Renewable Energy

Topics:

- Functions in Matlab
- Solar Energy
- Wind Energy
- Return on Investment

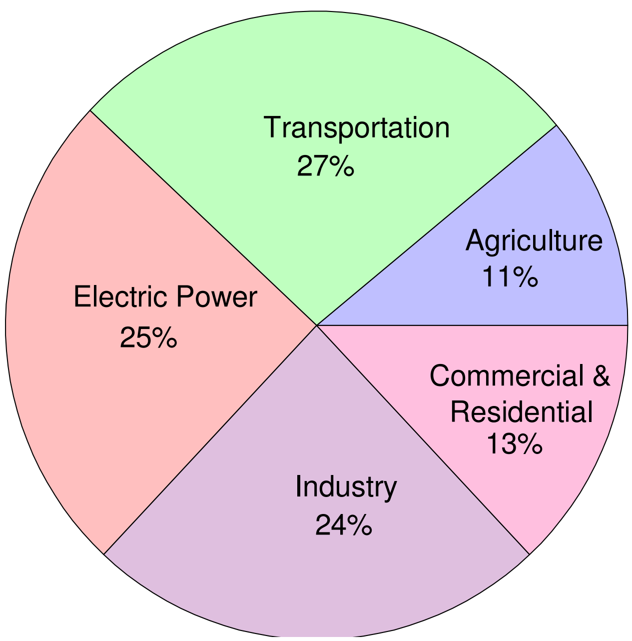
Background - Why ECE?

In the previous lecture, we covered solving N equations with N unknowns as well as curve fitting. Usine least-squares, we were able to determine lines and parabolas to fit any set of data, including

- Arctic sea ice,
- Global CO2 levels, and
- Global temperatures.

These all point to the same conclusion: CO2 levels are going up, temperatures are increasing, and the Arctic is melting. All things which are very concerning.

One of the good things about electrical and computer engineering is we are able to do something about this. In 2020, electricity and heat production accounted for 25% of U.S. greenhouse gas emissions with transportation accounting for 27% of emissions.



Total U.S. Greenhouse Gas Emissions by Economic Sector in 2020
www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Wind, solar, and nuclear energy help reduce greenhouse gas emissions related to electric power and residential heating. The first two are things ECE majors work on. Electric vehicles help reduce greenhouse gas emissions related to the transportation sector. This too is a field related to ECE.

If current trends worry you and you want to do something about it, ECE is a very good major to choose. It's also a very good major to choose if this doesn't worry you.

Another good thing about majoring in engineering is you get the mathematical tools you need to analyze and answers questions yourself: you don't need to rely on experts to tell you what does and doesn't work.

In this lecture, we're going to look at two types of renewable energy: solar and wind. What we'll try to answer is

- How much energy can a given solar installation be expected to produce?
- How much energy can a given wind turbine be expected to produce?
- Is this solar installation a good investment from a purely economic standpoint?, and
- Is this wind turbine a good investment from a purely economic standpoint?

Solar Enegy in Fargo

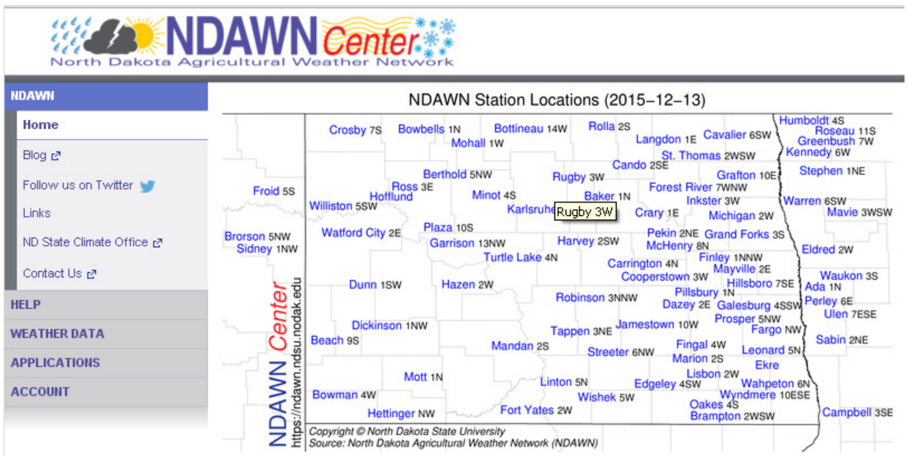
Let's start with solar energy. If you check out ebay, you can find turn-key solar installation kits such as the one below. This is a 10kW Solar Power System which sells for $15,640 as of September 17, 2019.

www.ebay.com

Specifically, let's answer the questions:

- If installed in Fargo, ND, how much energy will these panels produce on an hourly basis during the month of April 2018?
- What is the total amount of energy these will produce in kWh?,
- How many pounds of coal would this offset, and
- How long will you have to wait for these panels to pay for themselves assuming electricity sells for $0.10 / kWh (i.e. are these a good investment from a purely economic standpoint)

To start out, we need data: we need to know how much sunshine we can expect to get. One place to get this data is the NDSU NDAWN web site:

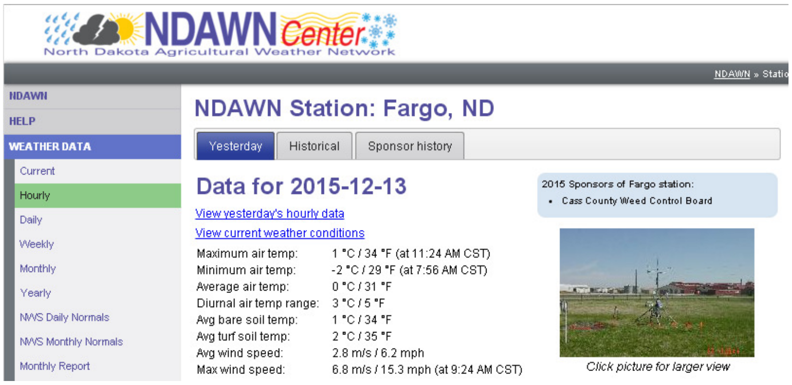


ttps://ndawn.ndsu.nodak.edu/

NDAWN is a part of NDSU Ag Extension service. Its goal is to provide data across North Dakota so that drought, blight, and other conditions can be predicted and mitigated for our farmers and ranchers. It also is a good source of data for other uses, such as solar energy and wind speeds.

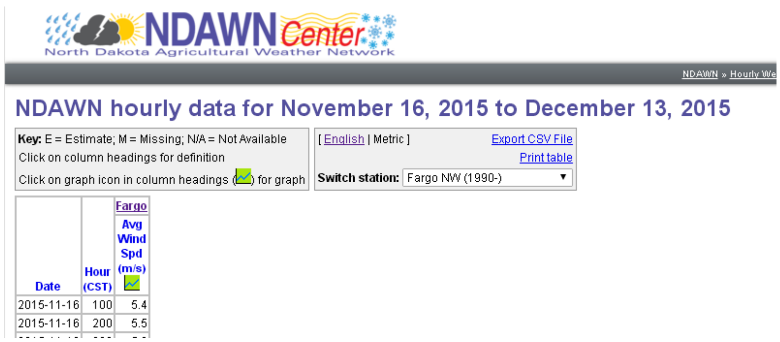
What we want is the amount of solar energy a given sight can expect to get (or, assuming the future resembles the past, the amount of solar energy a given location got in the past). To get this data,

- Click on Weather Data, Hourly



- Select Fargo North Dakota, Solar Radiation for April 2018

- Export to a CVS file



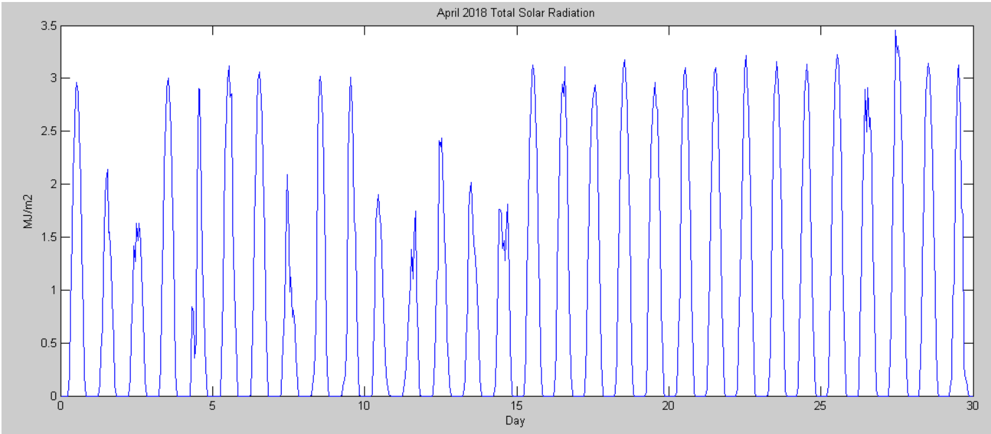
Open the CVS file (this should open up in Excel) and copy the last column. Paste into Matlab:

```
MJ = [                    start of matrix
     paste your data here
       ];                 end of matrix
```

This data (or graph) shows the density of energy received in Fargo over the month of April 2018. Note that

- Each bump corresponds to a day: the energy density is zero at night, reaches a peak during the day, and then goes back to zero.
- Some days have more energy than others: this depends upon the amount of cloud cover each day.
- Each month varies as well with a minimum in December and January (cloudy and low sun angle) and a maximum in May/June/July (highest sun angle).

This is hourly data and looks like the following:



Hourly Solar Energy in Fargo, ND over the month of April 2018.

To convert to energy in kWh, you need to know

- The area of the solar panel,
- The efficiency of the solar cells, and
- The conversion from MJ to kWh

Assume a 40-pack Grid Tied solar panel:

- Area = 40 x 1.5m x 1.0m = 60 m2
- Efficiency of solar cells = 19% (approximate)
- 3.6kWh = 1MJ

To convert from MJ per square meter to kWh, scale this data by

$$1\left(\frac{MJ}{m^2}\right)(60m^2)\left(\frac{kWh}{3.6MJ}\right)(0.19) = 3.167kWh$$

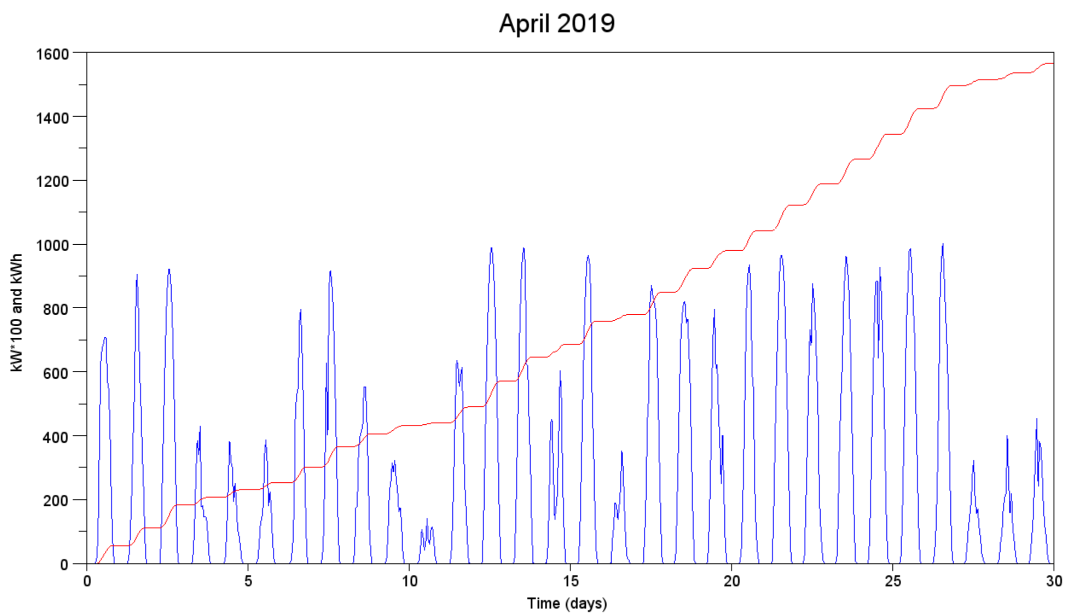
Assuming the sun is constant over the hour, the conversion from solar intensity to power output for these 40 solar panels is

$$1\frac{MJ}{m^2} = 3.167kW$$

In Matlab:

```
MJ = [                     start of matrix
  paste the data here
        ];                 end of matrix

kWh = 3.167*MJ;

size(kW)

   720      1          there are 720 hours in April, 2018

hr = [1:720]';
kWh = Integrate(hr,kW);
```

```
plot(hr/24,kWh,'r',hr/24,kW*100,'b')
xlabel('Day');
ylabel('Energy (kWh');
title('April 2018: Solar Energy');
```



Solar Radiation on an hourly basis x 100 (blue) and Total Energy Produced (kWh = red)
Note: Graph is incorrect. It should wind up at 1595 kWh

Note that since the time unit is hours, the total area under the curve is just the sum of the data (sum of width times height where the width is one)

```
>> kWh = sum(kW)

  1595.8
```

Over the month of April, 2018, this solar array would produce 1595 kWh. We can now answer the questions we original set out:

If installed in Fargo, ND, how much energy will these panels produce on an hourly basis during the month of April 2018?

See the red line in the above figure. This is the integral of the energy produced by that solar array.

What is the total amount of energy these will produce in kWh?,

```
>> kWh = sum(kW)

kWh = 1565.8
```

How many pounds of coal would this offset?

Milton Young power station in North Dakota takes 1.78 pounds of lignite coal to produce 1 kWh. The amount of coal offset is thus

```
>> Pounds = kWh * 1.78

Pounds = 2785.7 pounds of coal per month
```

These solar panels would offset more than a ton of coal in a single month (!).

How long will you have to wait for these panels to pay for themselves assuming electricity sells for $0.10 / kWh (i.e. are these a good investment from a purely economic standpoint)

At $0.10 / kWh, this panel will produce $156.9 worth of electricity during this month. In order for this to pay for itself, you'd have to wait 137.9 months (11.5 years)

$$\text{Payback Time} = \left(\frac{\$15{,}640}{\$156.9/mo}\right) = 99.68 \text{ months}$$

$$\text{Payback Time} = 8.3 \text{ years}$$

In business, a rule of thumb is that if an investment that pays for itself in 7 years or less, you do it. If it takes more than 7 years, you don't.

A payback time of 8.3 years means that you shouldn't invest in solar panels in the city of Fargo today.

However, 8.3 years is really close to 7 years.

- If the price of solar panels drop by 15%, this will be a good investment from a purely economic stadndpoint.
- If the efficiency of solar panels can be increased from 19% to 23%, this will be a good investment
- If you take in to account environmental issues, you might still want to invest in solar panels.
- If you lived somewhere that gets more sun than Fargo, ND, the payback time will drop as well.

Even in Fargo, ND, a place not known for being sunny, solar energy is almost viable today.

Another question you could ask is

What is the cost of solar energy on a $ / kWh basis?

Answer: Using the previous data, assuming the solar panels produce energy comperable to April every month of the year for 12 years, (somewhat questionable),

$$\left(1595.8\ \frac{kWh}{mo}\right)\left(12\ \frac{mo}{y}\right)(20y) = 382{,}992\ kWh$$

would be produced over a 20 year life. An initial cost of $15,640 results in

$$\left(\frac{\$15{,}640}{382{,}992 kWh}\right) = \$0.0408\ /kWh$$

In comparison, other forms of energy cost:

- Wind 1.88 cents / kWh
- Nuclear[1] 2.438 cents / kWh
- Coal / Steam[1] 3.088 cents / kWh *no carbon capture*
- Solar 4.08 cents / kWh
- Gas[1] 6.44 cents / kWh
- Hydro[1] 9.32 cents / kWh
- Coal w/ CC 25 - 32 cents / kWh *with carbon capture*

(1) U.S. Energy and Information Adminsitration

In 2018, the price of solar was almost competitive with coal. In 2023, the price of solar has dropped to the point where it's cheaper to shut down coal plants and replace them with solar.

Wind Energy in Fargo:

Now let's look at wind energy. Specifically, let's look at one of the largest commercial wind turbines on the market today, a Vestas V172-7.2MW wind turbine

https://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/enventus/enventus-platform-brochure/?page=1

To give an idea of what this wind turbine looks like

- The diameter of the blades is 172m (larger than a football field)
- The hub is 114m to 199m above the ground
- The cost is approximately $9.36 million, ($1300/kWh) including installation cost, tower, generators, etc.

Specifically, let's investigate

- How much energy would this wind turbine produce on an hour-by-hour basis if installed in Fargo, ND
- How many pounds of coal would this offset?
- How long you would have to wait until the wind turbine pays for itself (i.e. is it a good investment from a purely economic standpoint)

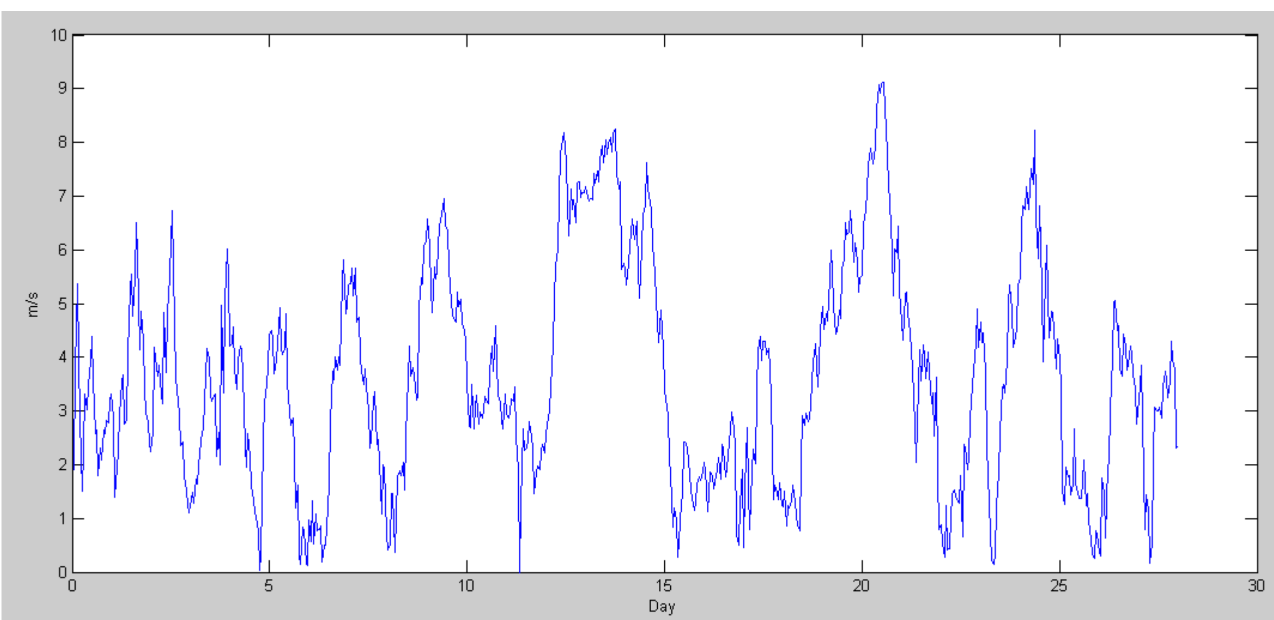
First, you need wind speed data: the energy produced is related to the wind speed.

- Going to the NDAWN site (https://ndawn.ndsu.nodak.edu/)
- Select Fargo, ND, Average Wind Speed on an hourly basis
- Select metric units and download to a CVS file.
- Open the CVS file in Xcel and copy the last column

Paste into MATLAB as

https://ndawn.ndsu.nodak.edu/

```
>> Wind = [ <paste data
   }
>> length(Wind)
   672

>> hr = [1:672]';
>> plot(hr/24,Wind)
>> xlabel('Day');
>> ylabel('m/s');
```



Wind speed in Fargo from Dec 5, 2022 to Jan 2, 2023

This is the wind speed at a height of 2m. Up at 180m above the ground, the wind will be higher. A rough approximation for this is (source: https://en.wikipedia.org/wiki/Wind_gradient)

$$v_w(h) = v_{10}\left(\frac{h}{h_{10}}\right)^{\alpha}$$

where

v_{10} is the wind velocity at a height of 10m

h_{10} is the height the wind was measured (2m in this case)

h is the height of the wind turbine (180m here)

α is a constant, 0.16 for neutral air above a flat open coast (sort of like North Dakota)

or, in other words, the wind speed at 180m would be approximately 2.05x the wind velocity recorded

```
Wind @ 80m = 2.2 * Wind @ 2m;
```

Note that wind speed is not energy. The conversion from wind speed to the power it produces is from the data sheets

Wind Speed (m/s)	0..3	4	5	6	7	8	9	10	11	12	13+
kW	0	53	496	1,096	1,882	2,857	3,968	5,102	6,100	6,803	7,200

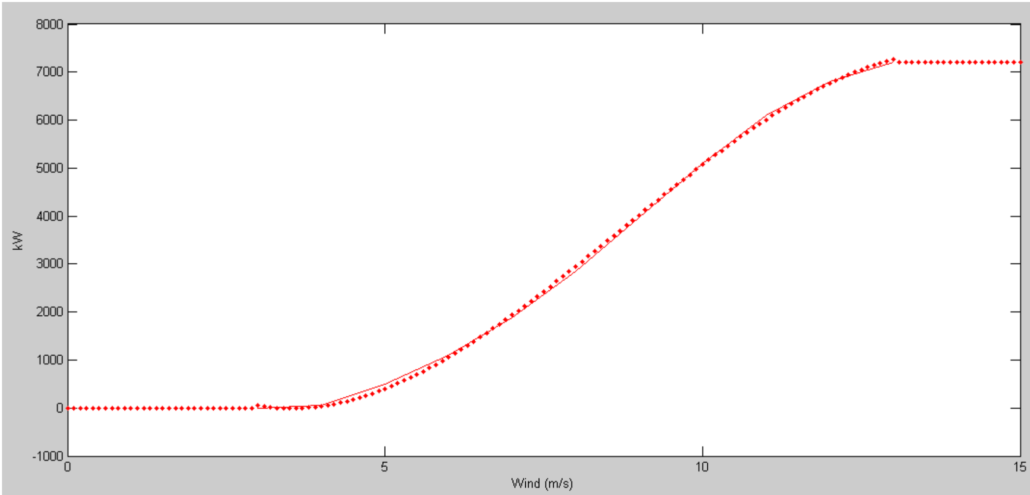
Power Curve for a Vestas V172-7.2MW Wind Turbine
https://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/enventus/enventus-platform-brochure/?page=1

Determine a function in Matlab to approximate this curve.

```
function [kW] = PowerCurve( Wind )

x = [3,4,5,6,7,8,9,10,11,12,13]';
y = [0,53,496,1096,1882,2857,3968,5102,6100,6803,7200]';
B = [x.^3, x.^2, x, x.^0];
A = inv(B'*B)*B'*y;

kW = 0*Wind;
for i=1:length(Wind)
    if(Wind(i) < 3)
        kW(i) = 0;
    elseif(Wind(i) > 13)
        kW(i) = 7200;
    else
        kW(i) = [Wind(i)^3, Wind(i)^2, Wind(i), 1]*A;
    end
end

plot(x,y,'r',Wind,kW,'r.')
end
```

Checking this in Matlab

```
>> Wind = [0:0.1:15]';
>> kW = PowerCurve(Wind);
```

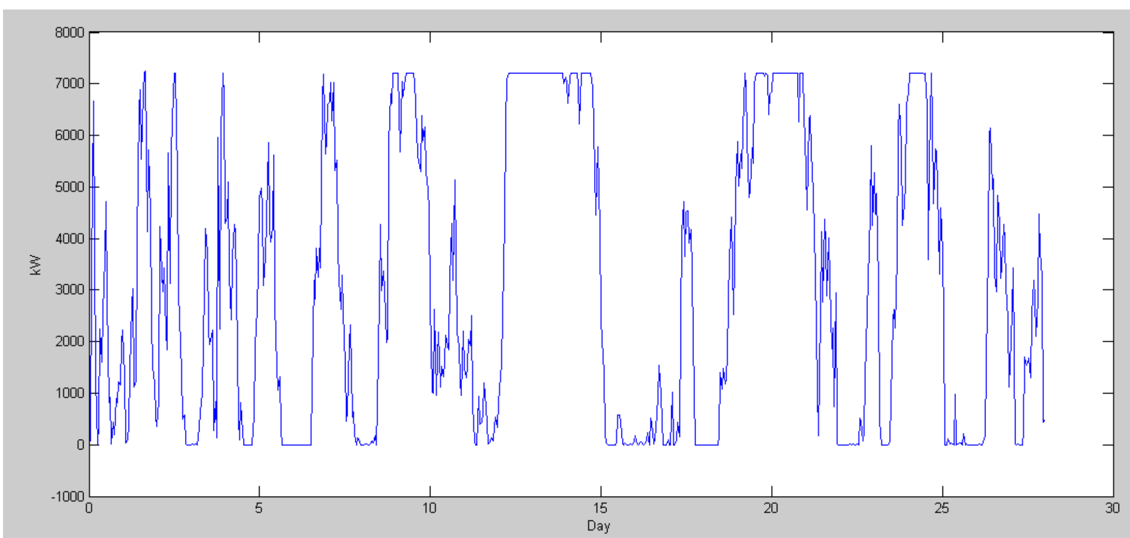


Power Curve (solid red) and Curve Fit (dotted red)

From the graph, the function *PowerCurve()* appears to be a good approximation to the data

Use this function to compute how much power a Vestas V172-7.2MW wind turbine would produce from the wind data your found in problem 3.

```
>> kW = PowerCurve(Wind * 2.05);
>> hr = [1:length(Wind)]';
>> plot(hr/24, kW)
>> xlabel('Day');
>> ylabel('kW');
```



Approximate Energy a Vestas V172-7.2MW Wind Turbine Would Produce

With this data, we can now answer some questions:

How much energy would this wind turbine produce on an hour-by-hour basis if installed in Fargo, ND?

This is the sum of the kWh produced over the month.

```
>> mean(kW)
ans =  3061.2
```

The average output of this wind turbine would be 30061MW

- 42.5% of the nameplate rating of 7200MW
- 42.5% utilization factor

```
>> kWh = sum(kW) * 1
kWh =  2.0571e+006
```

Over these four weeks, the wind turbine would produce 2.057 million kWh

How many pounds of coal would this offset?

It takes 1.78 pounds of North Dakota lignite coal to produce 1kWh:

```
>> Pounds = kWh * 1.78

Pounds =  3.6616e+006
```

Each month, this wind turbine offsets 3,661,600 pounds of coal

How long would you have to wait for this wind turbine to pay for itself?

Assume

- This wind turbine costs $9.36 million to build ($1300 / kW), and
- You get $0.11 / kWh for the energy you produce,

the revenue generated is:

```
>> Dollars = kWh * 0.11

Dollars =  2.2628e+005
```

At 11 cents per kWh, the wind turbine would generate $226,280 over this four week span

Assuming this was a typical month, the number of days and years it will take for this wind turbing to pay for itself is:

```
>> Days = 9.36e6 / (Dollars/28)

Days =  1.1582e+003

>> Years = Days / 365

Years =    3.1732
```

Extrapolating, the wind turbine should pay for itself in 3.17 years. It is a very good invenstment.

What is the cost / kWh to produce energy with wind?

Assume a 20 year life. The total production over these 20 years will be (assuming this was a typical month)

$$\left(2,057,100\ \tfrac{kWh}{mo}\right)(12mo)(20y) = 493,704,000\ kWh$$

$$\left(\frac{\$9{,}300{,}000}{493{,}704{,}000\ kWh}\right) = \$0.0188\ /kWh$$

In comparison with other sources, wind energy is easily the cheapest form of energy:

- Wind 1.88 cents / kWh
- Nuclear[1] 2.438 cents / kWh
- Coal / Steam[1] 3.088 cents / kWh *no carbon capture*
- Solar 4.08 cents / kWh
- Gas[1] 6.44 cents / kWh
- Hydro[1] 9.32 cents / kWh
- Coal w/ CC 25 - 32 cents / kWh *with carbon capture*

(1) U.S. Energy and Information Adminsitration

How much energy could we produce with wind energy in North Dakota?

The National Renewable Energy Administration estimates that North Dakota wind could produce 1.182TWh of electricity - enough to supply 25% of the nation's electricity needs.

<https://www.nrel.gov/docs/fy00osti/28054.pdf>

At $0.1 / kWh, that would bring in $118 billion each year to North Dakota.

To put that in perspective, $118 billion is

- $157,000 per person in North Dakota,
- More than double the entire GDP for North Dakota in 2016 ($47.6 billion) - source http://www.deptofnumbers.com/gdp/north-dakota/
- More if you consider that the average cost of electricity in the United States is $0.15 / kWh