

15-Power Curve

ECEGR 452
Renewable Energy Systems



Overview

- Power Coefficient
- Power Curve
- Empirical Power Curve
- Wind Power Modeling



Power Coefficient

- Recall the power in a mass of moving air is:

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

- Mechanical power available is:

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

- C_p : is the unitless power coefficient (more on this in the next lecture)



Power Curve

- Relationship between power output of a wind turbine and the wind speed is known as the **Power Curve**
- Power Curve depends on wind turbine type, model, manufacturer

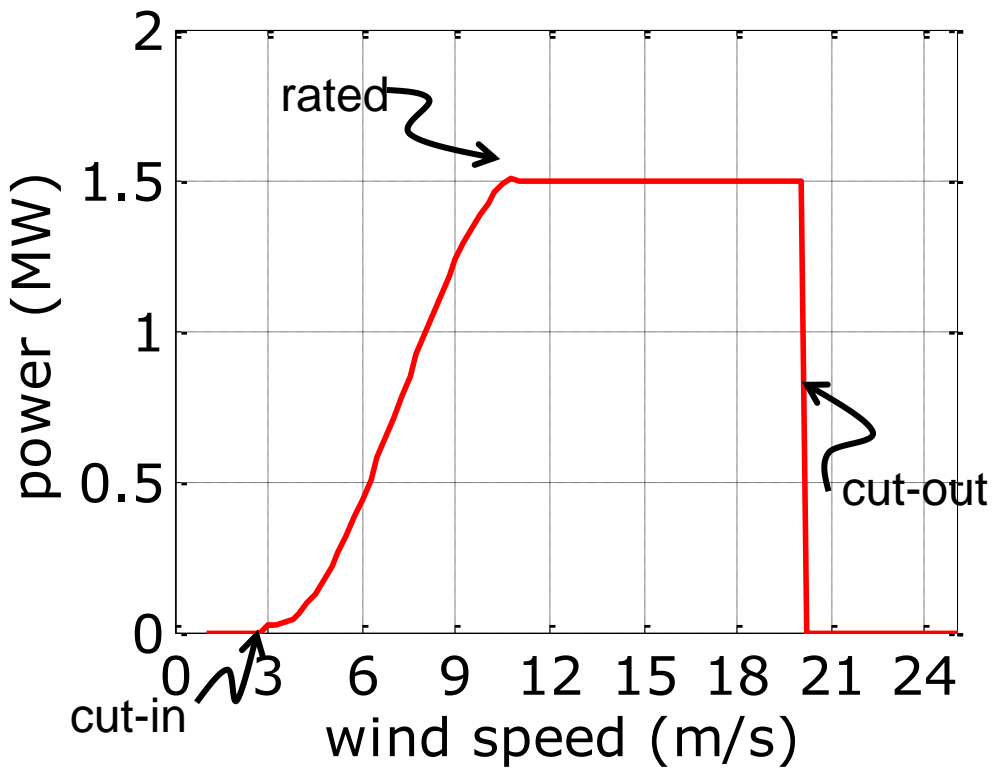


Power Curve

- Power curve is dictated by:
 - **Cut in wind speed**: minimum wind speed for power generation
 - **Cut out wind speed**: maximum wind speed for which the wind turbine produces power
 - **Rated wind speed**: wind speed at which the wind turbine produces rated (nameplate) power
- Also density of the air
 - We will assume it is constant

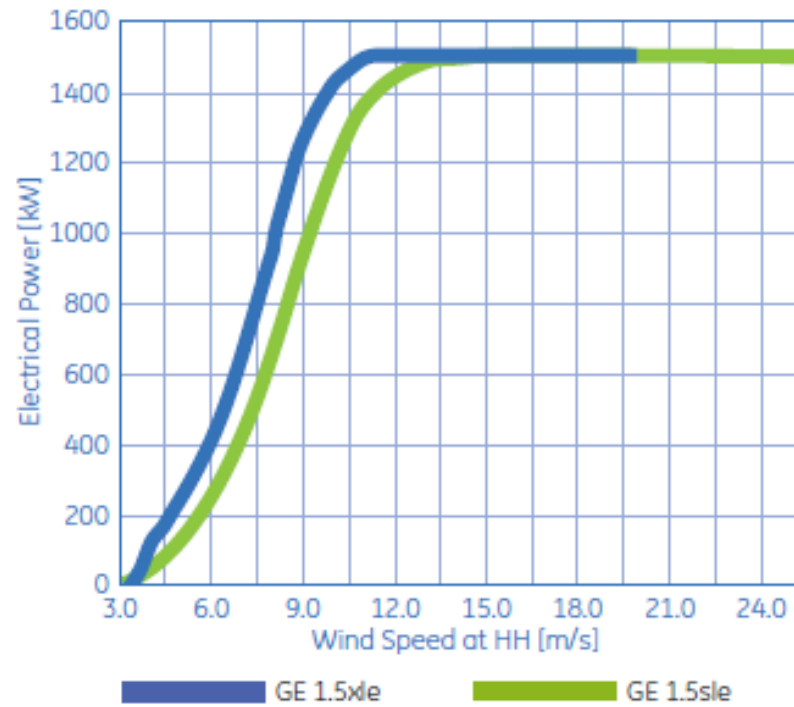


Power Curve





Power Curve



GE 1.5MW Product Brochure



Power Curve

- For a given wind speed, the power output of a wind turbine can be computed directly from the power curve
- Power curve is non-linear
- Subdivide it into four regions
- Compute power output based upon region



Power Curve

- Region 1:

$$v < v_{cut-in}$$

$$P = 0$$

- Region 2:

$$v_{cut-in} \leq v < v_{rated}$$

$$P = h(v)$$

- Region 3:

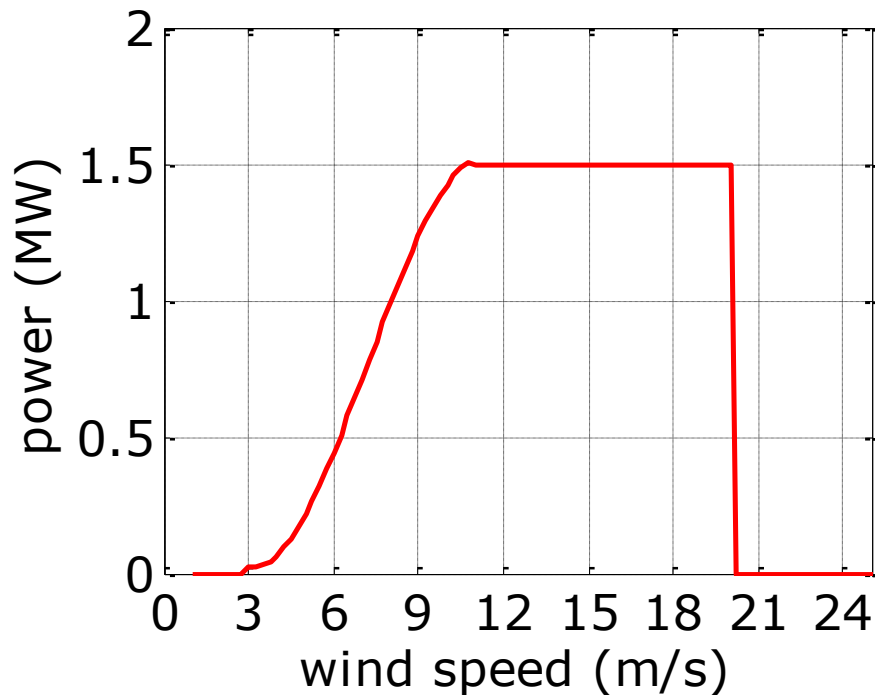
$$v_{rated} \leq v < v_{cut-out}$$

$$P = P_{rated}$$

- Region 4:

$$v_{cut-out} \leq v$$

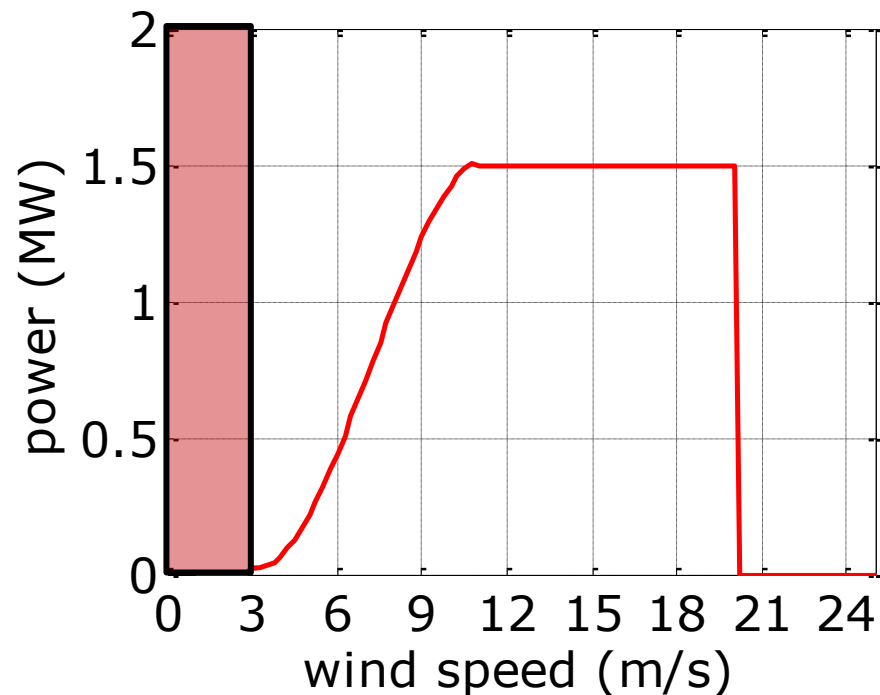
$$P = 0$$





Below Cut-In

- At low wind speeds no electrical power is produced
- C_p is zero
- Power in the wind is not enough to either overcome the friction of the drivetrain, or to result in positive net power production



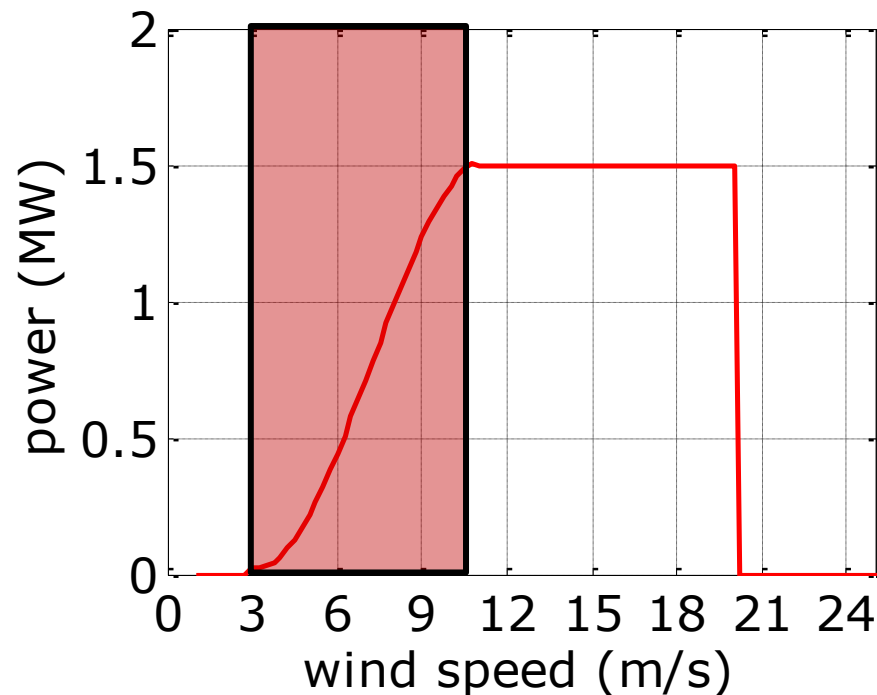
$$P = \frac{1}{2} C_p A \rho v^3$$



Between cut-in and rated wind speed

- When the wind speed is between the cut-in and rated wind speed (v_r), the wind turbine generates power.
- C_p is maximized
- Nearly cubic wind speed-turbine power relationship is observed

$$h(v) = av^3 - bP_{\text{rated}}$$



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



Between cut-in and rated wind speed

- $h(v)$ can be found by:

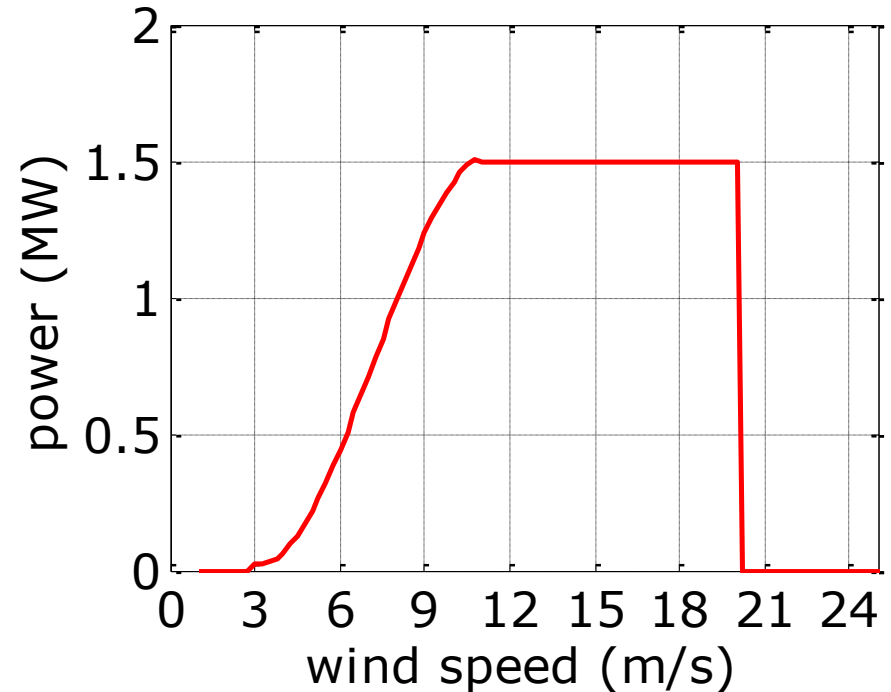
- fitting a line to data points
- solving for a and b in

$$h(v) = av^3 - bP_{\text{rated}}$$

noting that

$$P_{\text{rated}} = av_{\text{rated}}^3 - bP_{\text{rated}}$$

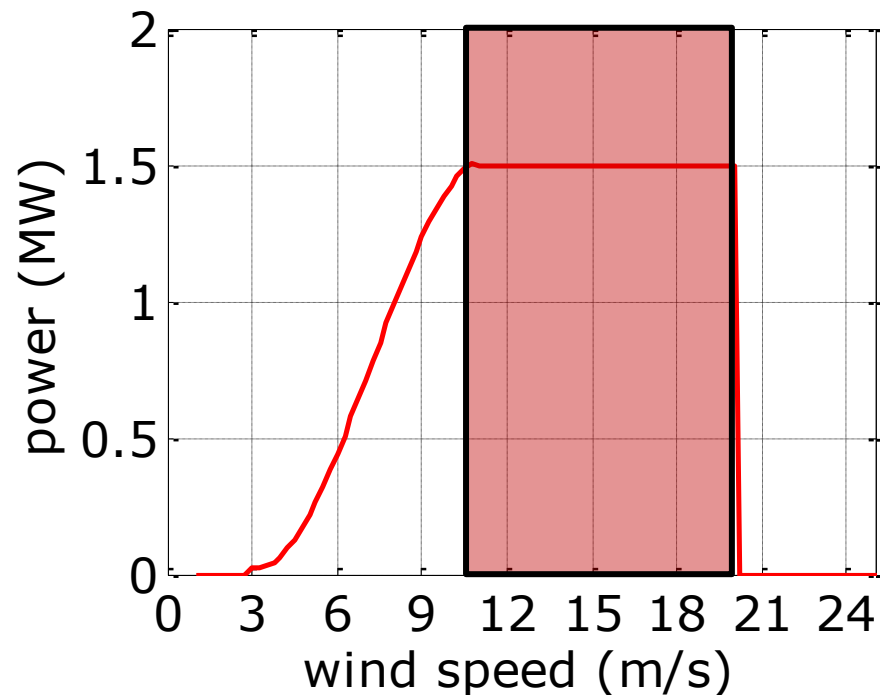
$$0 = av_{\text{cut-in}}^3 - bP_{\text{rated}}$$





Between rated and cut-out wind speed

- At wind speeds above rated and below cut-out (v_{co}), the wind turbine is controlled to maintain constant power production.
- Constant power is maintained by reducing C_p through active pitch control or passive stall design

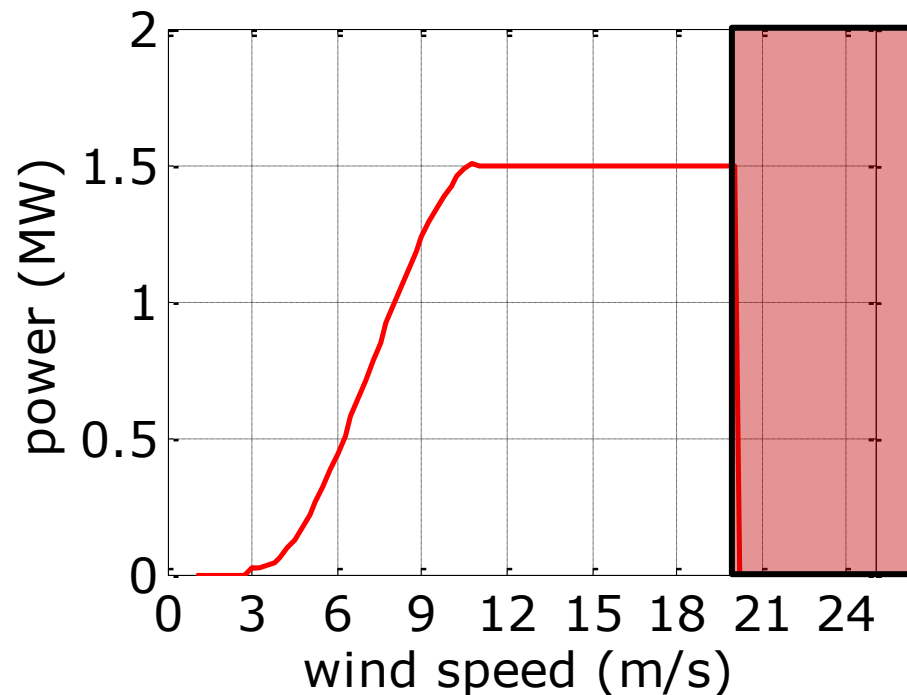


$$P = \frac{1}{2} C_p A \rho v^3$$



At and above cut-out wind speed

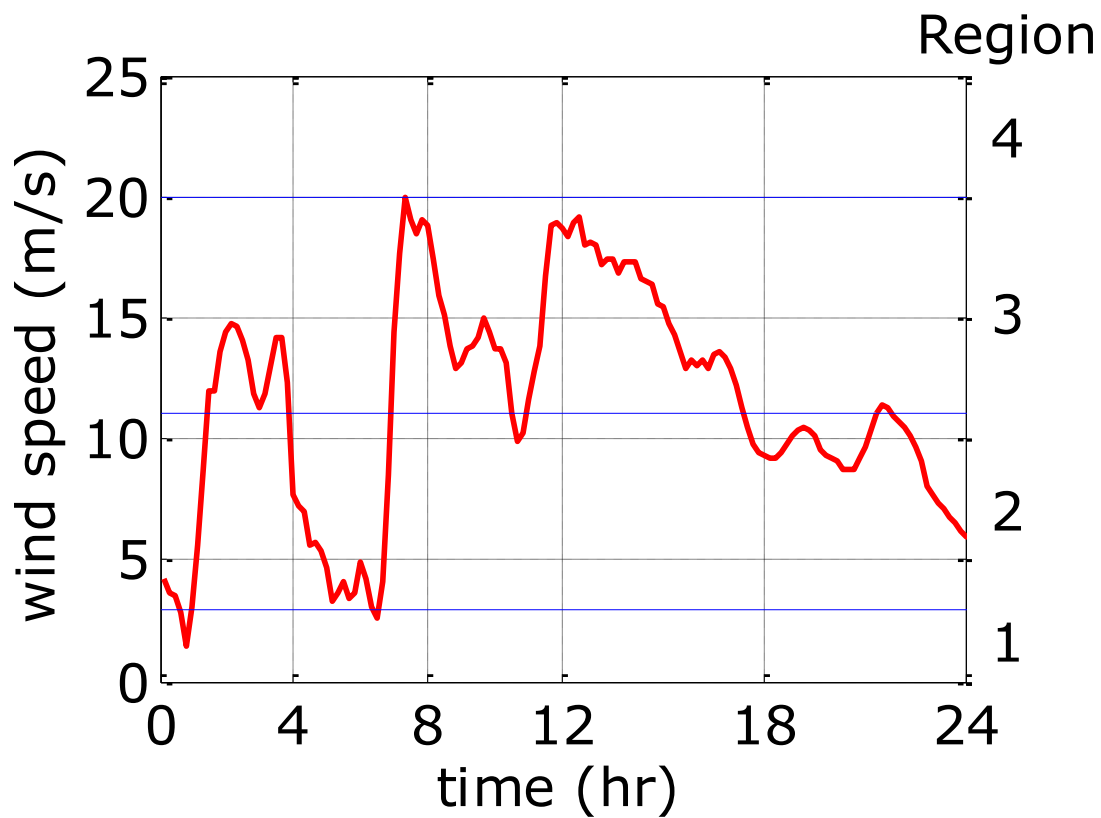
- At excessively high wind speeds, the wind turbine is in danger of mechanical failure
- Turbine is aerodynamically slowed and stopped, and then mechanically locked into place to prevent rotation
- C_p is zero



$$P = \frac{1}{2} C_p A \rho V^3$$



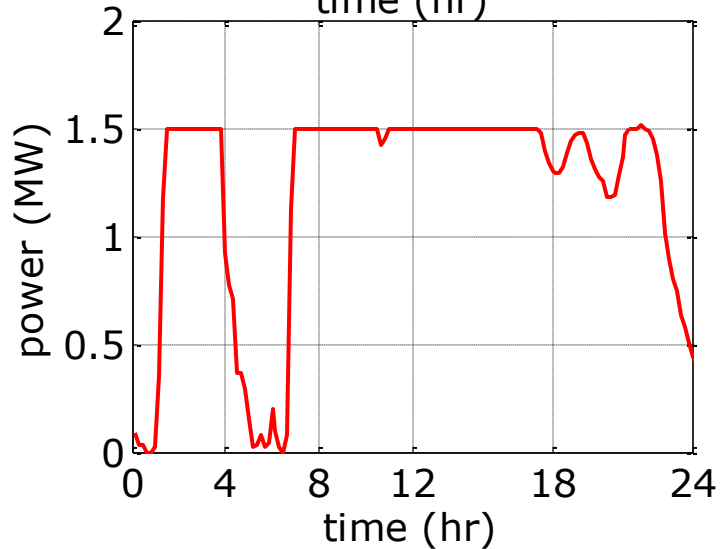
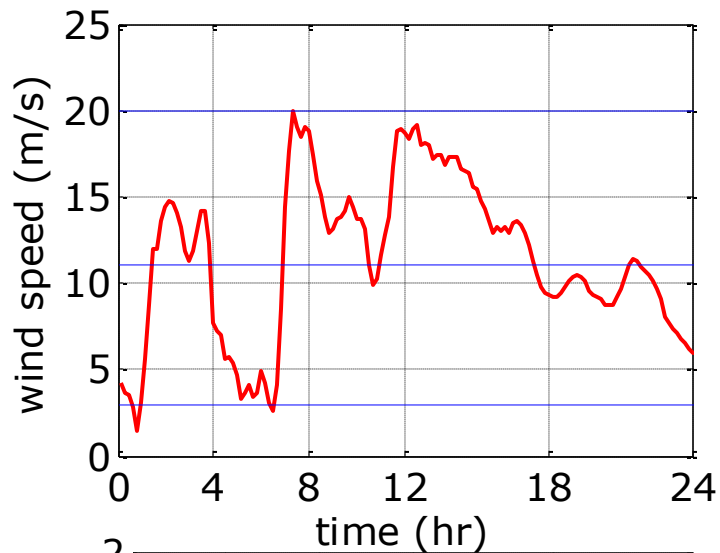
Wind Power Modeling



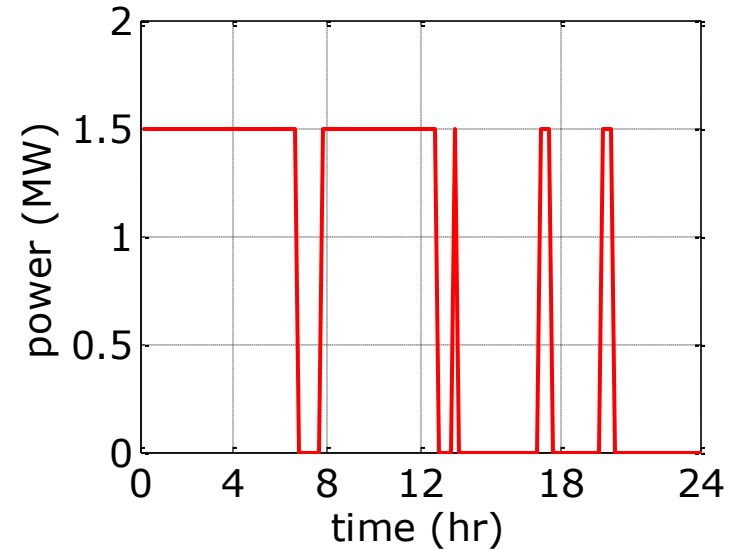
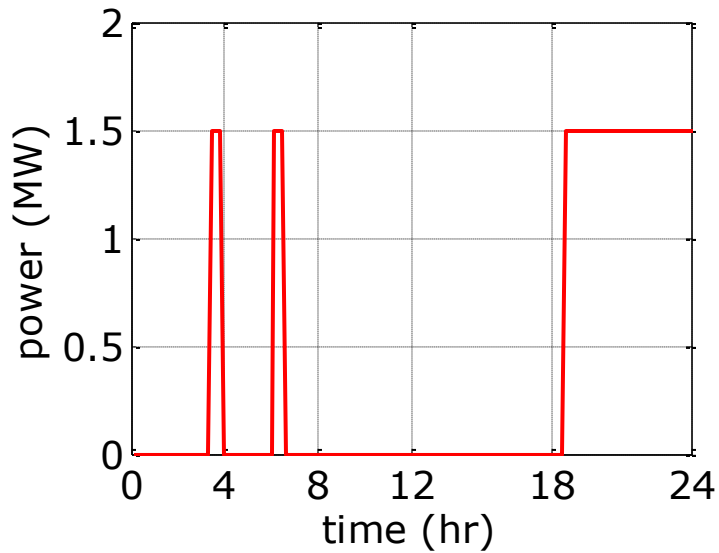
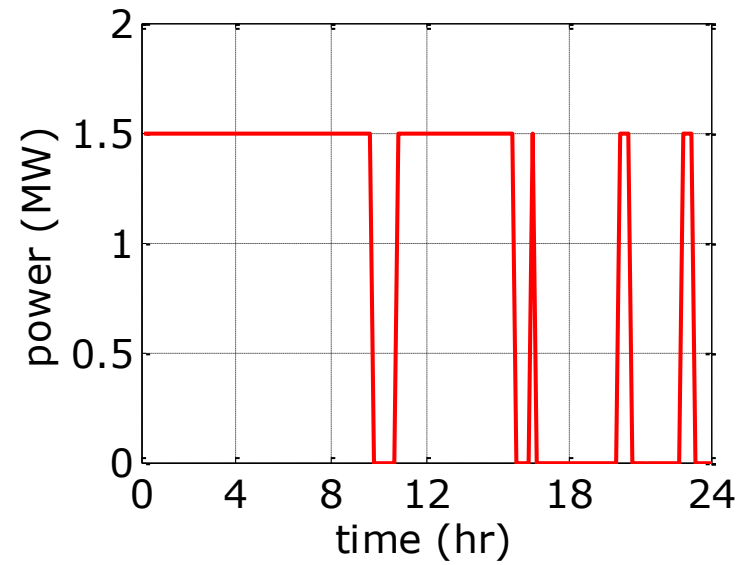
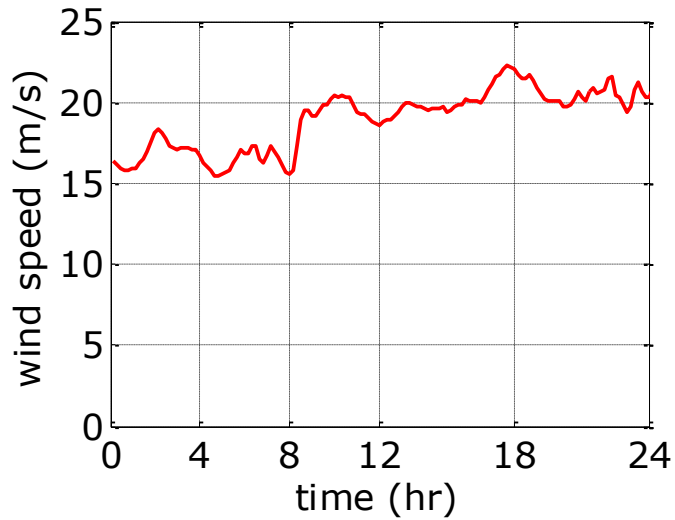
GE 1.5XLE



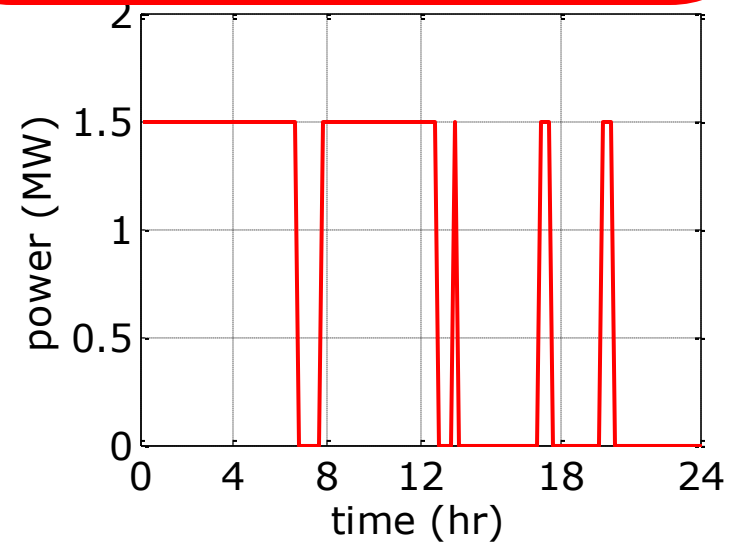
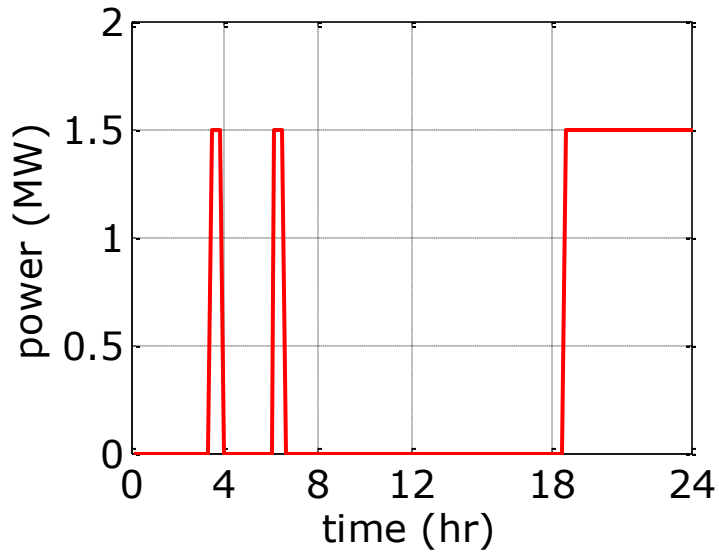
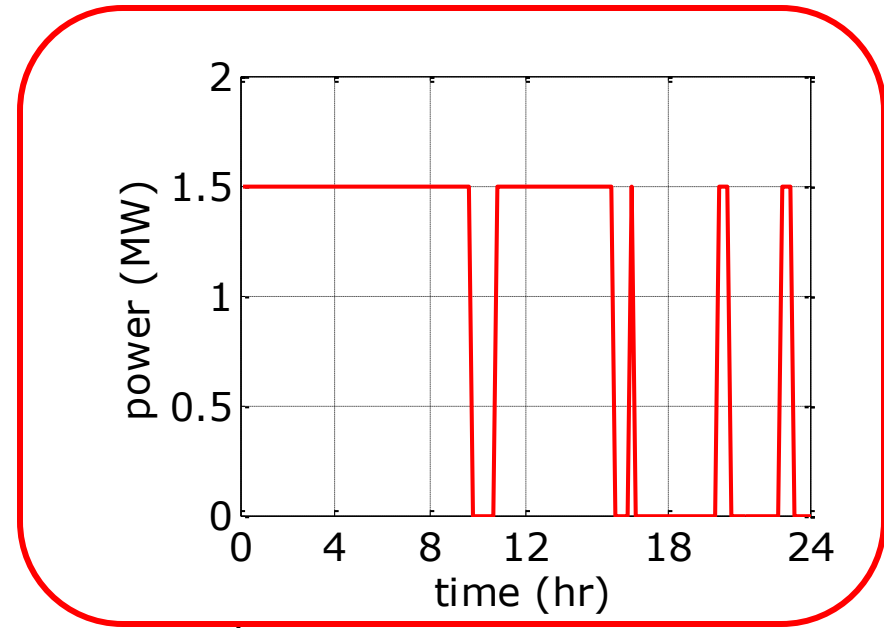
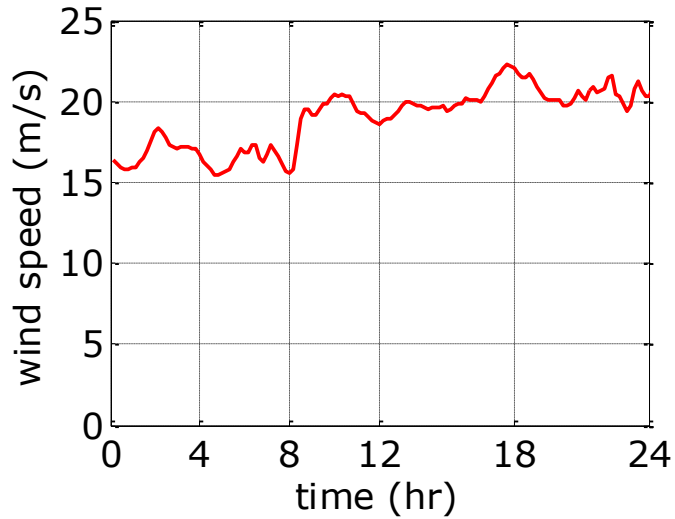
Wind Power Modeling



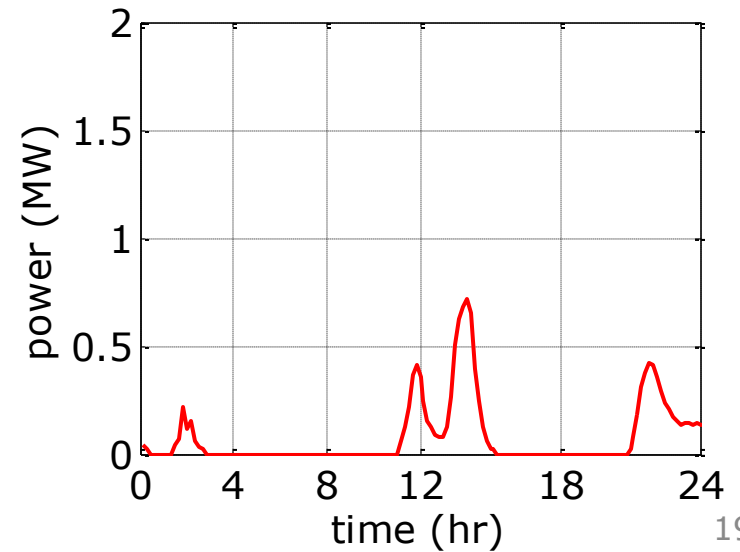
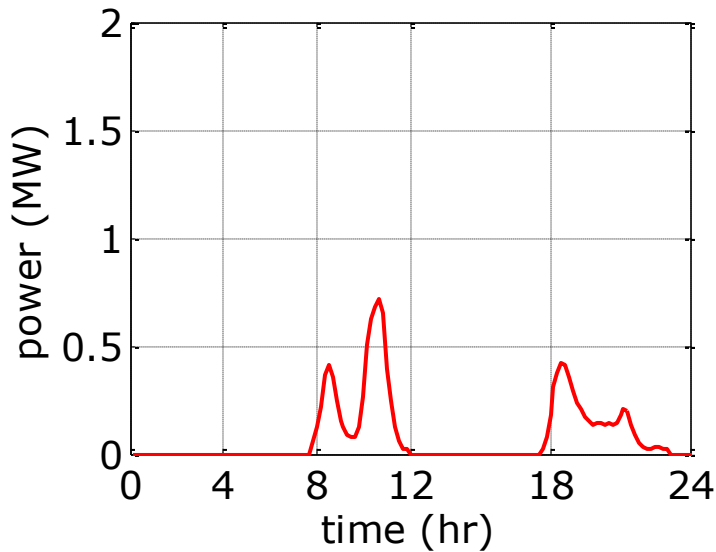
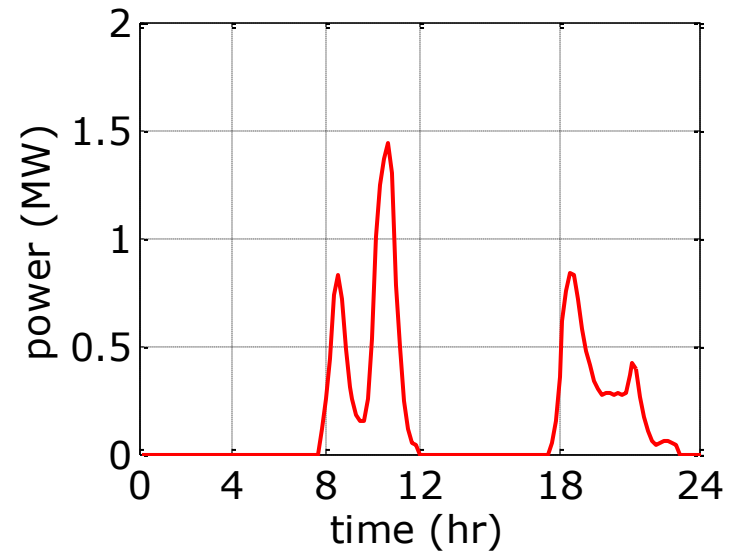
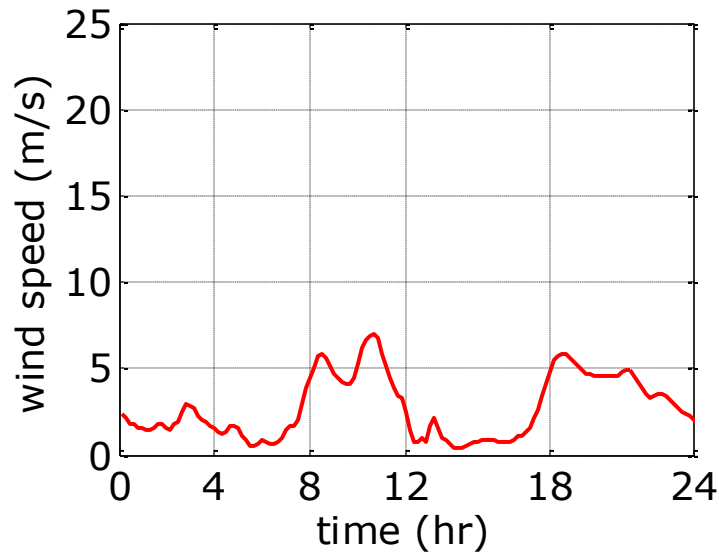
Match the Power Output with the Wind Speed



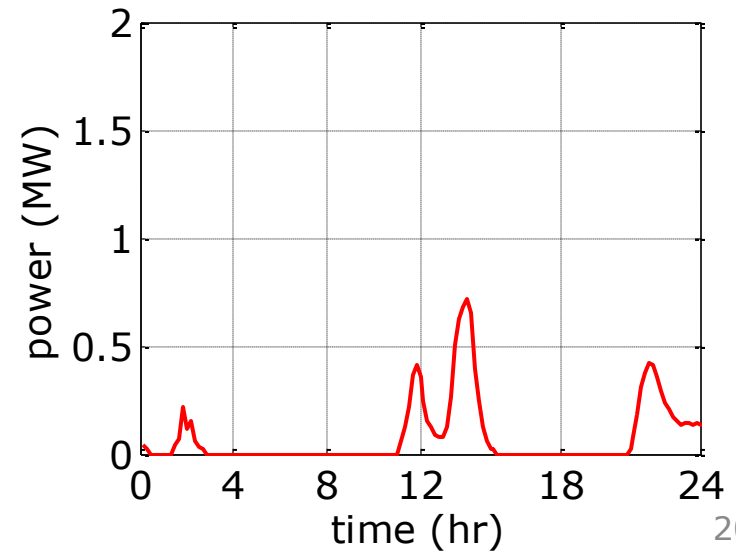
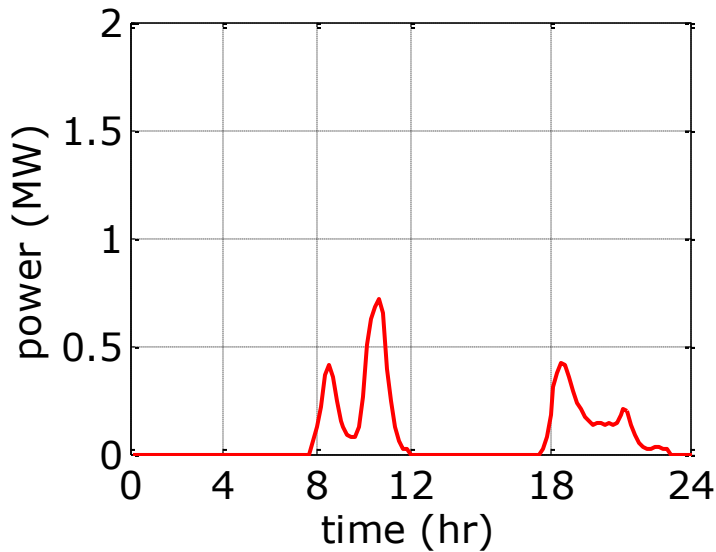
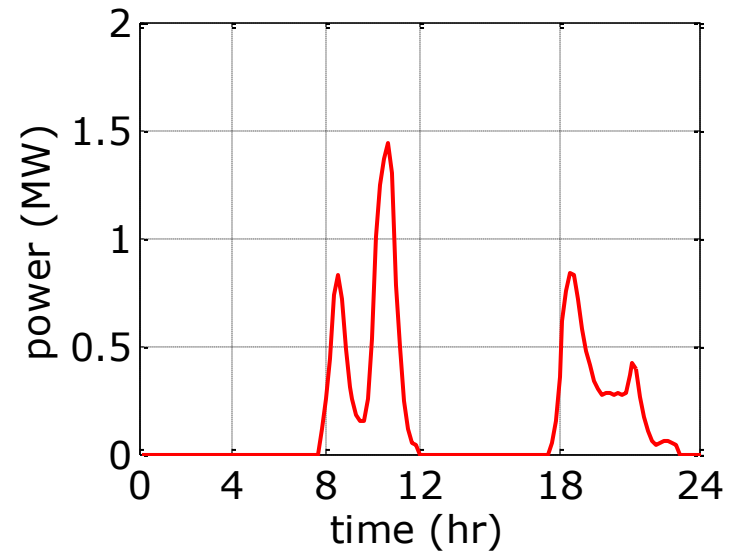
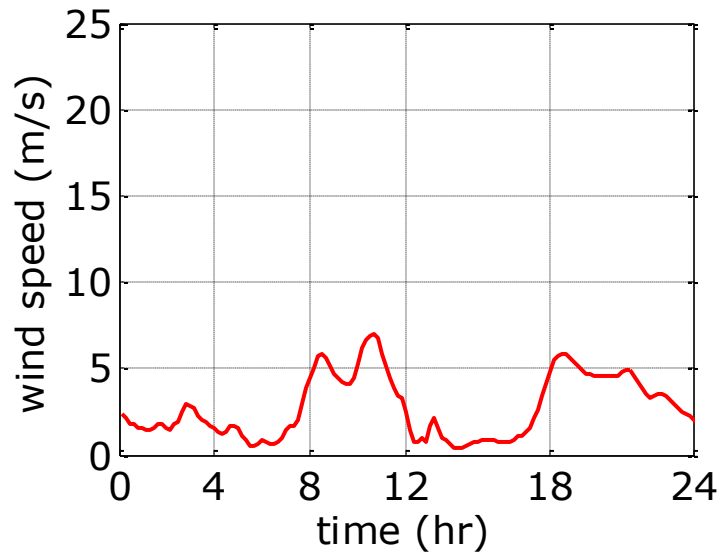
Match the Power Output with the Wind Speed



Match the Power Output with the Wind Speed



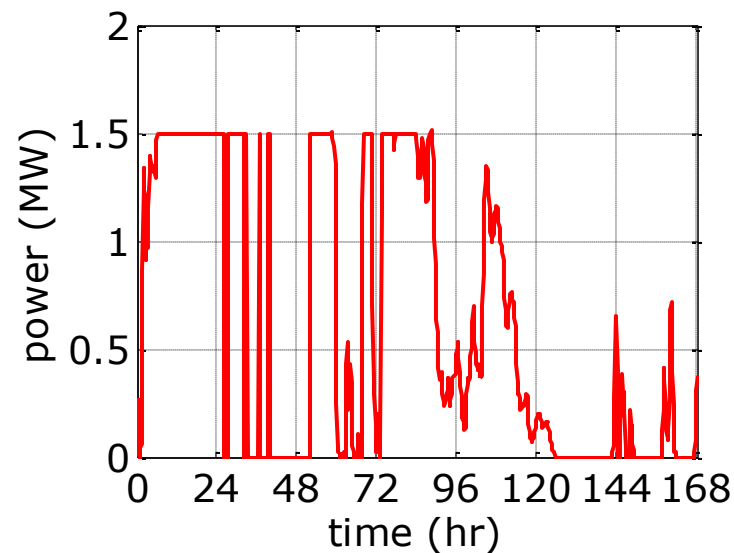
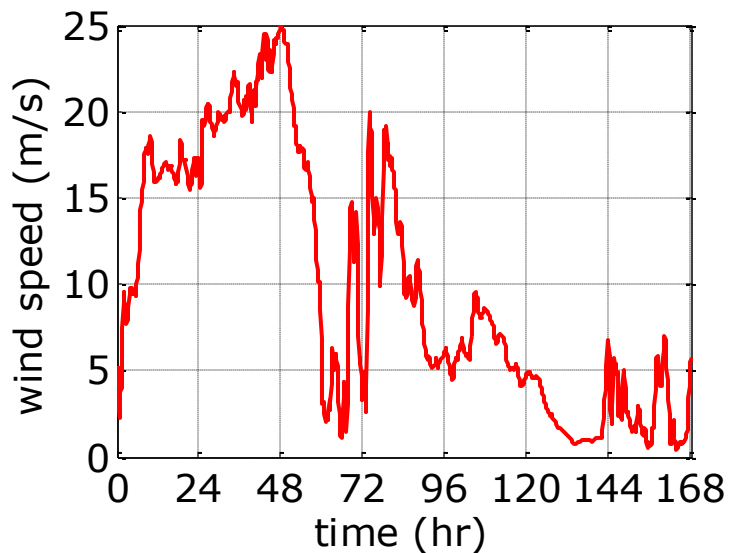
Match the Power Output with the Wind Speed





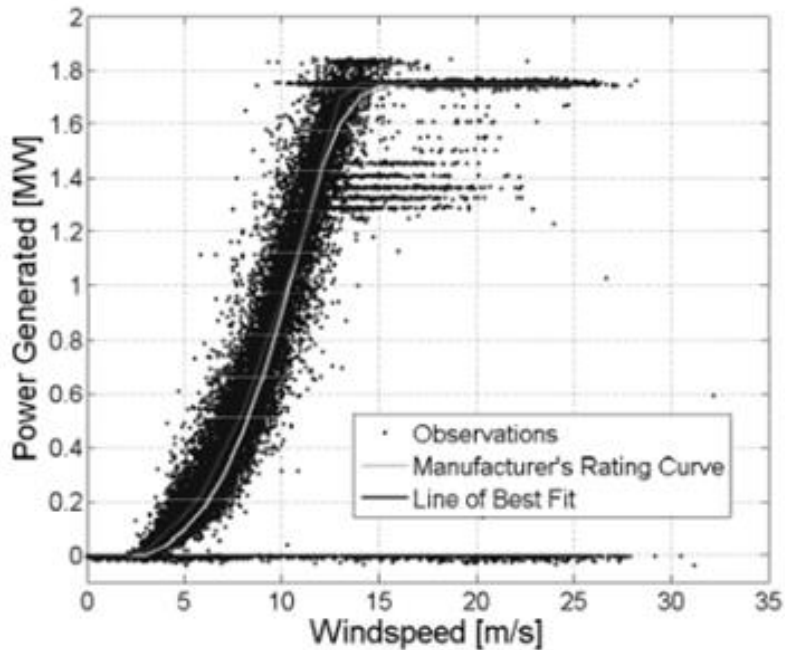
Wind Power Modeling

- Wind turbine power output is highly variable
- Like wind speed, it is useful to develop a probabilistic model of wind turbine power





Empirical Power Curve

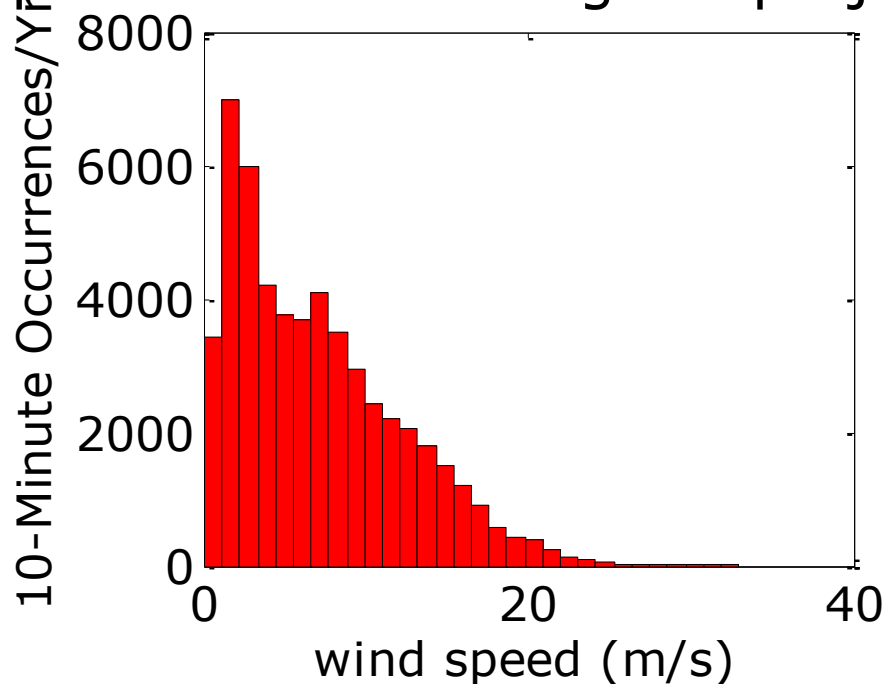


What causes departures in Power production from the power curve?



Wind Power Modeling

- Assume the following histogram of wind speed distribution is given for a potential wind plant
- How much energy will be produced each year?
 - VERY important for financing the project



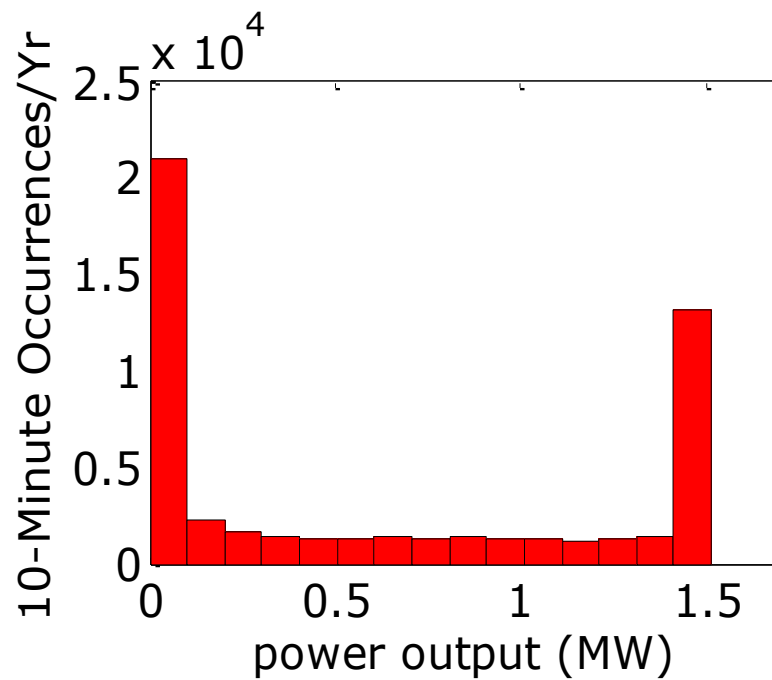
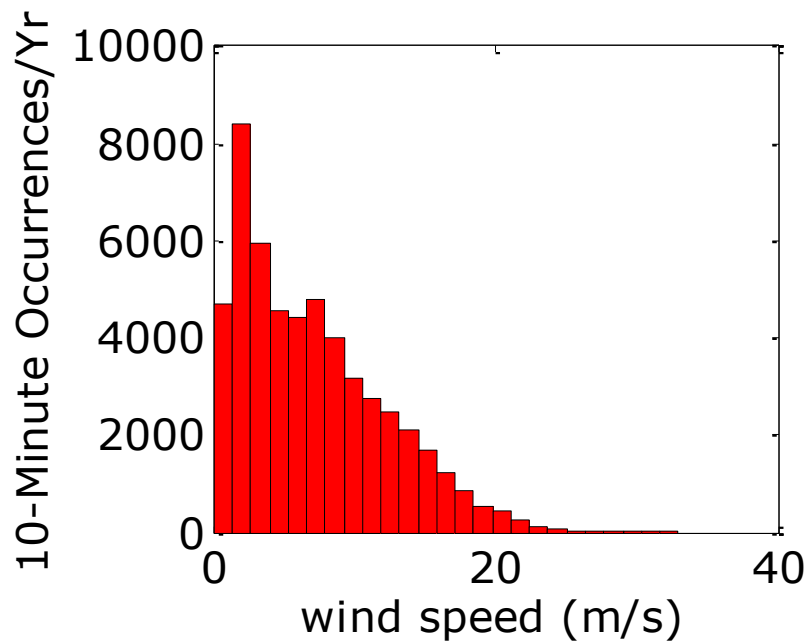


Wind Power Modeling

- We want the PDF of the power output
 - Let $\mathbf{P} = g(\mathbf{v})$
 - g is a function representing the power curve
 - Assume that we will first consider the GE 1.5XLE model
- PDF of power output can be found by computing $f(\mathbf{P}) = f(g(\mathbf{v}))$



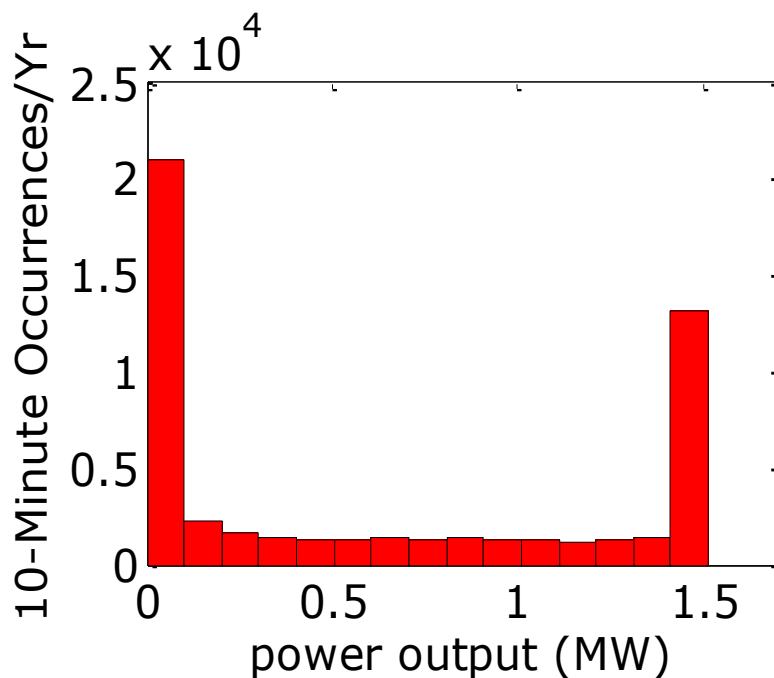
Wind Power Modeling





Wind Power Modeling

- Total energy can be found by through integration (carefully accounting for units)
- In this example: 5,545 MWh/year





Wind Power Modeling

- What is the capacity factor?
- Theoretical maximum energy is $1.5 \text{ MW} \times 8760 \text{ hrs} = 13,140 \text{ MWh}$
- $CF = 5545/13140 = 42\%$
- Since CF is unitless, it is often used to describe the desirability of the wind resource in an area
 - Different turbines will result in different capacity factors, so the turbine type must be specified
 - CF for time of day and season of interest (due to interaction with load profile and energy price)



Wind Power Modeling

Example 24 x 12 table showing average capacity factor by month and hour

	Jan.	Feb.	...	Nov.	Dec.
1:00	0.25	0.28		0.22	0.23
2:00	0.28	0.30		0.24	0.26
...					
23:00	0.24	0.24		0.20	0.23
24:00	0.25	0.29		0.20	0.24



Wind Power Modeling Notes

- How do you model a wind plant?
- Simplest way:
 - Compute power output of 1 turbine, multiply by number of turbines in the wind plant

$$P_{wp} = NP$$

- Where
 - P: power output of the modeled turbine (MW)
 - N: number of wind turbines in the wind plant
 - P_{wp} : power output of the wind plant

A satellite map of a rural landscape with a network of roads and fields. A blue location pin is placed on a road, labeled "Horse Hollow 1". A red horizontal line is drawn below the pin, with a white box containing the text "1.3 miles" positioned below the line. Above the pin, a white box contains the text "wind turbines". Four white arrows point from this box: one to the left, one to the right, and two downwards towards the road network.

wind turbines

Horse Hollow 1

1.3 miles



Wind Power Modeling Notes

- Wind speed is not uniform over a wind plant
- Different turbines will experience different wind speeds
- Direction of wind becomes important
- Compute/estimate wind speeds at each wind turbine

$$P_{wp} = \sum_{i=1}^N P_i$$

- Where:
 - i : wind turbine number



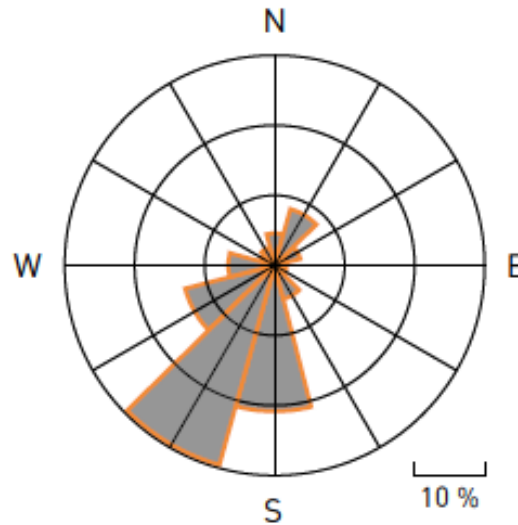
Other Modeling Considerations

- Wind turbines consume power for monitoring and other supervisory control functions (few kW per turbine)
- Outages (planned and unplanned) can be common and last for hours or longer (much longer for offshore wind turbines)
 - Rare for all wind turbines to be operational in a large wind farm
- Collector system has losses (up to 5 percent)
- Air density is not constant nor consistent



Effect of Direction

- Wind Power Rose showing percent of power by direction



Source: 3TIER, Inc.



Reading

R. Thresher, M. Robinson and P. Veers "To Capture the Wind", IEEE Power & Energy Magazine, Vol. 5, No. 6, Dec 2007