ECEN 667
Power System Stability

Lecture 24: Direct Methods (Overview), Modeling Wind and Solar

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Announcements

- Read Chapters 8 and 9 (8.6 covers stabilizers)
- Homework 7 should be done before the second exam
- As noted in the syllabus, the second exam is on Thursday Nov 30, 2023
  - On campus students will take it during class (80 minutes) whereas distance learning students should contact Sanjana.
  - The exam is comprehensive, but emphasizes the material since the first exam; it will be of similar form to the first exam
  - Two 8.5 by 11 inch hand written note sheets are allowed, front and back, as are calculators

Stability Phenomena and Tools

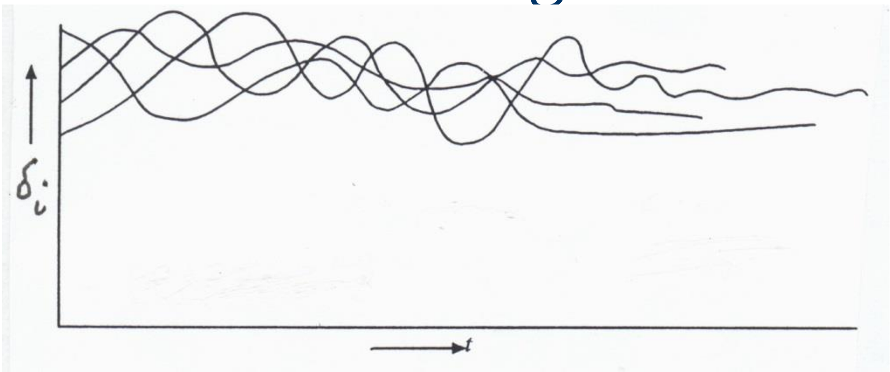
- Large Disturbance Stability (Non-linear Model)
- Small Disturbance Stability (Linear Model)
- Structural Stability (Non-linear Model)
- <u>Tools</u>
  - Simulation
  - Repetitive time-domain simulations are required to find critical parameter values, such as clearing time of circuit breakers.
  - Direct methods using Lyapunov-based theory (also called Transient Energy Function (TEF) methods)
    - Can be useful for screening
  - Sensitivity based methods.

Transient Energy Function (TEF) Techniques

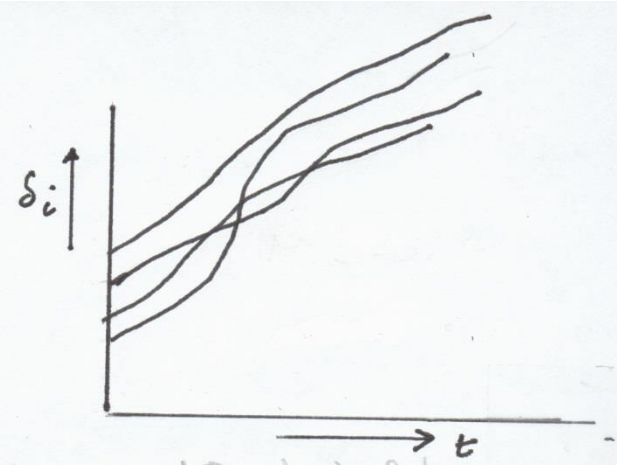
- No repeated simulations are involved.
- Limited somewhat by modeling complexity.
- Energy of the system used as Lyapunov function.
- Computing energy at the “controlling” unstable equilibrium point (CUEP) (critical energy).
- CUEP defines the mode of instability for a particular fault.
- Computing critical energy is <u>not</u> easy.

Judging Stability / Instability

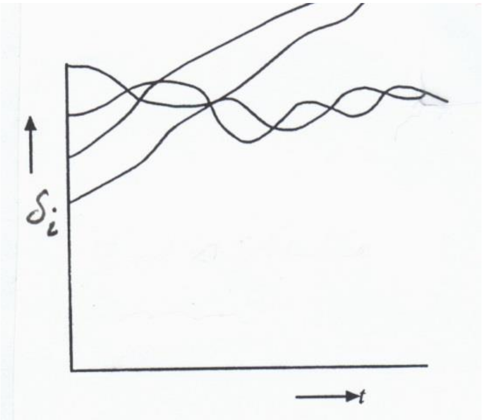
Monitor Rotor Angles



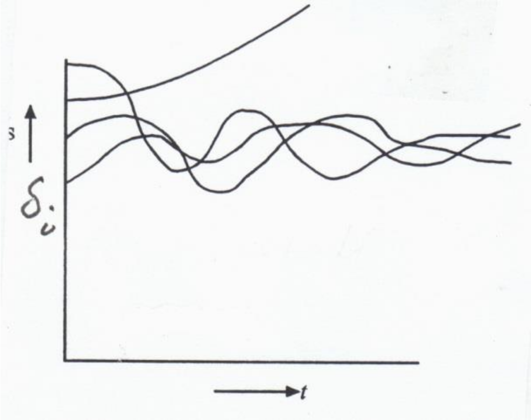
(a) Stable



(b) Stable



(c) Unstable



(d) Unstable

Stability is judged by Relative Rotor Angles.

Mathematical Formulation

- A power system undergoing a disturbance (fault, etc), followed by clearing of the fault, has the following model

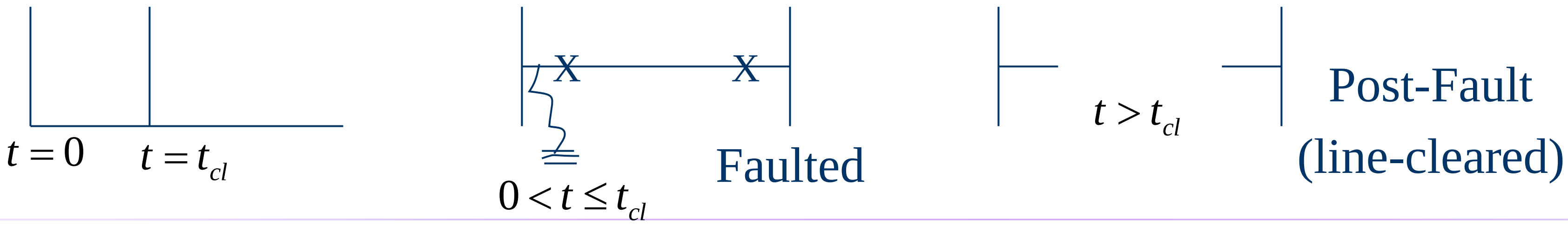
$$\dot{\mathbf{x}}(t) = \mathbf{f}^{\mathbf{I}}(\mathbf{x}(t)) \quad -\infty < t \leq 0 \qquad (1)$$

$$\dot{\mathbf{x}}(t) = \mathbf{f}^{\mathbf{F}}(\mathbf{x}(t)) \quad 0 < t \leq t_{cl} \qquad (2)$$

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t)) \quad t_{cl} < t \leq \infty \qquad (3)$$

T_{cl} is the clearing time

  - (1) Prior to fault (Pre-fault)
  - (2) During fault (Fault-on or faulted)
  - (3) After the fault (Post-fault)

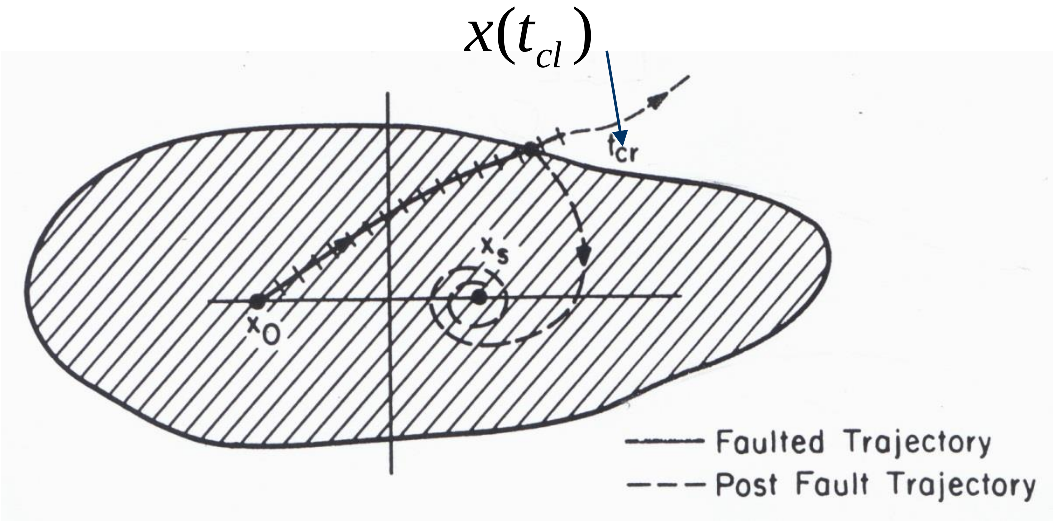


Critical Clearing Time

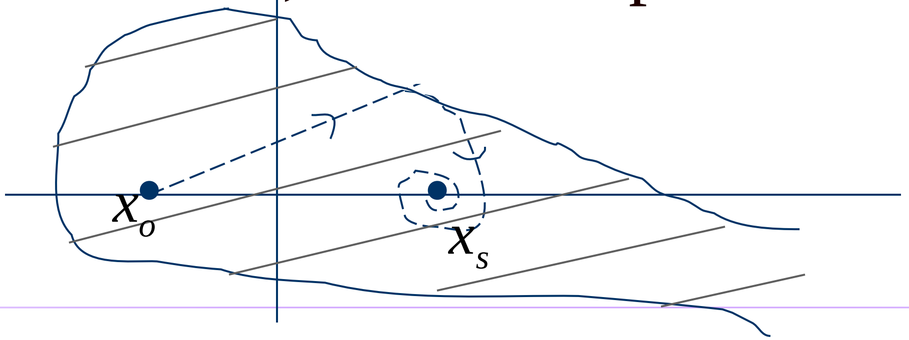
- Assume the post-fault system has a stable equilibrium point $\mathbf{x}_s$
- All possible values of $\mathbf{x}(t_{cl})$ for different clearing times provide the initial conditions for the post-fault system
  - Question is then will the trajectory of the post fault system, starting at $\mathbf{x}(t_{cl})$, converge to $\mathbf{x}_s$ as $t \rightarrow \infty$
- Largest value of t_{cl} for which this is true is called the critical clearing time, t_{cr}
- The value of t_{cr} is different for different faults

Region of Attraction (ROA)

All faulted trajectories cleared before they reach the boundary of the ROA will tend to $\mathbf{x}_s$ as $t \to \infty$ (stable)



The region need not be closed; it can be open:



Methods to Compute RoA

- Had been a topic of research in power system literature since early 1960’s.
- The stable equilibrium point (SEP) of the post-fault system, $\mathbf{x}_s$, is generally close to the pre-fault EP, $\mathbf{x}_0$
- Surrounding $\mathbf{x}_s$ there are a number of unstable equilibrium points (UEPs).
- The boundary of ROA is characterized via these UEPs

$$\mathbf{x}_{u,i}\ , i = 1, 2 \ldots$$

$$\mathbf{f}(\mathbf{x}) = 0 \quad i.e. \quad \mathbf{f}(\mathbf{x}_{u,i}) = 0 \quad i = 1, 2 \ldots$$

Characterization of RoA

- Define a scalar energy function V(**x**) = sum of the kinetic and potential energy of the post-fault system.
- Compute $V(\mathbf{x}_{u,i})$ at each UEP, i=1,2,…
- Defined V_{cr} as

$$V_{cr} = Min\ V(\mathbf{x})\Big|_{\mathbf{x}_{u,i}}$$

  - RoA is defined by $V(\mathbf{x}) < V_{cr}$
  - But this can be an extremely conservative result.
- Alternative method: Depending on the fault, identify the critical UEP, $\mathbf{x}_{u,cr}$, towards which the faulted trajectory is headed; then $V(\mathbf{x}) < V(\mathbf{x}_{u,cr})$ is a good estimate of the ROA.

Lyapunov's Method

- Defining the function V(**x**) is a key challenge
- Consider the system defined by

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}), \quad \mathbf{f}(\mathbf{x}_s) = \mathbf{0}$$

- Lyapunov's method: If there exists a scalar function V(**x**) such that

1) $V(\mathbf{x}_s) = 0$

2) $V(\mathbf{x}) > 0$ for all $\mathbf{x}$ around $\mathbf{x}_s$

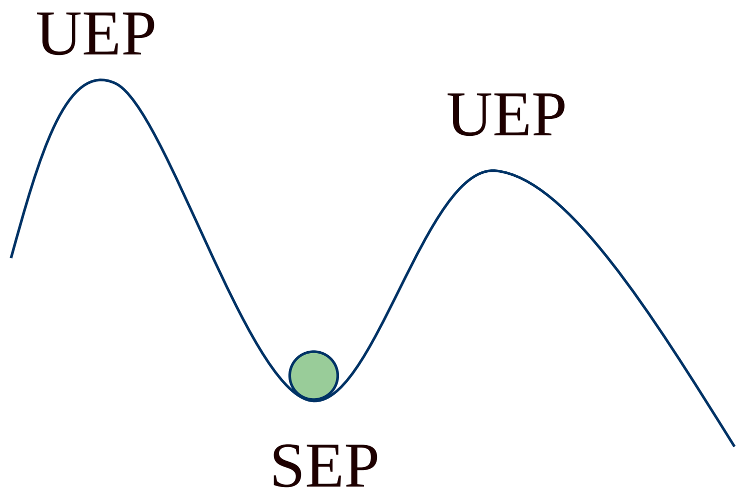
3) $\dot{V}(\mathbf{x}) \leq 0$ for all $\mathbf{x}$ around $\mathbf{x}_s$

Then $\mathbf{x}_s$ is stable in the sense of Lyapunov

EP $\mathbf{x}_s$ is asympotically stable if $\dot{V}(\mathbf{x}) < 0$ for $\mathbf{x} \neq \mathbf{x}_s$ around $\mathbf{x}_s$

Ball in Well Analogy

- The classic Lyapunov example is the stability of a ball in a well (valley) in which the Lyapunov function is the ball's total energy (kinetic and potential)



- For power systems, defining a true Lyapunov function often requires using restrictive models

Power System Example

- Consider the classical generator model using an internal node representation (load buses have been equivalenced)

$$M_i \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i - \sum_{\substack{j=1 \\ j\neq i}}^{m} (C_{ij} \sin\delta_{ij} + D_{ij}\cos\delta_{ij})$$

$$P_i = T_{Mi} - E_i^2 G_{ii}$$

C_{ij} are the susceptance terms, D_{ij} the conductance terms

Functionally

$$M_i \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i - P_{ei}(\delta_1, \ldots, \delta_m) \qquad i = 1, \ldots, m$$

$$\dot{\delta}_i = \omega_i - \omega_s$$

$$\dot{\omega}_i = \frac{1}{M_i}\left(P_i - P_{ei}(\delta_i, \ldots, \delta_m) - D_i(\omega_i - \omega_s)\right)$$

Constructing the Transient Energy Function (TEF)

- The reference frame matters. Either relative rotor angle formulation, or COI reference frame.
  - COI is preferable since we measure angles with respect to the “mean motion” of the system.
- TEF for conservative system (i.e., zero damping)

$\delta_o = \frac{1}{M_T}\sum_{i=1}^{m} M_i \delta_i$ With center of speed as $\omega_o = \frac{1}{M_T}\sum_{i=1}^{m} M_i \omega_i$

where $M_T = \sum_{i=1}^{m} M_i$. We then transform the variables to the

COI variables as $\theta_i = \delta_i - \tilde{\delta}_o$, $\omega_i = \omega_i - \omega_o$.

It is easy to verify $\dot{\theta}_i = \dot{\delta}_i - \dot{\delta}_o = \omega_i - \tilde{\omega}_o \triangleq \omega_i$

TEF

- We consider the general case in which all M_i's are finite. We have two sets of differential equations:

$$M_i \frac{d\tilde{\omega}_i}{dt} = f_i^F(\theta) \quad 0 < t \le t_{cl} \qquad (Faulted)$$

$$\frac{d\theta_i}{dt} = \tilde{\omega}_i, \quad i = 1, 2, ..., m$$

And

$$M_i \frac{d\tilde{\omega}_i}{dt} = f_i(\theta) \quad t > t_{cl} \qquad (Post\ fault)$$

$$\frac{d\theta_i}{dt} = \tilde{\omega}_i, \quad i = 1, 2, ..., m$$

- Let the post fault system has a SEP at $\boldsymbol{\theta} = \boldsymbol{\theta}^s, \tilde{\boldsymbol{\omega}} = \mathbf{0}$
- This SEP is found by solving

$$\mathbf{f}_i(\boldsymbol{\theta}) = \mathbf{0}, \; i = 1, .., m$$

TEF

- Steps for computing the critical clearing time are:
  - Construct a Lyapunov (energy) function for the post-fault system.
  - Find the critical value of the Lyapunov function (critical energy) for a given fault
  - Integrate the faulted equations until the energy is equal to the critical energy; this instant of time is called the critical clearing time
- Idea is once the fault is cleared the energy can only decrease, hence the critical clearing time is determined directly
- Methods differ as to how to implement steps 2 and 3.

Potential Energy Boundary Surface

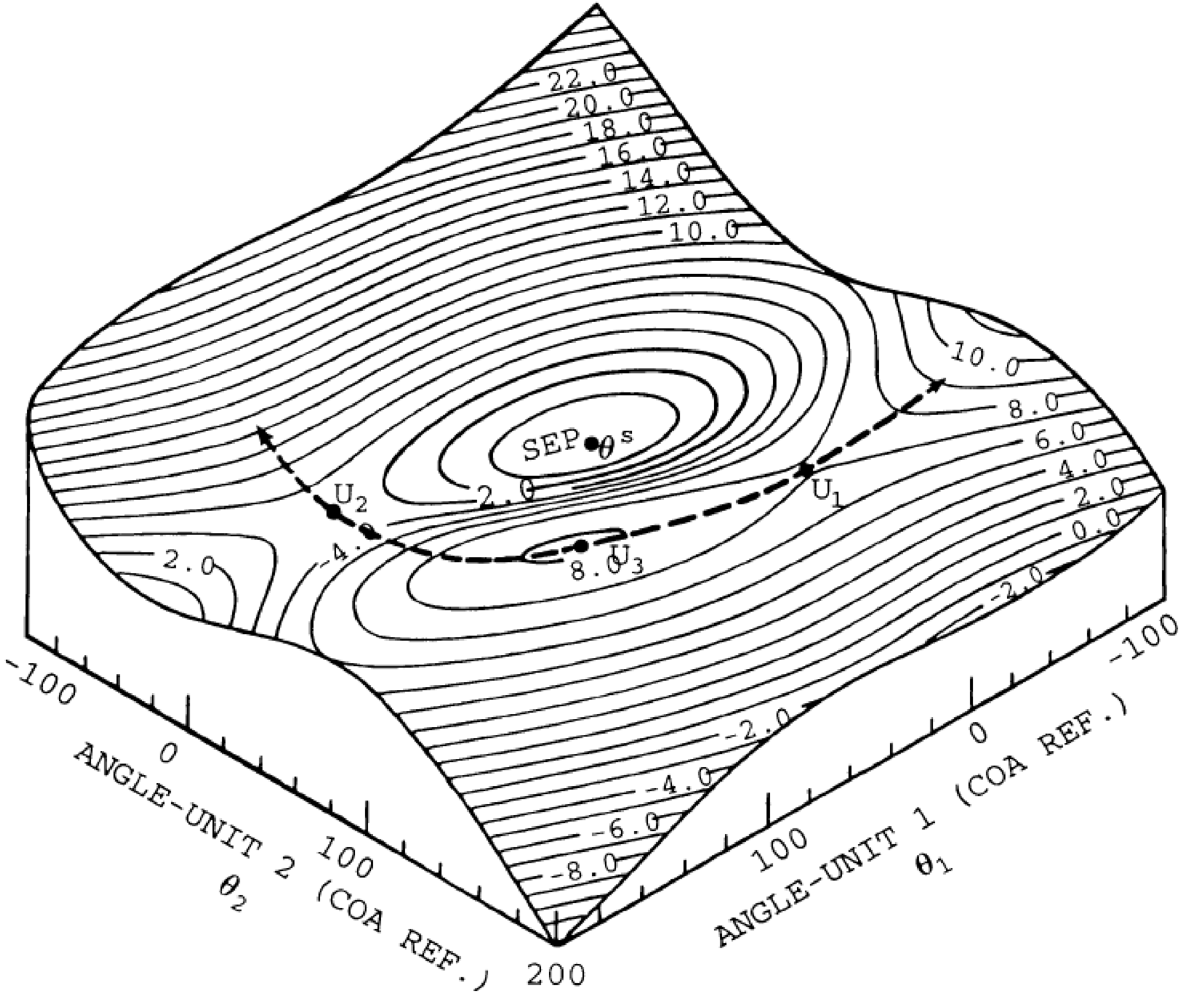


Figure 9.10: The potential energy boundary surface (reproduced from [97])

Figure from course textbook

TEF

- Integrating the equations between the post-fault SEP and the current state gives

$$V(\theta,\omega)=\frac{1}{2}\sum_{i=1}^{m}M_i\omega_i^2-\sum_{i=1}^{m}\int_{\theta_i^s}^{\theta_i}f_i(\theta)d\theta_i$$

$$=\frac{1}{2}\sum_{i=1}^{m}M_i\omega_i^2-\sum_{i=1}^{m}P_i(\theta_i-\theta_i^s)-\sum_{i=1}^{m-1}\sum_{j=i+1}^{m}[C_{ij}(\cos\theta_{ij}-\cos\theta_{ij}^s)]$$

$$-\int_{\theta_i^s+\theta_j^s}^{\theta_i+\theta_j}D_{ij}\cos\theta_{ij}d(\theta_i-\theta_j)]$$

$$=V_{KE}(\omega)+V_{PE}(\theta)$$

C_{ij} are the susceptance terms, D_{ij} the conductance terms; the conductance term is path dependent

TEF

- $V(\boldsymbol{\theta}, \tilde{\boldsymbol{\omega}})$ contains path dependent terms.
- Cannot claim that $V(\boldsymbol{\theta}, \tilde{\boldsymbol{\omega}})$ is p.d.
- If conductance terms are ignored then it can be shown to be a Lyapunov function
- Methods to compute the UEPS are
  - Potential Energy Boundary Surface (PEBS) method.
  - Boundary Controlling Unstable (BCU) equilibrium point method.
  - Other methods (Hybrid, Second-kick etc)

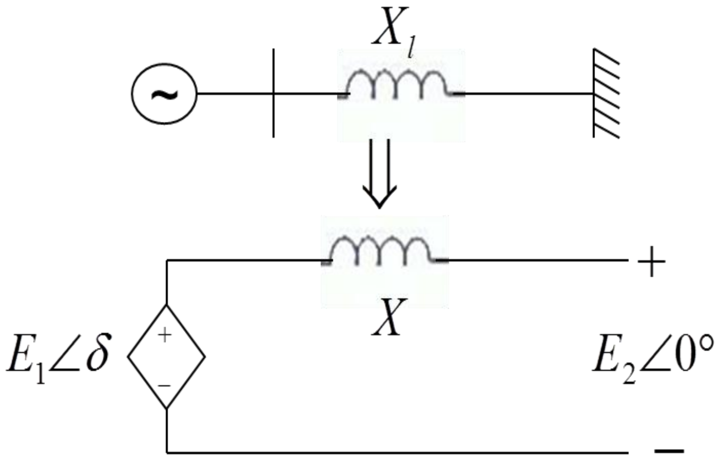
(a) and (b) are the most important ones.

Equal Area Criterion and TEF

- For an SMIB system with classical generators this reduces to the equal area criteria
  - TEF is for the post-fault system
  - Change notation from T_m to P_m

$$M\frac{d^2\delta}{dt^2} = P_m - P_e^{\max}\sin\delta \qquad (1)$$

$$P_e^{\max} = \frac{E_1 E_2}{X^I}\sin\delta \qquad (2)$$



$$X = X^F \quad (Faulted)$$

$$X = X^I \quad (Post-fault)$$

$$P_e = \frac{E_1 E_2}{X^F}\sin\delta \quad (Faulted)$$

$$P_e = \frac{E_1 E_2}{X^I}\sin\delta \quad (Post-fault)$$

TEF for SMIB System

$$M\frac{d^2\delta}{dt^2} = P_m - P_e^{max}\sin\delta \qquad (1)$$

The right hand side of (1) can be written as $-\frac{\partial V_{PE}}{\partial \delta}$,where

$$V_{PE}(\delta) = -P_m\delta - P_e^{max}\cos\delta \qquad (2)$$

Multiplying (1) by $\frac{d\delta}{dt}$, re-write

$$\frac{d}{dt}\left[\frac{M}{2}\left(\frac{d\delta}{dt}\right)^2 + V_{PE}(\delta)\right] = 0$$

$\frac{d\delta}{dt} = \omega$ since

$$\frac{d}{dt}\left[\frac{1}{2}M\omega^2 + V_{PE}(\delta)\right] = 0$$ i.e

$$\frac{d}{dt}[V(\delta,\omega)] = 0$$ i.e

Hence, the energy function is

$$V(\delta,\omega) = \frac{1}{2}M\omega^2 + V_{PE}(\delta)$$

TEF for SMIB System (contd)

- The equilibrium point is given by

$$0 = P_m - P_e^{\max} \sin \delta \qquad (1)$$

$$\delta^s = \sin^{-1}\left(\frac{P_m}{P_e^{\max}}\right) \qquad (2)$$

- This is the stable e.p.
- Can be verified by linearizing.
- Eigenvalues on jω axis. (Marginally Stable)
- With slight damping eigenvalues are in L.H.P.
- TEF is still constructed for undamped system.

TEF for SMIB System

- The energy function is

$$V(\delta,\omega) = V_{KE} + V_{PE}(\delta) = \tfrac{1}{2} M\omega^2 - P_m\delta - P_e^{\max}\cos\delta$$

- There are two UEP: $\delta^{u1} = \pi - \delta^s$ and $\delta^{u2} = -\pi - \delta^s$
- A change in coordinates sets $V_{PE}=0$ for $\delta=\delta^s$

$$V_{PE}(\delta,\delta^s) = -P_m(\delta-\delta^s) - P_e^{\max}(\cos\delta - \cos\delta^s)$$

- With this, the energy function is

$$V(\delta,\omega) = \tfrac{1}{2} M\omega^2 - P_m(\delta-\delta^s) - P_e^{\max}(\cos\delta - \cos\delta^s)$$

$$= V_{KE} + V_{PE}(\delta,\delta^s)$$

- The kinetic energy term is $V_{KE} = \tfrac{1}{2} M\omega^2$

Equal-Area Criterion

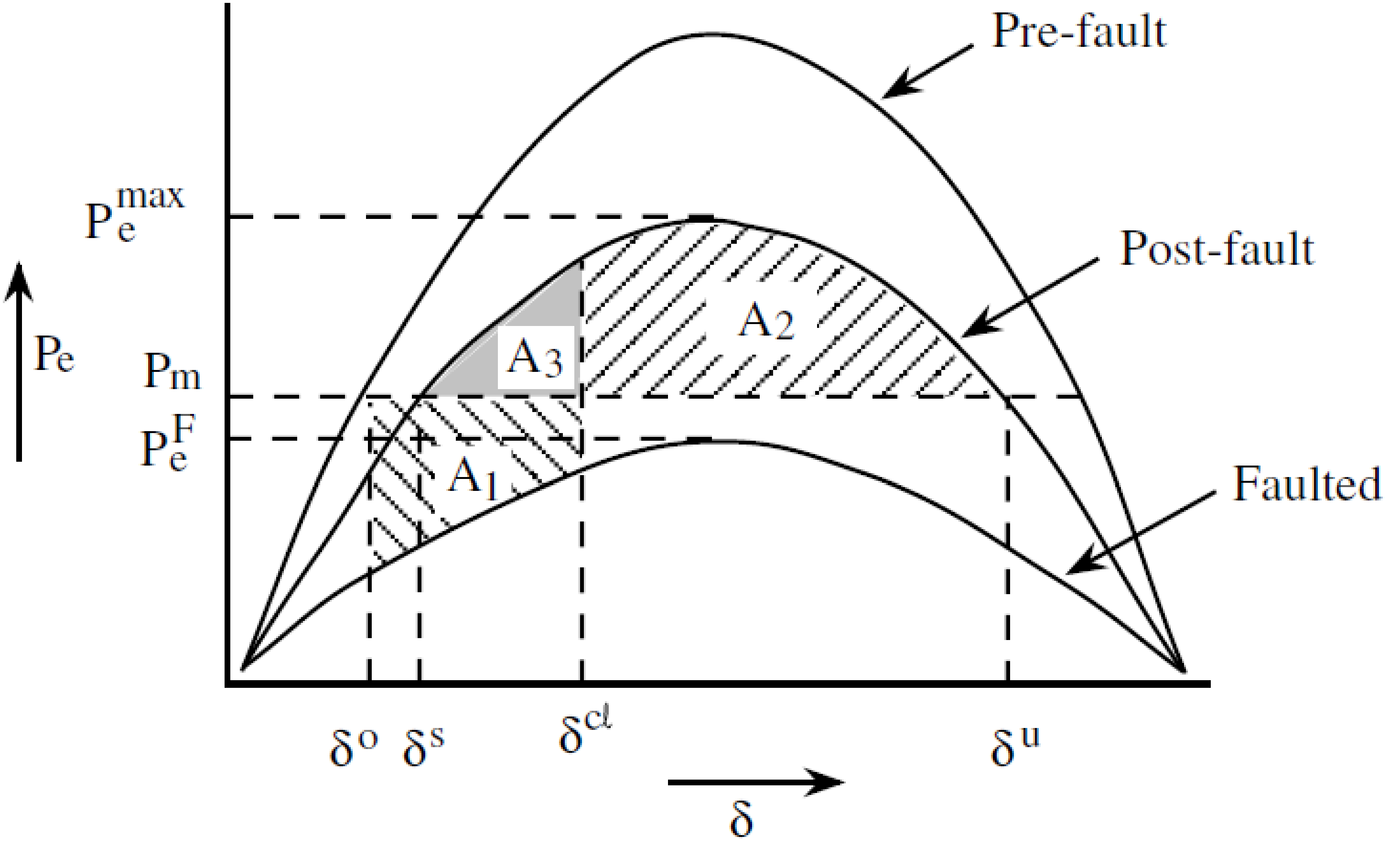


Figure 9.9: Equal-area criterion for the SMIB case

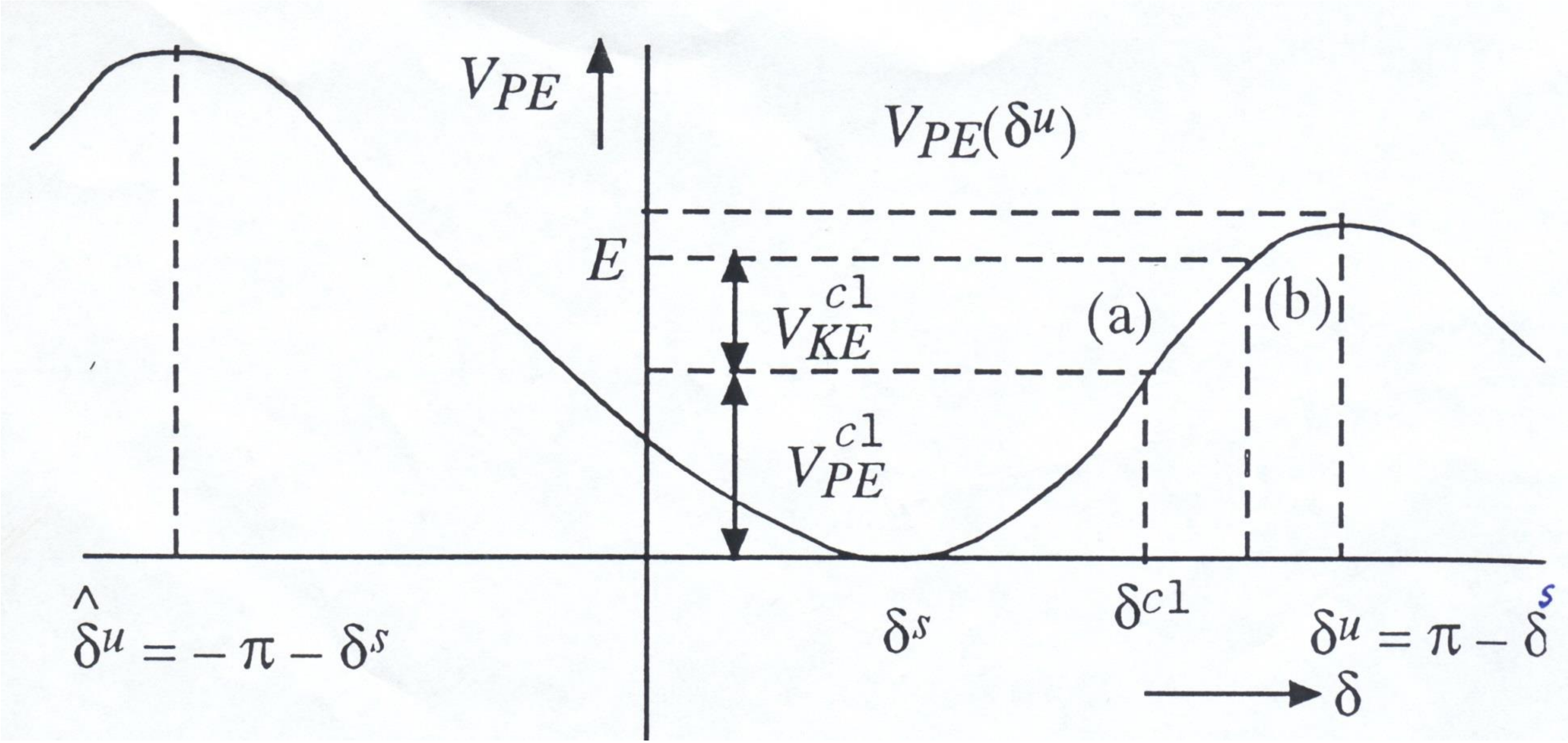
During the fault A_1 is the gain in the kinetic energy and A_3 the gain in potential energy

Figure from course textbook

Energy Function for SMIB System

- $V(\delta,\omega)$ is equal to a constant E, which is the sum of the kinetic and potential energies.
- It remains constant once the fault is cleared since the system is conservative (with no damping)
- $V(\delta,\omega)$ evaluated at $t=t_{cl}$ from the fault trajectory represents the total energy *E* present in the system at $t=t_{cl}$
- This energy must be absorbed by the system once the fault is cleared if the system is to be stable.
- The kinetic energy is always positive, and is the difference between *E* and $V_{PE}(\delta, \delta^s)$

Potential Energy Well for SMIB System



We need to compute the energy (E) and the boundary energy

Structure Preserving Energy Function

- If we retain the power flow equations

$$\dot{\theta}_i = \omega_i - \omega_s \quad (9.69)$$

$$M_i\dot{\omega}_i = T_{Mi} - \sum_{j=1}^{n+m} V_i V_j B_{ij} \sin(\theta_i - \theta_j)$$

$$i = n+1, \ldots, n+m \quad (9.70)$$

$$P_{Li}(V_i) = \sum_{j=1}^{n+m} V_i V_j B_{ij} \sin(\theta_i - \theta_j) \;\; i = 1, \ldots, n \quad (9.71)$$

$$Q_L(V_i) = -\sum_{j=1}^{n+m} V_i V_j B_{ij} \cos(\theta_i - \theta_j) \;\; i = 1, \ldots, n. \quad (9.72)$$

Structure Preserving Energy Function

- Then we can get the following energy function

$$V(\tilde{\omega}, \tilde{\theta}, V) = V_{KE}(\tilde{\omega}) + V_{P1}(\tilde{\theta}, V) + V_{P2}(\tilde{\theta}) \quad (9.73)$$

where

$$V_{KE}(\tilde{\omega}) = \frac{1}{2}\sum_{i=1}^{m} M_i \tilde{\omega}_i^2$$

$$V_{p1}(\tilde{\theta}, V) = -\sum_{i=n+1}^{n+m} T_{Mi}(\tilde{\theta}_i - \tilde{\theta}_i^s) + \sum_{i=1}^{n} \int_{V_i^s}^{V_i} \frac{Q_{Li}(V_i)}{V_i} dV_i \quad (9.74)$$

$$\frac{1}{2}\sum_{1}^{n} B_{ii}(V_i^2 - (V_i^s)^2) \quad (9.75)$$

$$-\sum_{i=1}^{n+m-1} \sum_{j=i+1}^{n+m} B_{ij}(V_i V_j \cos\tilde{\theta}_{ij} - V_i^s V_j^s \cos\tilde{\theta}_{ij}^s) \quad (9.76)$$

$$V_{p2}(\tilde{\theta}) = -\sum_{1}^{n} P_{Li}(\tilde{\theta}_i - \tilde{\theta}_i^s). \quad (9.77)$$

Energy Functions for a Large System

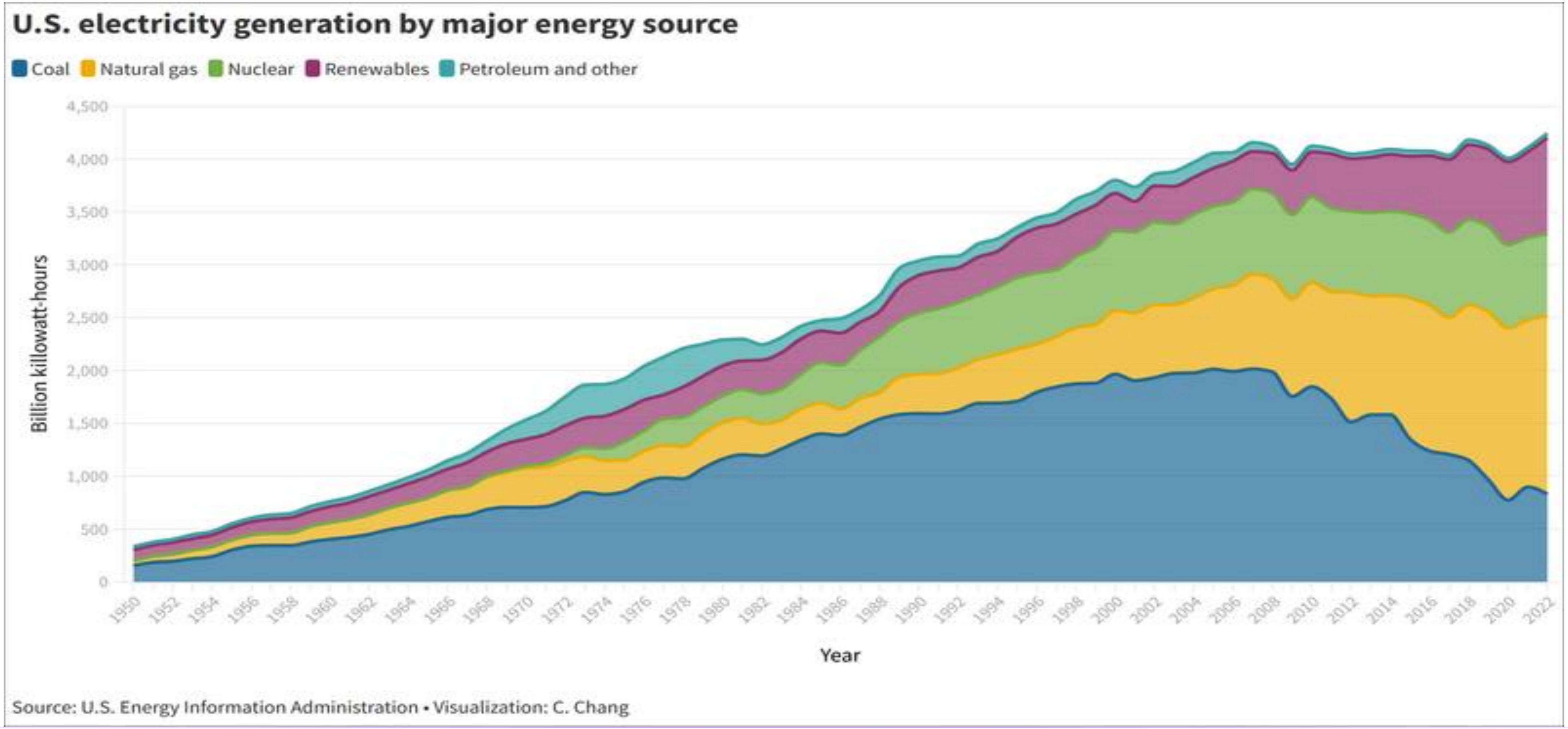
- Need an energy function that at least approximates the actual system dynamics
  - This can be quite challenging!
- In general there are many UEPs; need to determine the UEPs for closely associated with the faulted system trajectory (known as the controlling UEP)
- Energy of the controlling UEP can then be used to determine the critical clearly time (i.e., when the fault-on energy is equal to that of the controlling UEP)
- For on-line transient stability, technique can be used for fast screening

Renewable Resource Modeling

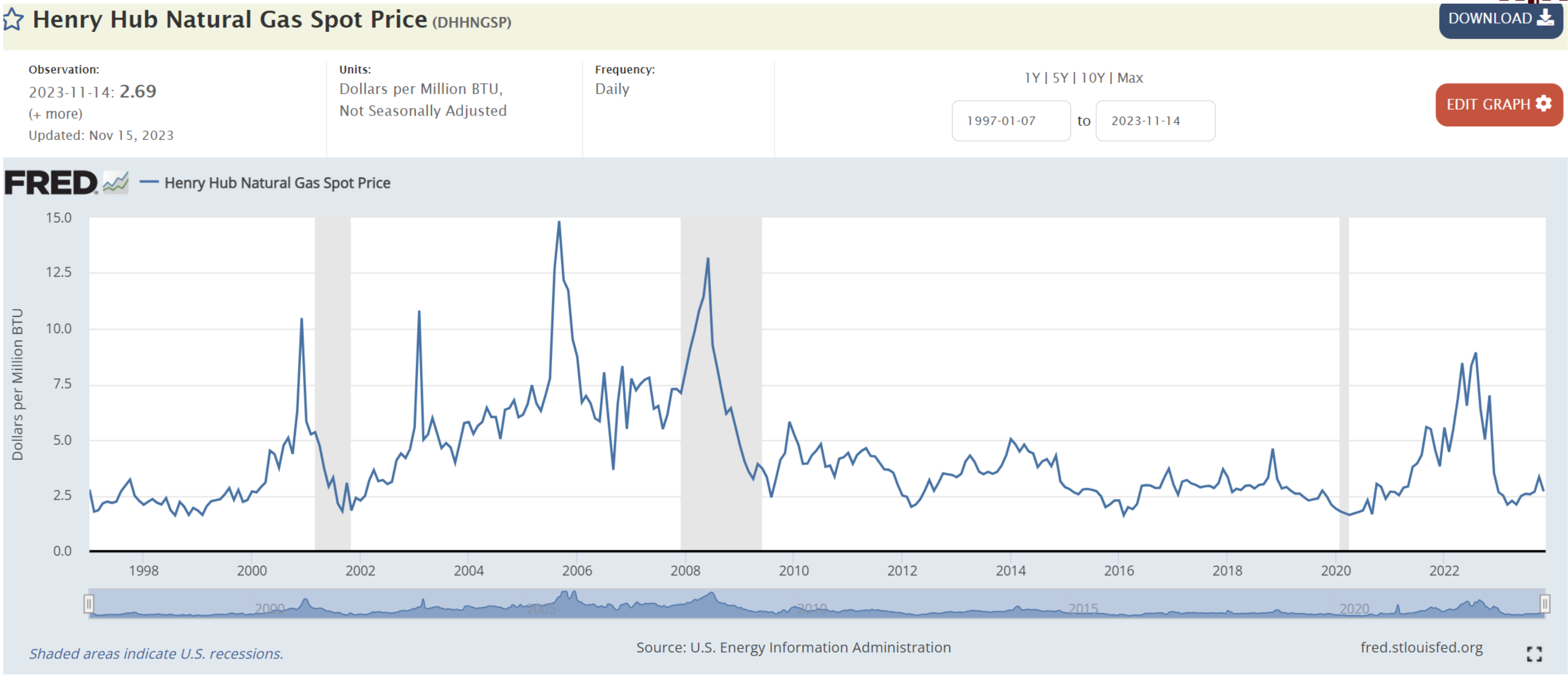
- With the advent of more renewable generation in power systems worldwide it is important to have correct models
- Hydro systems have already been covered
- Solar thermal and geothermal are modeled similar to existing stream generation, so they are not covered here
- Coverage will focus on transient 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

Changing Sources of Generation

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

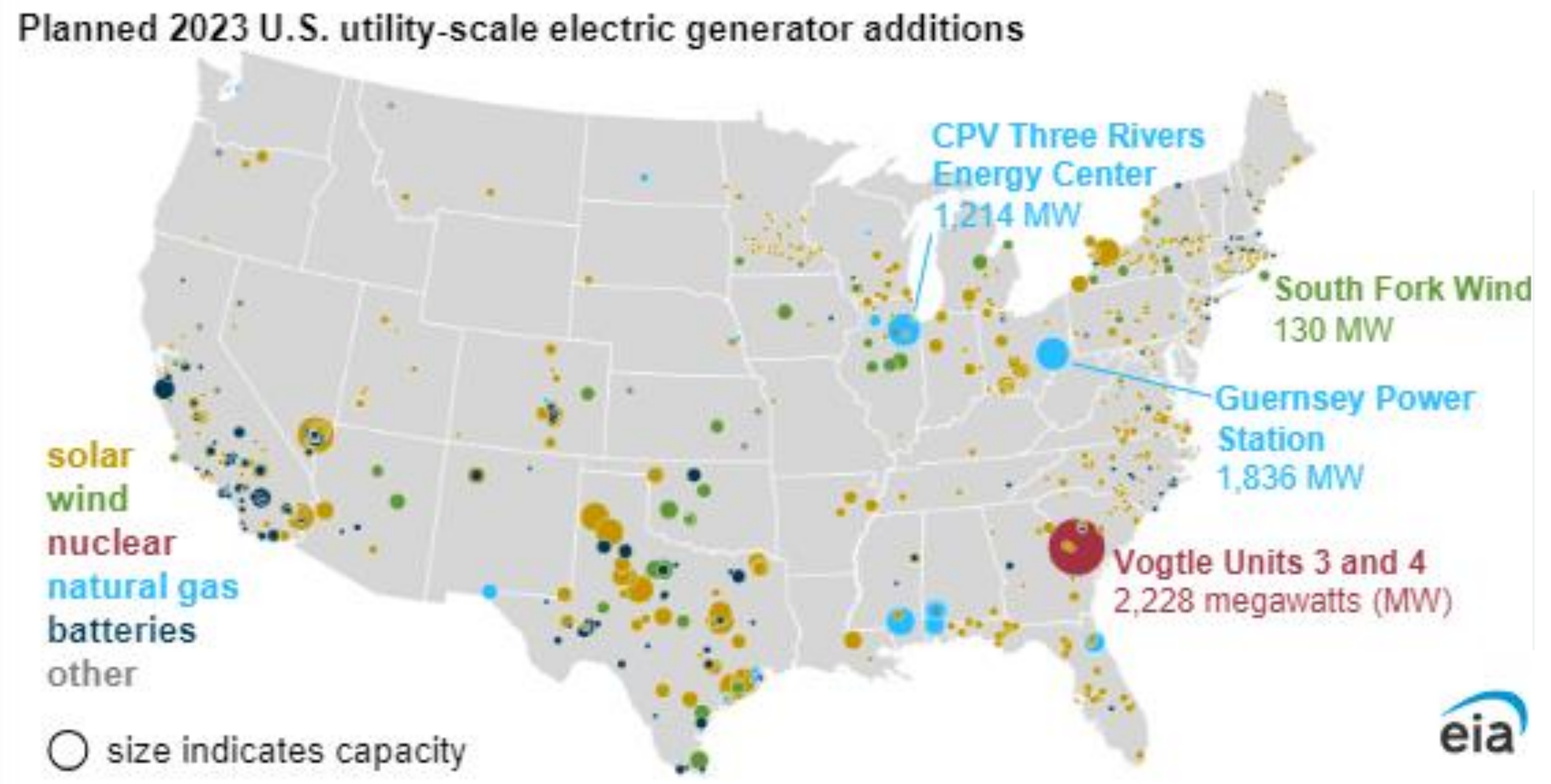


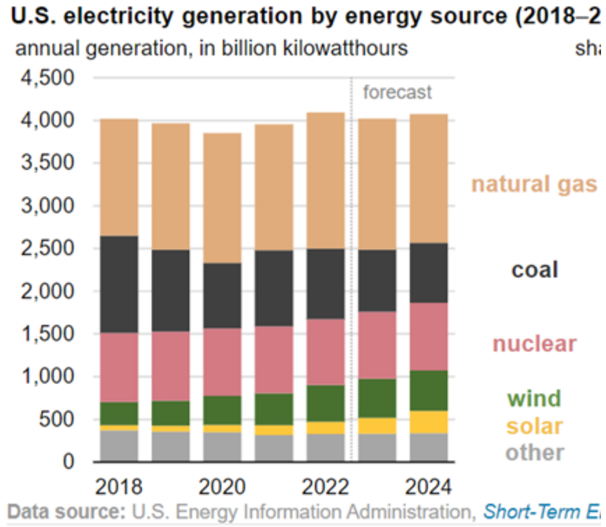
Natural Gas Prices



Source: fred.stlouisfed.org/series/DHHNGSP

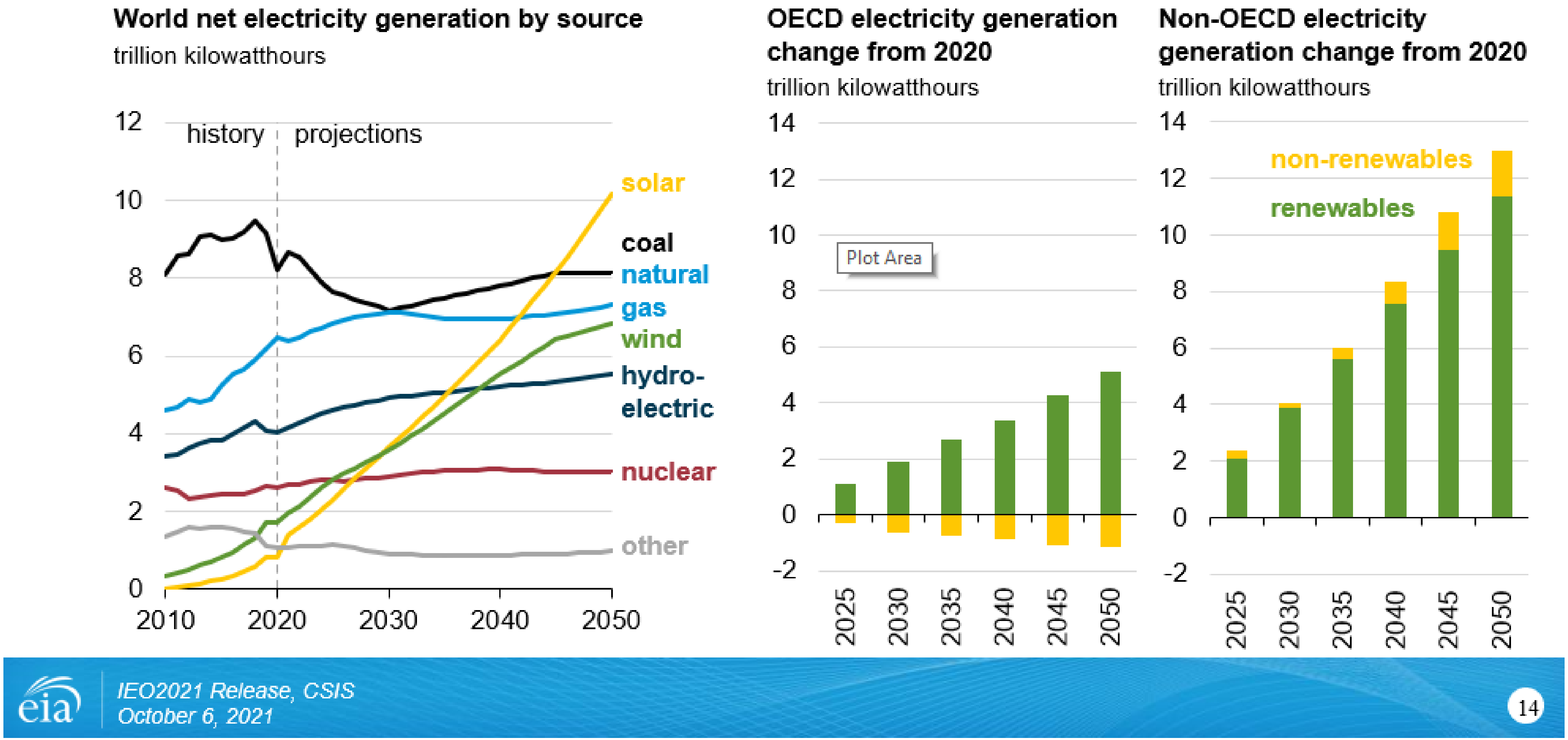
Planned New Generation 2023





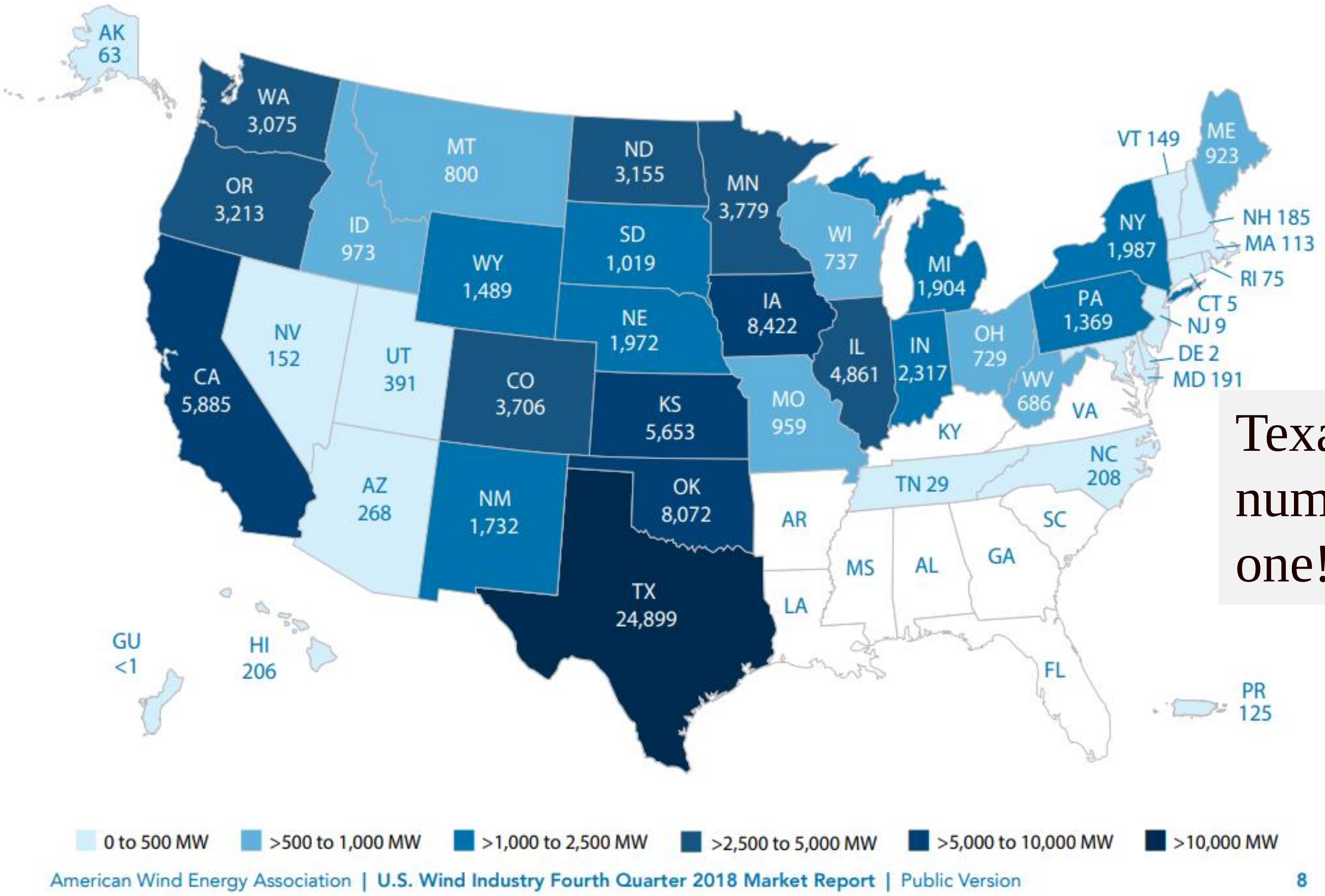
Vogtle 3 entered commercial operation on 7/31/23, and Vogtle 4 is suppose to start operating soon (its fuel load began on 8/17/23)

The World: Electricity Consumption by Source



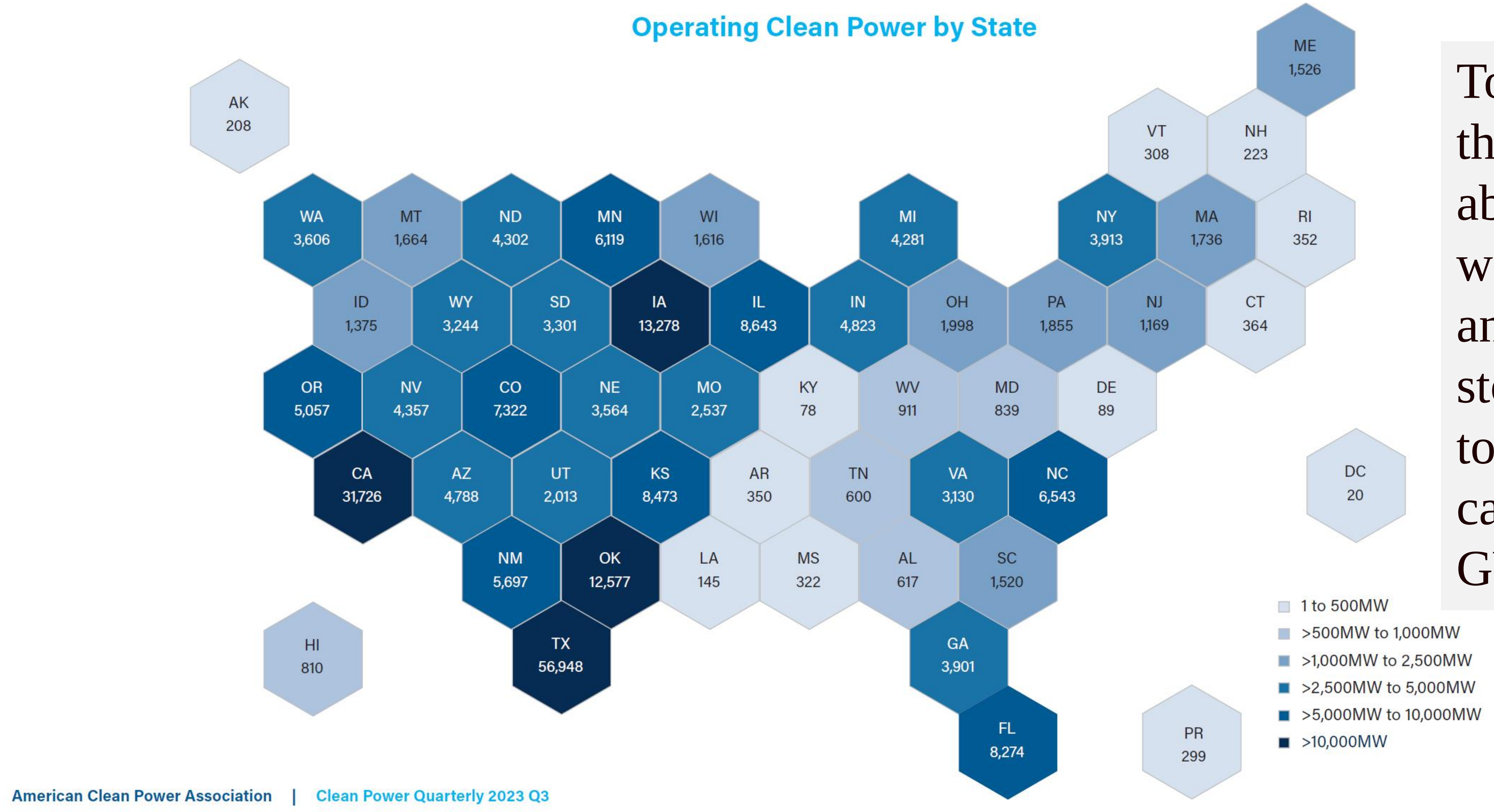
2018 Installed Wind Capacity by State

In January 2021 the American Wind Energy Association was succeeded by the American Clean Power Association



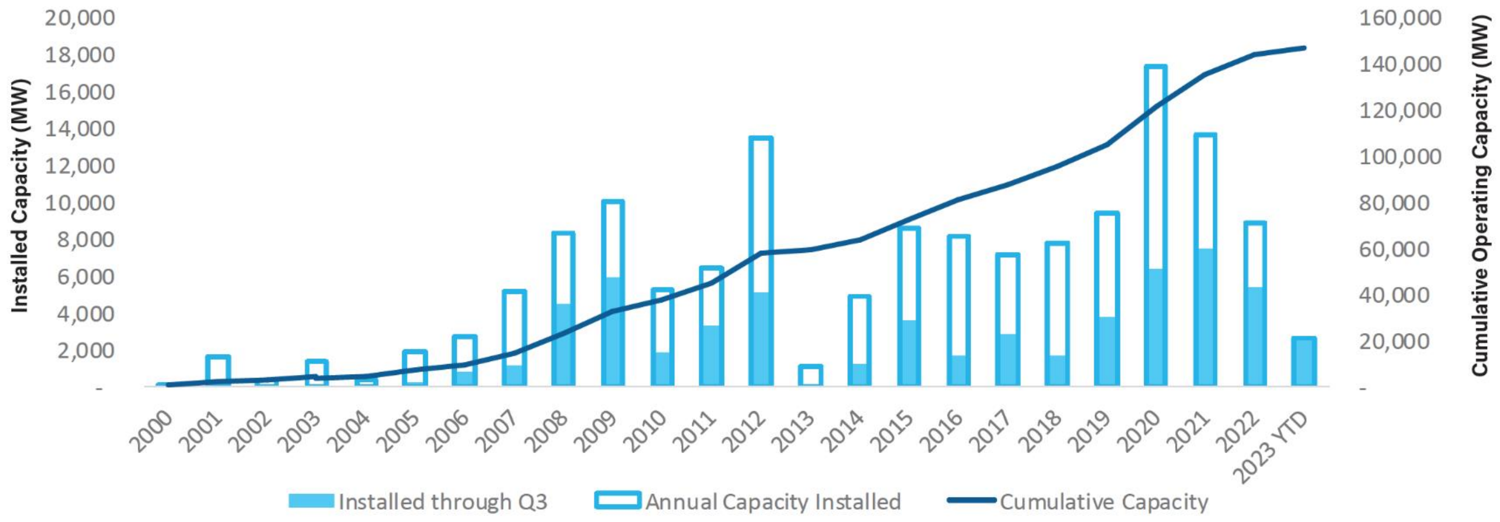
Texas is number one!

US Wind and Solar Capacity by State

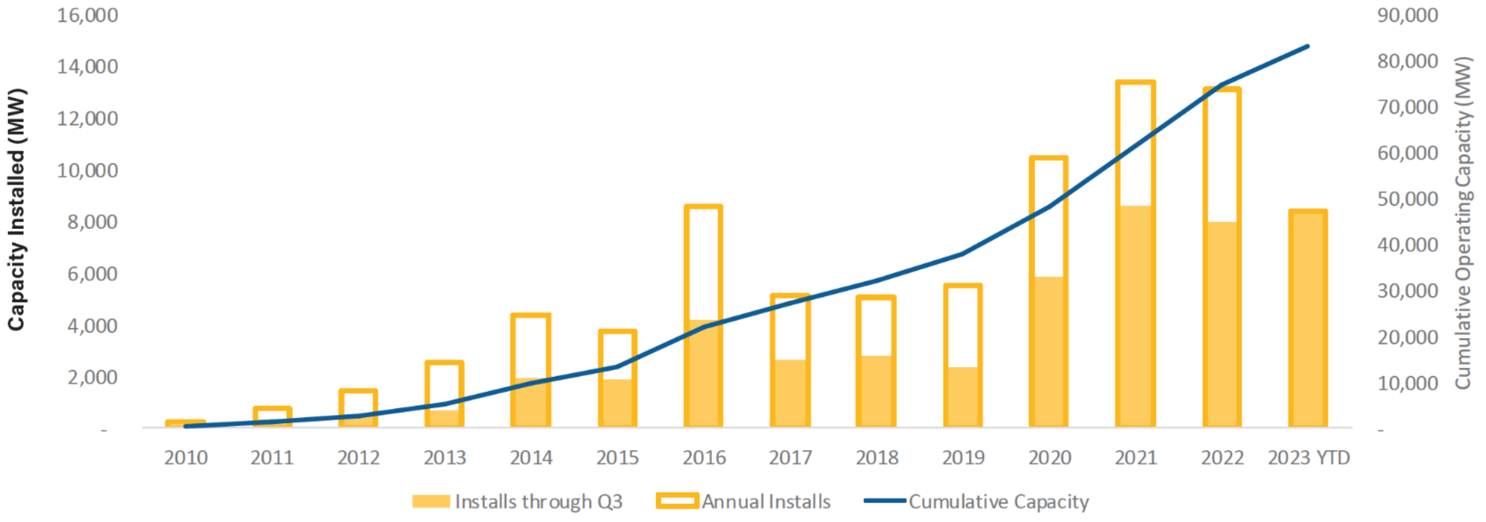


Total US capacity at the end of Q3 2023 is about 146 GW of wind, 83 GW of solar, and 13.4 GW of storage (compared to a total US generation capacity of about 1000 GW)

US Annual & Cumulative Wind & Solar Growth



Wind capacity



Solar capacity

Source: American Clean Power Quarterly, 2023 Q3

US Wind Farm Locations

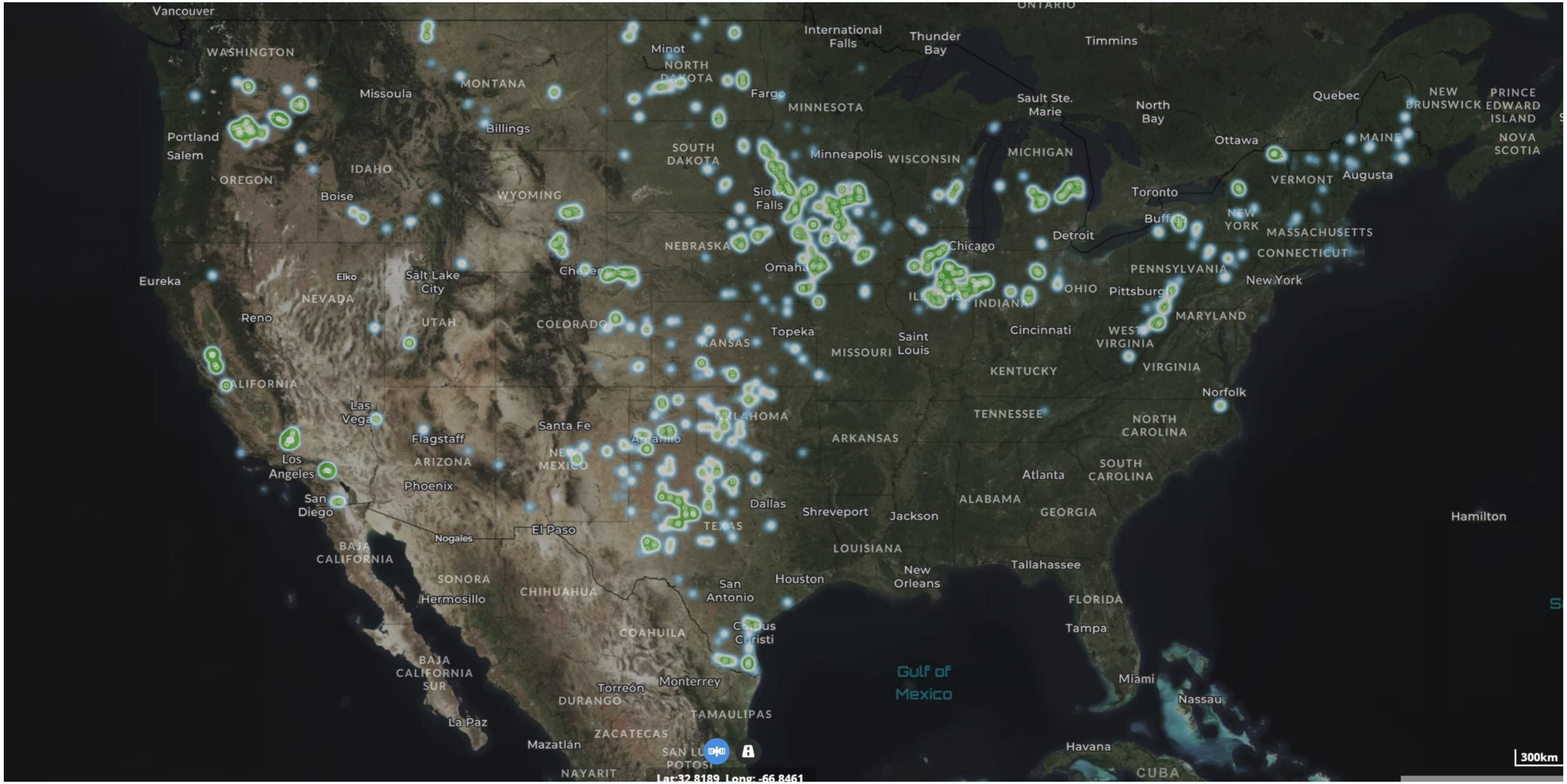
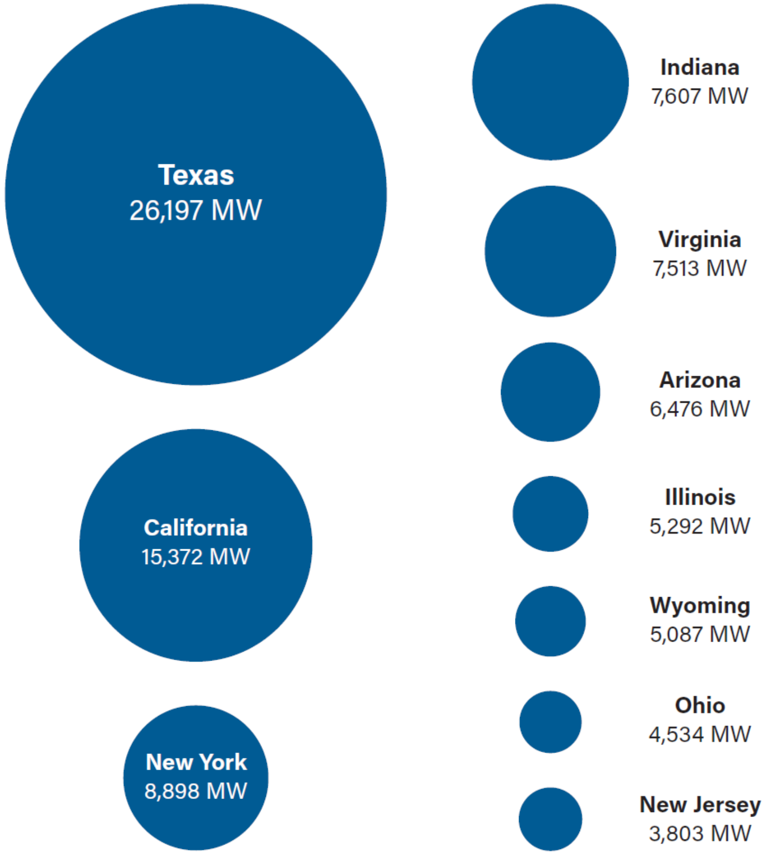


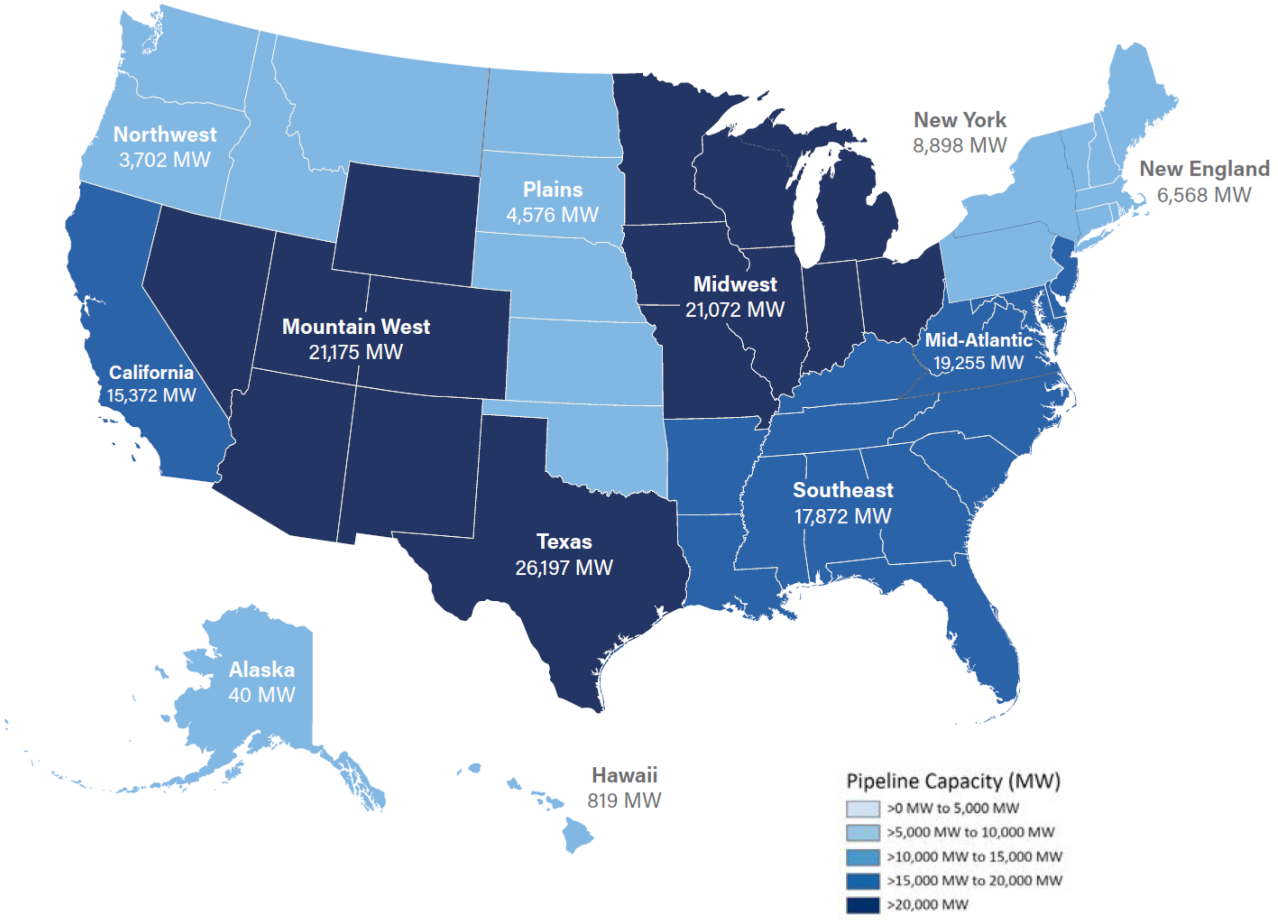
Image source: USGS at https://eerscmap.usgs.gov/uswtdb/

Wind, Solar and Storage Pipeline

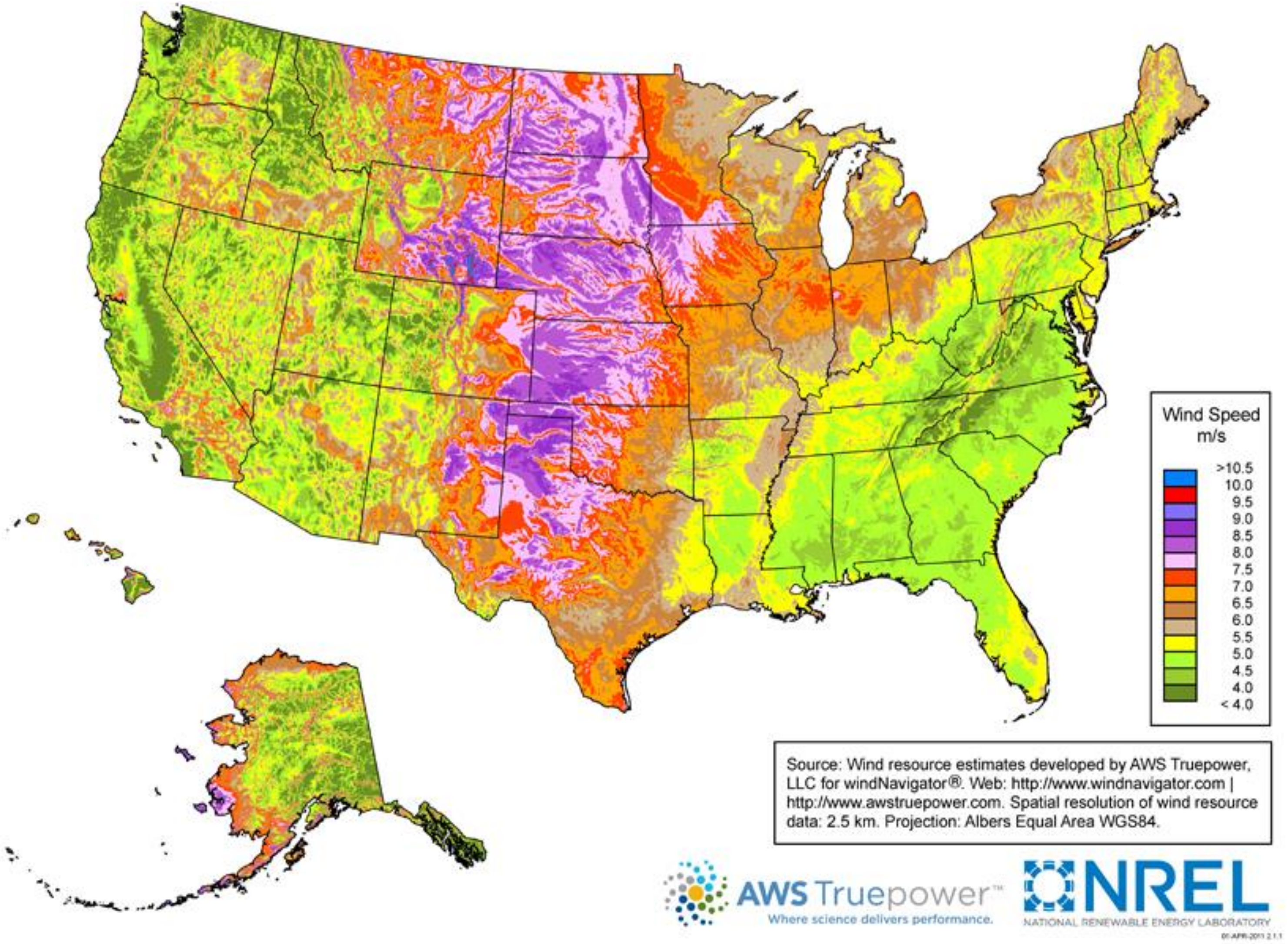
Top States, Clean Power Development Capacity



Clean Power Development Capacity by Region

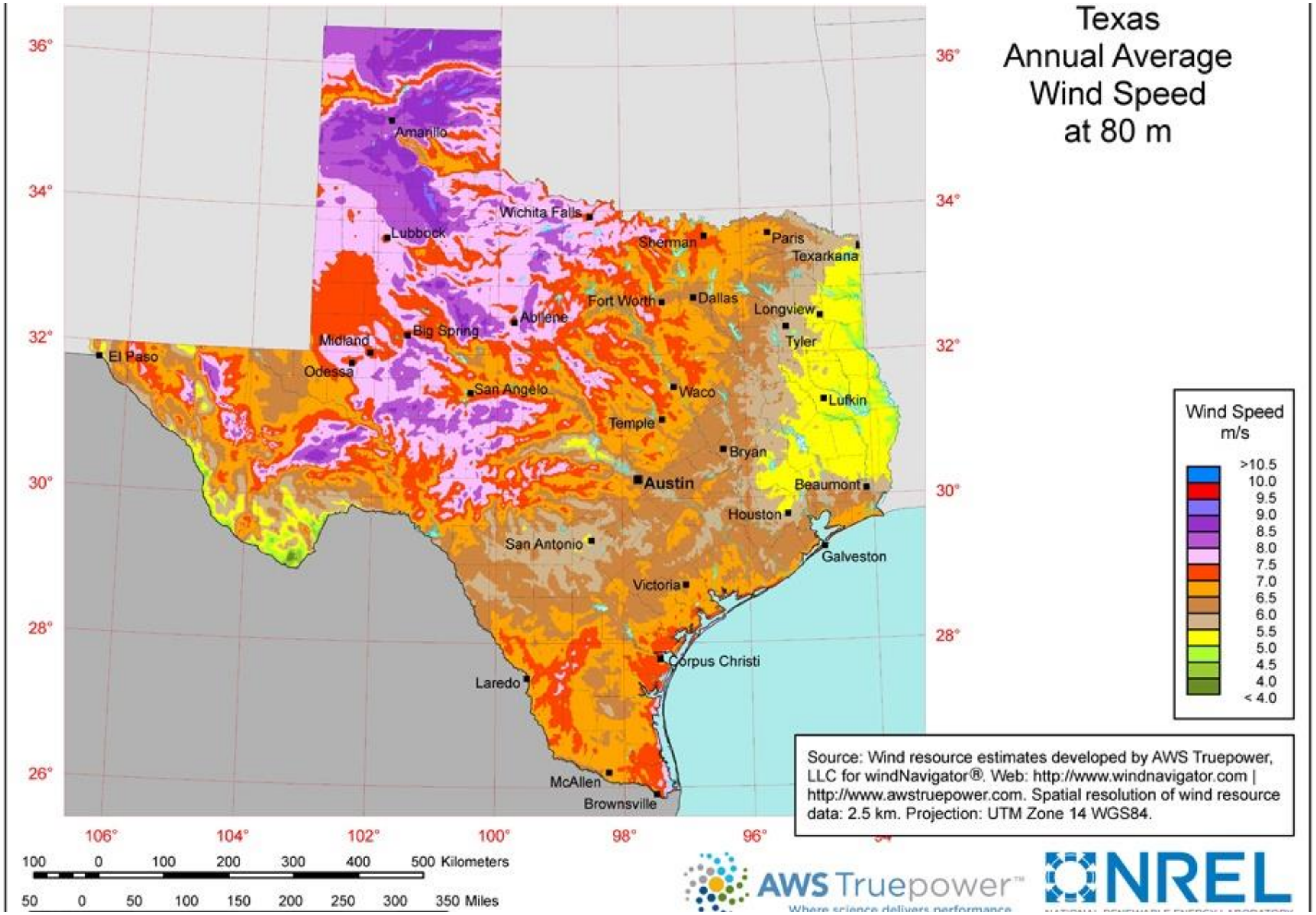


US Wind Resources



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

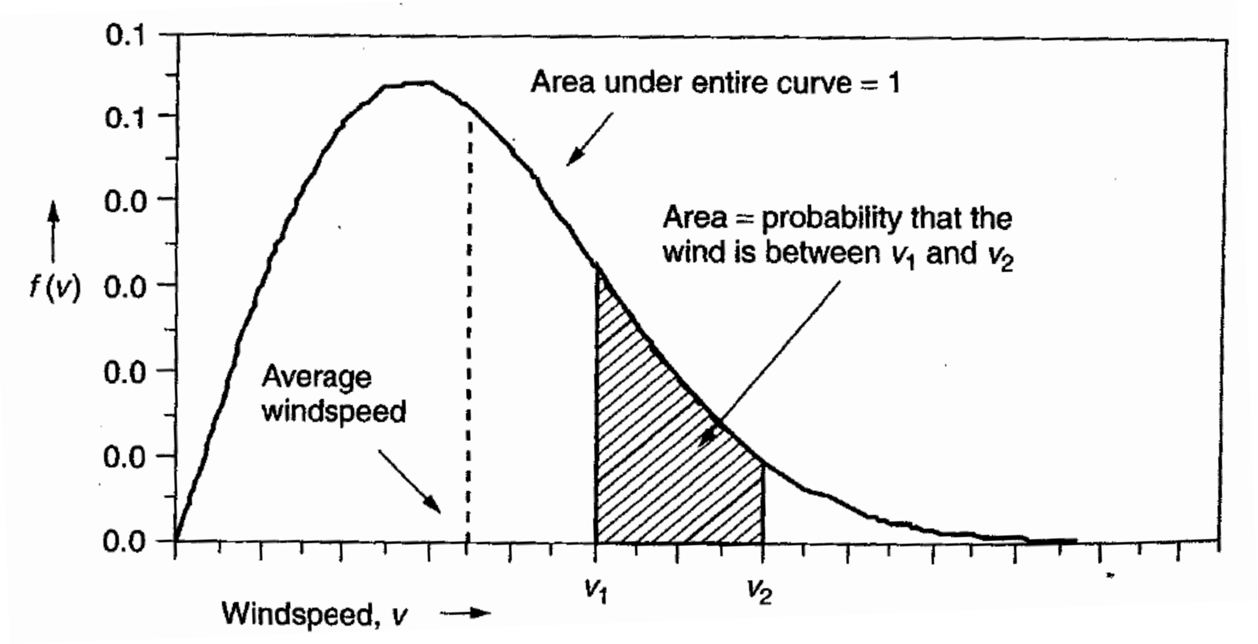
Wind Map Texas– 80m Height



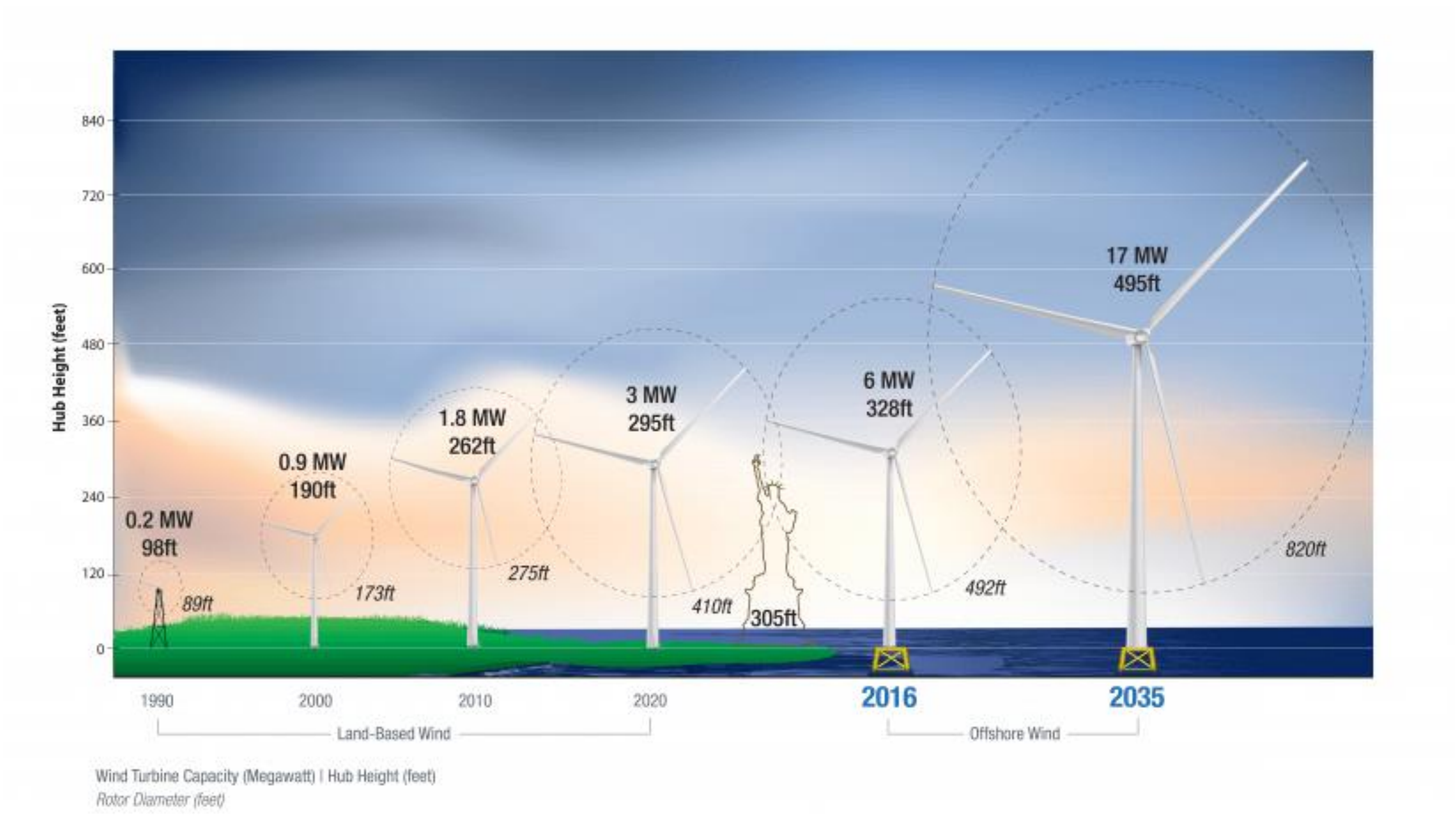
https://windexchange.energy.gov/files/u/visualization/image/tx_80m.jpg

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



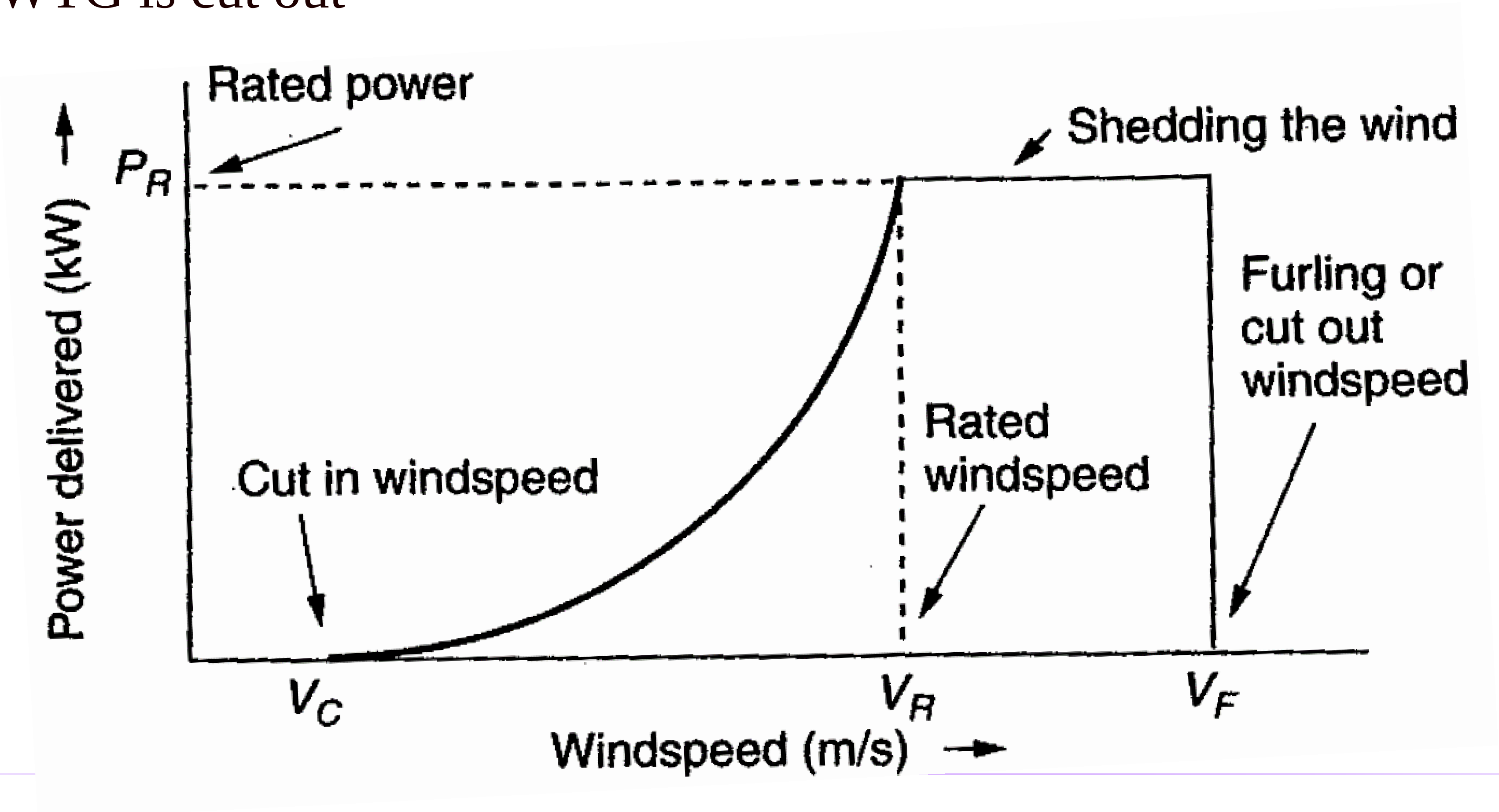
The current largest wind turbines by capacity are about 16 MW with rotor diameters of about 250 m

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

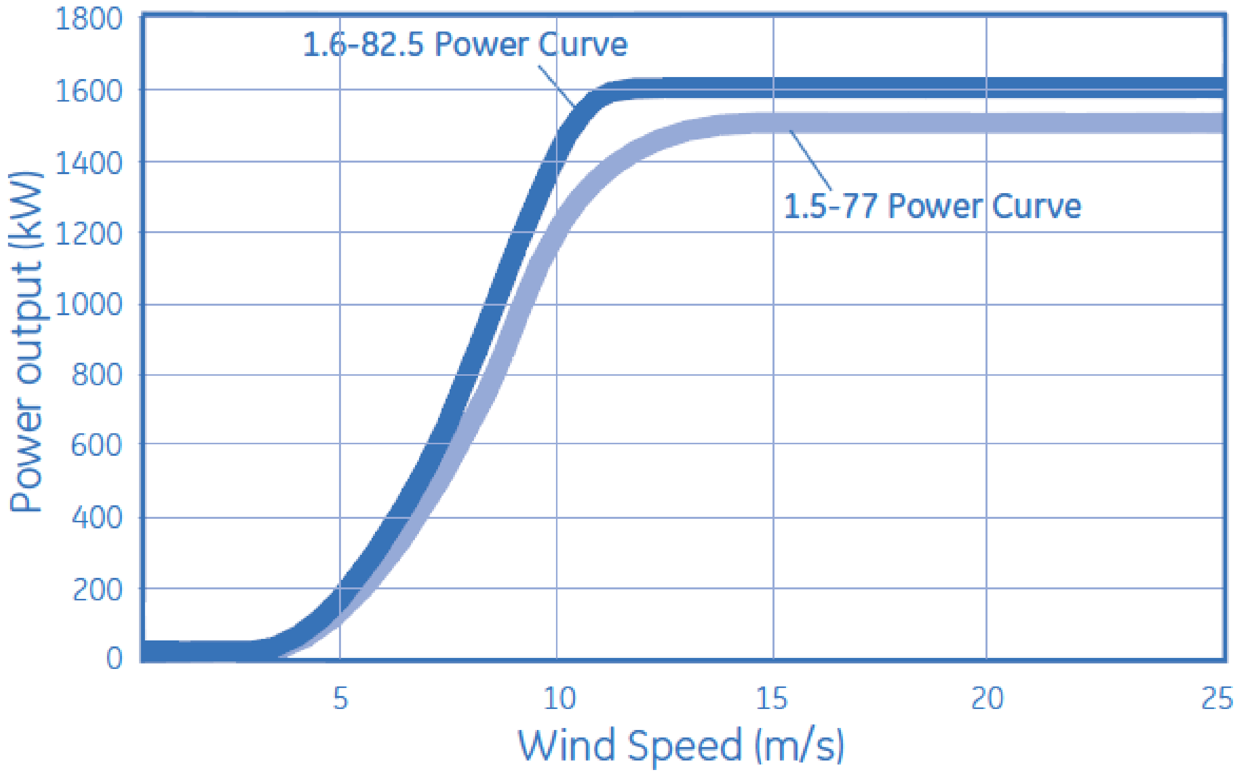
Extracted Power

- 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)

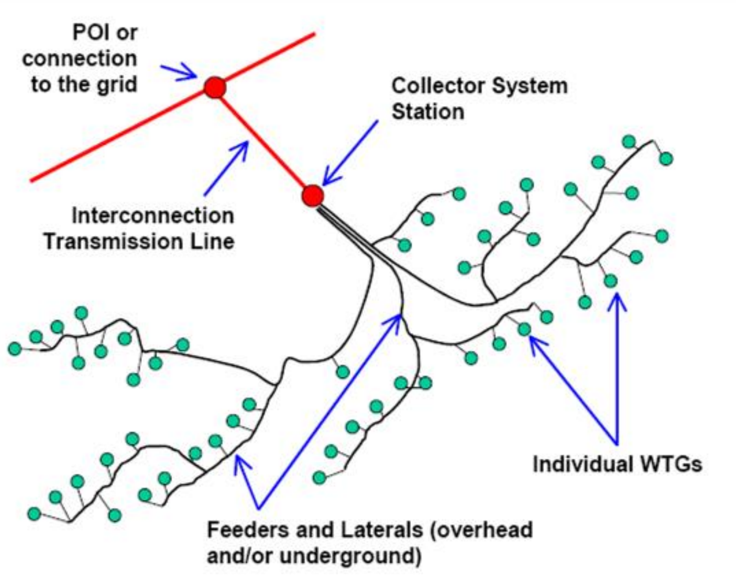


Photo Source: www.energyindustryphotos.com/photos_of_wind_farm_turbines.htm

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)

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 64 GW, with half of it in China and almost one quarter in the UK
  - US offshore wind is only 42 MW; while there is lots of interest, there are also major challenges including greatly increased costs
- Capacity factors tend to increase as turbines move further off-shore

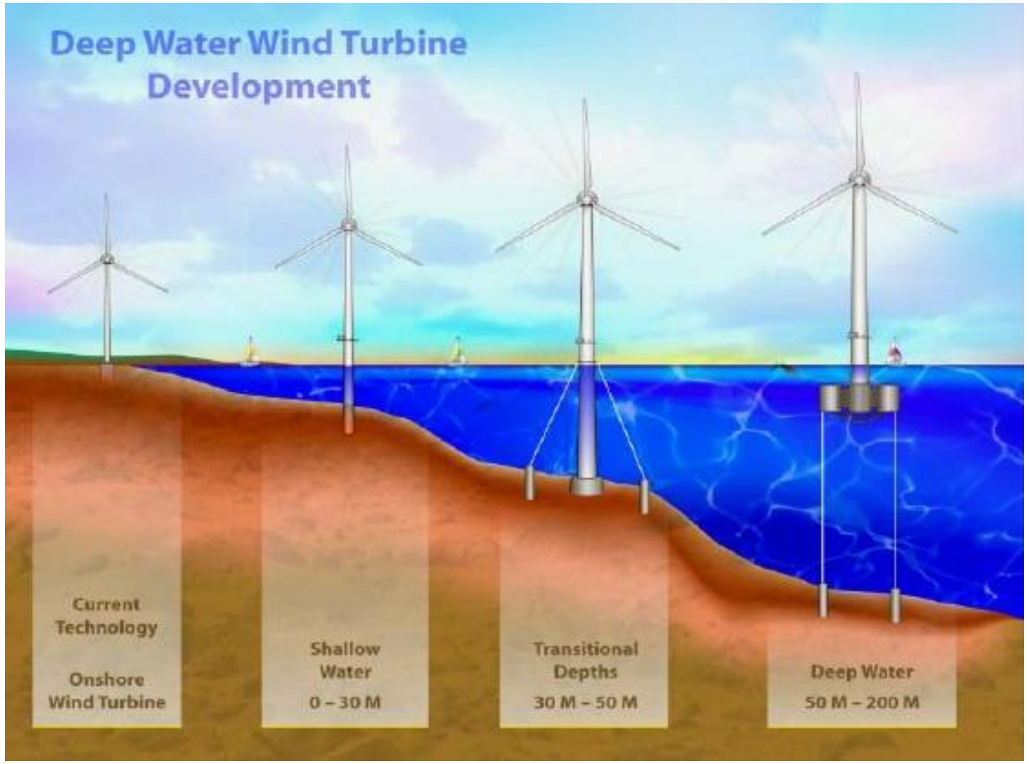


Image Source: National Renewable Energy Laboratory

Offshore: Advantages and Disadvantages

- All advantages/disadvantages are somewhat site specific
- Advantages
  - Can usually be sited much closer to the load (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 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 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 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
- NERC Standard PRC-024-2 requires specific low voltage performance

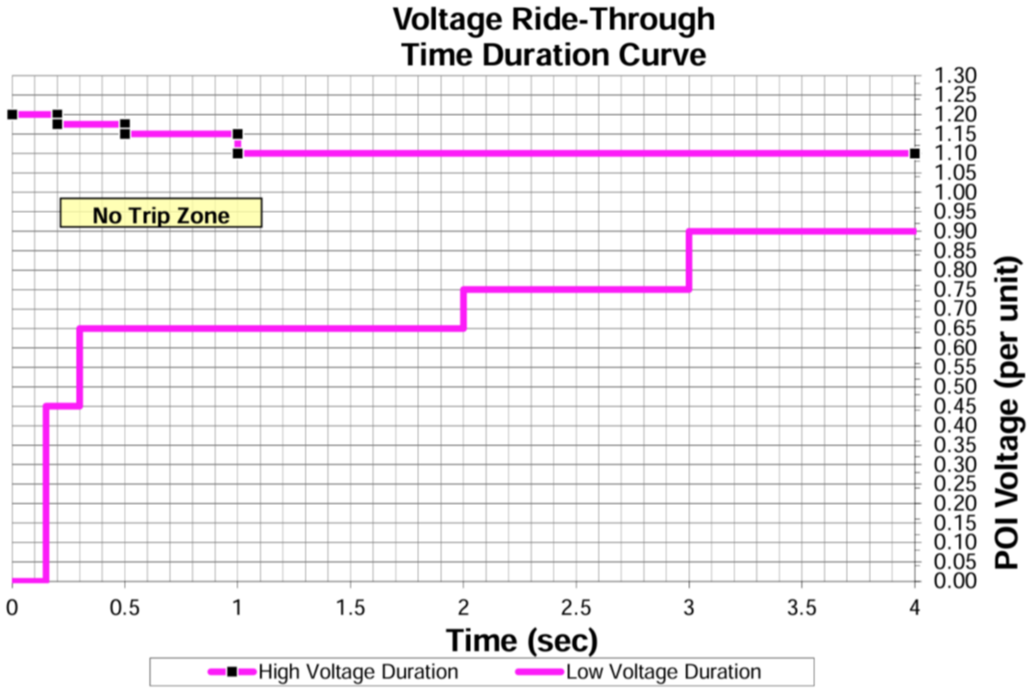


Image from NERC PRC-024-2

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

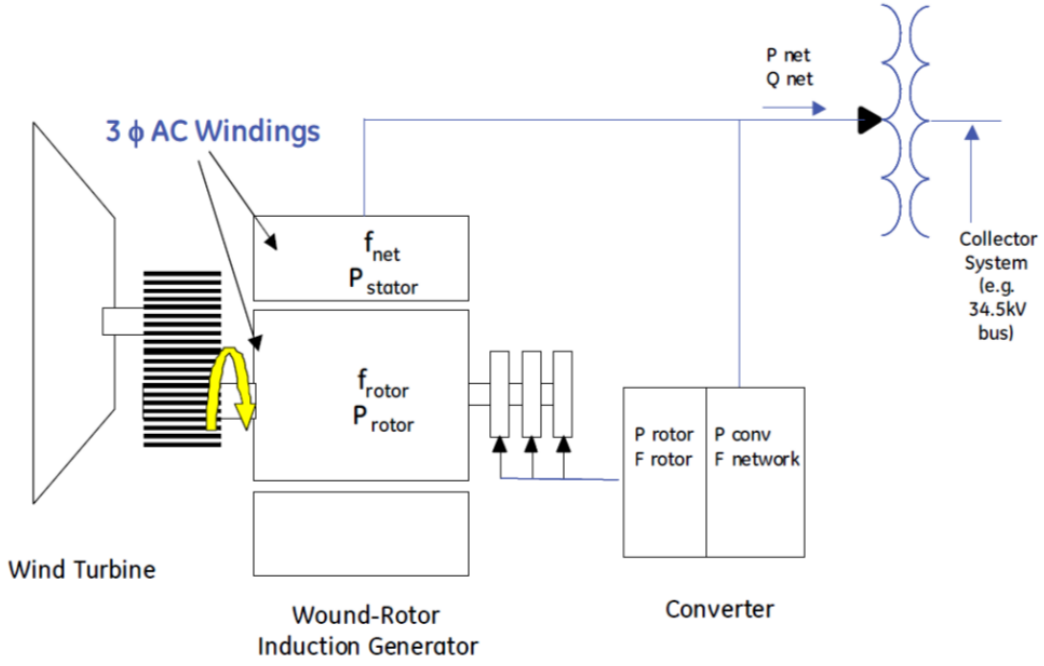


Figure 2-1. GE Doubly Fed Asynchronous WTG Major Components.

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

Example: Siemens SWT-2.3-113

- The Siemens-2.3-113 is a 2.3 MW WTG that has a rotor diameter of 113 m. It is a gearless design based on a compact permanent magnet generator
  - No excitation power, slip rings or excitation control system; there is also less maintenance, but upfront costs could be higher

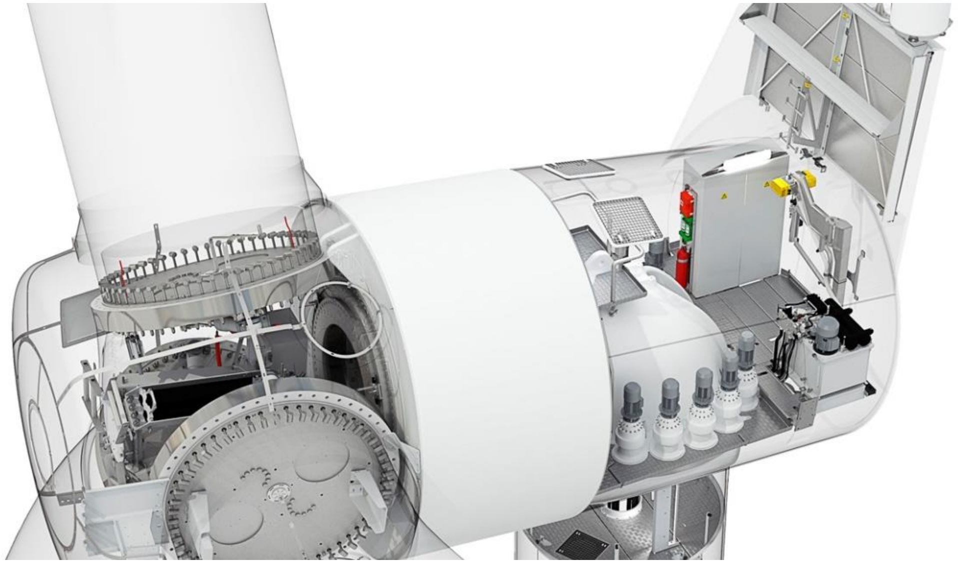
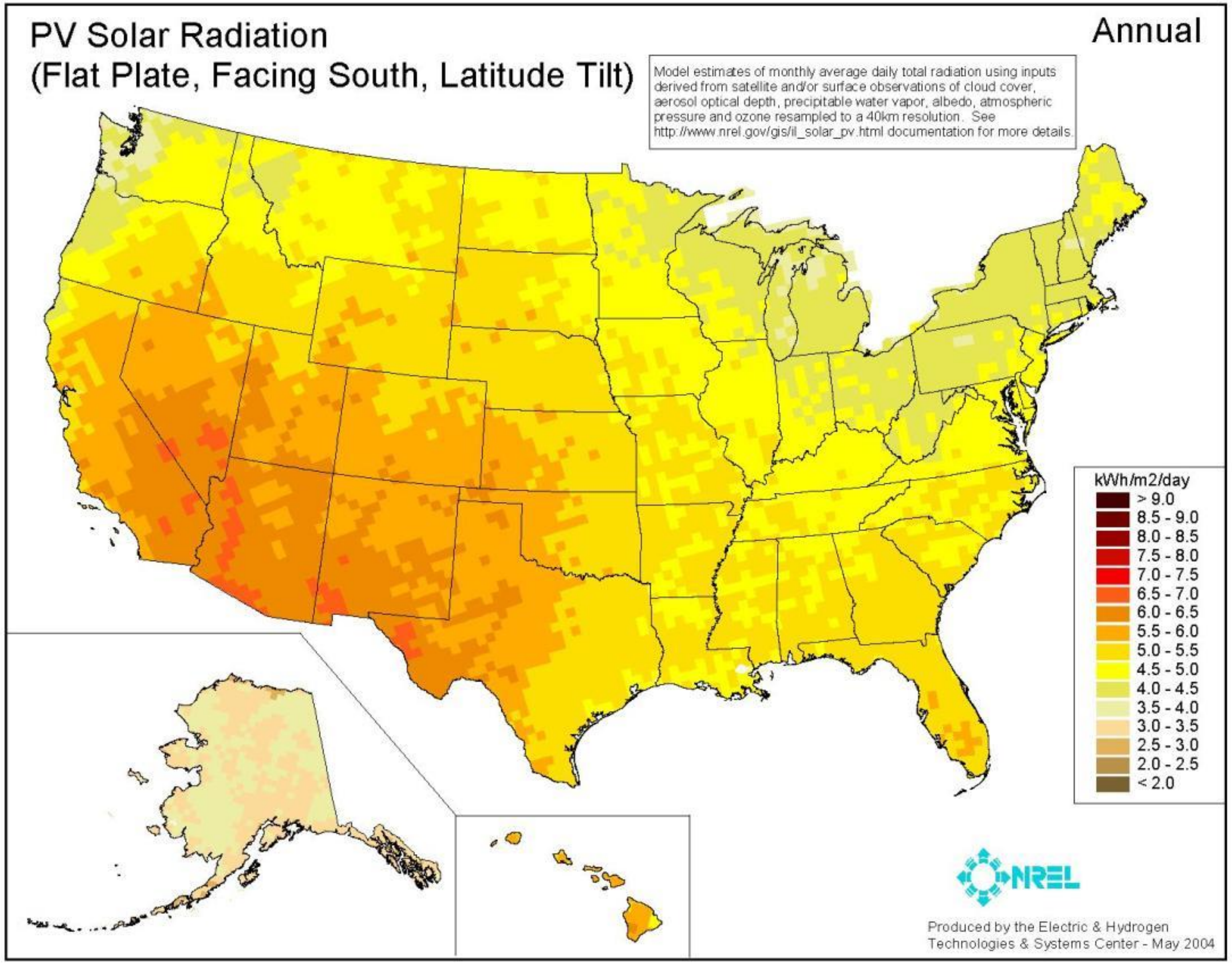


Image: www.siemens.com/press/pool/de/pressebilder/2011/renewable_energy/300dpi/soere201103-02_300dpi.jpg

Solar Photovoltaic (PV)

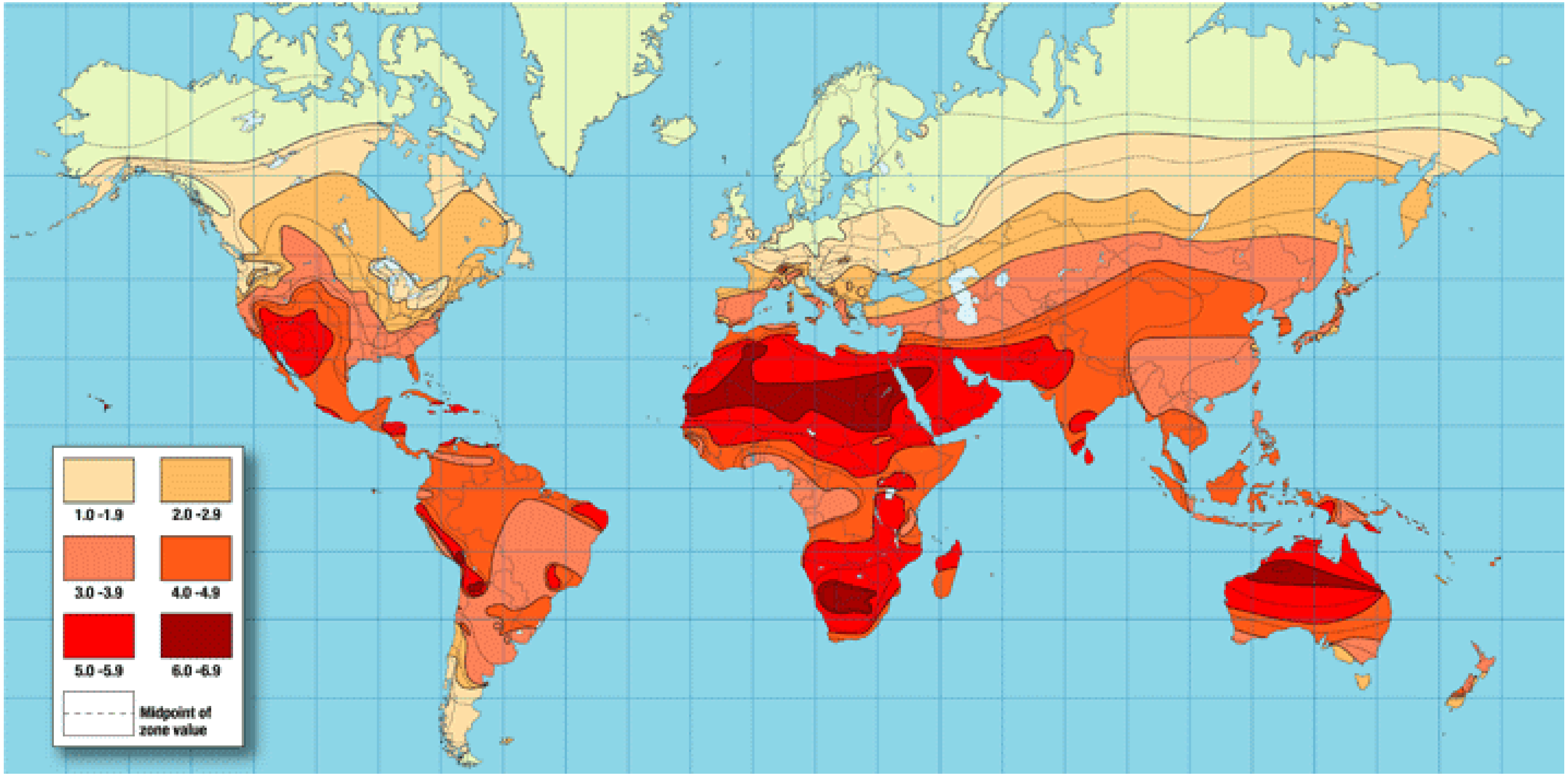
- **Photovoltaic definition-** a material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current
- Solar cells are diodes, creating dc power, which in grid applications is converted to ac by an inverter
- For terrestrial applications, the 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

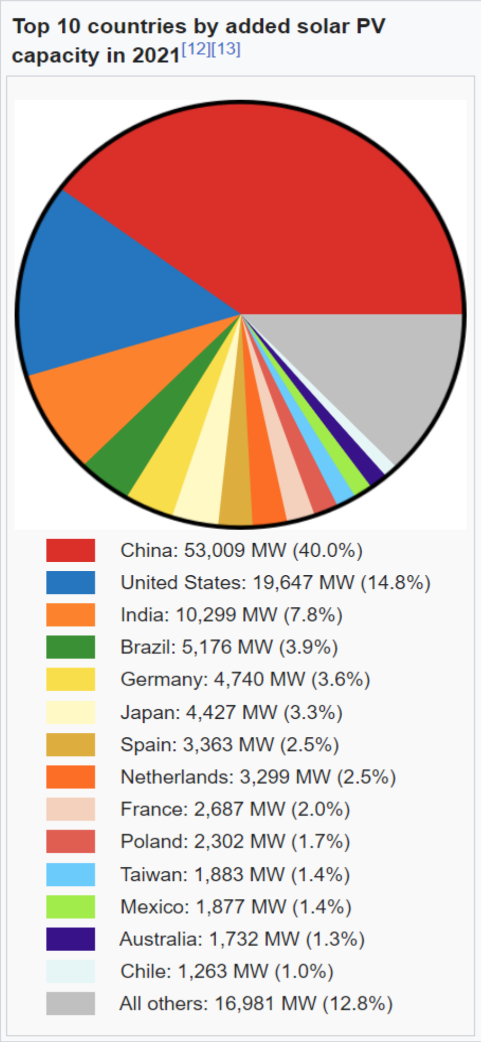


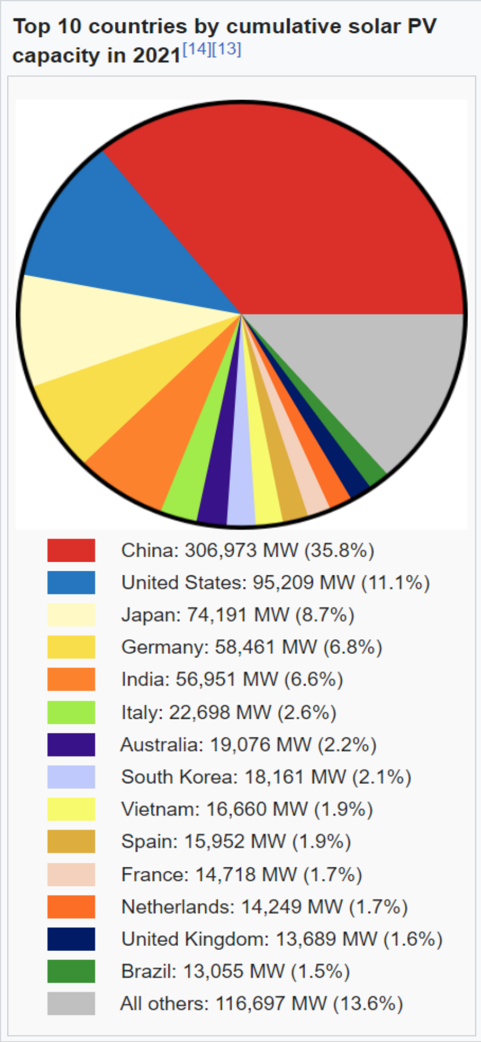
The capacity factor is roughly this number divided by 24 hours per day

Worldwide Annual Insolation



Solar Capacity by Country, 2021

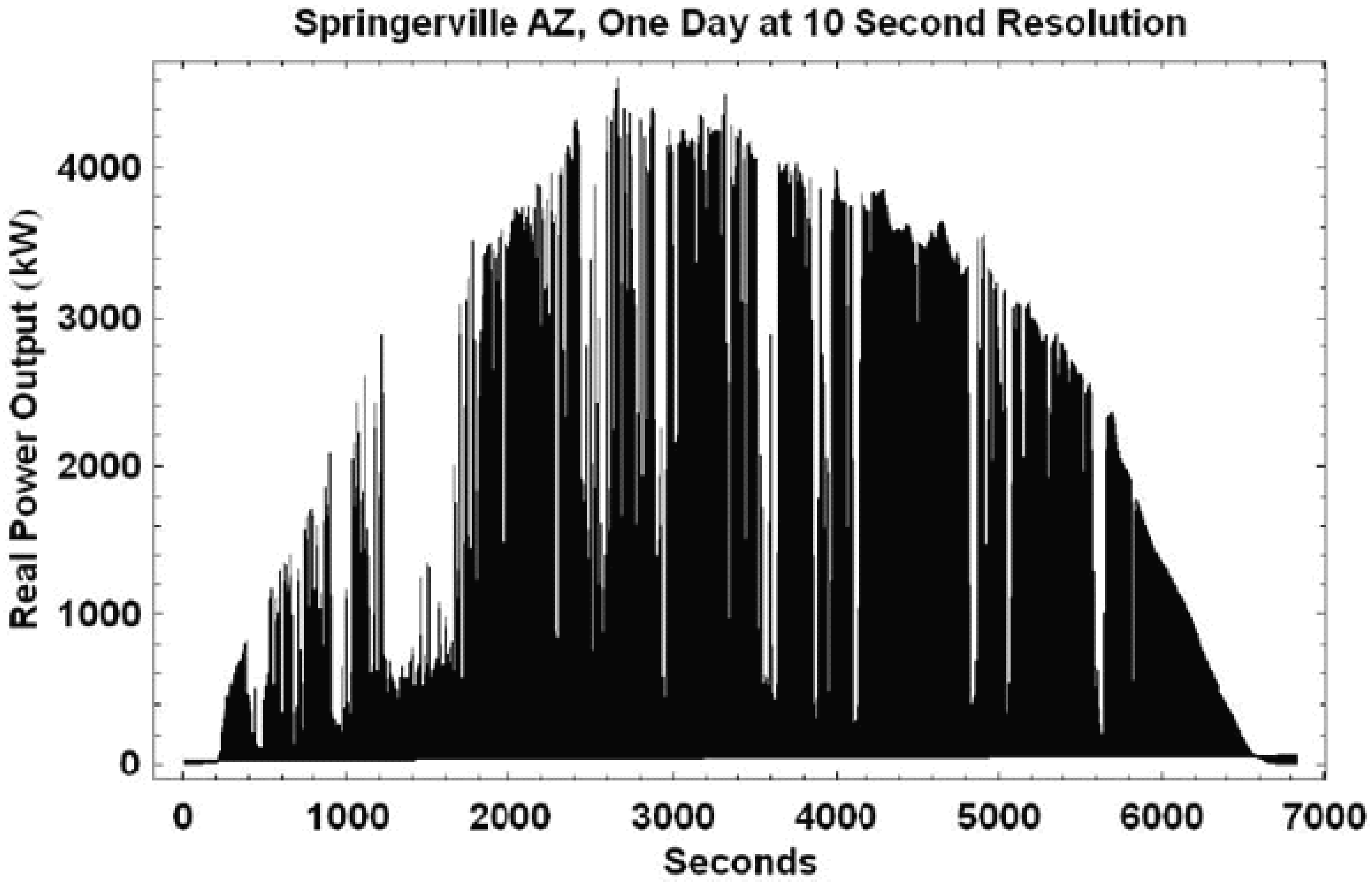




Total values in 2022 are 393 GW for China, 113 GW for the US, 79 GW for Japan, 66 GW for Germany and 63 GW for India

Source: en.wikipedia.org/wiki/Solar_power_by_country

Solar PV can be Intermittent Because of Clouds



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

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
- For the US 30% is at small installations, but in California its is 43% while in Texas it is 13%

Table 1.17.A. Net Generation from Solar Photovoltaic by State, by Sector, September 2023 and 2022 (Thousand Megawatthours)

	All Sectors						
	Estimated Generation From Utility and Small Scale Facilities			Generation at Utility Scale Facilities		Estimated Small Scale Generation	
Census Division and State	September 2023	September 2022	Percentage Change	September 2023	September 2022	September 2023	September 2022
New England	924	833	11.0%	321	303	603	529
Connecticut	144	132	9.0%	34	38	110	95
Maine	119	79	50.5%	54	43	65	37
Massachusetts	501	479	4.6%	178	171	324	308
New Hampshire	NM	23	NM	NM	0	28	22
Rhode Island	90	82	9.9%	36	34	55	48
Vermont	41	37	9.3%	20	18	21	19
Middle Atlantic	1,168	1,011	15.5%	411	330	757	680
New Jersey	448	429	4.5%	143	141	305	287
New York	587	488	20.4%	232	168	356	320
Pennsylvania	133	94	40.4%	36	22	96	73
East North Central	1,055	751	40.5%	780	521	275	230
Illinois	320	304	5.1%	178	180	142	124
Indiana	242	130	86.9%	208	102	35	28
Michigan	144	104	38.6%	115	79	30	25
Ohio	219	119	84.7%	178	87	41	32
Wisconsin	130	95	37.3%	102	73	28	21
West North Central	437	403	8.6%	278	288	159	115
Iowa	86	76	11.9%	47	46	39	30
Kansas	20	16	19.9%	7	8	12	8
Minnesota	219	233	-6.2%	184	209	35	24
Missouri	85	63	34.2%	16	15	69	48
Nebraska	12	13	-4.4%	8	9	5	4
North Dakota	0	0	21.9%	0	0	0	0
South Dakota	16	0	NM	15	0	0	0
South Atlantic	4,447	3,766	18.1%	3,750	3,249	696	517
Delaware	28	19	43.9%	12	6	16	14
District of Columbia	20	17	19.4%	2	2	18	15
Florida	1,517	1,087	39.6%	1,213	876	304	211
Georgia	750	642	16.9%	707	610	43	32
Maryland	203	178	13.6%	85	65	117	114
North Carolina	1,089	1,074	1.4%	1,025	1,023	64	51
South Carolina	300	250	20.3%	252	206	48	44
Virginia	535	496	7.9%	454	463	81	33
West Virginia	4	3	38.5%	0	0	4	3
East South Central	319	244	30.5%	295	224	23	20
Alabama	NM	93	NM	121	91	NM	NM
Kentucky	32	14	130.6%	20	4	13	10
Mississippi	59	60	-2.5%	57	58	2	2
Tennessee	104	77	36.3%	98	70	7	7
West South Central	3,330	2,828	17.7%	2,837	2,499	493	329
Arkansas	127	95	33.6%	89	73	38	22
Louisiana	54	49	9.1%	27	27	27	23
Oklahoma	22	15	50.8%	7	7	15	8
Texas	3,127	2,669	17.2%	2,714	2,393	413	276
Mountain	3,465	2,896	19.7%	2,611	2,169	854	727
Arizona	967	871	11.0%	593	539	374	332
Colorado	553	345	60.3%	400	224	153	120
Idaho	111	69	61.4%	87	50	25	19
Montana	42	8	398.4%	34	3	8	5
Nevada	991	920	7.7%	844	796	147	125
New Mexico	320	235	36.3%	261	185	60	50
Utah	461	427	7.9%	376	354	85	74
Wyoming	20	20	-0.7%	17	18	3	2
Pacific Contiguous	6,564	5,646	16.3%	3,888	3,365	2,676	2,281
California	6,244	5,406	15.5%	3,682	3,211	2,562	2,194
Oregon	228	192	18.4%	171	149	57	43
Washington	92	48	92.3%	35	4	57	44
Pacific Noncontiguous	191	169	12.9%	65	54	126	115
Alaska	NM	2	NM	NM	0	2	2
Hawaii	188	168	12.1%	64	54	124	[illegible]
U.S. Total	21,899	18,546	18.1%	15,236	13,002	6,663	[illegible]

Image: EIA Electric Power Monthly, Nov 2023

Distributed PV System Modeling

- PV in the distribution system is often operated at unity power factor
  - There is research investigating the benefits of changing this
- IEEE Std 1547-2018 now allows both non-unity power factor and voltage regulation
  - "Constant power factor mode with unity power factor setting shall be the default mode of the installed DER unless otherwise specified by the Area EPS operator"
- A simple model is just as negative constant power load
- An issue is tripping on abnormal frequency or voltage conditions
  - IEEE Std 1547-2018 says, "For short-circuit faults on the Area EPS circuit section to which the DER is connected, the DER shall *cease to energize* and *trip* unless specified otherwise by the Area EPS operator (note EPS is electric power system)

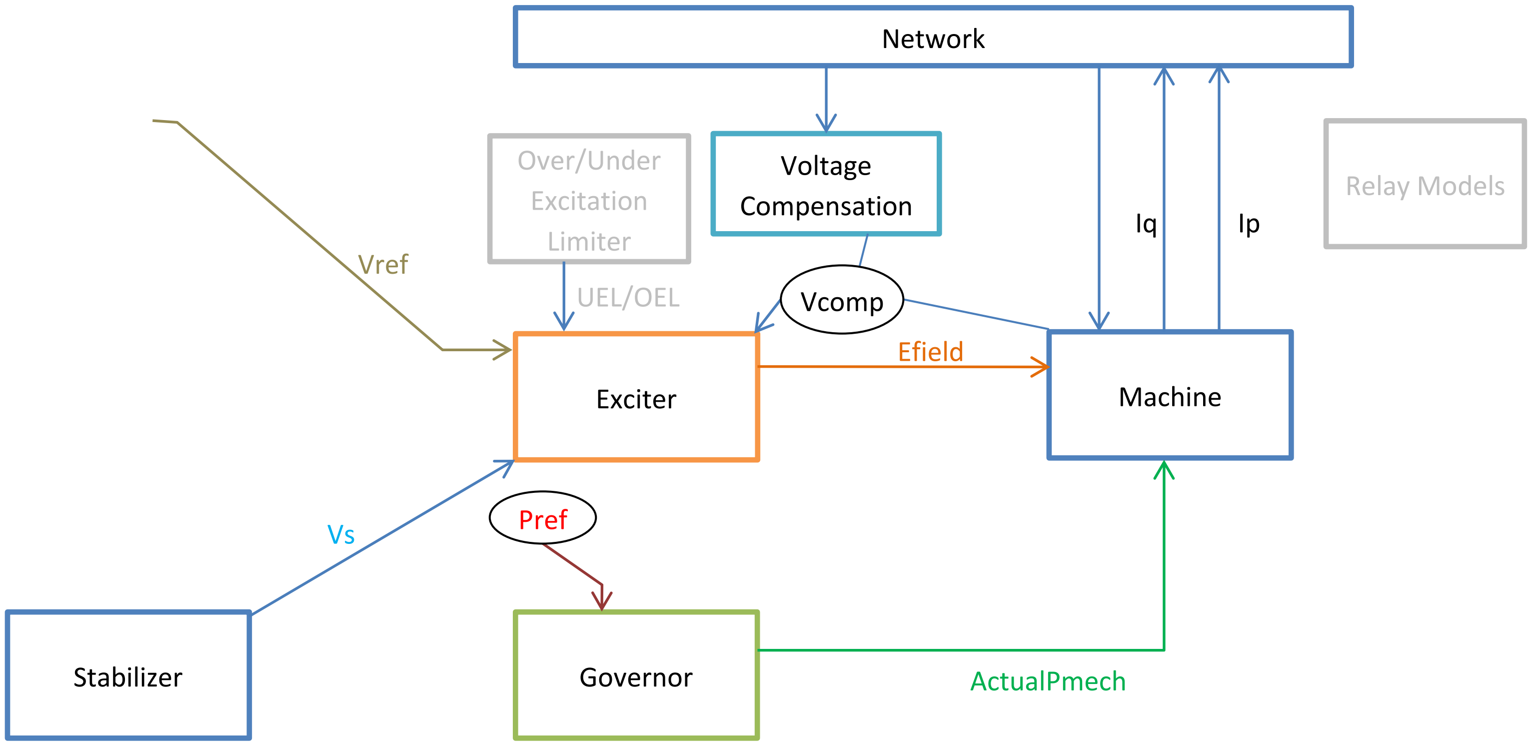
Distributed PV System Modeling

- An issue is tripping on abnormal frequency or voltage conditions (from IEEE 1547-2018
  - 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

Modular Approach to Wind and Solar Unit Modeling

- Industry has always used a modular approach for generator models
  - Machine
  - Exciter
  - Governor
  - Stabilizer
  - Under Excitation Limiter
  - Over Excitation Limiter
  - Relay Model
    - GP1, LHFRT, LHVRT
  - Compensator Model
    - Often is part of the machine model, but can also be a separate model
    - The old BPA IPF program models included this in the Exciter model

“Traditional” Synchronous Machine Modules

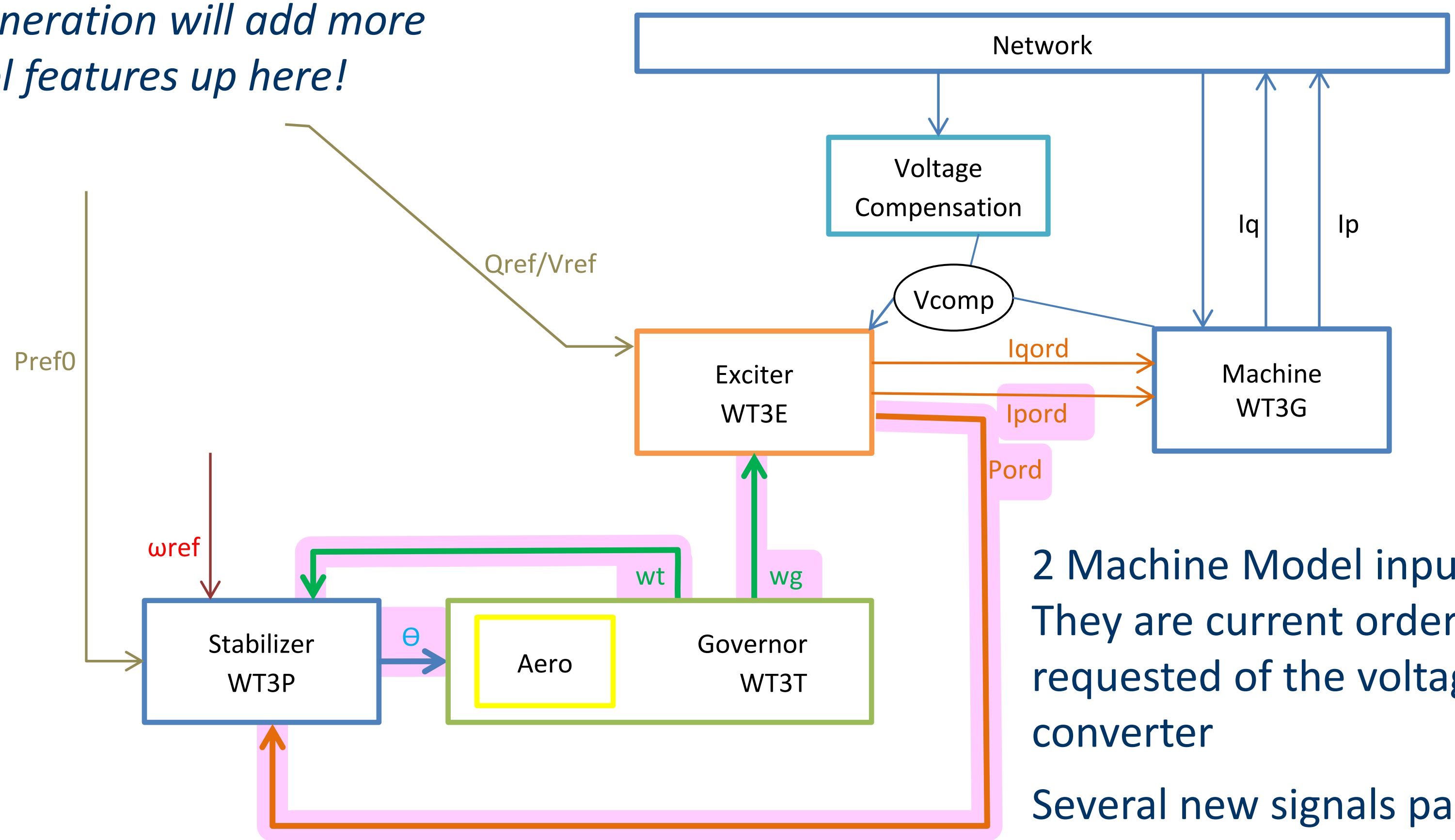


Modular Approach to Wind and Solar Unit Modeling

- First generation wind turbine models stuck with this structure
  - Added additional signals to pass between modules
  - Don’t get hung up on nomenclature “exciter” just means the electrical control
- Unrelated to wind turbine modeling, another module was added for better modeling of large steam plants
  - LCFB1 – extra controller feeding the governor allowing control of *Pref*

First Generation Type 3 Wind Turbine (WT3G, WT3E, WT3T, WT3P)

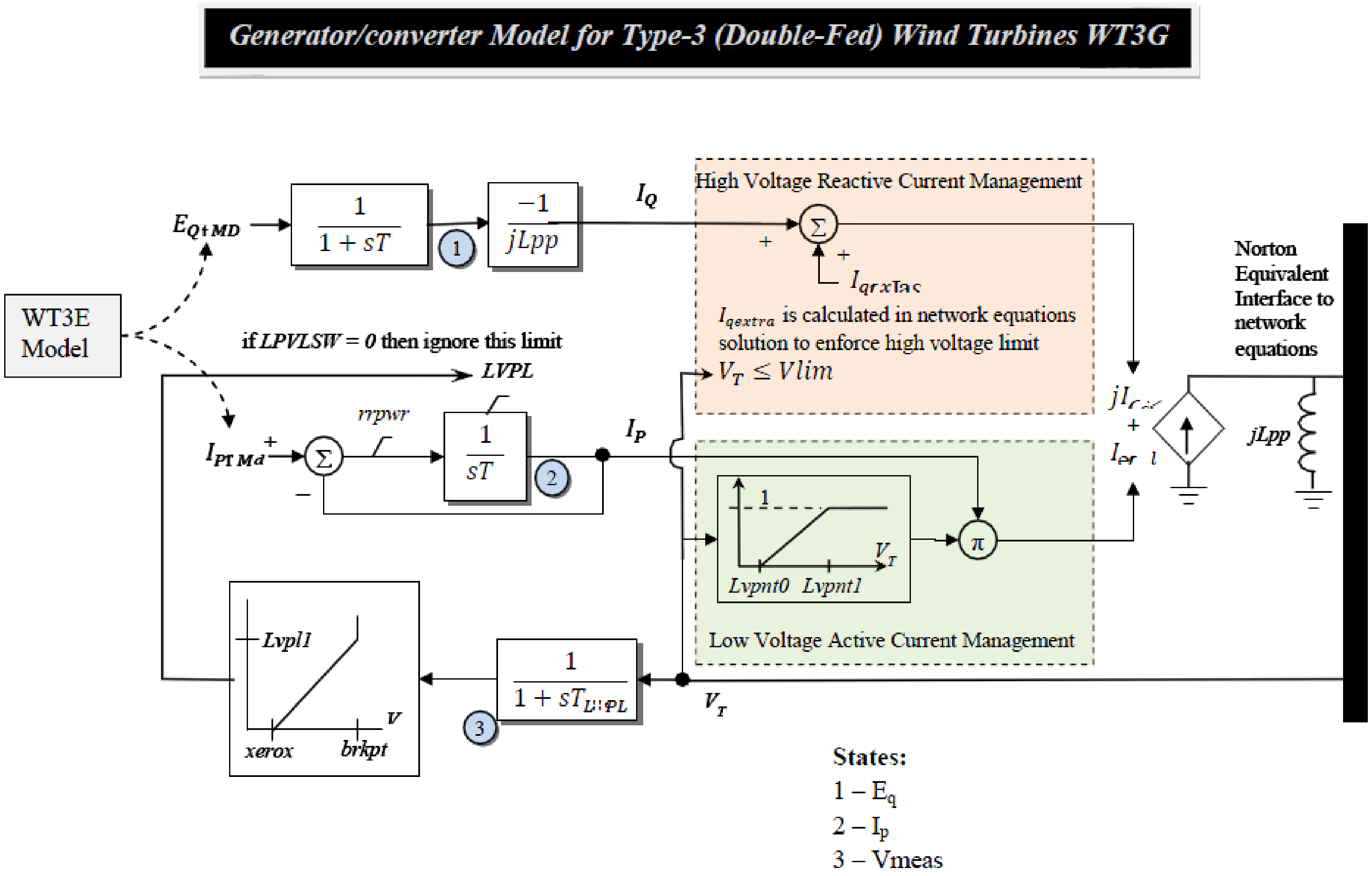
2nd Generation will add more control features up here!



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

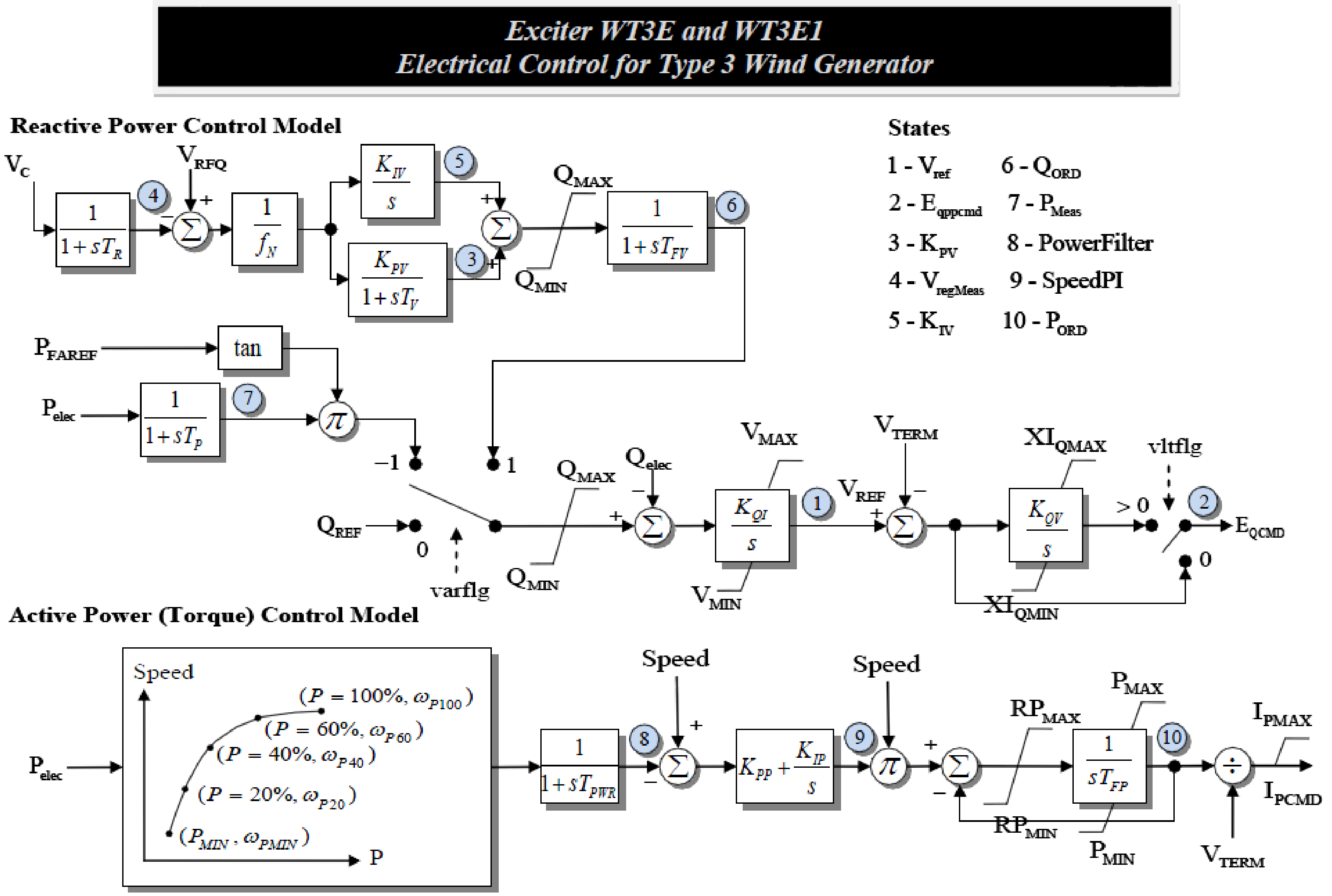
Several new signals passing around

Type 3 WT3G Converter Model



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

Type 3 Reactive Power Control

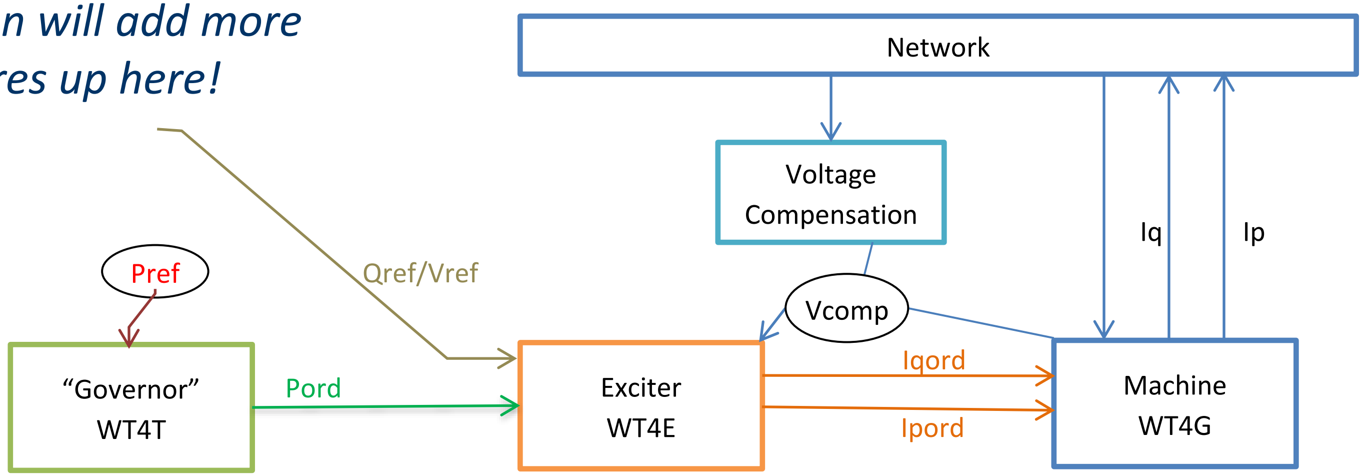


WT3E supported by PSLF with $RP_{MAX} = P_{wrat}$ and $RP_{MIN} = -P_{wrat}$, $T_{FV} = T_C$

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

First Generation Type 4 Wind Turbine (WT4G, WT4E, WT4T)

2nd Generation will add more control features up here!

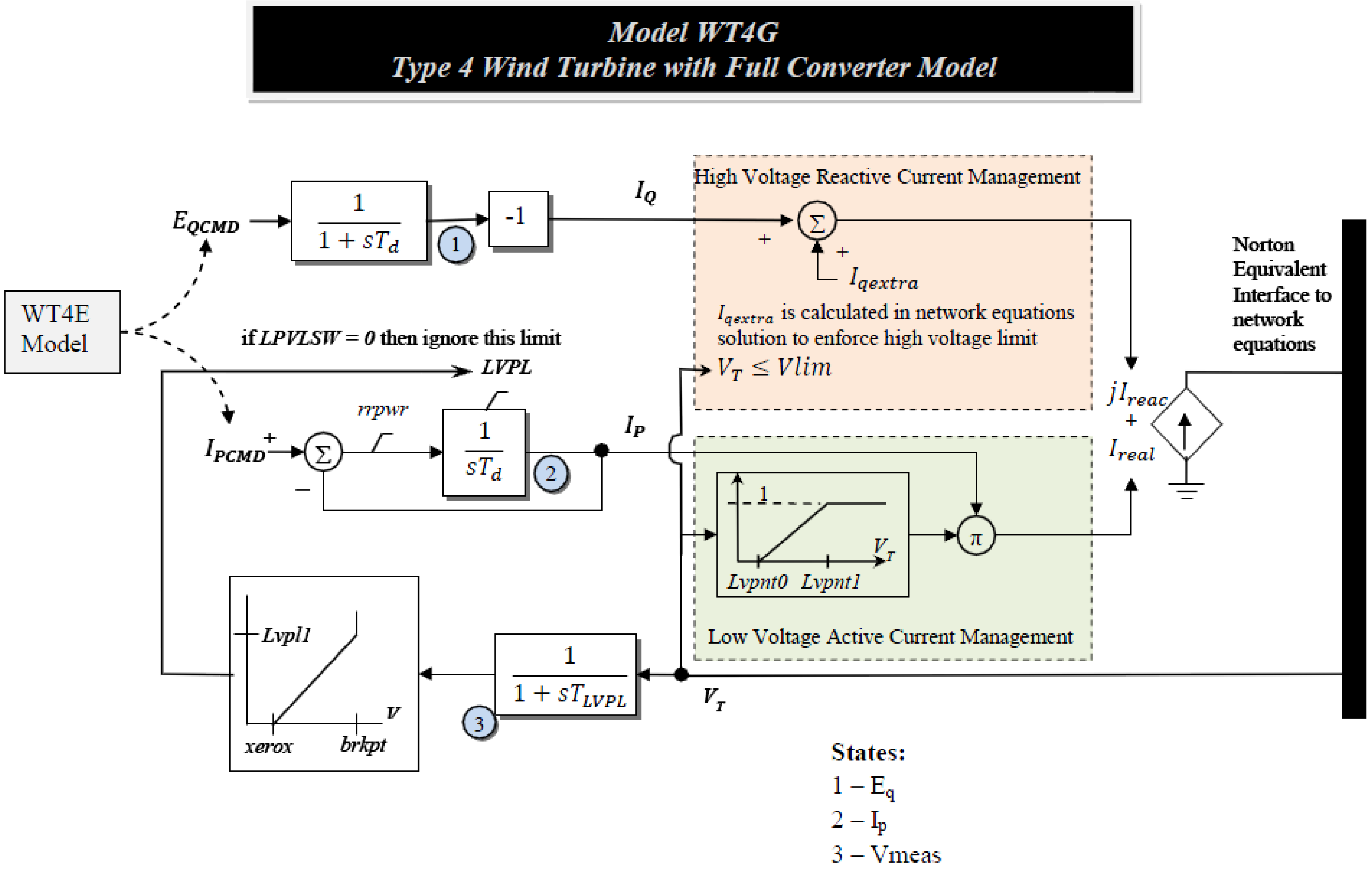


Legacy "Governor" WT4T

This really acts like the new PRef controller

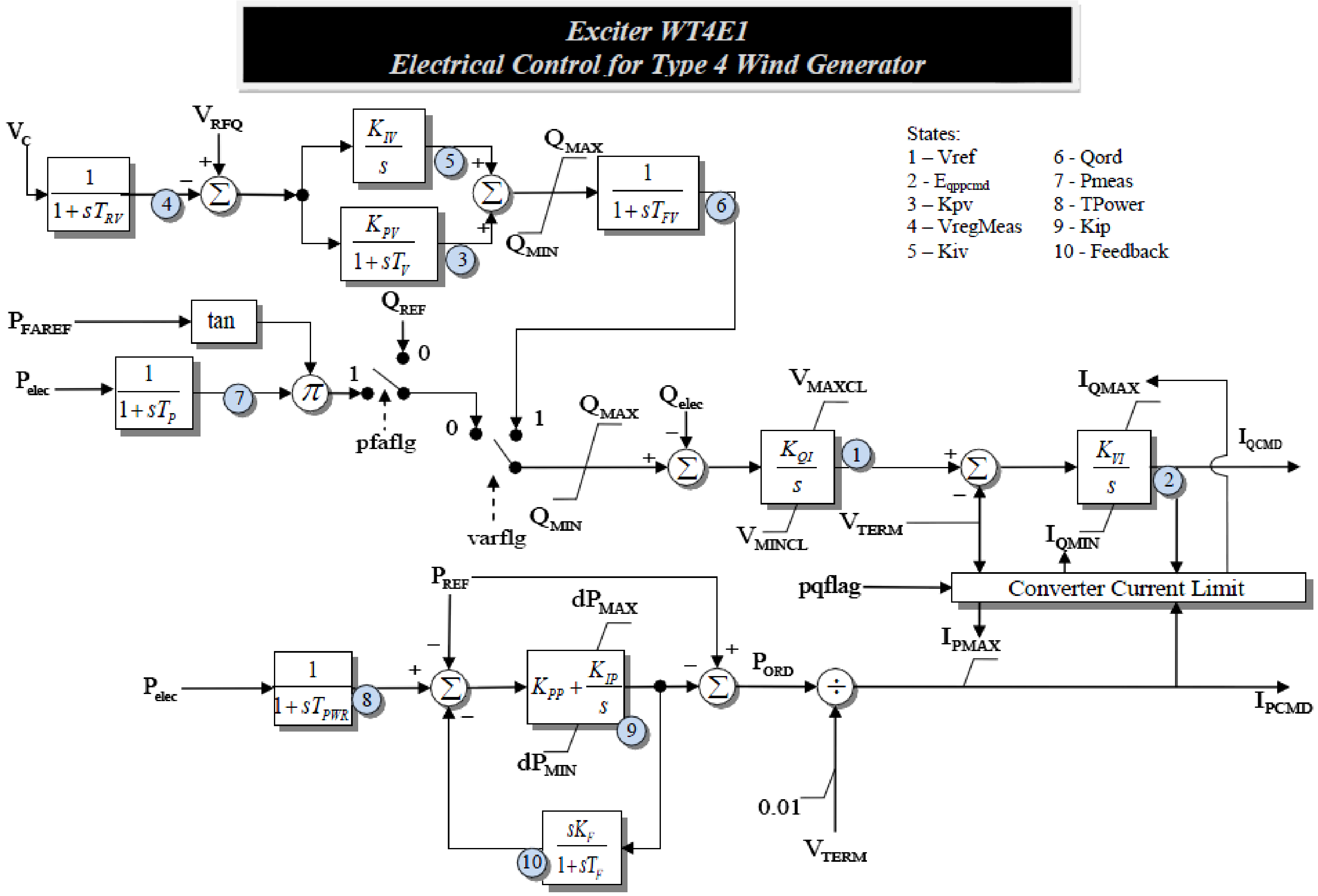
We will leave it in the toolbox as a "Governor" anyway

Type WTG4 Model



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

Type 4 Reactive Power Control



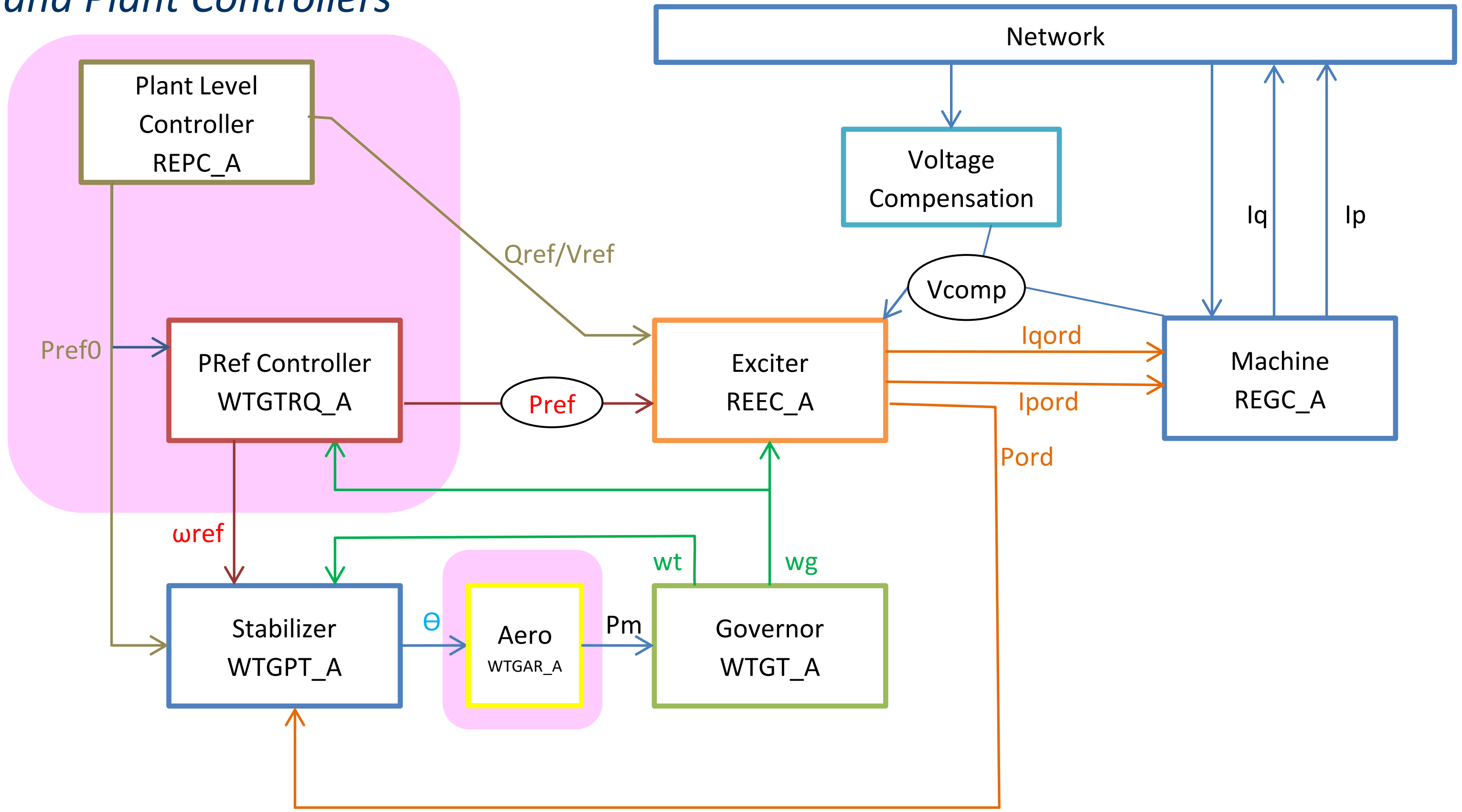
Also similar to the Type 3's, as are the other models

Limitations of First Generation Models

- First Generation model had few mechanisms to provide control features of
  - Real Power or Torque Control
  - Reactive Power
  - Voltage Control
  - For First Generation models, the wind turbine basically tried to bring values back to the initial condition
    - Pref bring power back to initial Power
    - Qref or Vref or PowerFactorRec

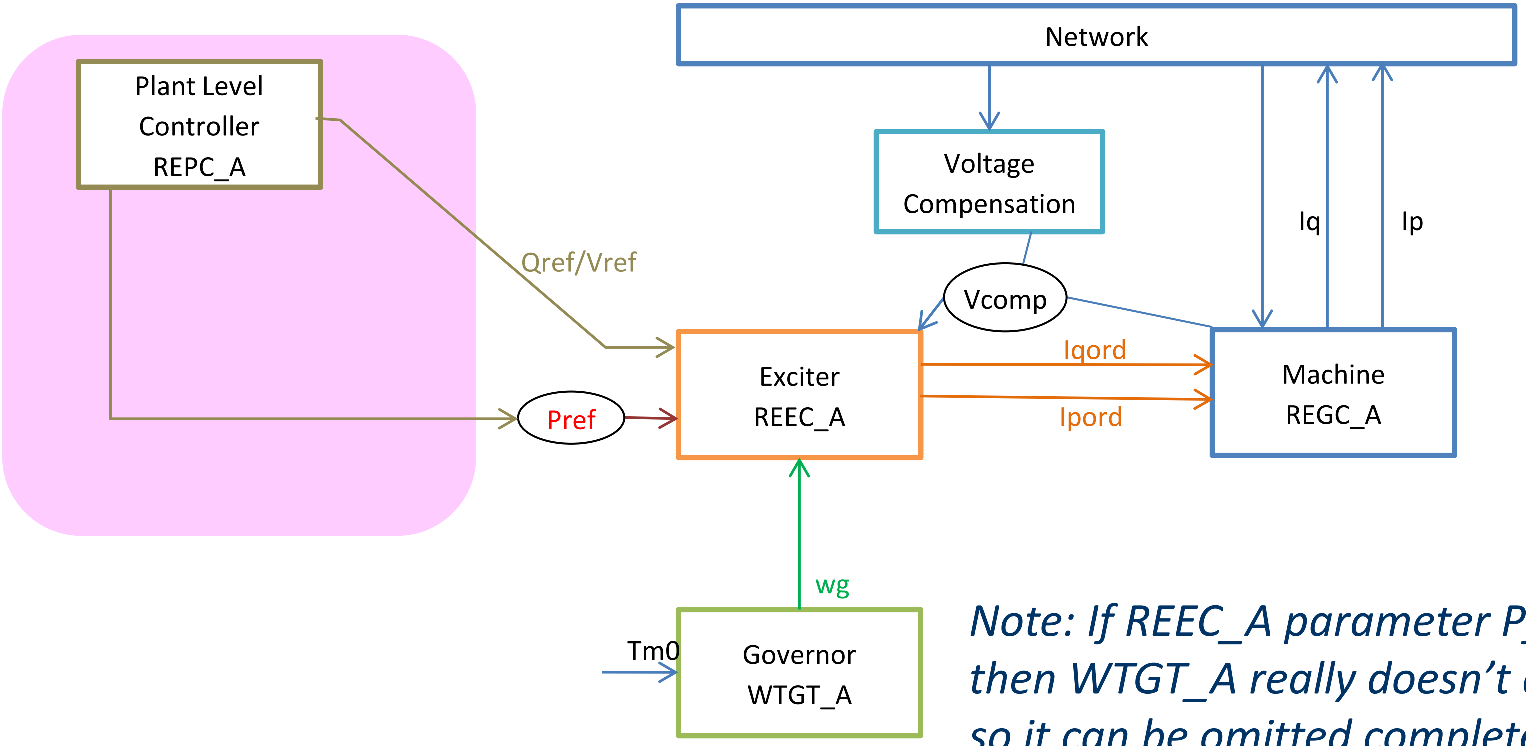
2^{nd} Generation Type 3 Wind Turbine
(REGC_A, REEC_A, WTGT_A, WTGAR_A, WTGPT_A, WTGTRQ_A, REPC_A)

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



2nd Generation Type 4 Wind Turbine

(REGC_A, REEC_A, WTGT_A, REPC_A)

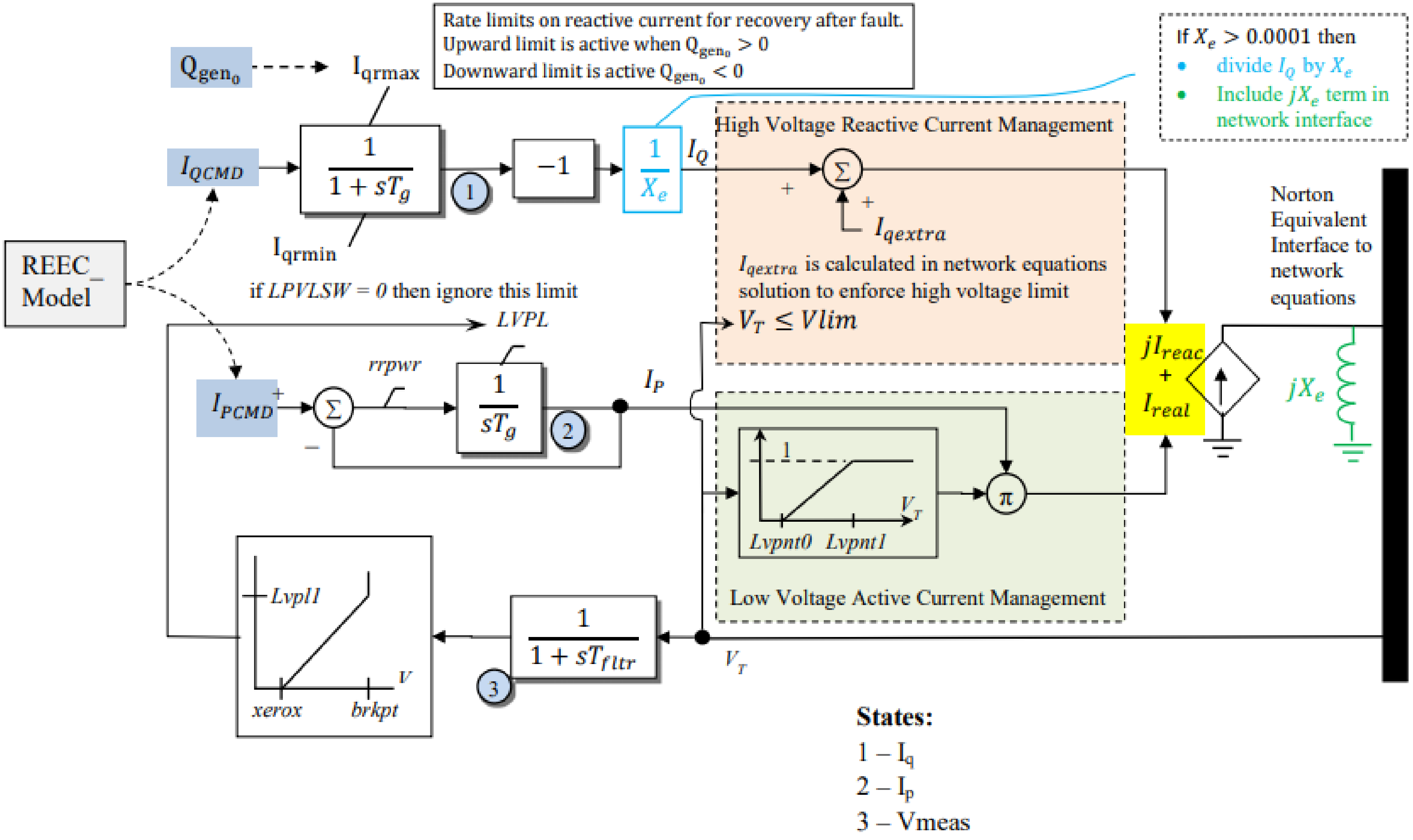


Note: If REEC_A parameter Pflag = 0, then WTGT_A really doesn't do anything so it can be omitted completely

REGC_A (or REGCA1)

- "Machine Model": Really a network interface

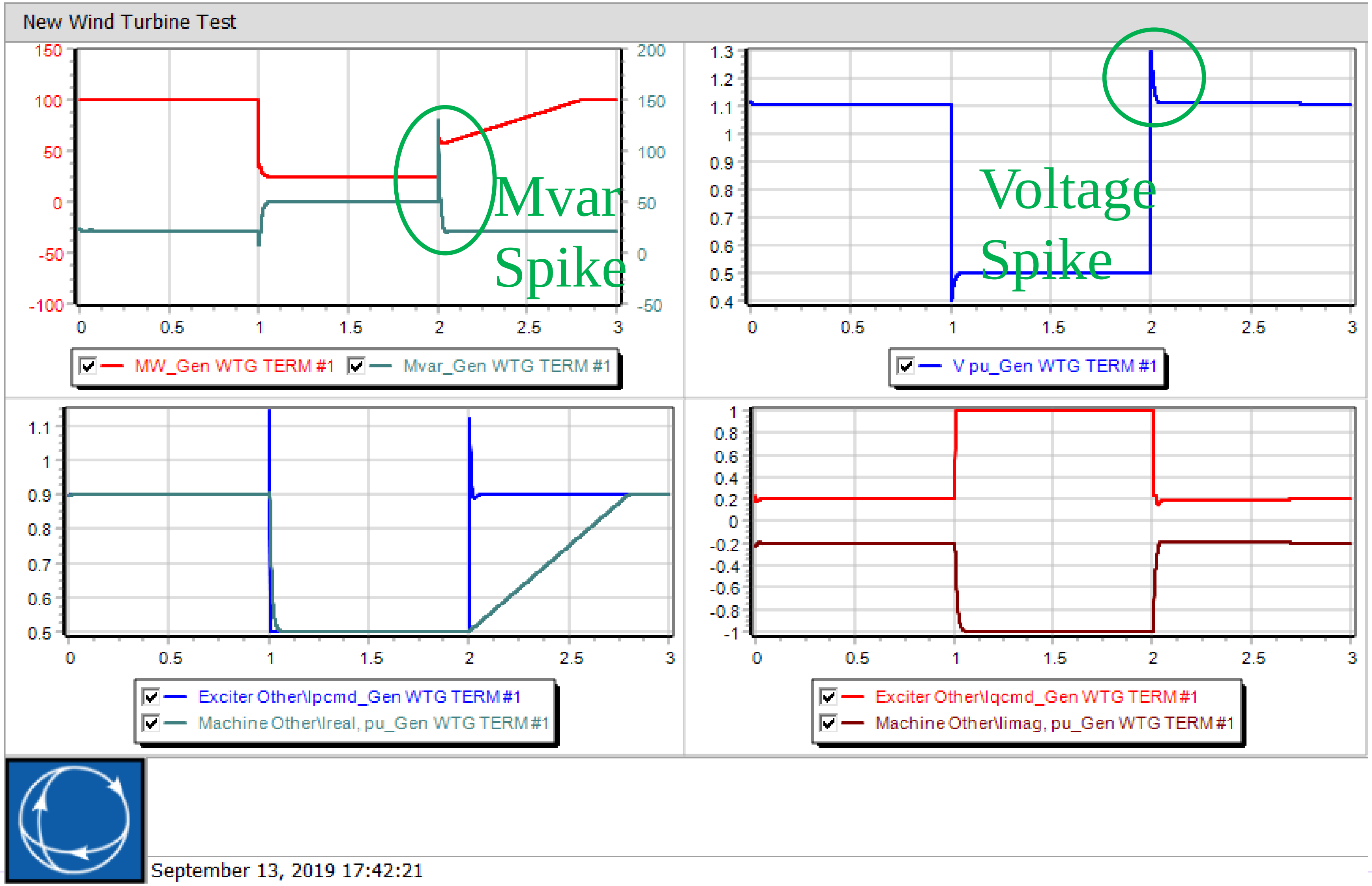
Inputs from REEC* electrical models



REGC_A Description

- This model is doing very little actually
  - Time delay Tg is the entirety of the converter model
    - Crudely, the model says "Electrical Controller asks for a real and reactive current → 0.020 seconds later the converter creates this"
    - We are NOT modeling any of the power electronics at all
      - We are not modeling any phase-locked-loop (PLL)
      - Our assumption is all of that stuff is really fast
- "High Voltage Reactive Current Management" and "Low Voltage Active Current Management"
  - These are a dubious names because we aren't modeling things in enough detail to really have "control" here
  - This control happens in the less than 1 cycle time-frame!

What is Happening? Voltage and Mvar Spike



Renewable Energy Models (Wind, Solar, Storage Models)

1st Generation Models

Class of Model Type	Wind Type 1	Wind Type 1	Wind Type 2	Wind Type 2	Wind Type 3	Wind Type 3	Wind Type 4	Wind Type 4	Solar PV
Machine	WT1G	WT1G1	WT2G	WT2G1	WT3G	WT3G1	WT4G	WT4G1	PV1G
Electrical Model			WT2E	WT2E1	WT3E	WT3E1	WT4E	WT4E1	PV1E
Mechanical	WT1T	WT12T1	WT2T	WT12T1	WT3T	WT3T1	WT4T		
Pitch Controller	WT1P	WT12A1	WT2P	WT12A1	WT3P	WT3P1			

2nd Generation Models

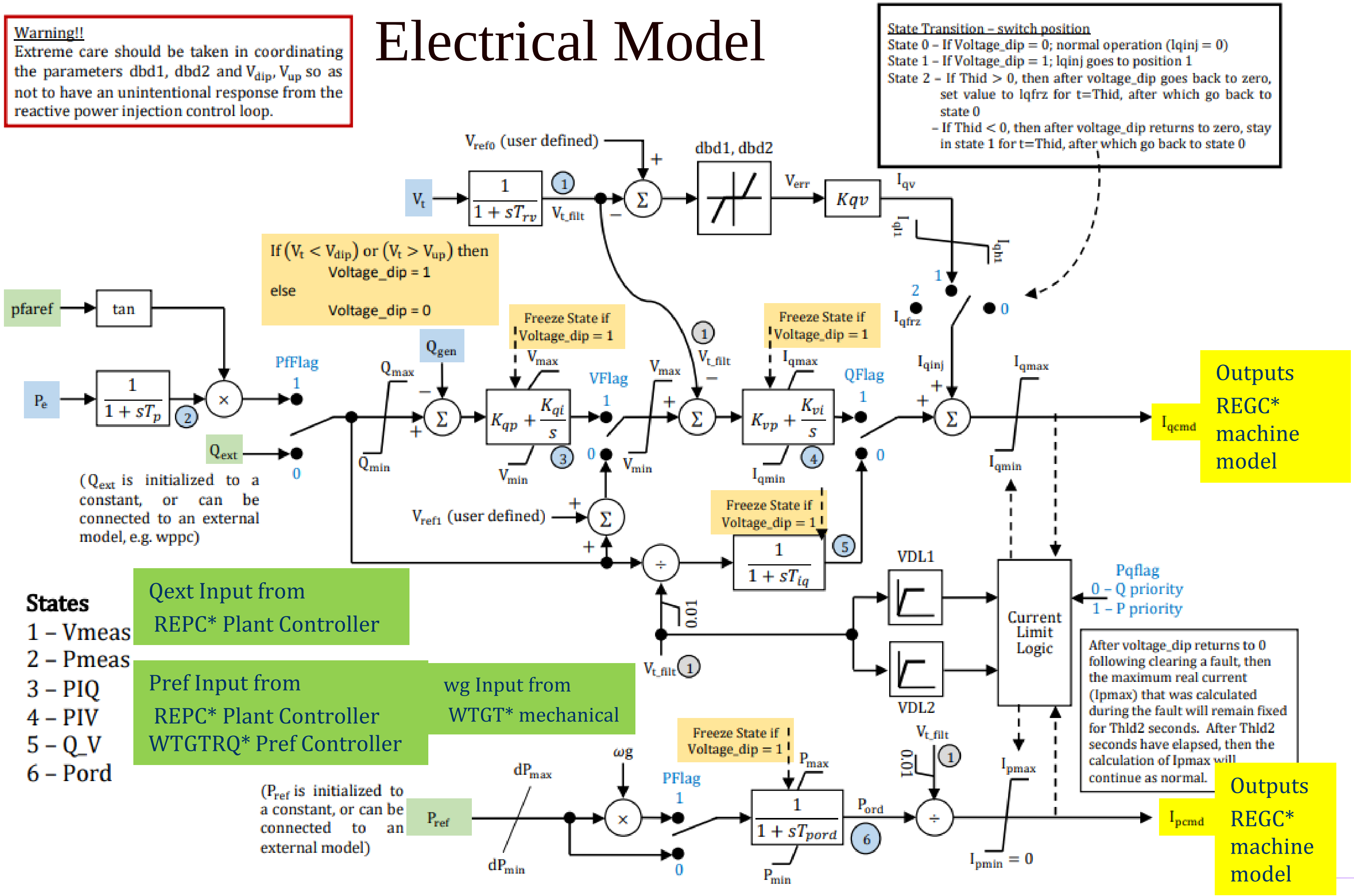
Class of Model Type	Wind Type 1	Wind Type 2	Wind Type 3	Wind Type 4	Solar PV	Distributed PV Model	Energy Storage
Machine	WT1G WT1G1	WT2G WT2G1	REGC_A	REGC_A	REGC_A	PVD1 DER_A	REGC_A
Electrical Model		WT2E WT2E1	REEC_A	REEC_A	REEC_B		REEC_C
Mechanical	WT1T WT12T1	WT2T WT12T1	WTGT_A	WTGT_A			
Pitch Controller	WT1P_B	WT2P WT12A1	WTGPT_A				
Aerodynamic			WTGA_A				
Pref Controller			WTGTRQ_A				
Plant Controller			REPC_A or REPC_B	REPC_A or REPC_B	REPC_A or REPC_B		REPC_A or REPC_B

Additional Uses

3 new classes of models

REPC_B = Plant controller for up to 50 machines and SVCs

REEC_A (same as REECA1)

- 

Comparing First and Second Generation Models

- Many parts actually change very little
  - "Machine": Voltage Source Converter model of the generator is nearly identical
    - WT3G/WT4G is pretty much same as REGC_A
  - "Governor": Mechanical Model of wind turbine is identical
    - Combination of WTGT_A and WTGAR_A is *identical* to WT3T
  - "Stabilizer": Pitch Control model has only a small addition
    - WT3P is pretty much same as WTGPT_A
- What's Different – Control System Models
  - The WT3E and WT4E models essentially embedded voltage control and power control inside the model
  - This is now split into separate models
    - REEC_A: models only control with setpoints are as inputs to this model. Control features a little more flexible than the WT3E and WT4E models
    - WTGTRQ_A: control system resulting in the output of PRef
    - REPC_A : control system resulting in output of both a P and V/Q signal