Is Wind Energy Right For Me?

by George Randolph & Heather Sauder

You can have three types of neighbors in Wyoming: people, horses and wind turbines. Only two of these will save you money on electricity and only one of these will save you money on electricity and hay. Commercial wind turbine development in Wyoming has skyrocketed in the last decade, as evidenced by the high number of wind turbines that pepper the landscape [1]. But this wind potential isn't limited to just large wind energy companies-- homeowners can also take advantage of this fantastic renewable resource. Unfortunately, it's not as simple as buying and assembling a LEGO® set. Successfully installing and operating a residential wind turbine demands knowledge of the power in the wind, sometimes referred to as the wind resource.

The Sun unevenly heats the surface of the Earth, resulting in variations in air temperature. These differences in air temperature correspond to differences in air pressure. Pockets of colder air have higher pressure compared to warm air. You feel this pressure imbalance as wind: air flows from areas of higher pressure to lower pressure. Larger differences in pressure correspond to higher wind speeds [2].

Wind speeds also increase with height. Suffice it to say, the effects of trees and buildings become moot at a certain height above the ground. That's why wind turbines are so tall. However, it's impractical to measure the wind speed at the operational height of your turbine. Amateur weather stations typically include an anemometer, a device to measure the wind speed. Using the following equation, it's possible to determine the wind speed at turbine height from just measuring the wind from, say, 6 feet off the ground.

$$v_{turbine} = v_{measured\ wind\ speed}\left(\frac{\text{height of turbine}}{\text{height of measurement}}\right)^{1/7}$$

This equation calculates the velocity of the wind at the height of the turbine $v_{turbine}$ from your measured wind speed, $v_{measured\ wind\ speed}$ and the ratio of the height of your measurement and the height of your turbine raised to the 1/7 power. As such, this equation is referred to as "the one seventh (1/7) Power Law" [3]. For example, say you measure the wind speed of 15 mph ($v_{measured\ wind\ speed}$) at a height of 6 feet above the ground. The height of your turbine is 50 feet. The wind speed at 50 feet ($v_{turbine}$) would then be:

$$v_{turbine} = 15\text{ mph} \times \left(\frac{50\text{ feet}}{6\text{ feet}}\right)^{1/7}$$
$$v_{turbine} = 20.3\text{ mph}$$

Now that you know what the wind speed is at the height of your turbine, you can calculate the power the turbine will produce. The power is proportional to the cube of the wind speed [3]. The United States is entrenched in the imperial system of measurements (feet for length, miles per hour for speed, pounds for mass and horsepower for power). However, the wind energy industry typically uses the metric system (meters for length, meters per second for speed, kilograms for mass and watts for power). The following equation is used to calculate the power output from a wind turbine

$$P = \frac{1}{2}\rho A e v^3$$

where

P is power	e is an efficiency
ρ is air density	v is the wind speed at the height of your turbine
A is the swept area of the turbine	

Air density decreases with altitude [2]. In Laramie, WY the air density is about 0.95 kg/m^3. The swept area is the area occupied by the blades, as illustrated in Figure 1.

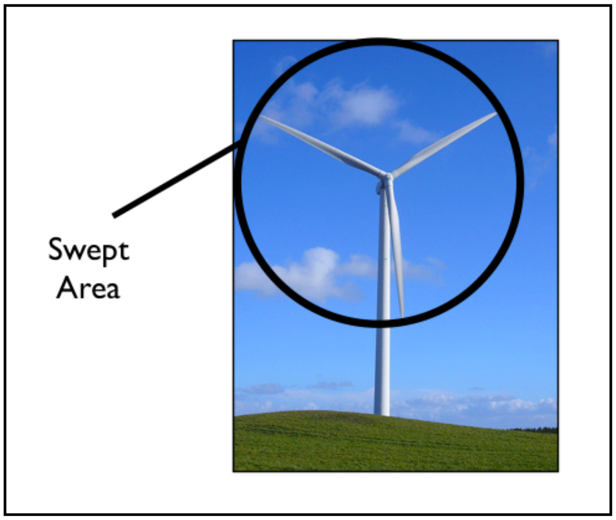


Figure 1: Illustration of the swept area. This is a parameter that is supplied by wind turbine manufacturers. Recall that the area of a circle is 3.14 × radius^2.

The efficiency of a wind turbine is given by the parameter *e*. Because of the physics associated with the design of wind turbines, the maximum efficiency is about 60%. As a reference, the efficiency of your car engine is about 20% [4]. The fact that a wind turbine can only extract 60% of the power from the wind is known as the "Betz Limit" [3]. It's important to realize that this is the absolute maximum efficiency for a wind turbine. Typical operational efficiencies are on the order of 50% [5]. This is like scoring 50 points on a test that's out of 60 points, meaning that your turbine efficiency is deceptively higher.

To calculate wind power, we'll convert the wind speed at turbine height (20.3 mph) to meters per second (9.1 m/s). Assuming a swept area of 10.87 m^2 and an efficiency of 50% or 0.5, the power of the wind turbine is

$$P = \frac{1}{2} \times \left(0.95\frac{\text{kg}}{\text{m}^3}\right) \times (10.87\ \text{m}^2) \times (0.5) \times \left(9.1\frac{\text{m}}{\text{s}}\right)^3$$

$$P = 1931\ \text{Watts (W)}$$

For reference, this turbine, operating for an hour at this wind speed, would power thirty-two 60 W lightbulbs.

Wind turbines are designed with a variety of thresholds. For the turbine to start producing power, the wind must surpass a minimum speed, known as the cut in speed. The maximum power that a turbine can produce is called the rated power and occurs at the rated speed. For safety reasons, wind turbines shut down when the wind exceeds a certain limit, called the cut out speed [3]. Figure 2 depicts a typical wind turbine power curve including all of these design features.

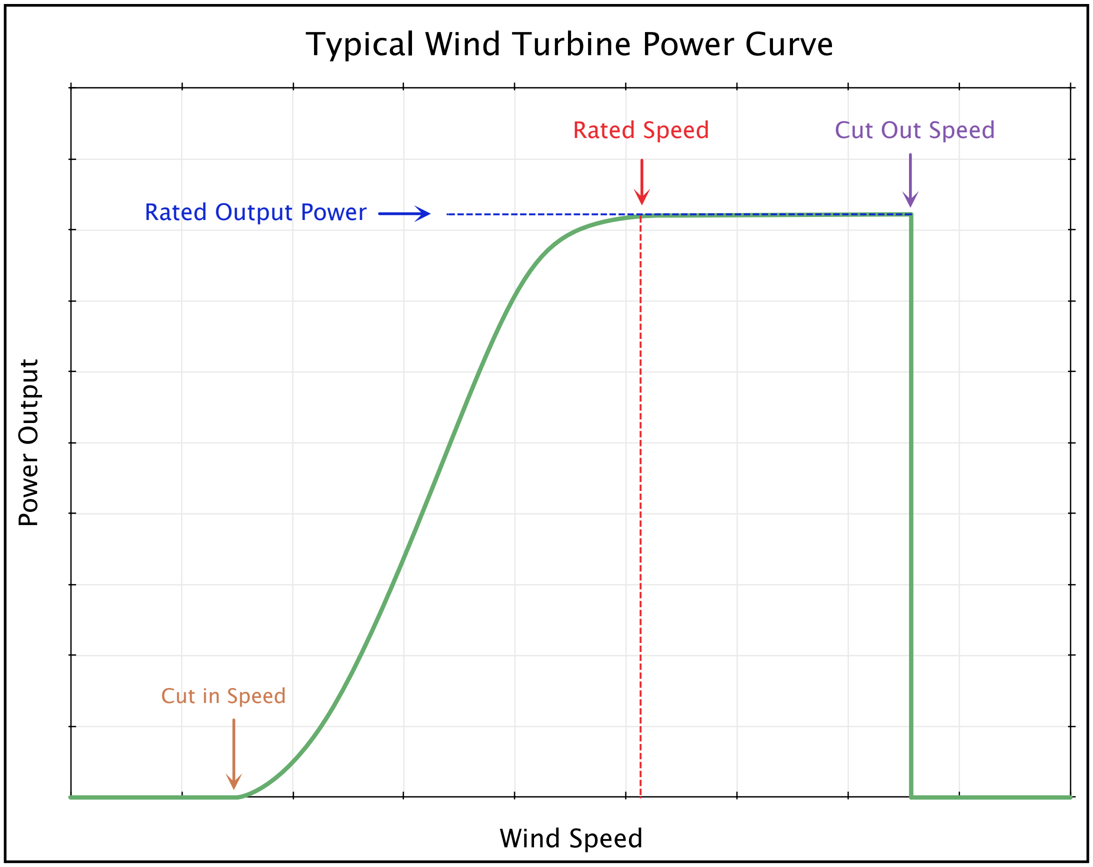


Figure 2: An example of a typical wind turbine power curve, adapted from *Wind Energy Explained*.

A final point to make about wind power is that it is proportional to the cube of the velocity. The difference in wind speed between 6 ft an 50 ft above the ground was only about 5 mph. The difference in wind power between these two wind speeds (15 mph versus 20 mph) is over 1000

W. Put another way, if you double the wind speed, you increase the power by a factor of 8. Thus, slight variations in wind speed have drastic effects on wind power.

Isolated high wind events have the potential of misrepresenting an area's wind power potential. For example, if you record the wind speeds at your house during a storm, cubing those high wind speeds results in significant values of wind power. But, under normal conditions of weaker wind speeds, the wind power is inherently lower. Measuring wind speeds under normal conditions, then, provides a more accurate representation of an area's power potential. To account for the variability in the wind, several measurements need to be taken over an extended period of time. Ample data recorded under typical weather conditions yield the most realistic depiction of the wind resource. Finally, when trying to calculate the mean, or average wind power given a series of wind measurements, it's necessary to cube all the wind speeds and then take the average, rather than averaging all the wind speeds and then cubing the mean. As an example, say you recorded the following wind speeds in m/s:

Wind Speeds		**Wind Speeds Cubed**	
6		216	
10		1000	
12		1728	
5		125	
Average(Wind Speeds)^3	561.5	**Average(Wind Speeds Cubed)**	767.3

Table 1: Comparison of wind speed averaging schemes.

Because you are calculating the mean wind power, it's essential that you cube the wind speeds and then take the average (column 2 in Table 1). The alternative method affords both incorrect and significantly lower results (column 1 in Table 1).

Given all this information, wind power density can be plotted to get a sense of the location of the high wind resource areas. The quantity of wind power density is nothing more than wind power divided by the swept area [6]. Neglecting the effects from the turbine, the efficiency term drops out; wind power density, therefore, is independent of turbine type and size, as the equation only depends on wind speed:

$$\text{Wind Power Density} = \frac{1}{2}\rho v^3$$

The wind energy industry typically divides wind speeds and the corresponding wind powers into seven wind classes so that the general public can easily understand an area's power potential [1]. Table 2 summarizes the seven different wind classes.

Wind Class	50 m Wind Power Density (W m^{-2})	50 m Wind Speed (m s^{-1})
1	0-200	0-5.6
2	200-300	5.6-6.4
3	300-400	6.4-7.0
4	400-500	7.0-7.5
5	500-600	7.5-8.0
6	600-800	8.0-8.8
7	800-2000	8.8-11.9

Table 2: Standard wind classes at 50 m.

Figures 3 and 4 illustrate simulations of wind power density in the western United States. The wind power density was calculated via the 1/7 power law using the recorded 10 m wind (the wind 10 m above the ground) to the desired height of 50 m. Hence, calculated at 50 m, it's referred to as the 50 m wind power density. Though 50 m is substantially higher than the height of a residential wind turbine, the behavior of the wind is essentially the same. In all subsequent wind power density maps, the color fills correspond to simulated 50 m wind power densities. Browns and greens represent places of low wind power densities; that is, poor areas for wind development (class 1 and 2 sites). Dark reds and whites represent places of very high wind power densities; that is, areas inclined for wind development (class 6 and 7 sites).

The wind speeds were not truncated when calculating the wind power densities in Figure 3. More applicable to residential wind turbines, Figure 4 employs a rated speed of 15 m/s at 50 m. Recalling Figure 2, once the wind surpasses the rated speed, the power output remains constant--there is no additional benefit from higher winds.

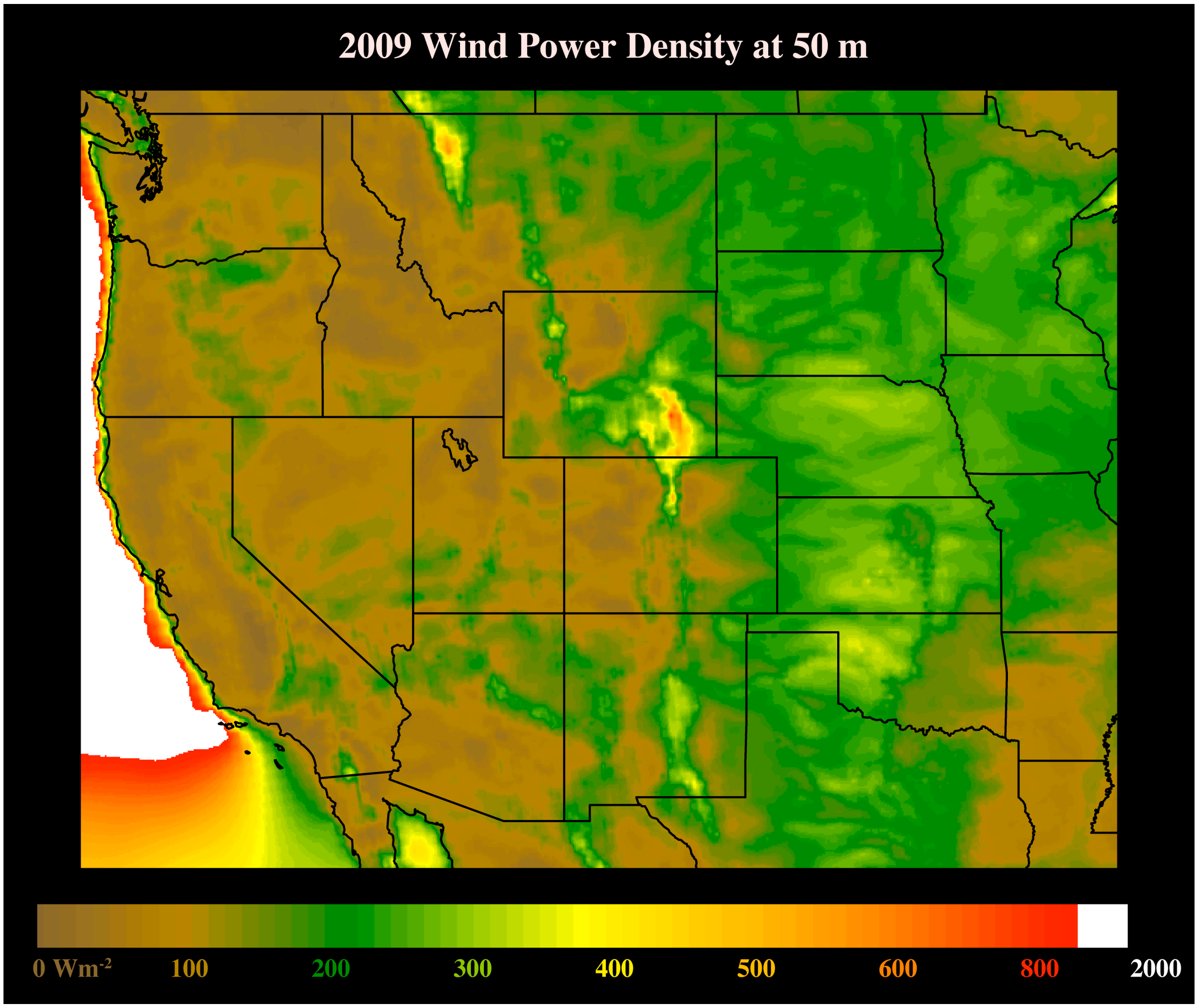


Figure 3: Simulated wind power densities for the western United States. Wind speeds were not truncated when calculating wind power densities.

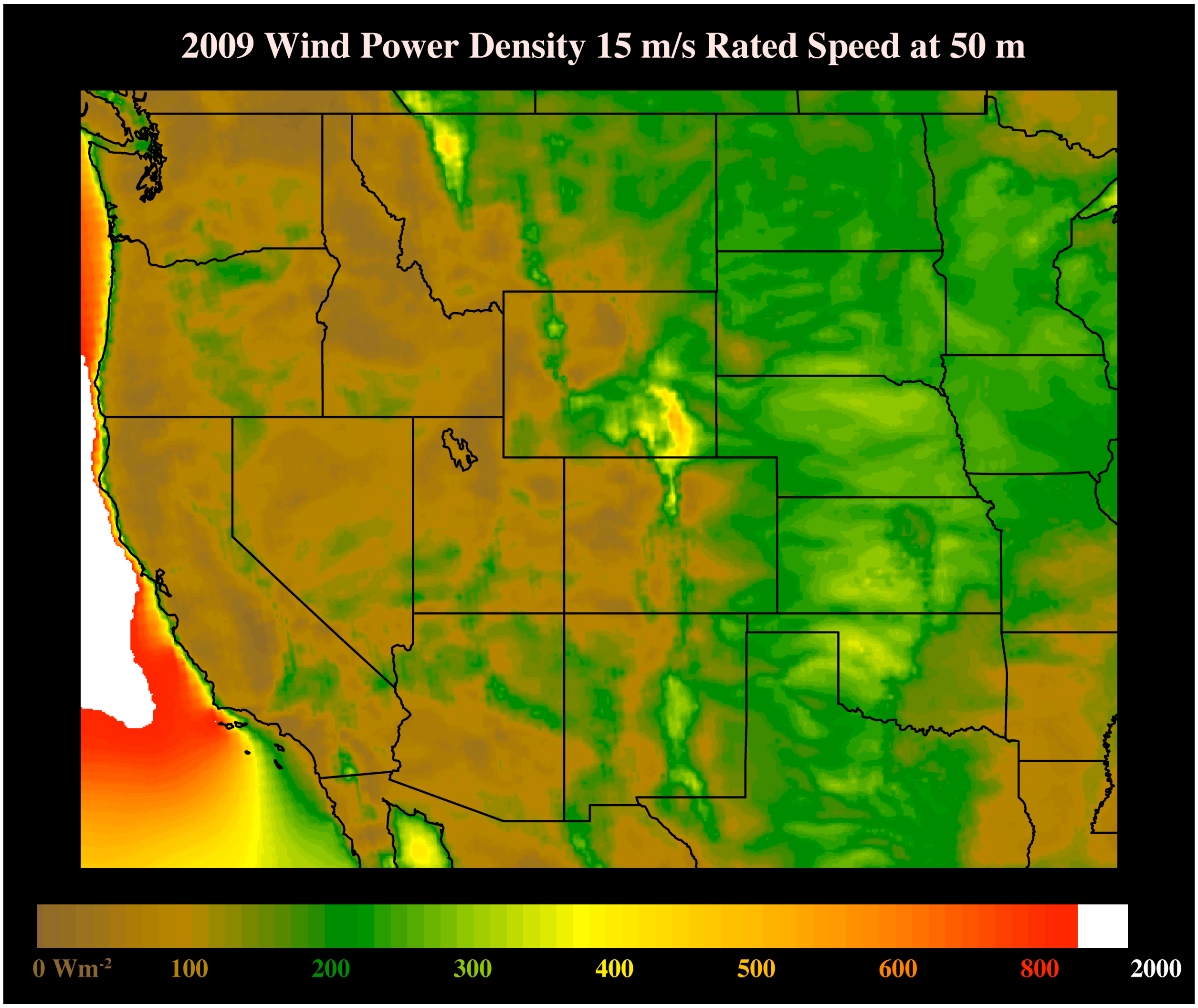


Figure 4: Simulated wind power densities for the western United States. Wind speeds were truncated at 15 m/s when calculating wind power densities.

There is very little difference between Figures 3 and 4, which speaks to the persistence of the wind resource. The area of exceptional wind resource in the southeastern corner of Wyoming is not an artifact of high wind events-- the wind in this region is frequently very strong, justifying wind energy as a worthwhile method of generating electricity in Wyoming.

Having established that Wyoming harbors superb wind resource, the seasonal changes in wind power density can be examined. Figure 5 illustrates the seasonal variation of the wind power density in Wyoming. Cities, county lines (black lines) and interstates (squiggly blue lines) are outlined for geographic reference. Table 3 outlines the seasonal divisions utilized in Figure 5.

Season	Months
Winter	December, January, February
Spring	March, April, May
Summer	June, July, August
Autumn	September, October, November

Table 3: Seasonal divisions by month.

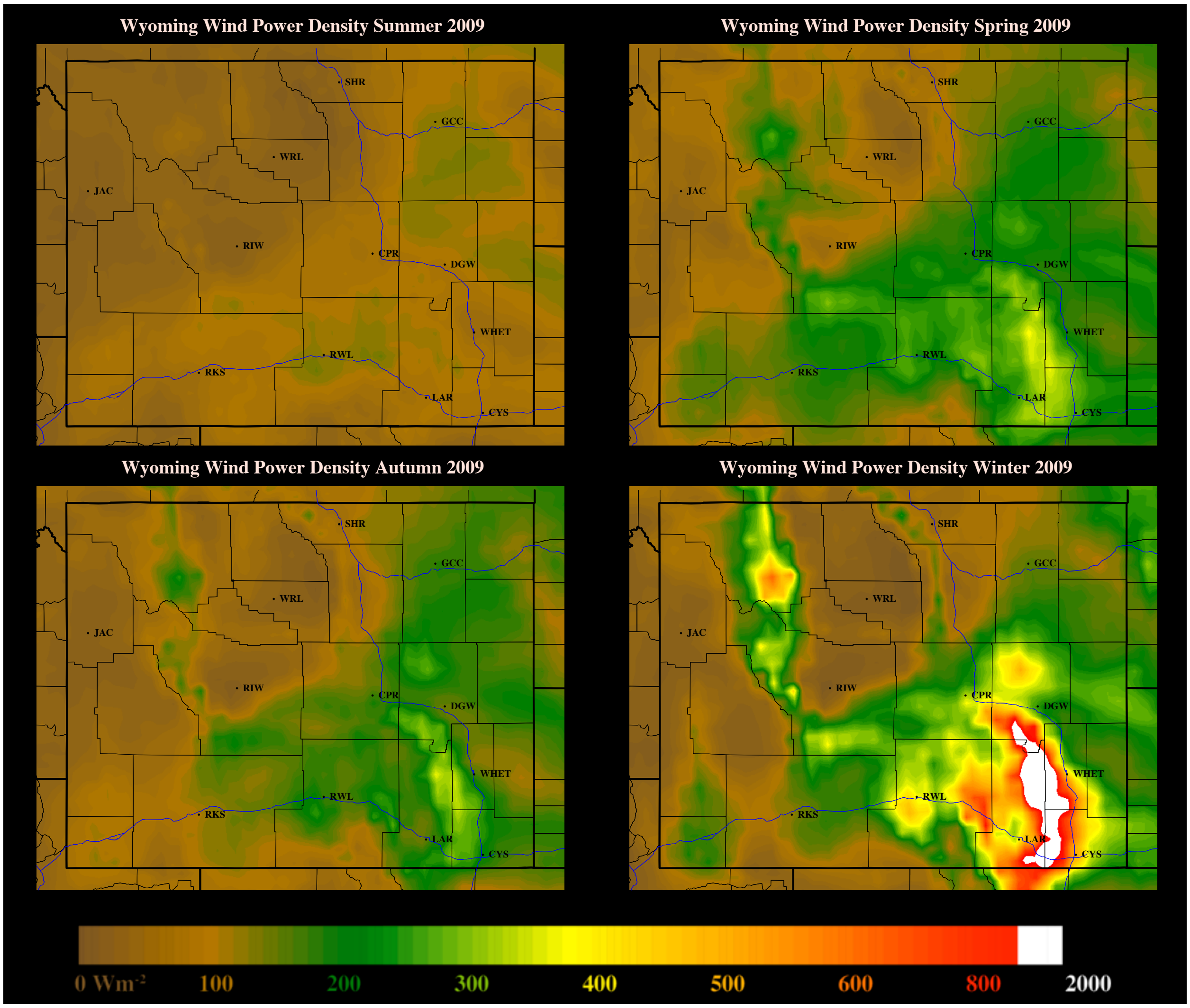
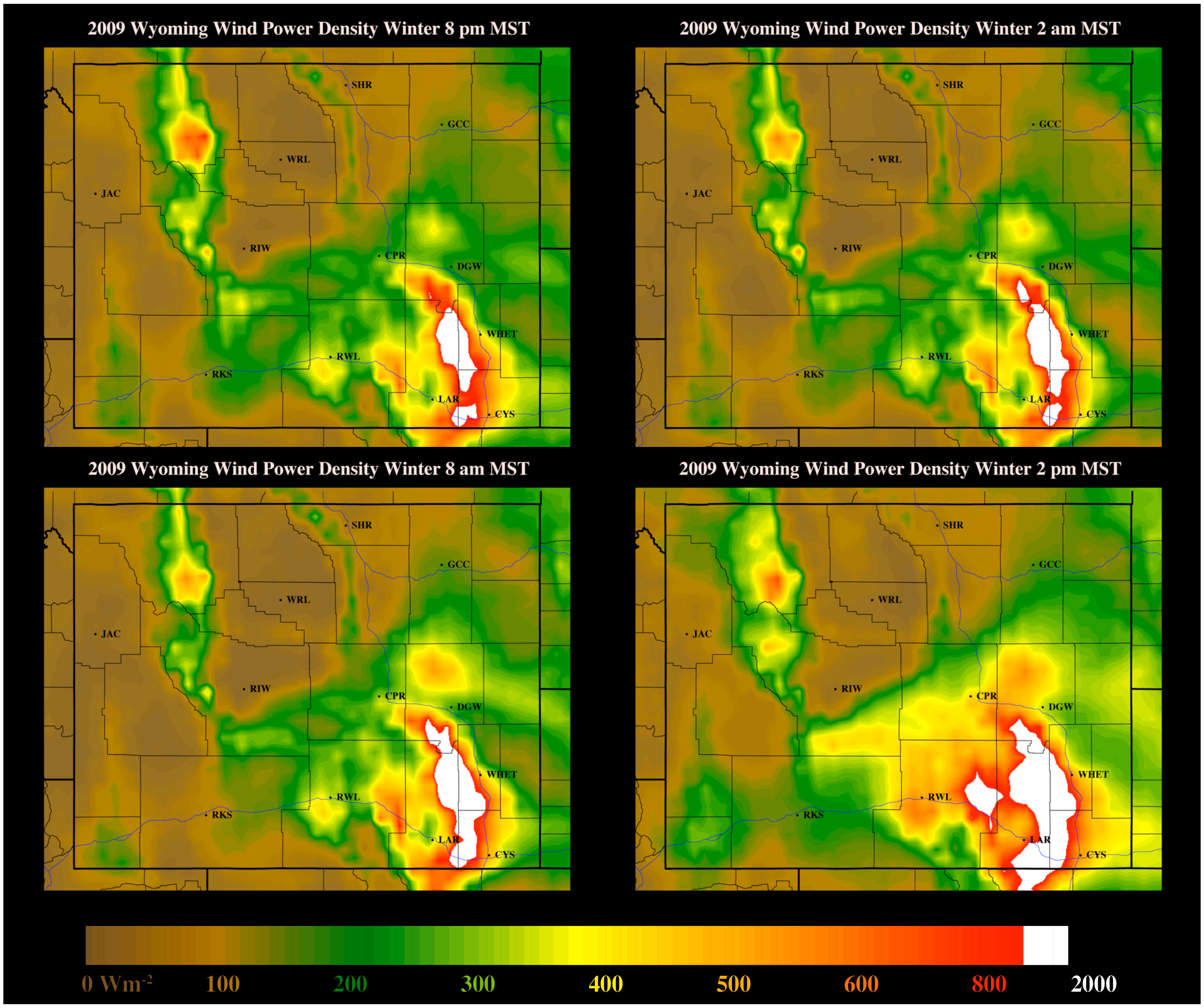


Figure 5: Seasonal variation of 50 m wind power density in Wyoming for 2009.

Inspection of Figure 5 reveals that summer has low wind power density, while spring and autumn exhibit moderate wind power density. It's the wintertime, however, that is the season of interest, especially the southeastern corner of the state. This bodes well for residents of Wyoming, as wintertime accounts for the greatest demand for electricity.

Upon further investigation, the winter also displays a diurnal variation: how the wind changes over the course of a day, as illustrated in Figure 6.



2009 Wyoming Wind Power Density Winter 8 pm MST

2009 Wyoming Wind Power Density Winter 2 am MST

2009 Wyoming Wind Power Density Winter 8 am MST

2009 Wyoming Wind Power Density Winter 2 pm MST

Figure 6: The diurnal variation of the 50 m wind power density in 2009 during the winter.

Striking about Figure 6 is the local maxima of wind power density observed in the afternoon. This makes sense from a physical point of view. The sun is most intense in the afternoon. Stronger surface heating leads to large differences in pressure which implies faster wind speeds. Thus, 2 pm MST exhibits the highest wind power density.

Armed with this knowledge of the variations in the wind, you are one step closer to assessing the practicality of installing a wind turbine at your house. The only remaining factor is the cost. Wind turbine owners fall into two camps, determined by their relationship with the electrical grid. Married to the grid, they can supplement the power provided to them with their own wind generated power; divorced from the grid, they generate 100% of their own electricity from the wind. Distance to existing power lines decides if this marriage will ever come to fruition [5].

An accepted rule of thumb is that if you live more than a quarter mile from existing power lines, it's cheaper to go the renewable energy route. Extending above ground power lines to a residence can cost upwards of $50,000 per mile. The critical aspect of living off the grid, though, stems from the need for a storage system. Since it's impractical to only cook or shower during wind storms, it's necessary to store the generated energy for later use. A residential turbine, such as the Skystream 3.7 manufactured by Southwest Windpower, costs $10,000. A typical battery storage system used in conjunction with the Skystream 3.7 costs about $12,000 [7]. Installation costs bring the total price to approximately $30,000.

Connected to the grid, residential wind turbines can supplement utility provided power. When the turbine is producing electricity, your home is essentially disconnected from the grid. If the turbine isn't producing enough electricity, the grid provides your house with needed power to meet your demands. If the turbine is producing more power than is needed, you can actually sell the excess power back to the utility company. Because the grid is present to provide power if needed, generated electricity doesn't need to be stored, reducing the initial price of a wind turbine [5].

Although these two scenarios afford quite different lifestyles, the common denominator is the significant upfront costs: installing a residential wind turbine is initially very expensive. Fortunately, you begin recouping these costs the moment your turbine begins producing electricity. Disconnected from the grid, years of independently generating electricity offsets the costs of the turbine and the energy storage system. Working in tandem with the grid, connected homes are able to recover the costs of installing a wind turbine from the profits of selling excess power back to utility companies. Either way, it's arguably cheaper to generate electricity with wind turbines rather than relying solely on utility companies, especially in an area as windy as Wyoming [5].

It's important to realize that, on a daily basis, the winds in Wyoming are rather chaotic and difficult to predict. The seasonal and diurnal variations previously discussed only highlight the trends in the wind: not every afternoon in the wintertime is going to be windy. This emphasizes the importance of continuously monitoring an area's wind speeds-- one or two measurements is insufficient. Since wind speeds increase with height, the 1/7 Power Law can be used to estimate the wind speeds at the operational level of your wind turbine, based on the surface winds. This is only an estimation, though. Under certain weather conditions, this equation may not be valid at all. Add to this, the sensitivity of wind power to wind speed and the challenges associated with assessing the wind resource become formidable at best. Despite this, efforts to extract the tremendous power residing in the wind have not been deterred. As dynamic as the resource itself, wind turbine technology continues to evolve, providing a more economical and responsible method of generating electricity. Plus, just think of all that money you'll save on hay.

Works Cited

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