list of U.S. cities on the list below, follow the links to the NOAA website to collect current barometric pressure, wind speed, and direction data. Note that the wind direction is listed on each cities site as coming from a direction, which you will need to convert to the direction the wind is blowing toward.
5. Draw an arrow to denote the wind direction at each city. Make the length of the arrow correspond to the wind speed measured using a scale of 1 mm = 1 mph
6. Repeat this for two other days during the week. Annotate on the maps which days you have used.
7. Analyze the maps to see the connection between the isobars and the wind direction and speed.
8. Answer the questions on the activity sheet.

ESA21: Environmental Science Activities

Activity Sheet
Wind Energy

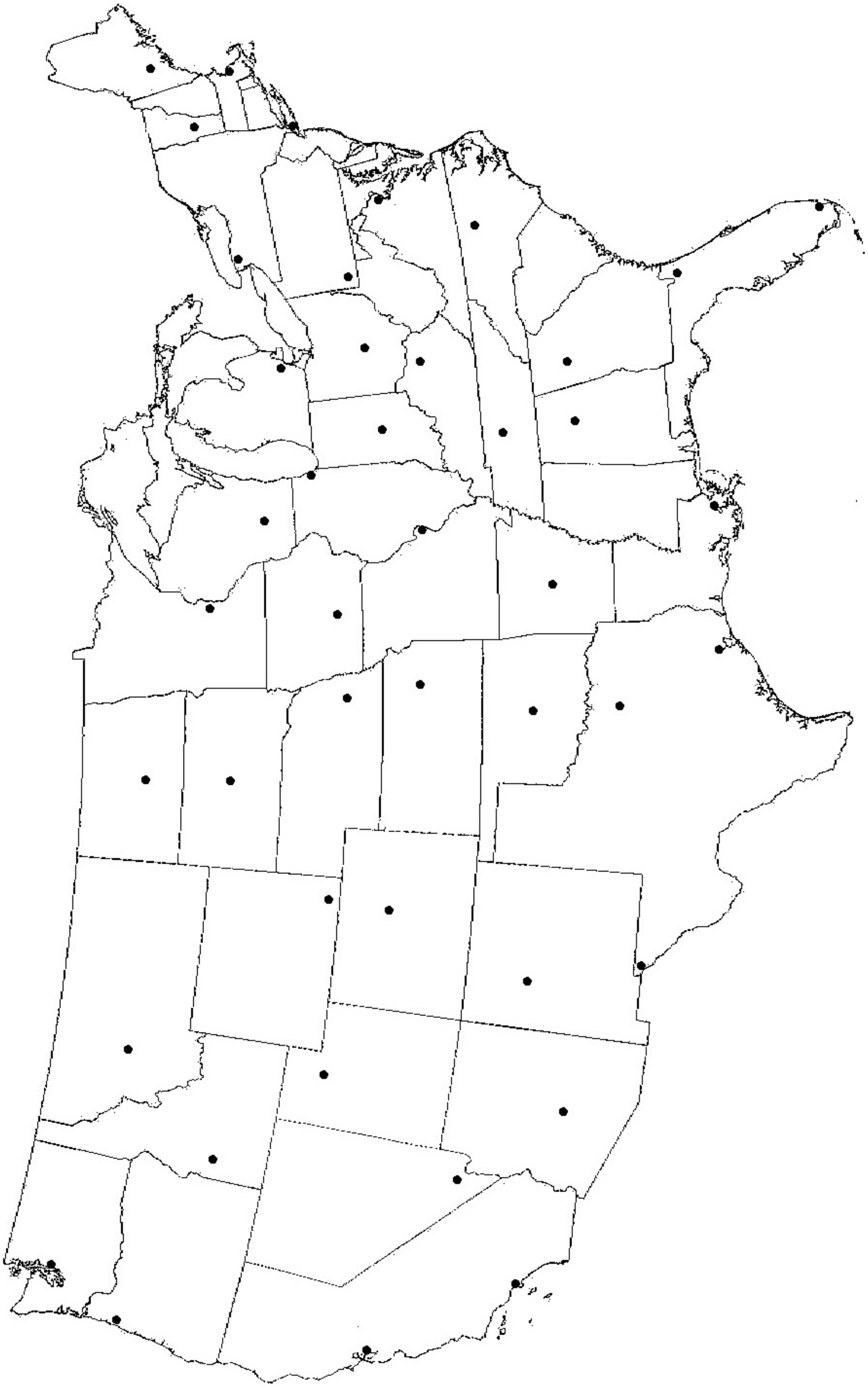
Name:

Attach copies of the three weather isobaric maps that you have drawn. Answer the following questions.

1. Is there any relationship on your maps between wind speed and the isobaric lines? If so, what is it and why do you think it is there? If not, did you expect to find any?

2. Is there any relationship on your maps between wind direction and the isobaric lines? If so, is it what you expected? Why or why not? If there is no relationship, did you expect to find any?

3. From just these three maps, can you see any region of the U.S. in which wind energy would look particularly promising?



City	Barometric Pressure	Wind Direction	Wind Speed
Los Angeles, CA			
Oakland, CA			
Portland, OR			
Seattle, WA			
Boise, ID			
Helena, MT			
Las Vegas, NV			
Phoenix, AZ			
Albuquerque, NM			
Salt Lake City, UT			
Denver, CO			
Cheyenne, WY			
Bismarck, ND			
Pierre, SD			
Lincoln, NE			
Topeka, KS			
OK City, OK			
Houston, TX			
Dallas, TX			
El Paso, TX			
New Orleans, LA			
Little Rock, AR			
St. Louis, MO			
Pittsburgh, PA			

City	Barometric Pressure	Wind Direction	Wind Speed
Des Moines, IA			
Minneapolis, MN			
Madison, WI			
Chicago, IL			
Indianapolis, IN			
Lexington, KY			
Nashville, TN			
Birmingham AL			
Jacksonville, FL			
Miami, FL			
Atlanta, GA			
Raleigh, NC			
Columbus, OH			
Washington, DC			
Augusta, ME			
Boston, MA			
Detroit, MI			
Buffalo, NY			
New York, NY			
Burlington, VT			

Print this sheet to use for recording your data. Each of the names of the cities is hyperlinked to the NOAA weather website for that city. Clicking on each name will take you to the data that you need to record for each city.