ECEN 460
Power System Operation and Control
Spring 2025

Lecture 24: Wind and Solar

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Announcements

- Please read Chapter 13
- Schedule for the rest of the semester is
  - No labs this Friday (Reading Day)
  - Lab 11 (project presentations) by the individual teams to their TA ideally before the end of classes (on or before April 29)
  - Exam 2 on Wednesday April 23 during class; comprehensive but more emphasis on material since the first exam; similar format to first exam, closed book, closed notes, but two 8.5 by 11 inch note sheets and calculators allowed
  - Design project due at 9:30 am on May 1 (i.e., at the end of our final slot; no final)

Renewable Resource Introduction and Modeling

- With the advent of more renewable generation in power systems worldwide it is important to have correct models
- Hydro systems have already been covered
- Solar thermal and geothermal are modeled similar to existing stream generation, so they are not covered here
- Coverage will focus on introducing wind and solar generation, along with their associated power flow and stability level models for wind and solar PV for integrated system studies
  - More detailed EMTP-level models may be needed for individual plant issues, like subsynchronous resonance
  - Models are evolving, with a desire by many to have as generic as possible models

Inverter-Based Resources (IBRs)

- The term inverter-based resources (IBRs) is used to refer to devices that connect to the power grid through an inverter
  - An inverter is a device that takes a dc input and converts it to ac at a specified frequency; a rectifier is the inverse of an inverter, dc to ac
- Inverters can produce or absorb reactive power, providing great flexibility; however, they are limited by their power rating
- IBRs are now widely used in the power grid to connect in wind turbines, solar photovoltaic arrays (pv), storage, and HVDC
- A short document describing IBRs is available from NERC at
  - www.nerc.com/pa/Documents/2023_NERC_Guide_Inverter-Based-Resources.pdf

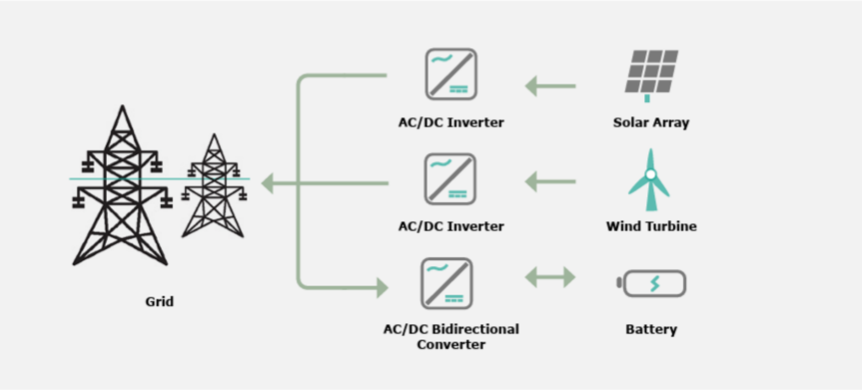
Differences between IBRs and Synchronous Generators

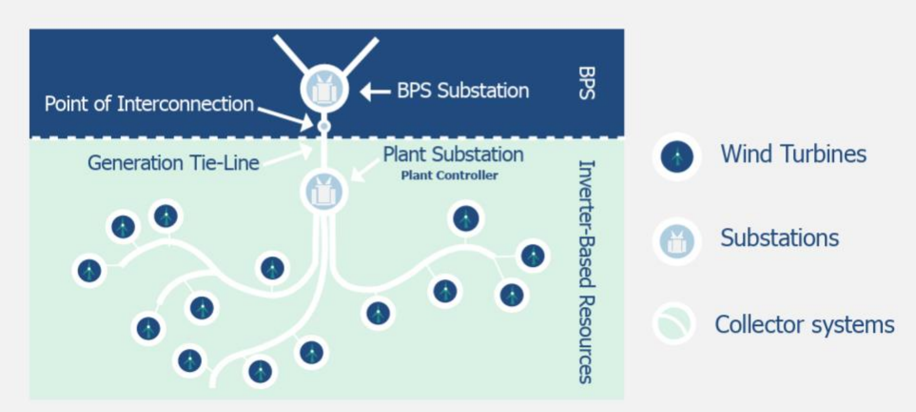
Differences between Inverter-Based Resources and Synchronous Generation

Inverter-Based Resources	Synchronous Generation
• Driven by power electronics and software	• Driven by physical machine properties
• No (or little) inertia	• Large rotating inertia
• Very low fault current	• High fault current
• Sensitive power electronic switches	• Rugged equipment tolerant to extremes
• Very fast and flexible ramping	• Slower ramping
• Very fast frequency control	• Inherent inertial response
• Minimal plant auxiliary equipment prone to tripping	• Sensitive auxiliary plant equipment
• Dispatchable based on available power	• Fully dispatchable
• Can provide essential reliability services	• Can provide essential reliability services

What is an inverter?

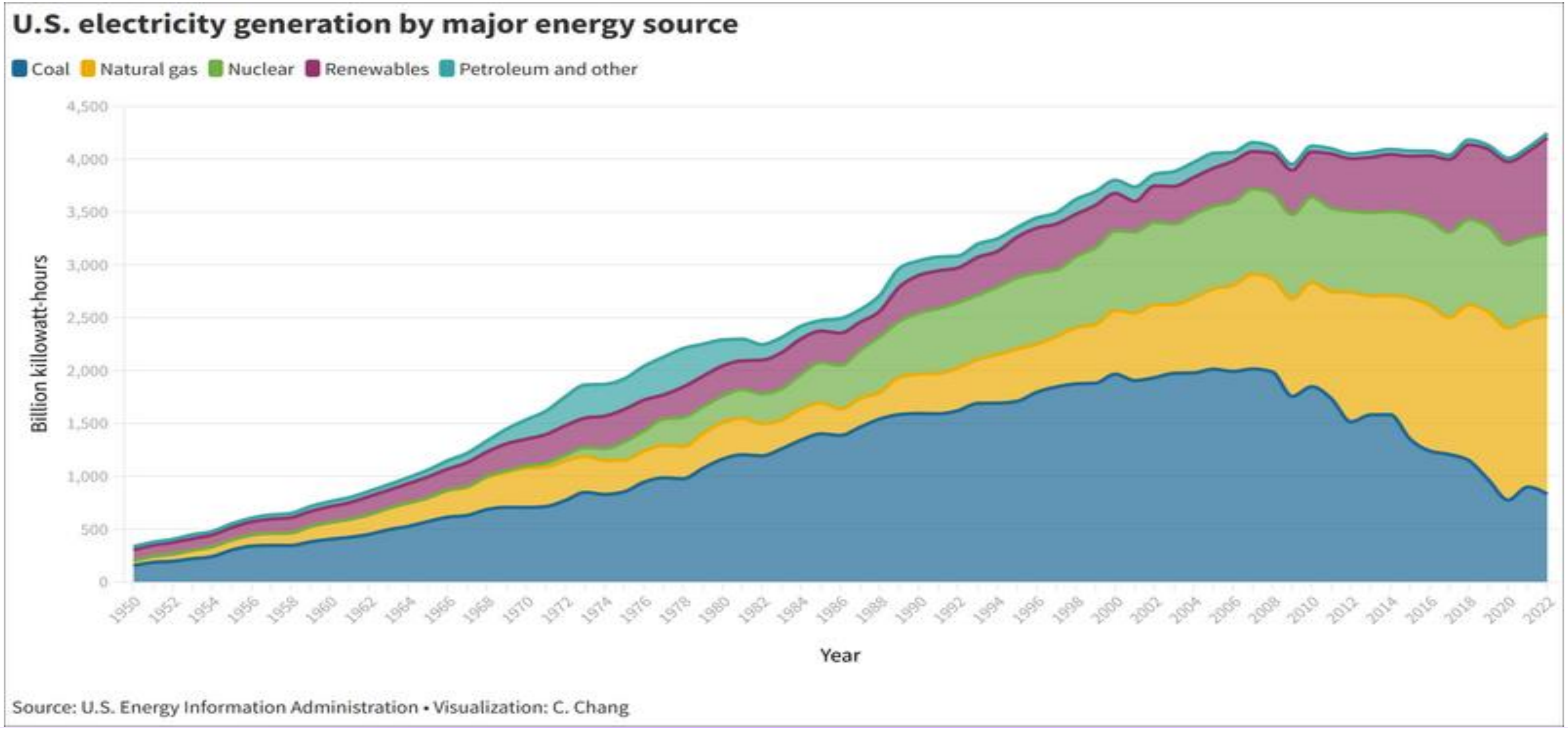
An inverter is a power electronic device that converts direct current (dc) electricity to alternating current (ac) electricity.





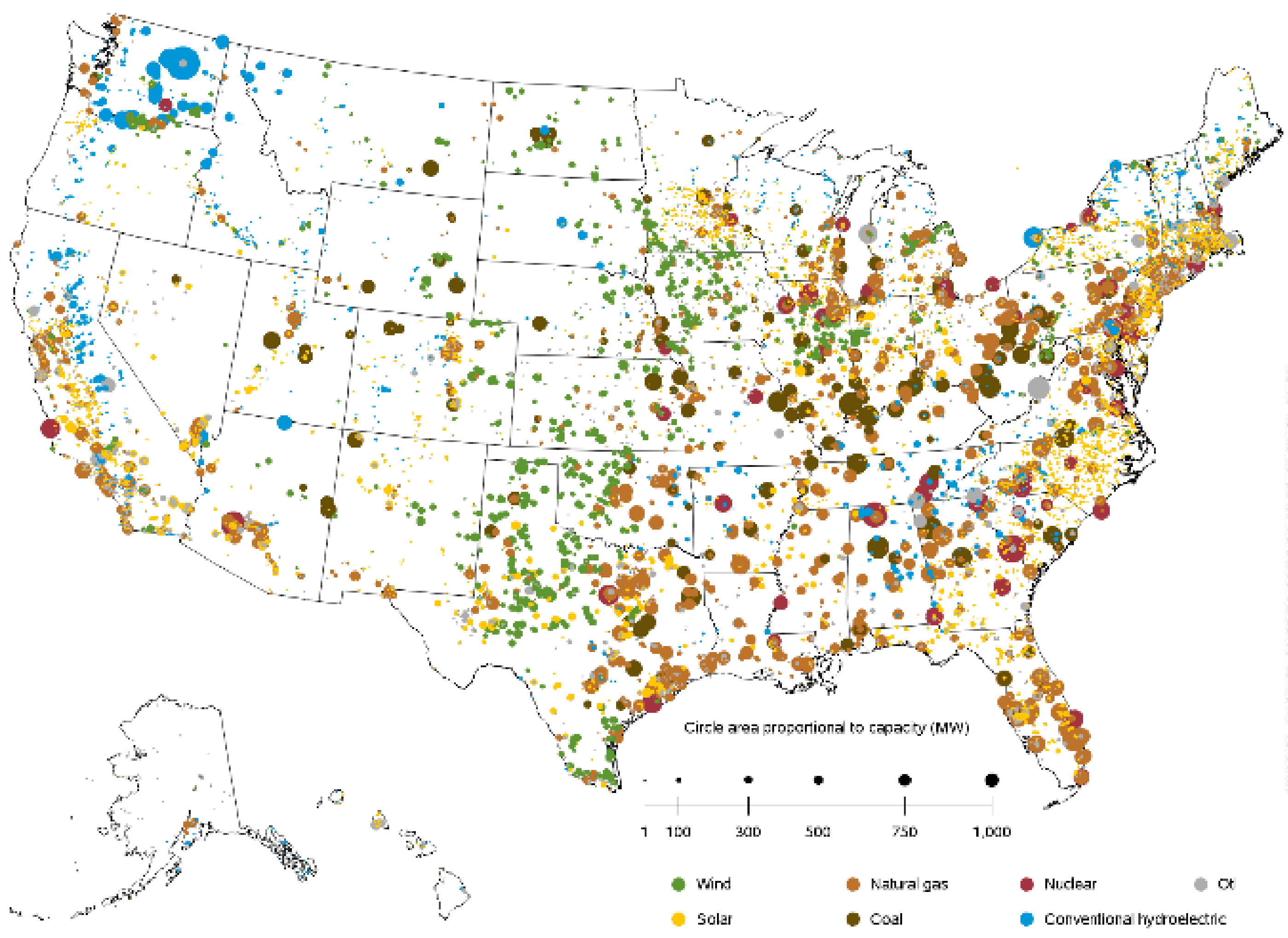
Changing Sources of Generation

- In the US and worldwide the sources of electricity are rapidly changing



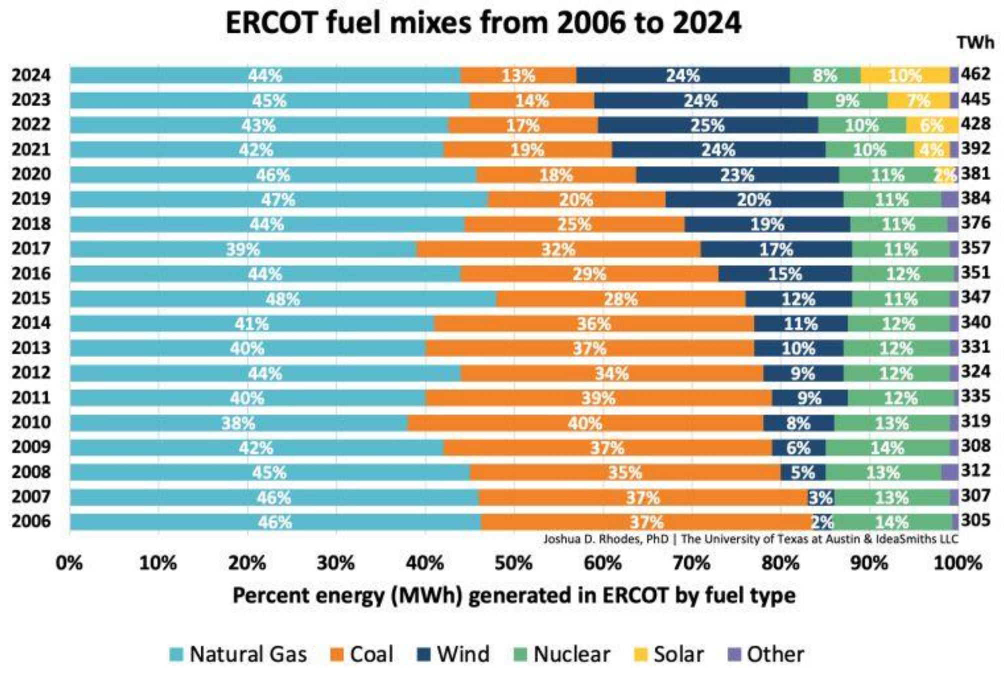
Changing Sources of Generation, cont.

Operable utility-scale electric generating units, as of November 2024



Data sources: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

The sources variety substantially by state, the below image shows the change in the ERCOT (Texas) generation



Natural Gas Prices, A Key Driver of Electricity Prices

Henry Hub Natural Gas Spot Price (MHHNGSP)

Observations
Mar 2025: **4.12**
Updated: Apr 2, 2025 12:31 PM CDT
Next Release Date: Apr 9, 2025

Units:
Dollars per Million BTU,
Not Seasonally Adjusted

Frequency:
Monthly

1Y | 5Y | 10Y | Max

1997-01-01 to 2025-03-01

Edit Graph

Download

Source: U.S. Energy Information Administration via FRED®

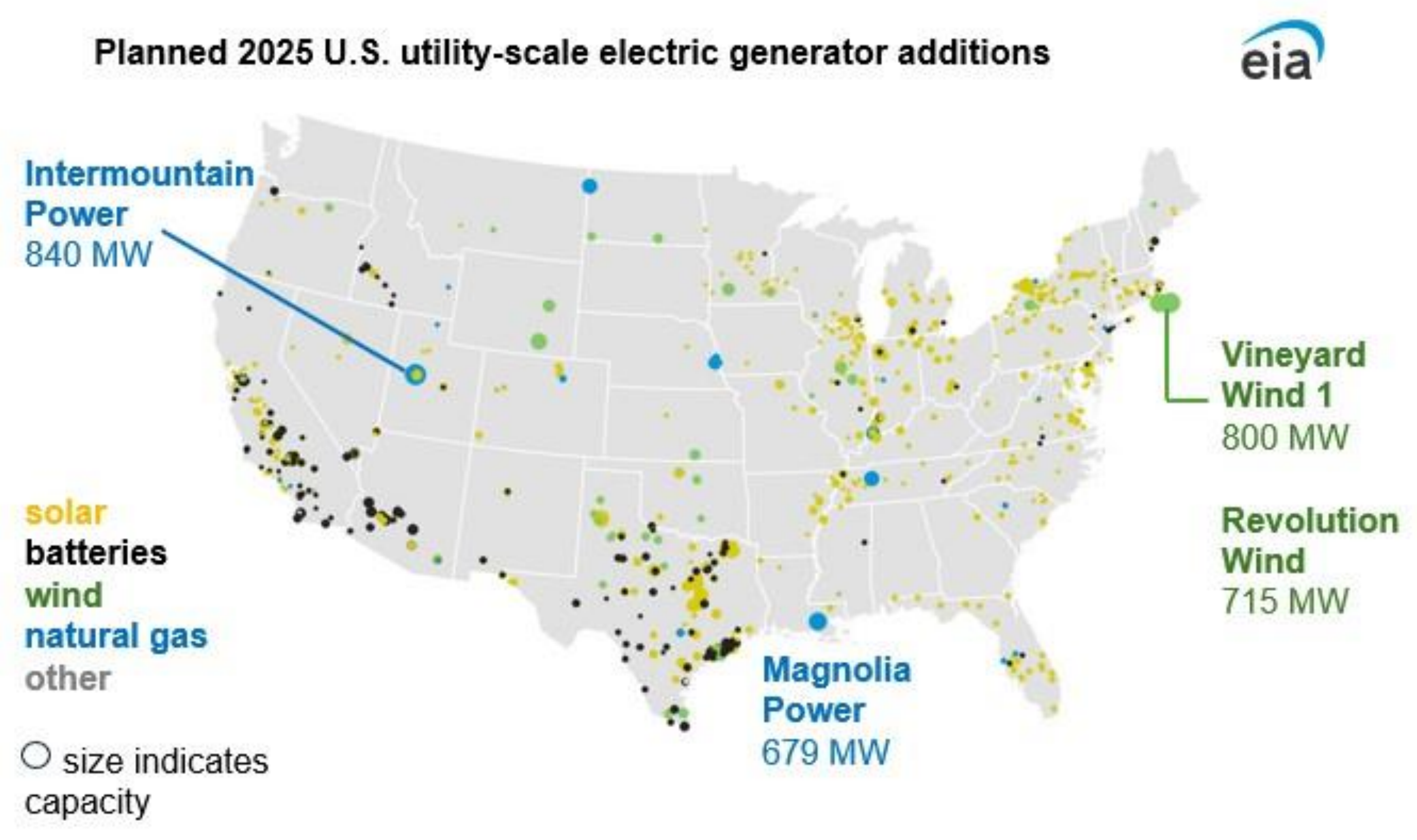
Shaded areas indicate U.S. recessions.

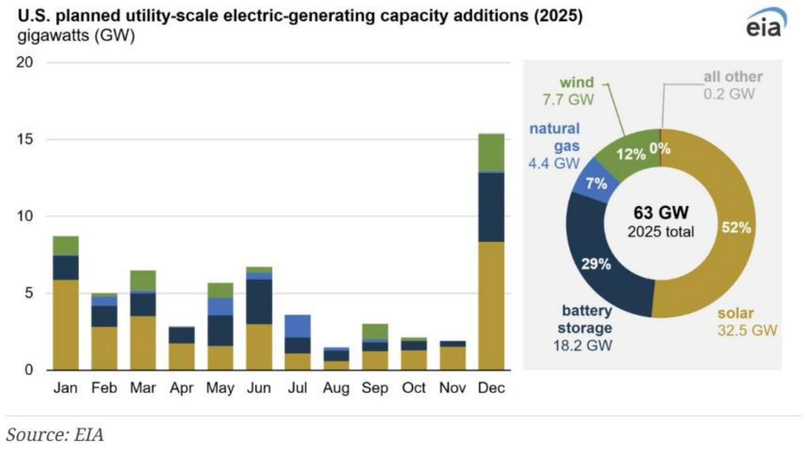
fred.stlouisfed.org

Fullscreen

Source: fred.stlouisfed.org/series/DHHNGSP

Planned New Generation 2025

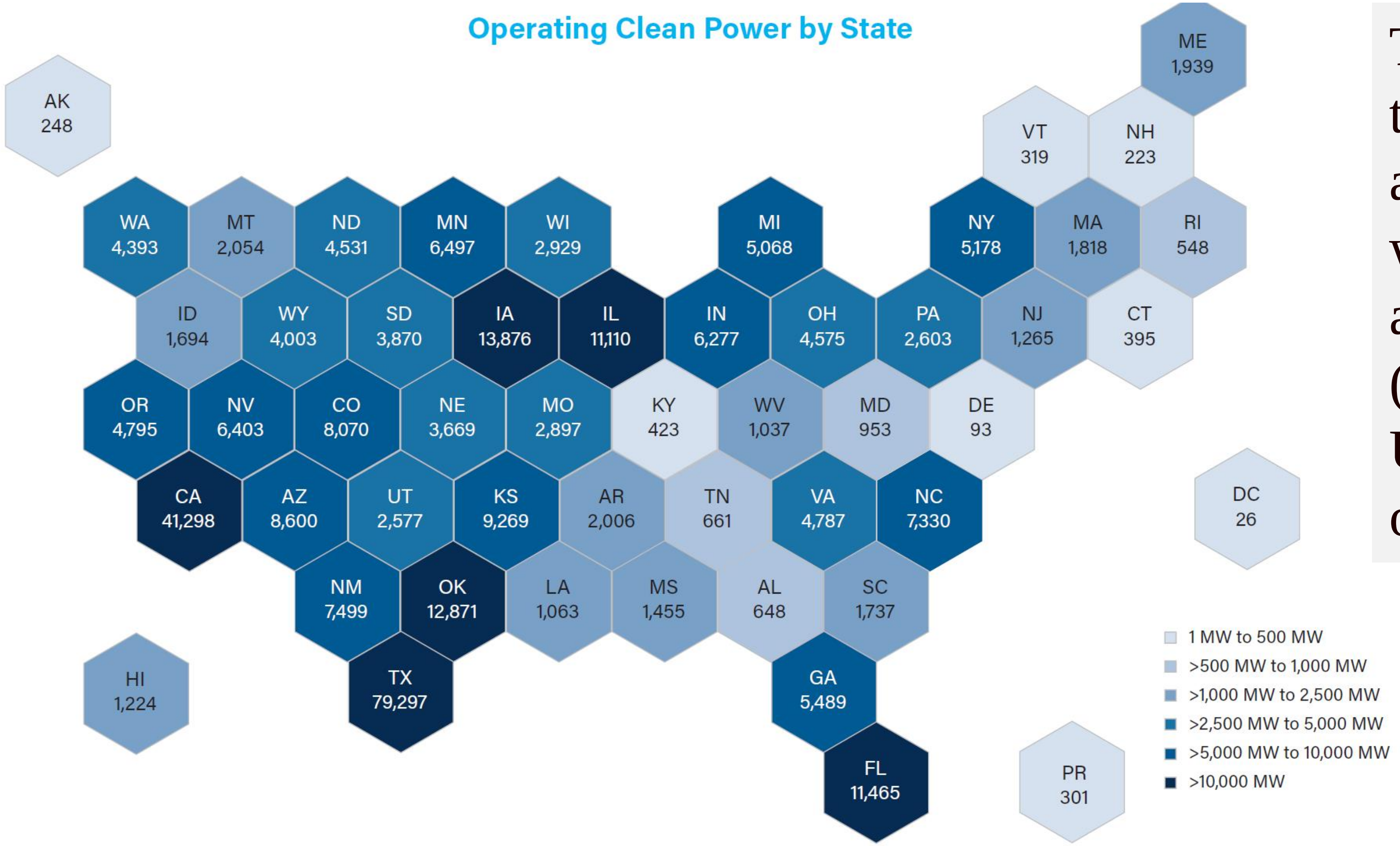




Vineyard Wind 1 is under construction and might enter operation in 2025; Revolution Wind might go into operation in 2026

Two 1100 MW nuclear units, Vogtle 3 and 4, entered commercial operation on 2023 and 2024 respectively; Texas is expected to add 6.7 GW of new storage in 2025

US Wind and Solar Capacity by State, 2024



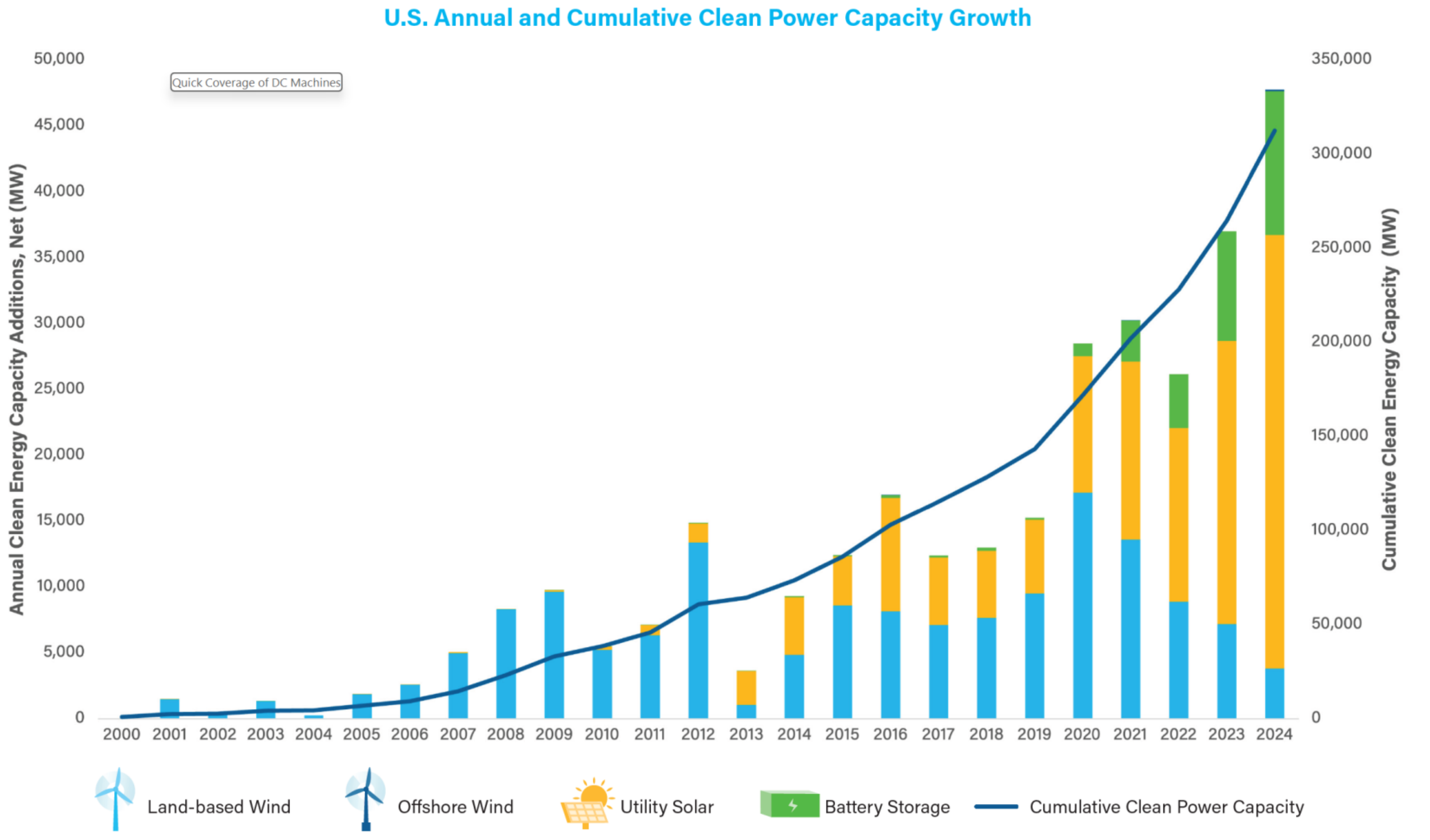
American Clean Power Association | Snapshot of Clean Power in 2024

Total US capacity at the end of Q4 2024 is about 155 GW of wind, 130 GW of solar, and 29 GW of storage (compared to a total US generation capacity of about 1300 GW)

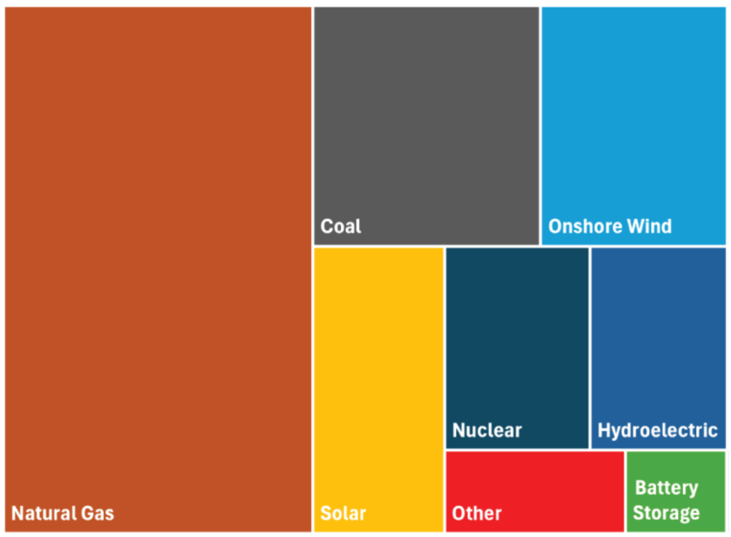
US Annual & Cumulative Wind & Solar Growth

CLEAN POWER LANDSCAPE: 2024

U.S. Clean Power Capacity Growth Over Time

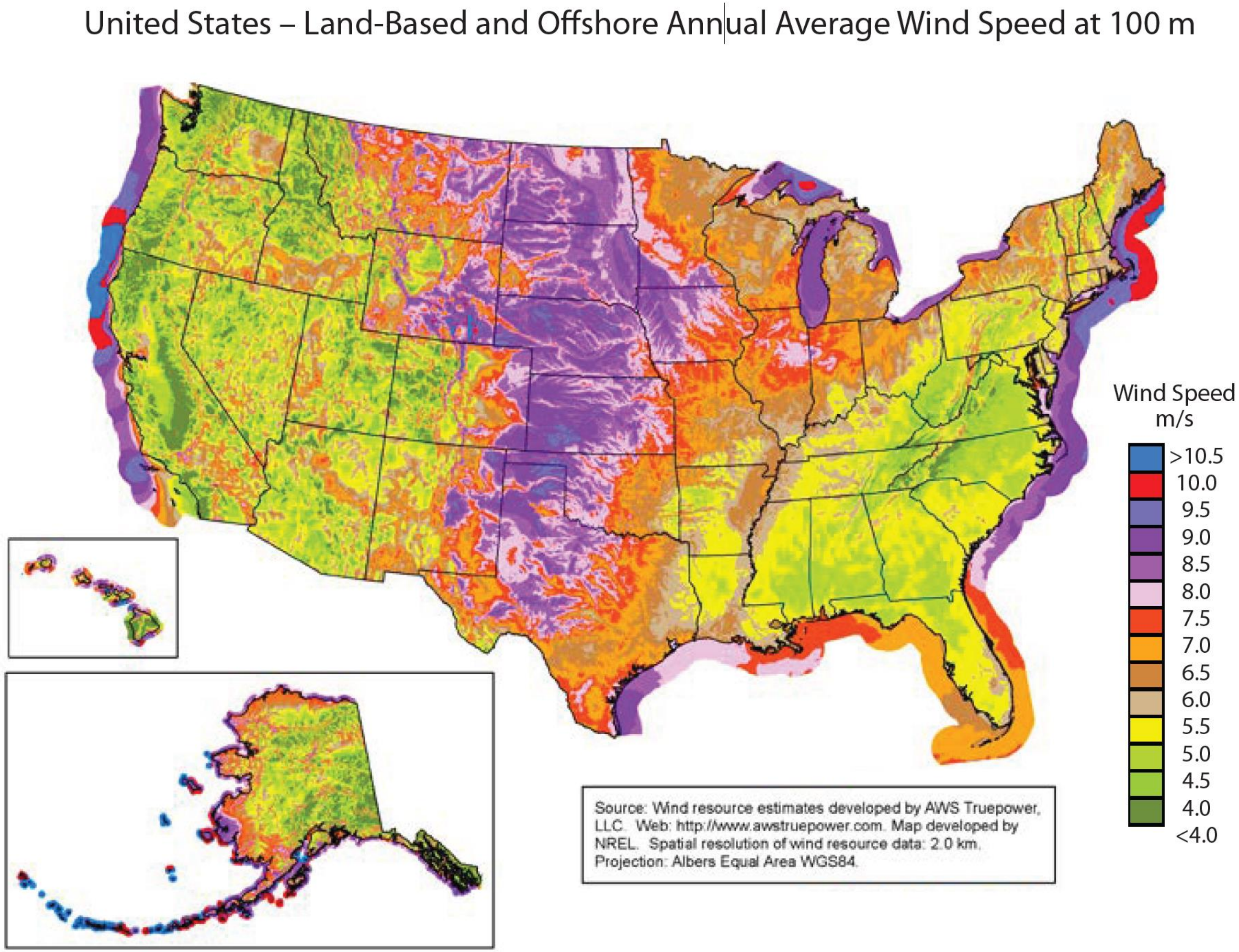


U.S. Operational Power Capacity by Technology



Source: American Clean Power Quarterly, 2024 Q4

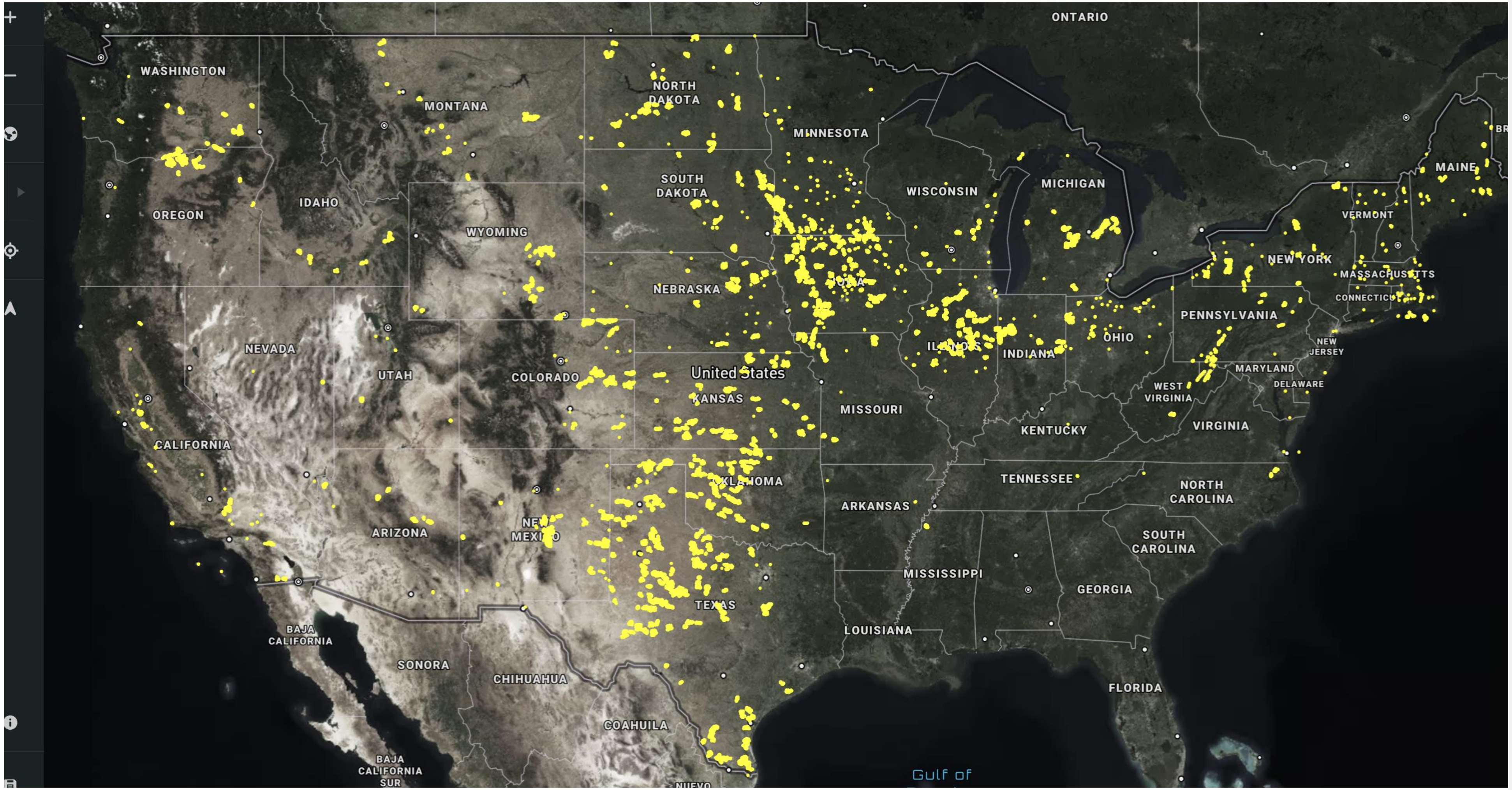
North America Wind Resources at 100 m



Wind speeds at say 100 m above the ground can be substantially higher than closer to the surface; above 7.5 m/s is economic

Source: www.nrel.gov/docs/fy15osti/64733.pdf

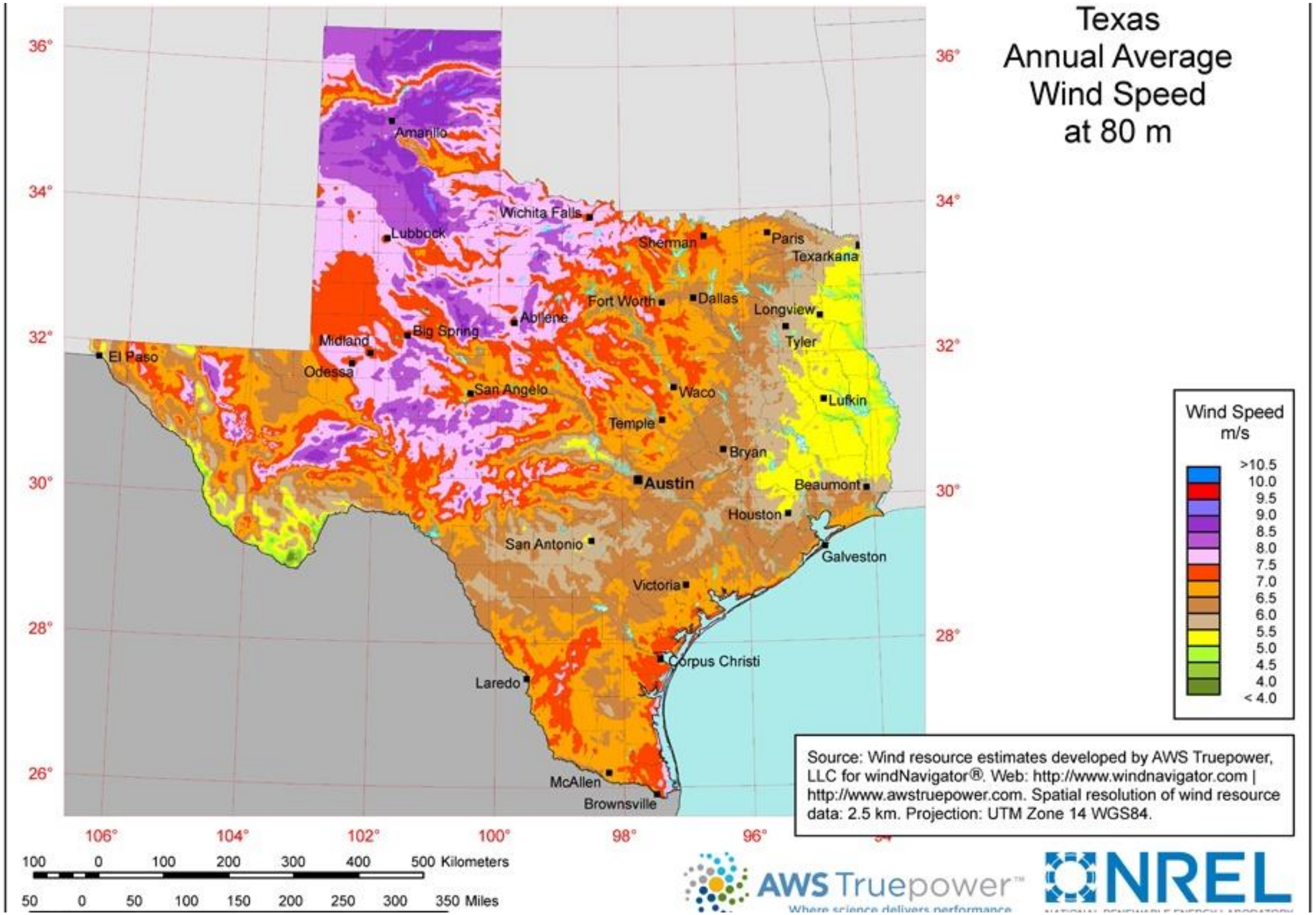
US Wind Farm Locations, Feb 2025



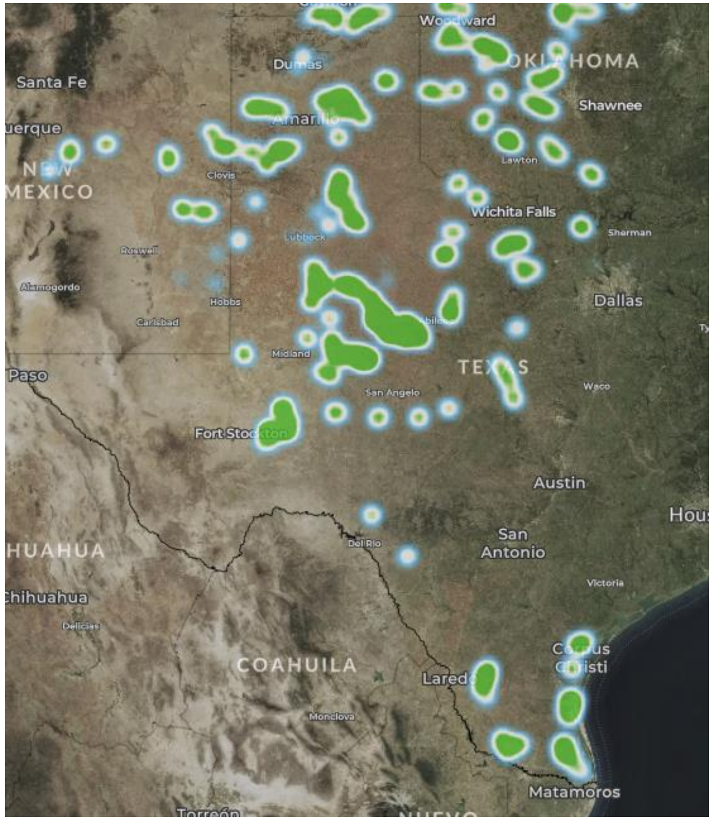
Many wind turbines are usually sited together, in groups known as either wind farms, wind parks, or wind power plants; single devices are known as wind turbines, with the term windmill usually used for devices that pump water

Image source: USGS at https://eerscmap.usgs.gov/uswtdb/

Wind Map Texas– 80m Height



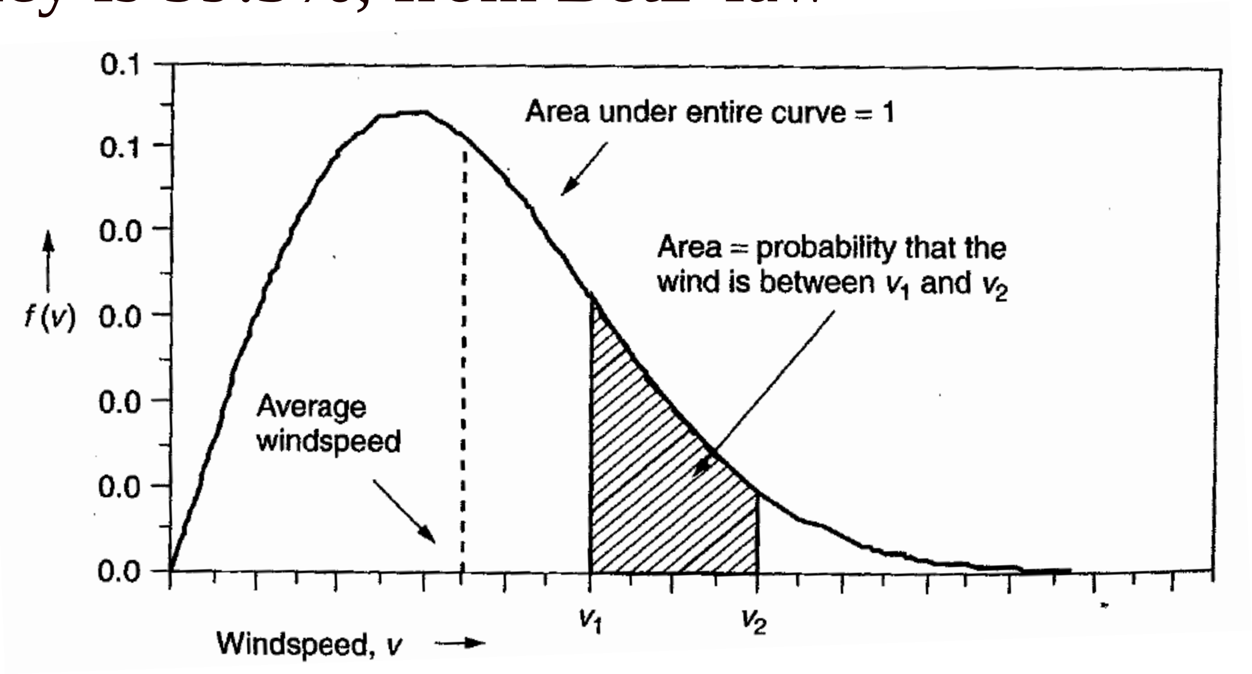
Wind farms in Texas



https://windexchange.energy.gov/files/u/visualization/image/tx_80m.jpg

Power in the Wind

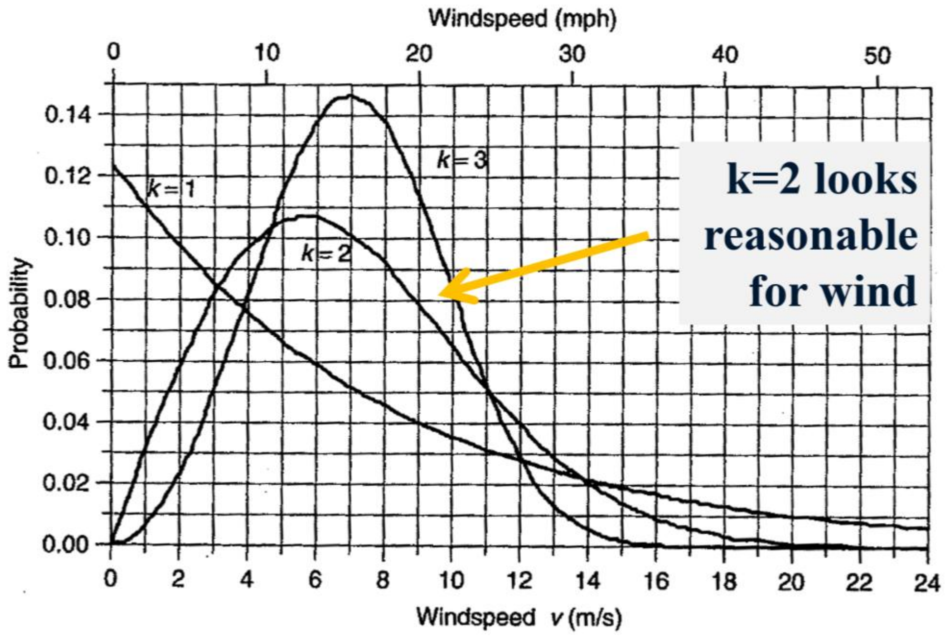
- The power in the wind is proportional to the cube of the wind speed
  - Velocity increases with height, with more increase over rougher terrain (doubling at 100m compared to 10m for a small town, but only increasing by 60% over crops or 30% over calm water)
- Maximum rotor efficiency is 59.3%, from Betz' law
- Expected available energy depends on the wind speed probability density function (pdf)



Determining Available Wind Energy

- Because the power in the wind varies with the cube of the wind speed, just knowing the average wind speed is not sufficient to determine the available wind energy; the wind speed probability distribution function (pdf) is also needed
- When the actual wind pdf is not available, it is common to assume a Rayleigh pdf, which is a Weibull pdf with a k = 2

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^{k}} \quad \text{Weibull pdf}$$

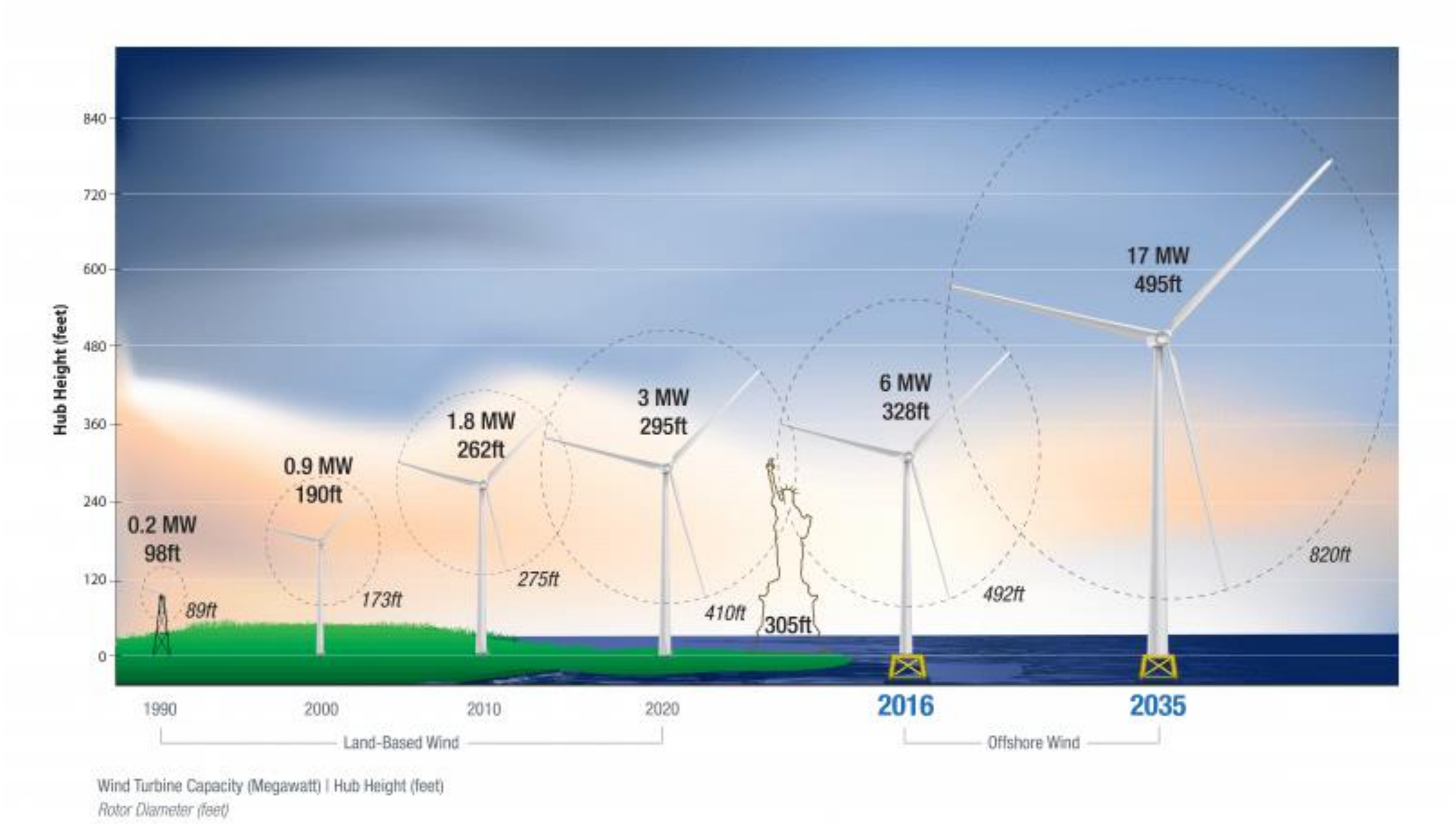


Weibull p.d.f. for c = 8

- For Rayleigh $c = \frac{2}{\sqrt{\pi}} v_{avg} = 1.128\overline{v}$

Wind Turbine Height and Size

The current largest wind turbines by capacity are about 26 MW with rotor diameters of about 340m; the below picture is for an 18 MW generator

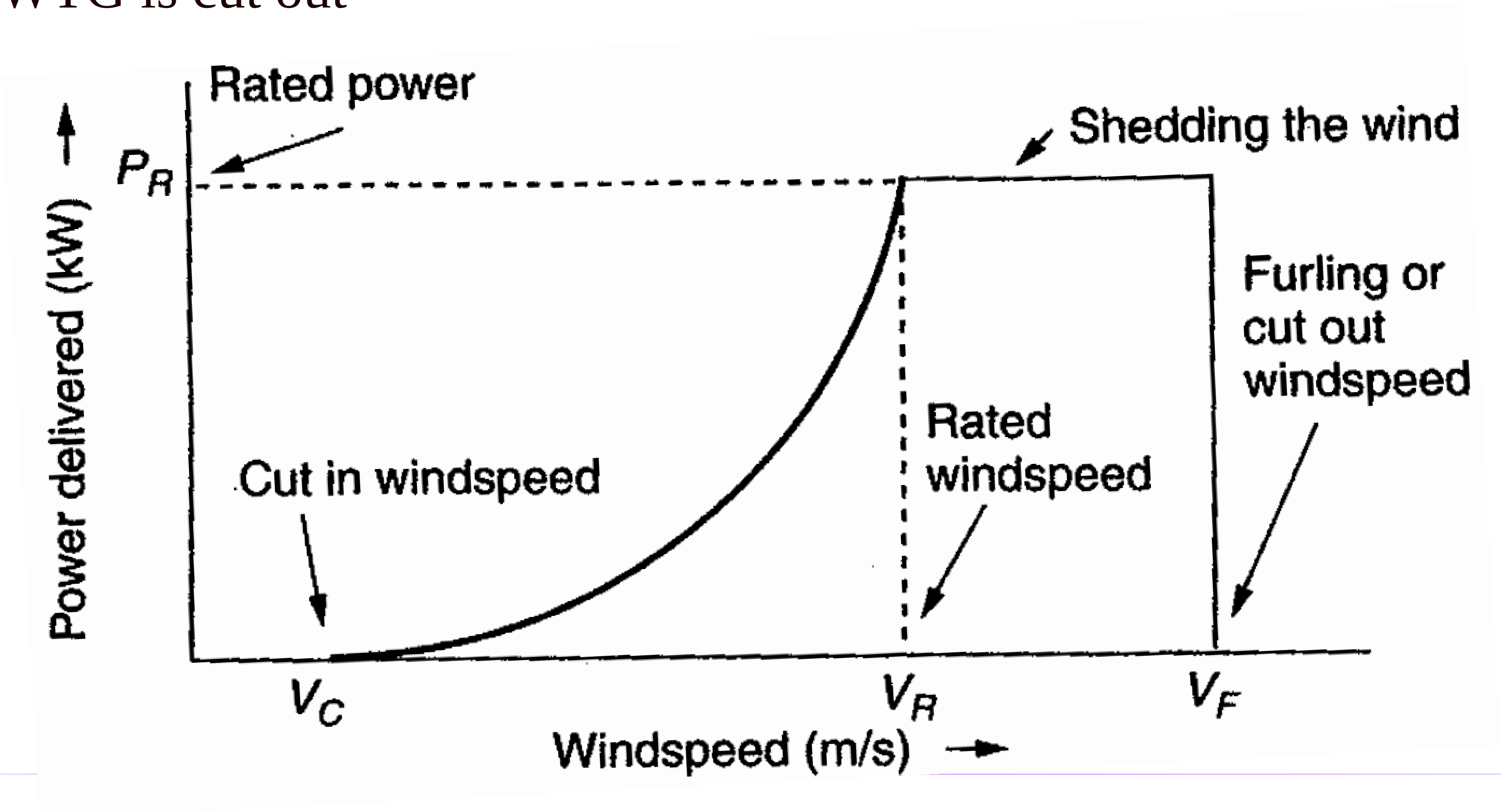


Average on-shore capacities are now over 3 MW, with hub heights approaching 100 m

https://www.energy.gov/eere/articles/wind-turbines-bigger-better

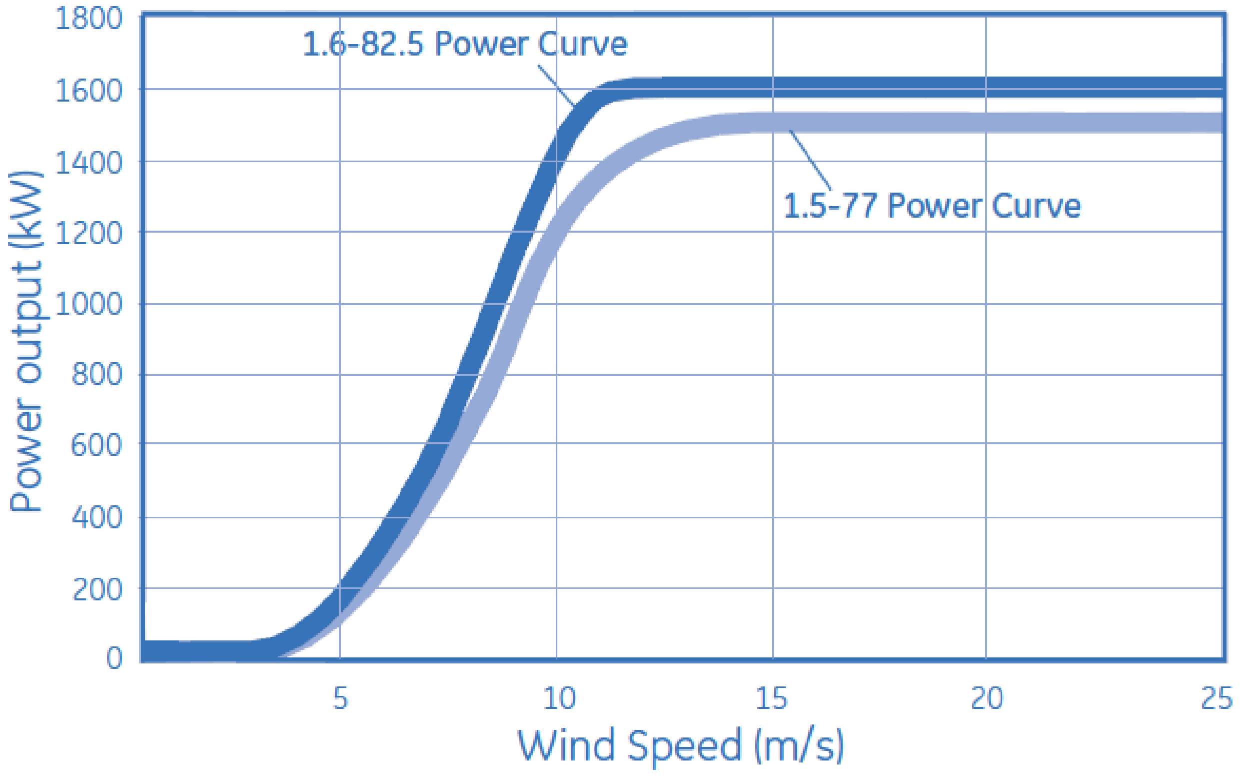
Extracted Power

- WTGs are designed for rated power and windspeed
  - For speeds above this blades are pitched to operate at rated power; at furling speed the WTG is cut out



Example: GE 1.5 and 1.6 MW Turbines

- Power speed curves for the GE 1.5 and 1.6 MW WTGs
  - Hub height is 80/100 m; cut-out at 25 m/s wind



Source: http://site.ge-energy.com/prod_serv/products/wind_turbines/en/15mw/index.htm

Wind Farms (or Parks)

- Usually, wind farm is modeled in aggregate for grid studies; wind farm can consist of many small (1 to 3 MW) wind turbine-generators (WTGs) operating at low voltage (e.g. 0.6kV) stepped up to distribution level (e.g., 34.5 kV)

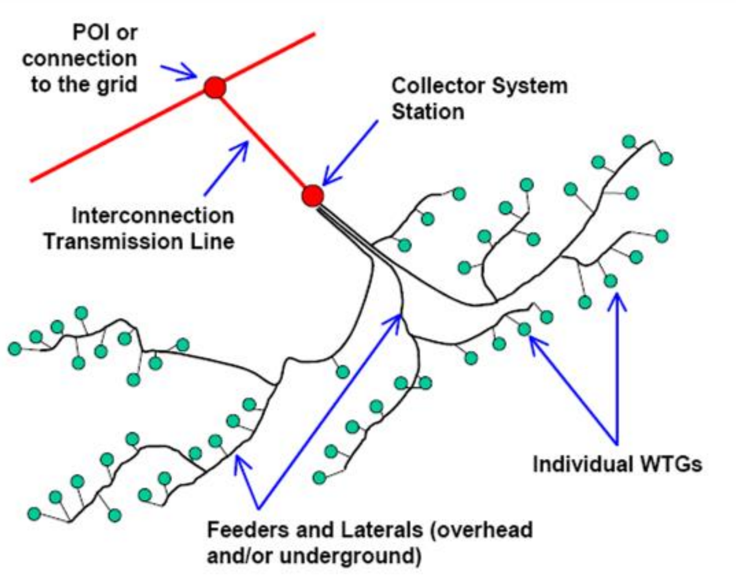


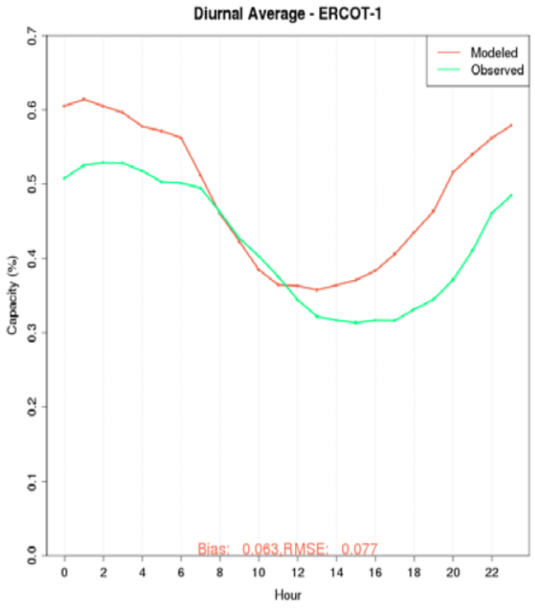
Photo Source: www.energyindustryphotos.com/photos_of_wind_farm_turbines.htm

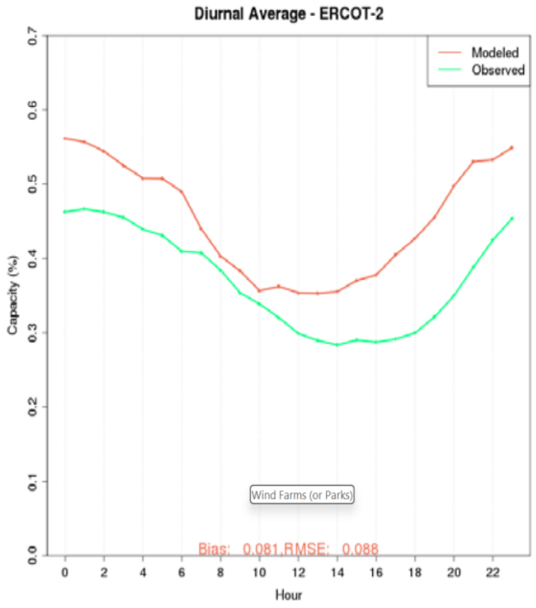
Economies of Scale

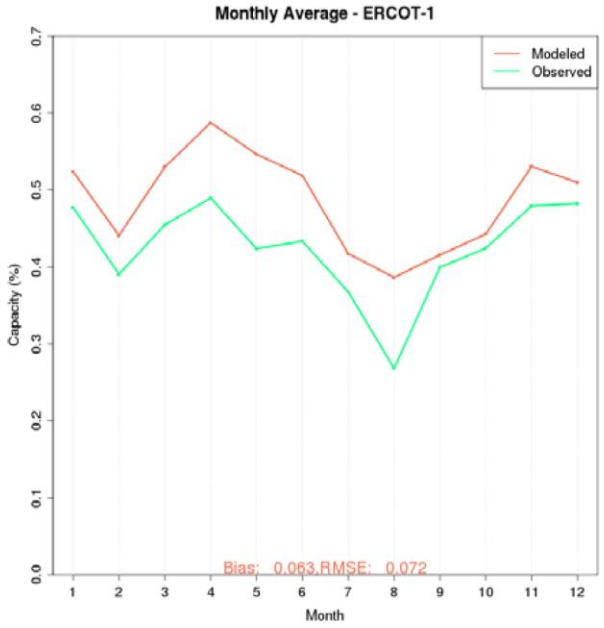
- Presently large wind farms produce electricity more economically than small operations
- Factors that contribute to lower costs are
  - Wind power is proportional to the area covered by the blade (square of diameter) while tower costs vary with a value less than the square of the diameter
  - Larger blades are higher, permitting access to faster winds, but size limited by transportation for most land wind farms
  - 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)

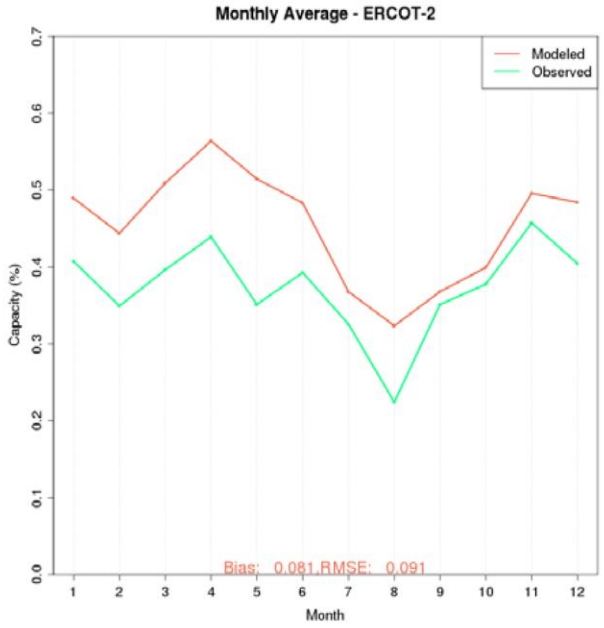
Wind Patterns

- Wind speeds, of course, vary. However, they usually exhibit daily and seasonal patterns that the be leveraged in electric grid planning and operation; the below images show data for ERCOT locations, both daily and monthly









Images: www.ercot.com/files/docs/2017/02/17/MemoReport_AWST_ERCOT_27Mar2015.pdf

Offshore Wind

- Offshore wind turbines currently need to be in relatively shallow water, so maximum distance from shore depends on the seabed
- Worldwide capacity is about 70 GW, with half of it in China and almost one quarter in the UK
  - US offshore wind is only 42 MW; while there had been lots of interest, there are also major challenges including greatly increased costs
- Capacity factors tend to increase as turbines move further off-shore

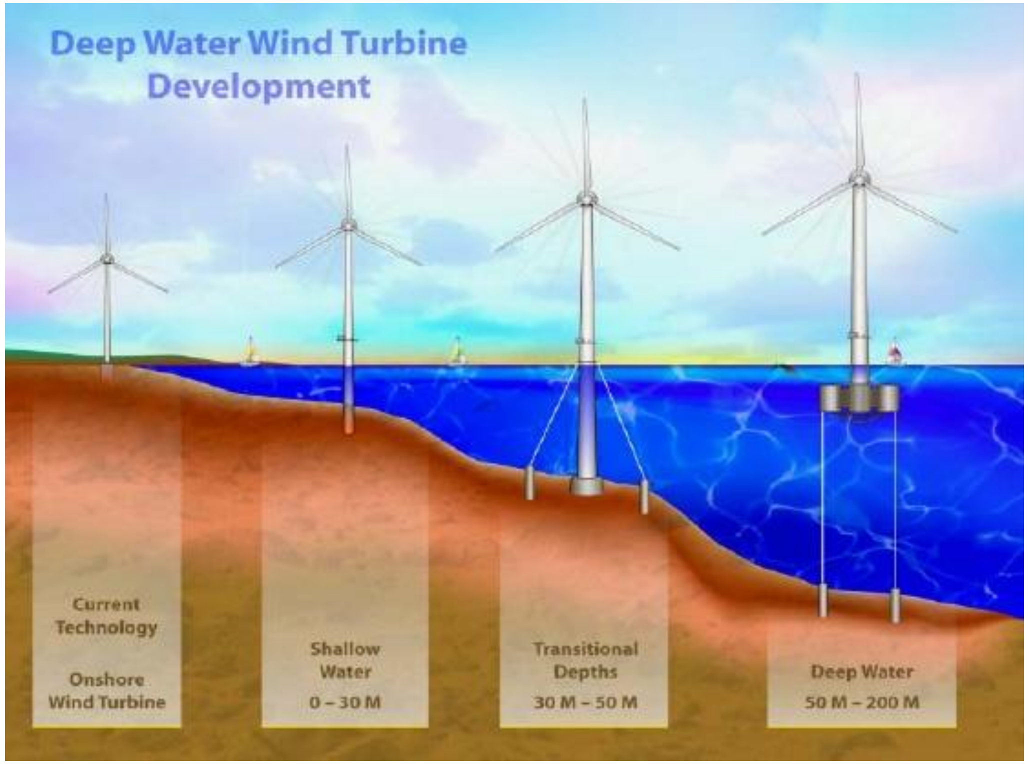


Image Source: National Renewable Energy Laboratory

Offshore: Advantages and Disadvantages

- All advantages/disadvantages are somewhat site specific
- Advantages
  - Can usually be sited much closer to the load (which is often by the coasts)
  - 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)

Types of Wind Turbines for Power Flow and Stability

- Several different approaches to aggregate modeling of wind farms in power flow and transient stability
  - Wind turbine manufacturers provide detailed, public models of their WTGs; these models are incorporated into software packages; for example, GE 1.5, 1.6 and 3.6 MW WTGs (see Modeling of GE Wind Turbine-Generators for Grid Studies, version 6.01, October 2017, GE Energy)
  - Proprietary models are included as user defined models; covered under NDAs to maintain confidentiality
  - Generic models are developed to cover the range of WTGs, with parameters set based on the individual turbine types
    - Concern by some manufacturers that the generic models to not capture their WTGs' behavior, such as during low voltage ride through (LVRT)

Types of Wind Turbines for Power Flow and Stability

- Electrically there are four main generic types of wind turbines
  - Type 1: Induction machine; treated as PQ bus with negative P load; dynamically modeled as an induction motor
  - Type 2: Induction machine with varying rotor resistance; treated as PQ bus in power flow; induction motor model with dynamic slip adjustment
  - Type 3: Doubly Fed Asynchronous Generator (DFAG) (or DFIG); treated as PV bus in power flow
  - Type 4: Full Asynchronous Generator; treated as PV bus in power flow
- New wind farms (or parks) are all of Type 3 or 4

Generic Modeling Approach

- The generic modeling approach is to divide the wind farm models by functionality
  - Generator model: either an induction machine for Type 1 and 2's or a voltage source converter for Type 3 and 4
  - Reactive power control (exciter): none for Type 1, rotor resistance control for Type 2, commanded reactive current for Type 3 and 4
  - Drive train models: Type 1 and 2 in which the inertia appears in the transient stability
  - Aerodynamics and Pitch Models: Model impact of changing blade angles (pitch) on power output

Wind Turbine Issues

- Models are designed to represent the system level impacts of the aggregate wind turbines during disturbances such as low voltages (nearby faults) and frequency deviations
- Low voltage ride through (LVRT) is a key issue, in which the wind turbines need to stay connected to the grid during nearby faults
- Active and reactive power control is also an issue

Low Voltage Ride Through (LVRT)

- The concern is if during low voltages, such as during faults, the IBRs trip, it could quickly setup a cascading situation particularly in areas with lots of wind, solar or storage
  - For WTGs rapid tripping had been a strategy to protect the DFAG from high rotor currents and over voltages in the dc capacitor.
  - When there were just a few WTGs, tripping was acceptable
- Different interconnects have varying requirements, with ERCOT having a more restrictive

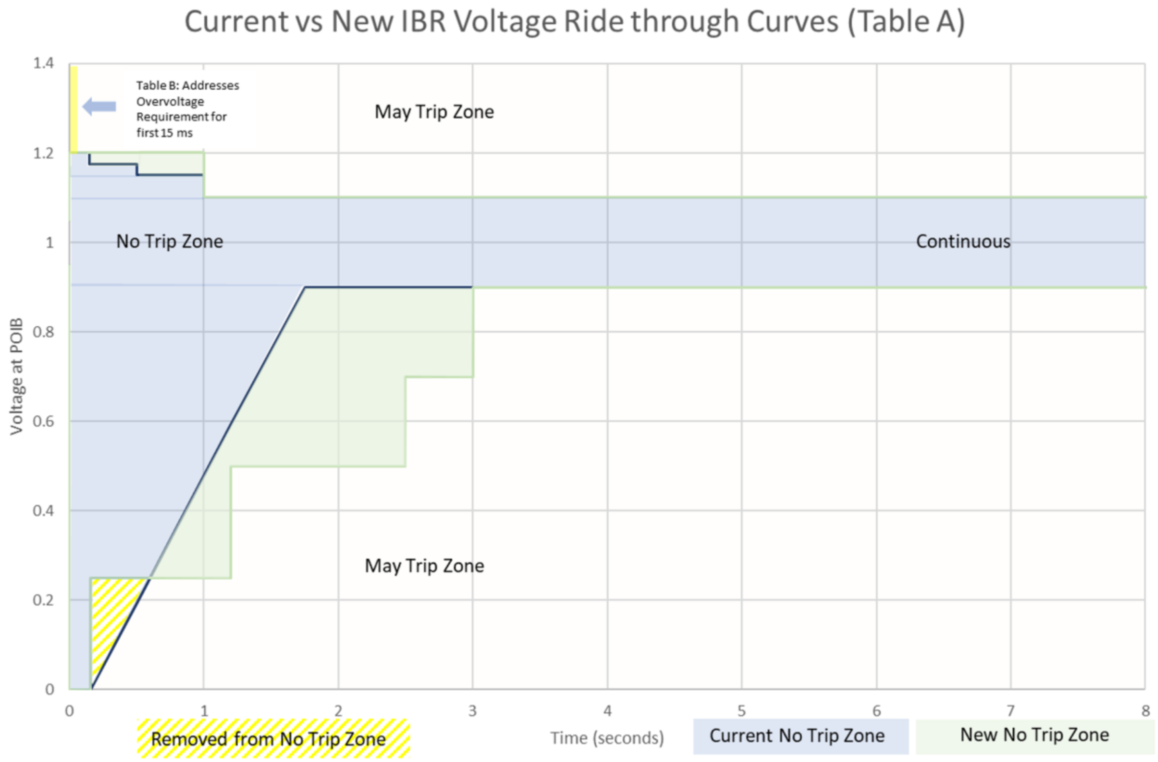


Image source: ERCOT, 2023

Type 3: Doubly Fed Asynchronous Generators (DFAG)

- Doubly fed asynchronous generators (DFAG) are usually a conventional wound rotor induction generator with an ac-dc-ac power converter in the rotor circuit
  - Power that would have been lost in external rotor resistance is now used
- Electrical dynamics are dominated by the voltage-source inverter, which has dynamics much faster than the transient stability time frame

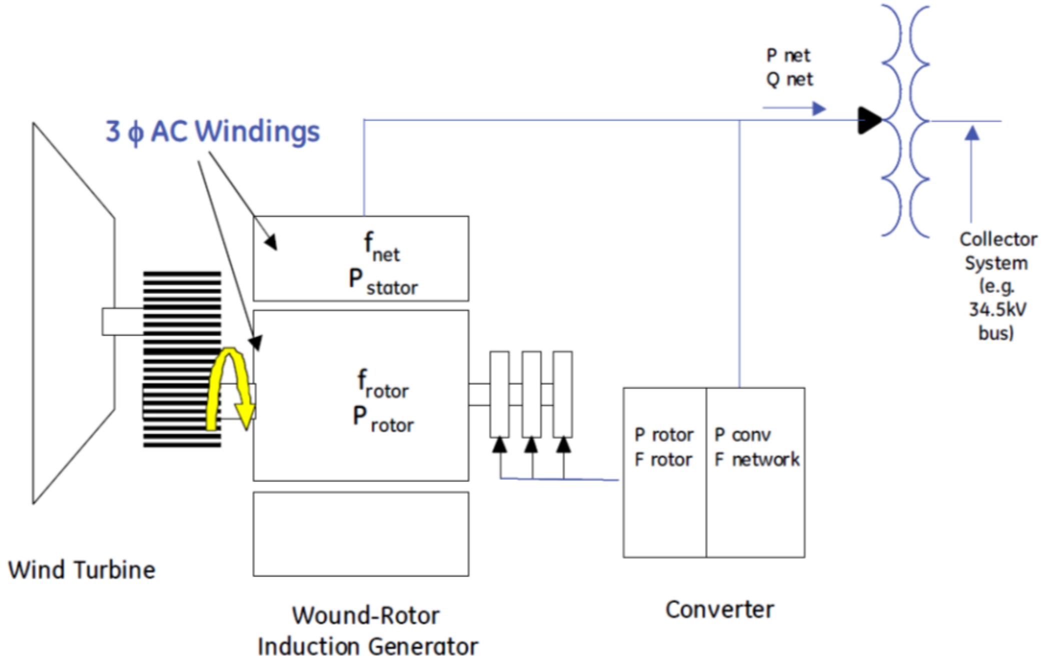


Figure 2-1. GE Doubly Fed Asynchronous WTG Major Components.

Image Source: Figure 2.1 from Modeling of GE Wind Turbine-Generators for Grid Studies, version 4.6, March 2013, GE Energy

Type 3 Converters

- A voltage source converter (VSC) takes a dc voltage, usually held constant by a capacitor, and produces a controlled ac output
- A phase locked loop (PLL) is used to synchronize the phase of the wind turbine with that of the ac connection voltage
  - Operates much faster than the transient stability time step, so is often assumed to be in constant synchronism
- Under normal conditions the WTG has a controllable real power current and reactive power current
- WTG voltages are not particularly high, say 600V

Type 3 Converters

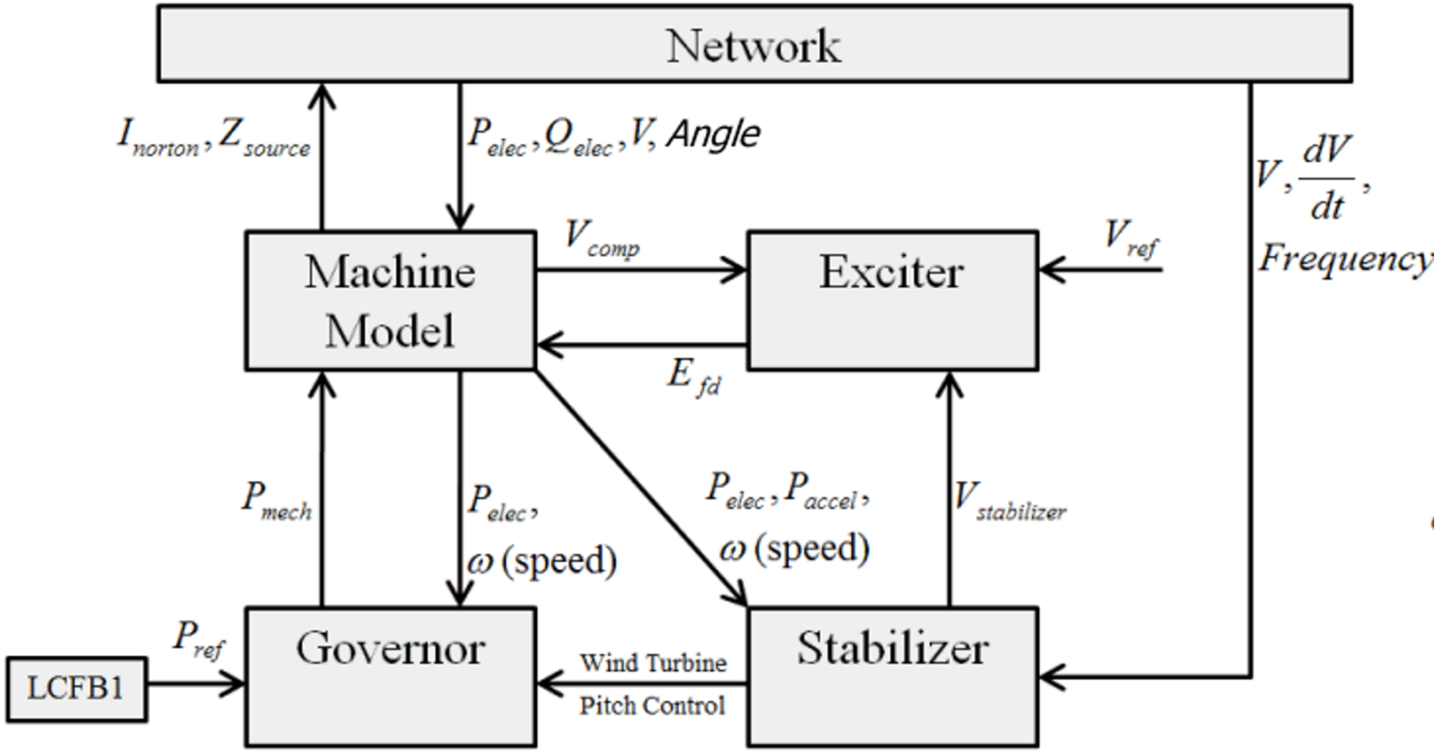
- Type 3 machines can operate at a potentially widely varying slip
  - Example, rated speed might be 120% (72 Hz for a 60 Hz system) with a slip of -0.2, but with a control range of +/- 30%
- Control systems are used to limit the real power during faults (low voltage)
  - Current ramp rate limits are used to prevent system stress during current recovery
- Reactive current limits are used during high voltage conditions

Type 4 Converters

- Type 4 WTGs pass the entire output of the WTG through the ac-dc-ac converter
- Hence the system characteristics are essentially independent of the type of generator
  - Because of this decoupling, the generator speed can be as variable as needed
  - This allows for different generator technologies, such as permanent magnet synchronous generators (PMSGs)
  - Traditionally gearboxes have been used to change the slow wind turbine speed (e.g., 15 rpm) to a more standard generator speed (e.g., 1800 rpm); with Type 4 direct drive technologies can also be used

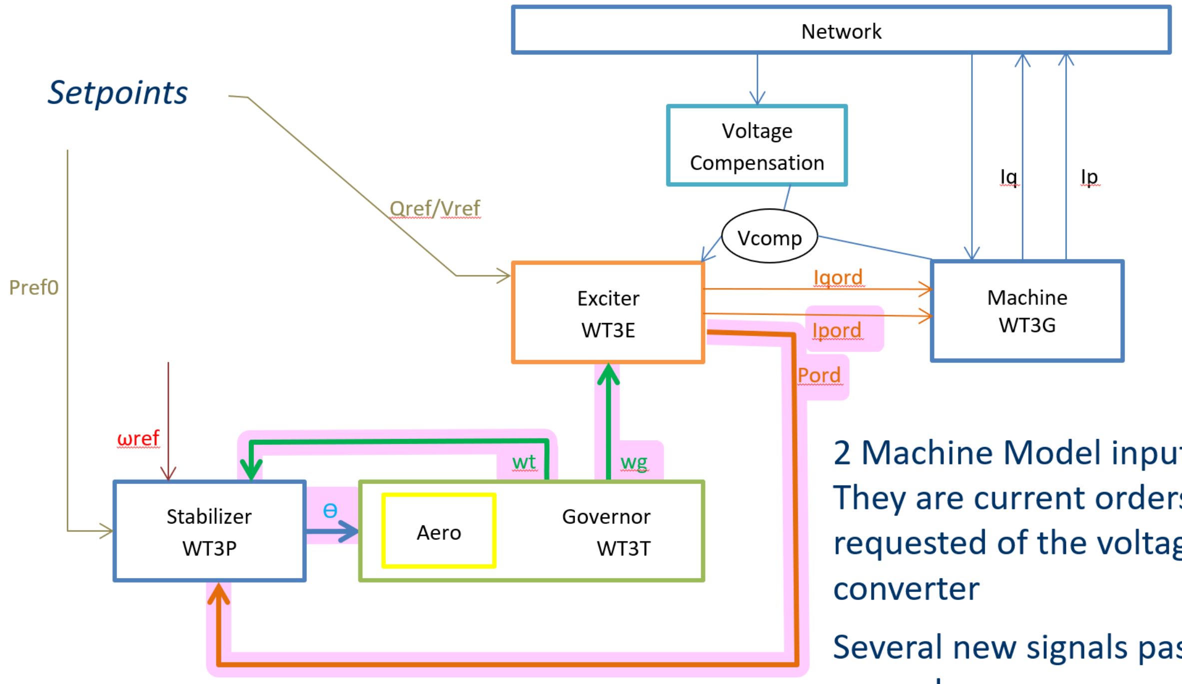
Stability Modeling of Wind Turbines

- As we've seen, traditionally the industry has used a modular approach for generator models
  - Machine
  - Exciter
  - Governor
  - Stabilizer
  - Under Excitation Limiter
  - Over Excitation Limiter
  - Relay Models
  - Compensator Model



This Approach Has Been Followed with Wind

- When wind started to appear in larger amounts, “first generation” models were developed following this same approach
- This initial models were a good start, but they are now considered obsolete
- First Generation model had few mechanisms to provide control features of
  - Real Power or Torque Control
  - Reactive Power
  - Voltage Control



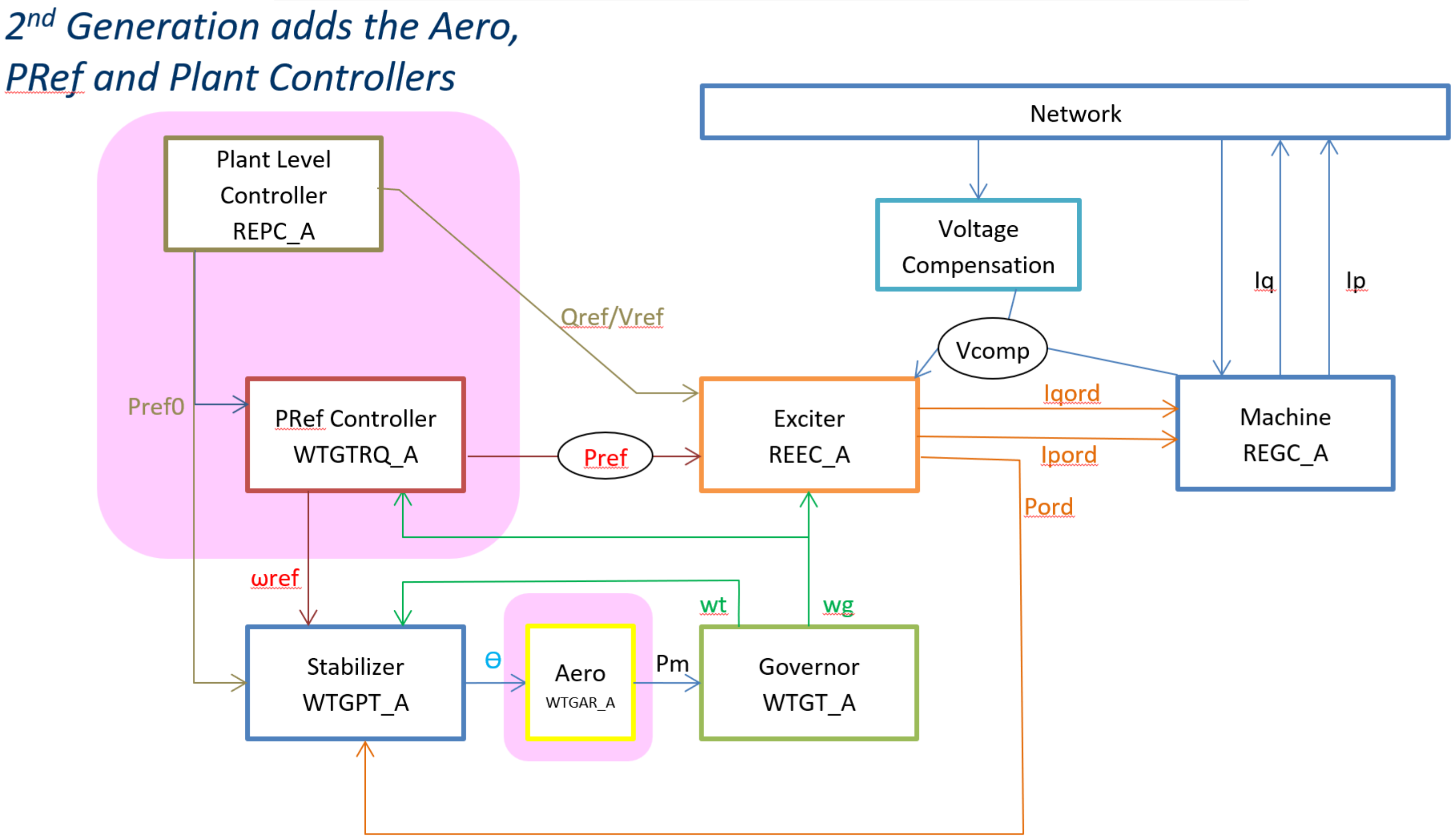
2 Machine Model inputs now. They are current orders requested of the voltage source converter

Several new signals passing around

Second Generation Stability Models

- The second generation models are a similar format, but provide for more realistic control; they have also been expanded to include solar and storage

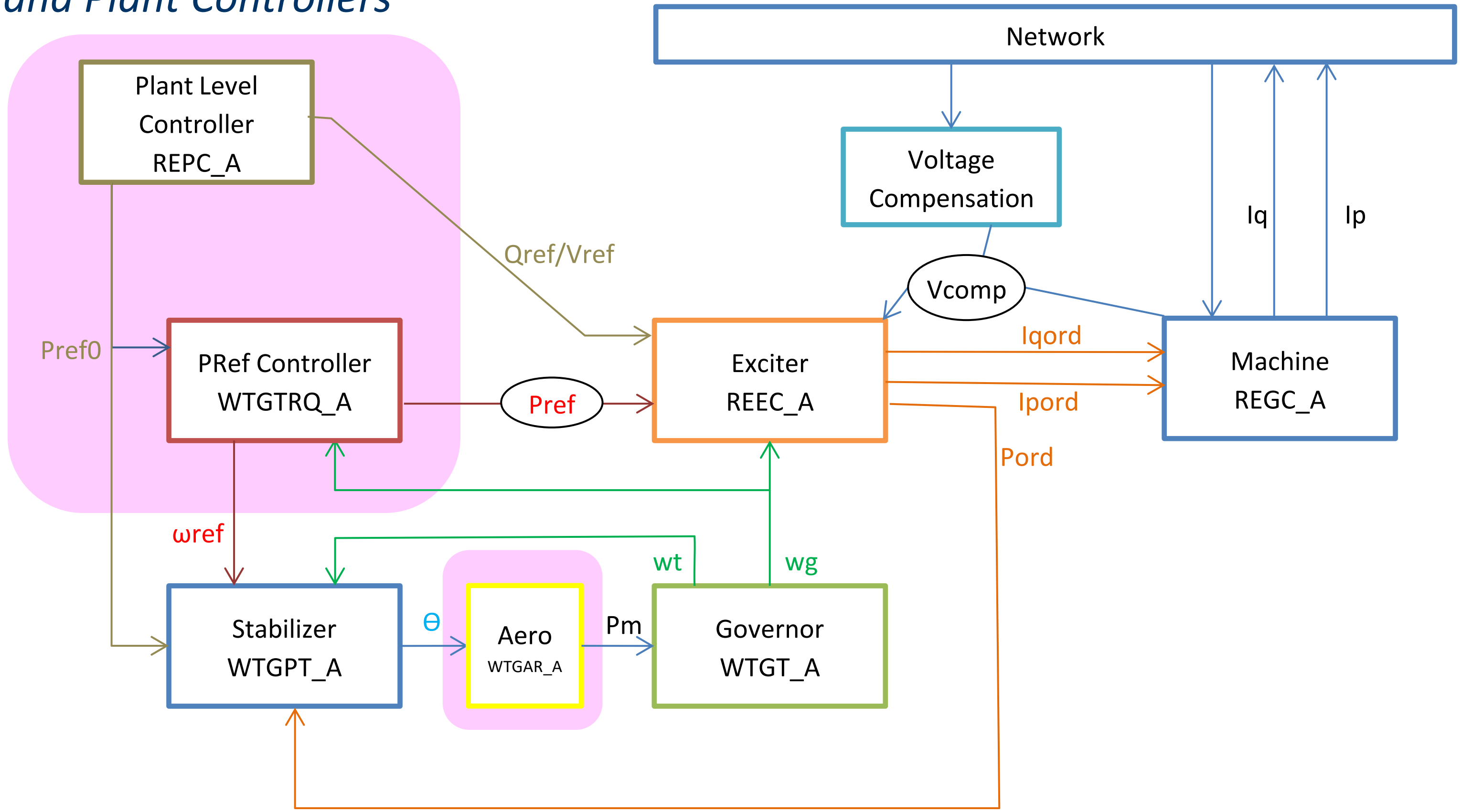
Second Generation Type 3 Models



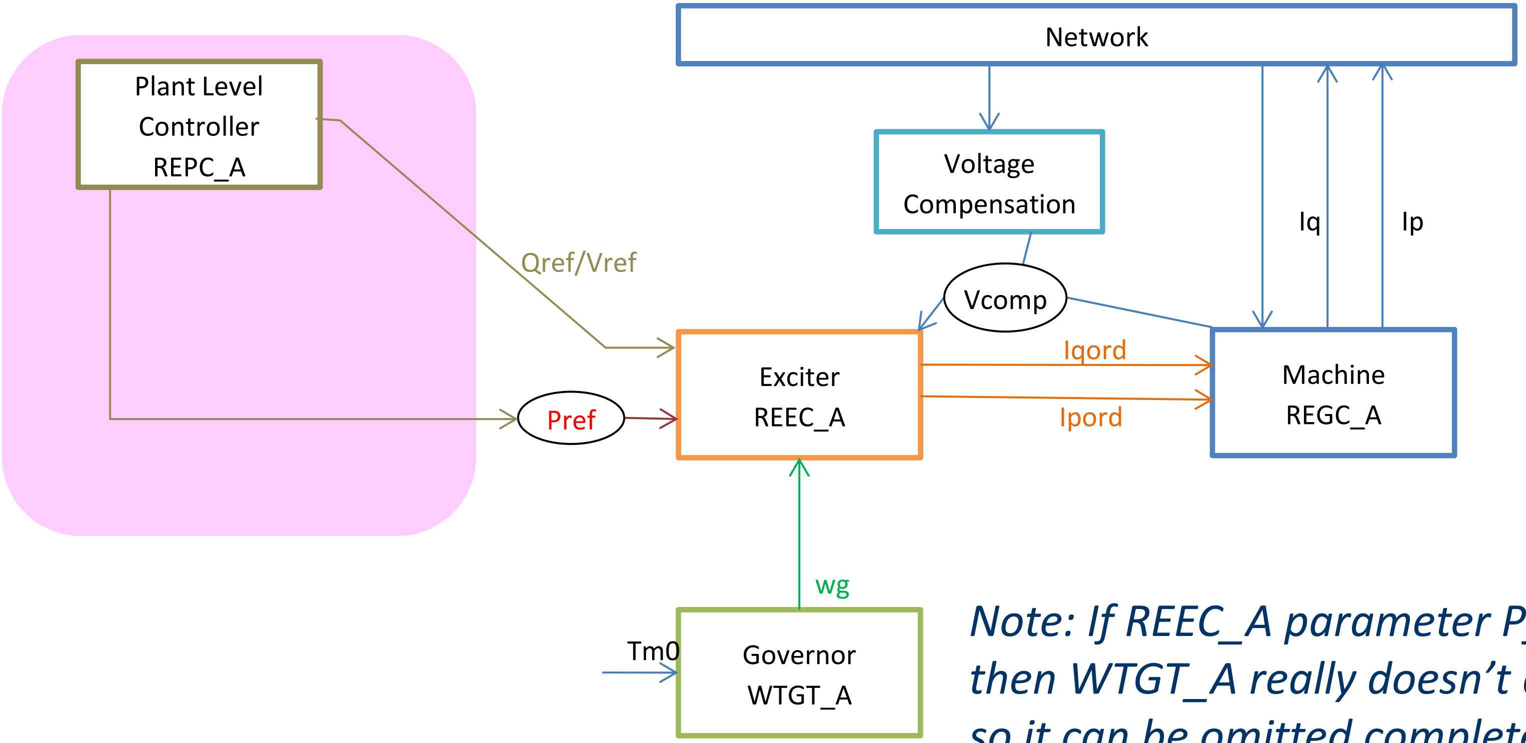
2^{nd} Generation Type 3 Wind Turbine

(REGC_A, REEC_A, WTGT_A, WTGAR_A, WTGPT_A, WTGTRQ_A, REPC_A)

2^{nd} Generation adds the Aero, PRef and Plant Controllers



2nd Generation Type 4 Wind Turbine
(REGC_A, REEC_A, WTGT_A, REPC_A)

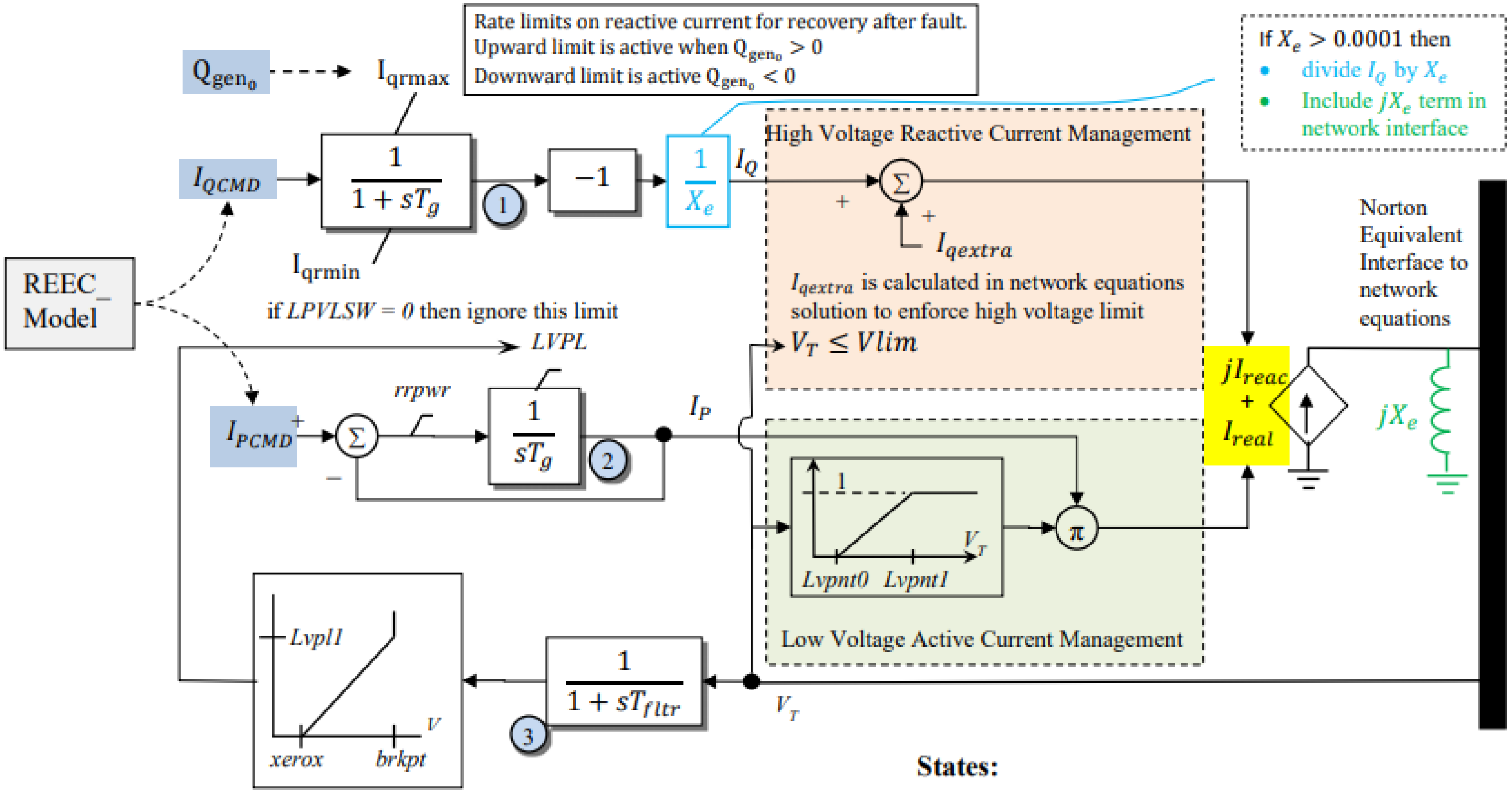


Note: If REEC_A parameter Pflag = 0, then WTGT_A really doesn't do anything so it can be omitted completely

Second Generation "Machine" Model, REGC_A (or REGCA1)

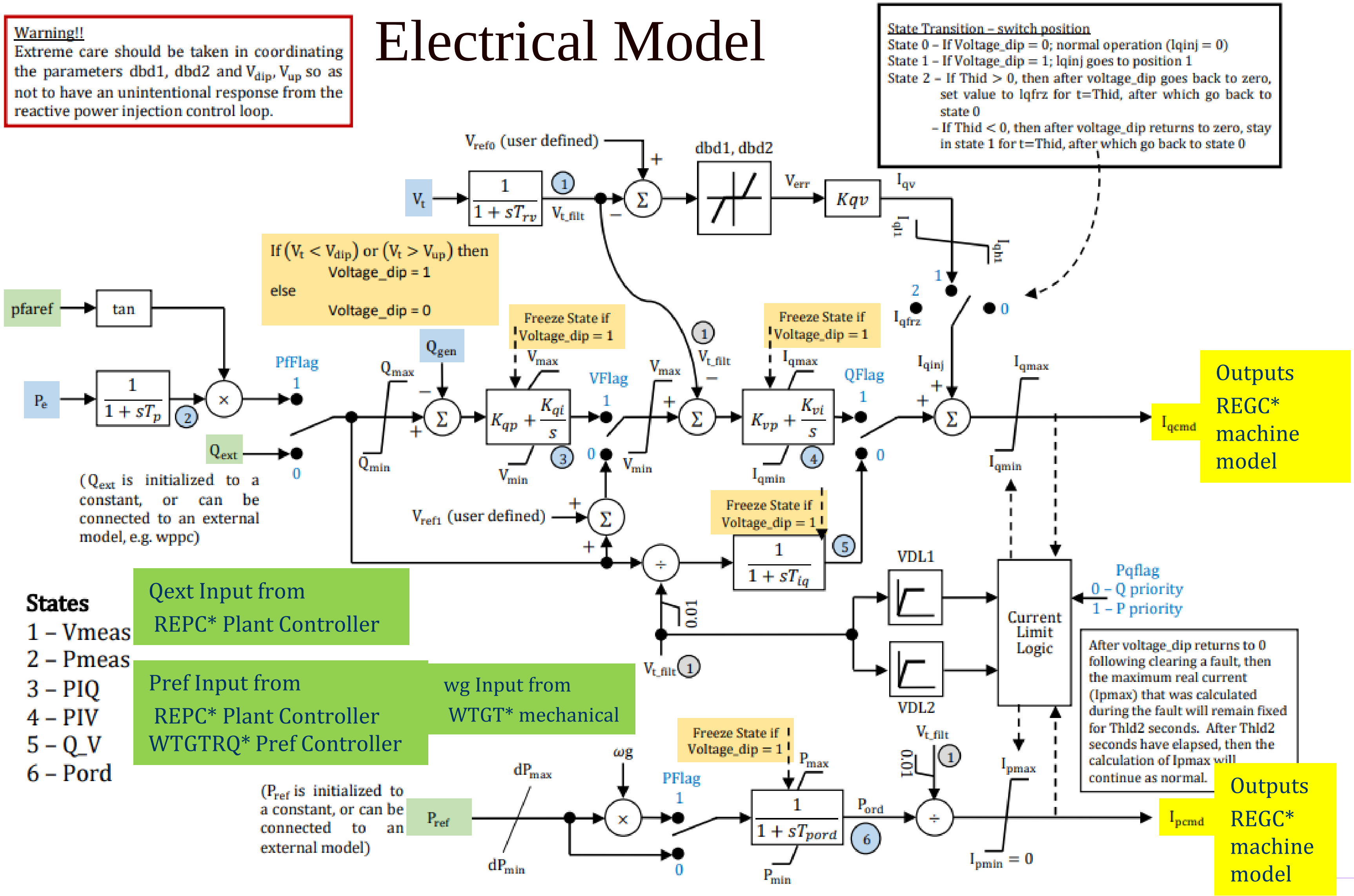
- "Machine Model": really a network interface

Inputs from
REEC* electrical
models



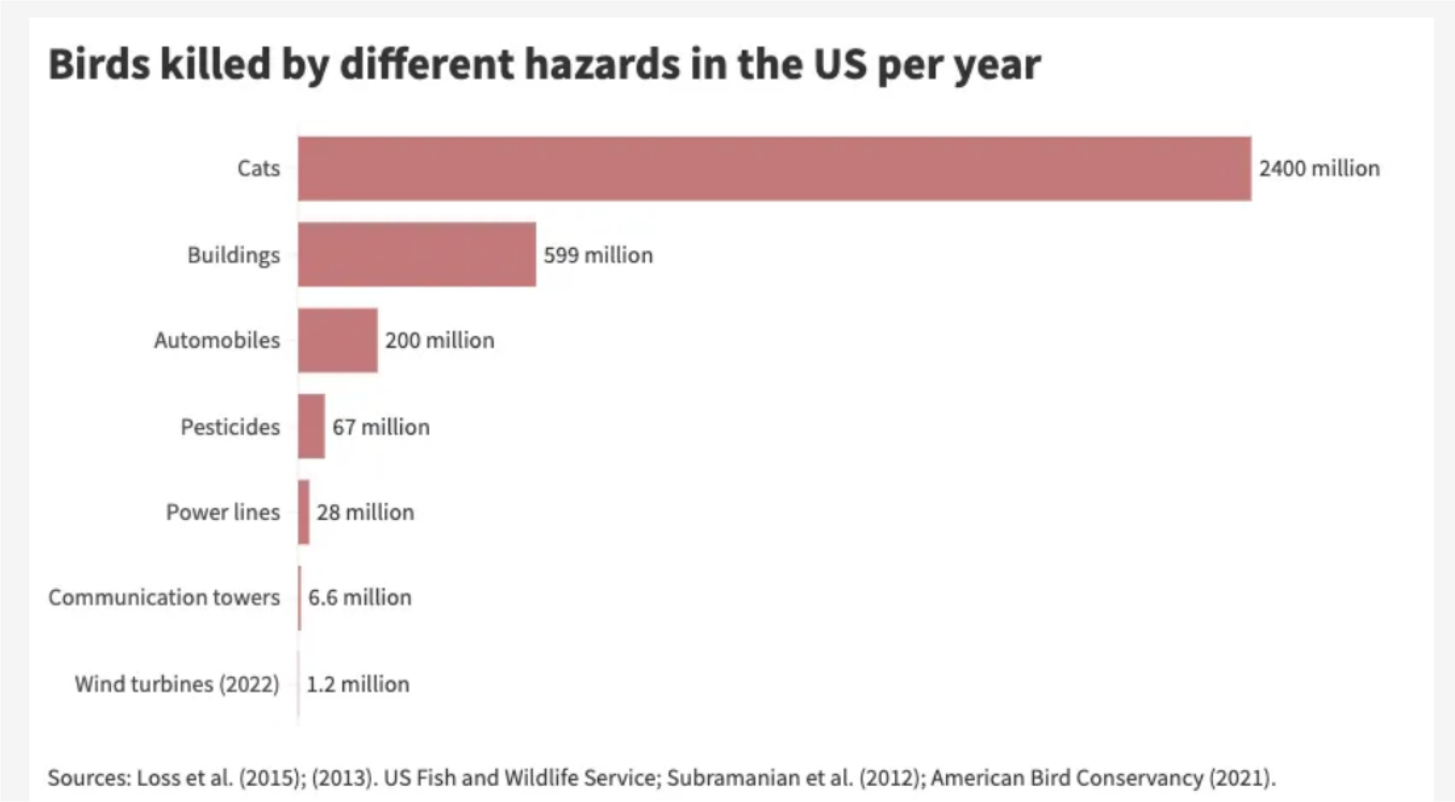
States:
1 – I_q
2 – I_p
3 – Vmeas

REEC_A (same as REECA1)

- 

Additional Wind Farm Issues

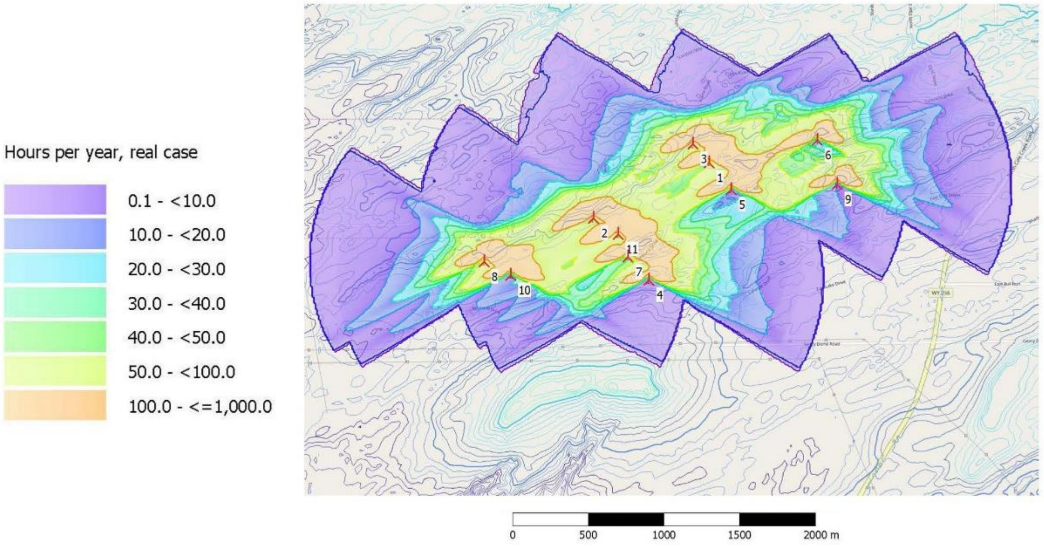
- Wind turbines certainly kill birds and bats, but so do lots of other things; however, wind turbines can kill the longer-lived, larger birds such as raptors that can be especially sensitive to adult mortabilites



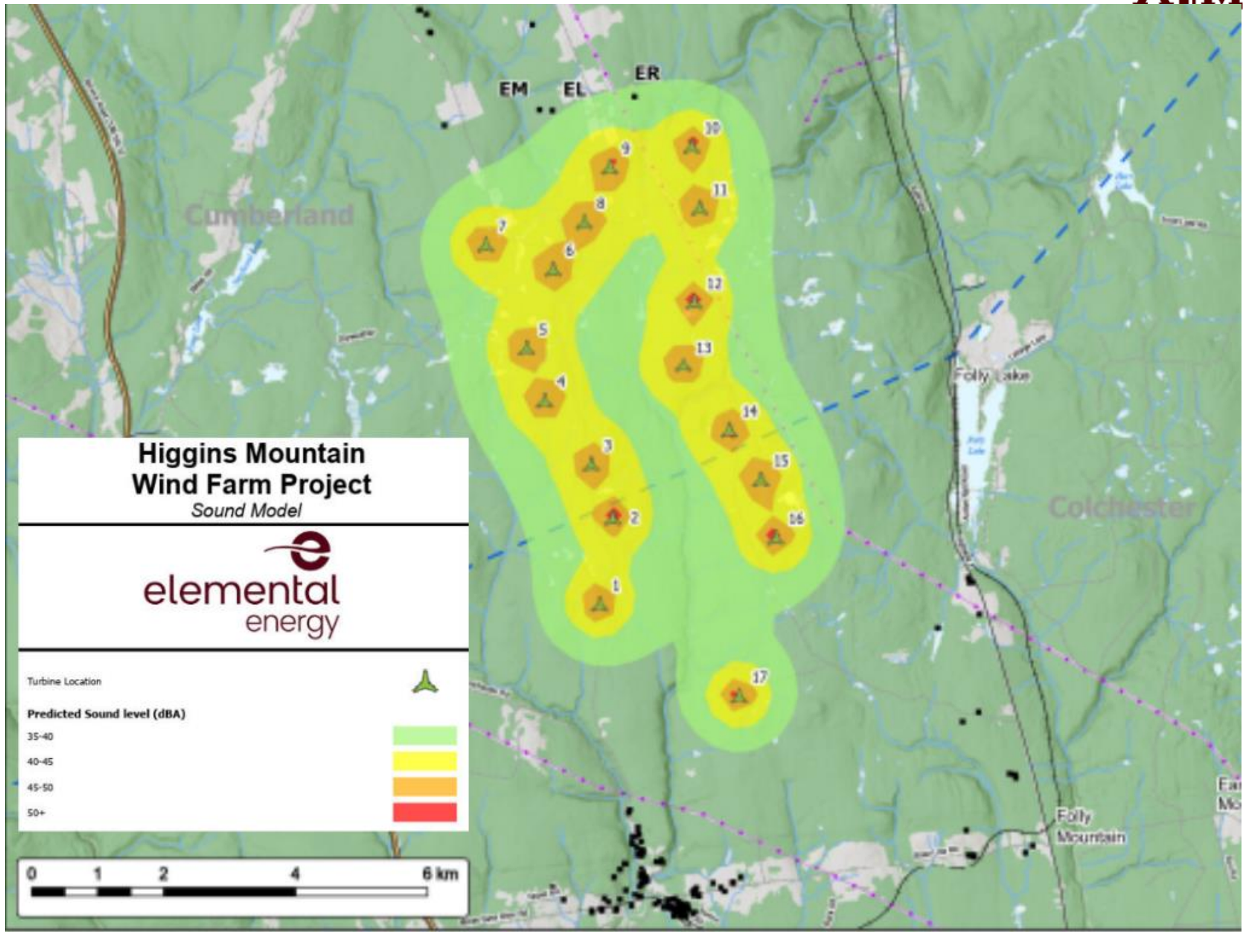
Additional Wind Farm Issues, cont.

- Wind turbines can 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
- Night lighting and aesthetics in general can be concerns

Example Noise and Shadow Flicker Maps



(B)



With noise, 40-50 dB is refrigerator or quiet office; however, low frequencies can be a concern for some people

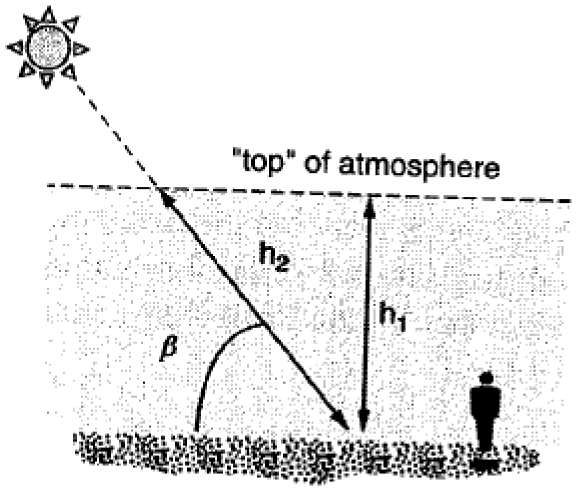
Left source: www.sciencedirect.com/science/article/pii/S2214629621005582; right source: https://netzeroatlantic.ca/hub/wind/onshore

Solar Photovoltaic (PV)

- **Photovoltaic definition-** a material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current
- Solar cells are diodes, creating dc power, which in grid applications is converted to ac by an inverter
- For terrestrial applications, the capacity factor is limited by night, relative movement of the sun, the atmosphere, clouds, shading, etc.
  - A ballpark figure for Texas is about 25%; US high of about 29%, some states go below 17%
  - "One sun" is defined a 1 kw/m^2,which is the maximum insolation the reaches the surface of the earth (sun right overhead)

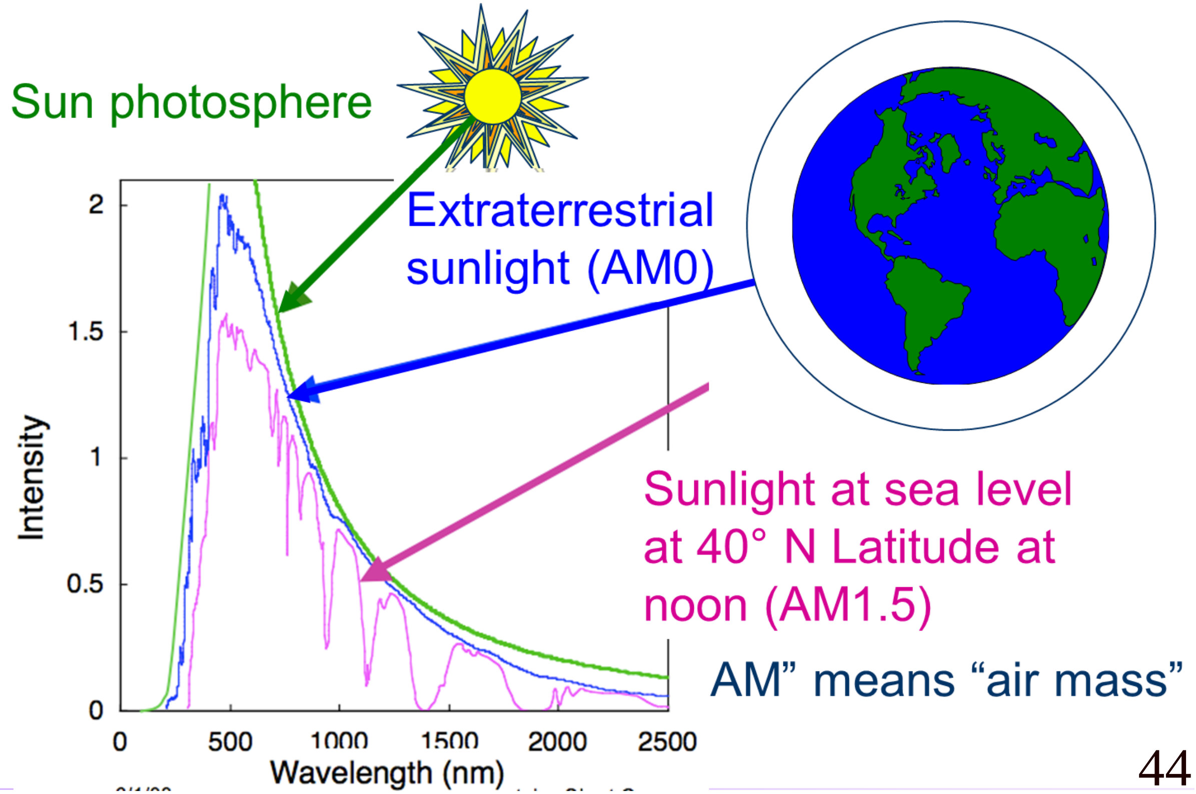
The Sun as a Resource

- In space the amount of solar radiation (i.e., sunlight) just depends on the distance from the sun, with a 100% capacity factor
- On earth the amount of solar radiation (i.e., sunlight) available at a location depends on many things, and varies significantly because of atmospheric attenuation



air mass ratio,

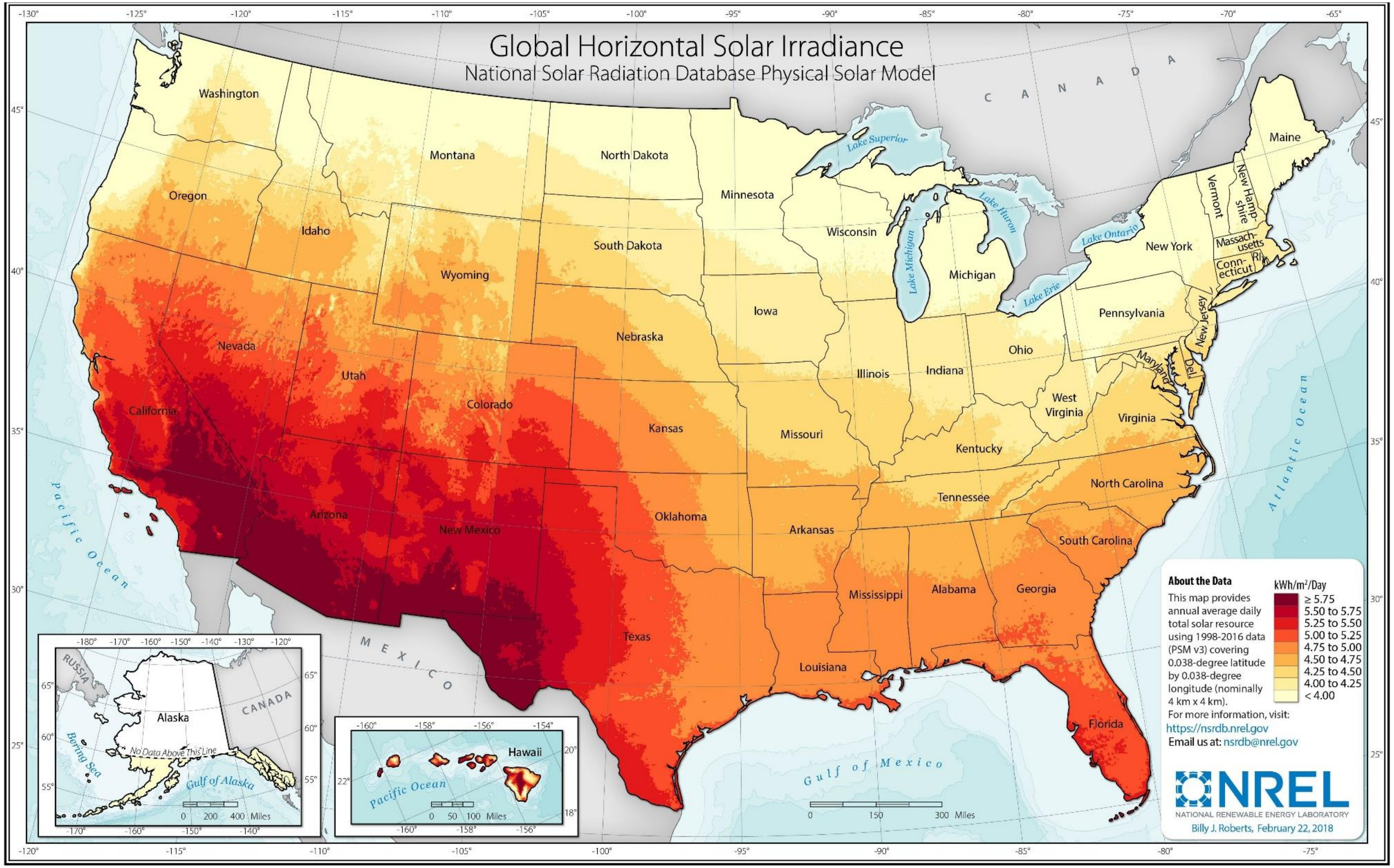
$$m = \frac{h_2}{h_1} = \frac{1}{\sin \beta}$$



Solar Radiation versus Irradiance

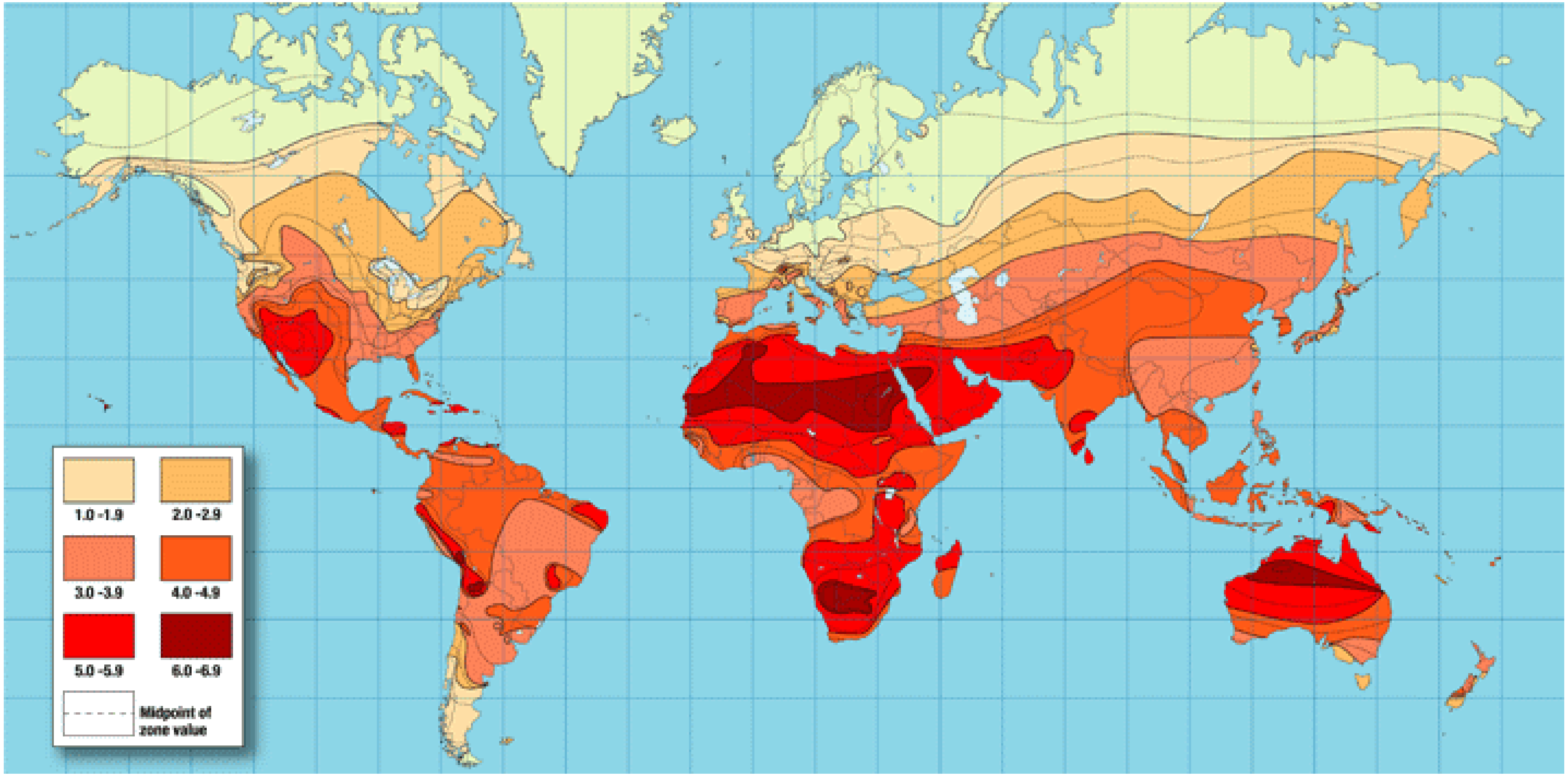
- Various terms are used to describe the energy emitted by the sun
- Solar radiation refers to the total energy emitted by the sun (visible, infrared, ultraviolet), and is mostly used in scientific fields
- Solar irradiance refers to the amount of energy received (e.g., watts per square meter), and is used more in engineering
  - The terms solar insolation or just insolation are also used
- With solar PV there are several standard values
  - Direct normal irradiance (DNI) is the amount of power received on a surface perpendicular to the sun
  - Diffuse horizontal irradiance (DHI) is the amount of power received from light scattering
  - Global horizontal irradiance (GHI) is the total amount on a horizontal surface

US Global Horizontal Irradiance (GHI)



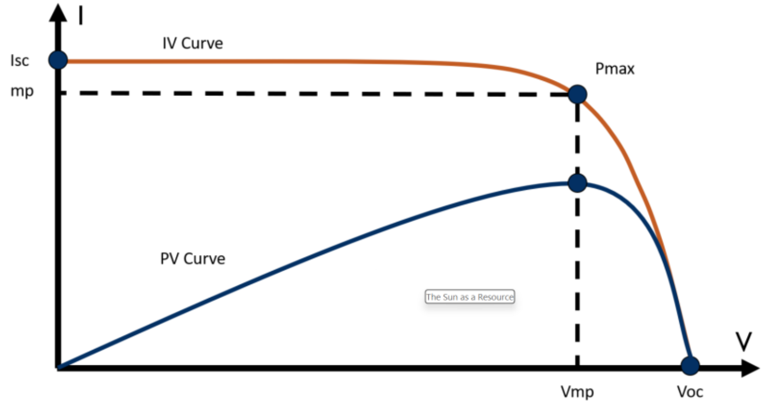
The capacity factor is usually about 1.25 times this number divided by 24 hours per day

Worldwide Annual Insolation



Solar Photovoltaics (PV)

- Photovoltaics is the conversion of light into electricity using semiconductors known as solar cells
  - It dates back to 1883, but really got going in the late 1950’s, driven by NASA
  - Solar cells produce a dc output, with the right image showing an example IV curve



- Solar modules are groups of solar cells; a PV panel is one or more modules wired together ready to mount
- A PV system often includes an inverter to produce ac electricity
- PV panels can either have a fixed mount, or be on a tracker; trackers can be one-axis or two-axis