Renewables Integration into Power Grid Systems

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UC San Diego MAE Dept.

MAE 119

Outline: Hierarchy of Issues to Consider

- What does a grid really look like?
- Instantaneous Power: Generation = Load
- Characterizing Renewable Electricity Variations:
  - Time-scales & Magnitudes
- A (painfully) simplified model to see the physics: AC Circuit
- Synchronous Generators
- Response to transient load-mismatch: Frequency Stability, Reactive Power Transients & Voltage Stability
- Need for Storage: Time-scales of response; Power & Energy Required

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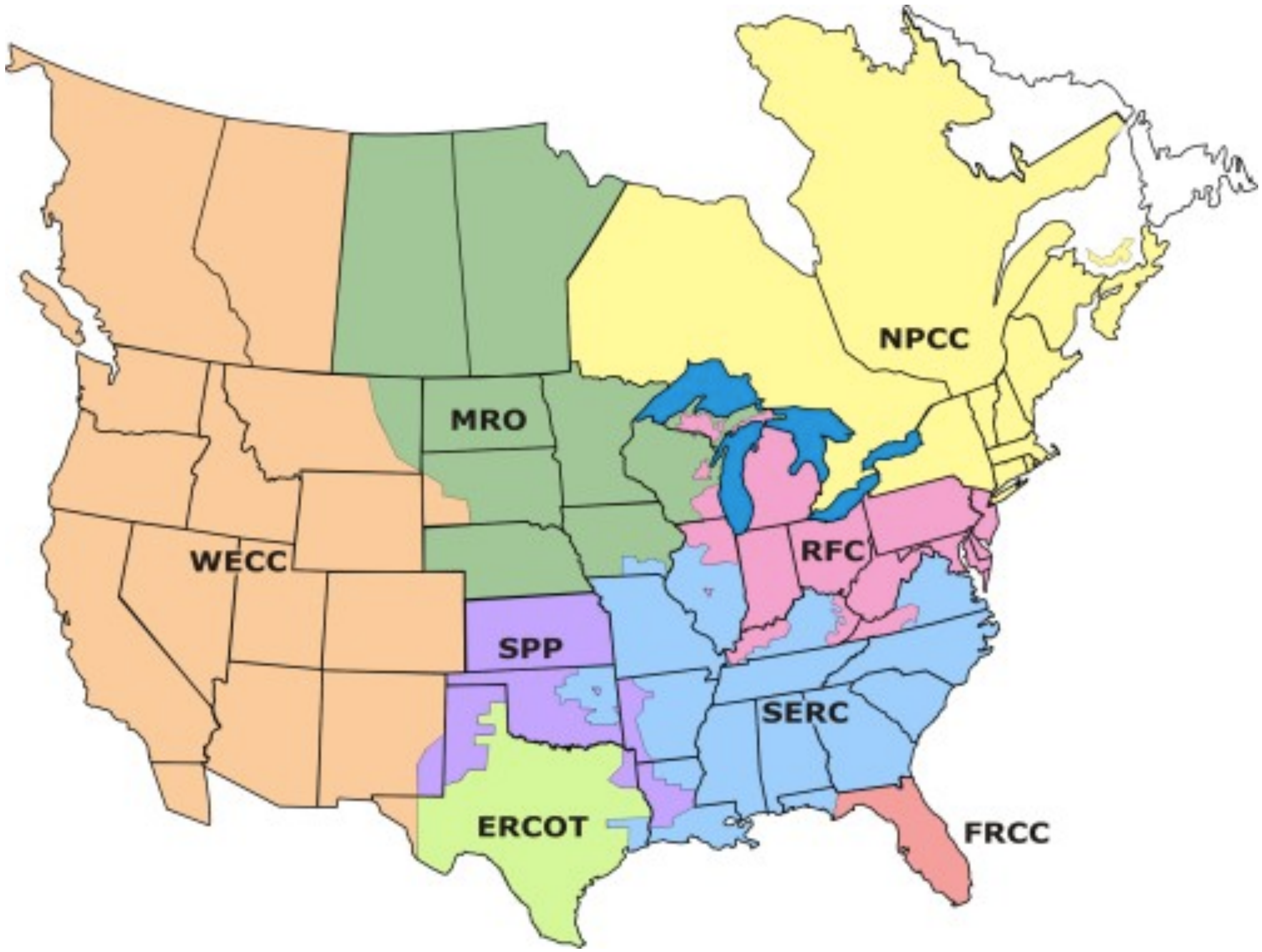
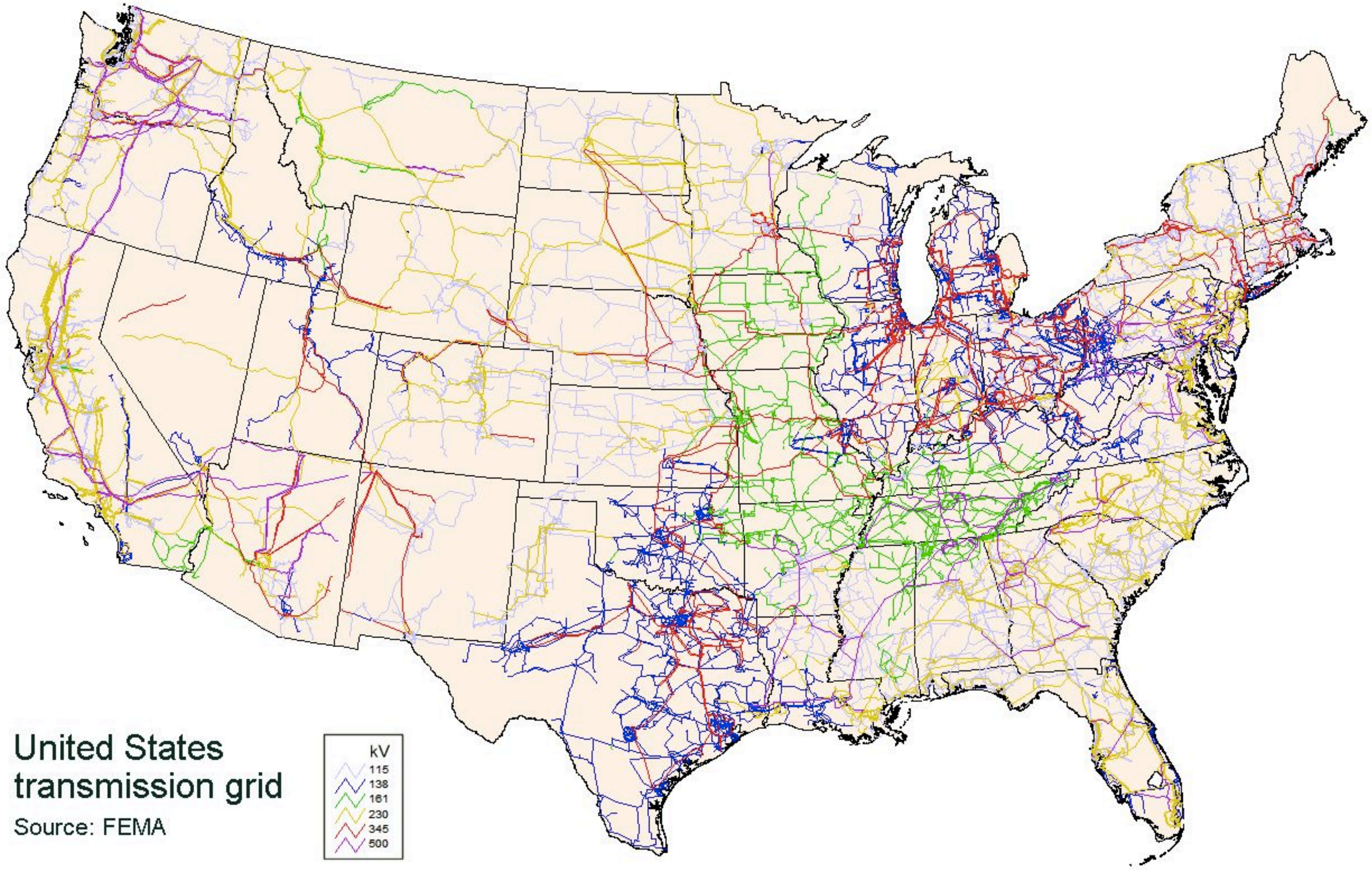
Continental scale view of interconnected regions in N. America



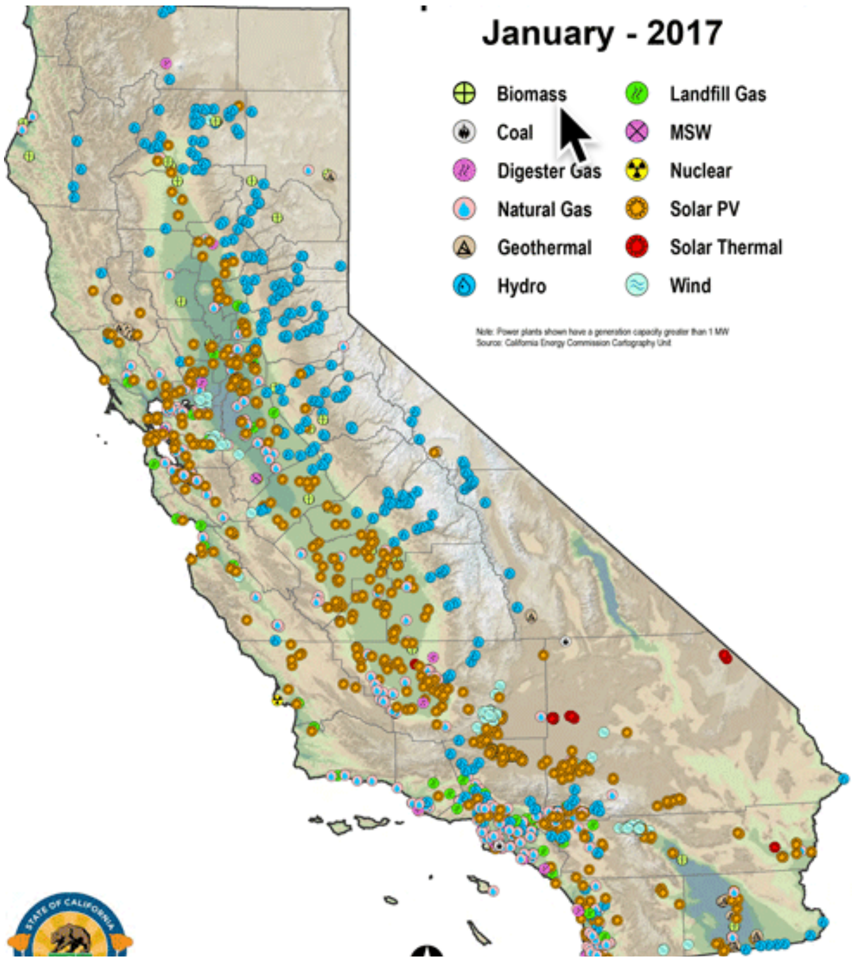
Global Energy Network Institute, NERC Regions

U.S. Transmission Grid



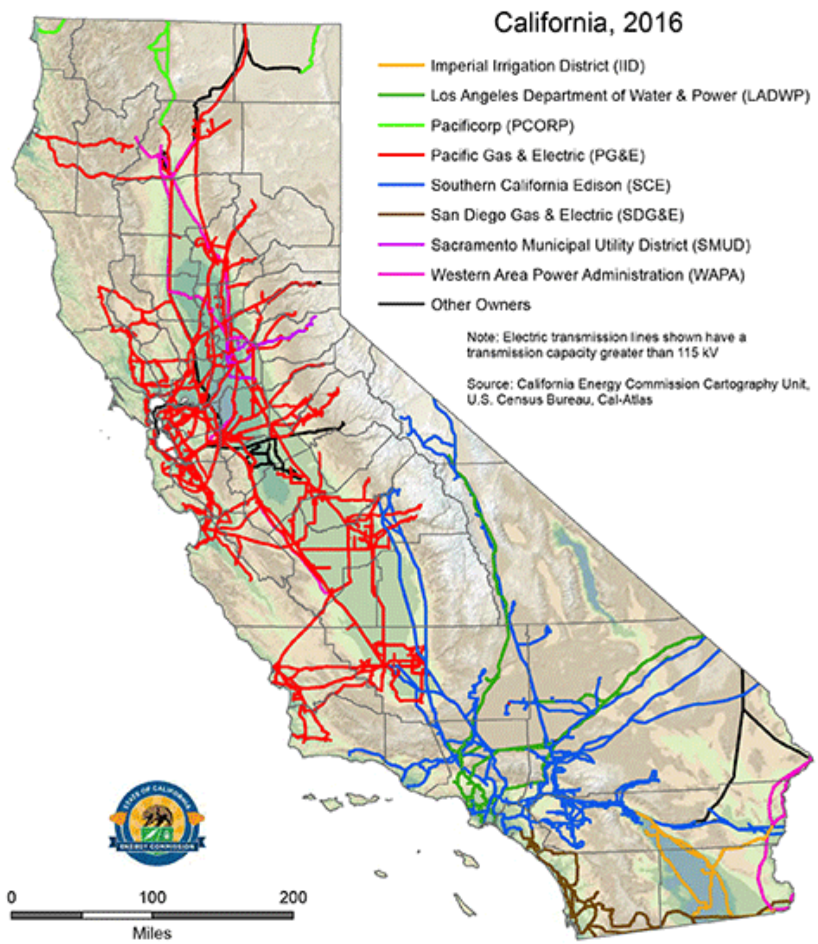
Source: FEMA

Electrical Power Generation Stations



- Multiple Sources
- Wide spatial distribution
- Wide range of sizes (10's MW up to ~1000MW)
- Q: How does energy get to load centers (i.e. where the people are located)?

Example: California Electrical Transmission Network

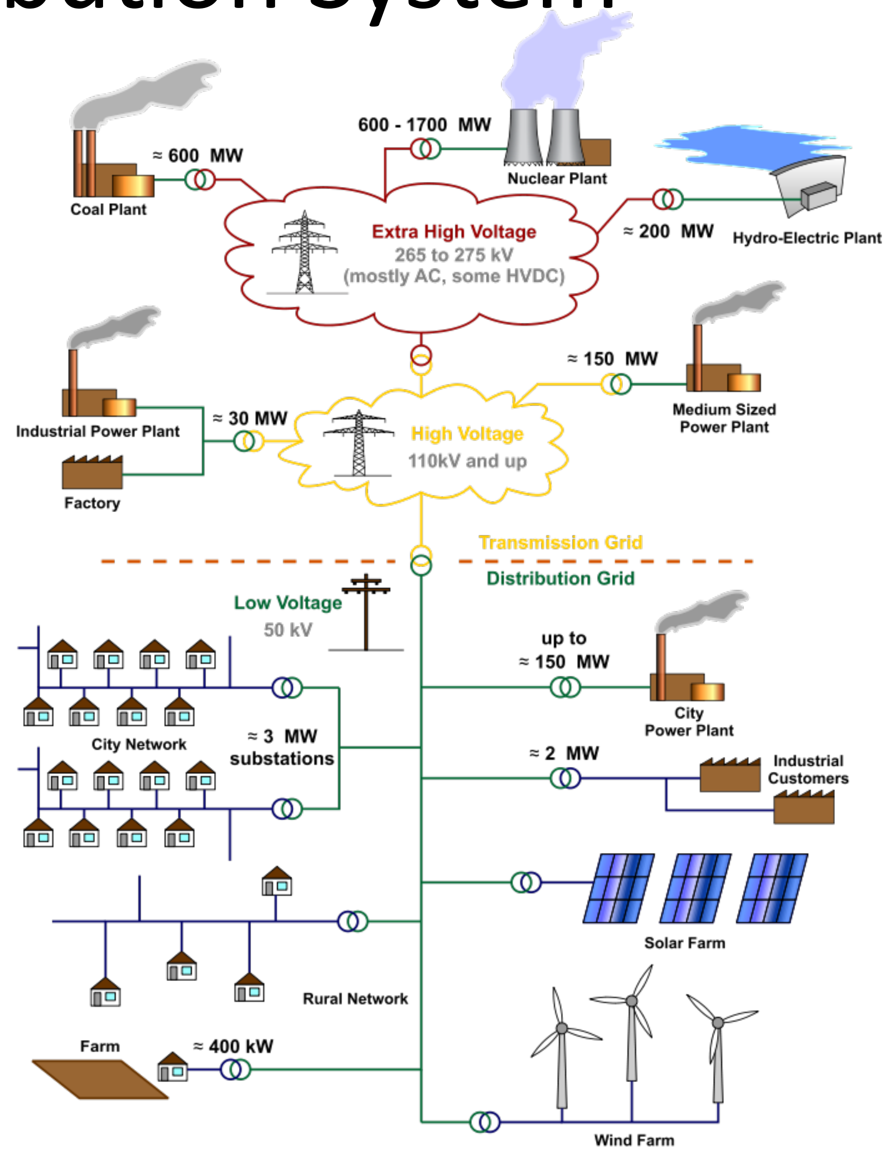


- Tranmission network w/ V>115kV shown
- Note interconnections across state borders
- Multiple transmission line owners/operators
- Power transferred over 100-1000 km's

Power to the People: The Transmission & Distribution System

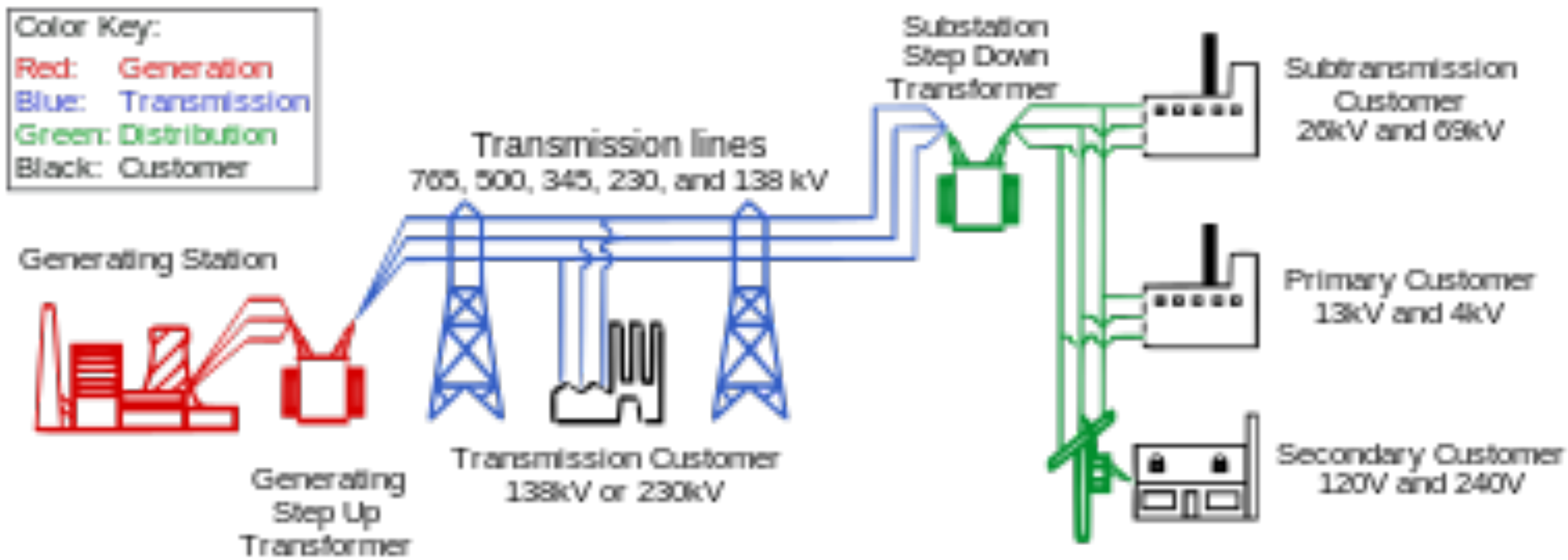
“Transmission” System

“Distribution” System



Source: Wikipedia

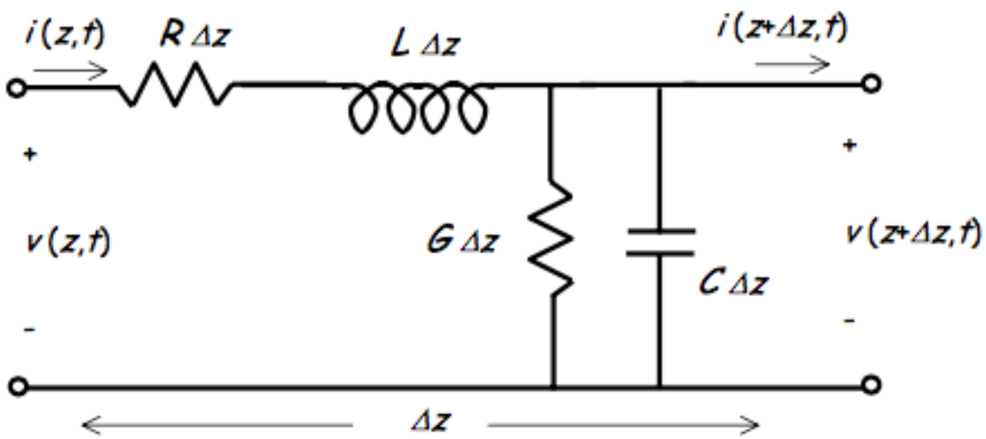
Distribution System Schematic



Source: Wikipedia

Simplified AC Circuit Models: **Transmission Line**

i.e.,



Where:

R = resistance/unit length
L = inductance/unit length
C = capacitance/unit length
G = conductance/unit length

∴ resistance of wire length Δz is $R\Delta z$.

Assuming sinusoidal
Time variations of V(z,t)
And I(z,t) then V and I obey
The ***Telegrapher's Equations:***

$$\frac{\partial V(z)}{\partial z} = -(R + j\omega L)I(z)$$

$$\frac{\partial I(z)}{\partial z} = -(G + j\omega C)V(z)$$

Source: http://www.ittc.ku.edu/~jstiles/723/handouts/
2_1_Lumped_Element_Circuit_Model_package.pdf

Simplified AC Circuit Models: **Transmission Line (**cont'd)

Can show V(z) and I(z) obey:

Source: http://www.ittc.ku.edu/~jstiles/723/handouts/
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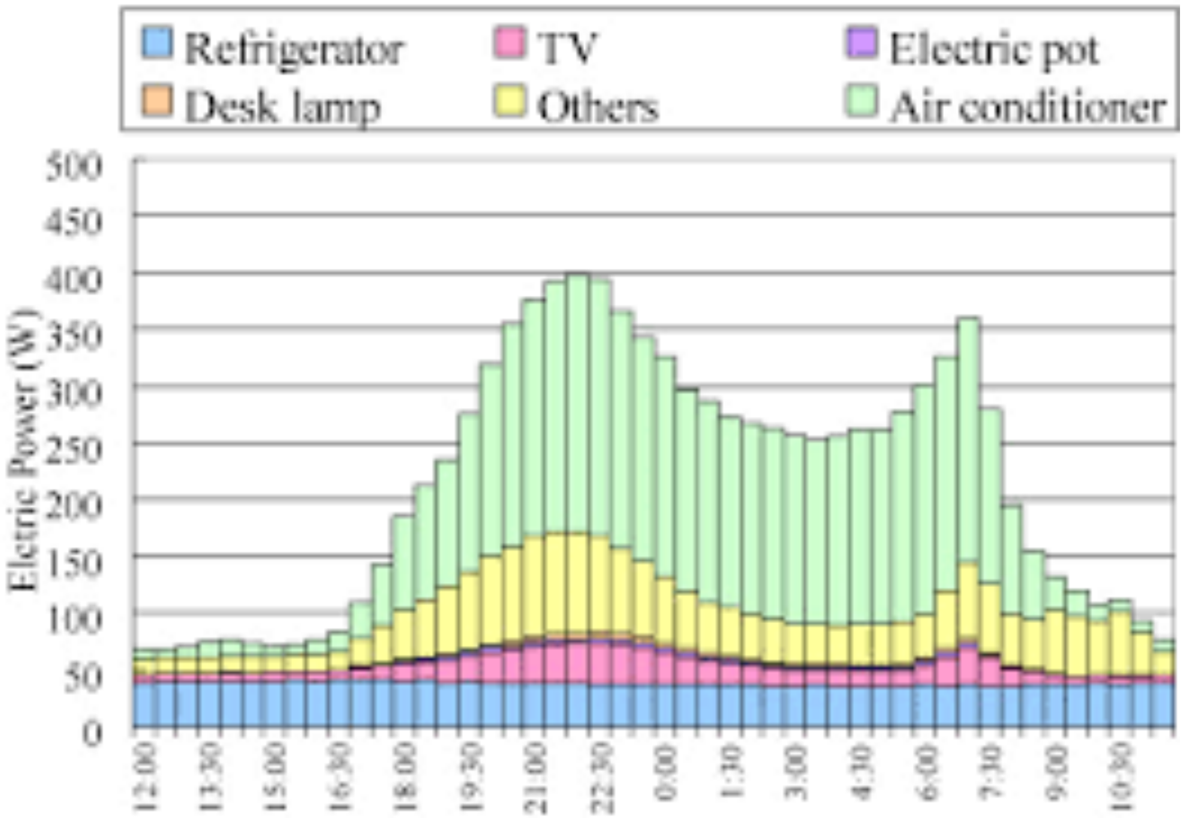
Safe & Stable Grid Operation Requires
Power Generated = Power Consumed

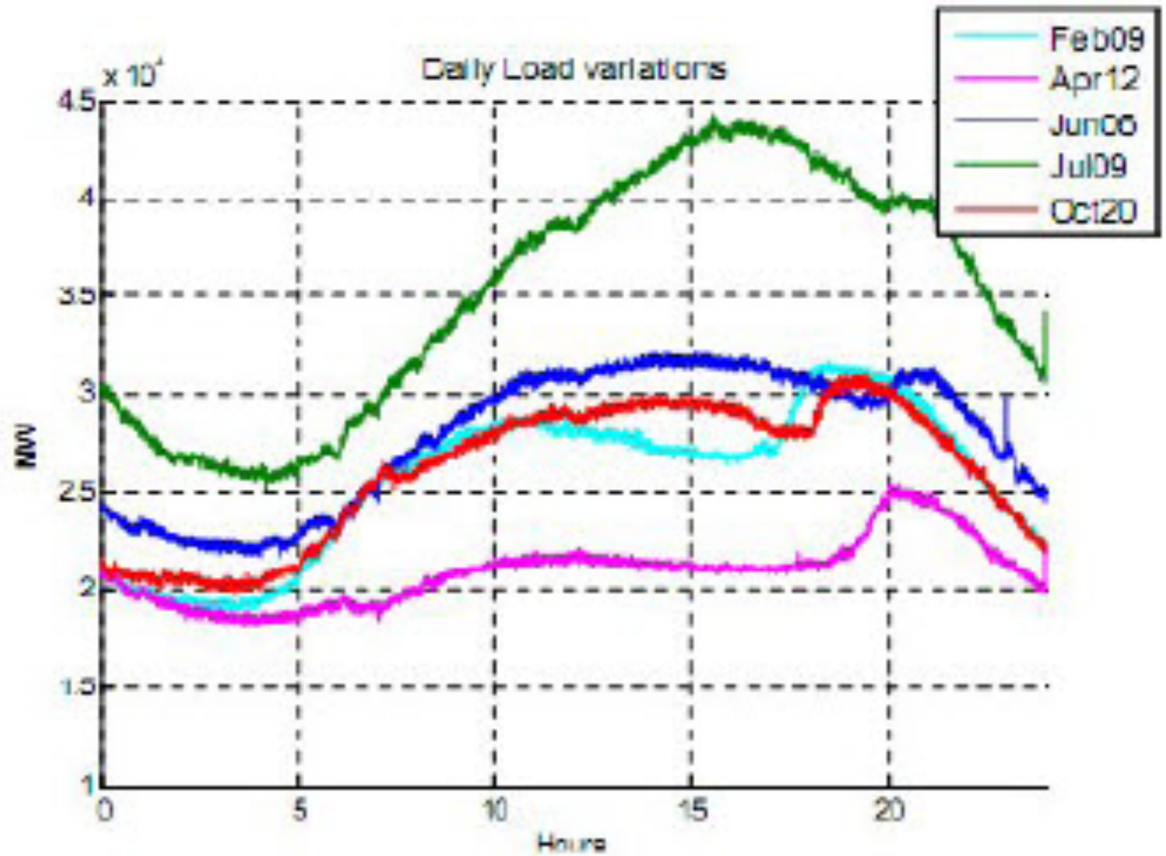
Demand Curve at Household Level:



Demand Curve at State Level (e.g. California) Shows Significant Diurnal and Seasonal Variation:

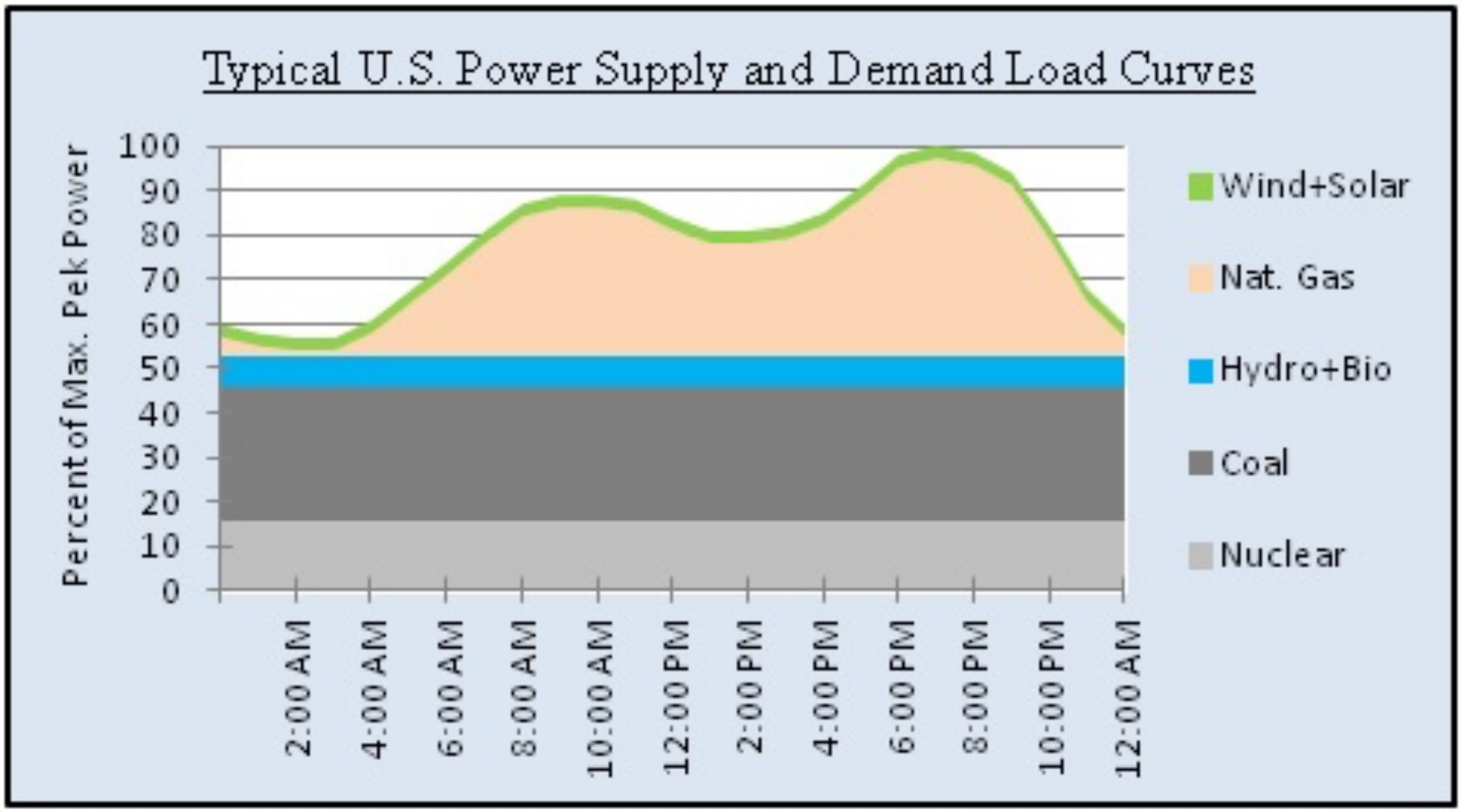
How can it be so different?

Typical daily load variations in California in various seasons, in 10,000 MWs



Source: CEC. June 2010

Demand & Supply Curve at National Level:



Source: The Energy Collective

Key Concept: Capacity Factor

- Capacity Factor, C_F defined as

$$C_F = \frac{P_{ave}}{P_{MAX}}$$

$C_F =$

$$where$$

$$P_{ave} = \frac{1}{T}\int_0^T P(t)\,dt$$

$$P_{MAX} \sim Max.System\ Design\ Power$$

Typical Capacity Factor

Energy Source	Capacity Factor (typ.)
Baseload Coal Plant	>90%
Baseload Nuclear/Hydro	>90%
Solar PV	15%
Wind	30-40%
Natural Gas CCGT (Baseload)	>90%
Natural Gas (Peaker)	<<90%

Capacity Factor Impacts Energy Production Over Extended Periods

e.g. A 1 GW_e Nuclear Plant w/ C_F=90% Produces ~7.9 TW-Hr of Electrical Energy/Year

e.g. A 1 GW_e Solar PV Plant w/ C_F=15% Produces ~1.3 TW-Hr of Electrical Energy/Year

Actual & Projected CA Demand Curves

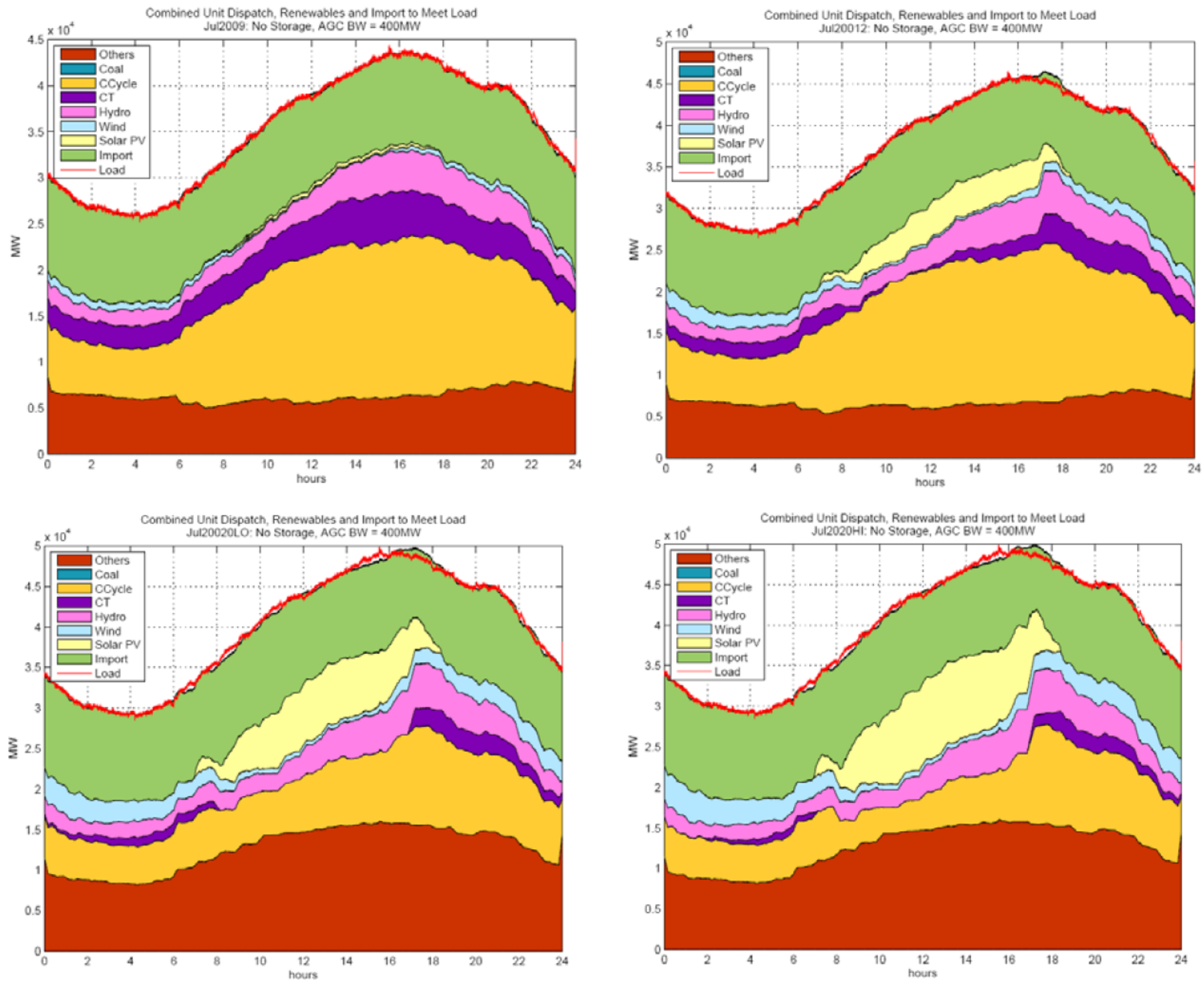


Figure 15. Generation by type and load for July days in 2009, 2012, and 2020

Source: model outputs

CEC, 2010

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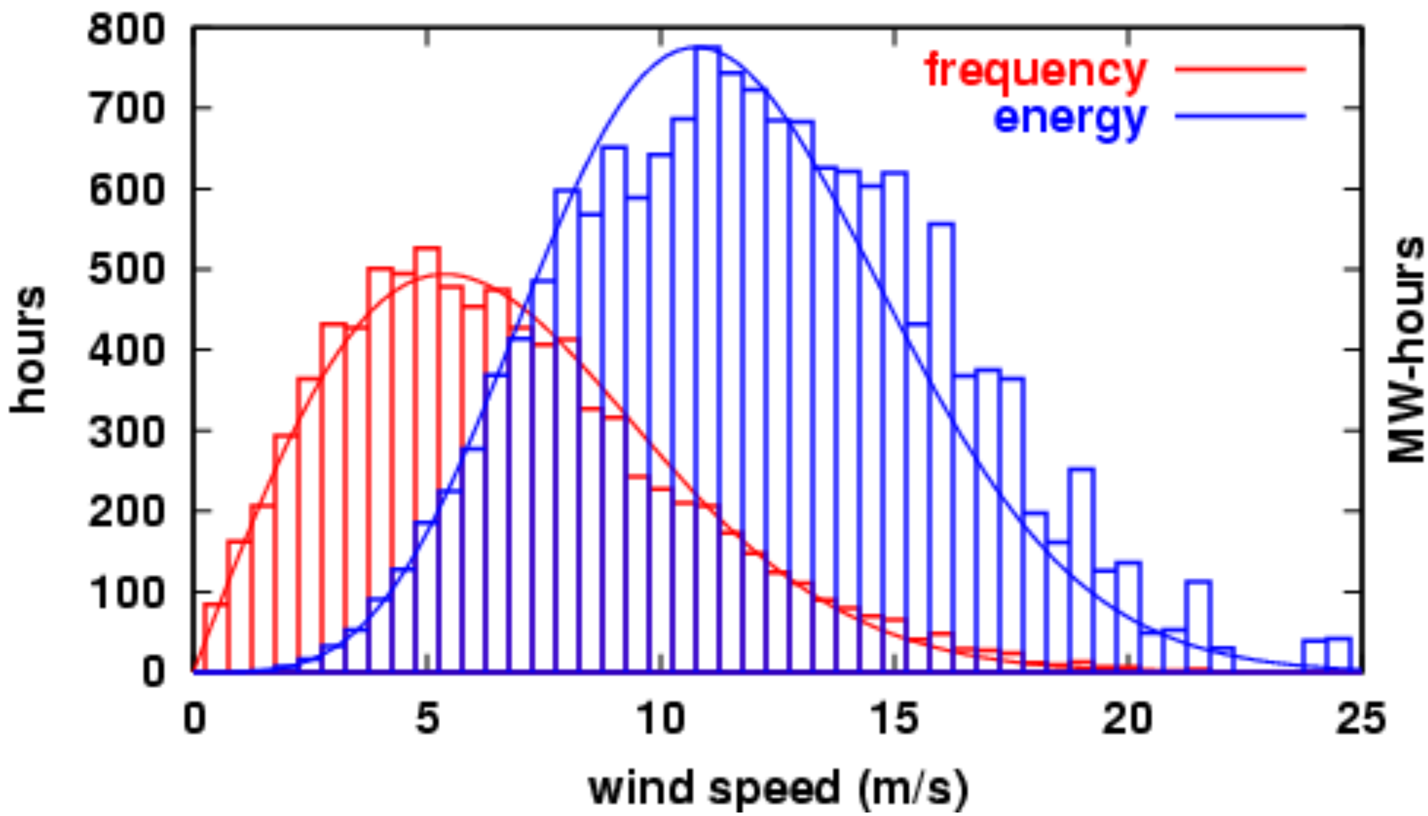
Variety of relevant time-scales for intermittency

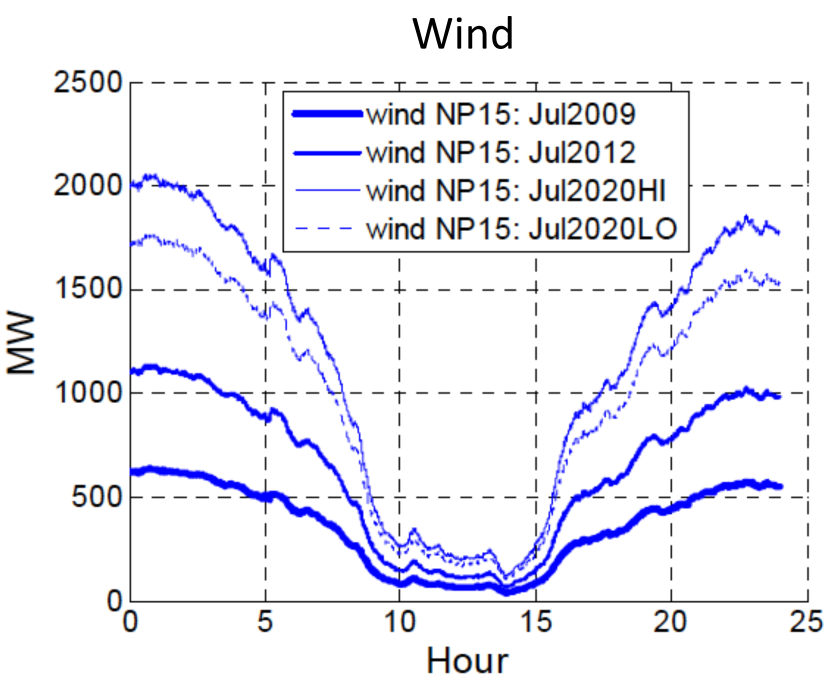
- Short term (seconds-minutes)
  - Wind gusts
  - Clouds, Contrails for CSP Systems
  - Clouds for PV Systems
- Intermediate term (hours – days)
  - Weather systems modify wind, DNI, GHI
- Long term (Weeks to Seasonal

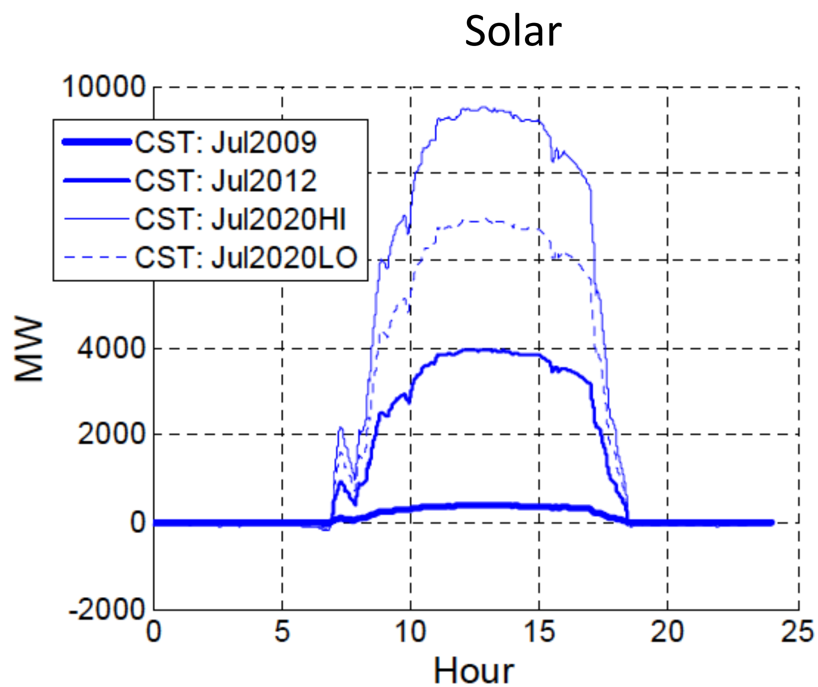
Short term effects – e.g. wind gusts



Source: http://en.wikipedia.org/wiki/Image:Lee_Ranch_Wind_Speed_Frequency.png

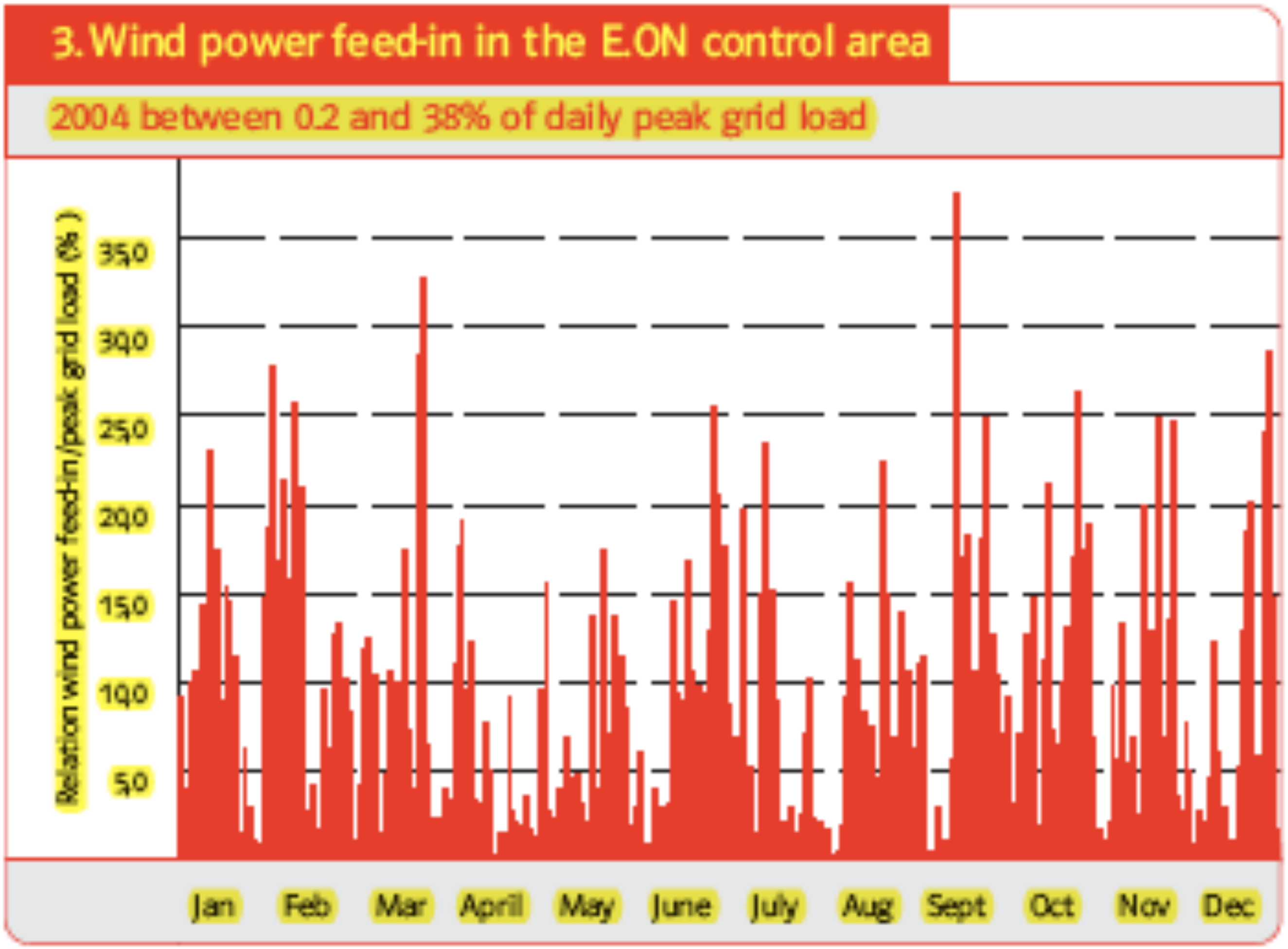
Diurnal & Seasonal Variability
CA Data & Projections





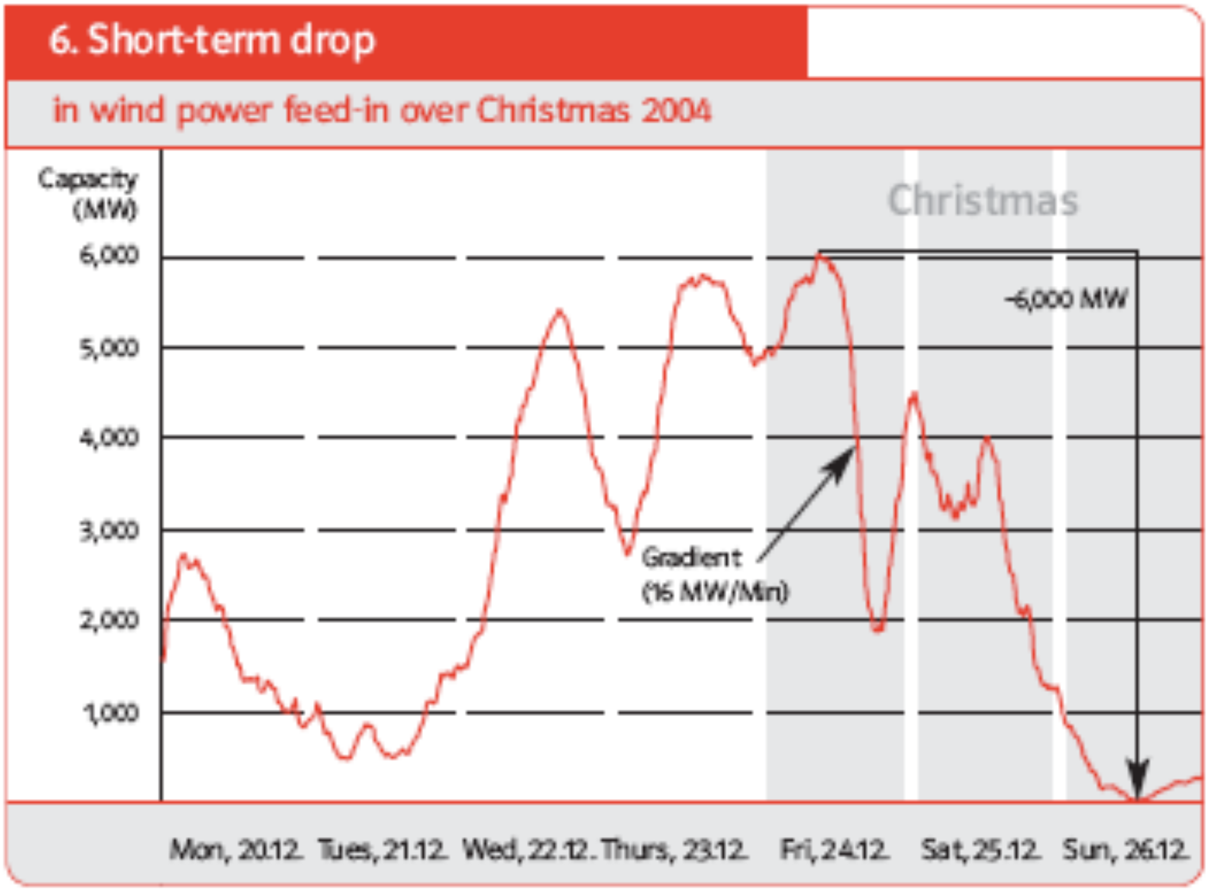
CEC, 2010

Wind Speed Variability Leads to Significant Variation in Wind-generated Power



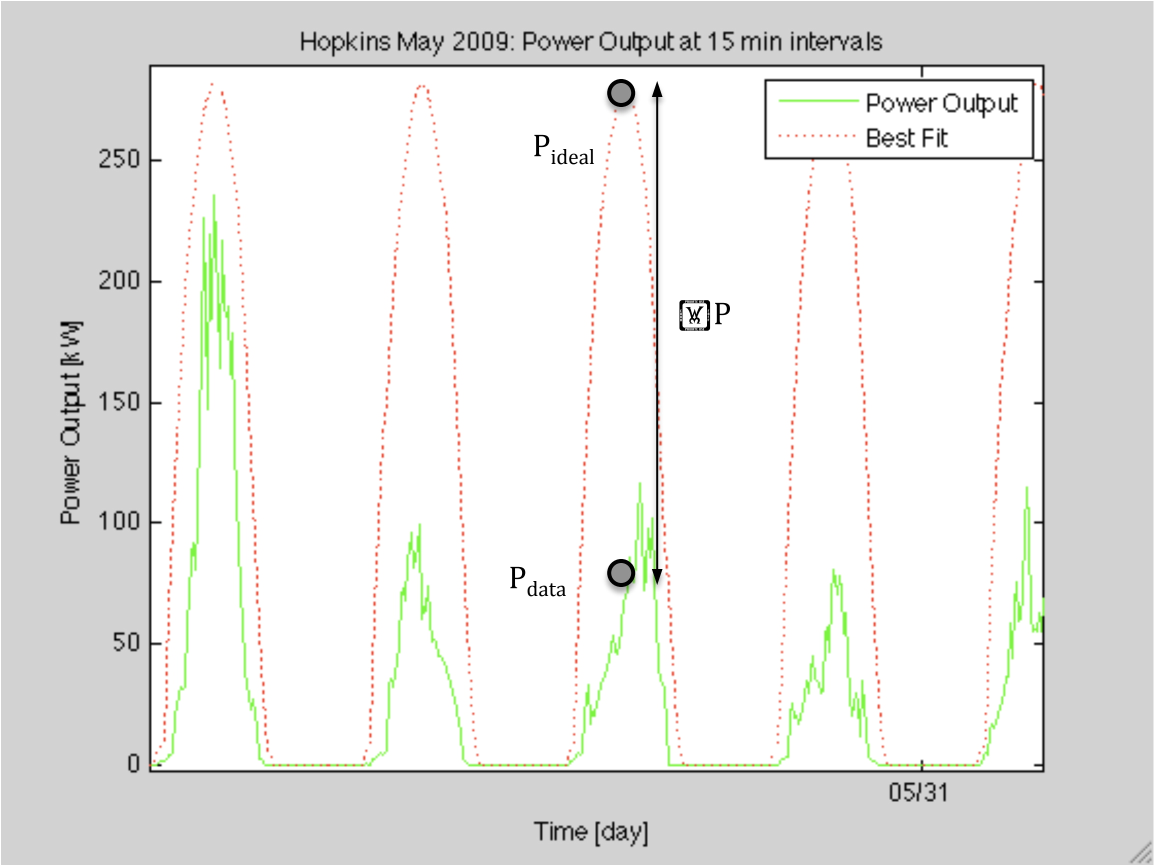
Source: E.On Netz, “Wind Report 2005

Can Also Experience Rapid Changes in Rate of Power Feed-In:



"Handling Such Significant Differences in Feed-in Level Poses a Major Challenge to Grid Operators" Source: E.On Netz, "Wind Report 2005

Another Example: UCSD PV System



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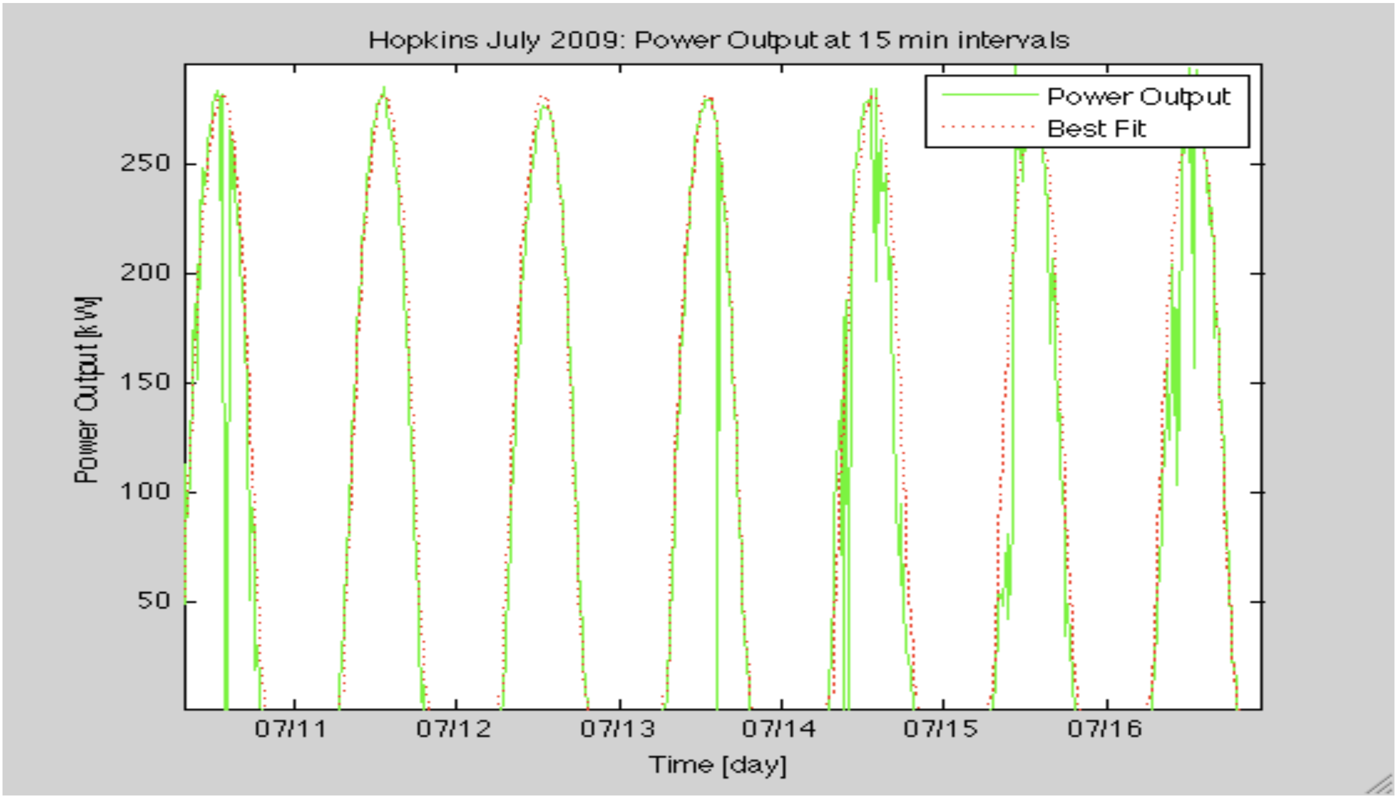
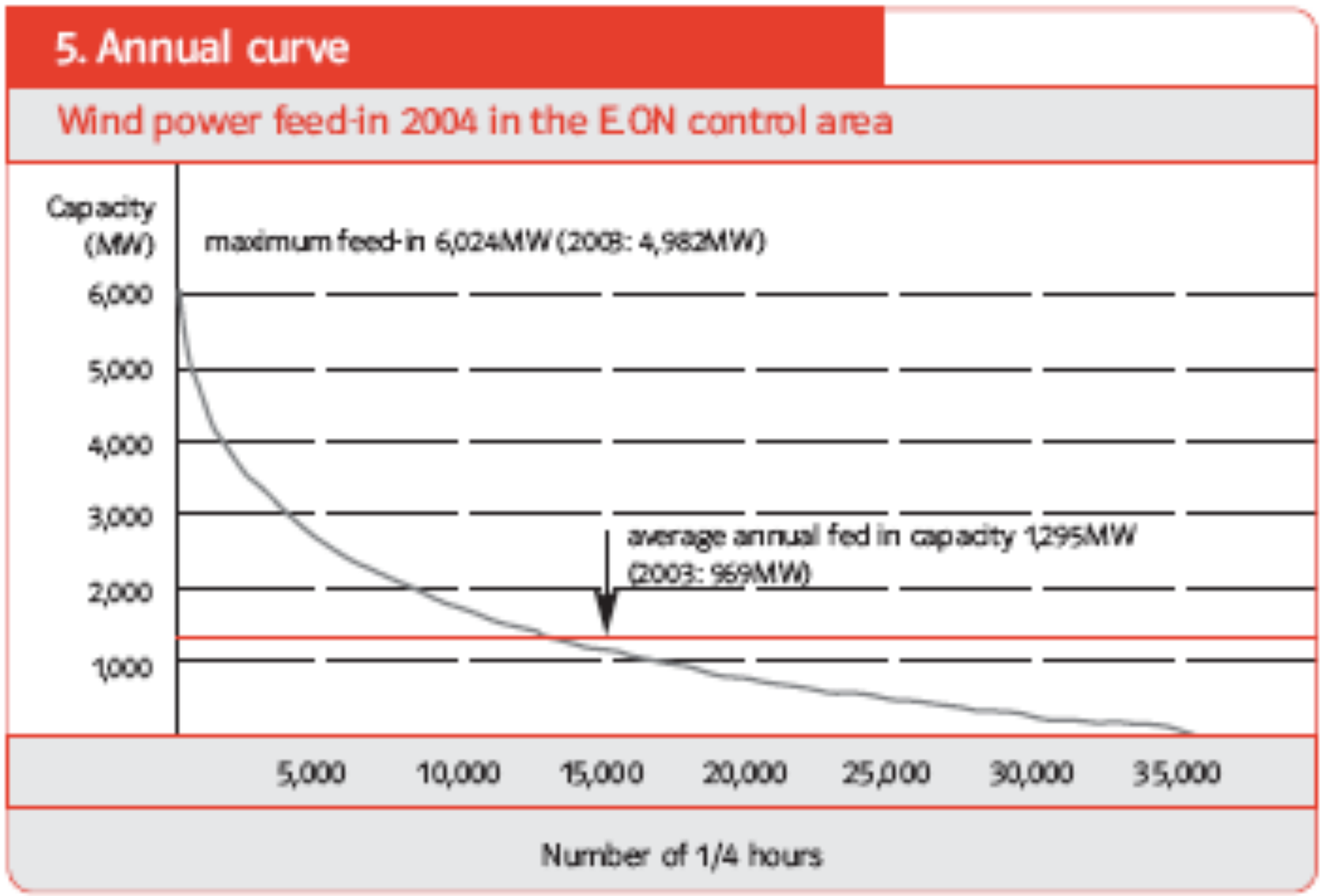


Plot in terms of Capacity v Amount of Time at that production rate.Result: Reduced Capacity Factor



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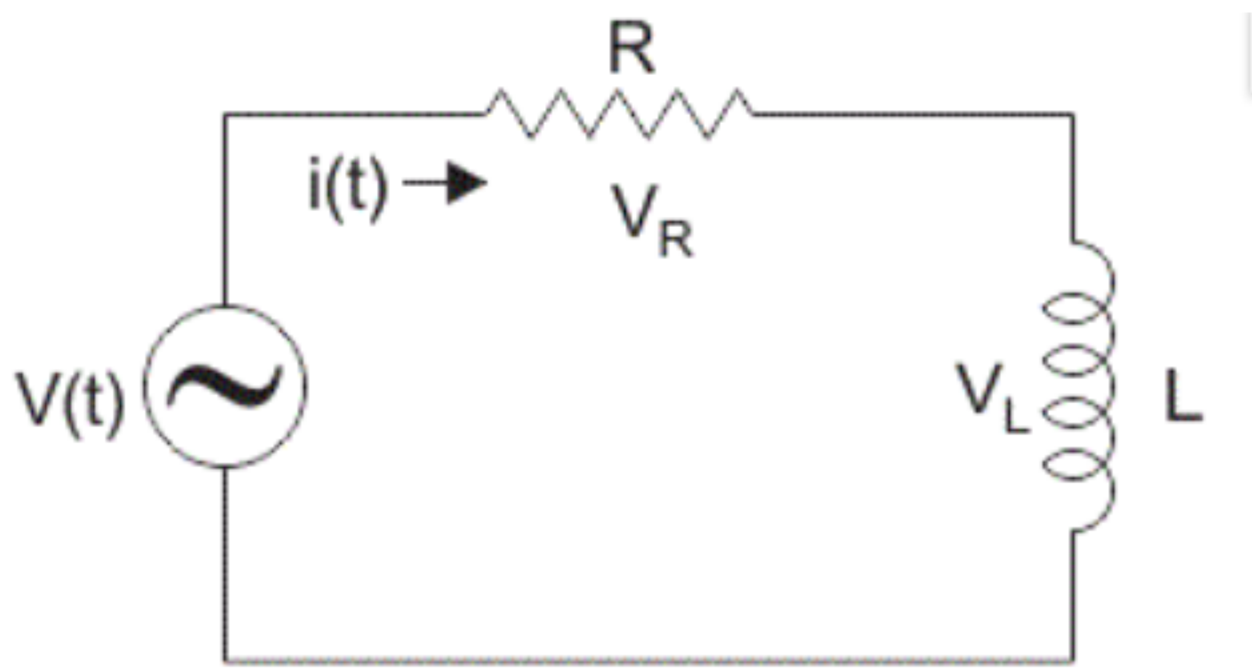
- A (painfully) simplified model to isolate the physics:
  - Simple 1st order AC Circuit
- What does voltage source really look like?
  - Synchronous Generators
- Response to transient source-load mismatch: Frequency Stability, Reactive Power Transients & Voltage Stability
- Need for Storage: Time-scales of response; Power & Energy Required
- Storage Technologies

1st order AC Circuit Model to Identify Key Issues:

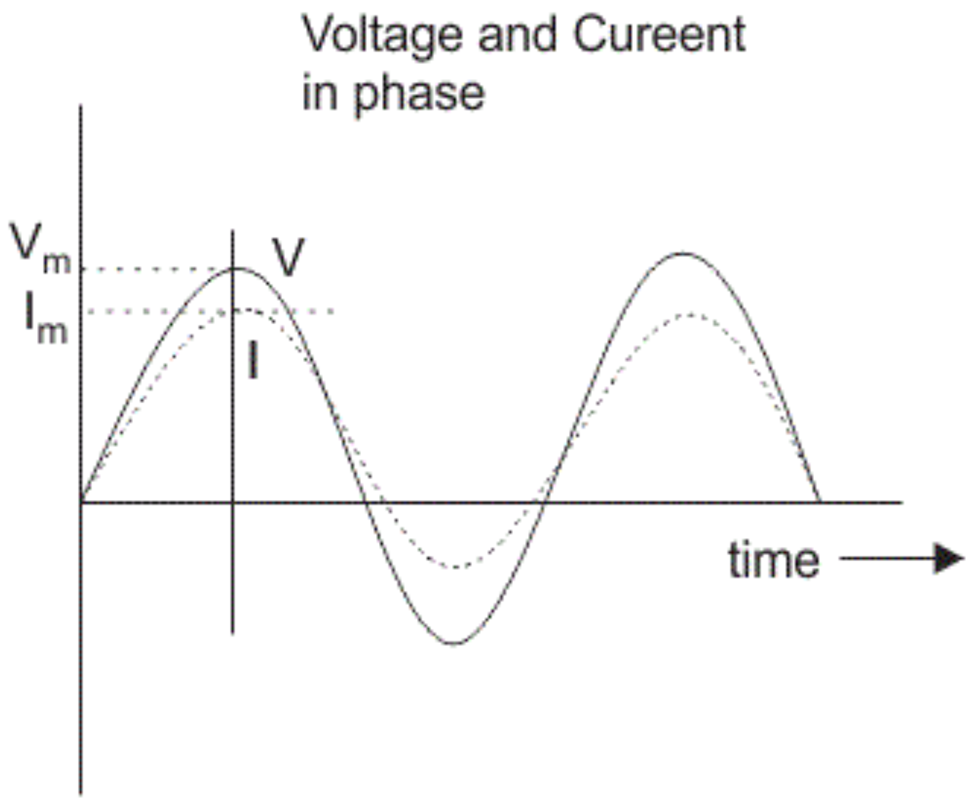
Think of distribution network as an equivalent circuit: Series LR Circuit



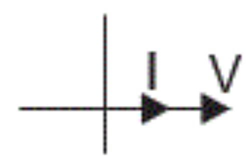
https://www.electrical4u.com/rl-series-circuit/

1st order AC Circuit Model to Identify Key Issues:

Recall: Current from an AC Voltage Across a Purely Resistive Load
Ohms Law V=IZ where Z=R (purely real) for resistive load:



Phasor representation



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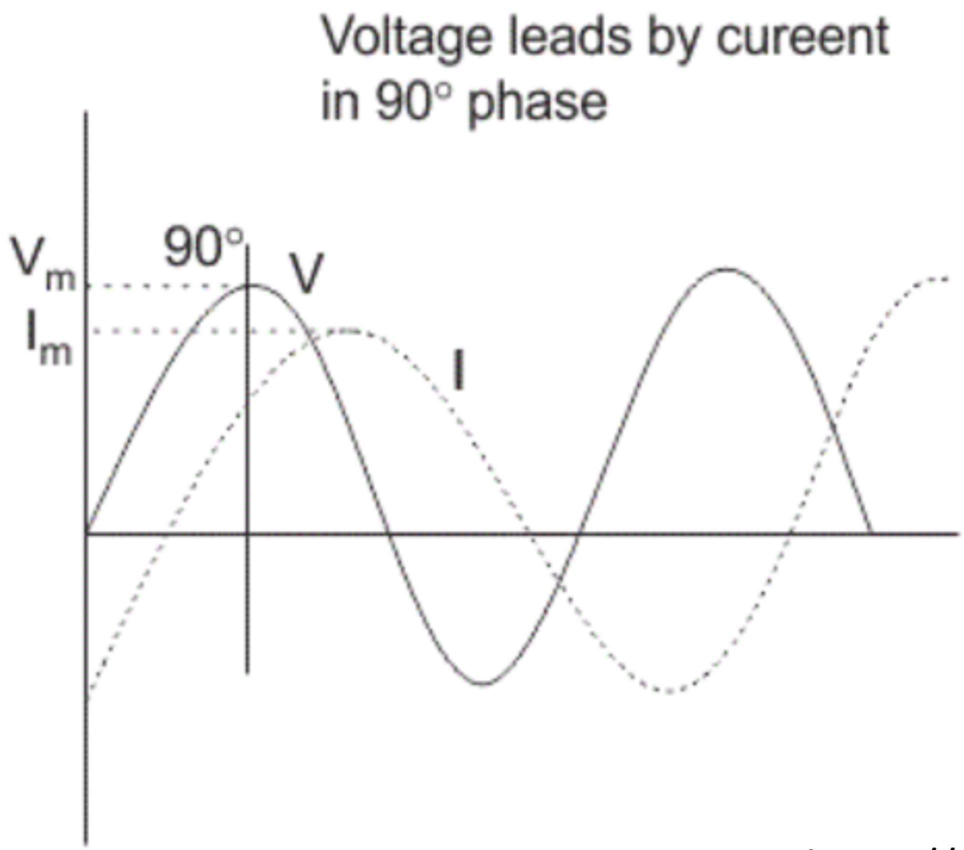
1st order AC Circuit Model to Identify Key Issues:

Recall: Current from an AC Voltage Across a Purely Inductive Load
Ohms Law with Impedence, Z= jωL (i.e. Z is purely Imaginary) Gives
V= jωLI(t) ➔ **phase shift between V(t) and I(t)**!



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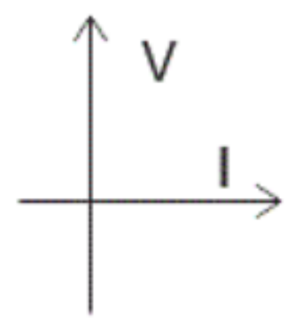

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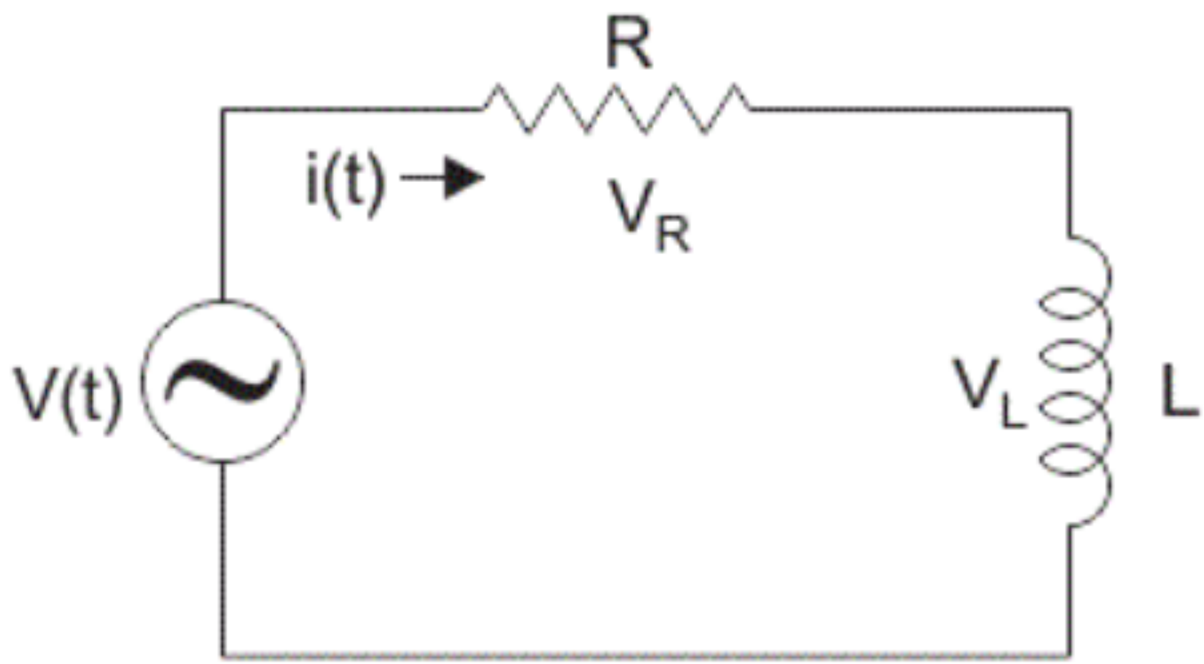
1st order AC Circuit Model to Identify Key Issues:

What does I(t) and V(t) across the RL load look like now?



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1^{st} order AC Circuit Model to Identify Key Issues:

What does I(t) and V(t) look like now? Solution:

Step- I. In case of series RL circuit, resistor and inductor are connected in series, so current flowing in both the elements are same i.e $I_R = I_L = I$. So, take current phasor as reference and draw it on horizontal axis as shown in diagram below.

Step- II. In case of resistor, both voltage and current are in same phase. So draw the voltage phasor, V_R along same axis or direction as that of current phasor. i.e V_R is in phase with I.

Step- III. We know that in inductor, voltage leads current by 90°, so draw V_L (voltage drop across inductor) perpendicular to current phasor.

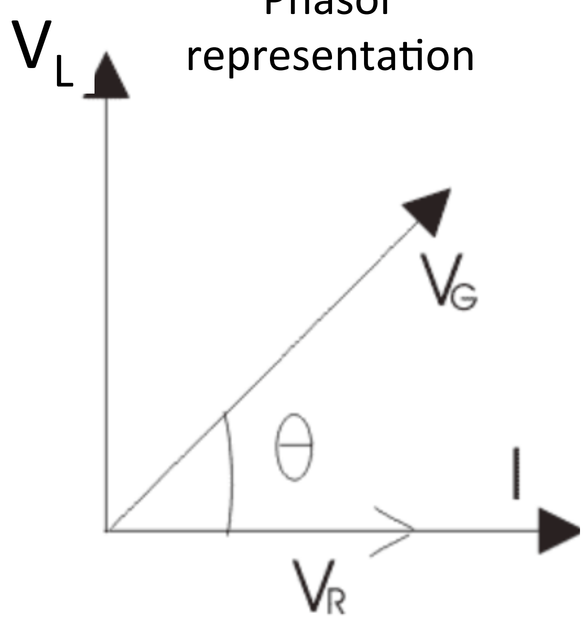
Step- IV. Now we have two voltages V_R and V_L. Draw the resultant vector(V_G) of these two voltages. Such as,

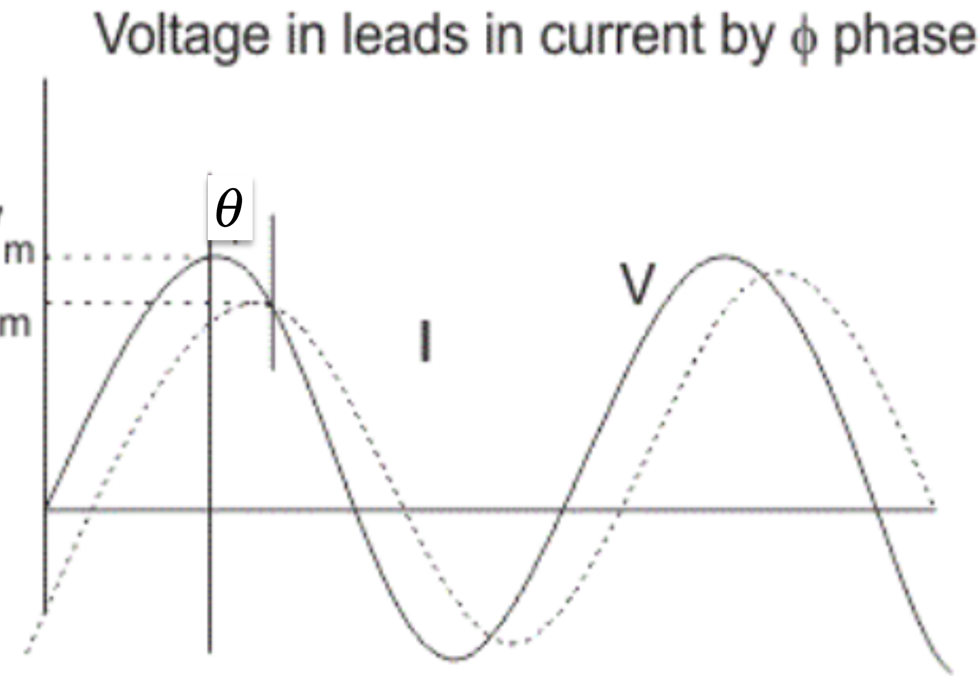
and from right angle triangle we get, phase angle

1st order AC Circuit Model to Identify Key Issues:

What does I(t) and V(t) look like now?

Phasor representation





$$\theta = Tan^{-1}\left(\omega L / R\right)$$

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1st order AC Circuit Model to Identify Key Issues:

How does POWER in circuit behave? Remember, P(t)=V(t)I(t)…

…So P(t) is COMPLEX:

Power in Resistive Load: $P_R(t) = Z_R I^2 = RI^2(t)$

Power in Inductive Load: $P_L(t) = Z_L I^2 = j\omega L I^2(t)$

Total Instantaneous Power: $P_{tot}(t) = \left(Z_R + Z_L\right) I^2 = \left(R + j\omega L\right) I^2(t)$

Real (aka "True") Power Dissipated in Load

Reactive Power (Oscillatory Energy Sloshing Around in the Circuit)

1st order AC Circuit Model to Identify Key Issues:

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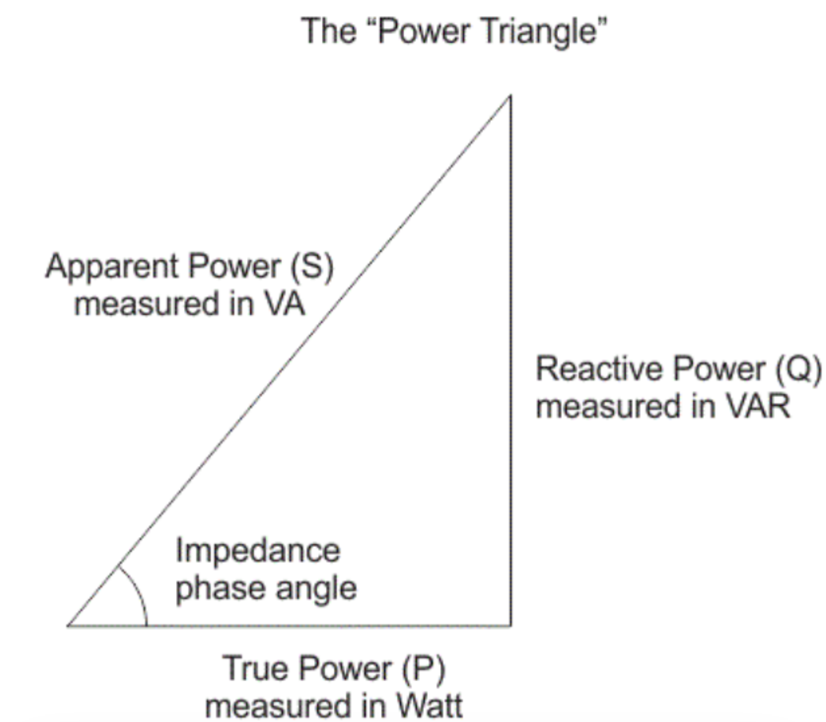

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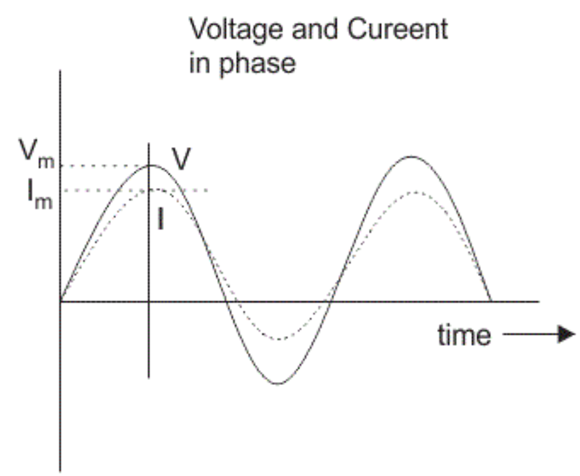
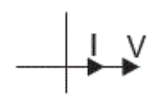
1^{st} order AC Circuit Model to Identify Key Issues:

P(t) is COMPLEX… Consider first the real part

Power in Resistive Load: $$P_R(t) = V_R(t)I(t)$$

Remember V(t) and I(t) thru R:





Q: What does *average* power look like (over one AC cycle?)

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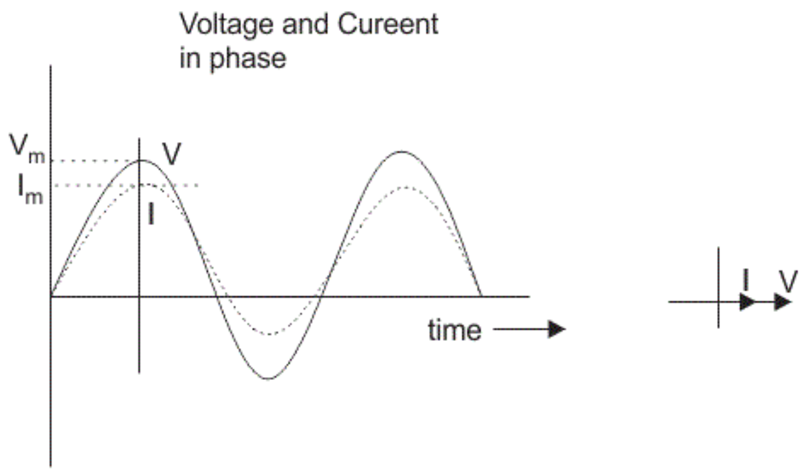


Q: What does *average* power look like (over one AC cycle?)

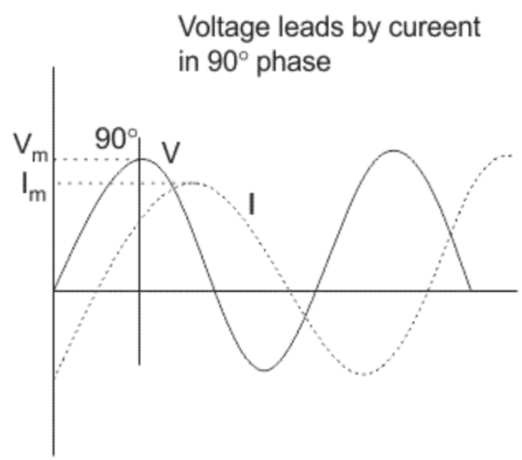
A: P(t)>0 *always* ➔ *<P(t)> is finite and positive* ➔ *represents rate of energy dissipation*

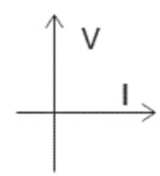
1^{st} order AC Circuit Model to Identify Key Issues:

P(t) is COMPLEX… Consider next the imaginary part

Power in Inductive Load: $P_L(t) = V_L(t)I(t)$

Remember V(t) and I(t) thru L:





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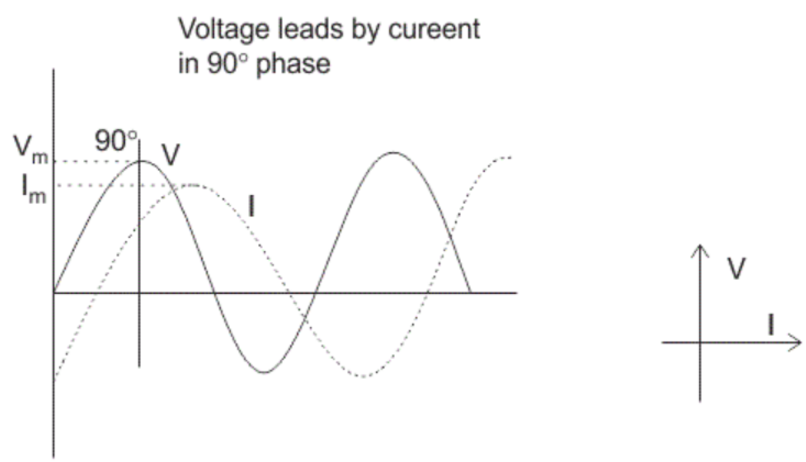


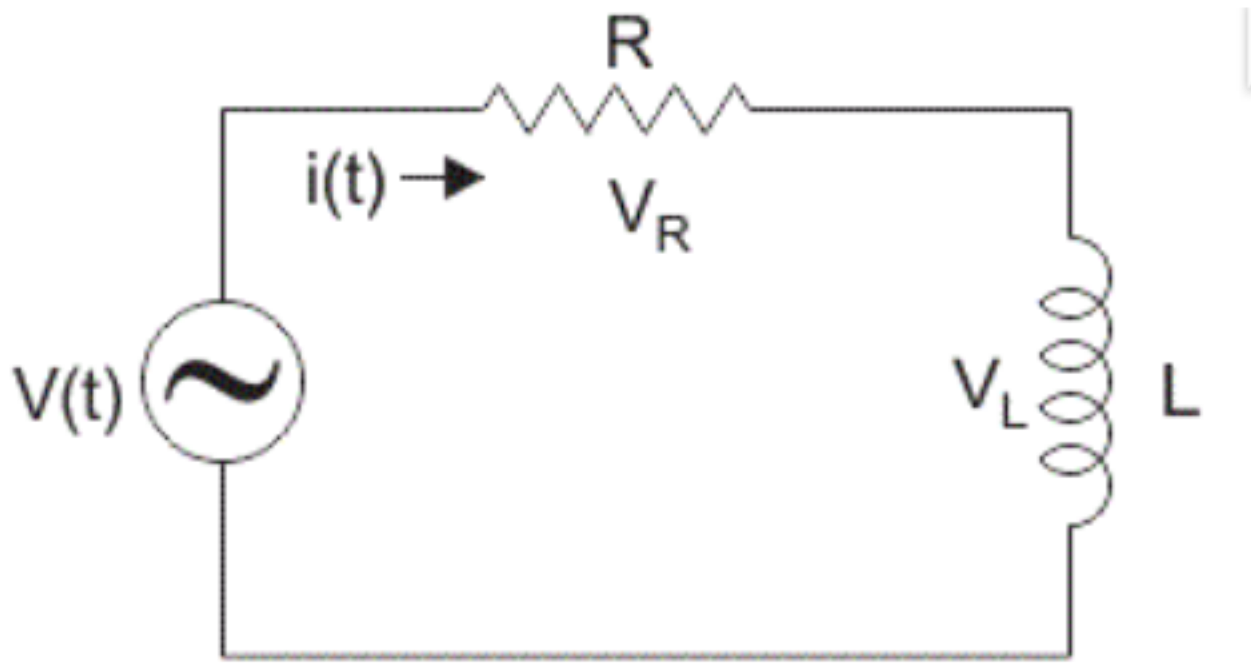
Q: What does *average* power look like (over one AC cycle?)

A: $P_L(t)$ OSCILLATES in time so that $\langle P_L(t) \rangle = 0$! ➔ Energy is stored In L for half-cycle, then returned in other half-cycle

So now back to our toy model of power grid:

Q: What actually determines V(t) (which we have assumed is sinusoidal?)

A: This is actually a real physical device: (usually) a “Synchronous Generator”



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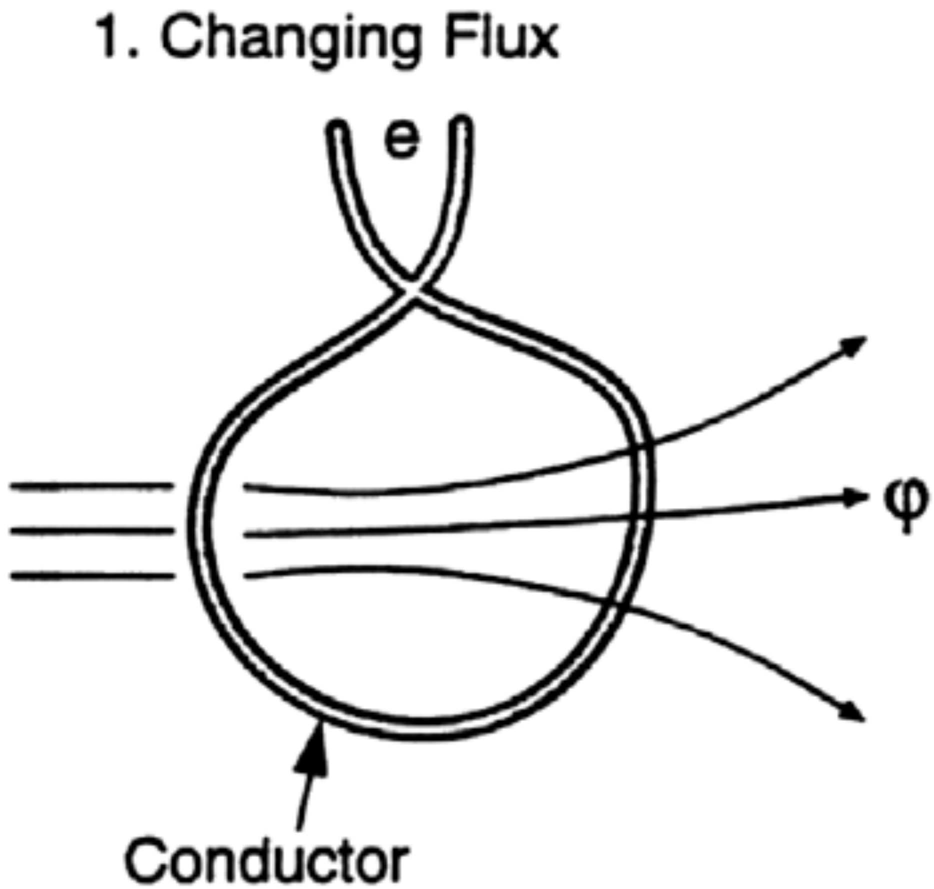
Basics of Synchronous Generator: Electromagnetic Induction

Lenz's Law

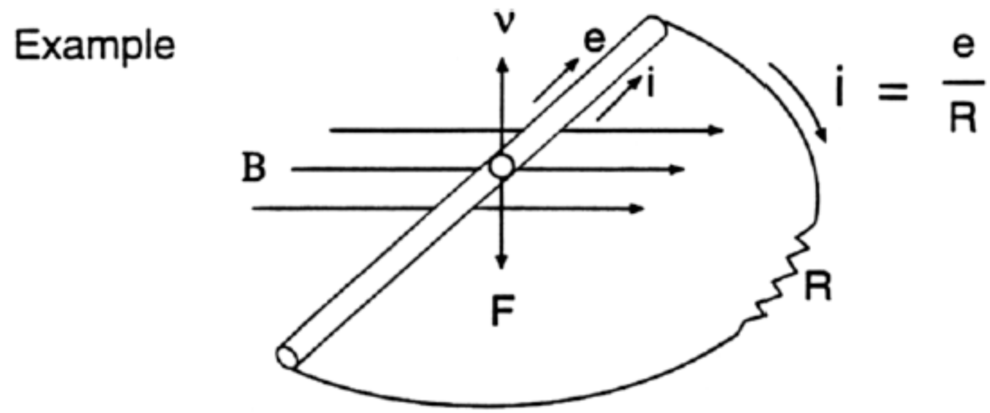


2. Induced Voltage:

$$V = -\frac{\partial \varphi}{\partial t} = -\frac{\partial}{\partial t}\int_C \vec{B} \cdot d\vec{A}$$

Principles of Operation of Sync. Machines, Wiley

Basics of Synchronous Generator: Electromagnetic Induction



1. The upward moving conductor in a magnetic field induces a voltage (Faraday)
2. Closing the circuit generates a current
3. The current creates a force opposing the movement (Ampere and Lenz)

Hint: Use the rule of the palm to show the direction of "F"

This phenomenon explains the torque applied by the generator on the turbine, when the unit is loaded

Principles of Operation of Sync. Machines, Wiley

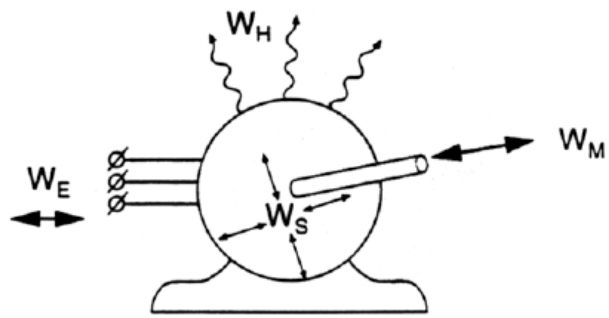
Basics of Synchronous Generator: Work & Energy Flow

W_E		W_M		W_S		W_H	
Input/output of electric energy	+	Input/output of mechanical energy	+	Change in stored energy	+	Heat dissipated	= 0

Change in stored energy:

Electrical = $\frac{1}{2} I^2 L + \frac{1}{2} V^2 C$

Mechanical = Rotational energy



W_H is always negative (i.e., heat is always released during the conversion process)

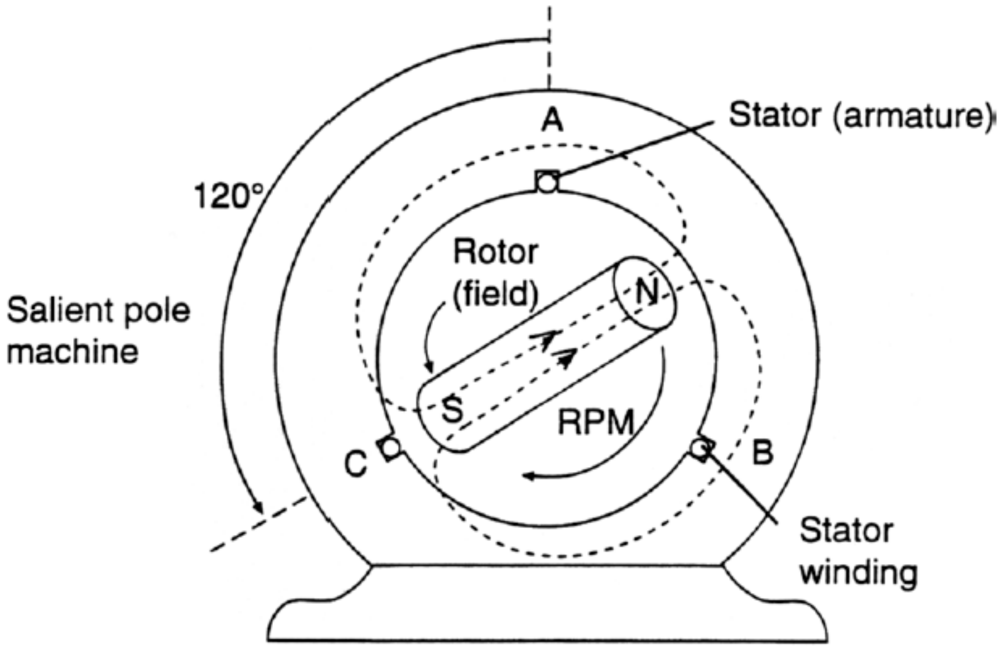
W_E, W_M and W_S can have "+" or "-" signs

W_E and W_M with a "plus" means input to the machine
"minus" means output from the machine

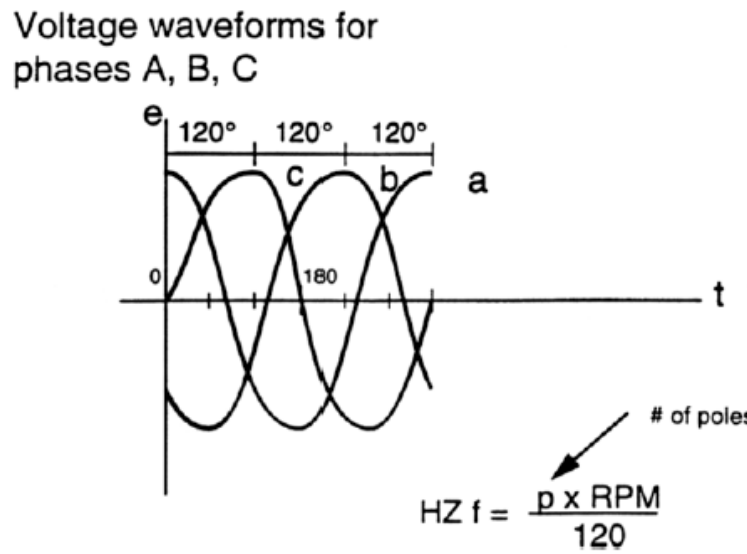
W_S with a "plus" means increase of stored energy
"minus" means decrease of stored energy

Principles of Operation of Sync. Machines, Wiley

Schematic of a Synchronous Generator:



Voltage waveforms for
phases A, B, C



Principles of Operation of Sync. Machines, Wiley

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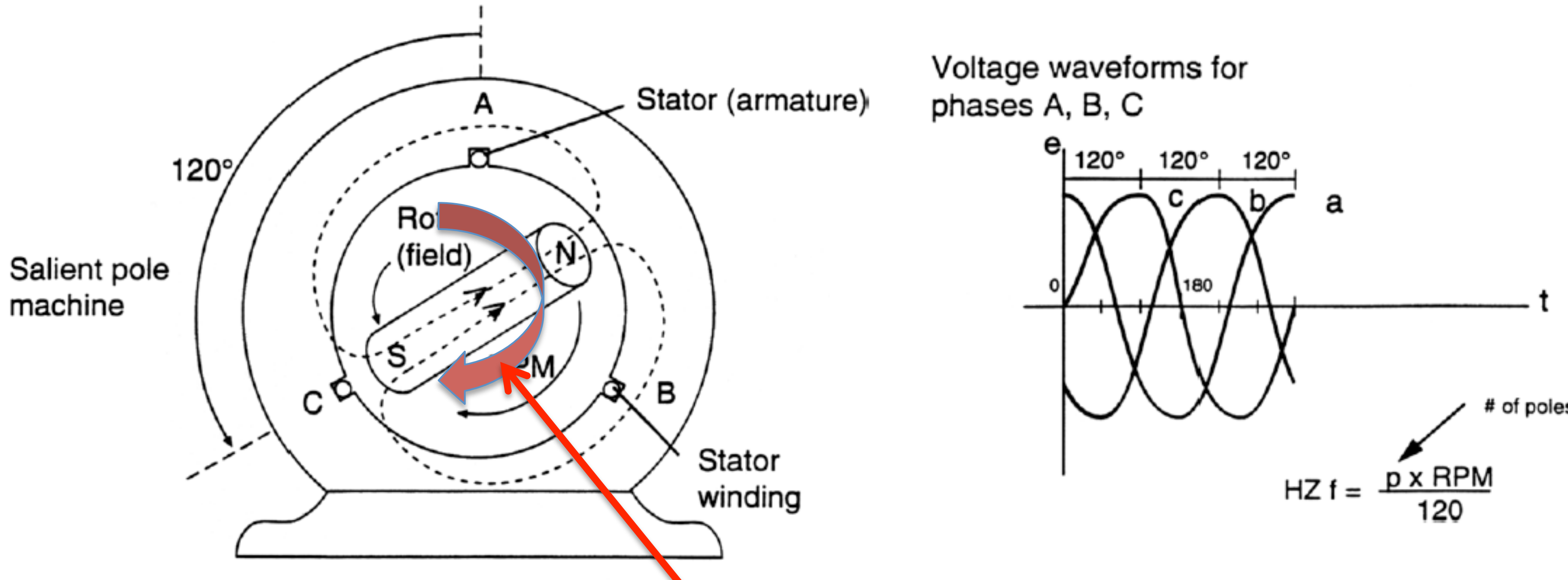


Voltage waveforms for phases A, B, C

External Torque Must be Applied To the Rotor to Keep in Spinning!

Q: Where does that torque come from?

A: Mechanical Work from a Heat Engine!

Principles of Operation of Sync. Machines, Wiley

Basics of Synchronous Generator: Power Balance Considerations

Synch. Generator Driven by Torque Input from External Source (HEAT ENGINE!).
Angular Momentum Conservation Gives:

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e$$

Where:

- J is the total moment of inertia of the rotor mass in kg-m^2
- θ_m is the angular position of the rotor with respect to a stationary axis in (rad)
- t is time in seconds (s)
- T_m is the mechanical torque supplied by the prime mover in **N**-m
- T_e is the electrical torque output of the alternator in **N**-m
- T_a is the net accelerating torque, in **N**-m

In Steady-state T_a=0 ←→ Generation Rate = Load

Basics of Synchronous Generator: Power Balance Considerations

Re-write as POWER by multiplying through by angular rotation

$$J\omega_S \frac{d^2\theta_m}{dt^2} = P_a = P_m - P_e$$

Where

P_a ~ change in kinetic energy of rotation of the generator

P_m ~ rate of mechanical work applied to the generator

P_e ~ rate of electrical work (i.e. electrical power) produced by generator

In Steady-state P_a=0 ←→ Generation Rate = Load

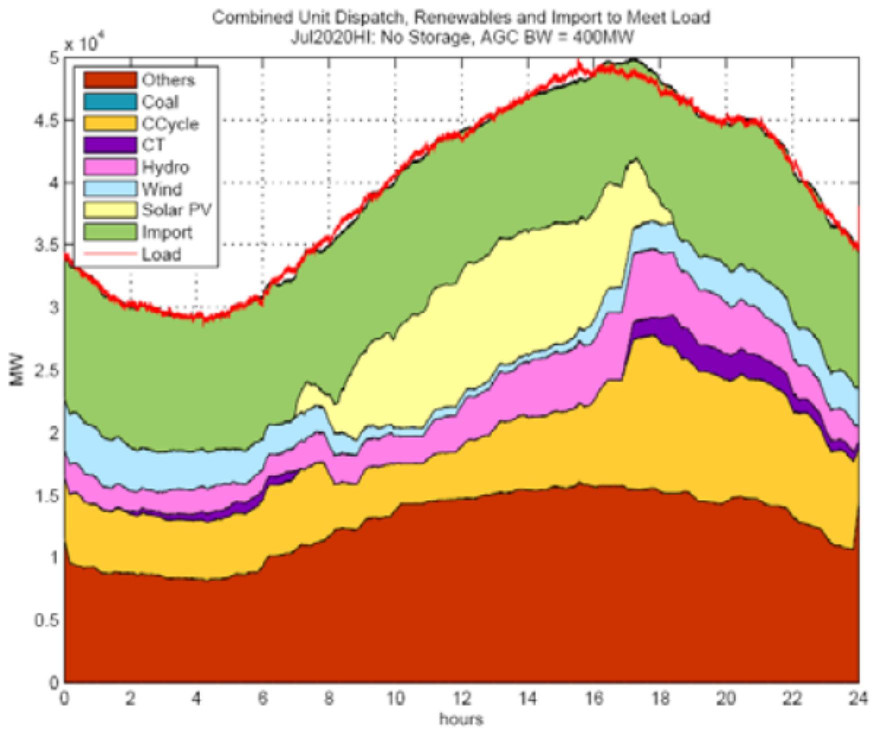
The rotation of heat engine can store significant energy:

Imagine this spinning at 3600 rpm

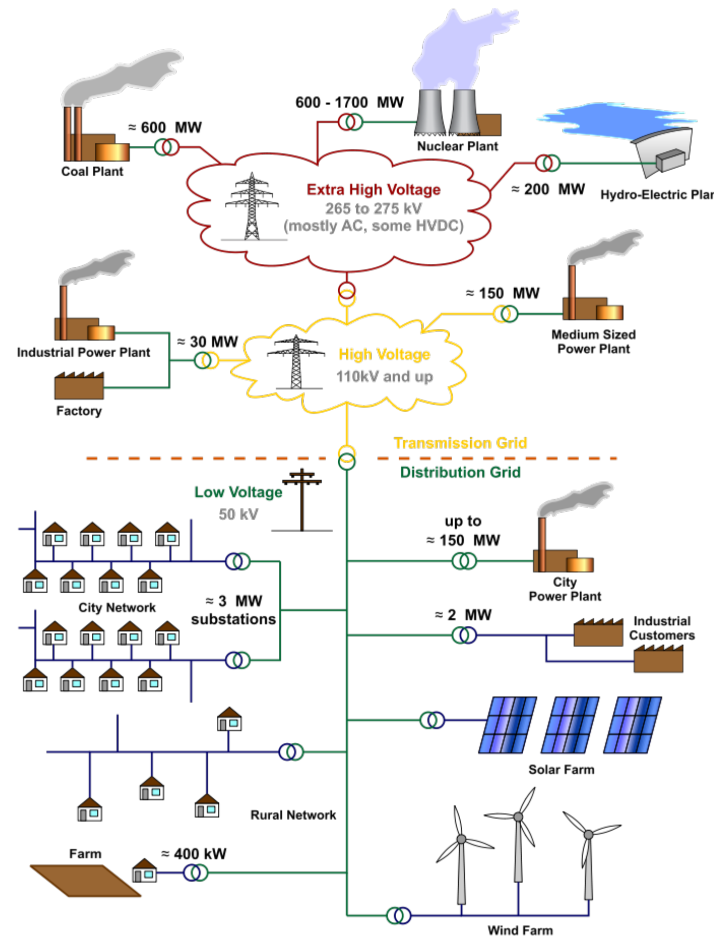
Photo: General Electric

Now consider a grid w/ mixture of heat engines & renewables w/o storage

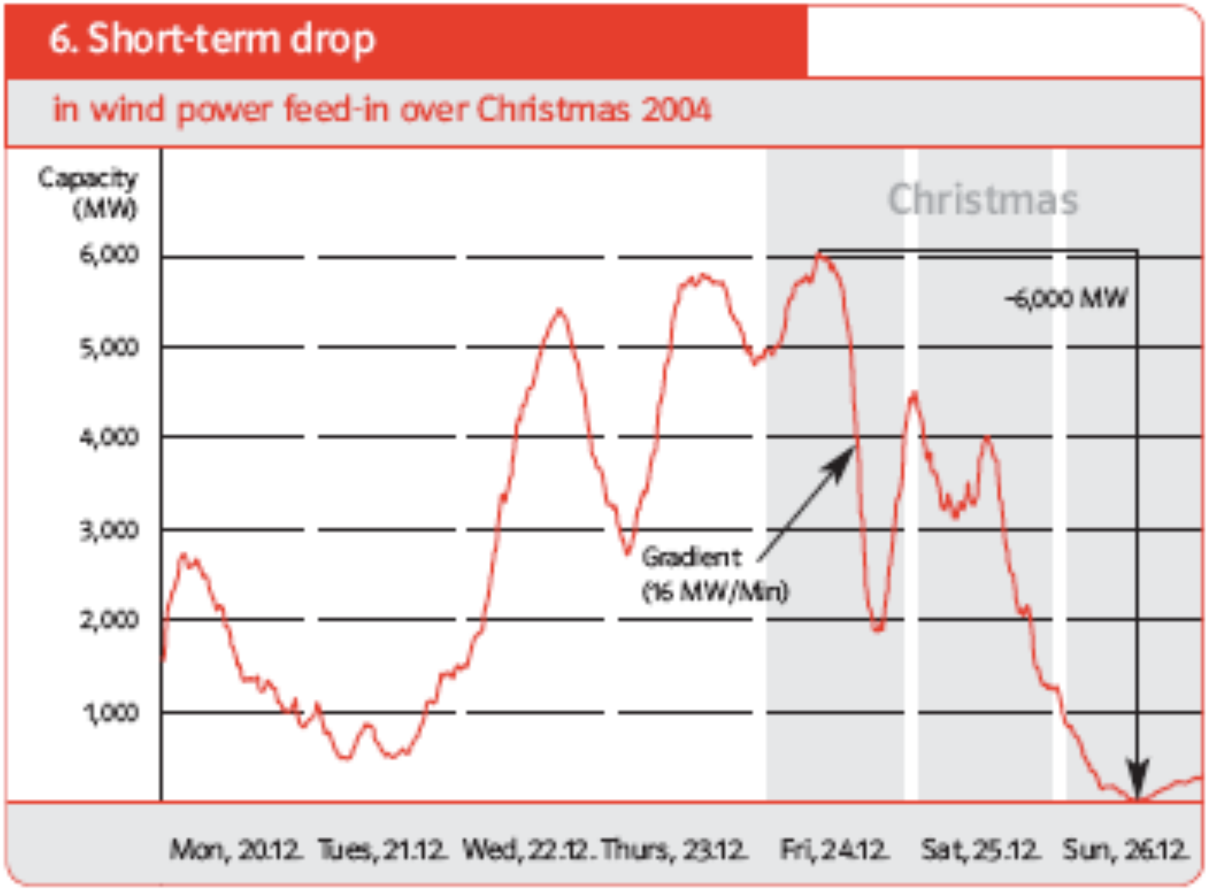
Projected demand curve for CA
In 2020 from 2010 CEC Study:



Schematic System Architecture



Weather-dependent Systems Can Experience Rapid Changes in Rate of Power Feed-In:



“Handling Such Significant Differences in Feed-in Level Poses a Major Challenge to Grid Operators” Source: E.On Netz, “Wind Report 2005

How does grid respond to a sudden loss of generation capacity from such a disturbance?

Recall Power Balance Eqn:

$$J\omega_S \frac{d^2\theta_m}{dt^2} = P_a = P_m - P_e$$

Where

P_a ~ change in kinetic energy of rotation of the generator

P_m ~ rate of mechanical work applied to the generator

P_e ~ rate of electrical work (i.e. electrical power) produced by generator

In Steady-state P_a=0 ←→ Generation Rate = Load

But w/ Reduction in Renewable Power Generation, Load now shift Remainder of System BUT… P_m=const! → $P_e > P_m$

How does grid respond? (cont'd)

With drop in renewables input we have $P_e > P_m$ ….

Now… Recall Power Balance Eqn at Synch. Generator:

$$J\omega_S \frac{d^2\theta_m}{dt^2} = P_m - P_e < 0$$

Remember definition:

$$\frac{d\theta_m}{dt} = \omega_S$$

So rotation frequency of generators begins to change!

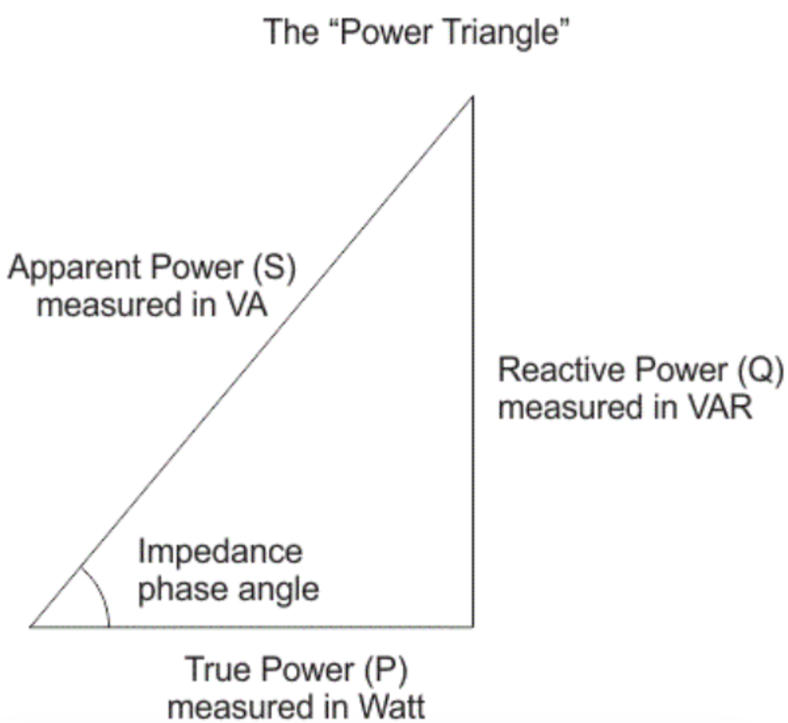
$$\frac{d\omega_S}{dt} = \frac{d^2\theta_m}{dt^2} < 0$$

Rotation frequency of generators = Frequency of AC Voltage → AC Freq. Changes!

How does grid respond (cont'd):

How does POWER in circuit behave? Remember, $P(t)=V(t)I(t)$...

...and $P(t)$ is COMPLEX:



RESULT OF LOAD IMBALANCE:

OSCILLATIONS IN MAGNITUDE
OF REACTIVE AND REAL POWER

→ OSCILLATIONS IN PEAK-PEAK VOLTAGE

→ RISK OF DAMAGING EQUIPMENT
→ (ARCING)

→ PROTECTIONS WILL DISCONNECT
→ CIRCUITS TO PREVENT PERMANENT
→ DAMAGE

https://www.electrical4u.com/rl-series-circuit/

Illustration of this…

Hipages | Fox Sports | SEEK | Carsguide | RealEstate | News Network

news.com.au

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environment

AEMO's third report highlights wind power link to South Australia blackout

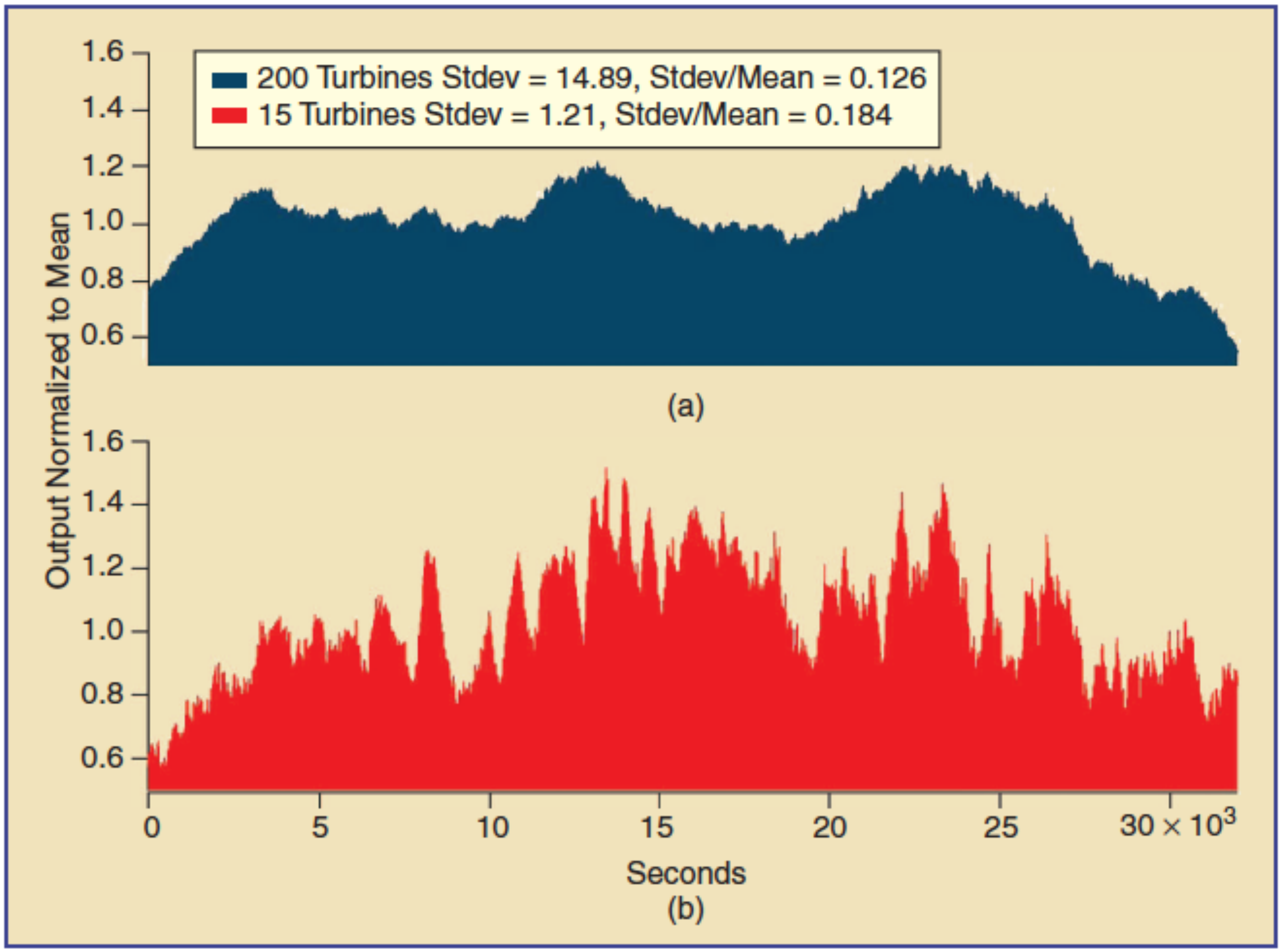
DECEMBER 12, 2016 4:32PM

A transmission tower carrying power lines, toppled by high winds near Melrose in South Australia. Picture: Debbie Prosser/AFP

http://www.news.com.au/technology/environment/aemos-third-report-highlights-wind-power-link-to-south-australia-blackout/news-story/2bbf105bc613f7096665946504363 3b0

How to mitigate these effects?

- Spatial Averaging: deploy renewables over large enough region to “average out” temporal variations



Wind Power Myths Debunked, IEEE 2009

How to mitigate these effects?

- Reduce Load Dynamically (Demand Response)
- Incorporate Energy Storage Into System
  - Repurposed Conventional Hydro
  - Pumped Hydro
  - Electrochemical (Batteries, Flow Batteries)
  - Large Capacitors
  - Fuel Production (e.g. H from water) w/ storage for later use
  - Flywheels
  - Compressed Air
  - Thermal Storage
- Q's for storage system spec's:
  - What is peak power required from system?
  - Over what duration is storage needed?
  - What is total stored energy requirement?
  - What is optimum position within grid?

Wind Power Myths Debunked, IEEE 2009

Order-of-Magnitude estimates of regional (e.g. WECC) storage requirements

Transient Description	Magnitude of Power Imbalance (MW)	Corresponding Energy (MJ)	Possible Technology?
AC Osc. Timescales (0.1-1 sec)	0.1 – 10's	0.1 - 100	???
Frequency Transients, 1-10 sec	1-100	0.1-100	????
Short-term RE Variability, $10\text{-}10^3$ sec	10 - 1000	$10^2\text{-}10^4$	????
Diurnal Variation 3-10 hours	100-10,000	$10^4\text{-}10^7$	????
Seasonal 10-100 days	1000-10,000	$10^9\text{-}10^{11}$	????