

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. Using 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.

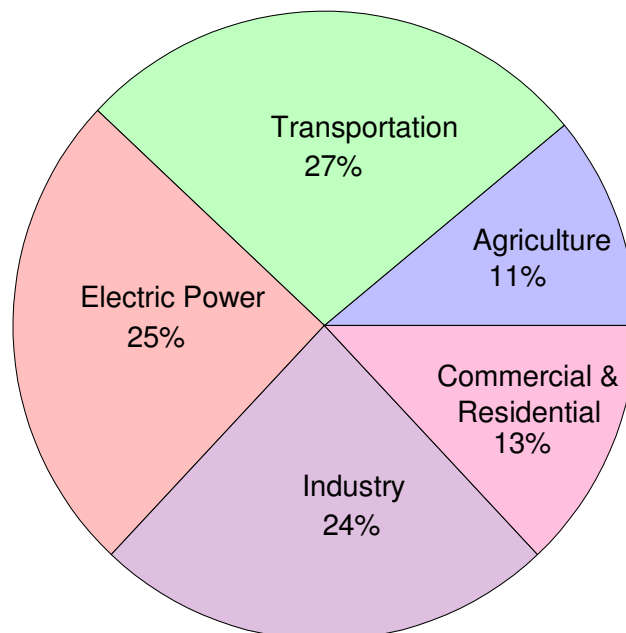


Figure 1: Total U.S. Greenhouse Gas Emissions by Economic Sector in 2020
www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

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 Energy 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 16kW Solar Power System which sells for \$18,999 as of June 29, 2023.

The image shows an eBay product listing for a solar panel kit. On the left, there is a large image of a solar panel array installed on a house roof, with a smaller inset image showing the components of the kit (panels, inverter, racking). The text 'Solar Panel Kit' is prominently displayed. Below it, the description reads '1.6-32 KW Solar Panel Kit with Inverter & Racking System VSUN400-108BMH'. On the right, the product details are listed: '1.6kW-32kWatt Solar Panels DIY Grid Tie Kit with Microinverter & Racking System'. The condition is 'New', the system power is '16KW', and the quantity is '1' with a 'Last One' warning. The price is 'US \$18,999.00'. Below the price, there is a link for financing: '\$124.77 for 24 months with PayPal Credit*'. At the bottom right, there are three buttons: 'Buy It Now', 'Add to cart', and 'Add to watchlist'.

Figure 2: 16kW solar panel kit for sale on ebay

Specifically, let's answer the questions:

- If installed across the river in Moorhead, MN (to take advantage of net-metering), 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 \$0.1456 / kWh (the average residential price of electricity for Xcel energy).
- 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:

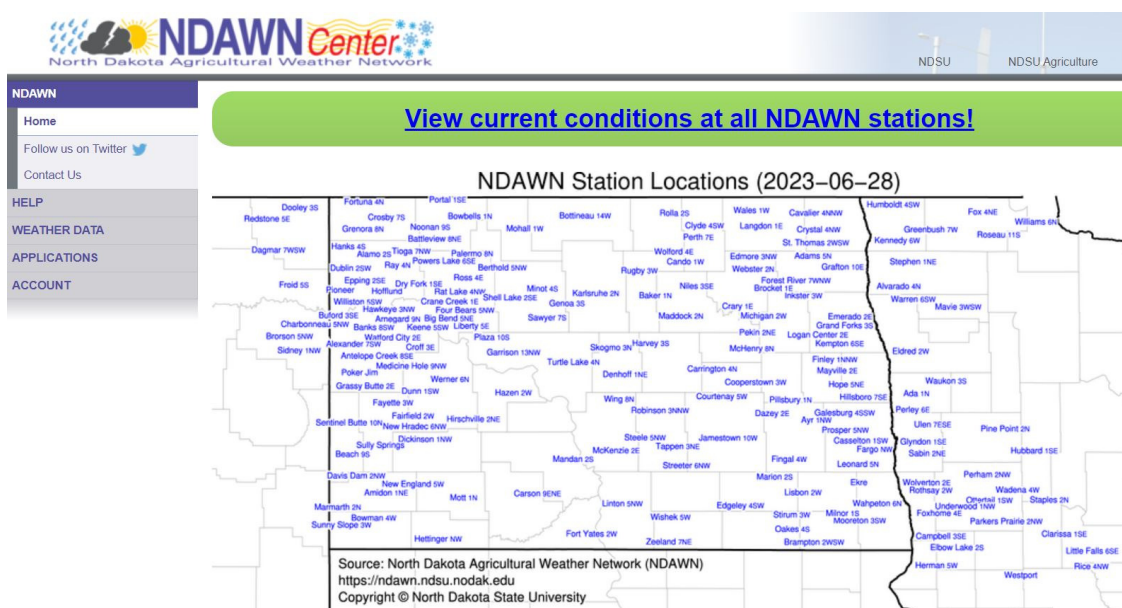


Figure 3: Location of NDAWN weather stations

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

Figure 4: Sample of what the Weather Data screen looks like on NDAWN

- Select Fargo North Dakota, Solar Radiation for April 2023
- Export to a CVS file

Figure 5: Select metric then export CVS file to get hourly weather data

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:

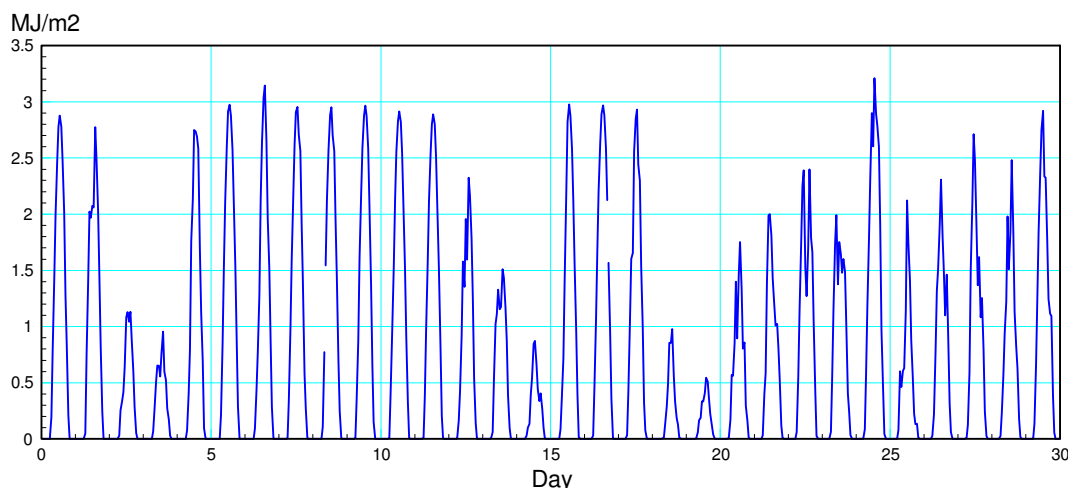


Figure 6: Hourly Solar Energy in Fargo, ND over the month of April 2023.

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 80 x 200W Ecoworthy solar panels to produce 16kW:

- Area = 80 x 1.480m x 0.670m = 79.328 m²
- Efficiency of solar cells = 21.5%
- 1MJ/m² for one hour = 4.7376kWh

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

$$1\left(\frac{\text{MJ}}{\text{m}^2}\right)(79.328\text{m}^2)\left(\frac{\text{kWh}}{3.6\text{MJ}}\right)(0.215) = 4.7376\text{kWh}$$

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 2023: Solar Energy');

```

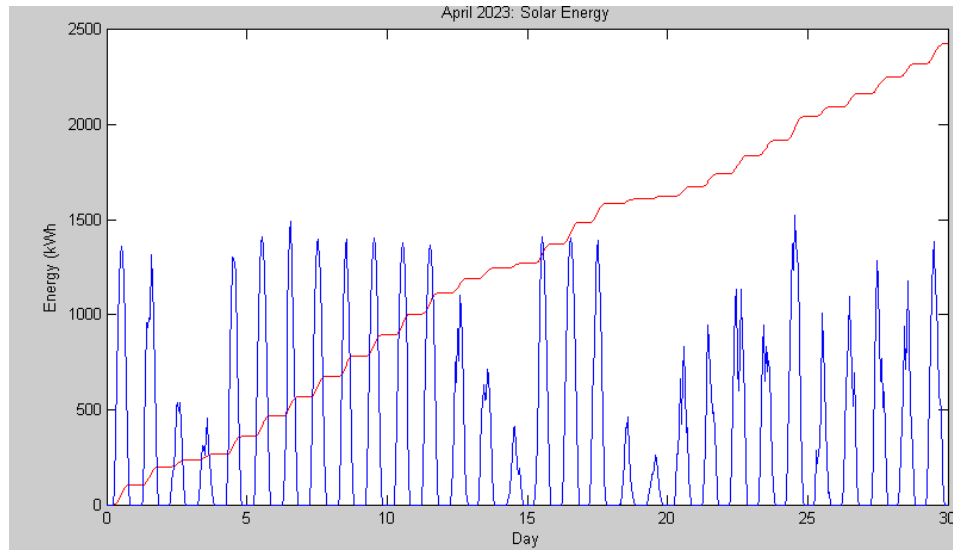


Figure 7: Solar Radiation on an hourly basis x 100 (blue) and Total Energy Produced (kWh = red)
 Note: Graph is incorrect. It should wind up at 1595 kWh

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)

2428.1

```

Over the month of April, 2023, this solar array would produce 2428.1 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 2023?

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 = 2428.1
```

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 = 4322.0 pounds of coal per month
```

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

How long will you have to wait for these panels to pay for themselves (i.e. are these a good investment from a purely economic standpoint)

It depends upon where you live, who your utility provider is, and what plan you're on.

Option #1: Assume

- You live in Moorhead, MN (across the river from Fargo, ND) and get your energy from Xcel Energy.
- You have net metering. This means you buy and sell electricity at the same price.
- You sign up for time-of-day metering. This means the price of electricity is:
 - \$0.15340/kWh 9am to 9pm (peak demand)
 - \$0.02559/kWh other times (off-peak)

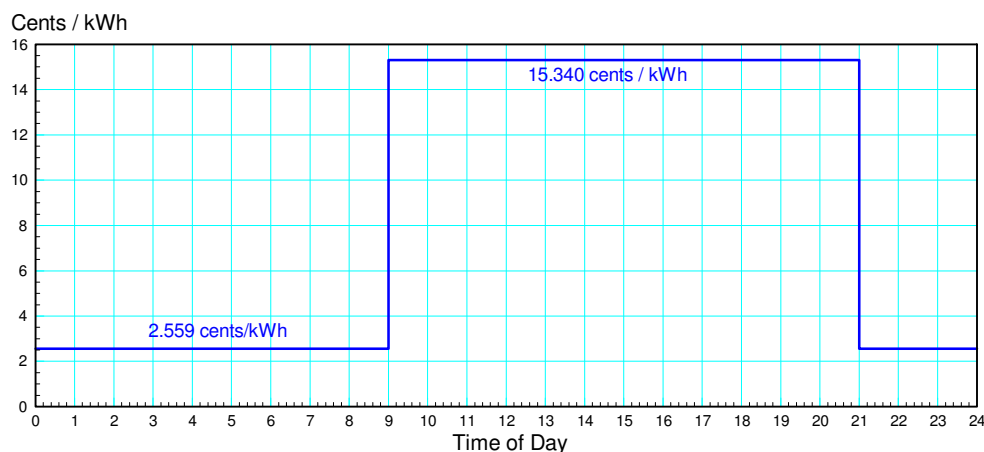


Figure 8: Price of Electricity assuming time-of-day metering in Moorhead, MN
With net billing, electricity you use is worth the same as electricity you don't use (and put back on the grid).

In Matlab, you can convert kWh to dollars using a table (a matrix which stores the price of electricity each hour).

At \$0.1485 / kWh, this panel will produce \$360.57 worth of electricity during this month. In order for this to pay for itself, you'd have to wait 52.48 months (4.46 years)

```
>> kW = 4.7376 * MJ;

>> Time = [1:720]';
>> hr = mod(Time, 24);
>> peak = (hr >= 9) .* (hr < 21);
>> offpeak = 1 - peak;

>> Price = peak * 0.15340 + offpeak * 0.02559;
>> Price(9:20) = 0.15340;
>> Price(21:24) = 0.02559;

>> Dollars = sum(Price .* kW)

    355.2553

>> Months = 18999 / Dollars

Months =    53.4799

>> Year = Months / 12

Year =     4.4567
```

Option #2: You live in Fargo, ND and get your energy from Cass County Electric. In North Dakota, instead being paid the same for electricity you use and produce, you

- pay \$0.11046 / kWh for electricity you use, and
- get \$0.02146 / kWh for electricity you put back on the grid.

This makes the revenue you get dependent upon how much of the electricity you produce you actually use at the time of production. Assume its half. This makes the effective value of the solar energy you produce the average of these two (\$0.06923 / kWh).

With this price of electricity, the payback time is computed as follows:

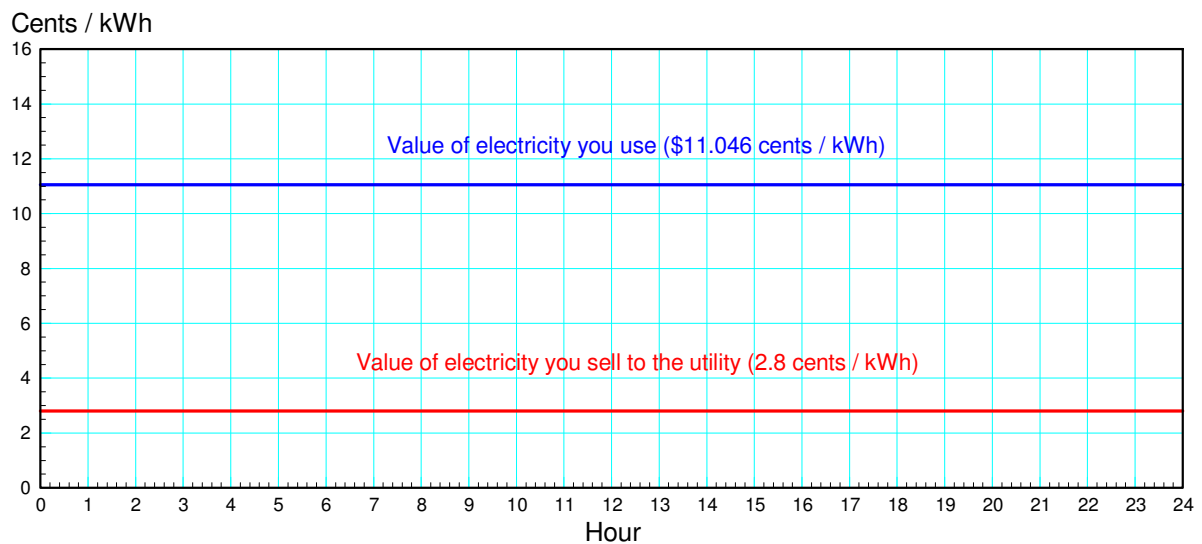


Figure 9: In North Dakota, the cost of electricity you use is different from the credit you get from over-producing.

rate of electricity

```
>> kWh = sum(kW) ;  
>> Dollars = kWh * 0.06923  
  
Dollars = 168.0974  
  
>> Months = 18999 / Dollars  
  
Months = 113.0238  
  
>> Years = Months / 12  
  
Years = 9.4186
```

If you live in Fargo, it would take 9.42 years for these panels to pay for themselves.

Note that these numbers are a little off:

- In 2023, you can get a 20% tax credit for installing solar panels. This reduces the net cost of the panels in this analysis.
- This doesn't take into account the cost of installation. For small arrays, this can be as much as the entire solar array. For larger utility-scale arrays, this cost becomes less significant.
- This analysis doesn't take into account the cost of the land. For roof-mounted solar, this cost is zero. For utility-scaled arrays, this adds to the cost of the project.

What this means is...

- If you live in Minnesota, solar panels are a good investment from a purely economic standpoint: they take less than seven years to pay for themselves.
- If you live in North Dakota, solar panels are not a good investment from a purely economic standpoint: they take more than seven years to pay for themselves.

However, 9.42 years payback time in North Dakota is really close to 7 years.

- If the price of solar panels drop by 26% (through tax breaks or price reduction), this will be a good investment from a purely economic standpoint.
- If the efficiency of solar panels can be increased from 21.5% to 28.9%, this will be a good investment
- If you take in to account environmental issues, you might still want to invest in solar panels.

Even in Fargo, ND, a place not known for being sunny, solar energy is almost viable today. Just across the river in Moorhead, MN, solar energy is already viable.

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 comparable to April every month of the year for 12 years, (somewhat questionable),

$$\left(2428.1 \frac{\text{kWh}}{\text{mo}}\right) \left(12 \frac{\text{mo}}{\text{y}}\right) (20\text{y}) = 582,744 \text{ kWh}$$

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

$$\left(\frac{\$18,999}{582,744 \text{ kWh}}\right) = \$0.0326 / \text{kWh}$$

In comparison, other forms of energy cost:

- | | | |
|-----------------------------|---------------------|----------------------------|
| • Wind | 1.59 cents / kWh | |
| • Nuclear ¹ | 2.438 cents / kWh | |
| • Coal / Steam ¹ | 3.088 cents / kWh | <i>no carbon capture</i> |
| • Solar | 3.26 cents / kWh | |
| • Gas ¹ | 6.44 cents / kWh | |
| • Hydro ¹ | 9.32 cents / kWh | |
| • Coal w/ CC | 25 - 32 cents / kWh | <i>with carbon capture</i> |

(1) U.S. Energy and Information Administration

Without any government subsidies, in 2023 the price of solar is almost the same as coal without carbon capture (meaning all waste is dumped into the atmosphere). It's about 90% cheaper than coal with carbon capture - assuming carbon capture works as advertised (which is a big question).

That is one of the reasons you're seeing so many solar farms going up across the country.



Figure 10: Mapleton, MN Solar Farm

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



Figure 11: Vestas V172-7.2MW wind turbines

<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)
720

>> hr = [1:720]';
>> plot(hr/24, Wind)
>> xlabel('Day');
>> ylabel('m/s');
```

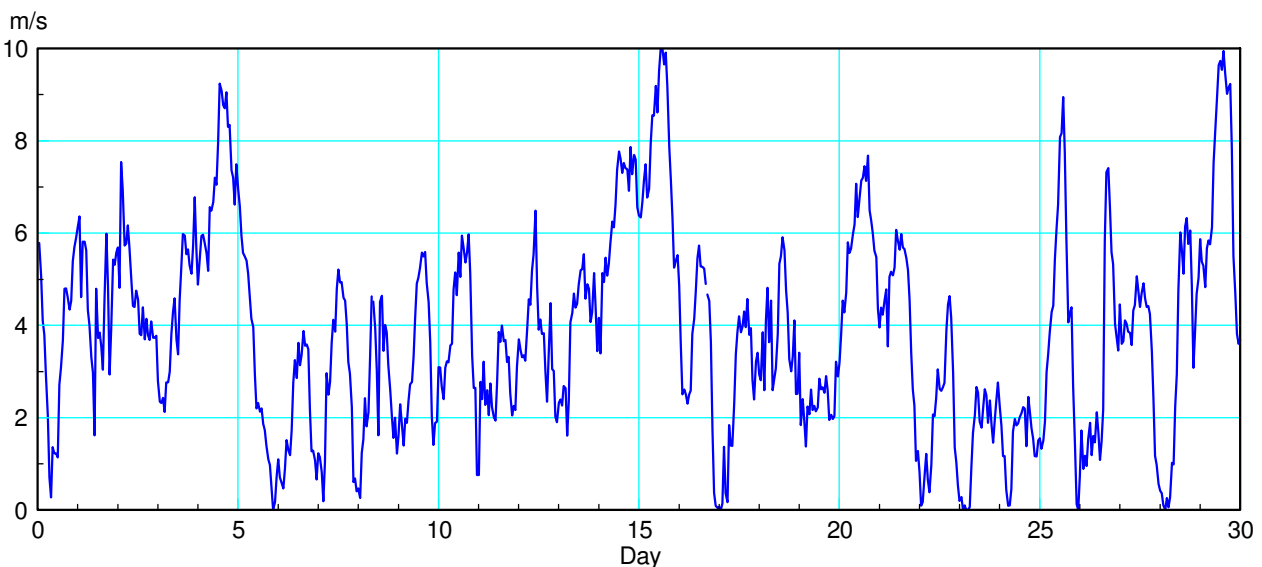


Figure 12: Wind speed in Fargo for April 2023

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

$$\text{Wind @ 80m} = 2.2 * \text{Wind @ 2m};$$

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

Table 1: 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);
```

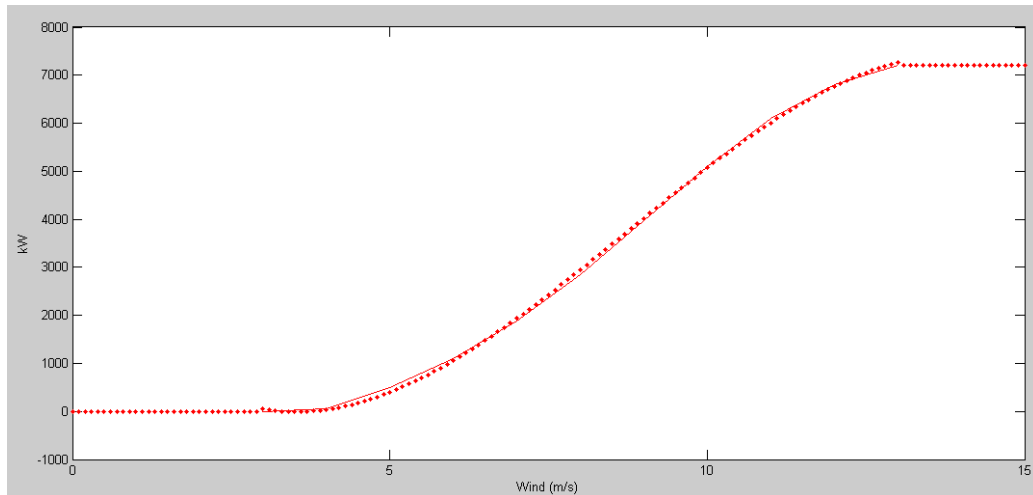


Figure 13: Power Curve (solid red) and Curve Fit (dotted red)

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 you found in problem 3.

```
>> kW = PowerCurve(Wind * 2.2);  
>> hr = [1:length(Wind)]';  
>> plot(hr/24, kW)  
>> xlabel('Day');  
>> ylabel('kW');
```

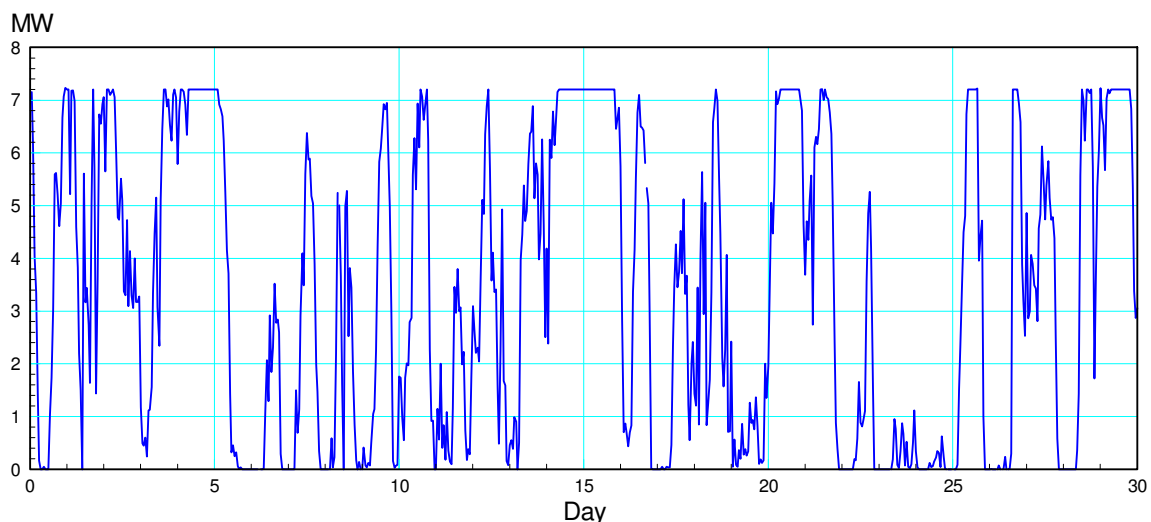


Figure 14: Approximate Energy a Vestas V172-7.2MW Wind Turbine Would Produce

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 = 3392.9
```

The average output of this wind turbine would be 3392.9MW

- 47.1% of the nameplate rating of 7200MW
- 47.1% utilization factor

```
>> kWh = sum(kW) * 1
kWh = 2.4429e+006
```

Over the month of April, the wind turbine would produce 2.4429 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 = 4.3484e+006
```

Each month, this wind turbine offsets 4,348,365 pounds of coal

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

Assume you live in Moorhead, MN:

- This wind turbine costs \$9.36 million to build (\$1300 / kW),
- You get \$0.15340 / kWh for the energy you produce from 9am - 9pm (peak demand)
- You get \$0.02559 / kWh for energy you produce other times (off-peak)

The revenue generated is:

```
>> kW = PowerCurve(Wind * 2.2);
>> Time = [1:length(kW)]';
>> hr = mod(Time, 24);
>> Peak = (hr >= 9) .* (hr < 21);
>> OffPeak = 1 - Peak;
>> Price = 0.15340*Peak + 0.02559*OffPeak;

>> Dollars = sum(kW .* Price)
Dollars = 2.5353e+005
```

In the month of April 2023, you would produce \$253,530 in revenue.

Assuming

- All months have the same wind, and
- \$9.36 million for the turbine,

the payback time is:

```
>> Months = 9.36e6 / Dollars  
  
Months =    36.9192  
  
>> Years = Months / 12  
  
Years =      3.0766
```

It would take 3.07 years for this wind turbine to pay for itself. Wind energy is a good investment in Minnesota.

If you look at North Dakota and assume a fixed rate of 6.923 cents per kWh, the payback time is

```
>> Price = 0.06923;  
>> Dollars = sum(kW * Price)  
  
Dollars = 1.6912e+005
```

At 6.923 cents per kWh, the wind turbine would generate \$169,120 over the month of April

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

```
>> Months = 9.36e6 / Dollars  
  
Months =    55.3446  
  
>> Years = Months / 12  
  
Years =      4.6121
```

Extrapolating, the wind turbine should pay for itself in 4.61 years. It is a very good investment.

Comment: The payback time is even less if you get more for the electricity you produce. At 15 cents / kWh (the national average cost of electricity), the payback time is 2.13 years (!). Wind energy is a very good investment from a purely economic standpoint.

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)

$$\left(2,442,900 \frac{kWh}{mo}\right)(12mo)(20y) = 586,300,000 kWh$$

$$\left(\frac{\$9,300,000}{586,300,000 kWh}\right) = \$0.0159 / kWh$$

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

- Wind 1.59 cents / kWh
- Nuclear¹ 2.438 cents / kWh
- Coal / Steam¹ 3.088 cents / kWh *no carbon capture*
- Solar 3.26 cents / kWh
- Gas¹ 6.44 cents / kWh
- Hydro¹ 9.32 cents / kWh
- Coal w/ CC 25 - 32 cents / kWh *with carbon capture*

(1) U.S. Energy and Information Administration

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

Summary

One of the great things about being an engineer is you don't have to rely upon experts to interpret data. With Matlab and the internet, you can analyze data yourself.

Matlab is a really useful tool. With it, you can

- Evaluate how much energy a solar array should produce at any given location in the area, and
- Evaluate how much energy a wind turbine should produce.

At present

- Solar energy is one of the least expensive ways to generate electricity.
- Wind energy is *the* least expensive way to produce electricity.

This is good news for ECE majors: it means we have jobs. It's also good news for the planet: producing clean energy is actually the least expensive way to go.