# ECEN 667
# Power System Stability

## Lecture 26: Renewable Energy Systems


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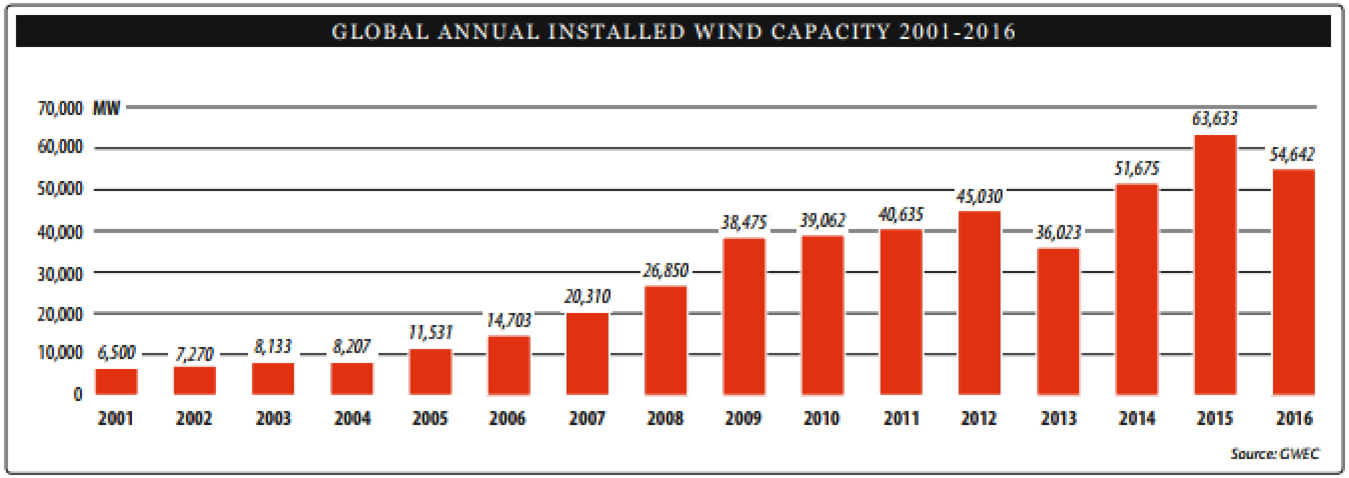
# Announcements

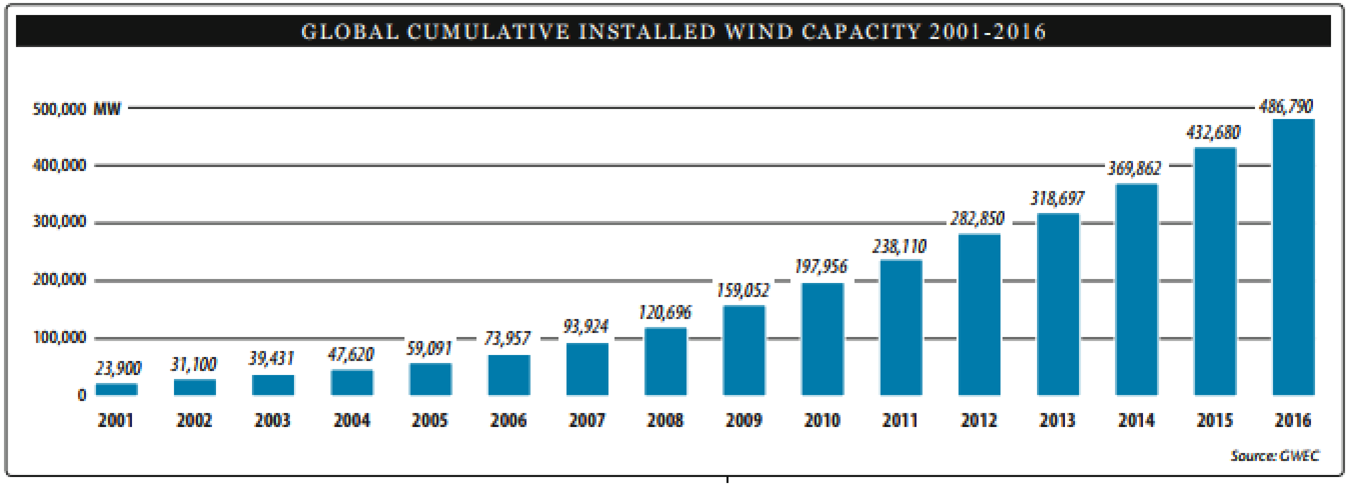
- Read Chapter 9
- Final is as per TAMU schedule.  That is, Friday Dec 8 from 3 to 5pm here

# Renewable Resource 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 transient 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

# Growth in Wind Worldwide

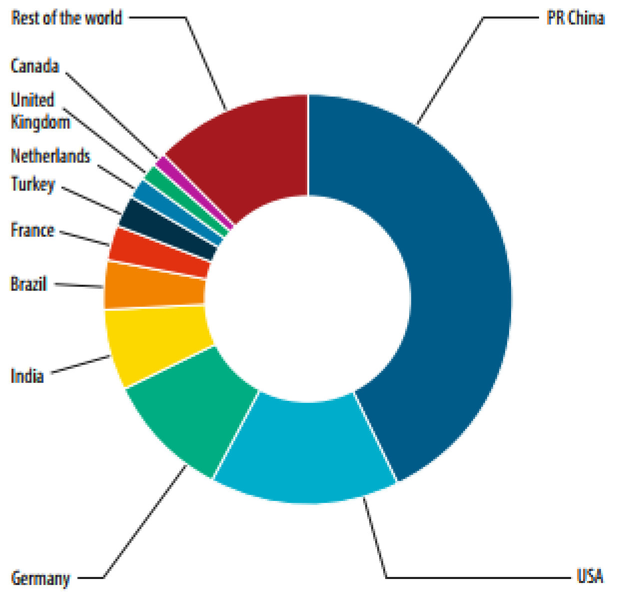



Source: Global Wind 2016 Report, Global Wind Energy Council

# Growth in Wind Worldwide

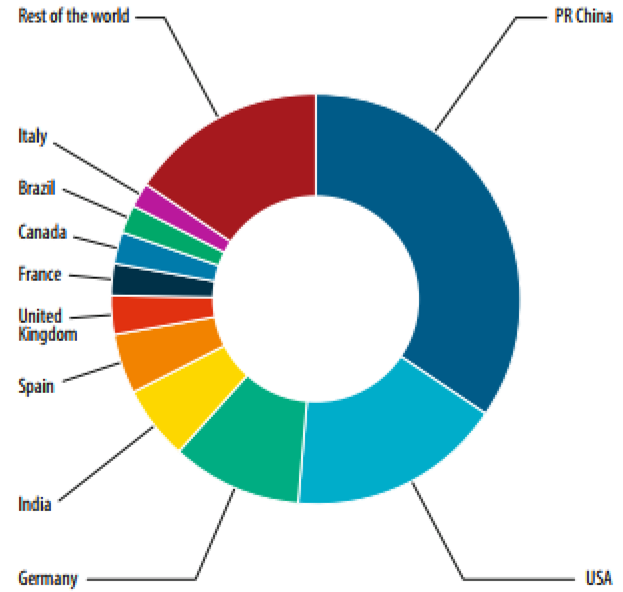
**TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2016**




| Country | MW | % Share |
|---|---|---|
| PR China | 23,370 | 42.8 |
| USA | 8,203 | 15.0 |
| Germany | 5,443 | 10.0 |
| India | 3,612 | 6.6 |
| Brazil* | 2,014 | 3.7 |
| France | 1,561 | 2.9 |
| Turkey | 1,387 | 2.5 |
| Netherlands | 887 | 1.6 |
| United Kingdom | 736 | 1.3 |
| Canada | 702 | 1.3 |
| Rest of the world | 6,727 | 12.3 |
| **Total TOP 10** | **47,915** | **88** |
| **World Total** | **54,642** | **100** |

Source: GWEC

**TOP 10 CUMULATIVE CAPACITY DEC 2016**




| Country | MW | % Share |
|---|---|---|
| PR China | 168,732 | 34.7 |
| USA | 82,184 | 16.9 |
| Germany | 50,018 | 10.3 |
| India | 28,700 | 5.9 |
| Spain | 23,074 | 4.7 |
| United Kingdom | 14,543 | 3.0 |
| France | 12,066 | 2.5 |
| Canada | 11,900 | 2.4 |
| Brazil* | 10,740 | 2.2 |
| Italy | 9,257 | 1.9 |
| Rest of the world | 75,576 | 15.5 |
| **Total TOP 10** | **411,214** | **84** |
| **World Total** | **486,790** | **100** |

Source: GWEC

Source: Global Wind 2016 Report, Global Wind Energy Council

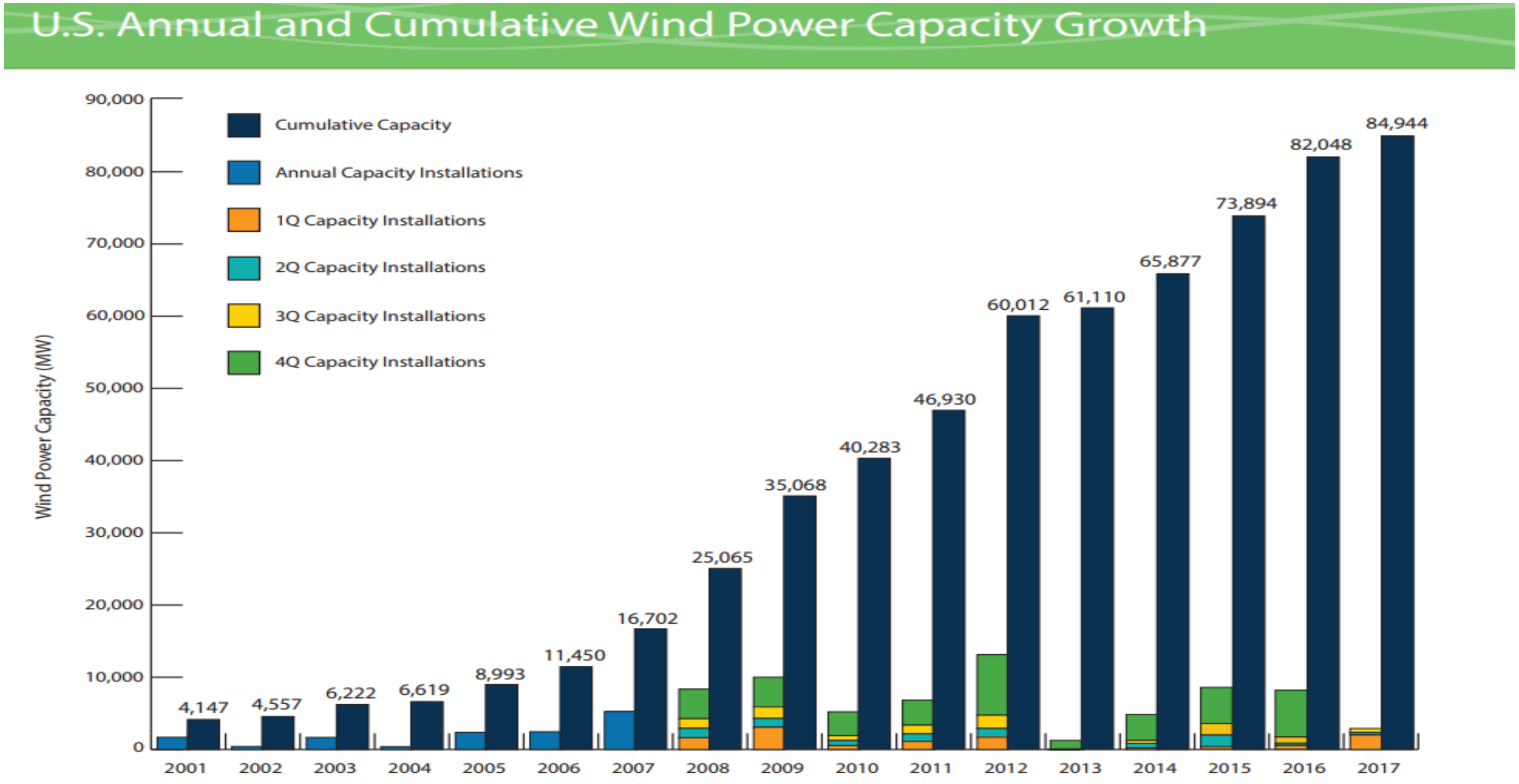
# Vestas Wind Systems Stock Price

- Vestas's stock has increased by more than 15times from their 2012/2013 lows!


Their price fell significantly in November due to increased competition in wind power markets

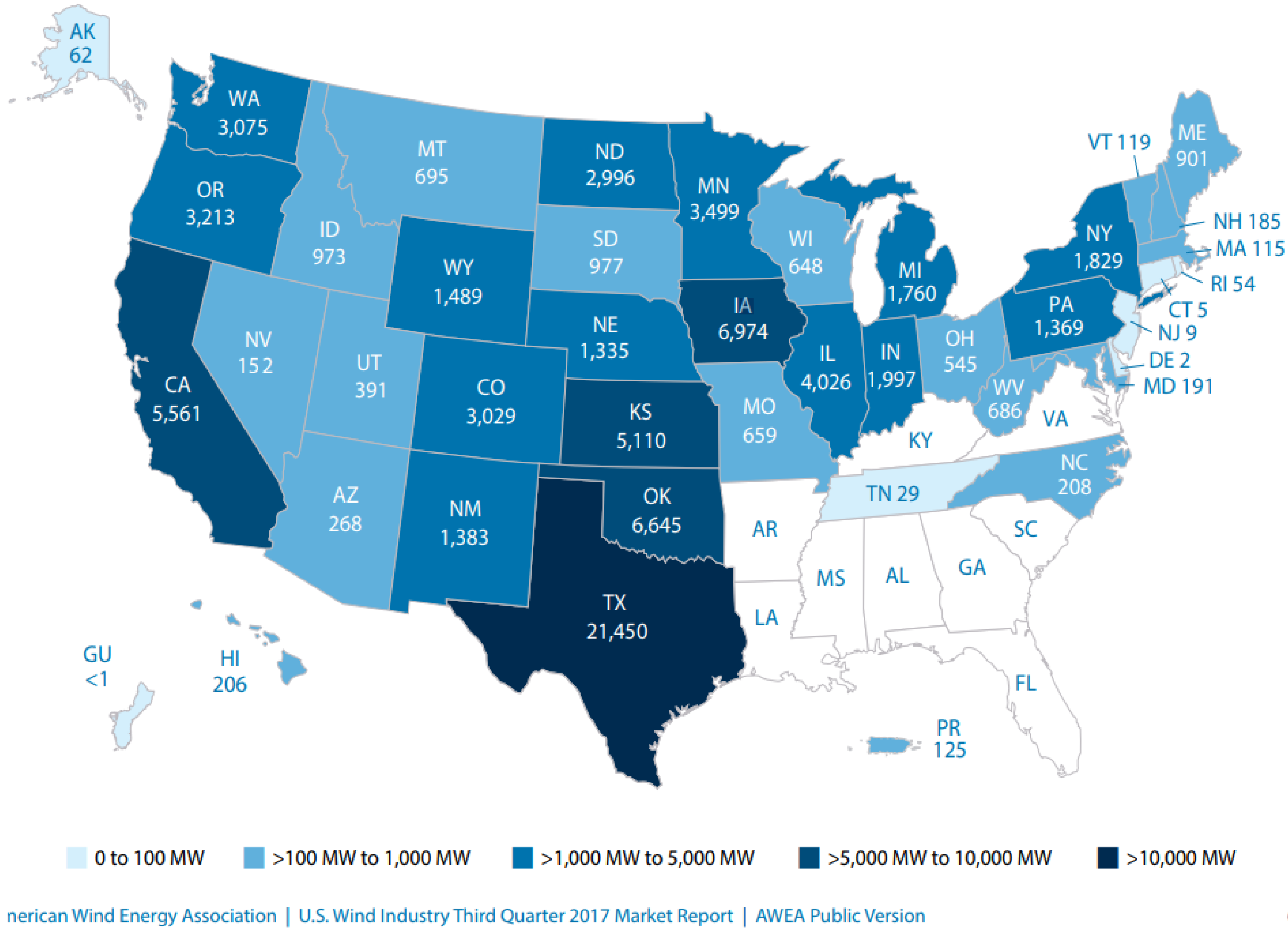
# Growth in US Wind

- Production tax credit of $24/MWh being phased out
  - 100% in 2016, 80% in 2017, 60% in 2018, 40% in 2019



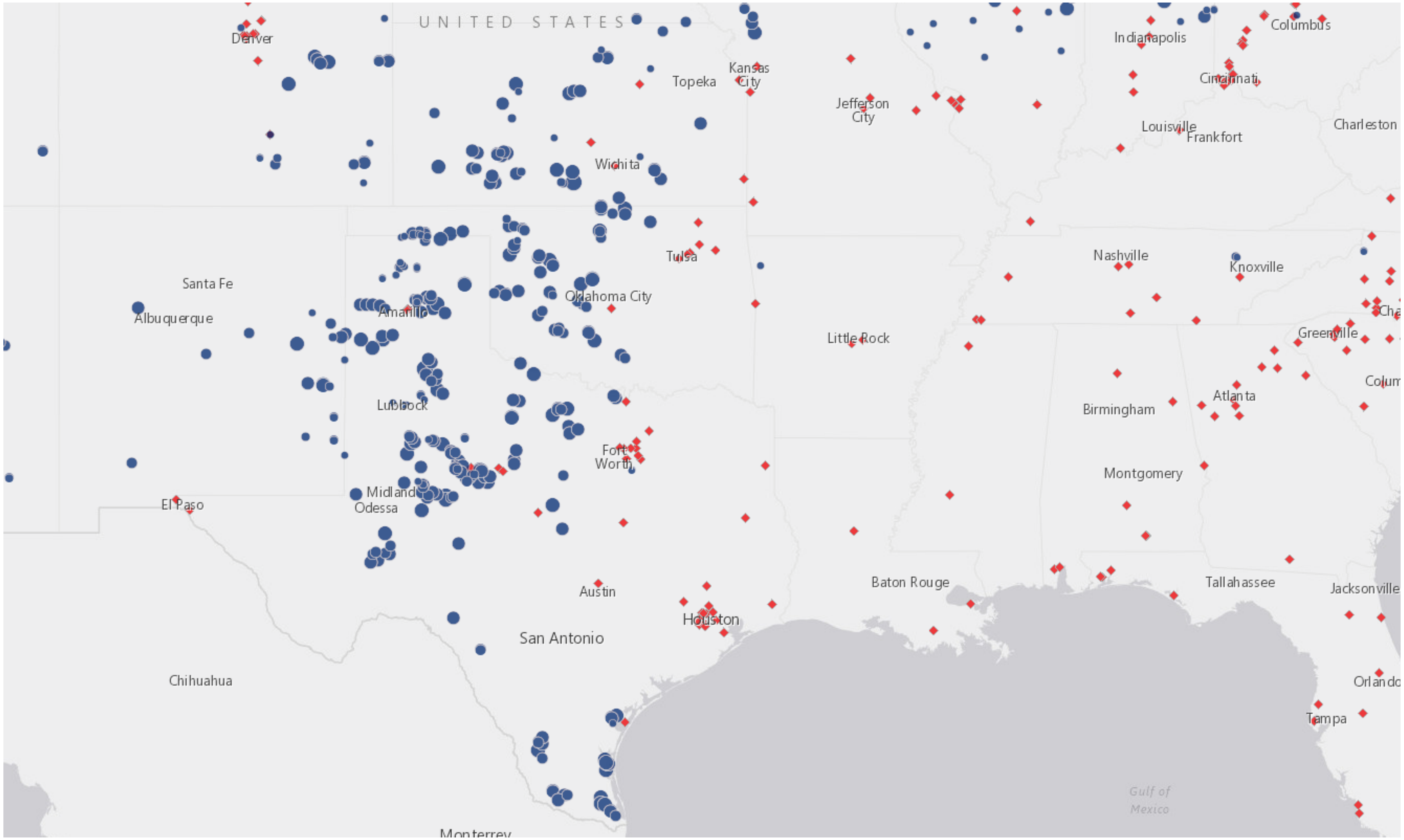

Source: American Wind Energy Association 2017 Third Quarter Market Report

# 2016 Installed Capacity by State: Texas Continues to Dominate!



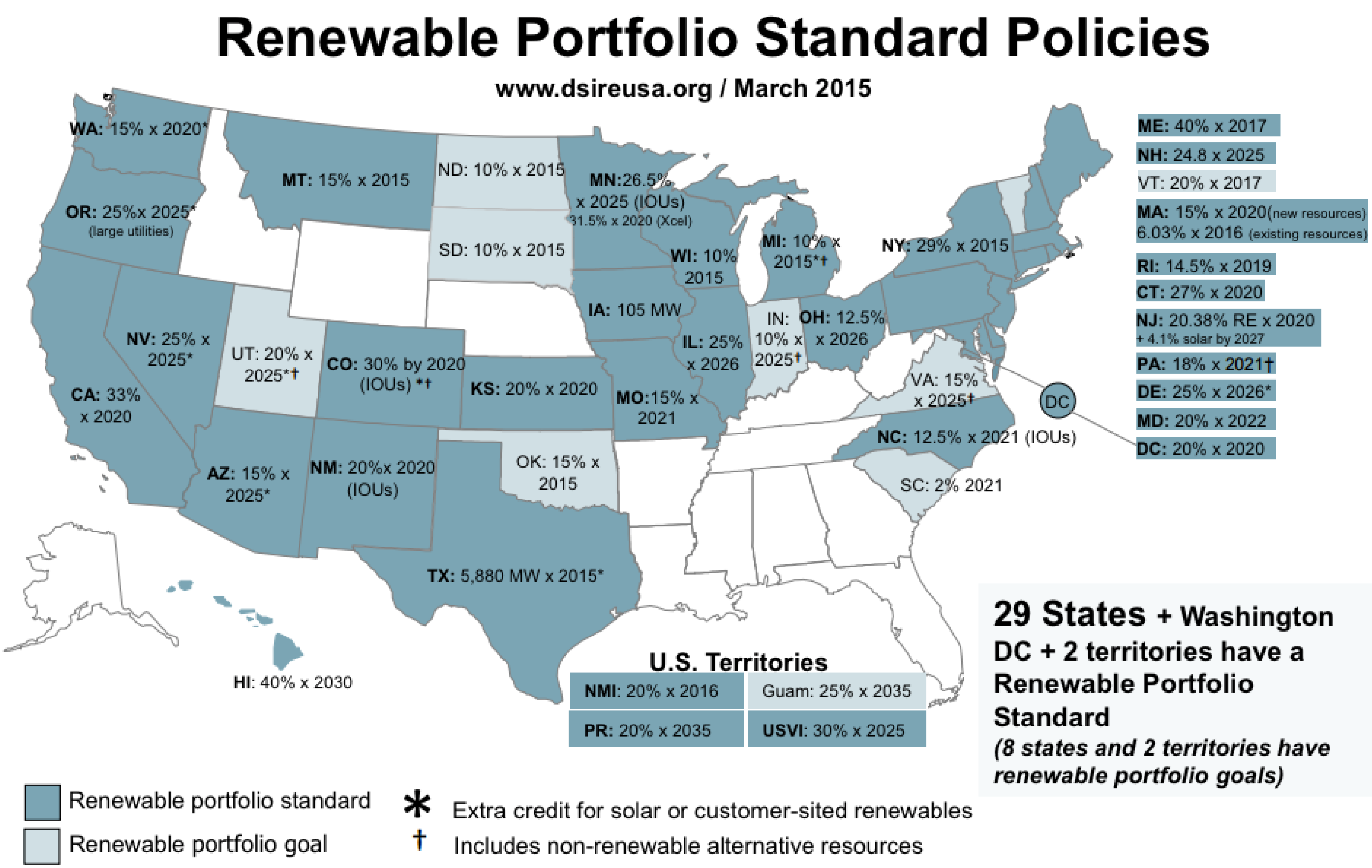

Source: American Wind Energy Association 2017 Third Quarter Market Report

# Wind Farm and Wind-Related Plant Locations




http://gis.awea.org/arcgisportal/apps/webappviewer/index.html?id=eed1ec3b624742f8b18280e6aa73e8ec

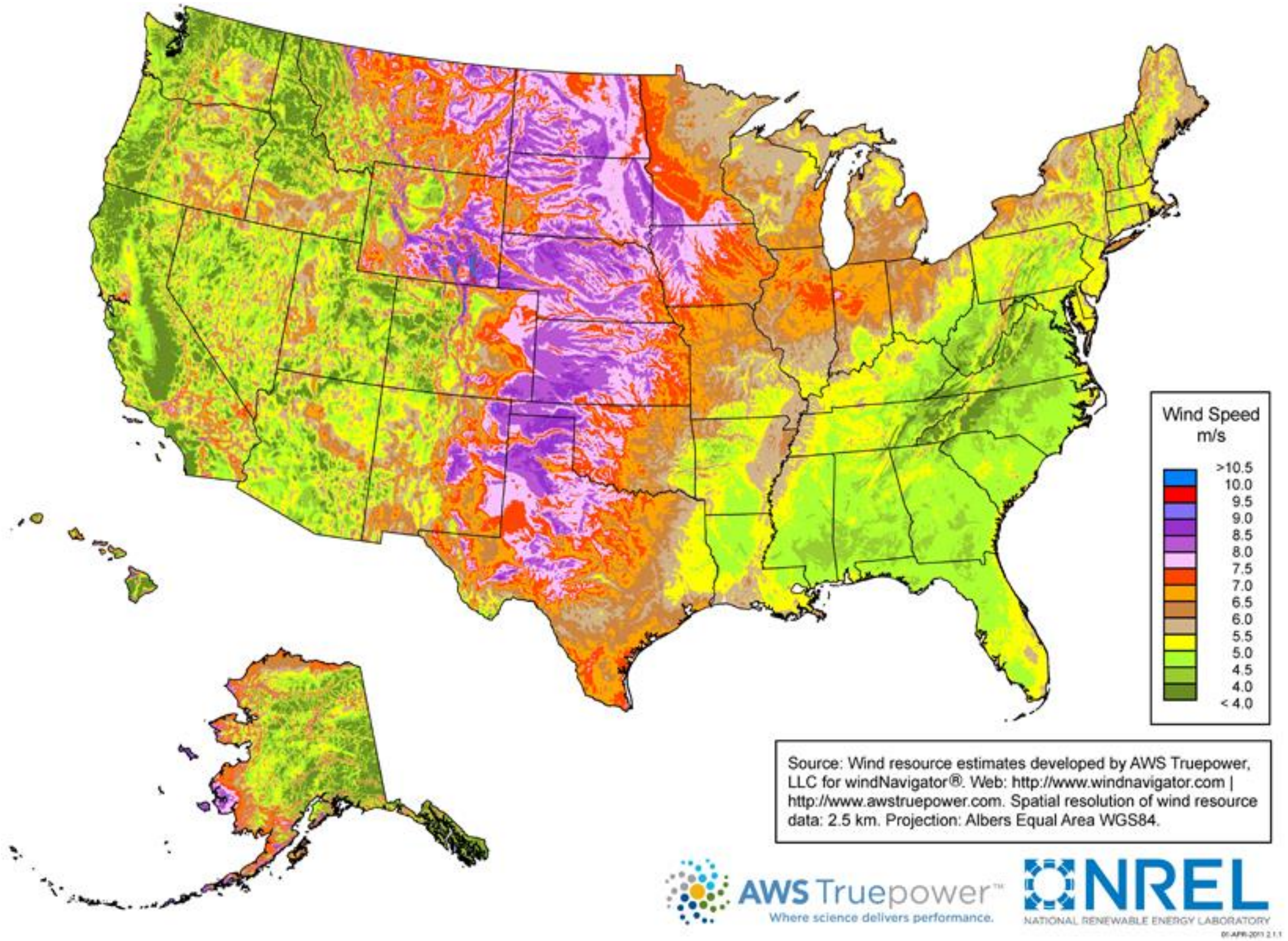
# State Renewable Portfolio Standards




Texas has a goal of 10 GW by 2025, but that has already been achieved (by more than double!)

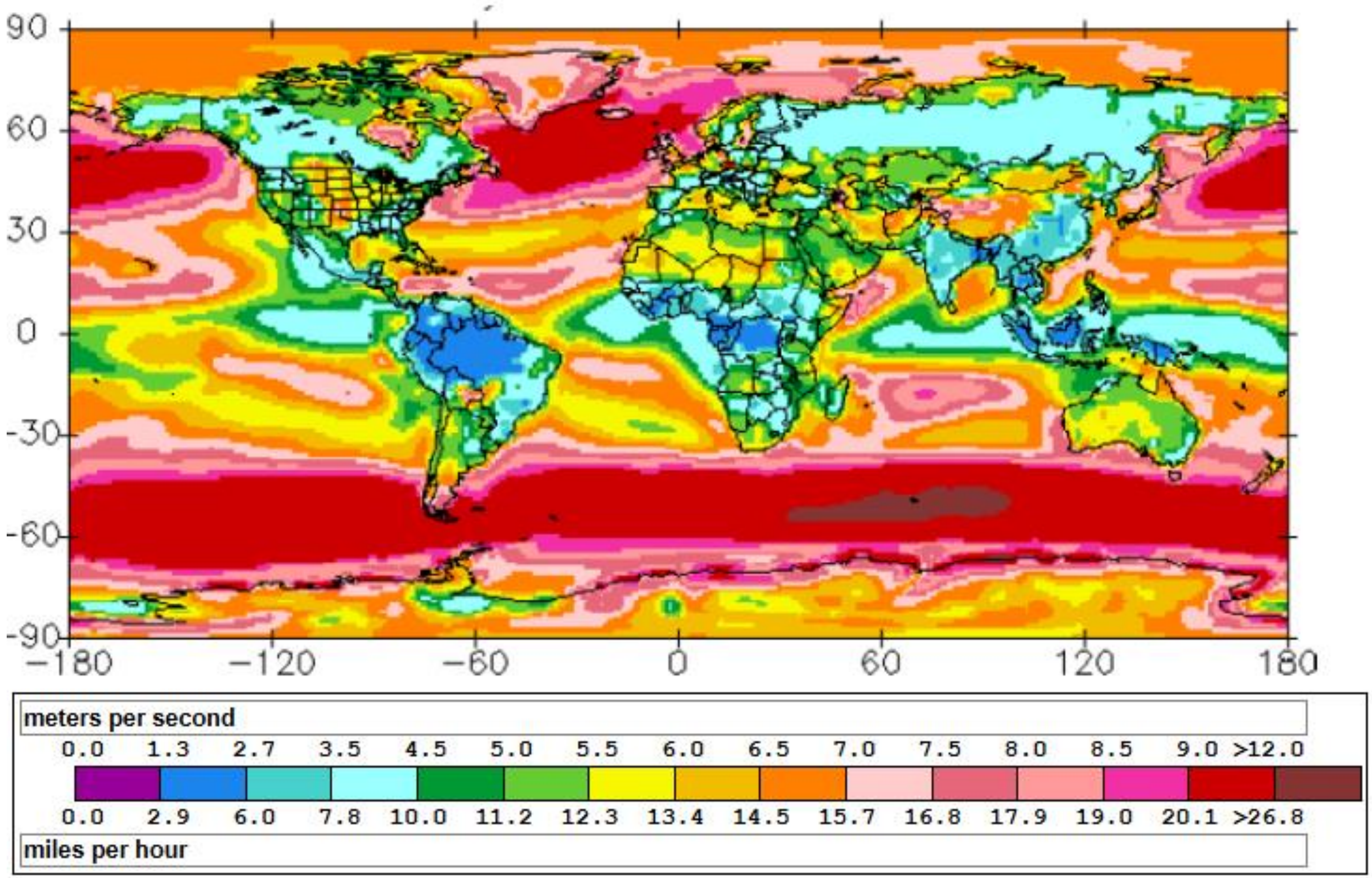
Image source: dsireusa.org (see for updated information)

# US Wind Resources



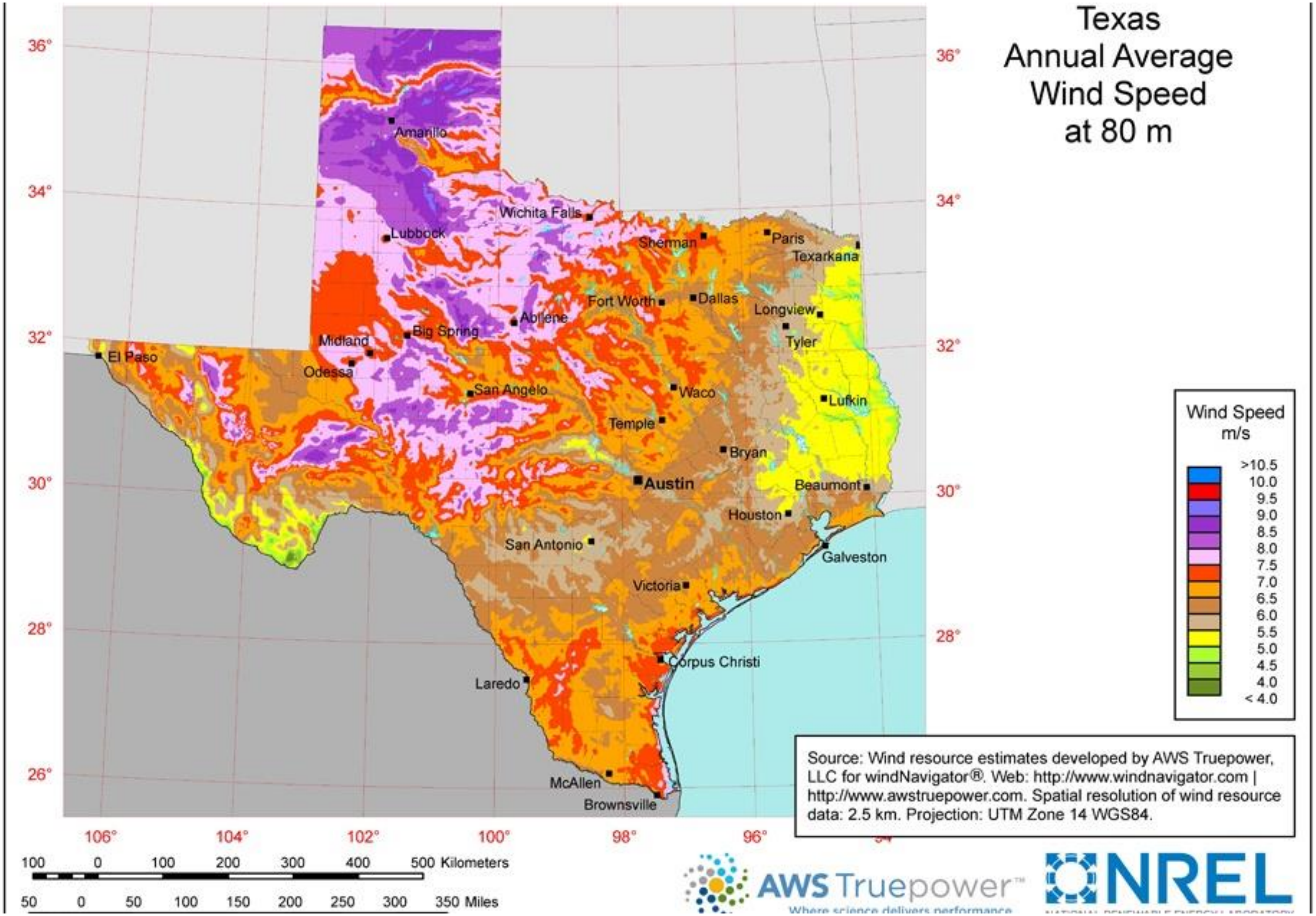

Source: http://www.windpoweringamerica.gov/wind_maps.asp

# Global Wind Speed 50m Map




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

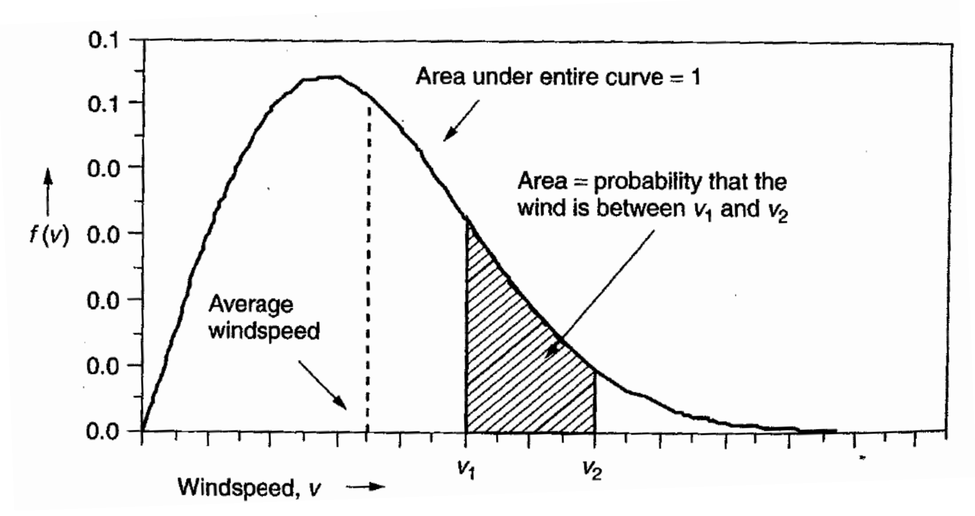
# Wind Map Texas– 80m Height



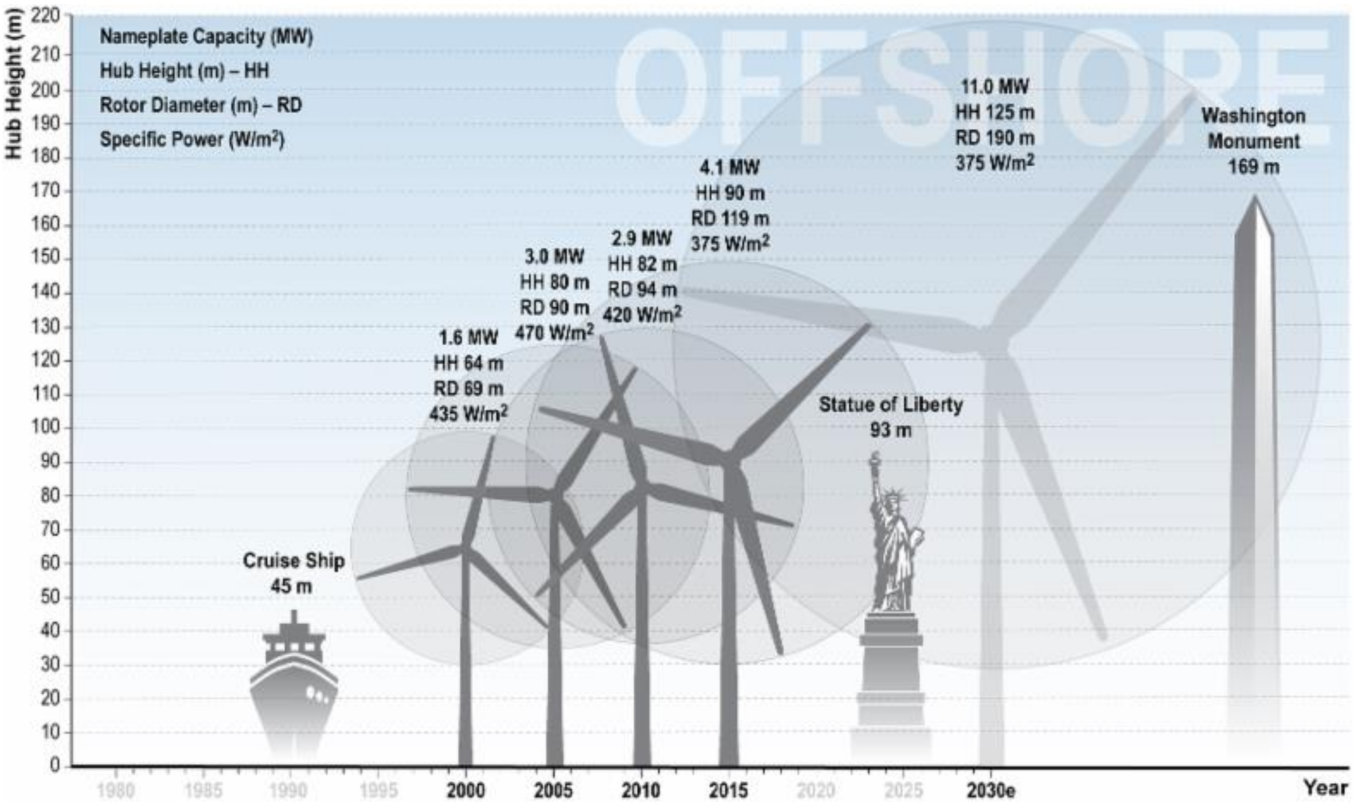

https://windexchange.energy.gov/files/u/visualization/image/tx_80m.jpg

# 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)



# Wind Turbine Height and Size

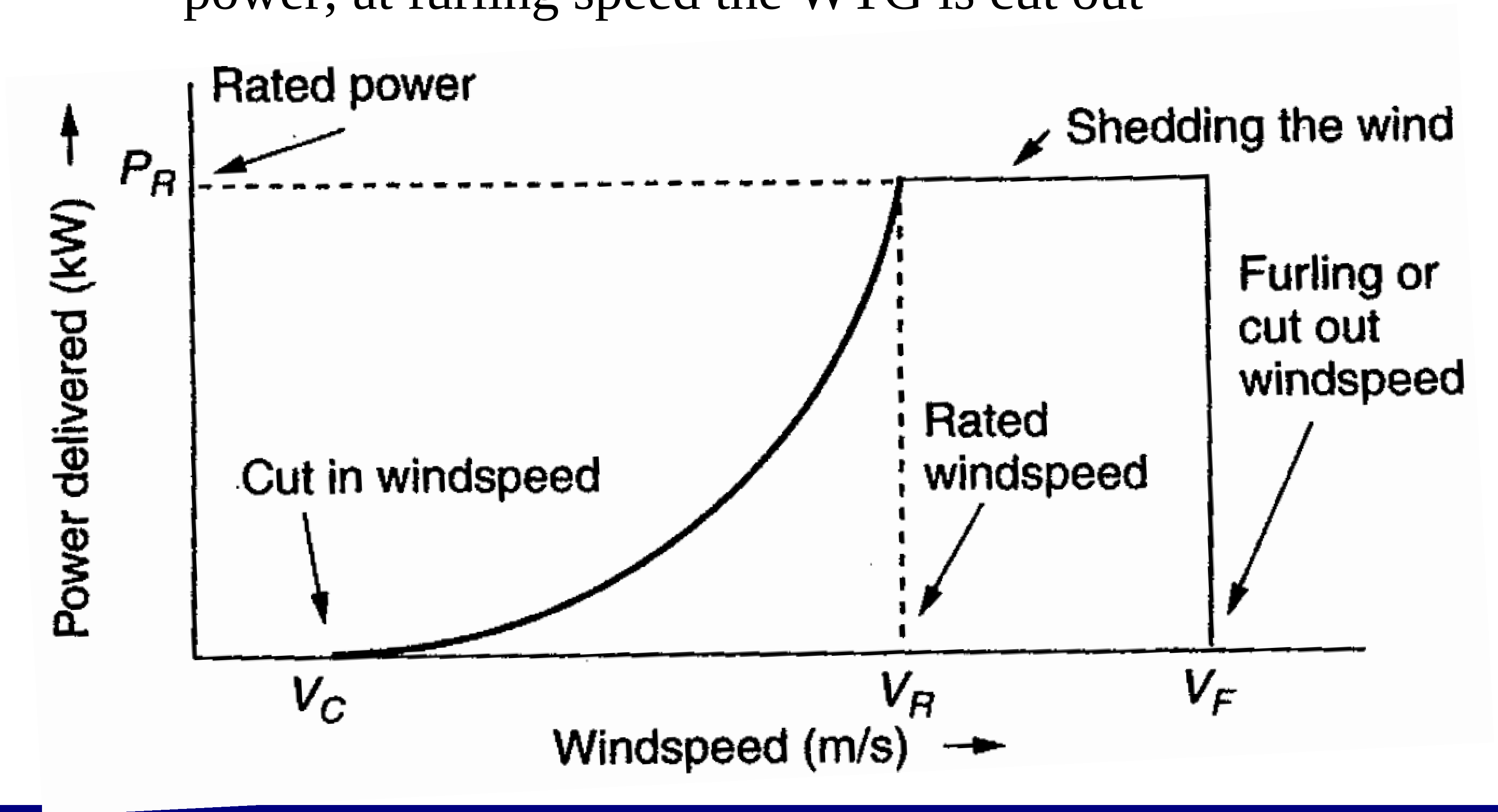



The current largest wind turbine by capacity is the Vestas V164 which has a capacity of 8 MW, a height of 220 m, and diameter of 164 m.

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

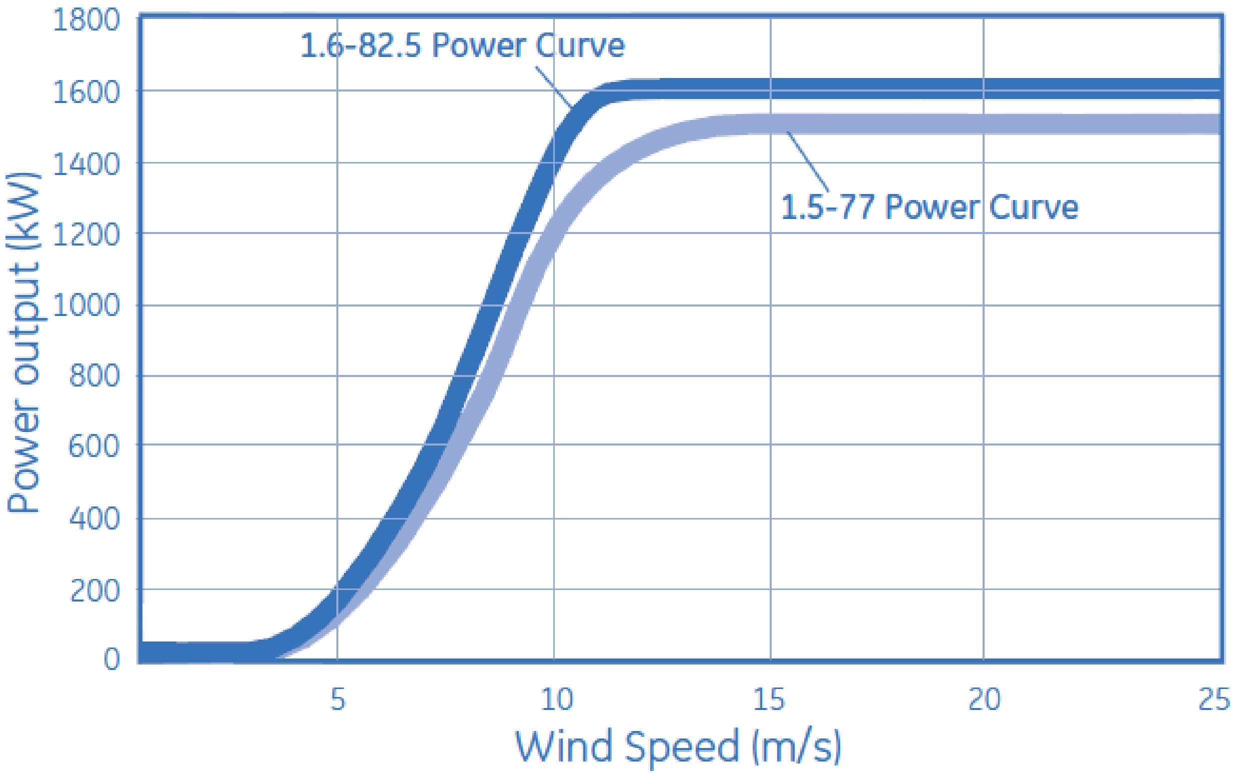
# Extracted Power

- 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




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)

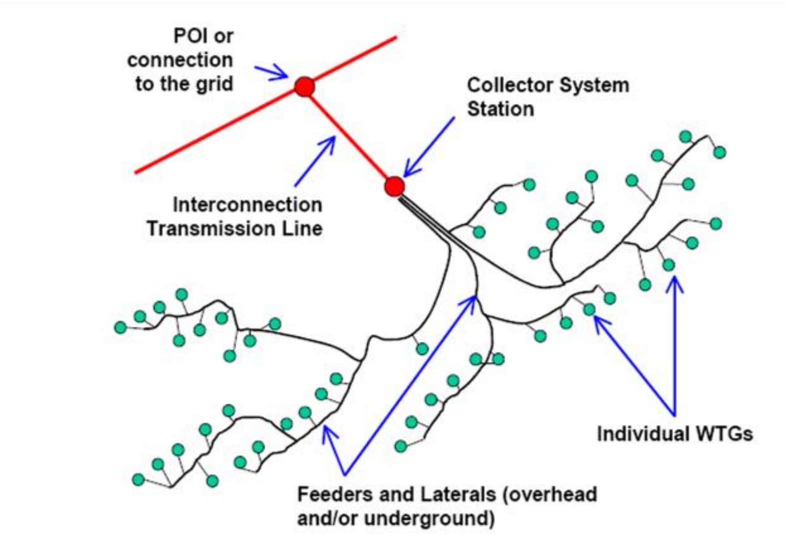


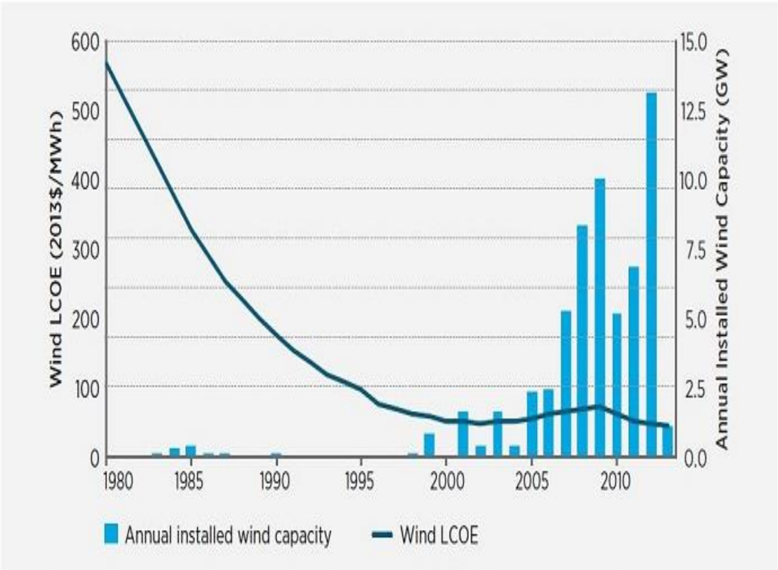

Photo Source: www.energyindustryphotos.com/photos_of_wind_farm_turbines.htm

# 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 Energy Economics

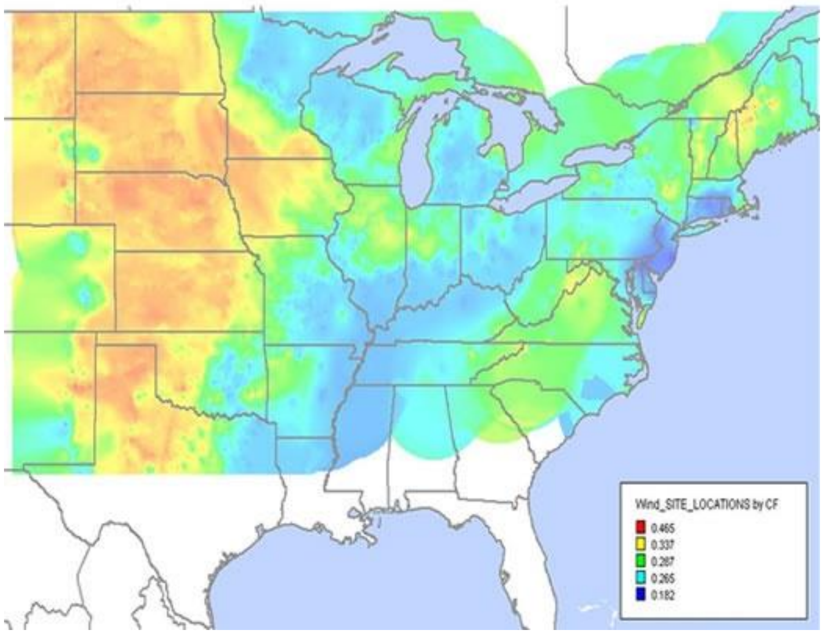
- Most of the cost is in the initial purchase and construction (capital costs); current estimate is about $1690/kW; how much wind is generated depends on the capacity factor, best is about 40%




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]

Wind Capacity




Source: www.awea.org/falling-wind-energy-costs

# 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

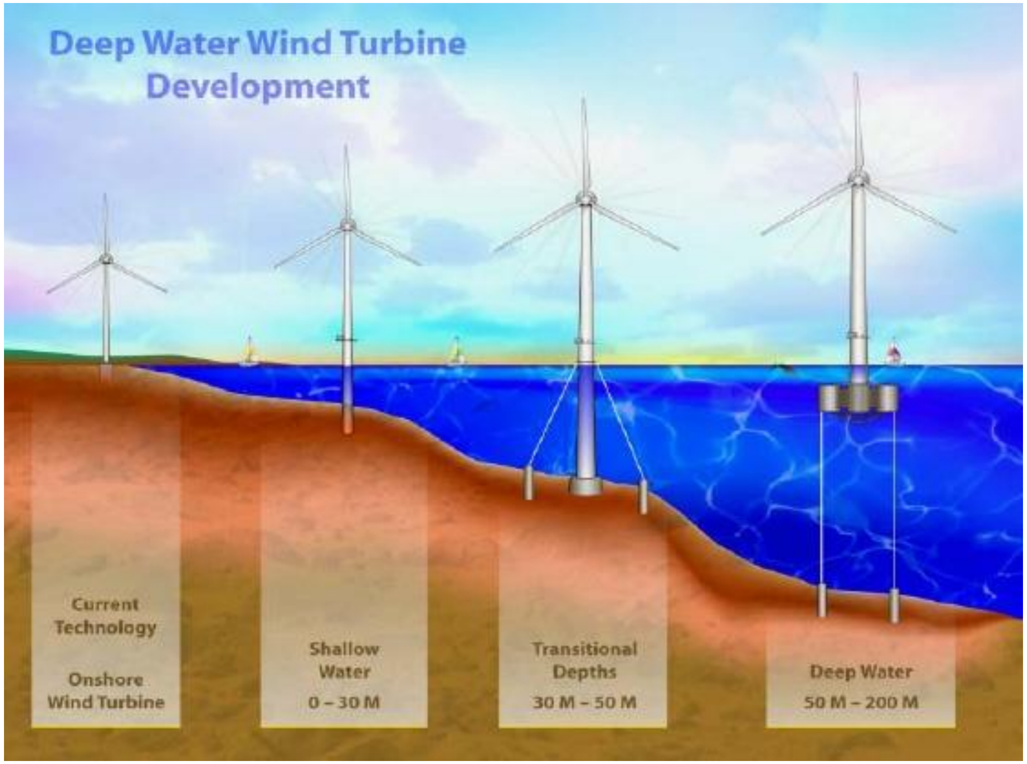
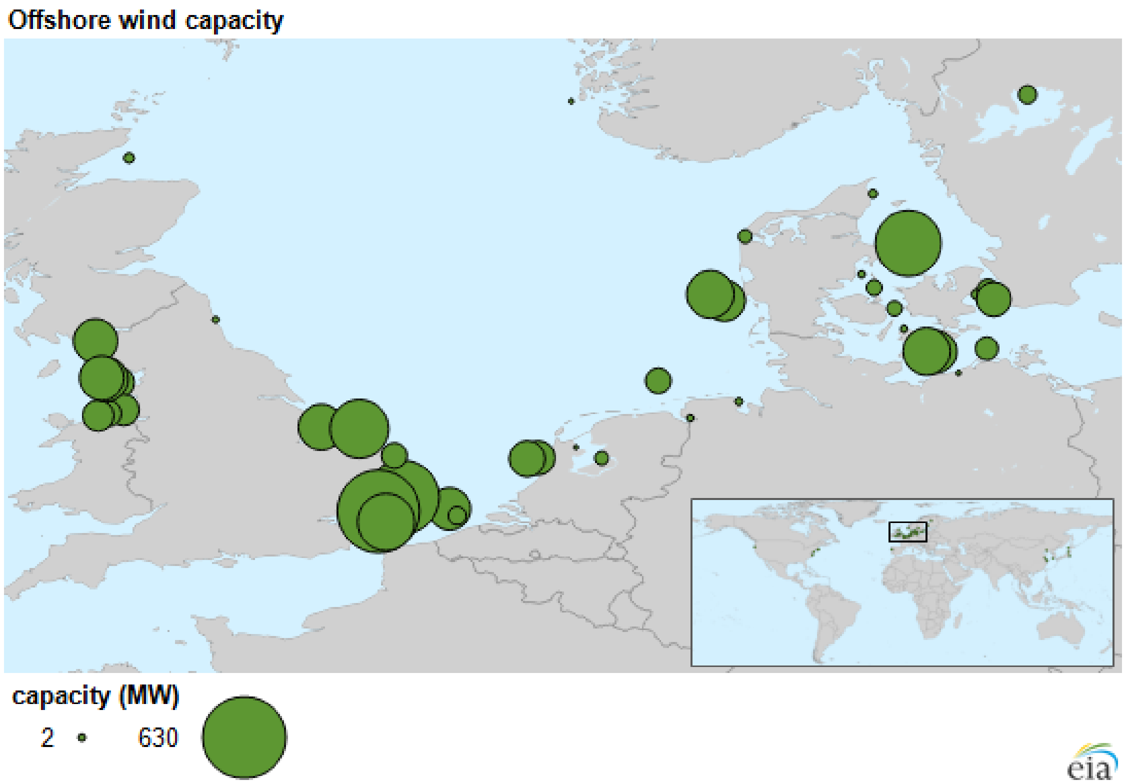
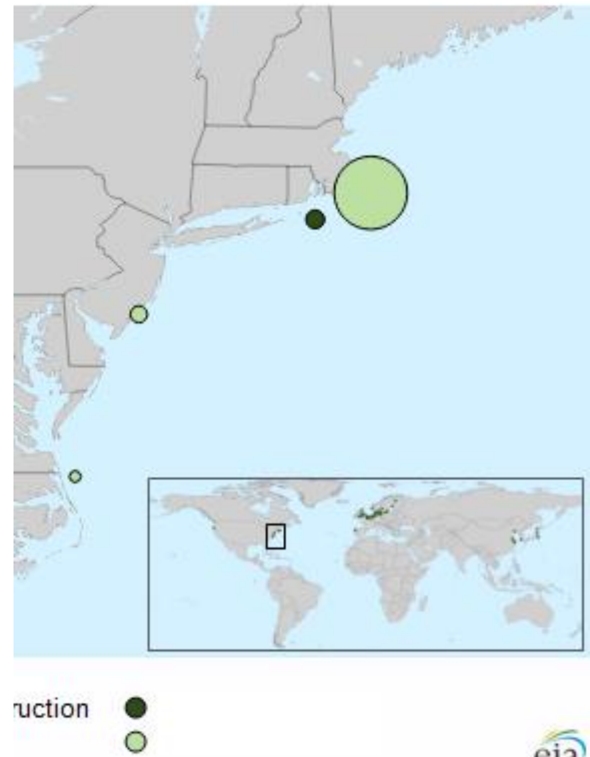



Image Source: National Renewable Energy Laboratory

# Offshore Wind Installations




The first US offshore wind, Block Island (Rhode Island) with 30 MW, became operational in December 2016; Cape Wind in Massachusetts was just officially cancelled this month

Source: EIA August 14, 2015 and dwwind.com/project/block-island-wind-farm/

# 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 for Power Flow and Transient 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; 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)

# Types of Wind Turbines for Power Flow and Transient 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 primarily 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 WTGs trip, it could quickly setup a cascading situation particularly in areas with lots of Type 3 WTGs
  - 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
- Standards now require specific low voltage performance

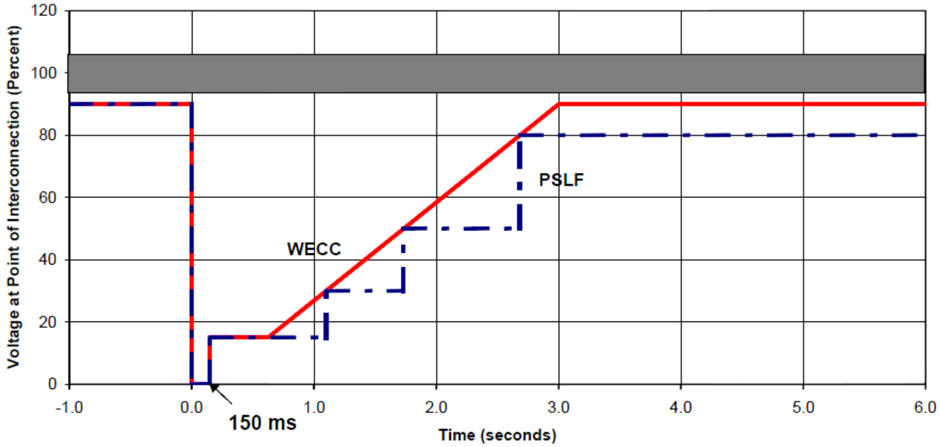



Image from California ISO presentation

# 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

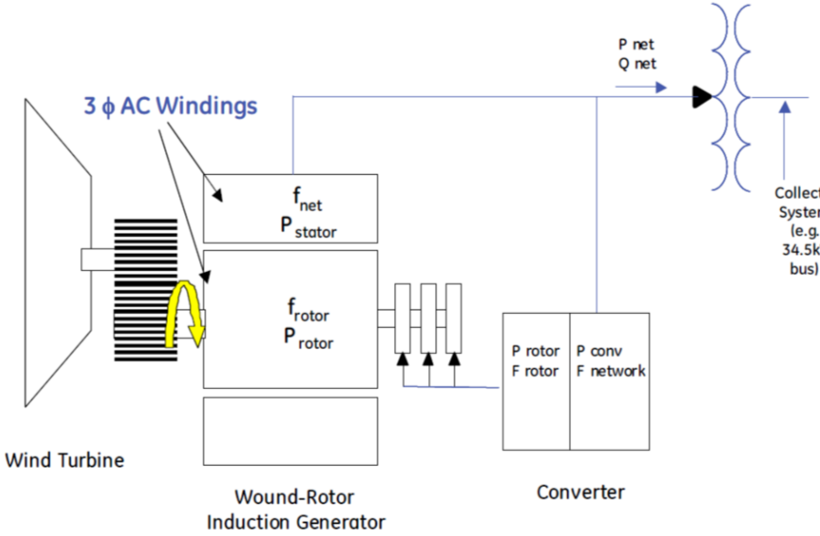


Figure 2-1. GE Doubly Fed Asynchronous WTG Major Components.

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

# Overall Type 3 WTG Model

Transient stability models are transitioning

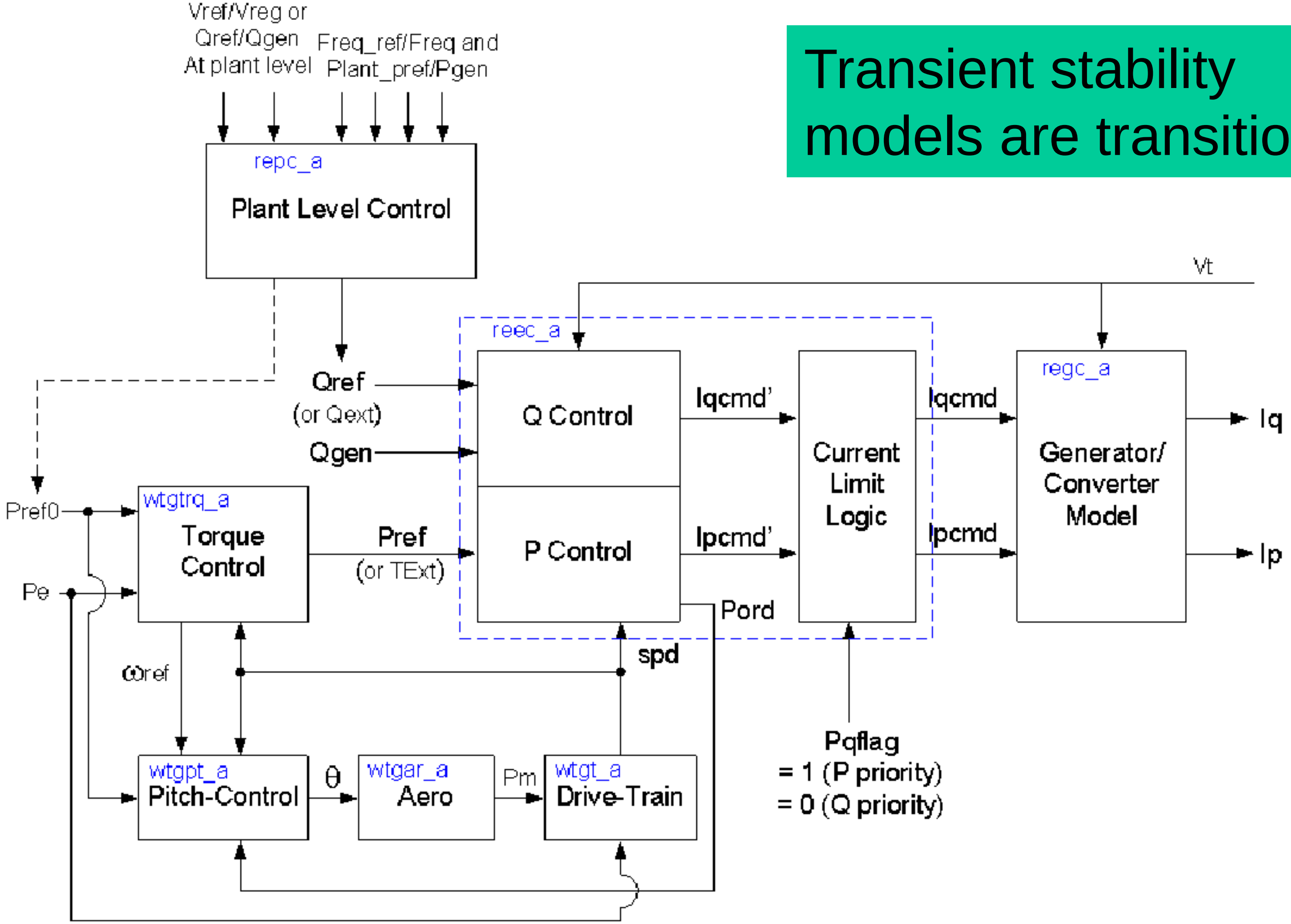


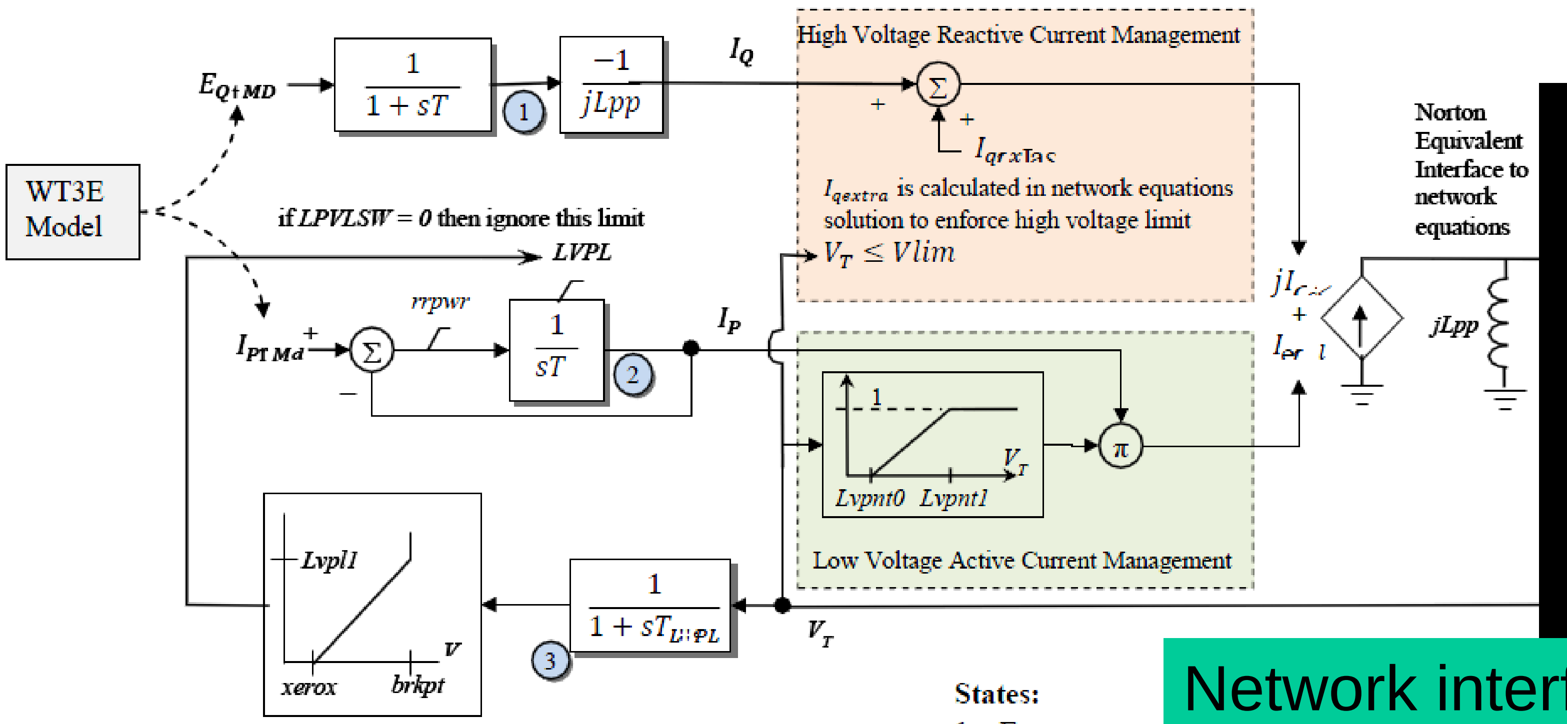

Image Source: WECC Type 3 Wind Turbine Generator Model –Phase II, January 23, 2014, WECC TSS

# 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 WT3G Converter Model

**Generator/converter Model for Type-3 (Double-Fed) Wind Turbines WT3G**



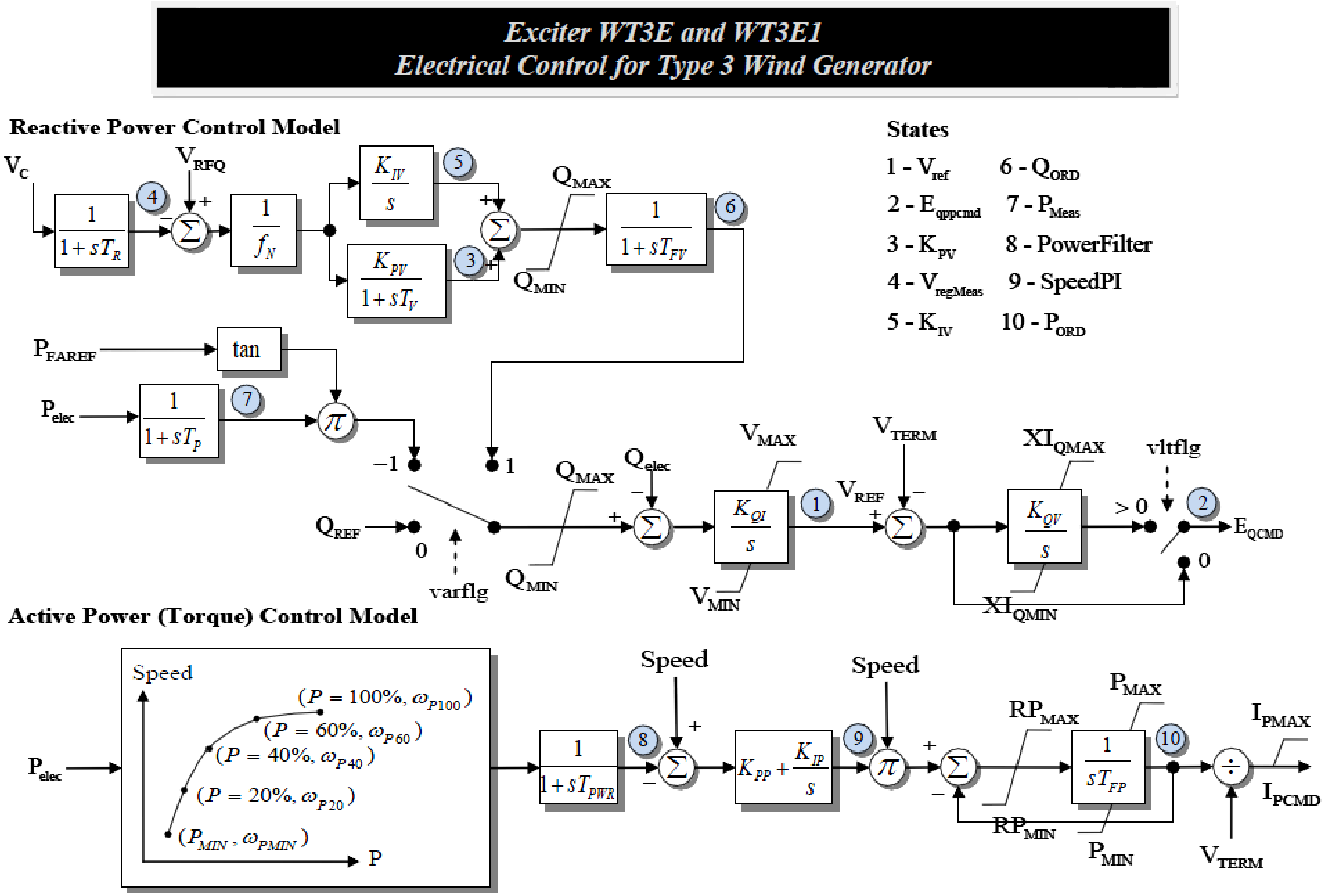

States:
1 – $E_q$
2 – $I_p$
3 – Vmeas

Network interface is a Norton current in parallel with a reactance jX"

# 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 3 Reactive Power Control




WT3E supported by PSLF with $RP_{MAX} = P_{wrat}$ and $RP_{MIN} = -P_{wrat}$, $T_{FV} = T_C$

WT3E1 supported by PSSE uses vltflg to determine the limits on $E_{QCMD}$. When vltflg > 0 Simulator always uses $XI_{QMAX}$ and $XI_{QMIN}$.

# Aerodynamics

- Type 3 and 4 models have more detailed models that directly incorporate the blade angle, so a brief coverage of the associated aerodynamics is useful
- The power in the wind is given by

$$P = \frac{\rho}{2} A v_w^3 C_p(\lambda, \theta)$$

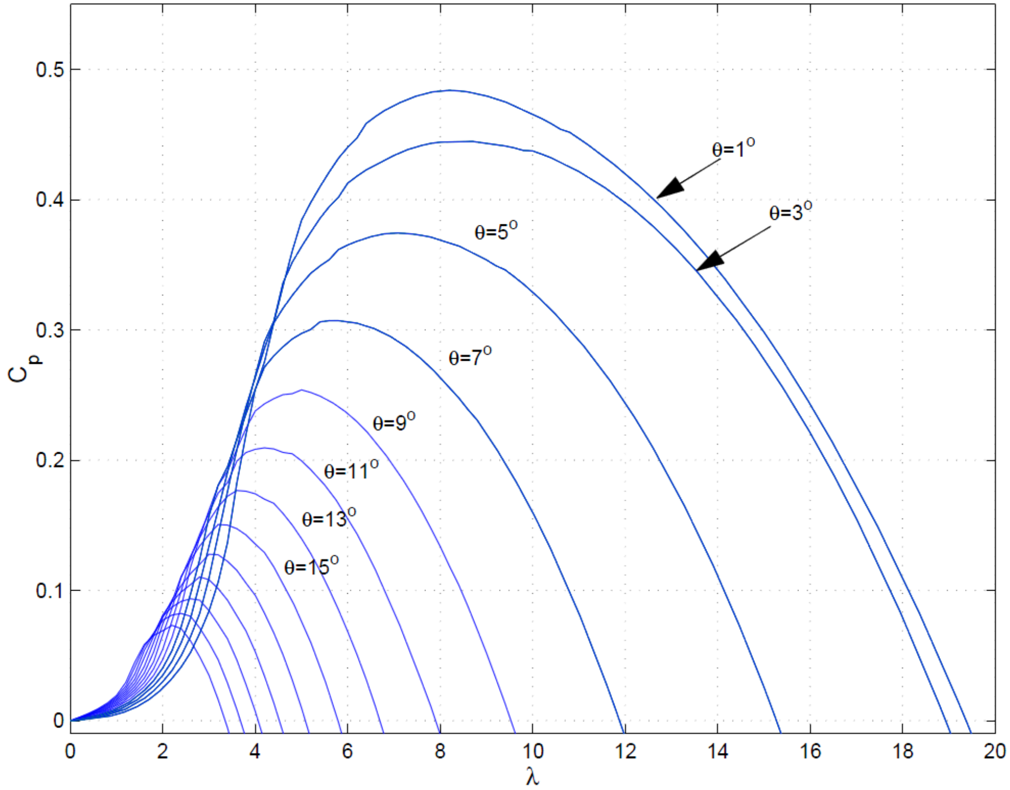
where $\rho$ is the density of air, $A$ is the area swept by the blades, $v_w$ is the wind velocity, $\lambda$ is the tip to wind speed ratio.

For a given turbine with a fixed blade length, $\lambda = K_b(\omega / v_w)$

Modeling of GE Wind Turbine-Generators for Grid Studies, version 4.6, March 2013, GE Energy

# Aerodynamics

- The $C_p(\theta,\lambda)$ function can be quite complex, with the GE 1.5 curves given below




If such a detailed curve is used, the initialization is from the power flow P. There are potentially three independent variables, $v_w$, $\theta$ and $\omega$. One approach is to fix $\omega$ at rated (e.g., 1.2) and $\theta$ at $\theta_{min}$

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

# Simplified Aerodynamics Model

- A more simplified model is to approximate this curve as

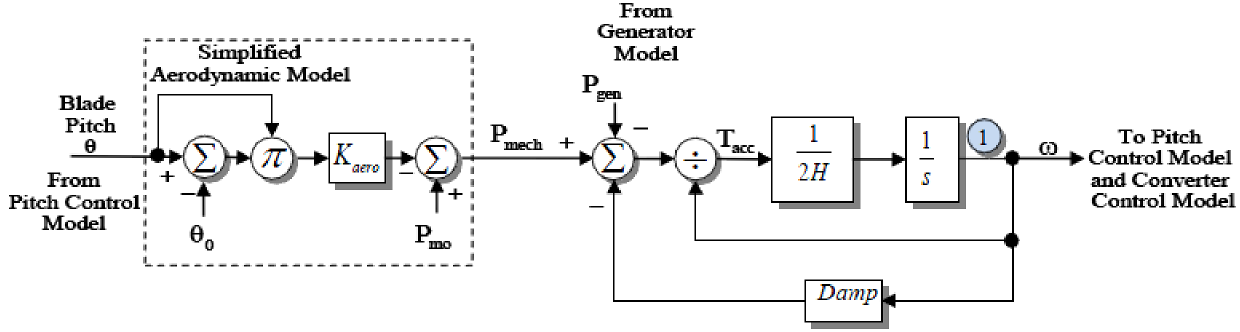
$$P_{mech} = \left(P_{m0} - K_{aero}\left(\theta - \theta_0\right)^2\right)$$

where $K_{aero}$ is a constant, $P_{m0}$ is set by the initial $P_{mech}$; $\theta_0$ is the initial angle, either set to $\theta_{min}$ (when the wind speed is below rated), or $\frac{Theta2}{0.75}\left(1 - \frac{1}{v_w^2}\right)$ with Theta2 a constant equal to the angle at twice rated speed

# WT3T Model (Drive Train and Aero)

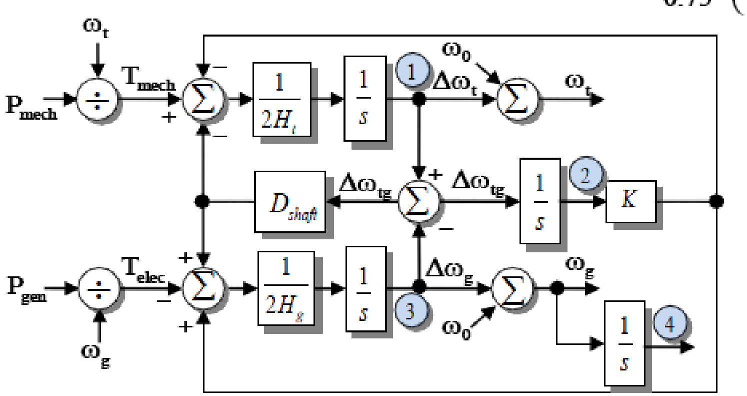
**Governor WT3T**

*Governor WT3T*
*Wind Turbine Model for Type-3 (Doubly-fed) Wind Turbines*




**Type 3 WTG Turbine One-mass Model**

When windspeed > rated windspeed, blade pitch initialized to $\theta = \frac{Theta2}{0.75}\left(1 - \frac{1}{V_W^2}\right)$




**Type 3 WTG Turbine Two-mass Model**

**States**

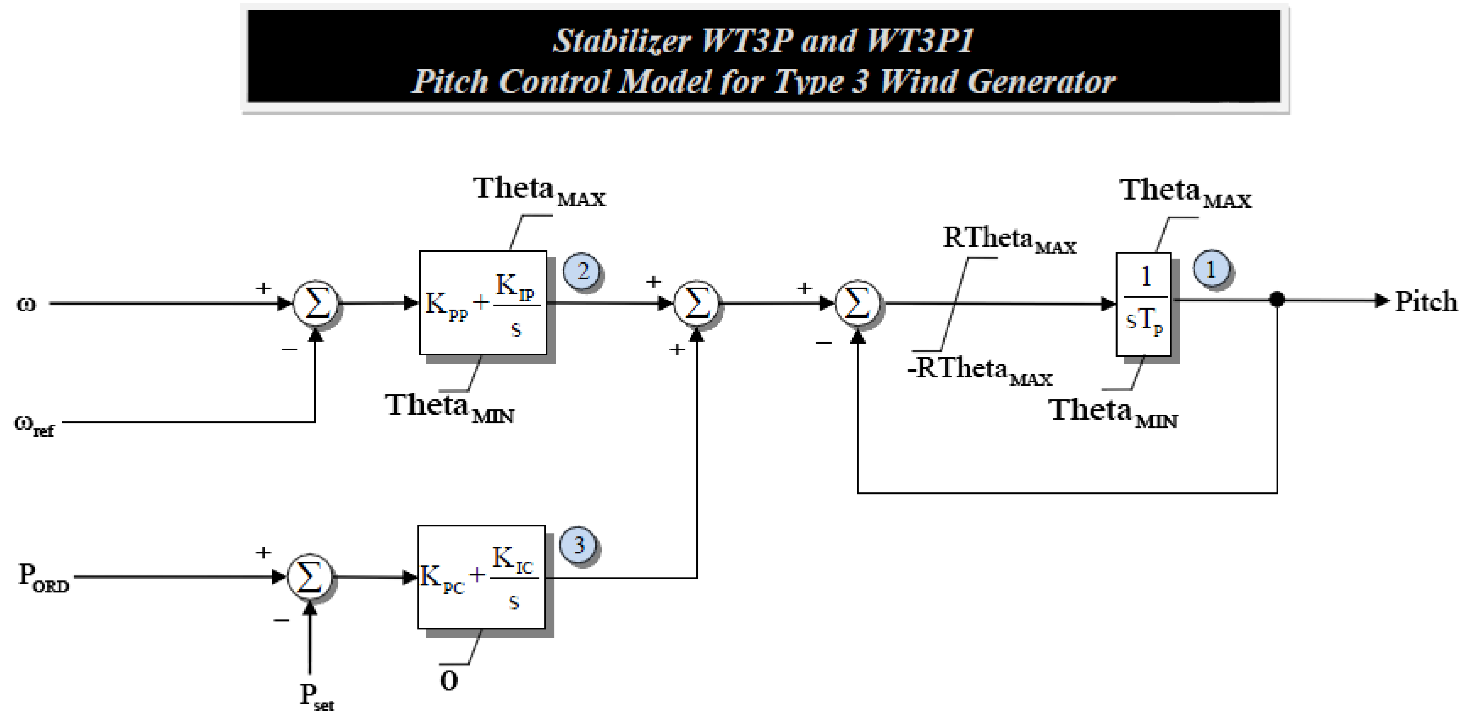
1 - TurbineSpeed
2 - ShaftAngle
3 - GenSpeed
4 - GenDeltaAngle

$H_t = H \times H_{tfrac}$

$H_g = H - H_t$

$$K = \frac{2H_t \times H_g \times (2\pi \times Freq1)^2}{H}$$

# WT3P Model (Pitch Control)




**States**

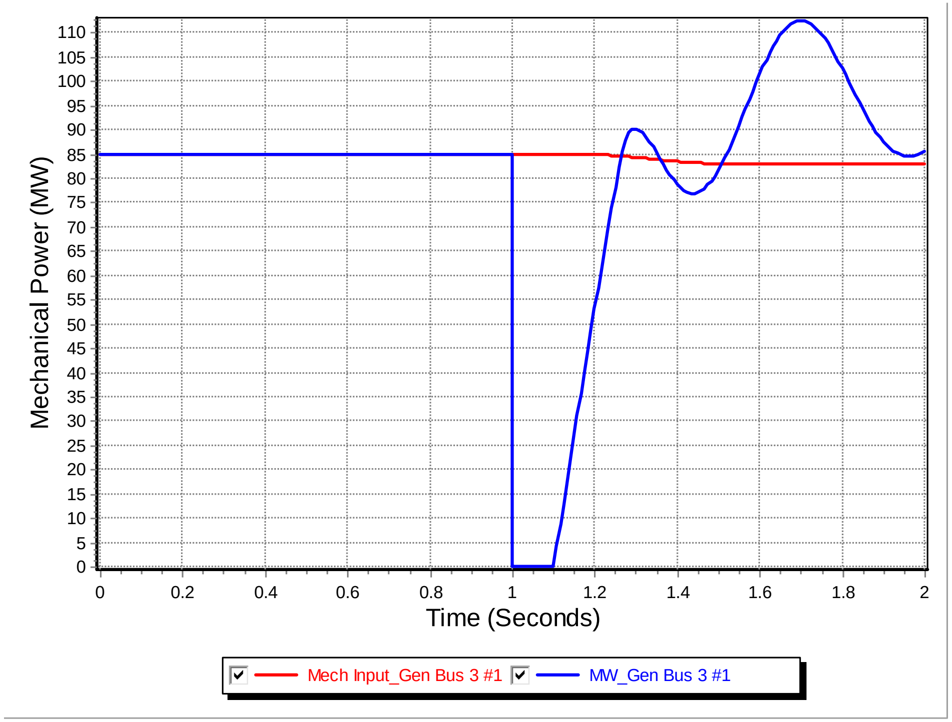
1 - Pitch

2 - PitchControl

3 - PitchComp

# Type 3 Example Case

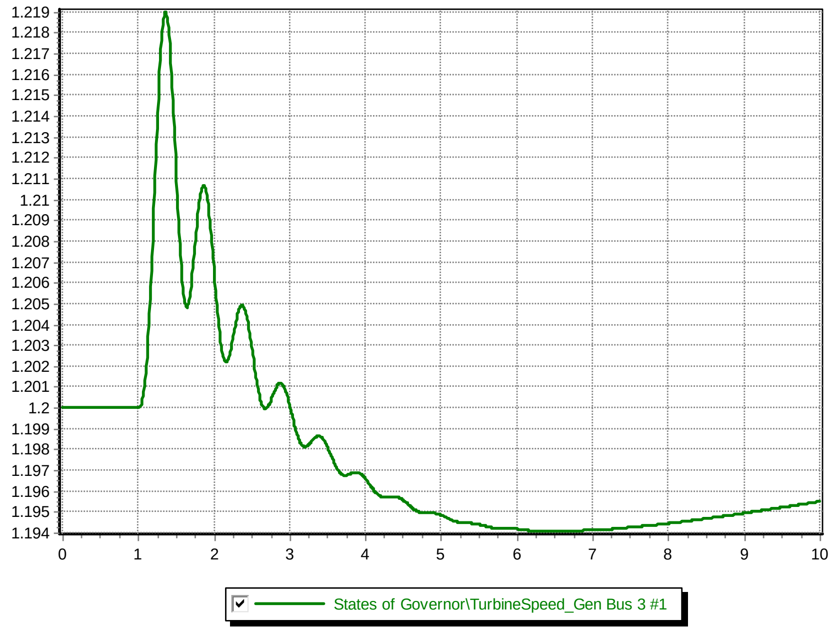
- Previous WSCC case, with the same line 6 to 9 fault, is modified so gen 3 is represented by a WT3G, WT3E, WT3T, and WT3P

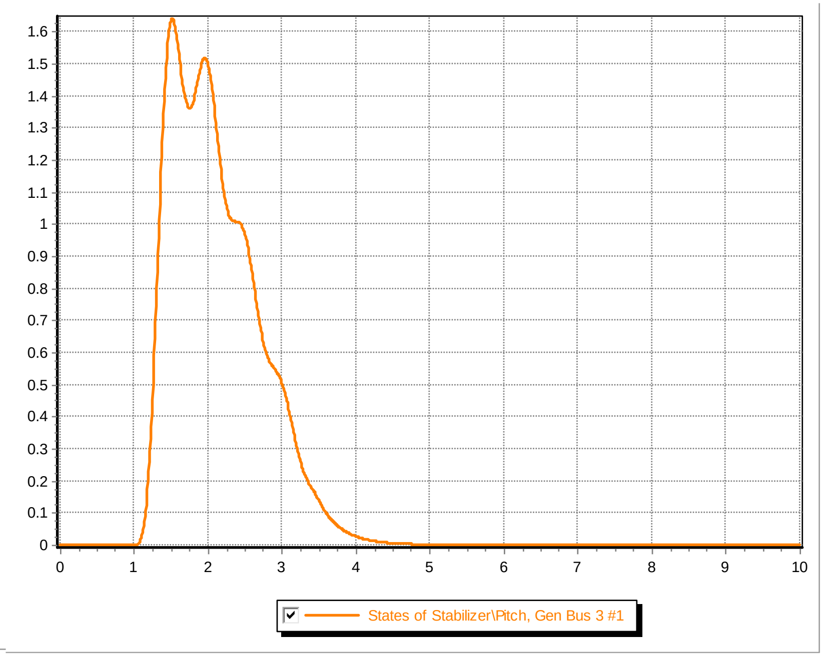



Graph at left shows a zoomed (2 second) view of the gen 3 real power output, with the value falling to zero during the fault, and then ramping back up

# Type 3 Example Case

- Below graphs show the response of the WTG speed and blade angle



# 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

# Example: Siemens SWT-2.3-113

- The Siemens-2.3-113 is a 2.3 MW WTG that has a rotor diameter of 113m. It is a gearless design based on a compact permanent magnet generator
  - No excitation power, slip rings or excitation control system

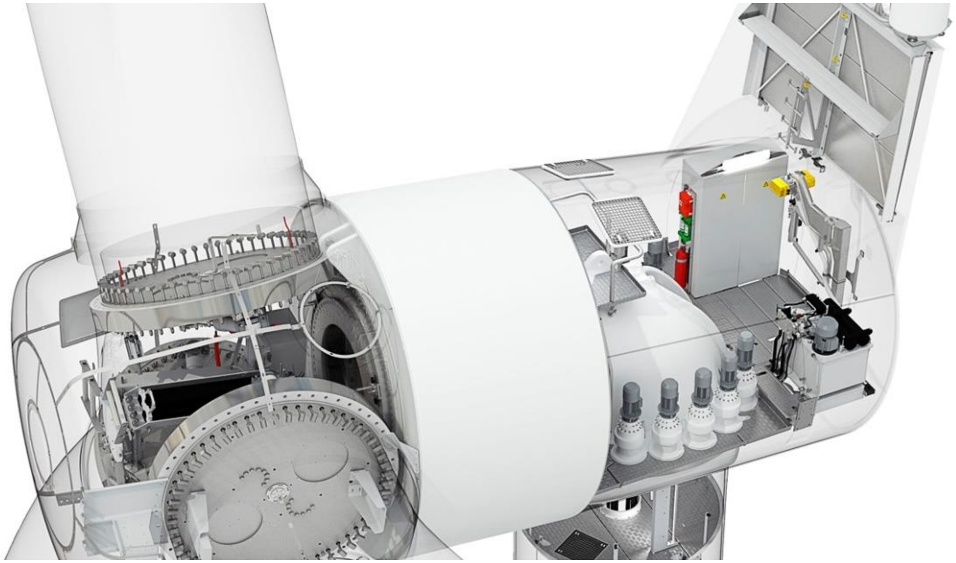
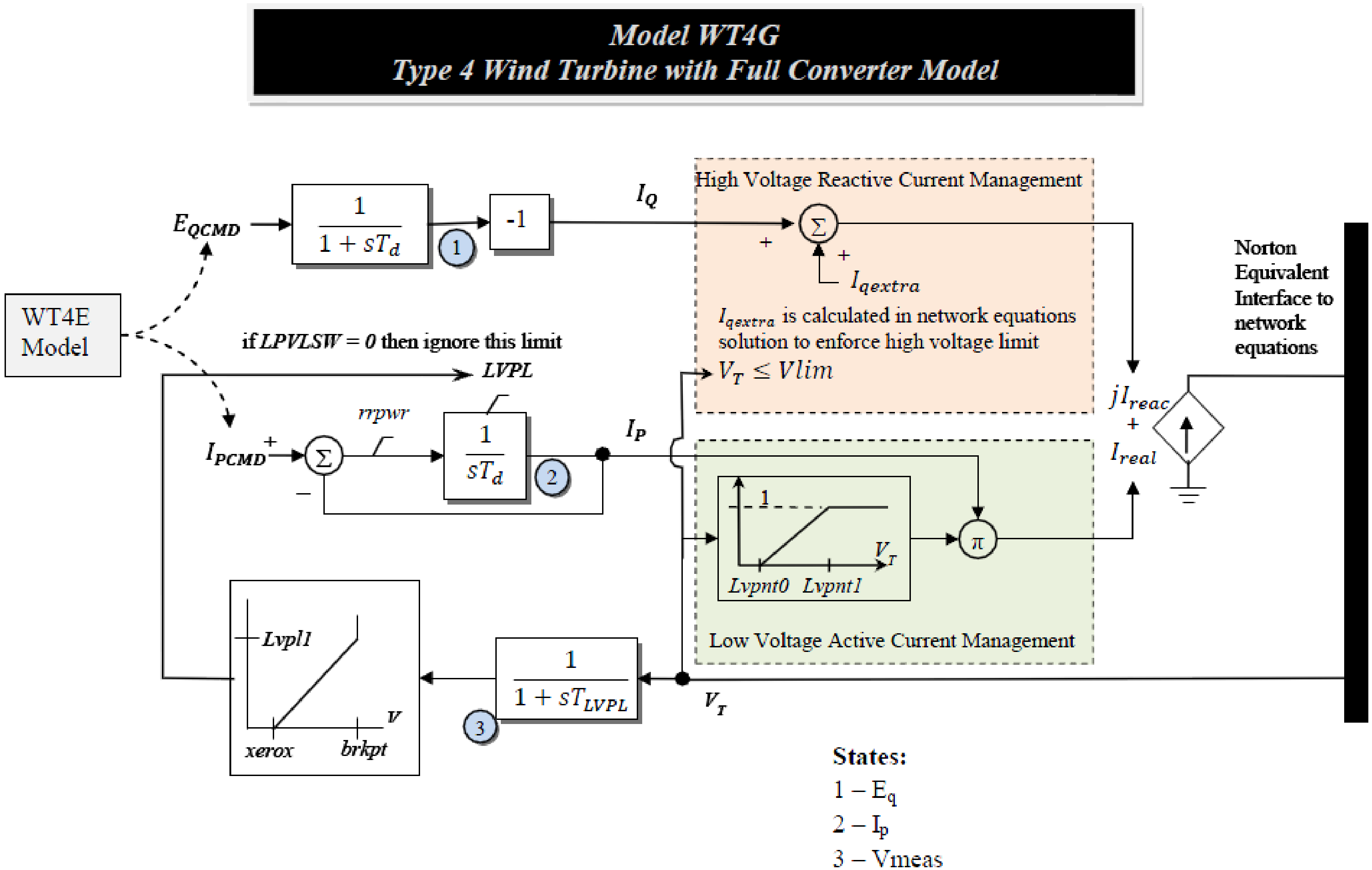


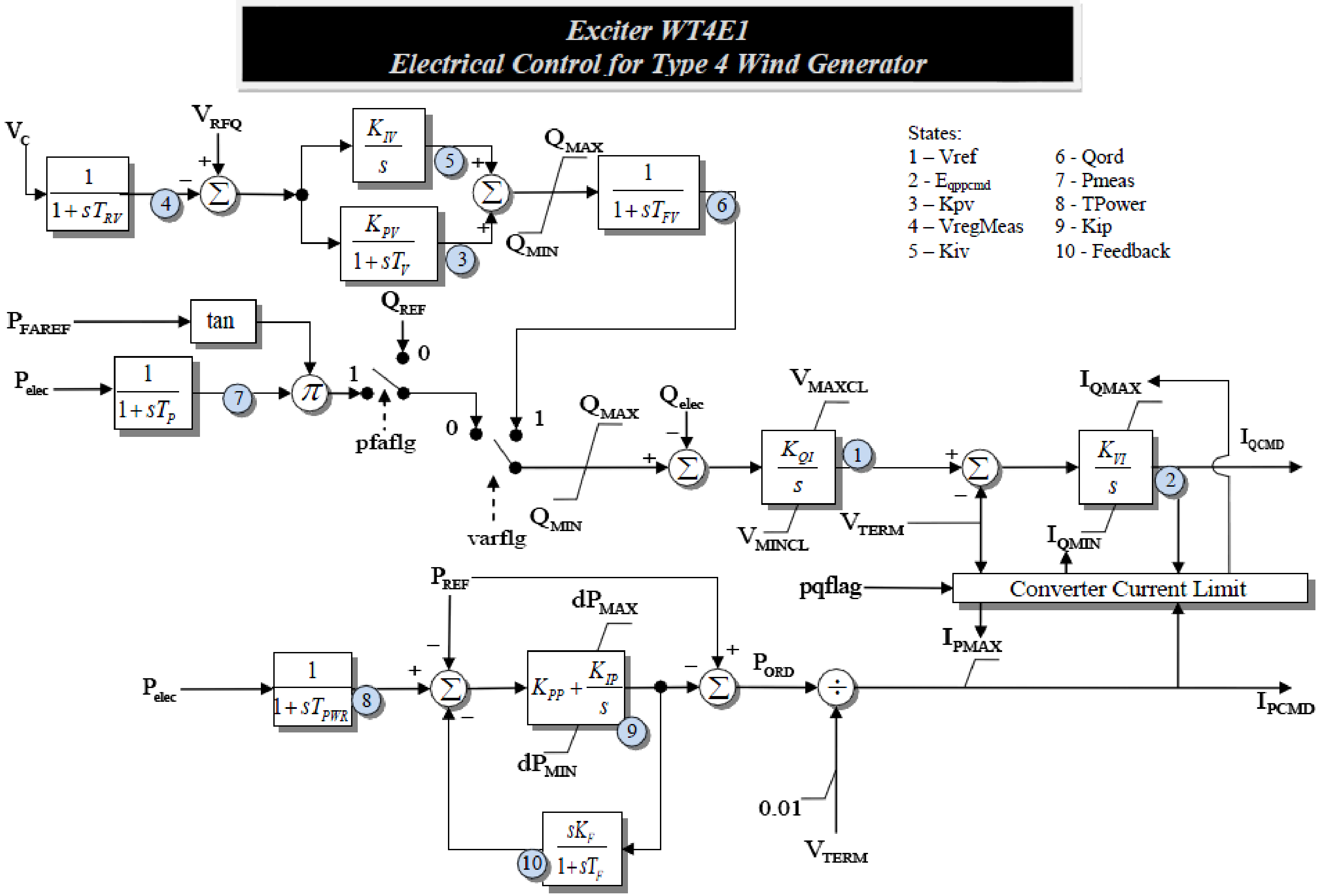
Image: www.siemens.com/press/pool/de/pressebilder/2011/renewable_energy/300dpi/soere201103-02_300dpi.jpg

# Type WTG4 Model




Very similar to the WTG3, except there is no X"

# Type 4 Reactive Power Control

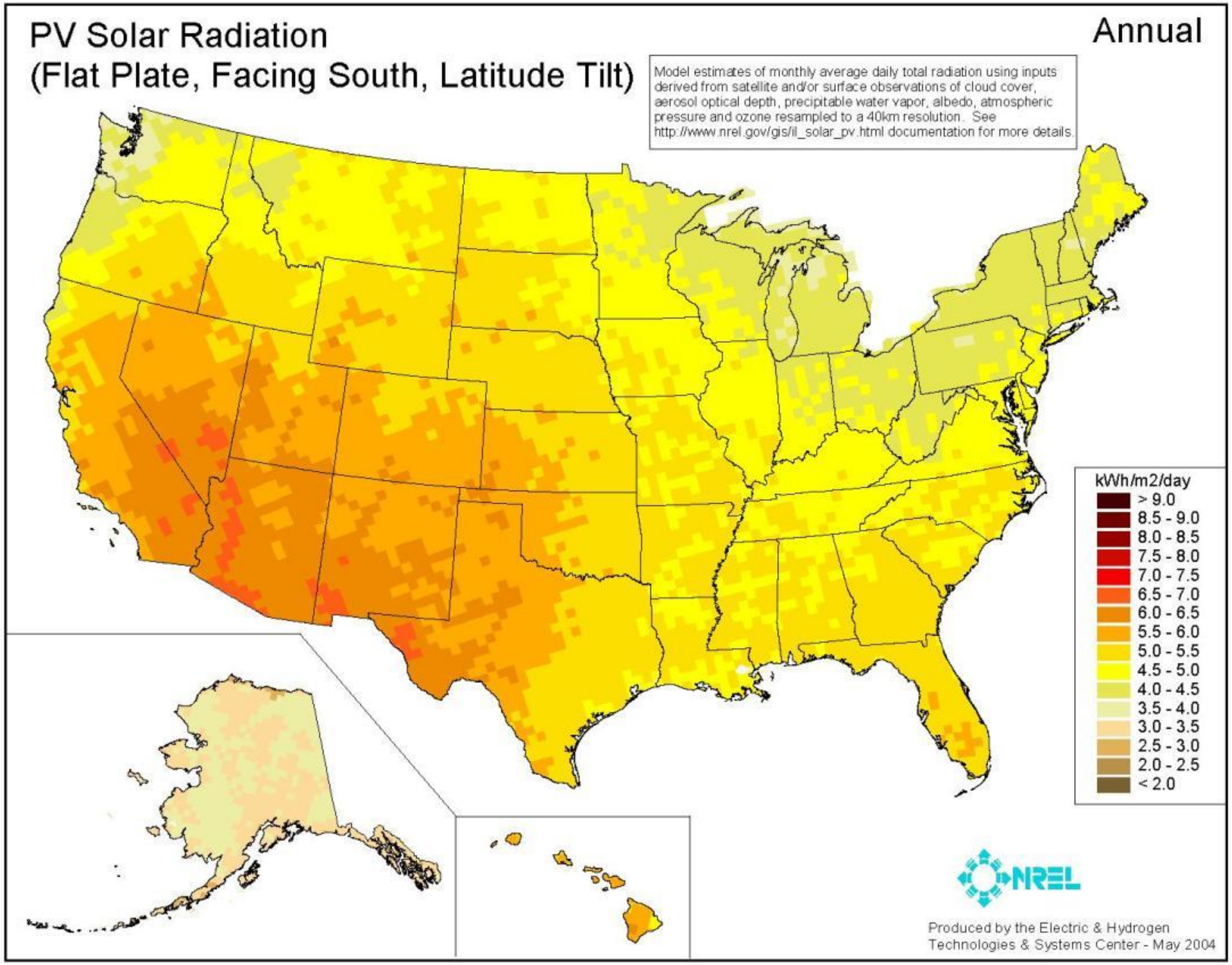



Also similar to the Type 3's, as are the other models

# Solar Photovoltaic (PV)

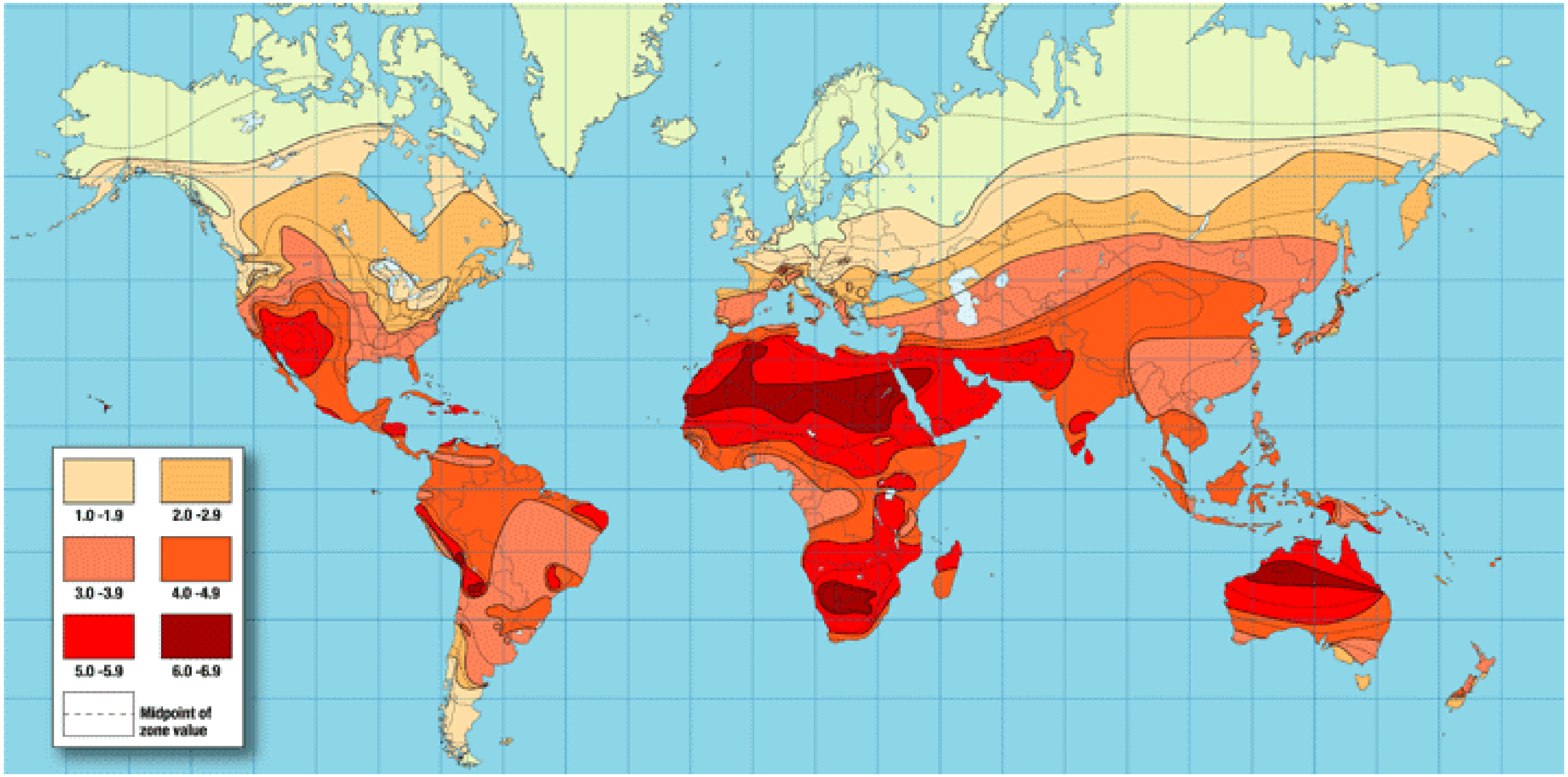
- **Photovoltaic definition-** a material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current
- Solar cells are diodes, creating dc power, which in grid applications is converted to ac by an inverter
- For terrestrial applications, the capacity factor is limited by night, relative movement of the sun, the atmosphere, clouds, shading, etc
  – A ballpark figure for Illinois is 18%
  – "One sun" is defined a 1 kw/m$^2$,which is the maximum insolation the reaches the surface of the earth (sun right overhead)

# US Annual Insolation




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

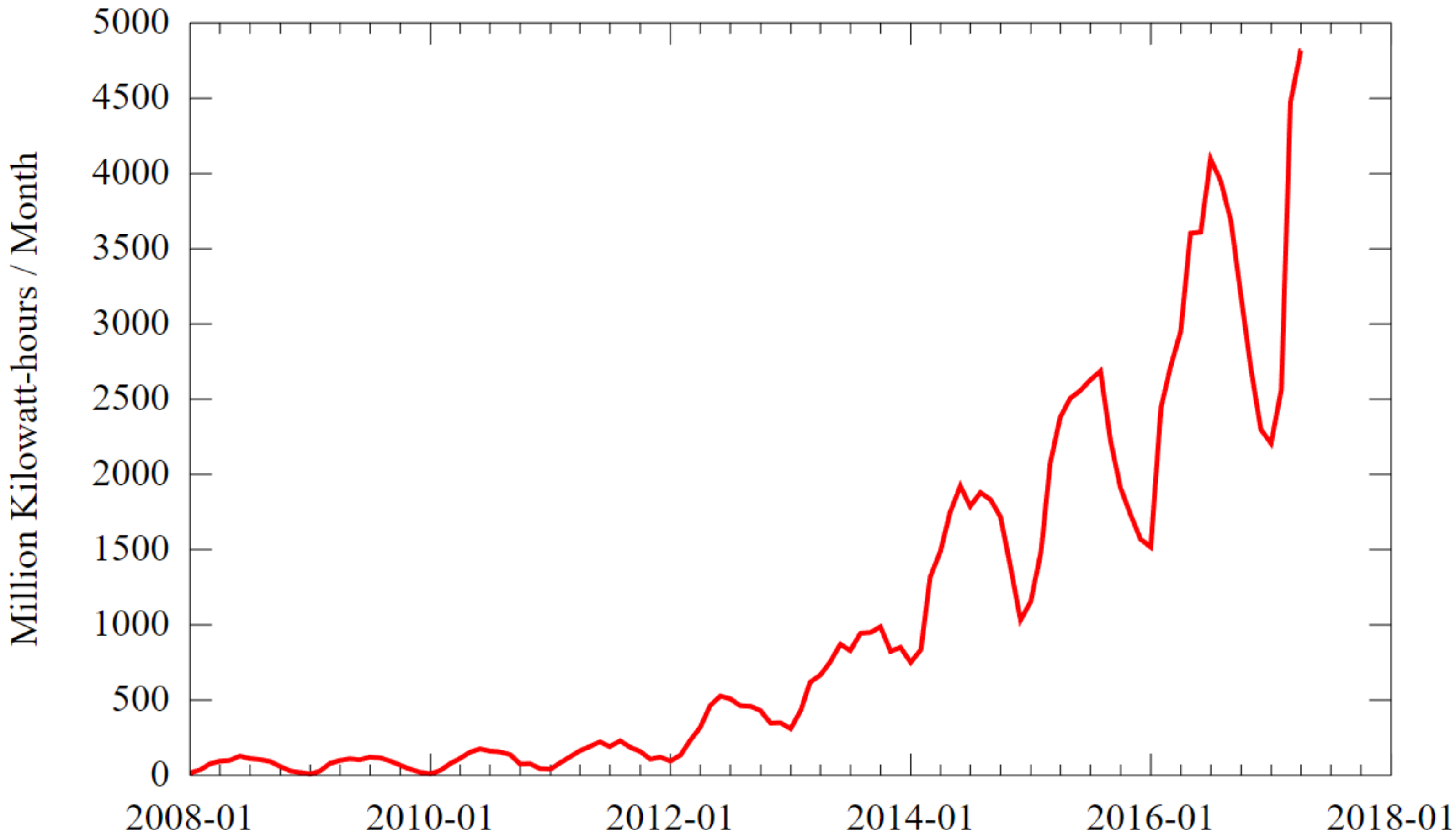
# Worldwide Annual Insolation




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);

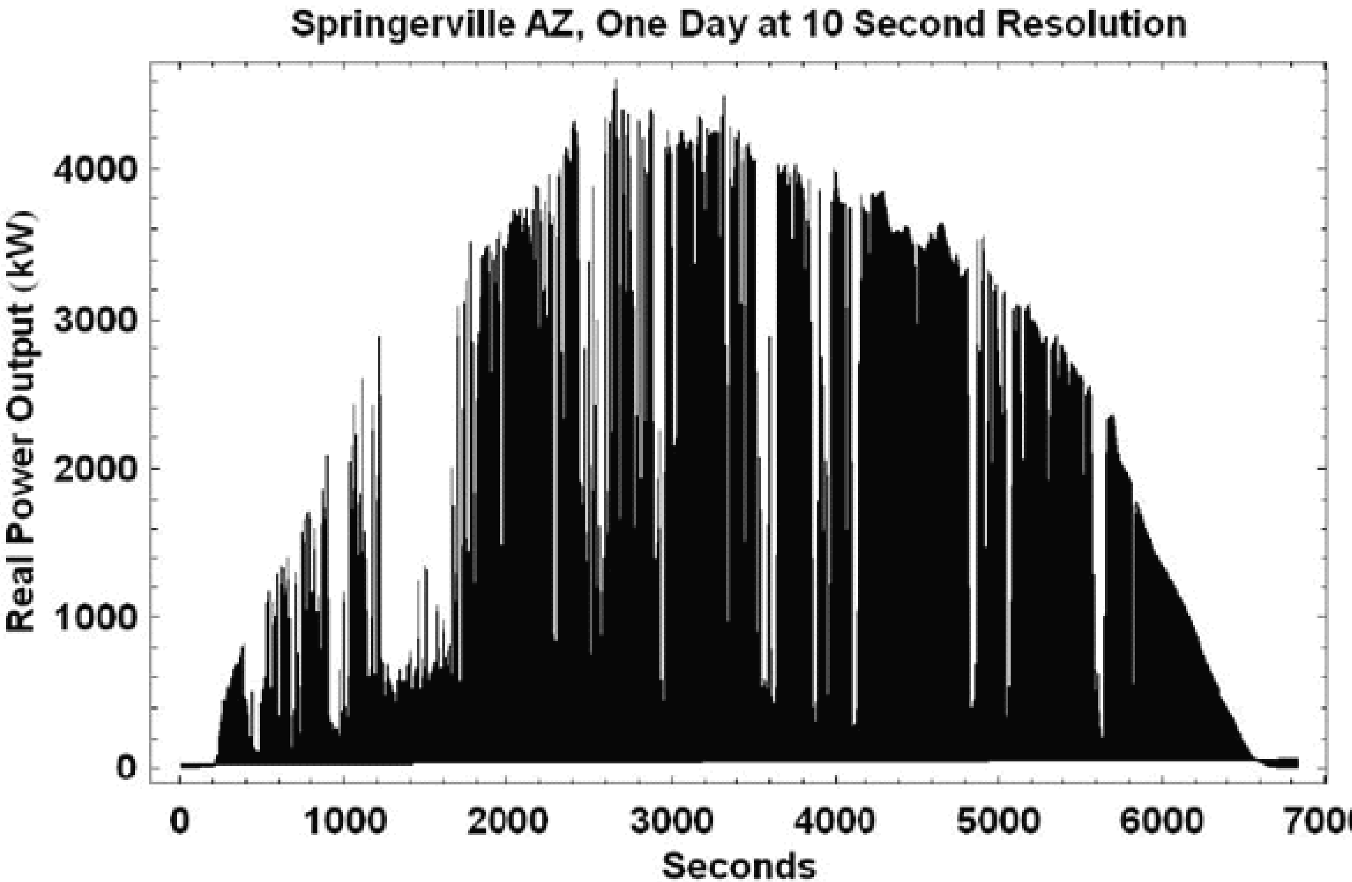
In just 2016 China added 34.5 GW, US 14.7, Japan 8.6, Indian 4 GW

# US Solar Generated Electricity




https://upload.wikimedia.org/wikipedia/commons/4/4e/US_Monthly_Solar_Power_Generation.svg

# Solar PV can be Quite Intermittent Because of Clouds




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

Image: http://www.megawattsf.com/gridstorage/gridstorage.htm

# Modeling Solar PV

- Since a large portion of the solar PV is distributed in small installations in the distribution system (e.g., residential rooftop), solar PV modeling is divided into two categories
  - Central station, which is considered a single generation plant
  - As part of the load model

# Central Station PV System Modeling

- The below block diagram shows the overall structure

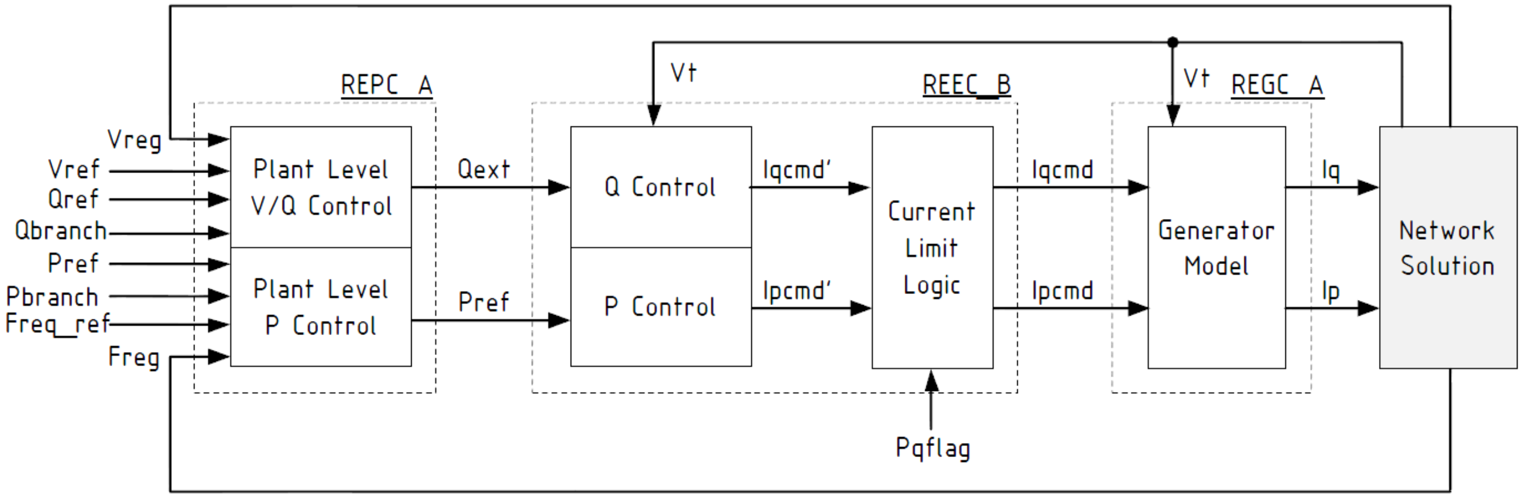



Figure 1. Overall Model Structure for Central Station PV System

Solar PV has no inertia, and in contrast to wind there is not even the ability to mimic an inertia response since there is no energy storage in the system

Source: "Generic Solar Photovoltaic System Dynamic Simulation Model Specification," WECC Renewable Energy Modeling Task Force, Sept. 2012 (same source for figures on the next three slides)

# Central Station PV System Modeling

- The generator model is similar to the Type 4 wind model, which is not surprising since this is modeling the converter operation

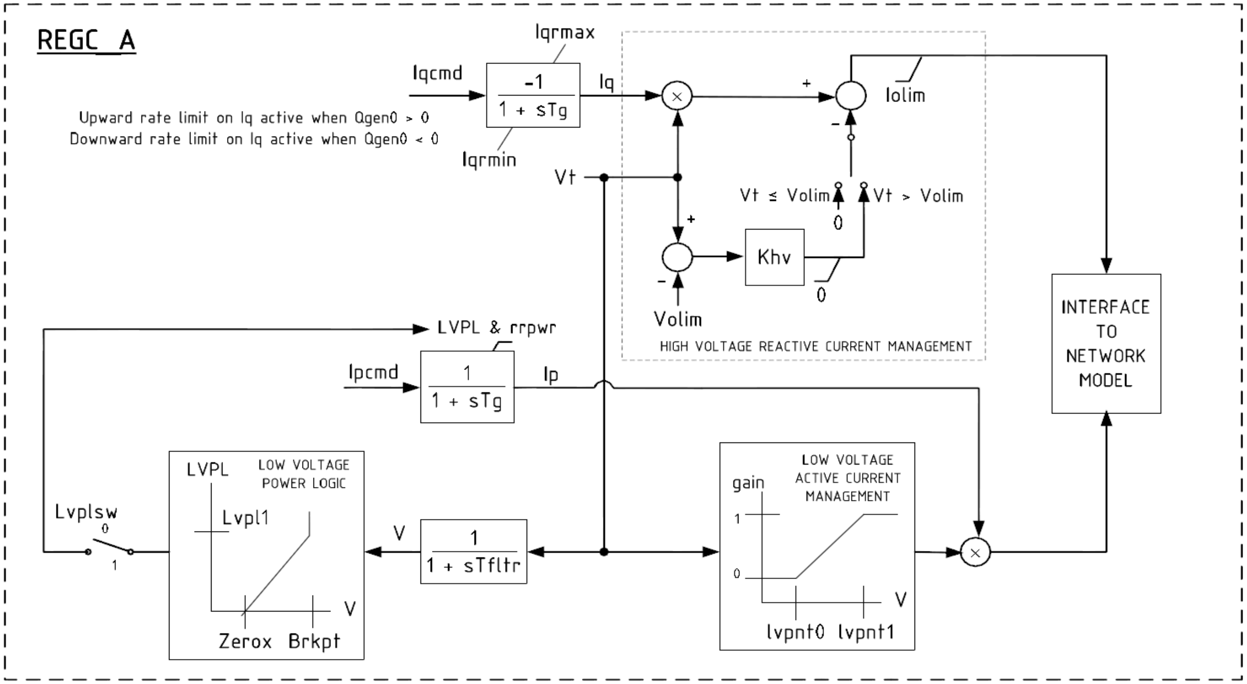



Figure 2. REGC_A Model Block Diagram

Source: "Generic Solar Photovoltaic System Dynamic Simulation Model Specification," WECC Renewable Energy Modeling Task Force, Sept. 2012

# 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

- 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