Fontes Renováveis Não-Convencionais

Parte III

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Converting Wind into Electric Energy

- Design challenge is to convert rotating mechanical energy into electrical energy
  - This is, of course, commonly done in most power plants. But the added challenges with wind turbines are: 1) the ***shaft is often rotating at variable speed*** [because of changes in the wind speed], and 2) the ***rate of rotation is relatively slow*** (dozens of rpm)
- Early wind turbines used a near fixed speed design which allowed use of well proven induction generators, but gave up aerodynamic efficiency.
- Modern turbines tend to use a ***variable speed design*** to keep tip-to-speed ratio near optimal

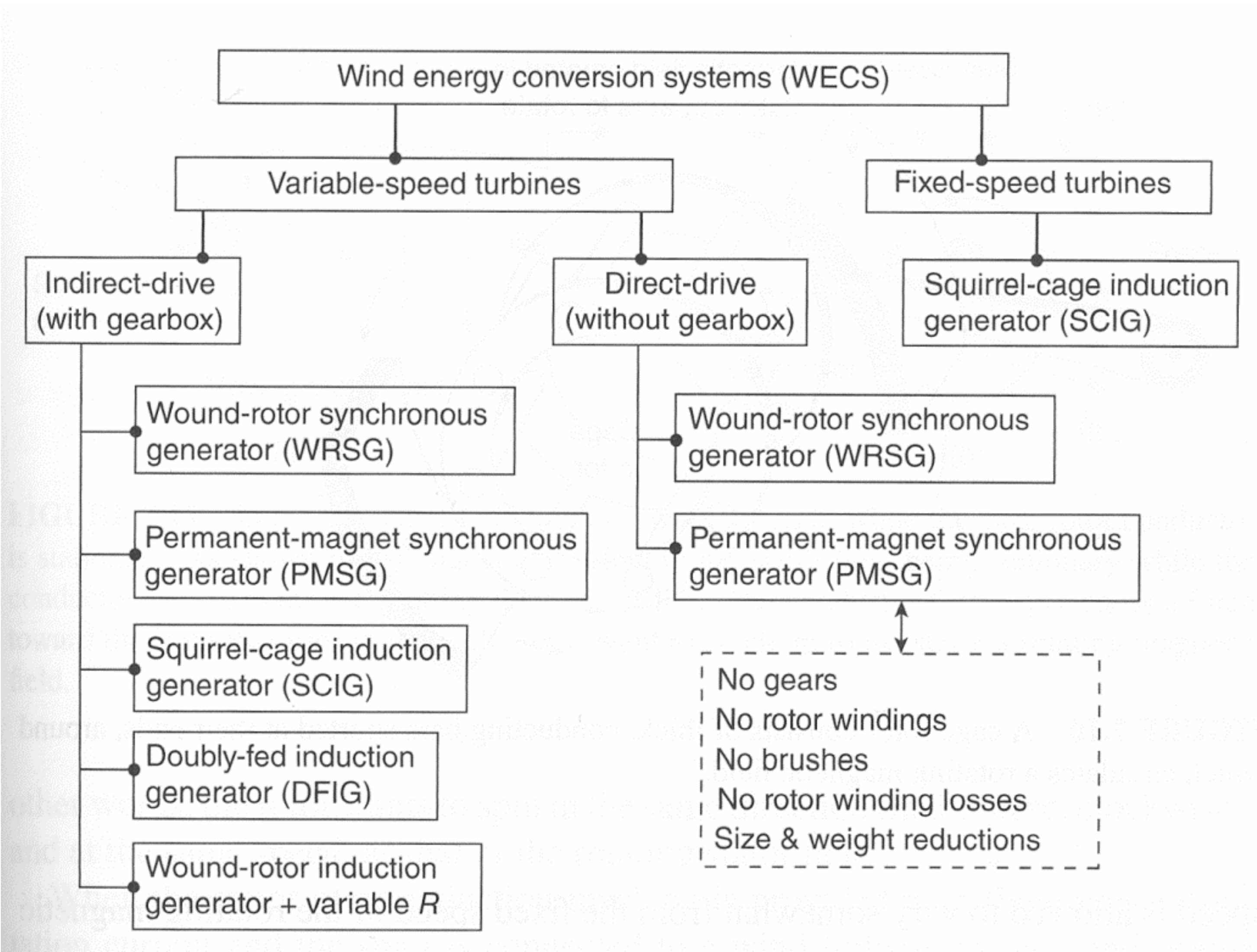
Electric Machines

- Electric machines can usually function as either a motor or as a generator
- Three main types of electric machines
  - DC machines: Advantage is they can directly operate at variable speed. For grid application the disadvantage is they produce a dc output. Used for small wind turbines.
  - AC synchronous machines
    - Operate at fixed speed. Used extensively for traditional power generation. The fixed speed had been a disadvantage for wind.
  - AC induction machines
    - Very rugged and allow some speed variation but usually not a lot for efficient operation.

Types of Wind Turbines by Machine

- From an electric point of view there are four main types of large-scale wind turbines (IEEE naming convention)
  - Type 1: Induction generator with fixed rotor resistance
  - Type 2: Induction generators with variable rotor resistance
  - Type 3: Doubly-fed induction generators
  - Type 4: Full converter generators which main use either a synchronous generator or an induction generator
- Most new wind turbines are either Type 3 or Type 4
- In Europe these are sometimes called Types A, B, C, D respectively.

Wind Generator Types

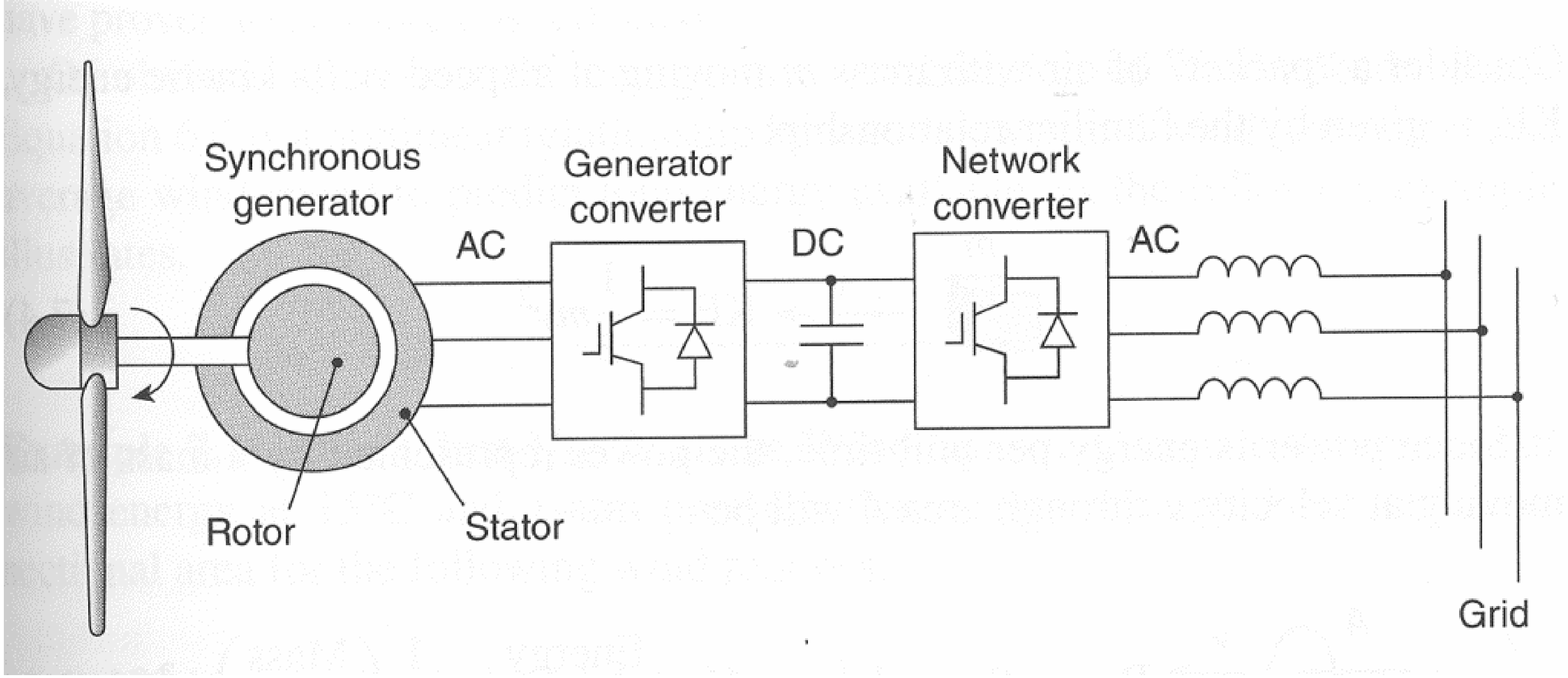


Synchronous Machines

- Spin at a rotational speed determined by the number of poles and by the frequency (3600 rpm at 60Hz, 2 pole)
- The magnetic field is created on their rotors
- Create the magnetic field by running DC through windings around the core
  - A permanent magnet can also be used
- A gear box if often needed between the blades and the generator
  - Some newer machines are designed without a gear box
- Slip rings are needed to get a dc current on the rotor

Variable Speed Synchronous Generator

- Full-capacity converter to gain control of speed;
- Wound-rotor or permanent-magnet SG;
- Larger number of poles: gear box can be eliminated.



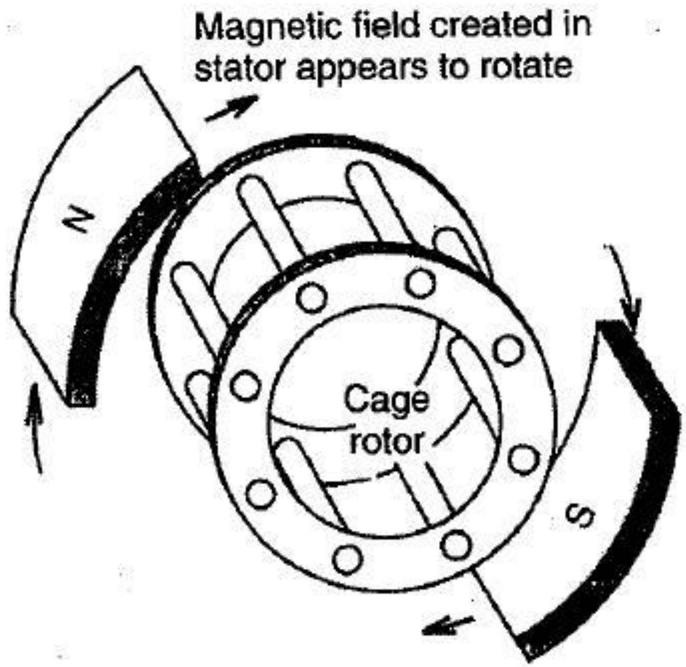
Asynchronous Induction Machines

- Do not turn at a fixed speed
- Acts as a motor during start up; can act as a generator when spun faster then synchronous speed
- Do not require exciter, brushes, and slip rings
  - Less expensive, require less maintenance
- The magnetic field is created on the stator not the rotor
- Current is induced in the rotor (Faraday's law: $v = d\lambda/dt$)
- Lorenz force on wire with current in magnetic field:

$$\mathbf{F} = I\mathbf{l} \times \mathbf{B}$$

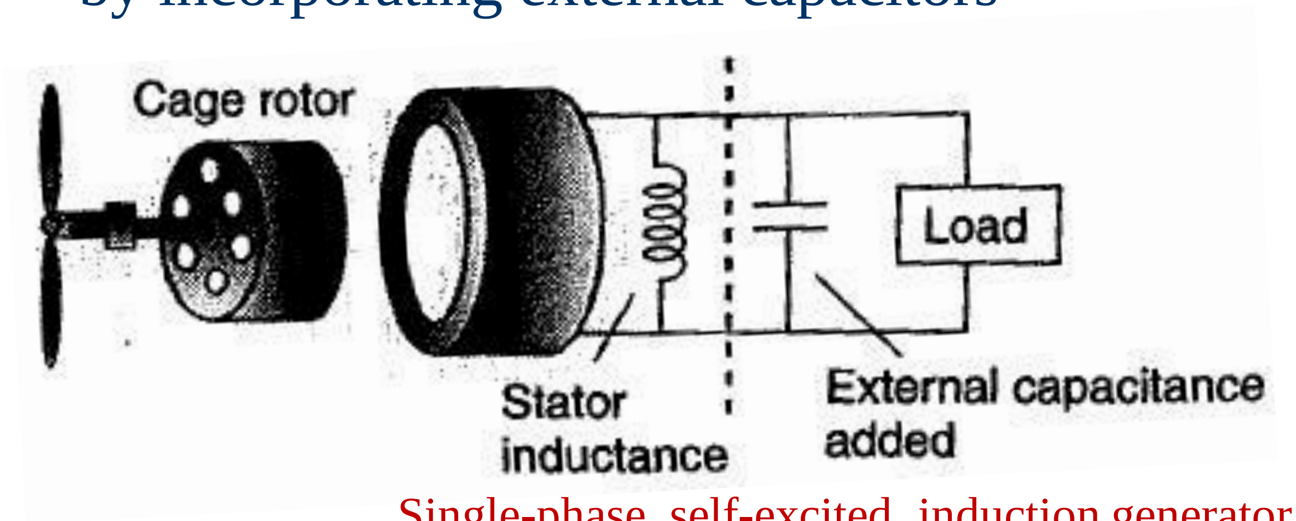
Squirrel Cage Rotor

- The rotor of many induction generators has copper or aluminum bars shorted together at the ends, looks like a cage
- Can be thought of as a pair of magnets spinning around a cage
- Rotor current i_R flows easily through the thick conductor bars



The Induction Machine as a Generator

- The stator requires excitation current
  - from the grid if it is grid-connected or
  - by incorporating external capacitors



Single-phase, self-excited, induction generator

- Wind speed forces generator shaft to exceed synchronous speed

The Induction Machine as a Generator

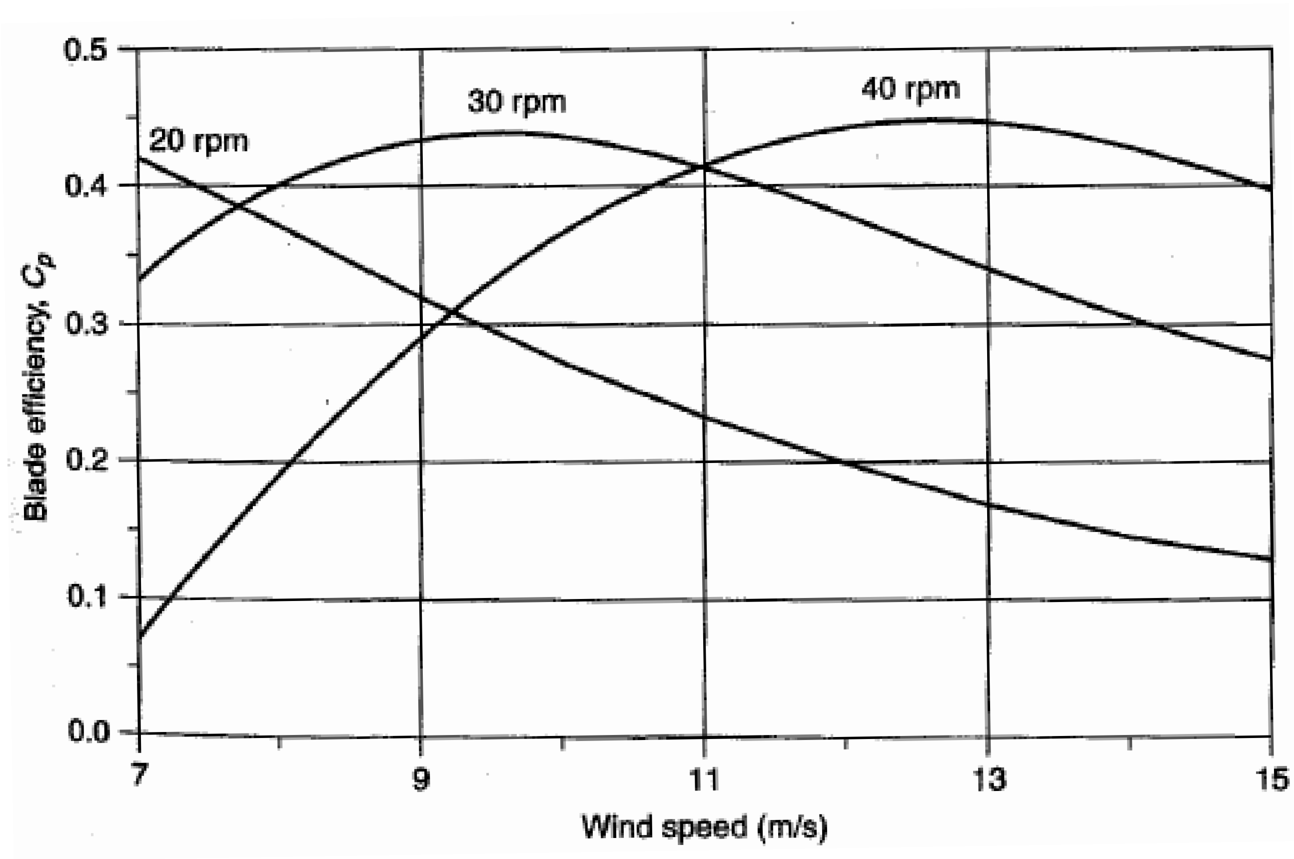
- Slip is negative because the rotor spins faster than synchronous speed
- Slip is normally less than 1% for grid-connected generator
- Typical rotor speed:

$$N_R = (1-s)N_S = [1-(-0.01)]\cdot 3600 = 3636 \text{ rpm}$$

Speed Control

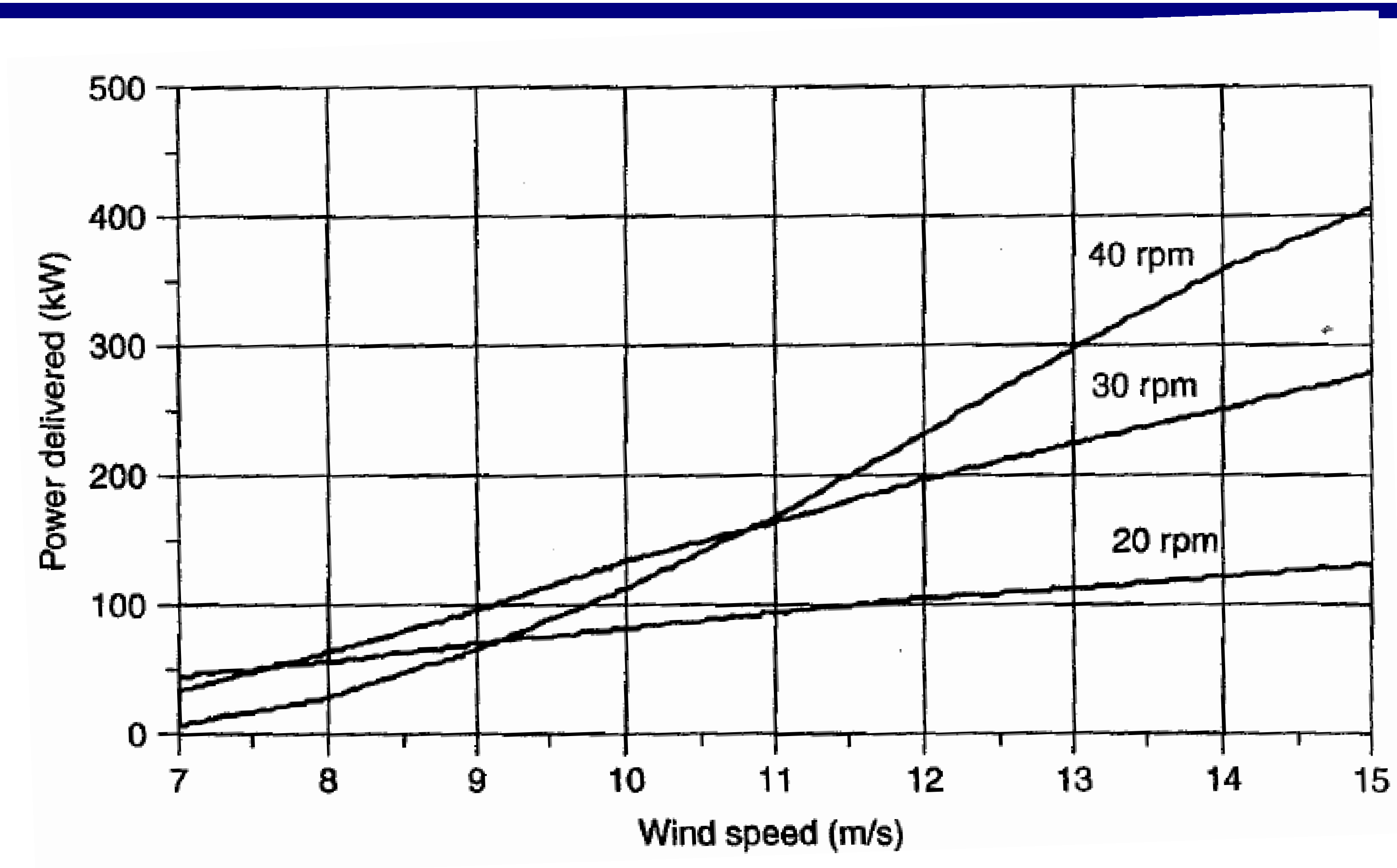
- Necessary to be able to shed wind in high-speed winds
- Rotor efficiency changes for different Tip-Speed Ratios (TSR), and TSR is a function of windspeed
- To maintain a constant TSR, blade speed should change as wind speed changes
- A challenge is to design machines that can accommodate variable rotor speed and fixed generator speed

Blade Efficiency vs. Windspeed



At lower windspeeds, the best efficiency is achieved at a lower rotational speed

Power Delivered vs. Windspeed



Impact of rotational speed adjustment on delivered power, assuming gear and generator efficiency is 70%

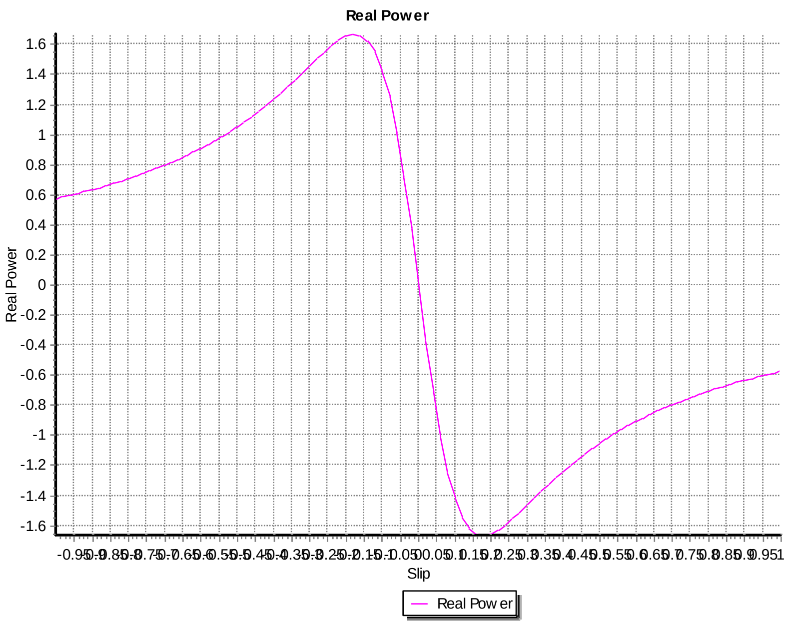
Pole-Changing Induction Generators

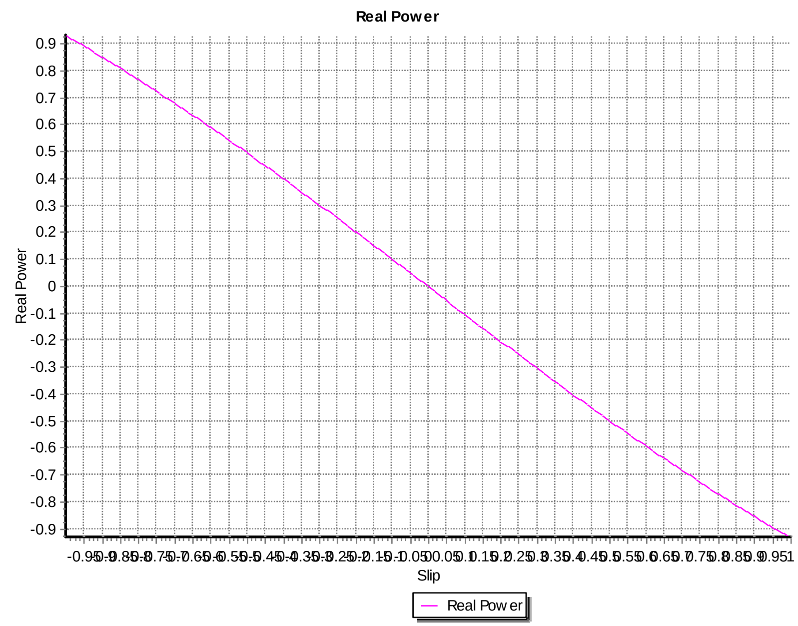
- Being able to change the number of poles allows you to change operating speeds [N(rpm) = 120f /p]
- A 2 pole, 60 Hz, 3600 rpm generator can switch to 4 poles and 1800 rpm
- Can do this by switching external connections to the stator and no change is needed in the rotor
- Common approach for 2-3 speed appliance motors like those in washing machines and exhaust fans
  - Increasingly this approach is being replaced by machine drives that convert ac at grid frequency to ac at a varying frequency.

Variable-Slip Induction Generators

- Purposely add variable resistance to the rotor
- External adjustable resistors - this can mean using a wound rotor with slip rings and brushes which requires more maintenance
- Instead, mount resistors and control electronics on the rotor and use an optical fiber link to send the rotor a signal for how much resistance to provide ➡ need of slip rings & brushes is avoided

Effect of Rotor Resistance on Induction Machine Power-Speed Curves





Left plot shows the torque-power curve from slip of -1 to 1 with external resistance = 0.05; right plot is with external resistance set to 0.99 pu.

Variable Slip Example: Vestas V80 1.8 MW

- The Vestas V80 1.8 MW turbine is example in which an induction generator is operated with variable rotor resistance (opti-slip).
- Adjusting the rotor resistance changes the torque-speed curve
- Operates between 9 and 19 rpm

Source: Vestas V80 brochure

Reactive Power Support

- Wind turbine generators can produce real power but consume reactive power
- This is especially a problem with **Types 1 and 2** wind turbines which are induction machines
- Capacitors or other power factor correction devices are needed
- **Types 3 and 4** can provide reactive support, details beyond the scope of this class.

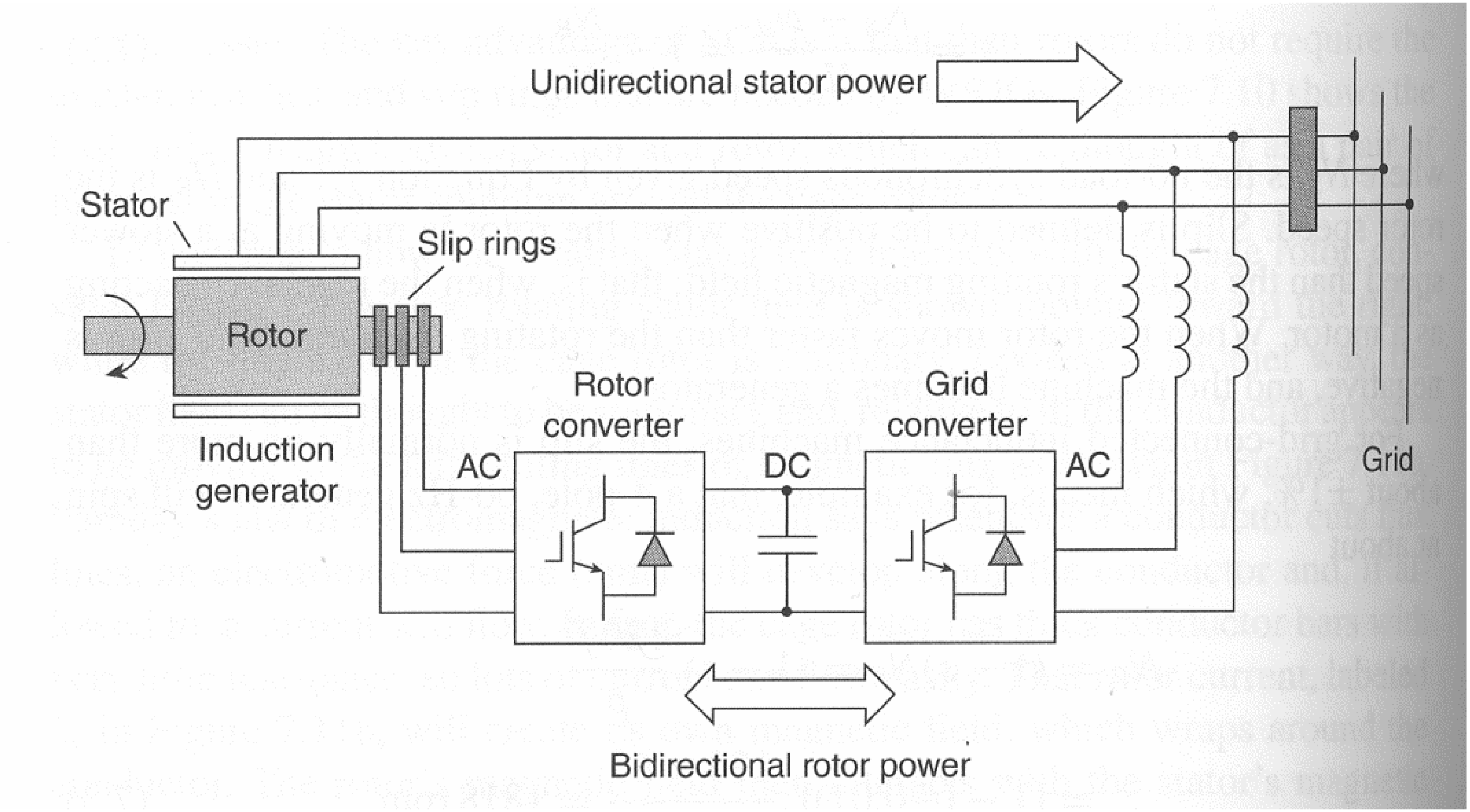
Doubly-Fed Induction Generators

- Another common approach is to use what is called a doubly-fed induction generator in which there is an electrical connection between the rotor and supply electrical system using an ac-ac converter
- This allows operation over a wide-range of speed, for example 30% with the GE 1.5 MW and 3.6 MW machines
- Called Type 3 wind turbines.

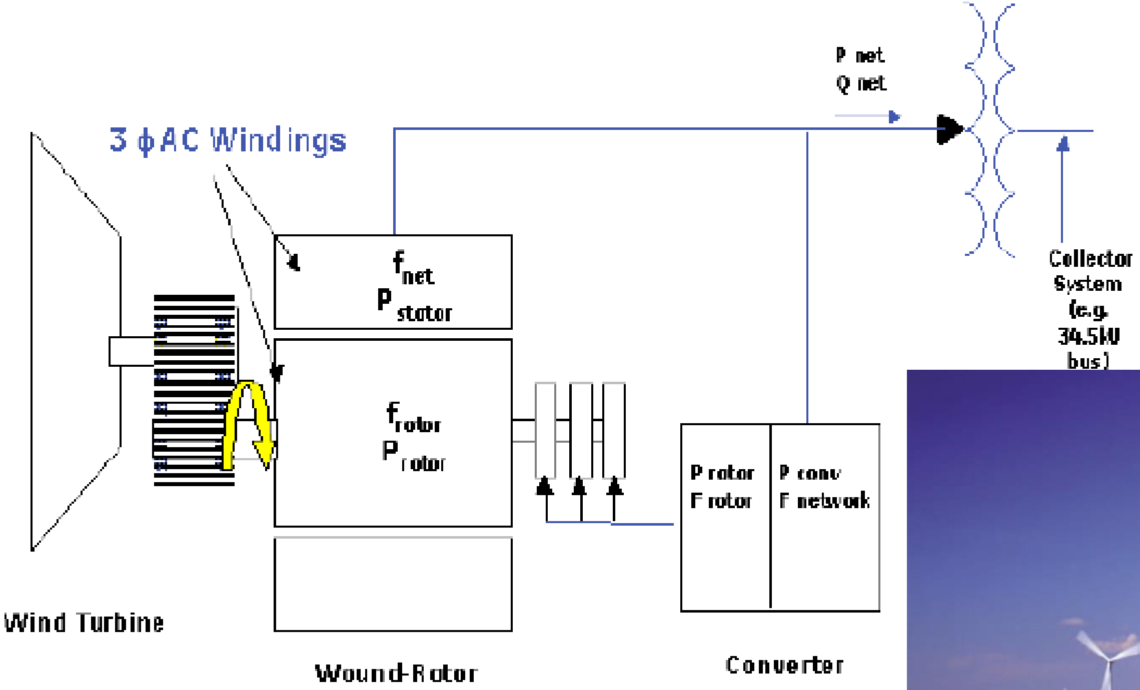
Doubly-Fed Induction Generators

- DFIGs are wound-rotor, doubly-fed induction machines;
- Conventional stator: grid provides 3-phase voltages;
- Rotor is set up to to allow bidirectional power flow to or from the grid;
  - $\omega < \omega_s$: acts like a motor, slowing down turbine;
  - $\omega > \omega_s$: power generated from rotor & sent to grid.
- The key to this scheme is a modestly sized back-to-back voltage converter, rated at approx. 30% turbine power (see figure).

Doubly-Fed Induction Generators



GE 1.5 MW DFIG Example

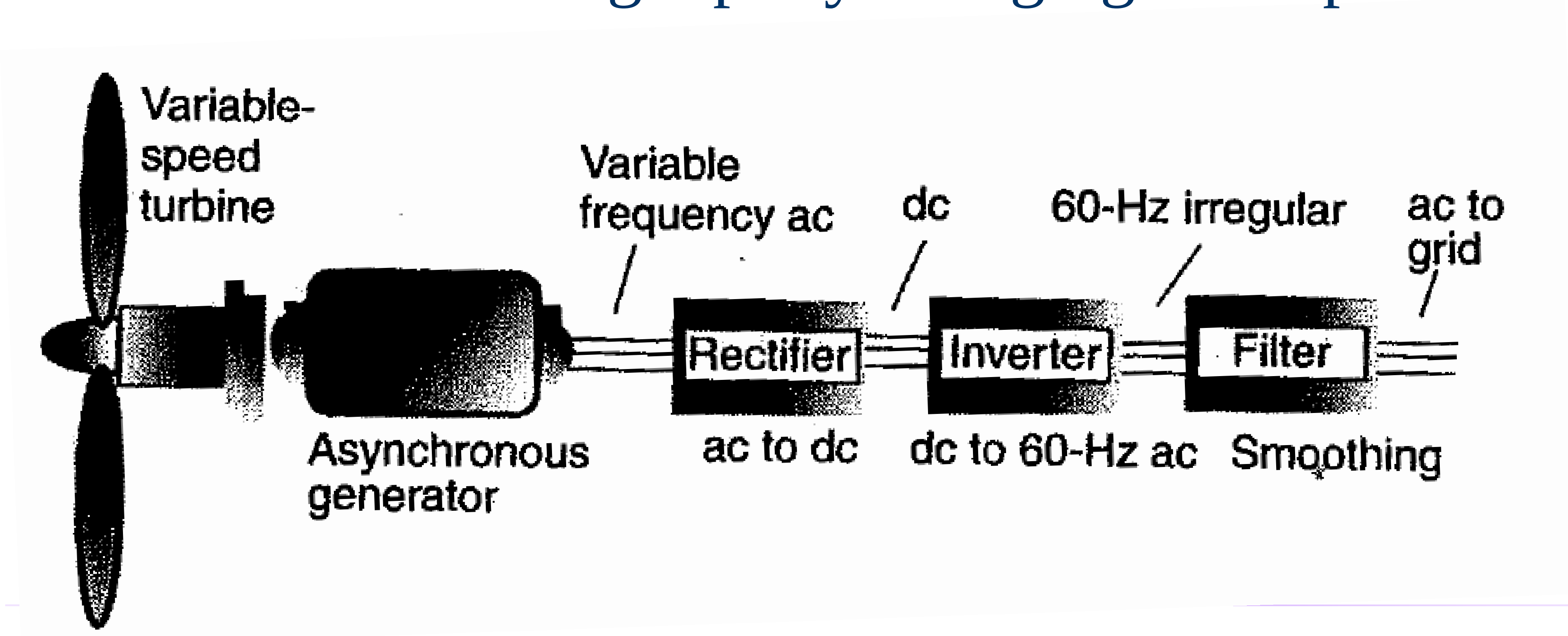


GE 1.5 MW turbines were the best selling wind turbines in the US in 2011

Source: GE Brochure/manual

Indirect Grid Connection Systems

- Wind turbine is allowed to spin at any speed
- Variable frequency AC from the generator goes through a rectifier (AC-DC) and an inverter (DC-AC) to 60 Hz for grid-connection
- Good for handling rapidly changing windspeeds



Wind Turbine Gearboxes

- A significant portion of the weight in the nacelle is due to the gearbox
  - Needed to change the slow blade shaft speed into the higher speed needed for the electric machine
- Gearboxes require periodic maintenance (e.g., change the oil), and have also be a common source of wind turbine failure
- Some wind turbine designs are now getting rid of the gearbox by using electric generators with many pole pairs (direct-drive systems)

Wind Farms

- Normally, it makes sense to install a large number of wind turbines in a wind farm or a wind park
- Benefits:
  - Able to get the most use out of a good wind site
  - Reduced development costs
  - Simplified connections to the transmission system
  - Centralized access for operations and maintenance
- How many turbines should be installed at a site?

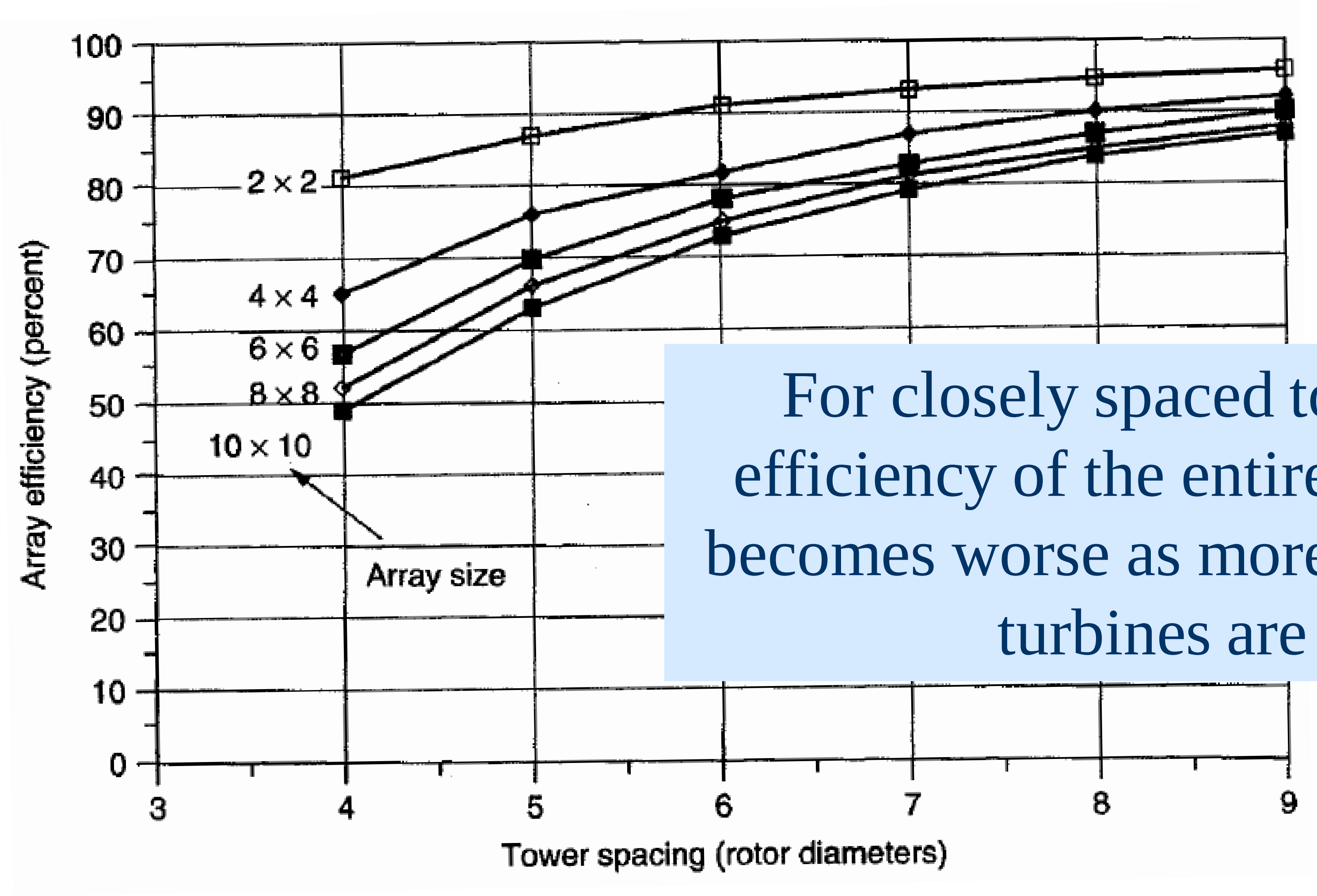
Wind Farms

- We know that wind slows down as it passes through the blades. Recall the power extracted by the blades:

$$P_b = \frac{1}{2}\dot{m}\left(v^2 - {v_d}^2\right)$$

- Extracting power with the blades reduces the available power to downwind machines
- What is a sufficient distance between wind turbines so that wind speed has recovered enough before it reaches the next turbine?

Wind Farms

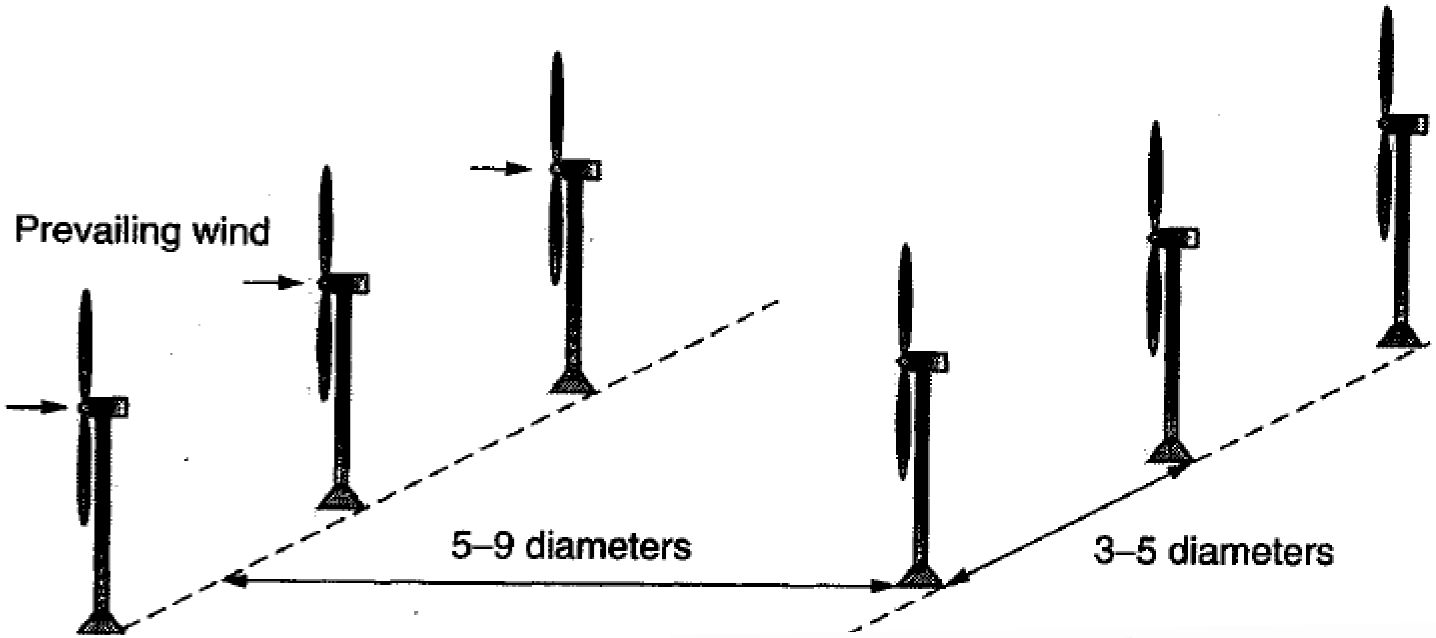


For closely spaced towers, efficiency of the entire array becomes worse as more wind turbines are added

Wind Farms

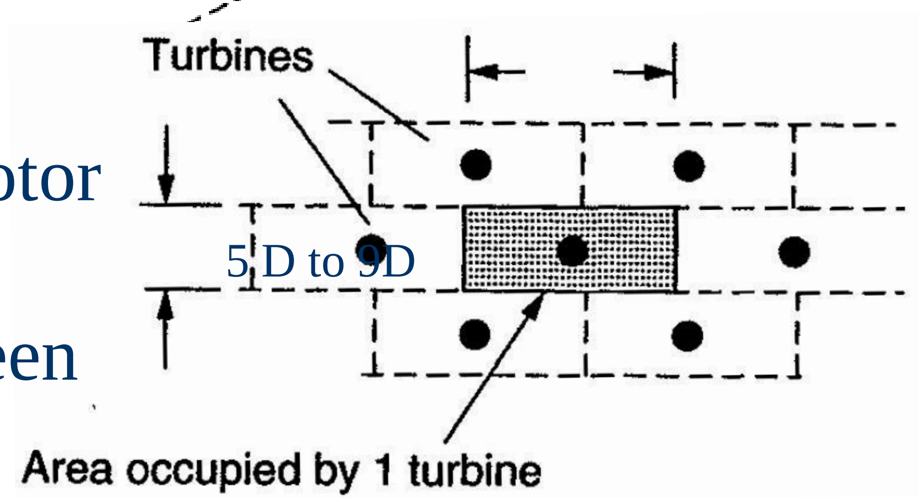
- The figure considered square arrays, but square arrays don’t make much sense
- Rectangular arrays with only a few long rows are better
- Recommended spacing is 3-5 rotor diameters between towers in a row and 5-9 diameters between rows
- Offsetting or staggering the rows is common
- Direction of prevailing wind is common.

Wind Farms – Optimum Spacing



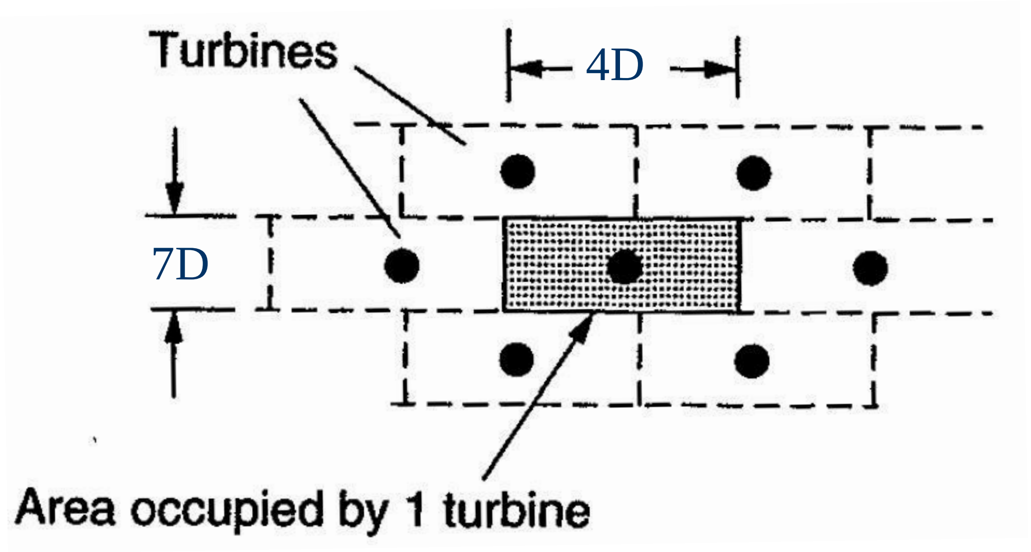
Ballpark figure for GE 1.5 MW in Midwest is one per 100 acres (6 per square mile)

Optimum spacing is estimated to be 3-5 rotor diameters between towers and 5-9 between rows

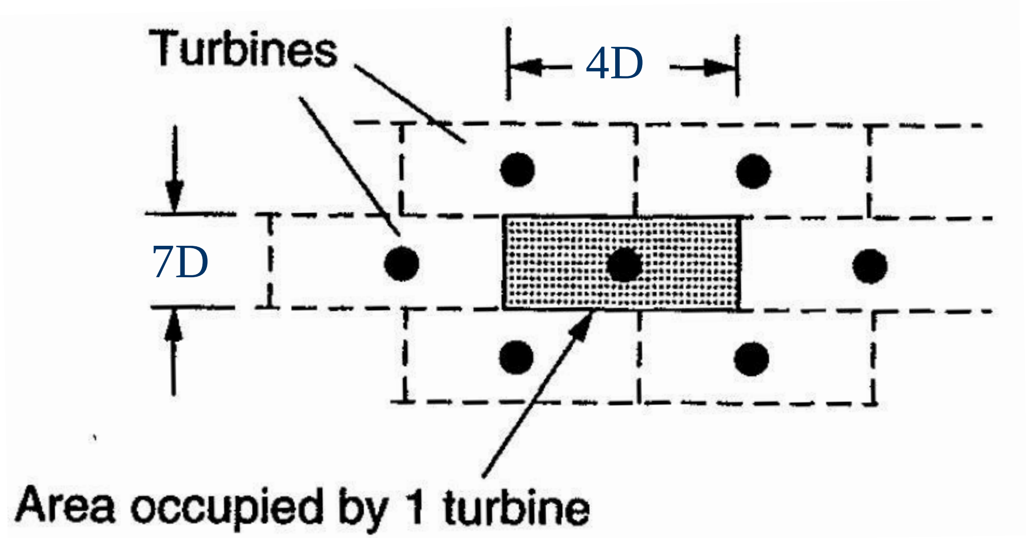


Example: Energy Potential for a Wind Farm

- A wind farm has 4-rotor diameter spacing along its rows, 7-rotor diameter spacing between the rows
- WTG efficiency is 30%, Array efficiency is 80%



Example: Energy Potential for a Windfarm



a. Find annual energy production per unit of land area if the power density at hub height is 400-W/m^2 (assume 50 m, Class 4 winds)

b. What does the lease cost in $/kWh if the land is leased from a rancher at $100 per acre per year?

Example: Energy Potential for a Windfarm

a. For 1 wind turbine:

$$\text{Land Area Occupied} = 4D \cdot 7D = 28D^2$$

$$\text{Annual Energy Production} = \frac{1}{2}\rho A v^3 \cdot \Delta t \cdot \eta$$

$$\text{where} \quad \frac{1}{2}\rho v^3 = 400 \text{ W/m}^2 \quad \text{and} \quad A = \frac{\pi}{4}\text{D}^2$$

Annual Energy Production/Land Area

$$= \frac{400 \text{ W}}{\text{m}^2} \cdot \frac{\pi}{4}\left(D \text{ m}\right)^2 \cdot \frac{8760 hr}{yr} \cdot 0.3 \cdot 0.8 \cdot \frac{1}{28D^2} = 23.588 \ \frac{\text{kWh}}{(\text{m}^2 \cdot \text{yr})}$$

Example: Energy Potential for a Windfarm

b. 1 acre = 4047m^2 Land Cost $= \dfrac{\$100}{\text{acre} \cdot \text{yr}}$

In part (a), we found

$$\frac{\text{Annual Energy}}{\text{Land Area}} = 23.588 \ \frac{\text{kWh}}{(\text{m}^2 \cdot \text{yr})}$$

or equivalently

$$23.588 \ \frac{\text{kWh}}{(\text{m}^2 \cdot \text{yr})} \cdot \frac{4047 \text{ m}^2}{\text{acre}} = 95,461 \frac{\text{kWh}}{(\text{acre} \cdot \text{yr})}$$

Then, the lease cost per kWh is

$$\text{lease cost} = \frac{\$100 \,/\, \text{acre} \cdot \text{yr}}{95,461 \text{ kWh} \,/\, \text{acre} \cdot \text{yr}} = \$0.00105/\text{kWh}$$

Idealized Power Curve

Cut –in windspeed, rated windspeed, cut-out windspeed

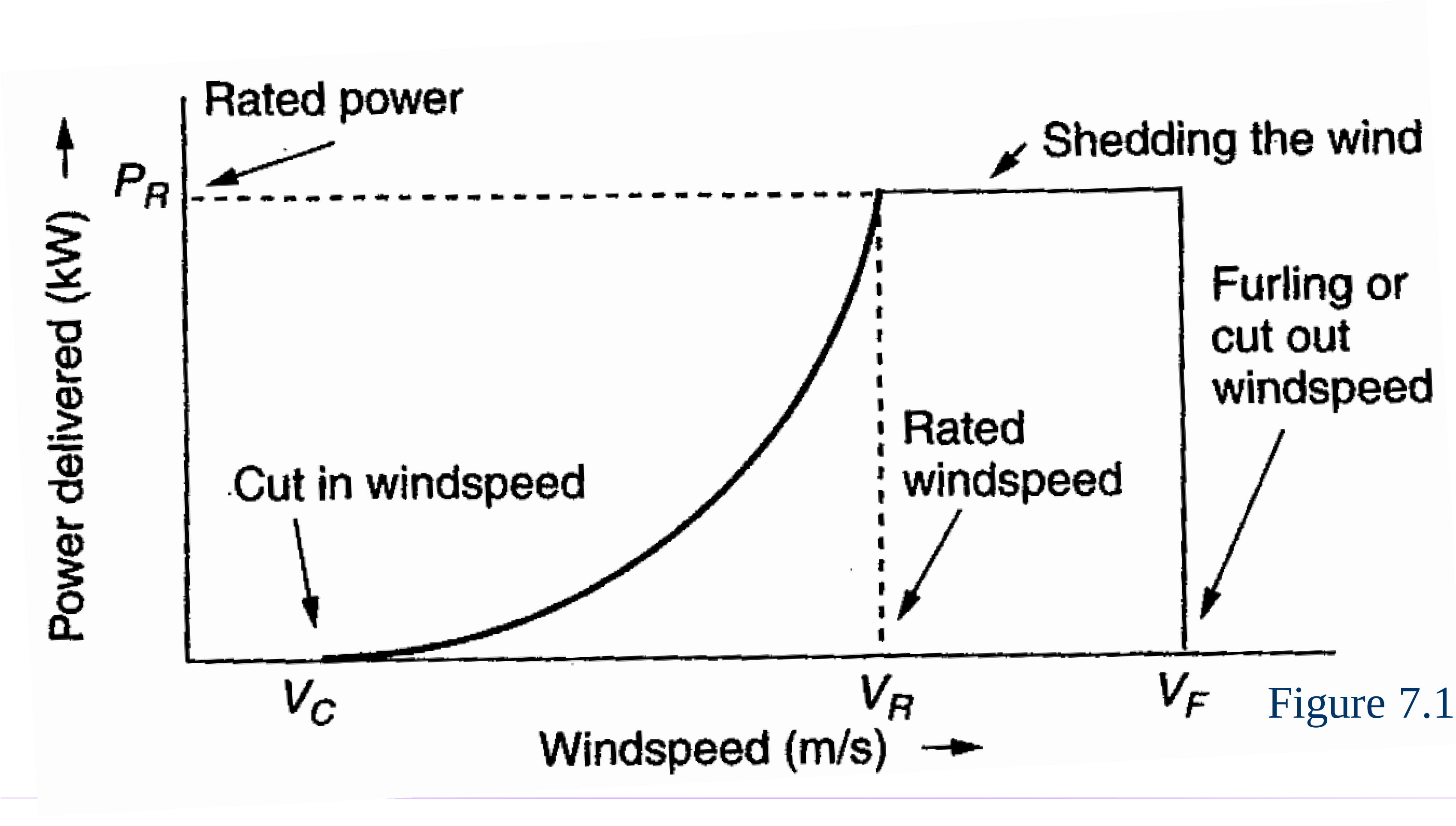


Figure 7.19

Idealized Power Curve

- Before the ***cut-in windspeed***, no net power is generated
- Then, power rises like the cube of windspeed
- After the ***rated windspeed*** is reached, the wind turbine operates at rated power (sheds excess wind)
- Three common approaches to shed excess wind
  - Pitch control – physically adjust blade pitch to reduce angle of attack
  - Stall control (passive) – blades are designed to automatically reduce efficiency in high winds
  - Active stall control – physically adjust blade pitch to create stall

Idealized Power Curve

- Above ***cut-out*** or ***furling windspeed***, the wind is too strong to operate the turbine safely, machine is shut down, output power is zero
- "Furling" –refers to folding up the sails when winds are too strong in sailing
- Rotor can be stopped by rotating the blades to purposely create a stall
- Once the rotor is stopped, a mechanical brake locks the rotor shaft in place

Economies of Scale

- Presently large wind farms produce electricity more economically than small operations
- Factors that contribute to lower costs are
  - Wind power is proportional to the area covered by the blade (square of diameter) while tower costs vary with a value less than the square of the diameter
  - Larger blades are higher, permitting access to faster winds
  - Fixed costs associated with construction (permitting, management) are spread over more MWs of capacity
  - Efficiencies in managing larger wind farms typically result in lower O&M costs (on-site staff reduces travel costs)

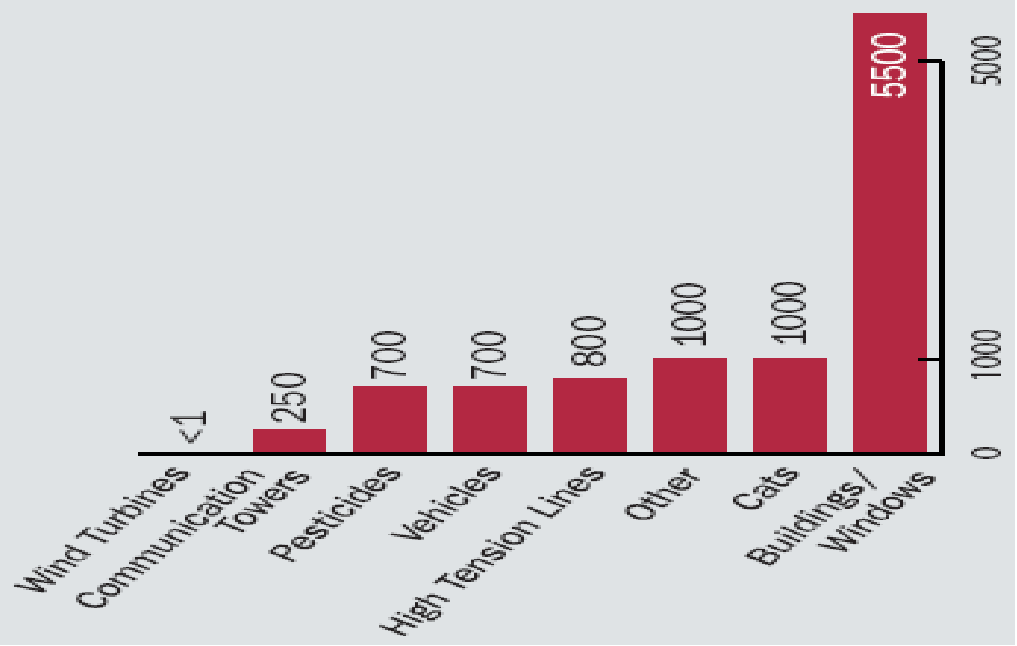
Environmental Aspects of Wind Energy

- US National Academies issued report on issue in 2007
- Wind system emit no air pollution and no carbon dioxide; they also have essentially no water requirements
- Wind energy serves to displace the production of energy from other sources (usually fossil fuels) resulting in a net decrease in pollution
- Other impacts of wind energy are on animals, primarily birds and bats, and on humans

Environmental Aspects of Wind Energy, Birds and Bats

- Wind turbines certainly kill birds and bats, but so do lots of other things; windows kill between 100 and 900 million birds per year

Estimated Causes of Bird Fatalities, per 10,000



Source: Erickson, et.al, 2002. Summary of Anthropogenic Causes of Bird Mortality

Environmental Aspects of Wind Energy, Human Aesthetics

- Aesthetics is often the primary human concern about wind energy projects (beauty is in the eye of the beholder); night lighting can also be an issue

Figure 4-1 of NAS Report, Mountaineer Project 0.5 miles

Environmental Aspects of Wind Energy, Human Well-Being

- Wind turbines often enhance the well-being of many people (e.g., financially), but some living nearby may be affected by noise and shadow flicker
- Noise comes from 1) the gearbox/generator and 2) the aerodynamic interaction of the blades with the wind
- Noise impact is usually moderate (50-60 dB) close (40m), and lower further away (35-45 dB) at 300m
  - However wind turbine frequencies also need to be considered, with both a "hum" frequency above 100 Hz, and some barely audible low frequencies (20 Hz or less)
- Shadow flicker is more of an issue in high latitude countries since a lower sun casts longer shadows

Wind Turbines and Radar

- "Wind Turbines interfere with radar. This has led the FAA, DHS and DOD to contest many proposed wind turbine sites."
  - Either through radar shadows, or Doppler returns that look like false aircraft or weather patterns
- No fundamental constraint with respect to radar interference, but mitigation might require either upgrades to radar or regulation changes to require, for example, telemetry from wind farms to radar

Source: www.fas.org/irp/agency/dod/jason/wind.pdf (2008)

Offshore Wind

- Offshore wind turbines currently need to be in relatively shallow water, so maximum distance from shore depends on the seabed
- Capacity factors tend to increase as turbines move further off-shore

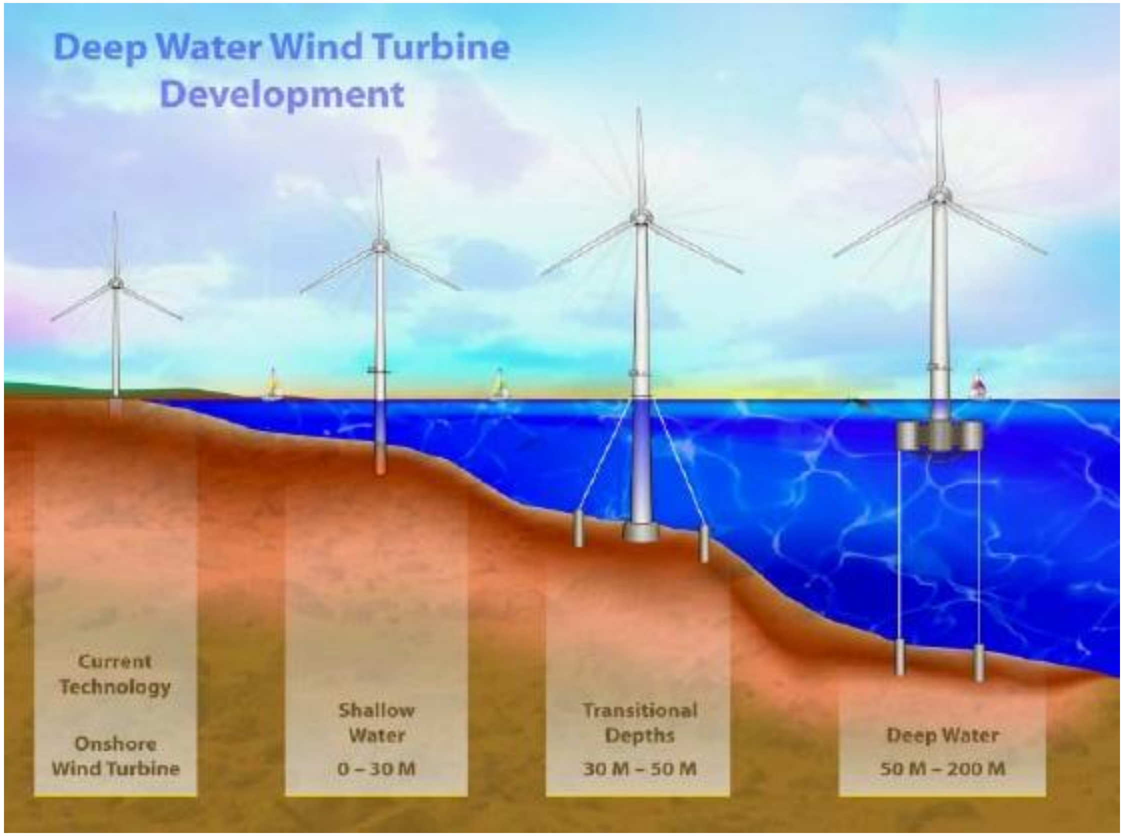


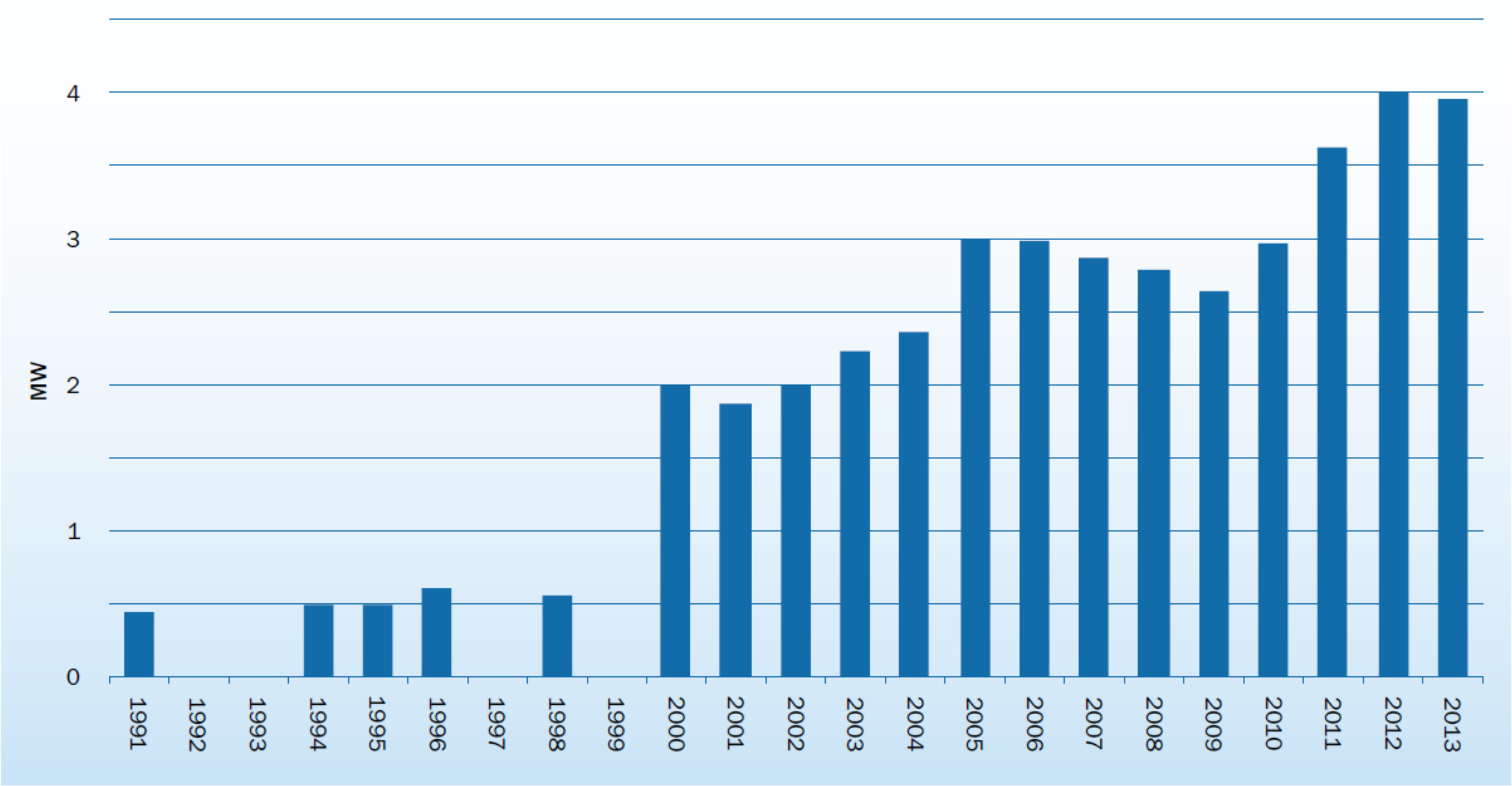
Image Source: National Renewable Energy Laboratory

Offshore: Advantages and Disadvantages

- All advantages/disadvantages are somewhat site specific
- Advantages
  - Can usually be sited much closer to the load (often by coast)
  - Offshore wind speeds are higher and steadier
  - Easier to transport large wind turbines by ship
  - Minimal sound impacts and visual impacts (if far enough offshore), no land usage issues
- Disadvantages
  - High construction costs, particularly since they are in windy (and hence wavy) locations
  - Higher maintenance costs
  - Some environmental issues (e.g., seabed disturbance)

Off Shore Wind Turbine Capacity (Europe)

FIG. 24: AVERAGE OFFSHORE WIND TURBINE RATED CAPACITY



http://www.ewea.org/fileadmin/files/library/publications/statistics/European_offshore_statistics_2013.pdf

Power Grid Integration of Wind Power

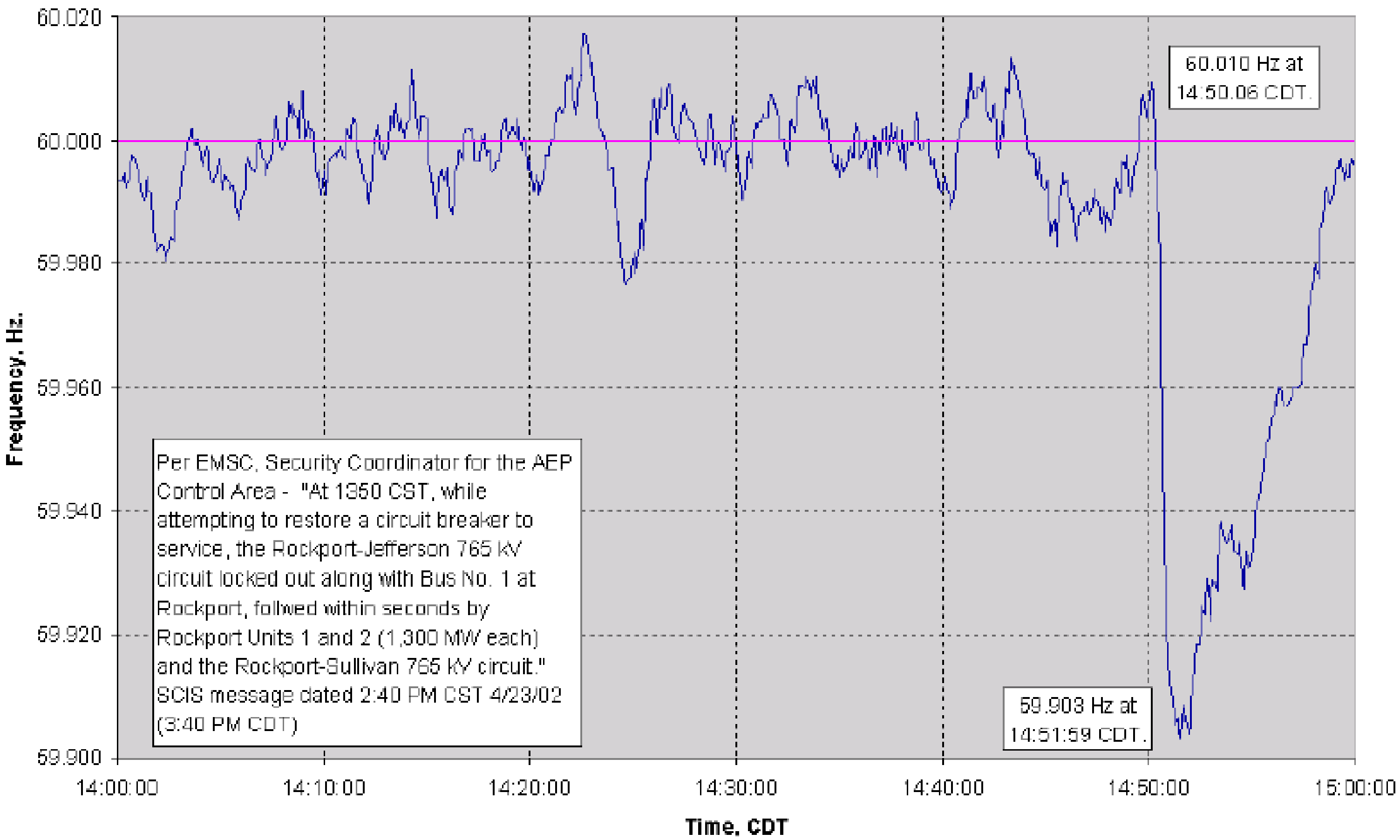
- Wind power had represented a minority of the generation in power system interconnects, so its impact of grid operations was small, but now the impact of wind needs to be considered in power system analysis
  - Largest wind farm in world is Roscoe Wind Farm in Texas with a total capacity of 781 MW, which matches the size of many conventional generators.
- Wind power has impacts on power system operations ranging from that of transient stability (seconds) out to steady-state (power flow)
  - Voltage and frequency impacts are key concerns

Wind Power, Reserves and Power Grid Frequency Regulation

- A key constraint associated with power system operations is pretty much instantaneously the total power system generation must match the total load plus losses
  - Excessive generation increases the system frequency, while excessive load decreases the system frequency
- Generation shortfalls can suddenly occur because of the loss of a generator; utilities plan for this occurrence by maintaining sufficient reserves (generation that is on-line but not fully used) to account for the loss of the largest single generator in a region (e.g., a state)

Wind Power, Reserves and Regulation, cont.

Eastern Interconnect Frequency Response for Loss of 2600 MW;



Wind Power, Reserves and Regulation, cont.

- A fundamental issue associated with "free fuel" systems like wind is that operating with a reserve margin requires leaving free energy "on the table."
  - A similar issue has existed with nuclear energy, with the fossil fueled units usually providing the reserve margin
- Because wind turbine output can vary with the cube of the wind speed, under certain conditions a modest drop in the wind speed over a region could result in a major loss of generation
  - Lack of other fossil-fuel reserves could exacerbate the situation