ECEN 460, Spring 2026
Power System Operation and Control

Class 4: Generators and Machines, Part 2

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Generators

- Sources of energy in the power system
  - Nuclear
  - Coal-fired steam
  - Gas
    - Gas turbine
    - Steam turbine
    - Combined Cycle
  - Hydro
  - Oil / Petroleum
  - Wind
  - Solar
  - Other

Synchronous Machines (Tuesday)

Power Electronics / Other (Today)

Renewable Energy Sources

- Renewable energy sources are ones where the energy source is constantly replenished
  - They help to make the system more sustainable over the long term
  - They are often more environmentally friendly as well
- Examples of sustainable energy sources
  - Hydroelectric
  - Wind
  - Solar (photovoltaic and solar thermal)
  - Geothermal
  - Biomass
  - Tidal and wave
- There has been significant growth in renewable electric energy in the last few decades, particularly with wind and solar

Hydroelectric Power

- Hydroelectric power is one of the oldest significant source of renewable electric power in the US

- A typical design uses a large, salient pole synchronous machine (modeled like most generators we have been studying)

- Availability for growth is limited in the US

- In some cases, dams can operate in reverse (pumped storage), acting as a source of energy storage

- Challenges include scheduling the hydro and coordinating with reservoir levels and wildlife/ecological constraints

Thermal and Ocean Power Sources

- Concentrated solar thermal power involves many mirrors concentrating sun's energy to heat chemicals to power a turbine.

Geothermal Power Plant
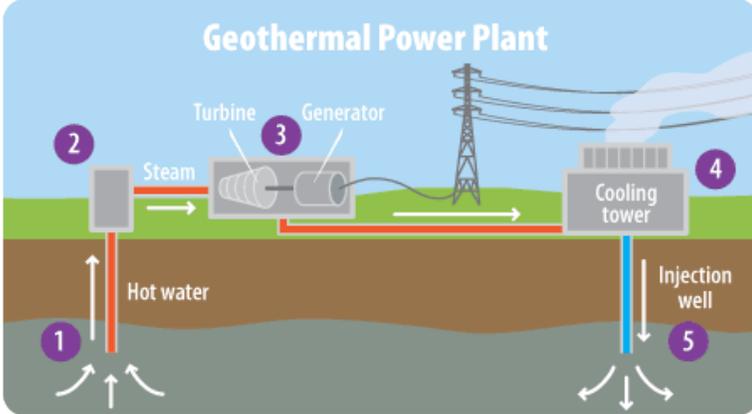
Geothermal powers a turbine with water heated below the earth's surface

Ocean power takes energy from natural processes of tides, waves, and ocean currents
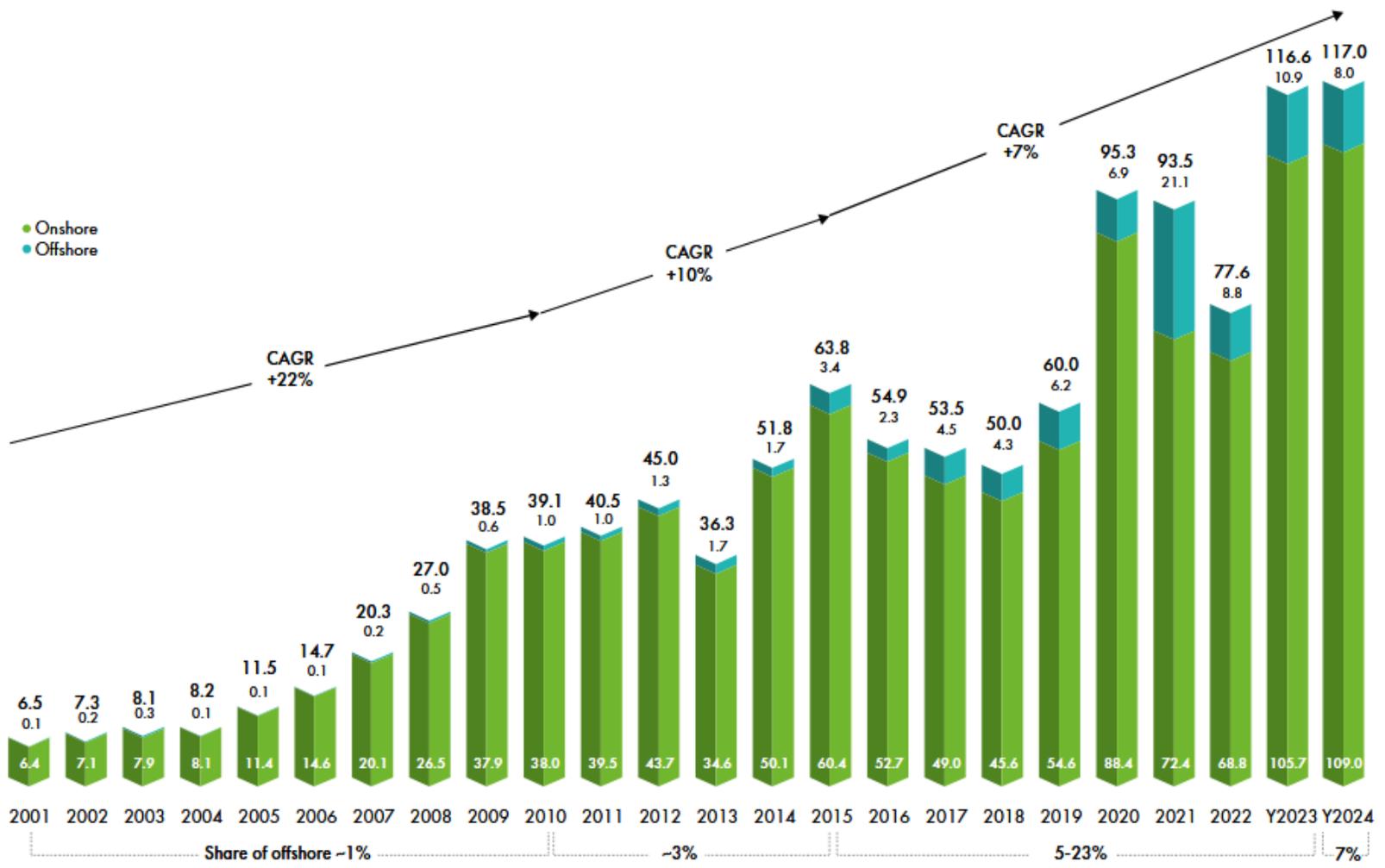
Wind and Solar

- Wind and solar are the focus of the next few slides

- These are the highest-growth renewable energy sources

- Goal is to develop models for integrated system studies

- Wind and solar plant modeling is different from synchronous machine modeling (fossil, nuclear, hydro)
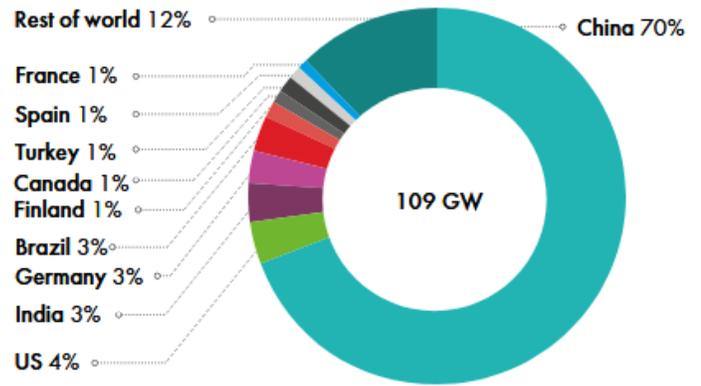
Growth in Wind Worldwide

Source: Global Wind 2025 Report,
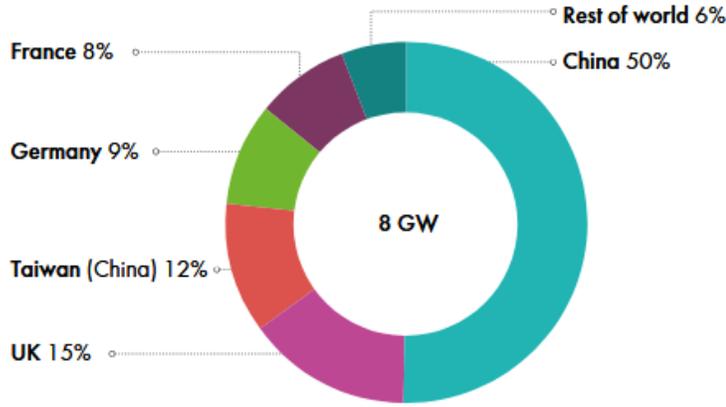Global Wind Energy Council
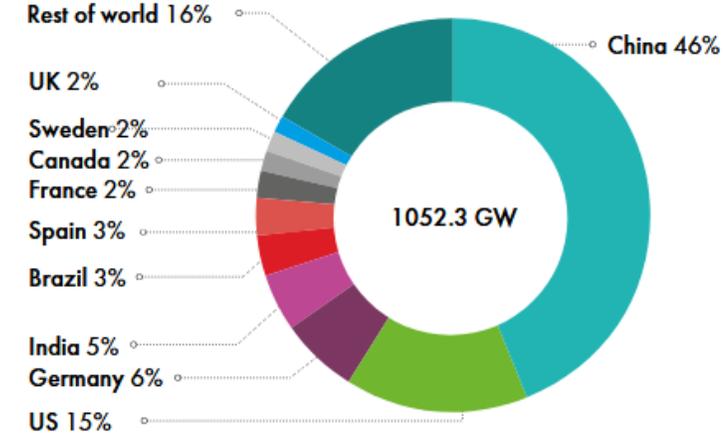
Growth in Wind Worldwide, 2

New installations onshore (%)

- China 70%
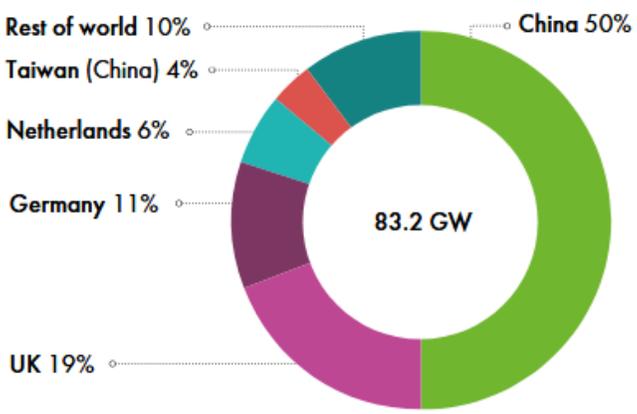- Rest of world 12%
- France 1%
- Spain 1%
- Turkey 1%
- Canada 1%
- Finland 1%
- Brazil 3%
- Germany 3%
- India 3%
- US 4%

109 GW

New installations offshore (%)

- Rest of world 6%
- China 50%
- France 8%
- Germany 9%
- Taiwan (China) 12%
- UK 15%

8 GW

Total installations onshore (%)

- China 46%
- Rest of world 16%
- UK 2%
- Sweden 2%
- Canada 2%
- France 2%
- Spain 3%
- Brazil 3%
- India 5%
- Germany 6%
- US 15%

1052.3 GW

Total installations offshore (%)

- China 50%
- Rest of world 10%
- Taiwan (China) 4%
- Netherlands 6%
- Germany 11%
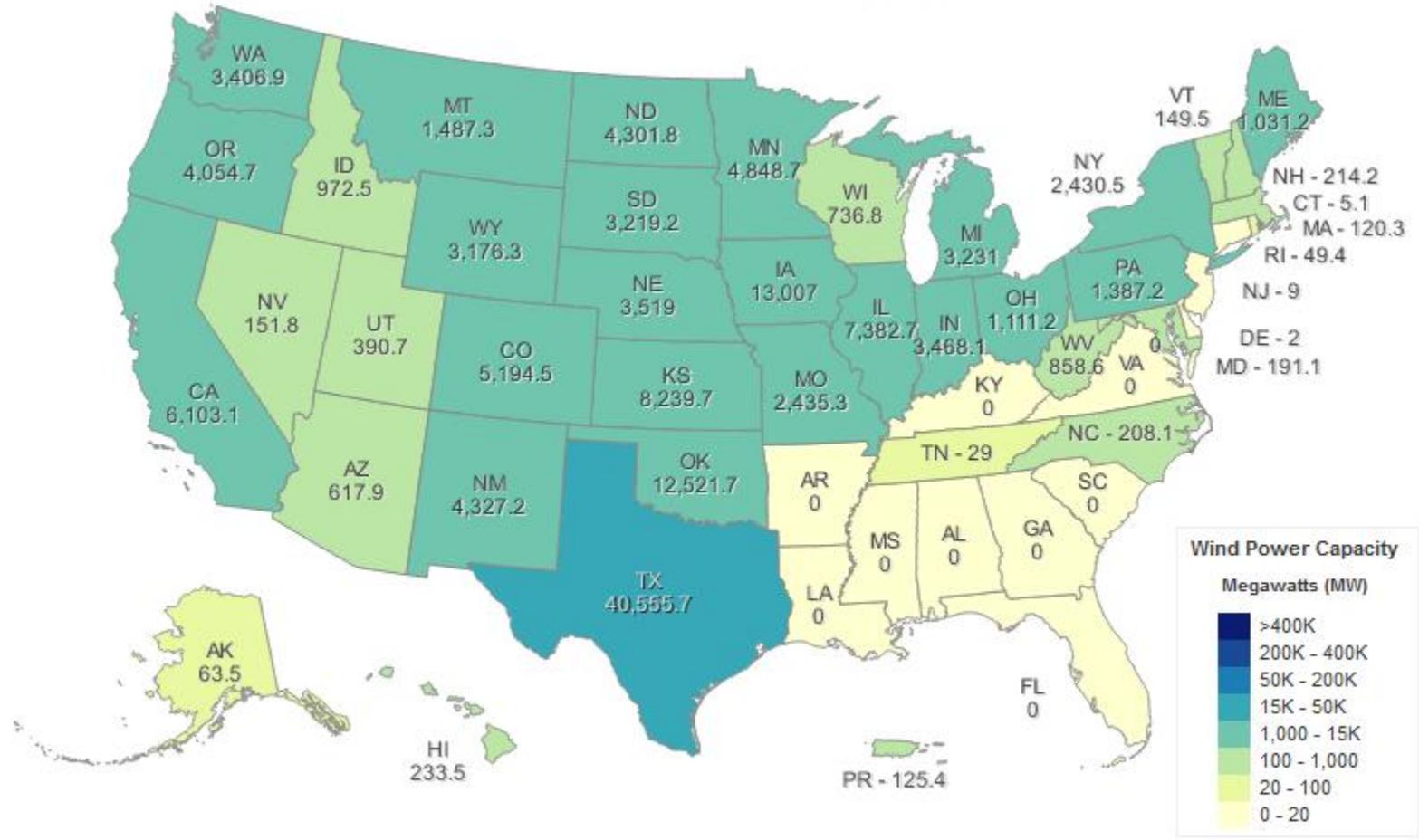- UK 19%

83.2 GW

Source: Global Wind 2025 Report, Global Wind Energy Council

2023 Installed Capacity by State: Texas Continues to Dominate!

Q1 2023 Installed Capacity by State
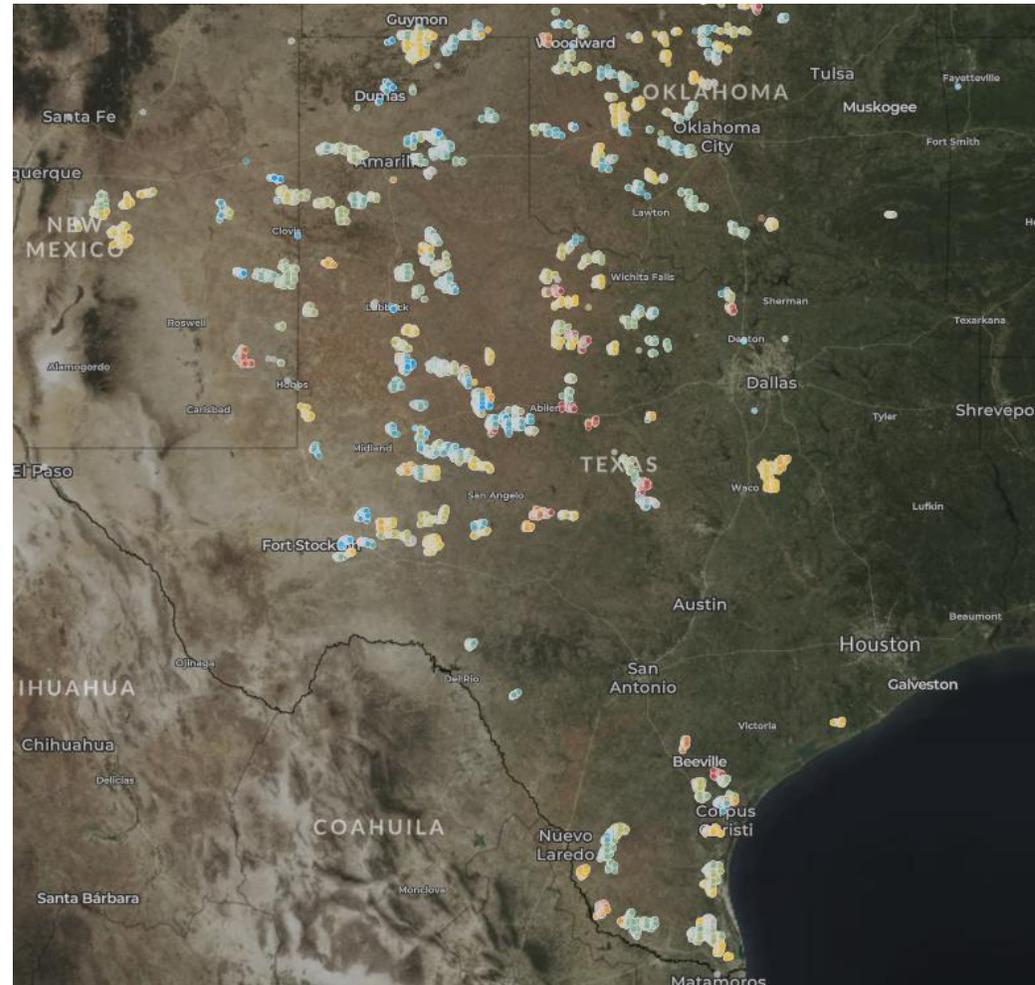
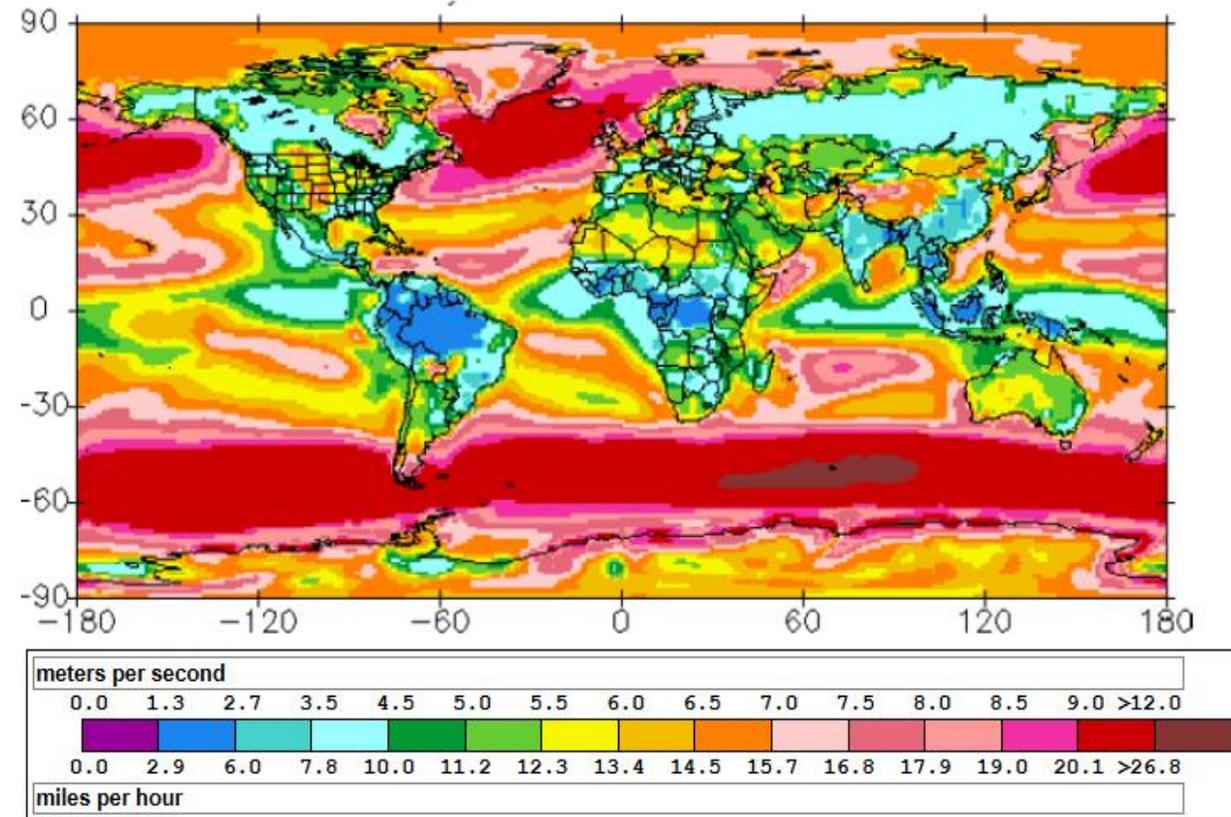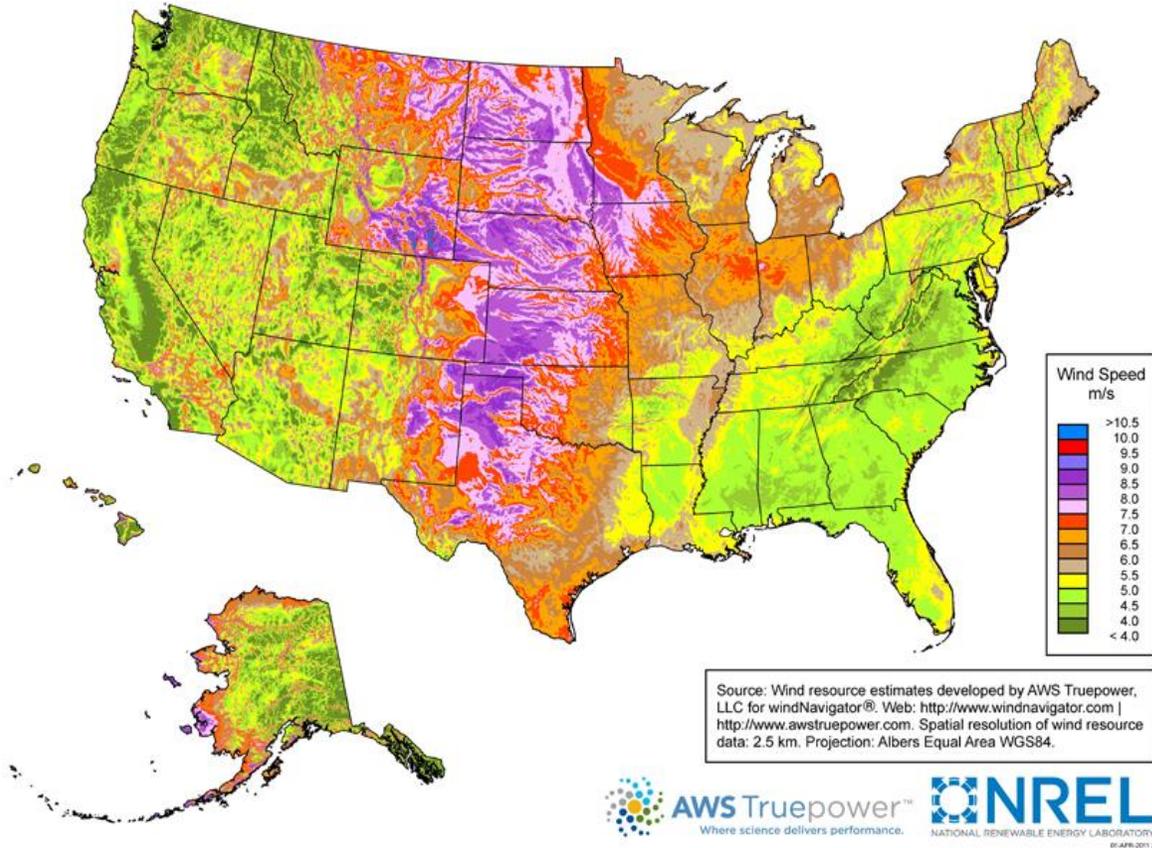| State	Capacity (MW)
WA	3,406.9
OR	4,054.7
MT	1,487.3
ND	4,301.8
MN	4,848.7
ID	972.5
SD	3,219.2
WI	736.8
MI	3,231
NY	2,430.5
VT	149.5
ME	1,031.2
NH	214.2
CT	5.1
MA	120.3
RI	49.4
WY	3,176.3
NE	3,519
IA	13,007
IL	7,382.7
IN	3,468.1
OH	1,111.2
PA	1,387.2
NJ	9
DE	2
MD	191.1
NV	151.8
UT	390.7
CO	5,194.5
KS	8,239.7
MO	2,435.3
WV	858.6
VA	0
KY	0
CA	6,103.1
AZ	617.9
NM	4,327.2
OK	12,521.7
AR	0
TN	29
NC	208.1
SC	0
TX	40,555.7
LA	0
MS	0
AL	0
GA	0
FL	0
AK	63.5
HI	233.5
PR	125.4

Wind Power Capacity
Megawatts (MW)

- >400K
- 200K – 400K
- 50K – 200K
- 15K – 50K
- 1,000 – 15K
- 100 – 1,000
- 20 – 100
- 0 – 20

Total Installed Wind Capacity: 145,569 MW

https://windexchange.energy.gov/maps-data/321

Wind Farm and Wind-related Plant Locations

https://eerscmap.usgs.gov/uswtdb/viewer/#5.34/31.787/-99.912

Wind Resources in the US and Globally

Source: http://www.windpoweringamerica.gov/wind_maps.asp

http://www.climate-charts.com/World-Climate-Maps.html#wind-speed

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)
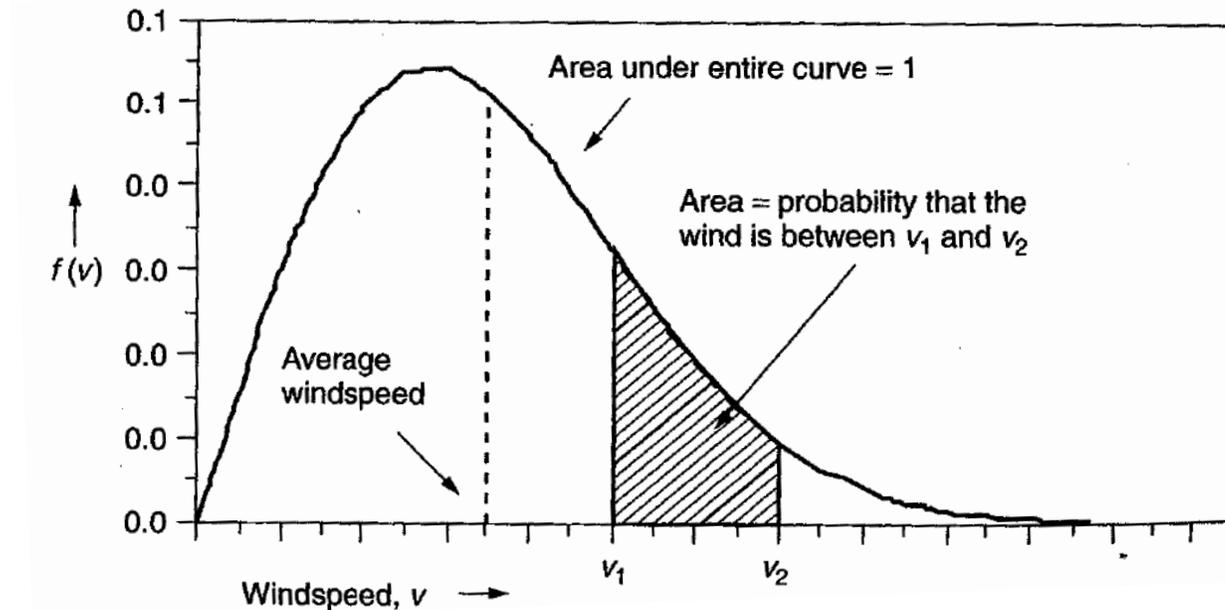
Wind Turbine Height and Size
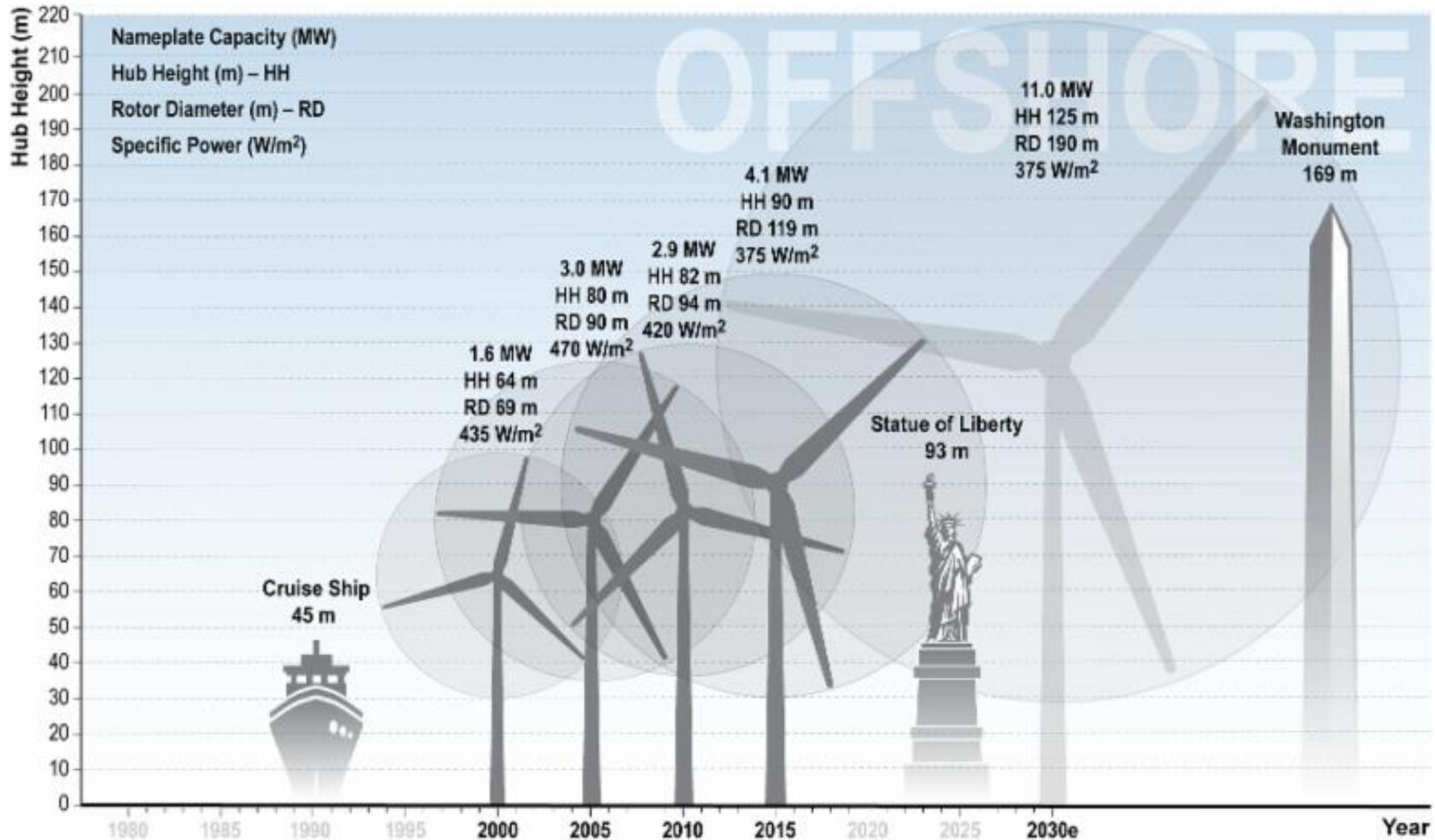
The largest wind turbine by capacity is the Vestas V164 which has a capacity of 8 MW, a height of 220 m, and diameter of 164 m.

Source: cdn.arstechnica.net/wp-content/uploads/2016/11/6e9cb9fc-0c18-46db-9176-883cbb08eace.png
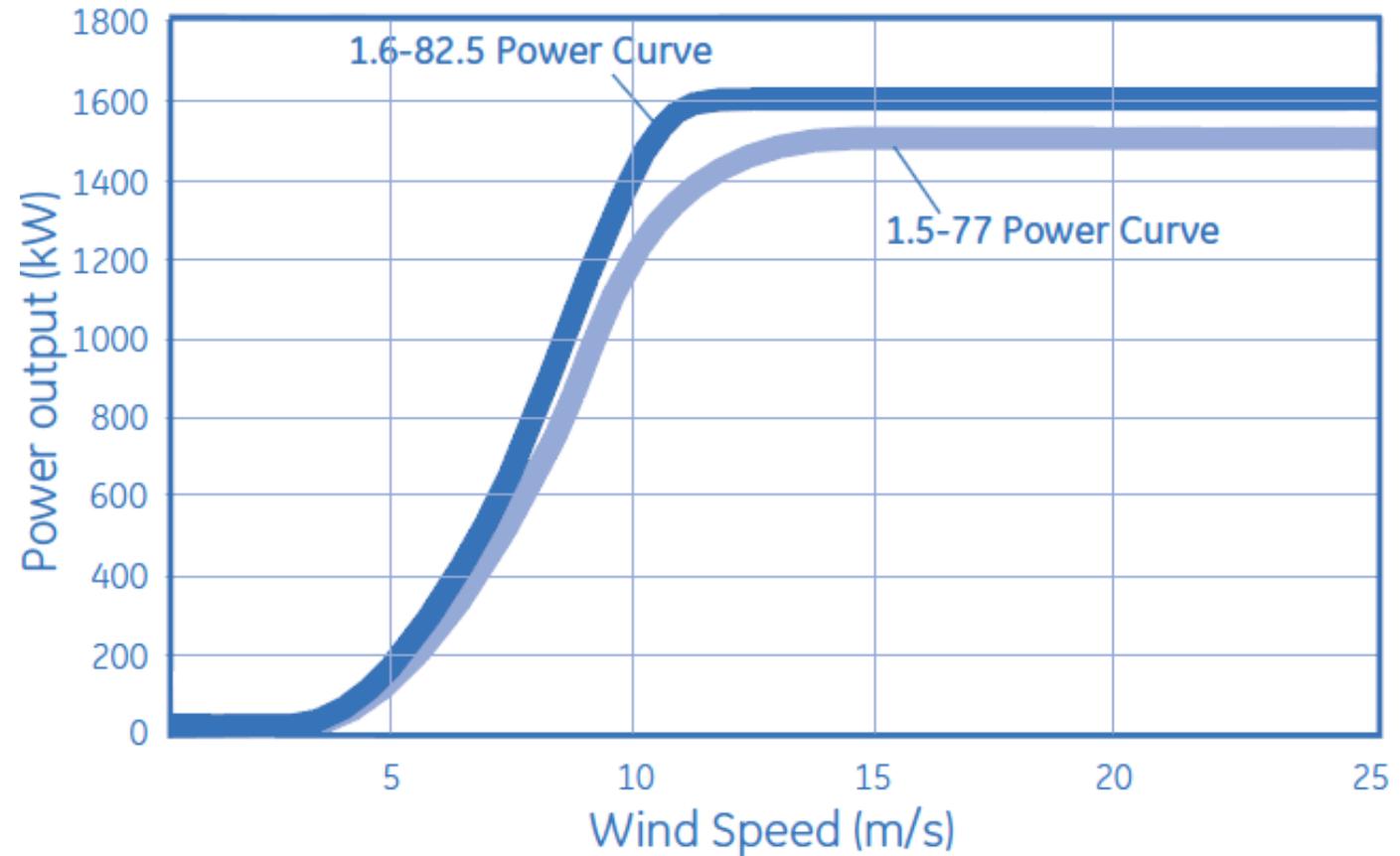
Extracted Power

- 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
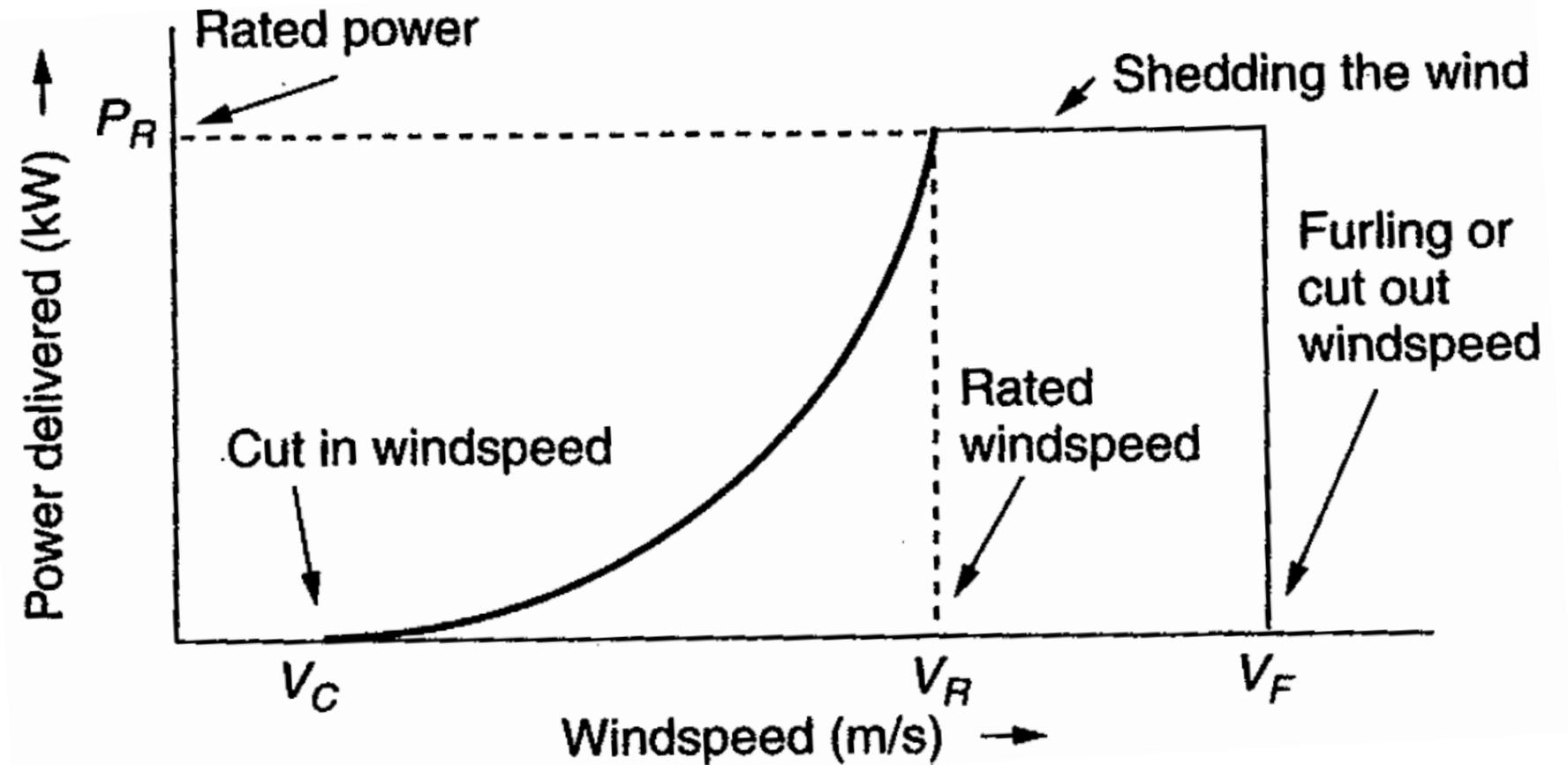
Example: GE 1.5 and 1.6 MW Turbines

- 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

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
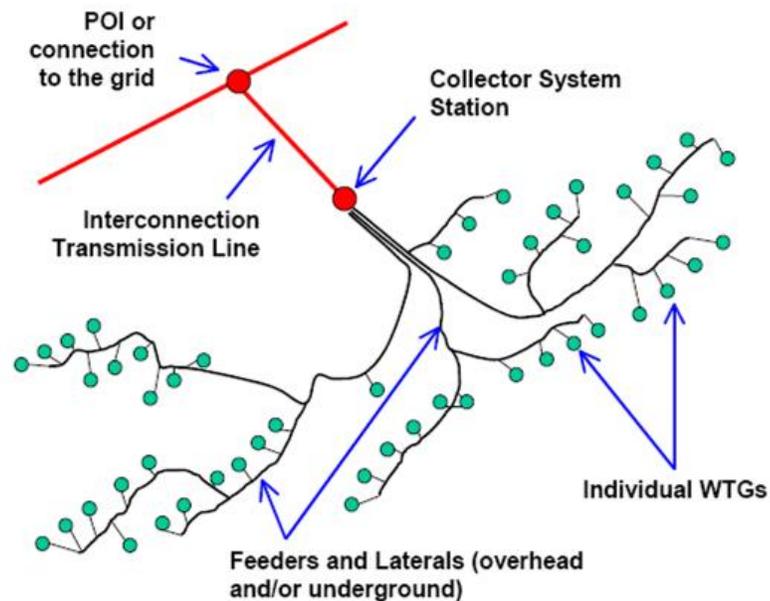
Economies of Scale

- 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 Energy Economics

- Most of the cost is in the initial purchase and construction (capital costs); current estimate is about $1690/kW; how much wind is generated depends on the capacity factor, best is about 40%
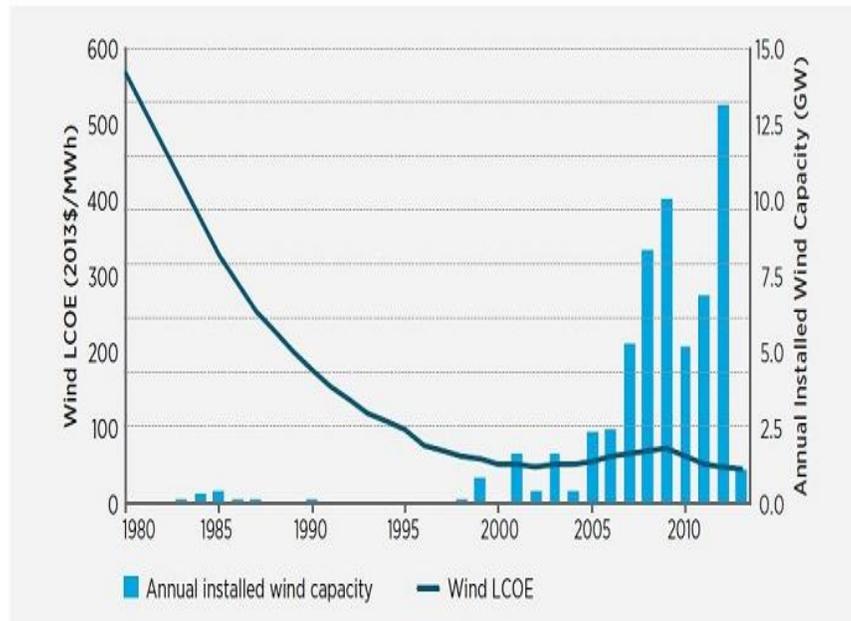
Note: In the *Wind Vision*, 'good to excellent sites' are those with average wind speeds of 7.5 meters per second (m/s) or higher at hub height. LCOE estimates exclude the PTC.

Source: Adapted from Lawrence Berkeley National Laboratory 2014 data [23]
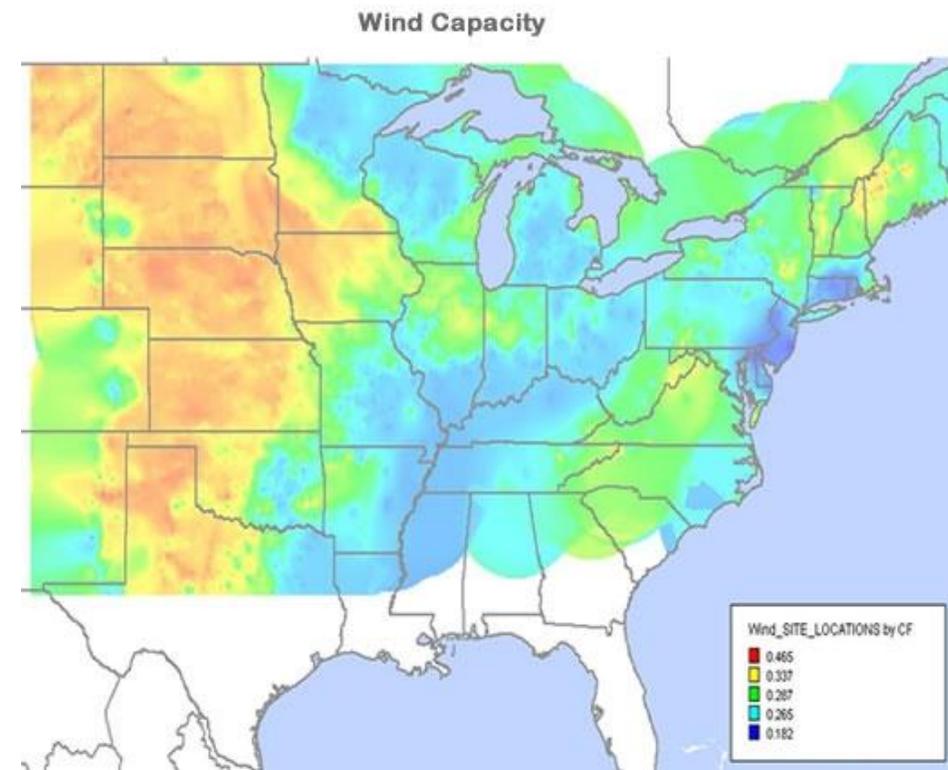
Source: www.awea.org/falling-wind-energy-costs

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 (aesthetic, noise, shadow)

Offshore Wind

- Offshore wind turbines currently need to be in relatively shallow water, so maximum distance from shore depends on the seabed

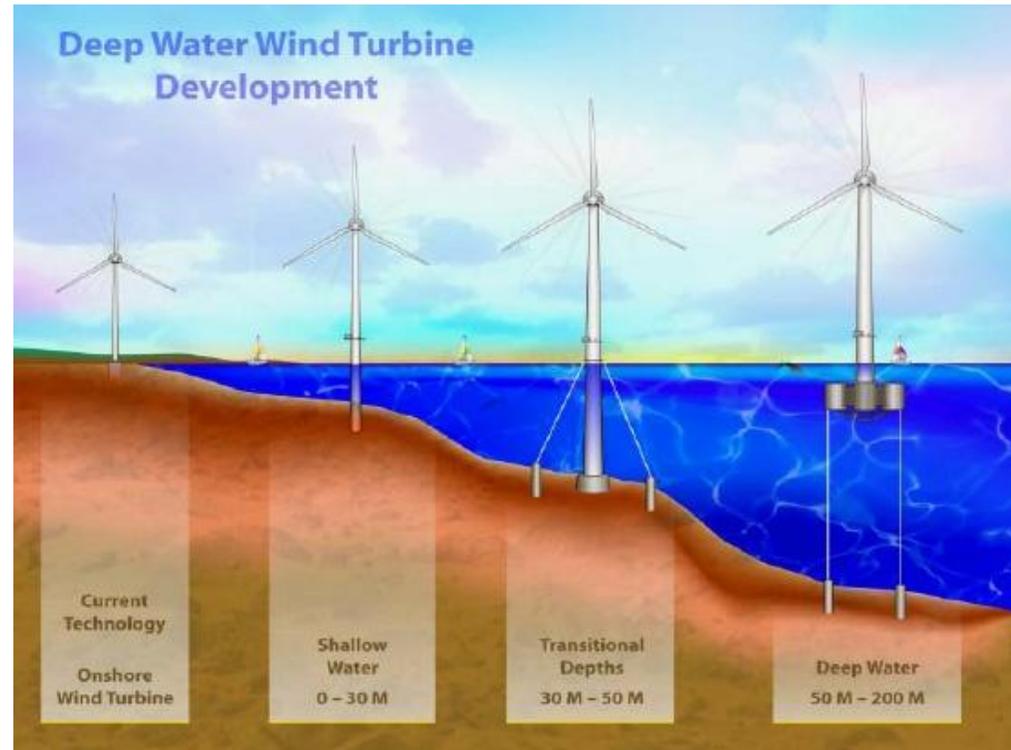- Capacity factors tend to increase as turbines move further off-shore

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)

Types of Wind Turbines

- Electrically there are four main generic types of wind turbines
  - Type 1: Induction machine
  - Type 2: Induction machine with varying rotor resistance to adjust slip
  - Type 3: Doubly Fed Asynchronous Generator (DFAG) (or DFIG)
  - Type 4: Full Asynchronous Generator
- New wind farms are primarily of Type 3 or 4

Types of Wind Turbines, 2

- Several different approaches to aggregate modeling of wind farms in power system analysis
  - Wind turbine manufacturers provide detailed, public models of their WTGs; these models are incorporated into software packages; example is GE 1.5, 1.6 and 3.6 MW WTGs (see Modeling of GE Wind Turbine-Generators for Grid Studies, version 4.6, March 2013, 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)
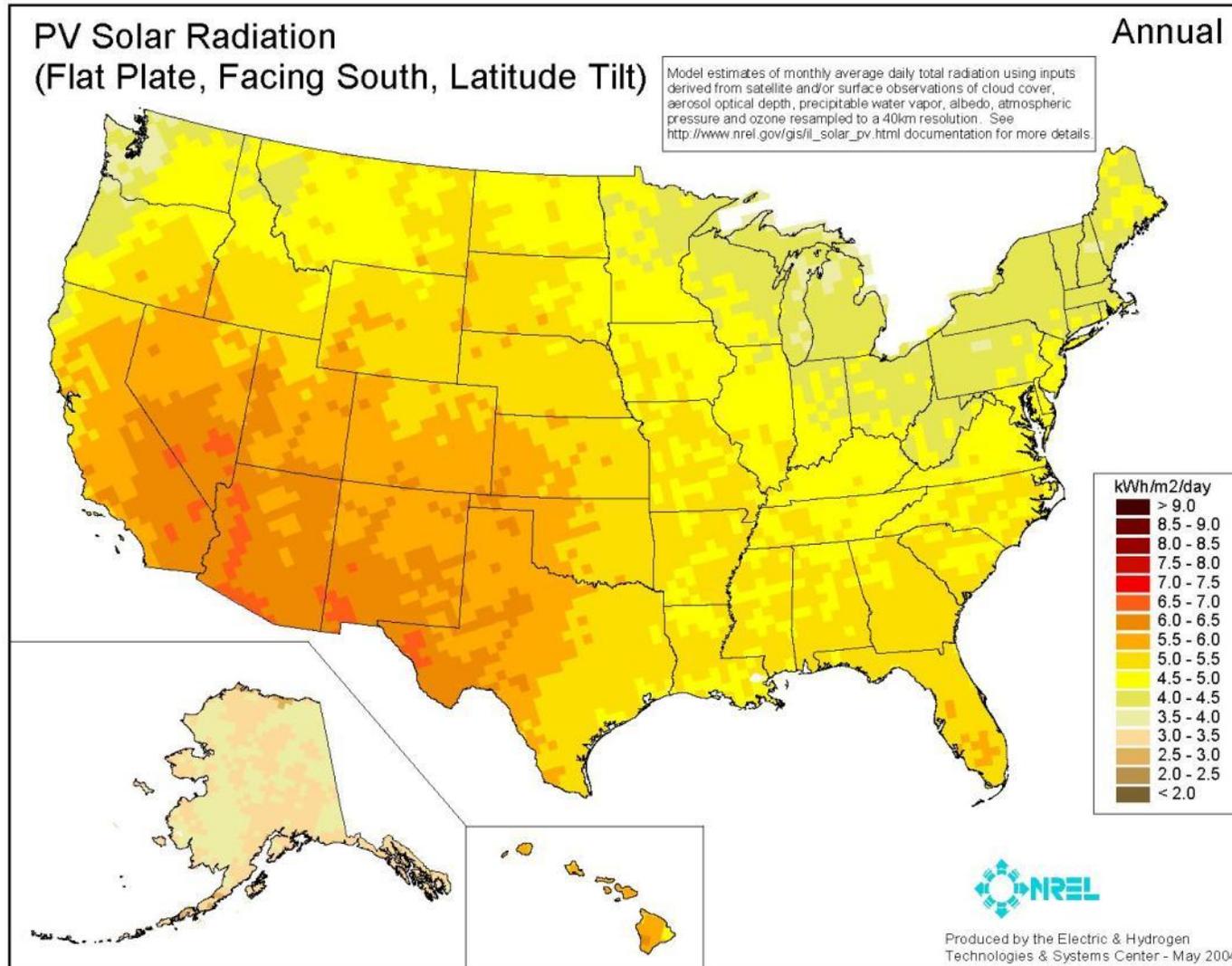
Solar Photovoltaic Energy

- Solar energy is rapidly growing, both in the US and worldwide

- Takes energy provided by the sun, with the amount available having substantial geographic and time variation

  - Maximum is about 1 kW per square meter

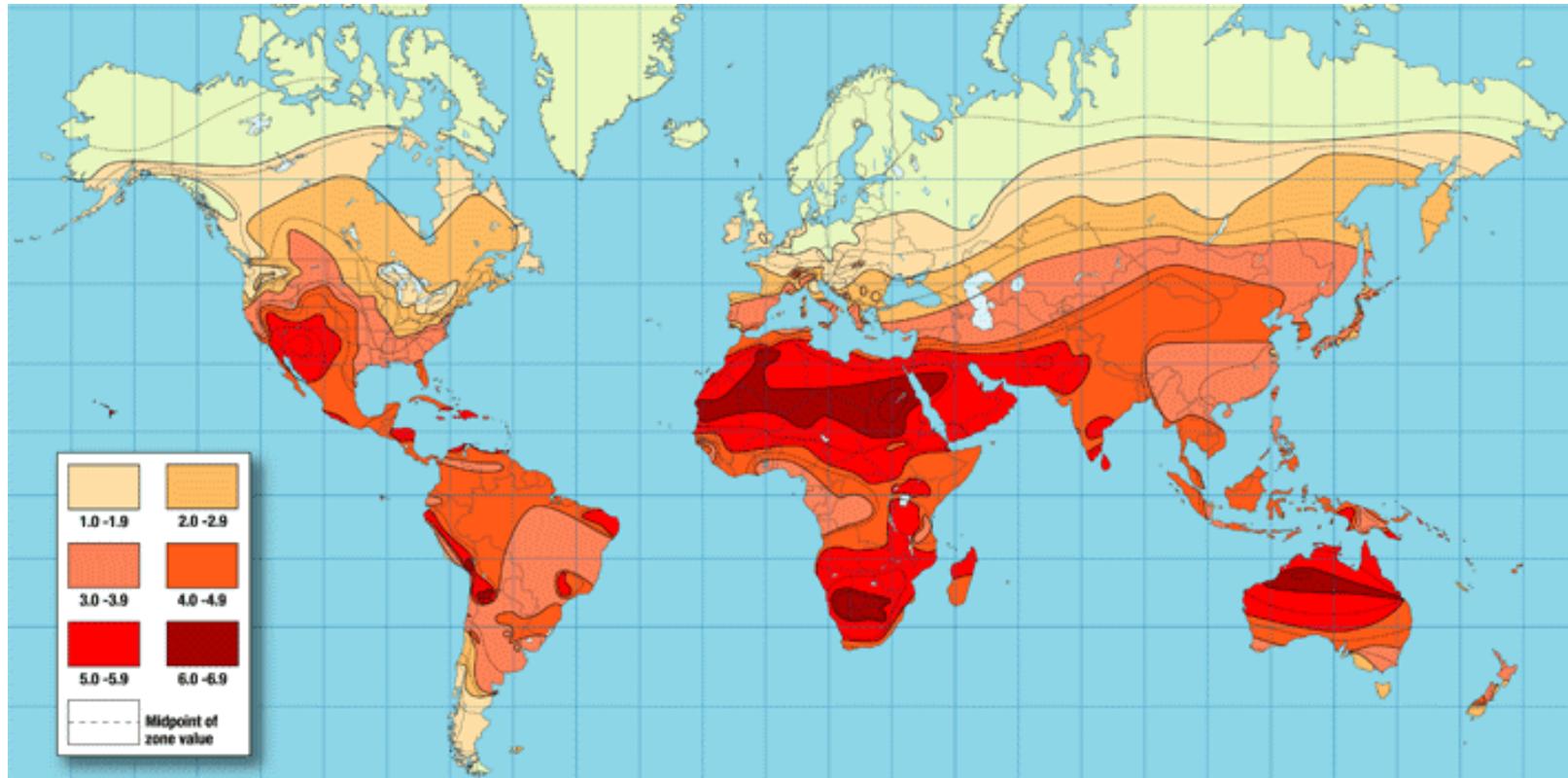- Total average energy available is often given in kWh/m2 per day averaged over a year
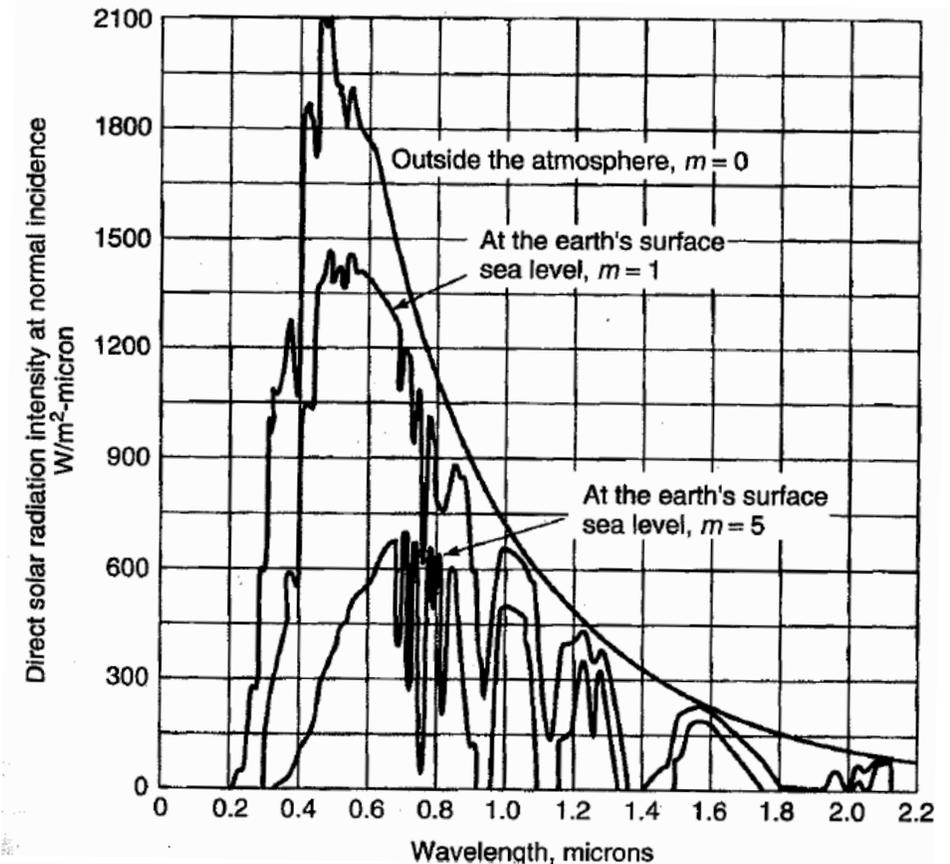
US Annual Insolation

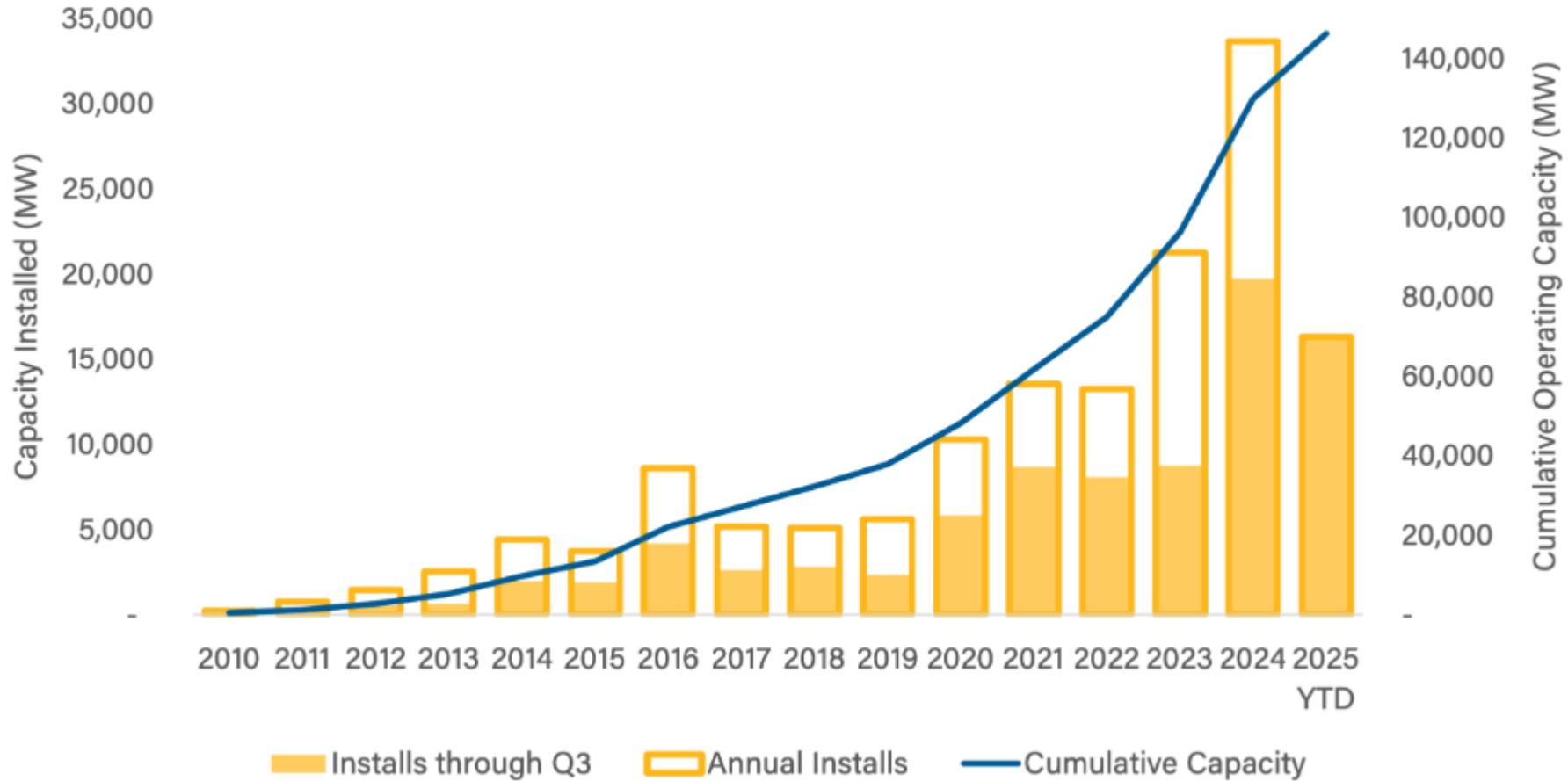The capacity factor is roughly this number divided by 24 hours per day
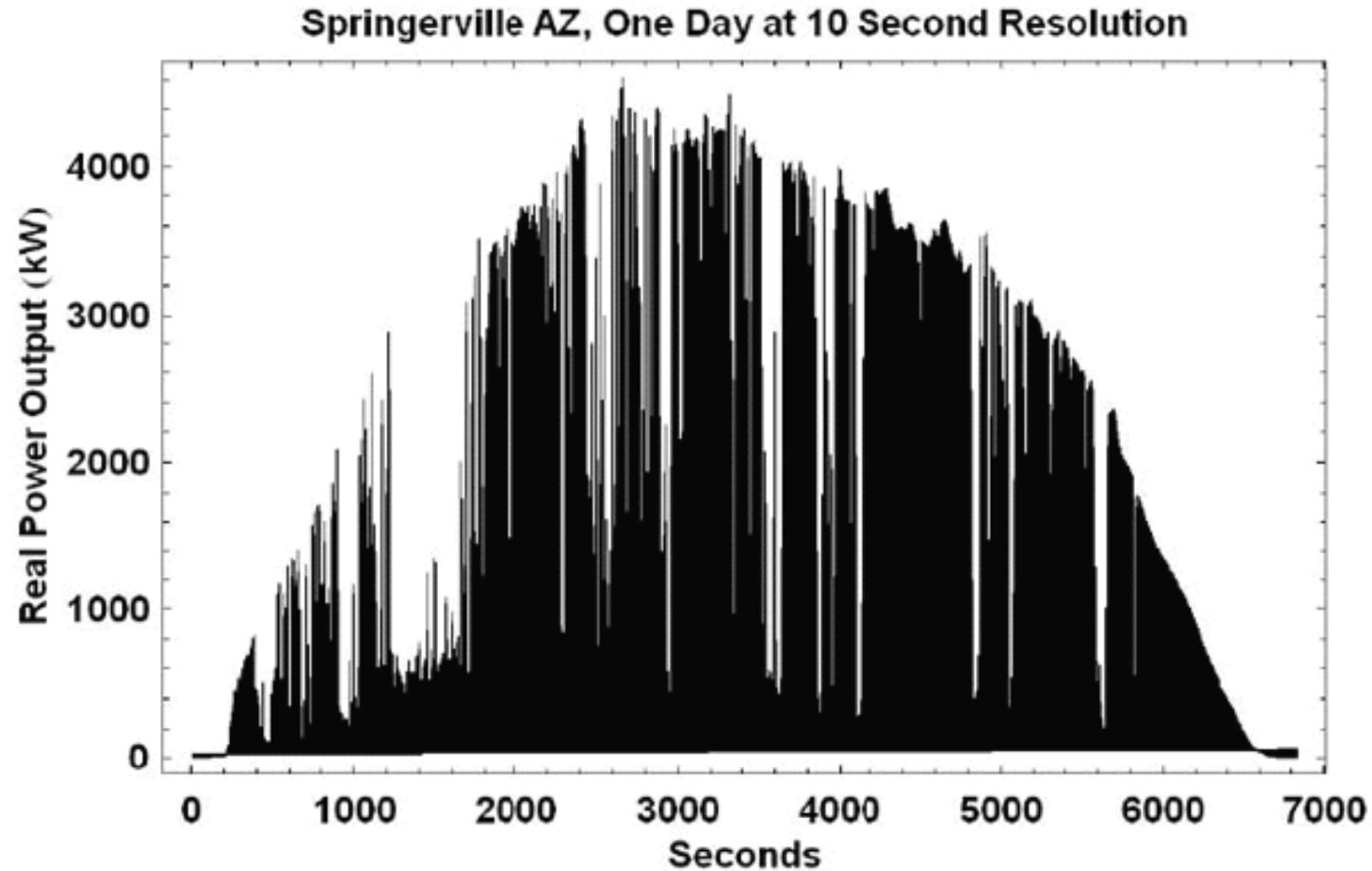
Worldwide Annual Insolation

In 2016 the top countries for total solar capacity are China (78.1 GW), Japan (42.8 GW), Germany (41.2 GW), US (40.3), Italy (19.3);

In just 2016 China added 34.5 GW, US 14.7, Japan 8.6, Indian 4 GW

Source: http://www.iea-pvps.org/

US Solar Generated Electricity

Clean Power Quarterly, 2025 Q3

Impact of Clouds

Springerville AZ, One Day at 10 Second Resolution
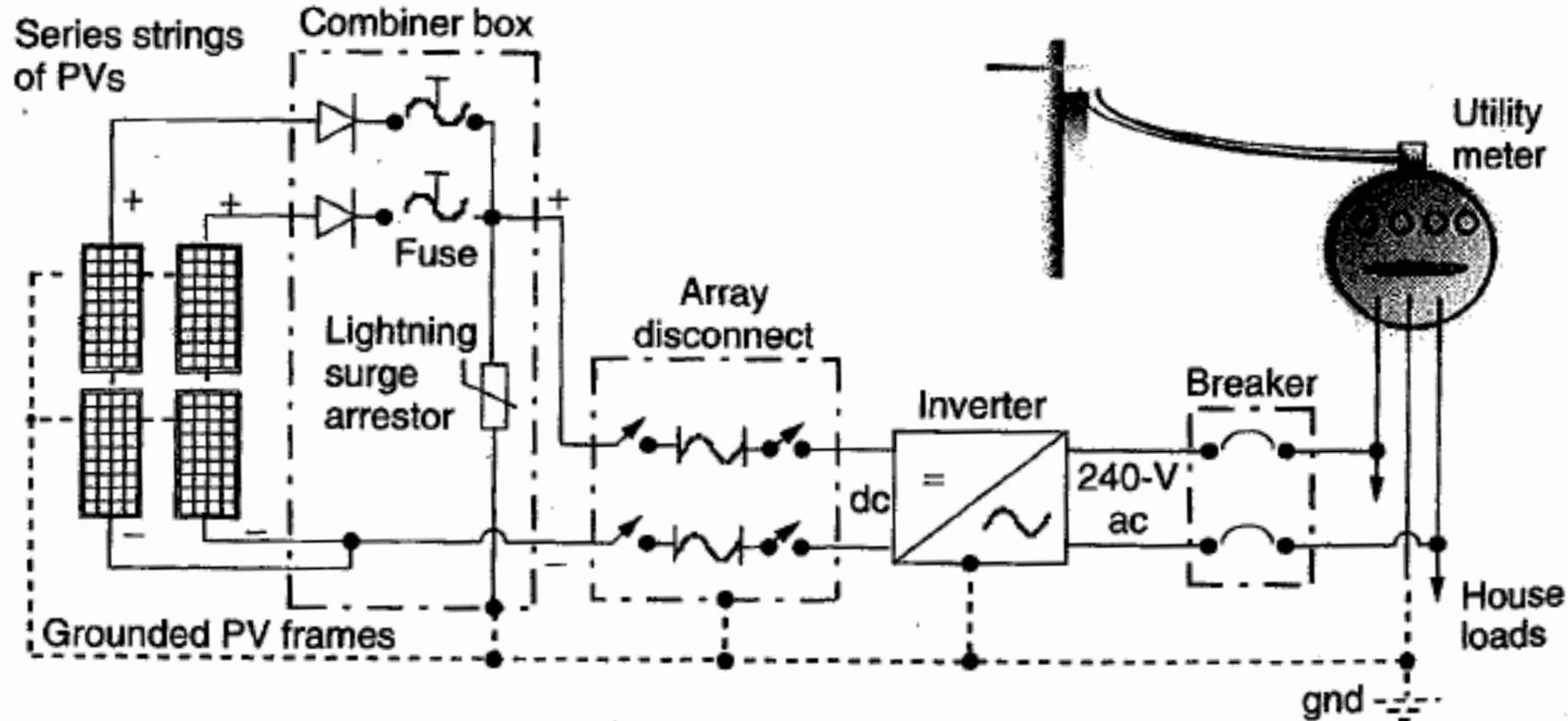
Image: http://www.megawattsf.com/gridstorage/gridstorage.htm

Intermittency can be reduced some when PV is distributed over a larger region; key issue is correlation across an area

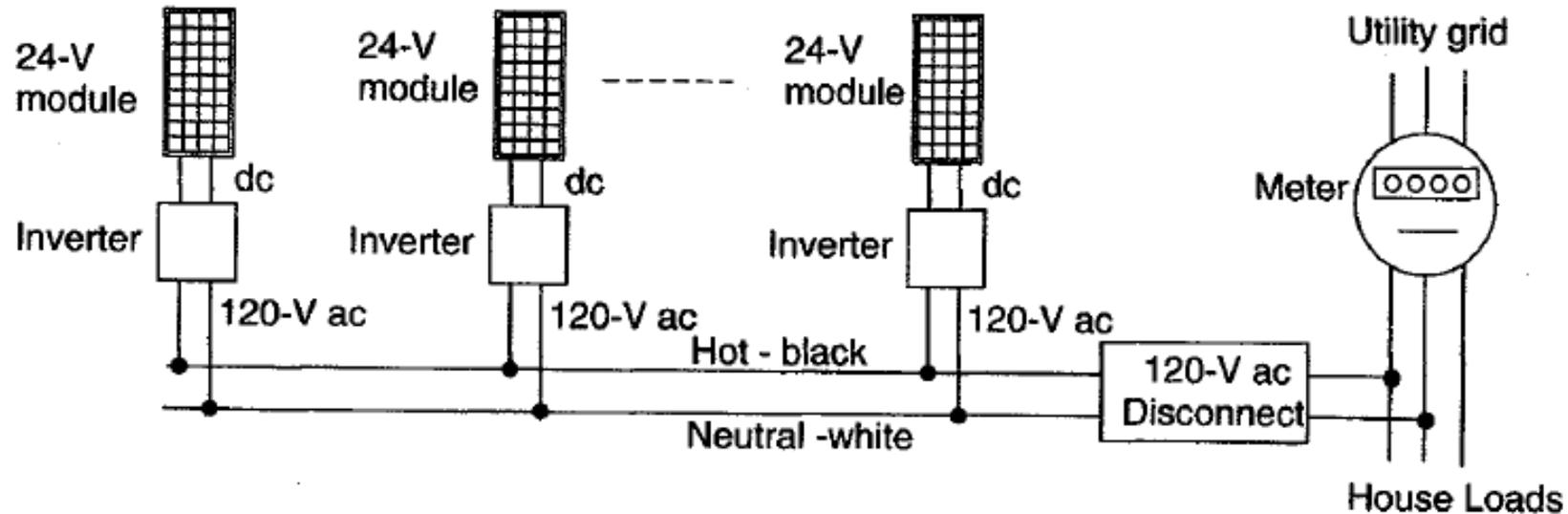# Components of Grid-connected PV

Figure 9.20 Principal components in a grid-connected PV system using a single inverter.

Individual Inverter Concept

- Easily allow expansion
- Connections to house distribution panel are simple
- Less need for expensive DC cabling

Figure 9.21 AC modules each have their own inverters mounted on the backside of the collector, allowing simple system expansion at any time.

Distributed PV System Modeling

- PV in the distribution system is usually operated at unity power factor
  - There is research investigating the benefits of changing this
  - IEEE Std 1547 now allows both non-unity power factor and voltage regulation
  - A simple model is just as negative constant power load
- An issue is tripping on abnormal frequency or voltage conditions
  - IEEE Std 1547 says, "The DR unit shall cease to energize the Area EPS for faults on the Area EPS circuit to which it is connected." (note EPS is electric power system)

Distributed PV System Modeling, 2

- An issue is tripping on abnormal frequency or voltage conditions (from IEEE 1547-2003, 2014 amendment)
  - This is a key safety requirement!
  - Units need to disconnect if the voltage is < 0.45 pu in 0.16 seconds, in 1 second between 0.45 and 0.6 pu, in 2 seconds if between 0.6 and 0.88 pu; also in 1 second if between 1.1 and 1.2, and in 0.16 seconds if higher
  - Units need to disconnect in 0.16 seconds if the frequency is > 62 or less than 57 Hz; in 2 seconds if > 60.5 or < 59.5
  - Reconnection is after minutes
  - Values are defaults; different values can be used through mutual agreement between EPS and DR operator