13-Wind Turbine Power Curves

ECEGR 4530

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)

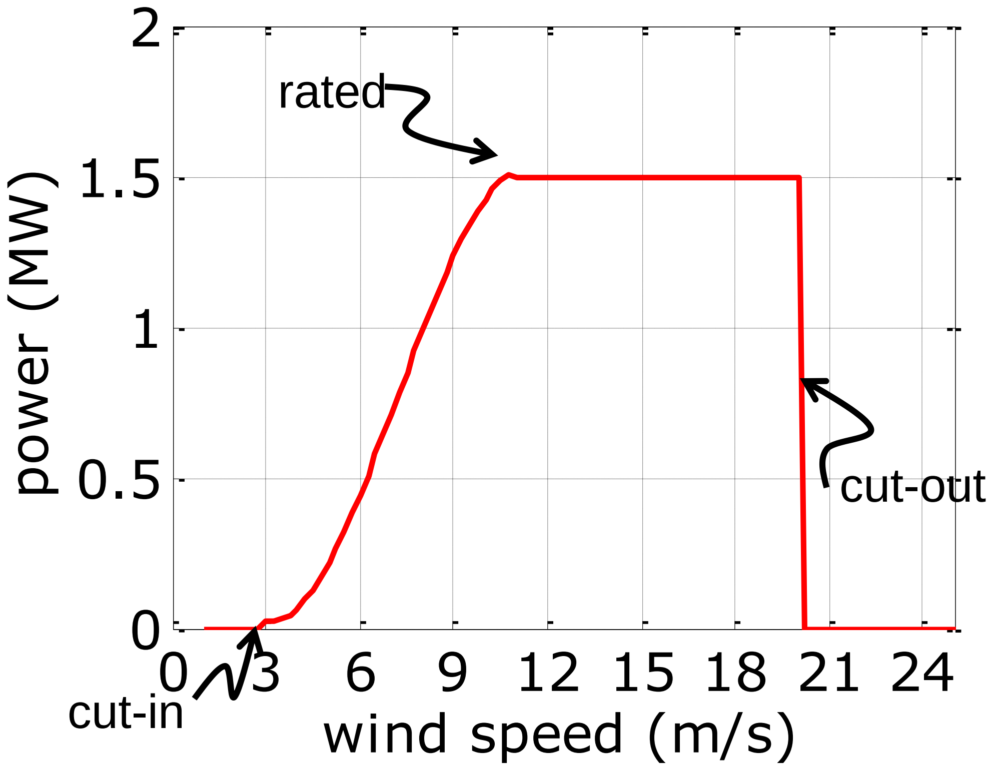
Power Curve

- 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

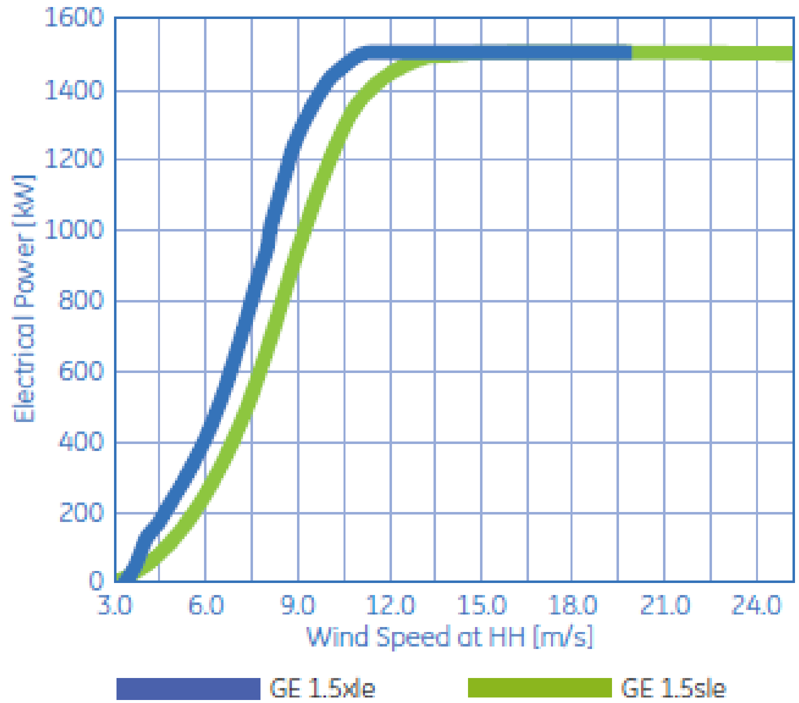
- Power curve is dictated by:
  - Cut in wind speed: minimum wind speed for power generation
  - Cut out wind speed: maximum wind speed for which the wind turbine produces power
  - Rated wind speed: wind speed at which the wind turbine produces rated (nameplate) power
- Also density of the air
  - We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

Power Curve



2
1.5
1
0.5
0
power (MW)
rated
cut-out
cut-in
0
3
6
9
12
15
18
21
24
wind speed (m/s)

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:

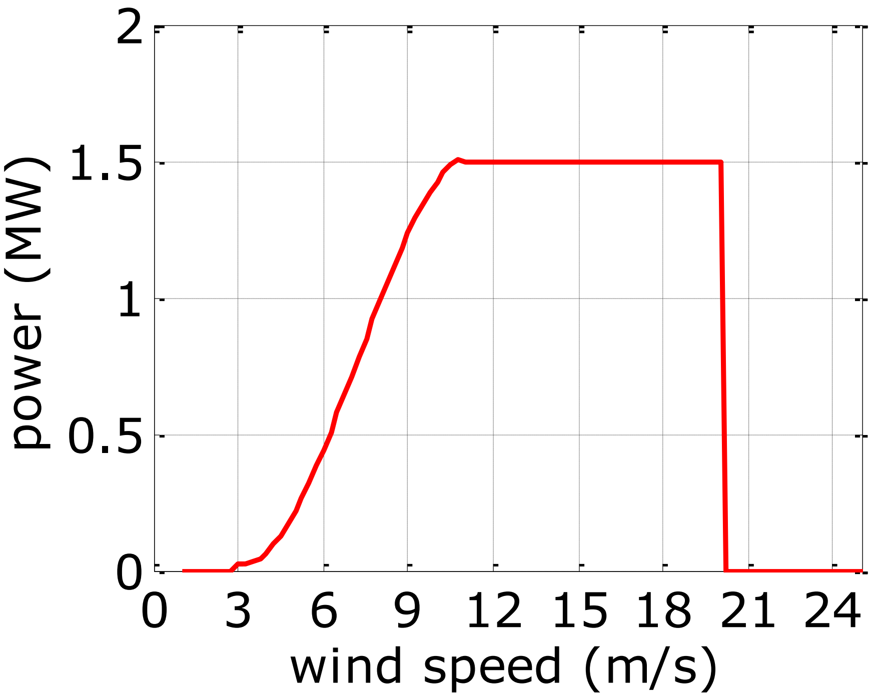
$$v_{cut-in} \le v < v_{rated}$$
$$P = h(v)$$

- Region 3:

$$v_{rated} \le v < v_{cut-out}$$
$$P = P_{rated}$$

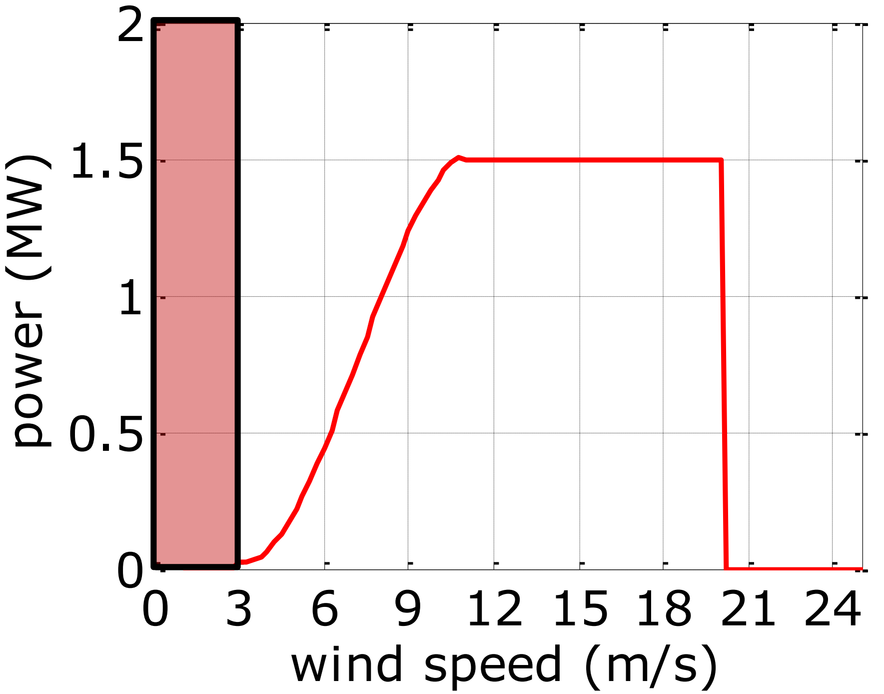
- Region 4:

$$v_{cut-out} \le v$$
$$P = 0$$



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

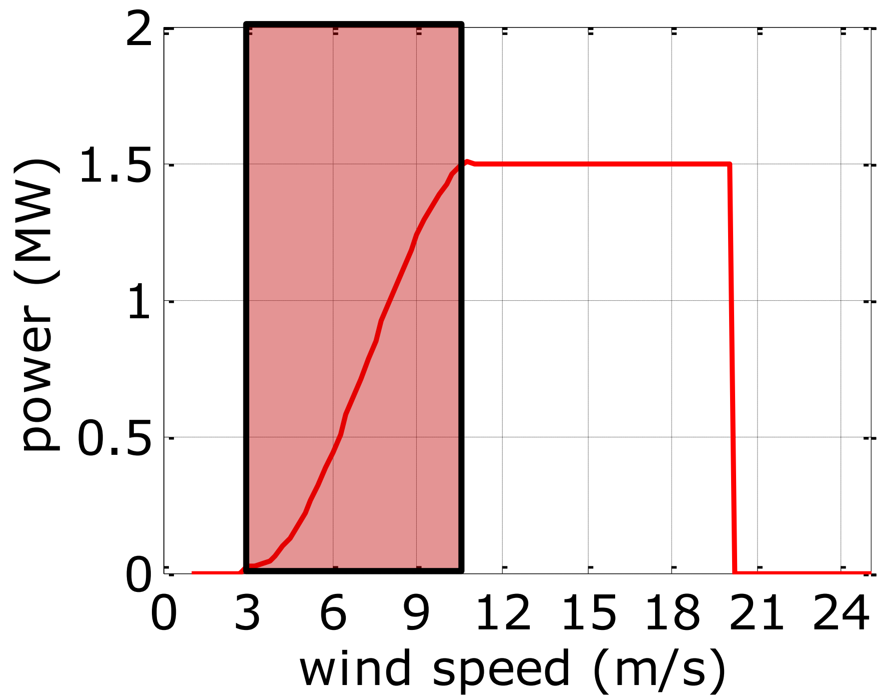


$$P = \frac{1}{2} C_p A \rho v^3$$

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

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



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

Between cut-in and rated wind speed

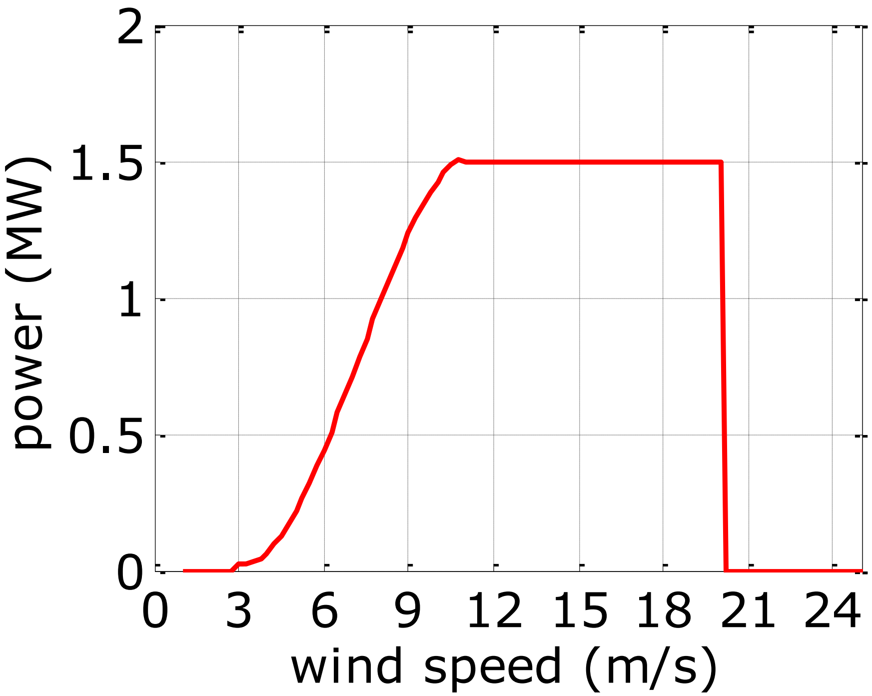
- h(v) can be found by:
  - fitting a line to data points
  - solving for a and b in

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

noting that

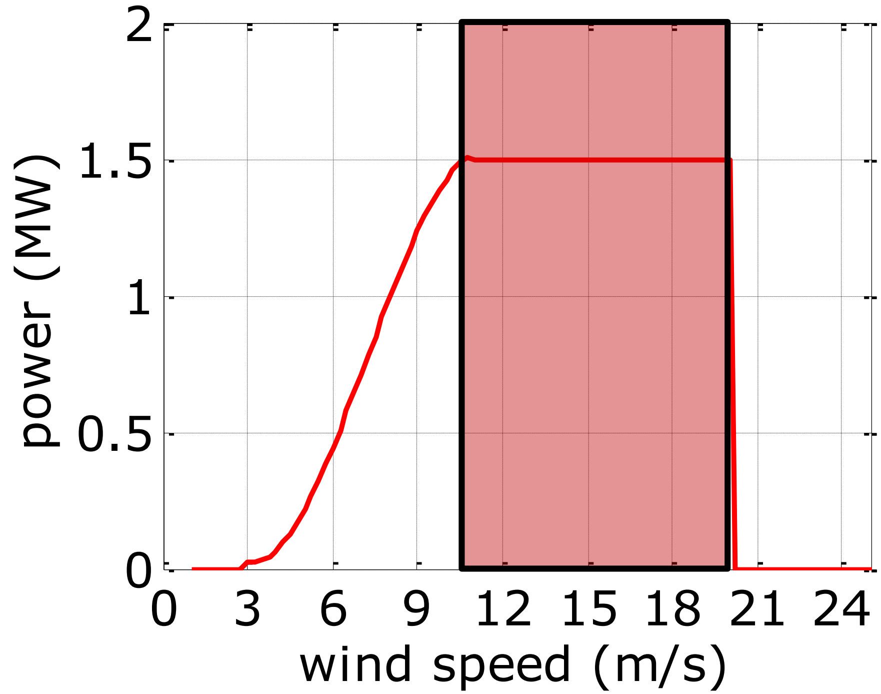
$$P_{rated} = av^3_{rated} - bP_{rated}$$

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



Between rated and cut-out wind speed

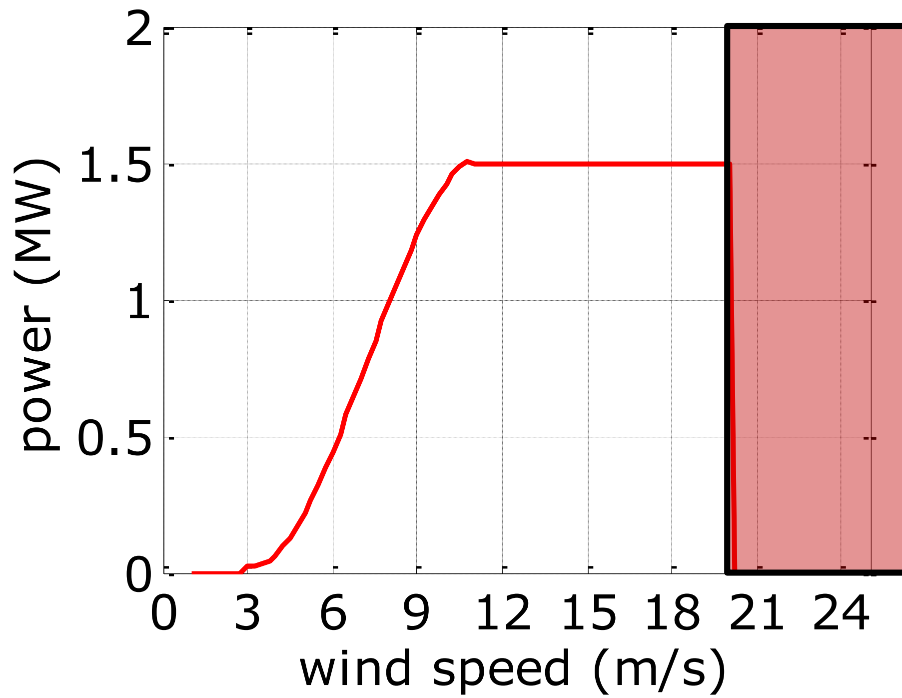
- At wind speeds above rated and below cut-out (v_{co}), the wind turbine is controlled to maintain constant power production.
- Constant power is maintained by reducing C_p through active pitch control or passive stall design



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

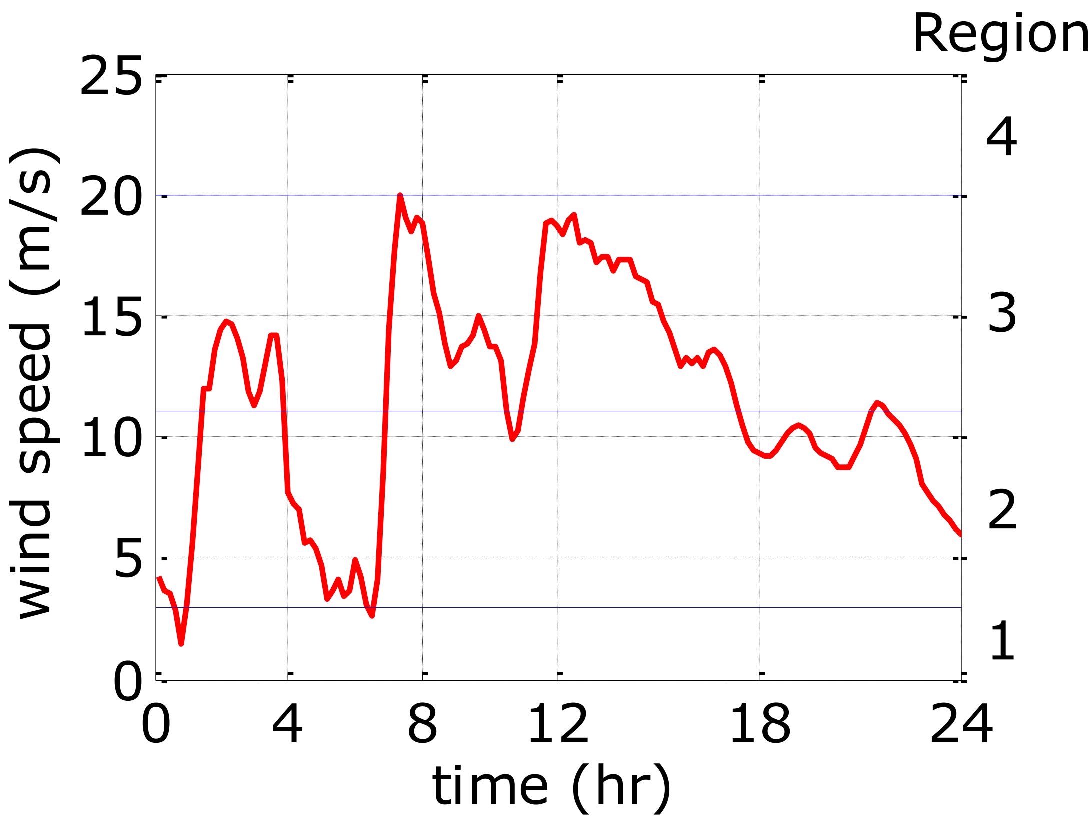
At and above cut-out wind speed

- 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



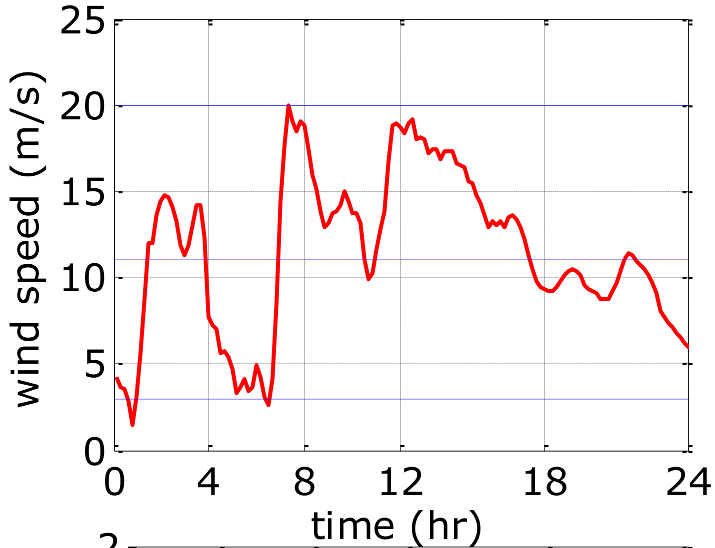
$$P = \frac{1}{2} C_p A \rho v^3$$

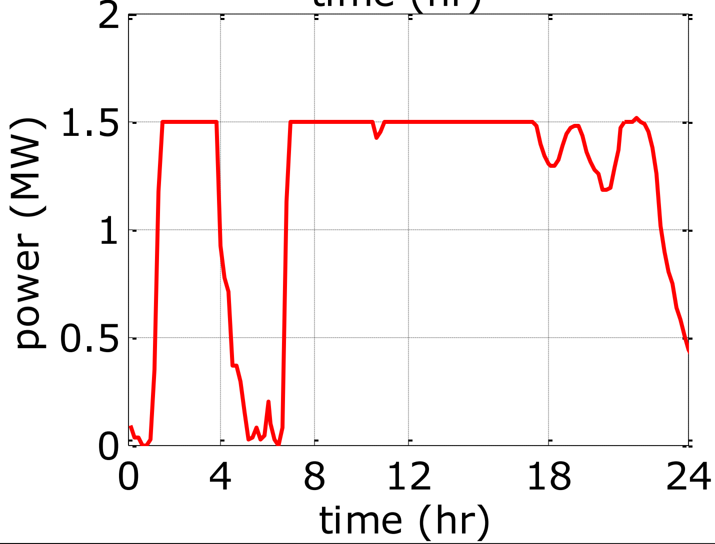
Wind Power Modeling



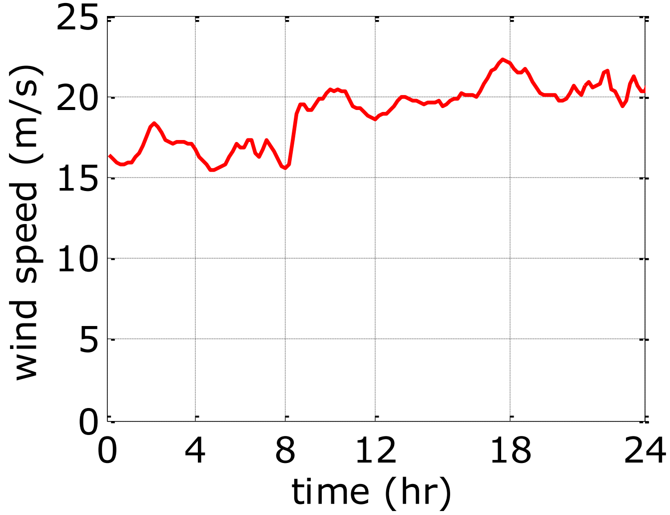
GE 1.5XLE

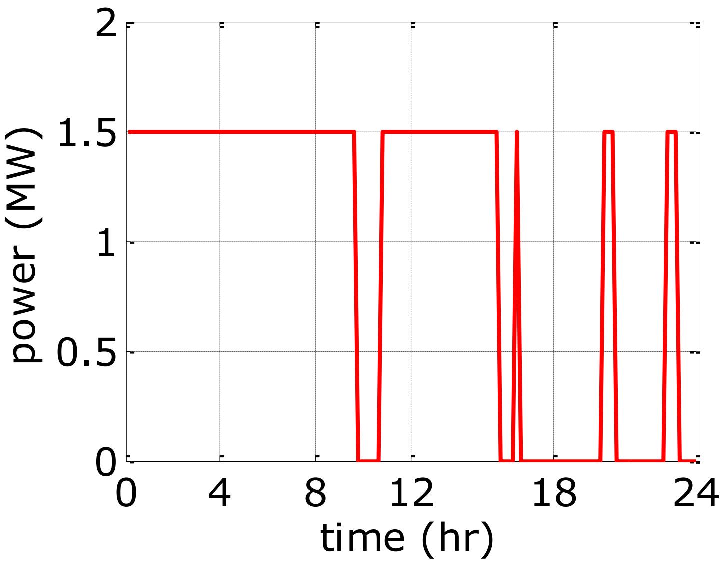
Wind Power Modeling

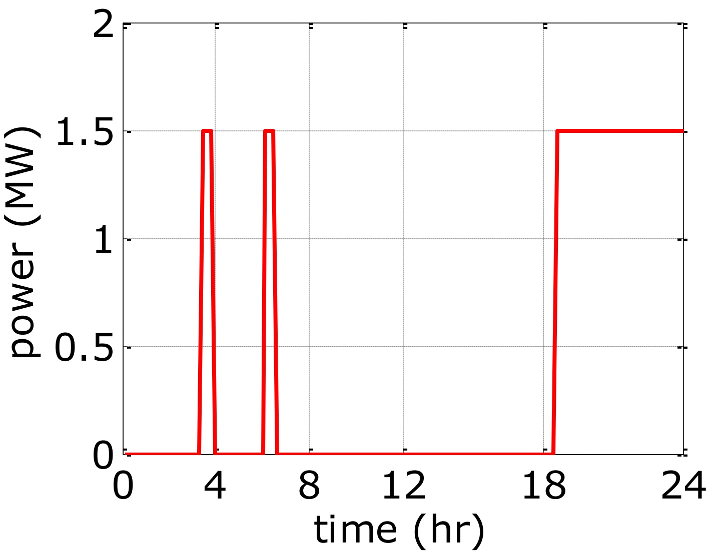


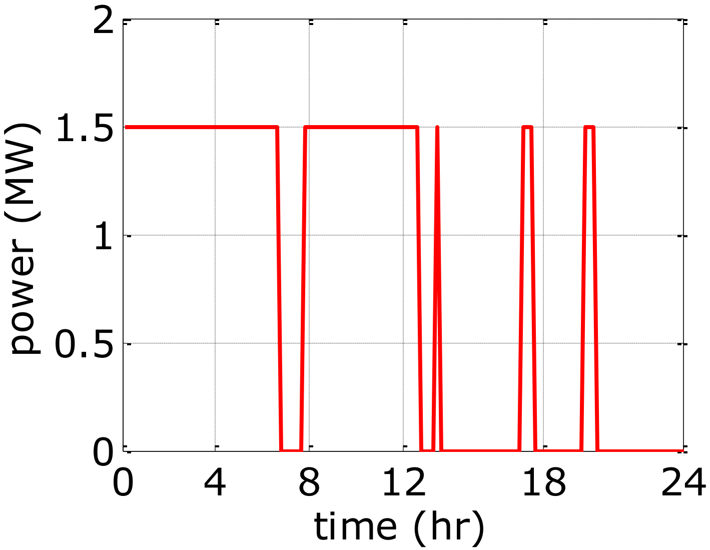


Match the Power Output with the Wind Speed









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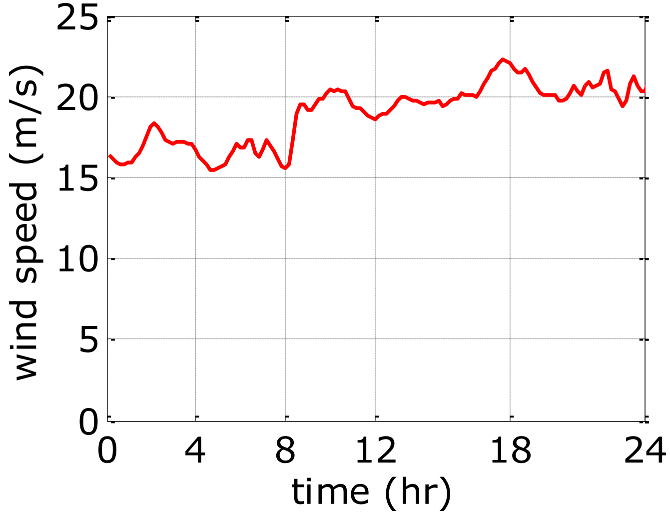

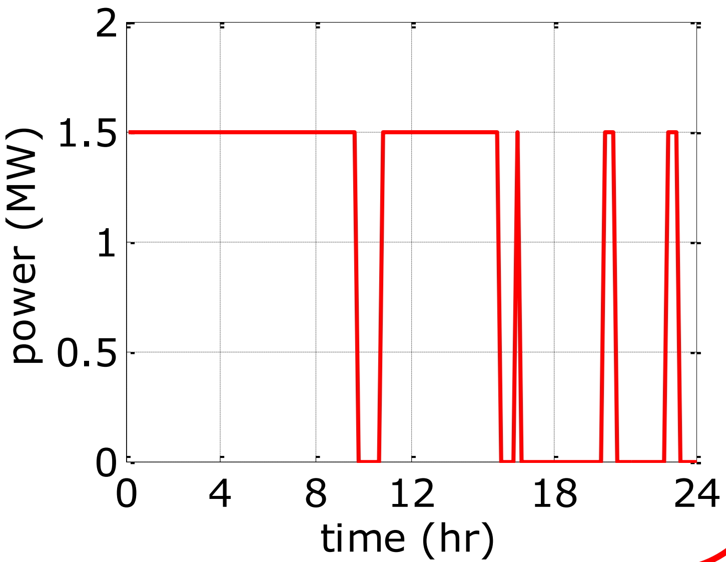

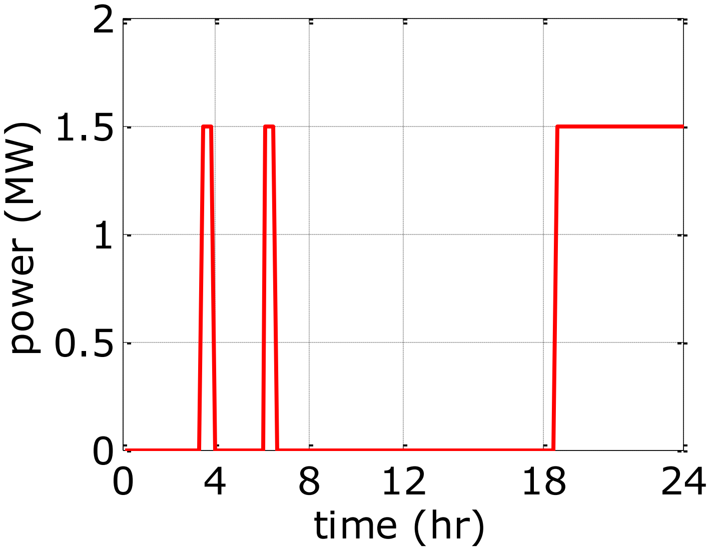

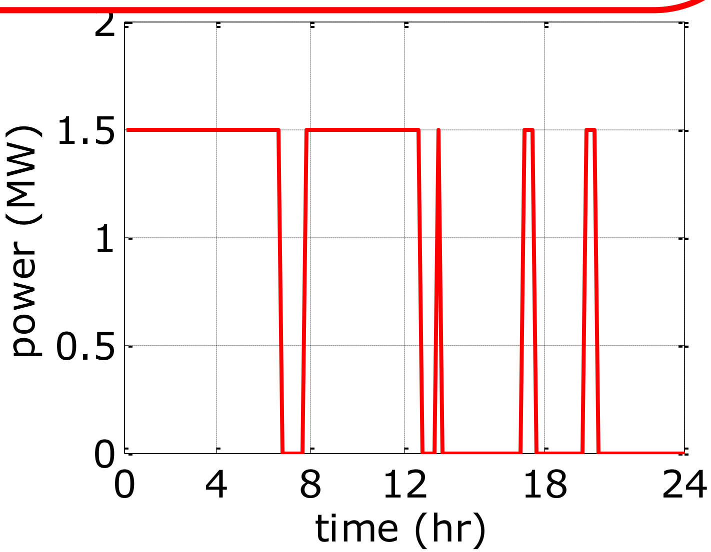

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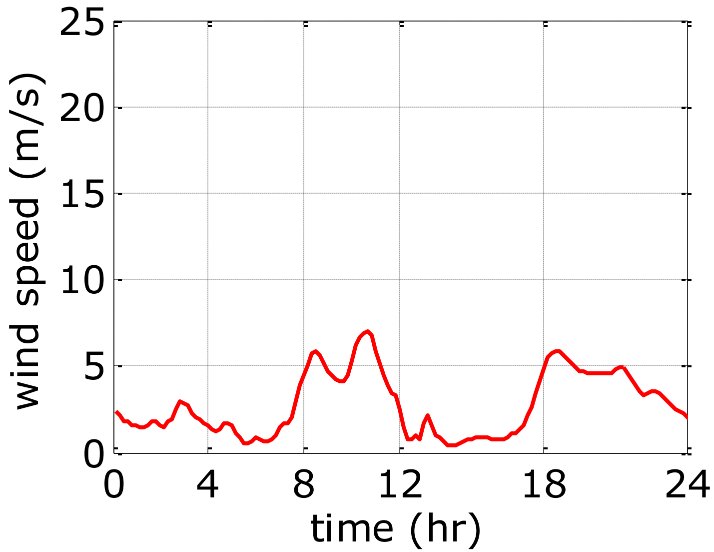
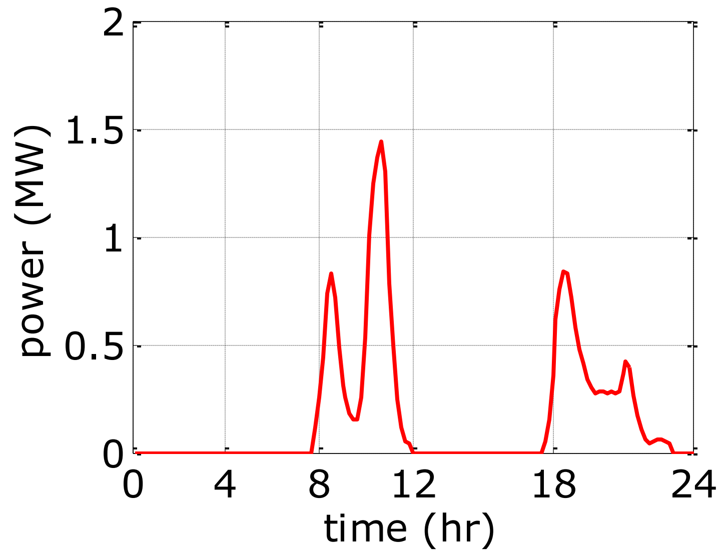
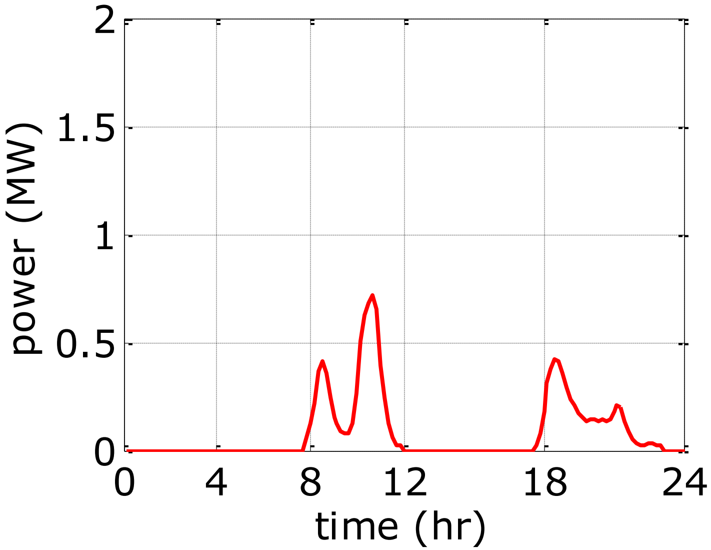
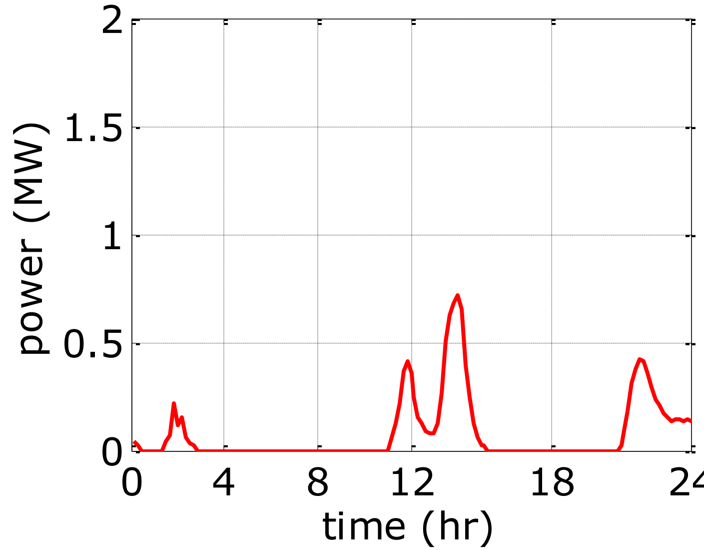
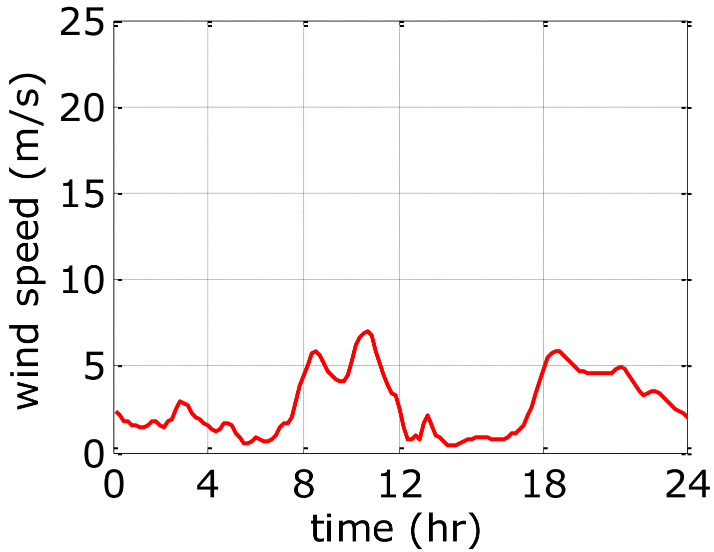


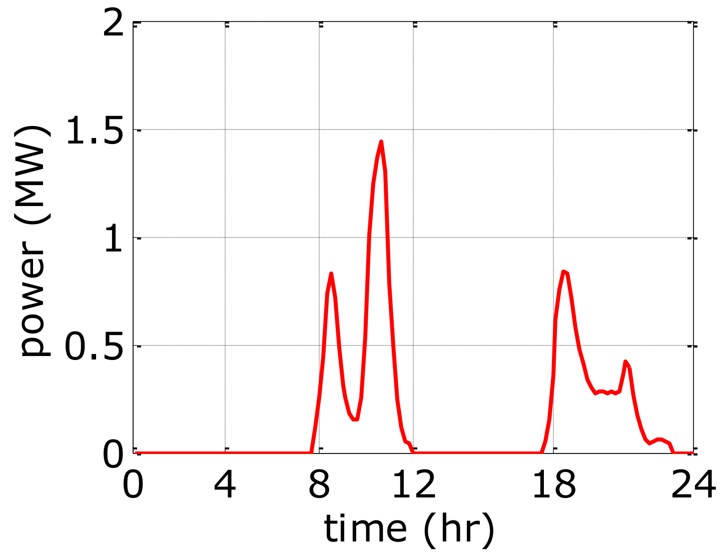


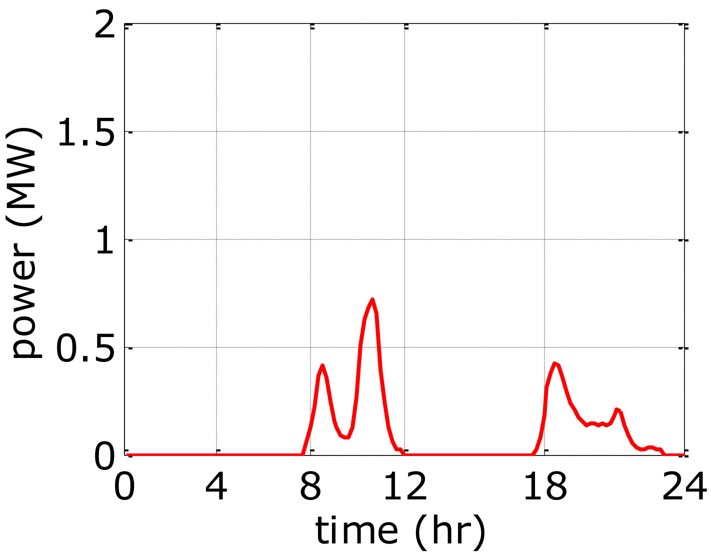


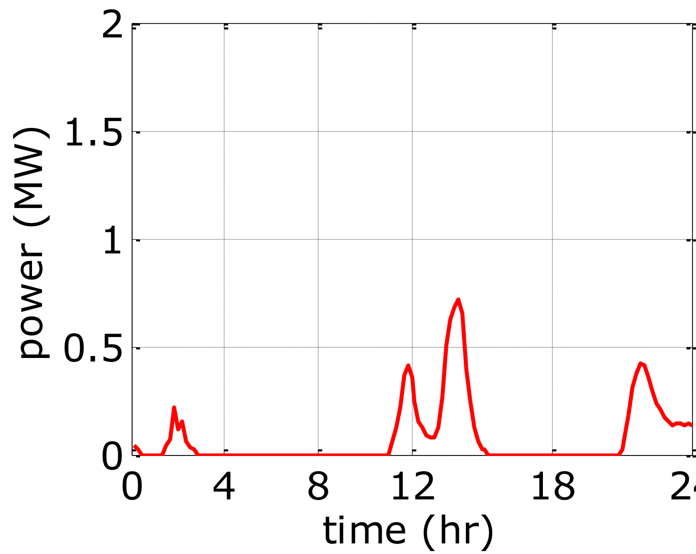


Match the Power Output with the Wind Speed



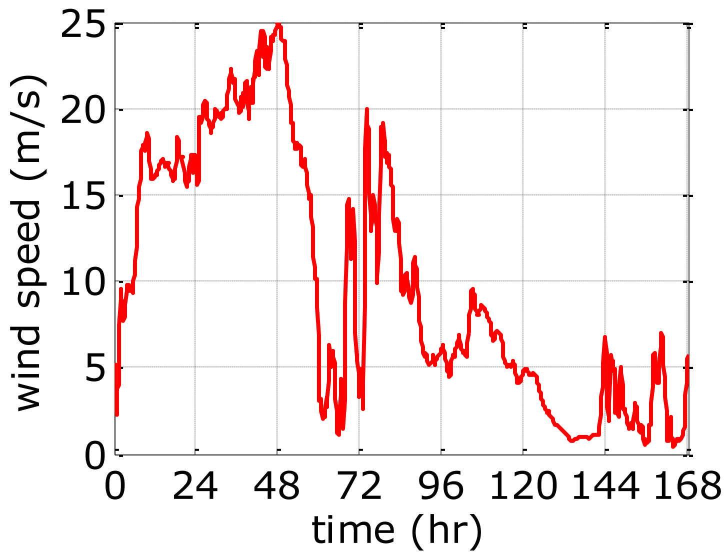


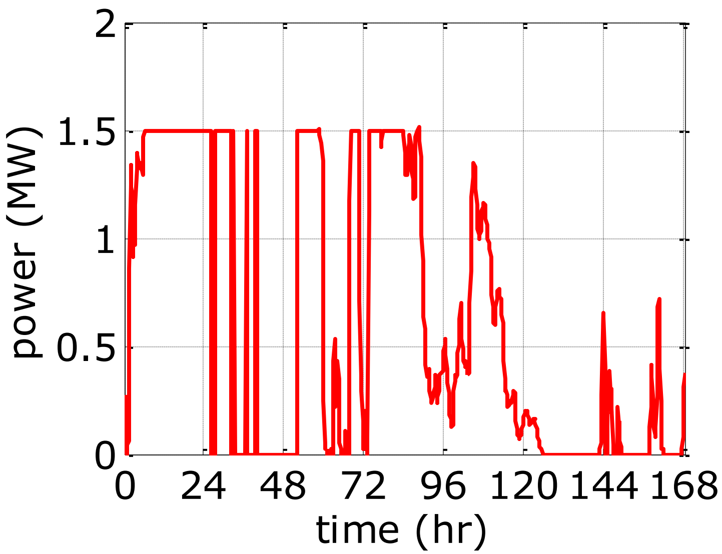




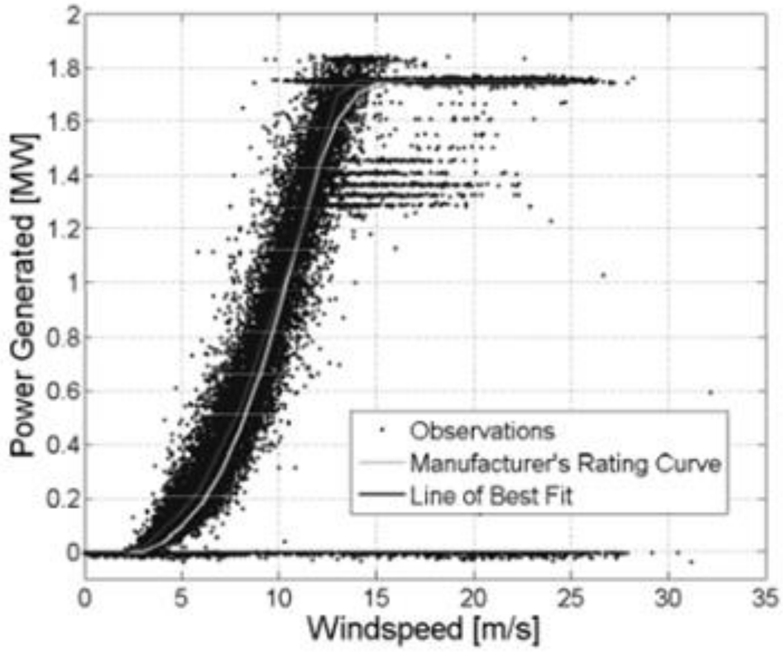
Wind Power Modeling

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





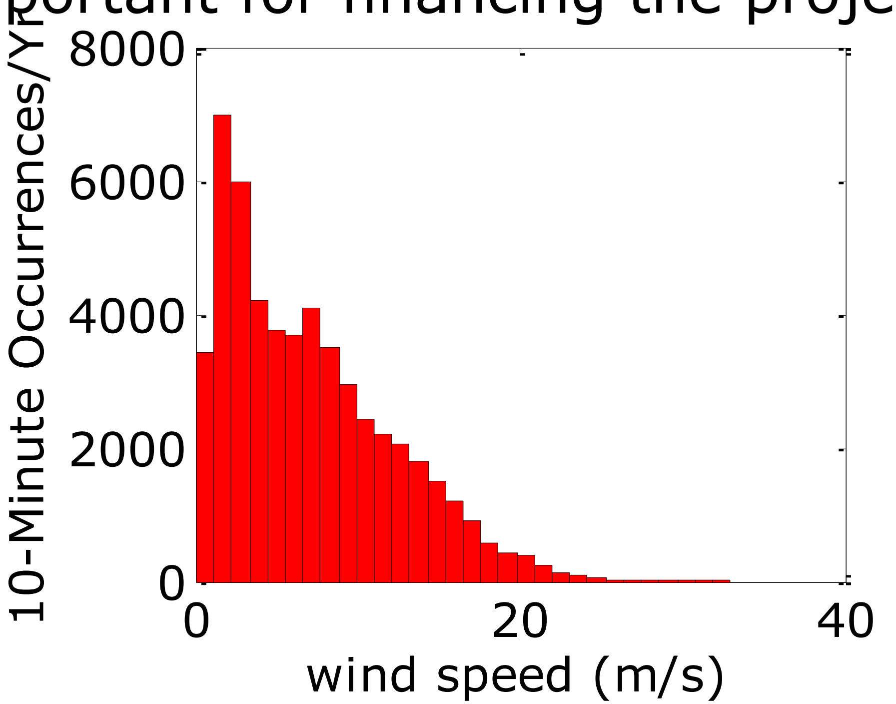
Empirical Power Curve



What causes departures in Power production from the power curve?

Wind Power Modeling

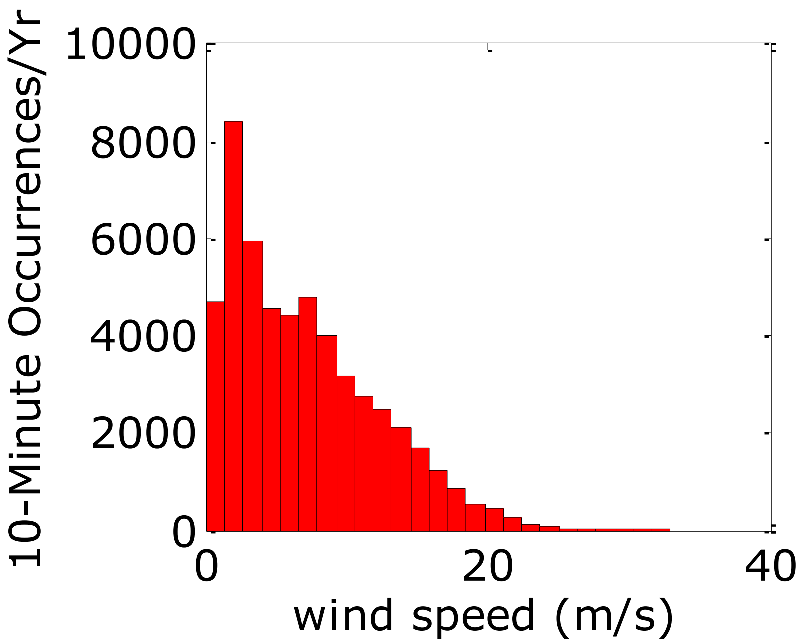
- Assume the following histogram of wind speed distribution is given for a potential wind plant
- How much energy will be produced each year?
  - VERY important for financing the project

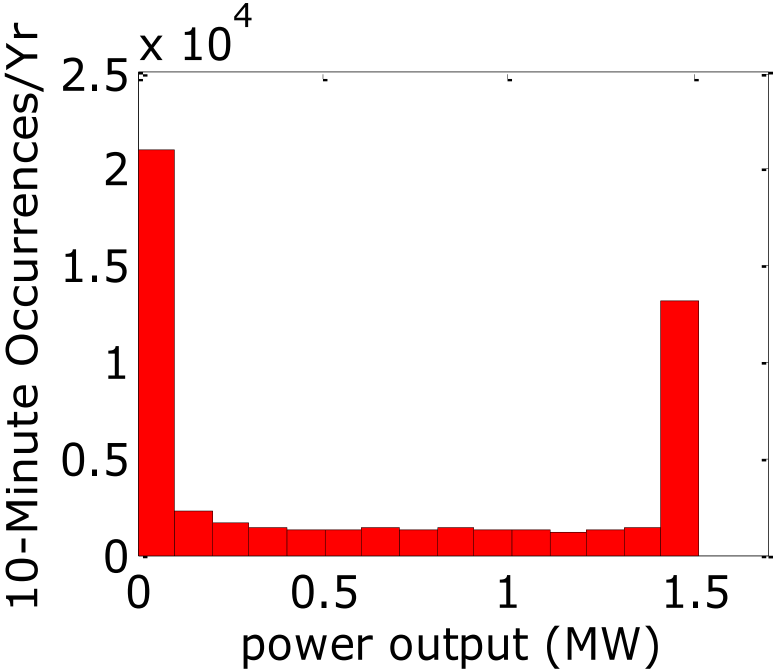


Wind Power Modeling

- 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 $f(\mathbf{P}) = f(g(\mathbf{v}))$

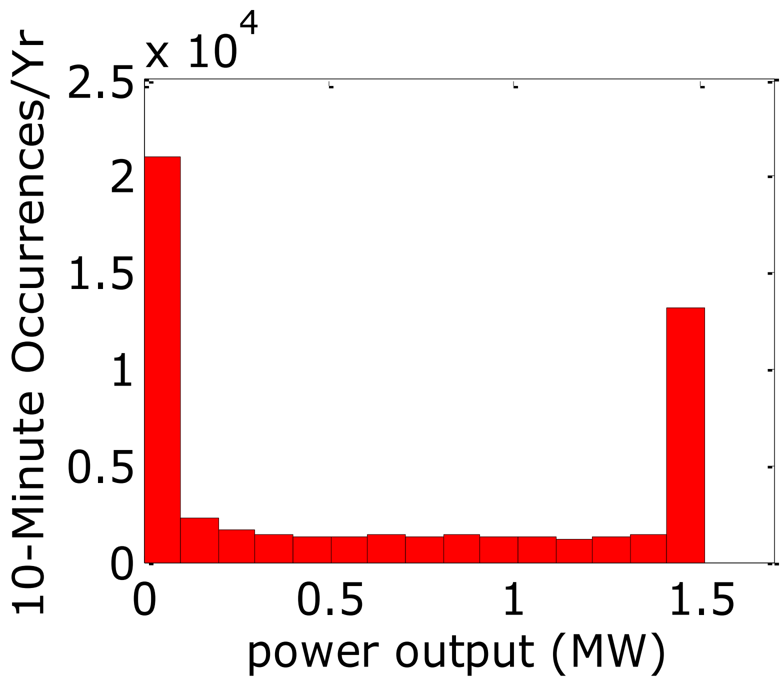
Wind Power Modeling





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 MW x 8760 hrs = 13,140 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 <u>wind plant</u>?
- 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


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

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

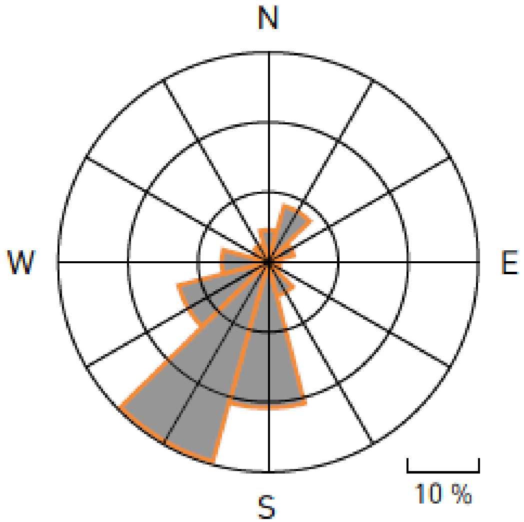
- Where:
  - i: wind turbine number

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