

## The “Physical” Layer of Energy Systems

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### Announcement!!!

- Power Delivery System Tutorial
  - Alexandra von Meier, Sonoma State
  - 1000-1630 (lunch & afternoon breaks)
  - Room 250, Citris Building
- This is a fantastic opportunity, and it is worth the effort to attend this even if you can only make a portion of the day
- PDF of the Tutorial available on the course web site



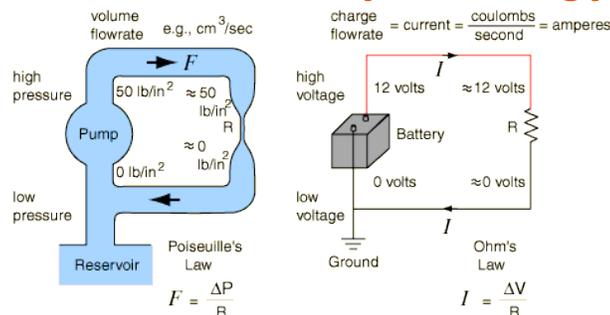
## Physical Layer: The Network Analogy

- PHY: first and lowest layer in the seven-layer OSI model of computer networking
- Consists of:
  - Basic hardware transmission technologies
  - Fundamental layer underlying the logical data structures of the higher level functions
  - Most complex layer in the OSI architecture due to diverse hardware technologies
- Defines means of transmitting raw bits rather than logical data packets over a physical link connecting network nodes
  - Bit stream grouped into code words or symbols and converted to a physical signal that is transmitted over a hardware transmission medium
  - Provides electrical/mechanical/procedural interface to transmission medium
  - Properties of electrical connectors, broadcast frequencies, modulation schemes, etc.
- PHY translates logical communications requests from the Data Link Layer into hardware-specific operations to effect transmission or reception of electronic signals



[http://en.wikipedia.org/wiki/Physical\\_Layer](http://en.wikipedia.org/wiki/Physical_Layer)

## Water-Electricity Analogy



- DC circuit: voltage (V, volts) an expression of available energy per unit charge that drives electric current (I, amps) around a closed circuit
  - Increasing resistance (R, ohms) proportionately decreases I driven through the circuit by V

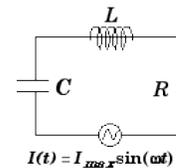
<http://hyperphysics.phy-astr.gsu.edu/HBASE/electric/watcir.html>

## Basic DC Circuit Relationships

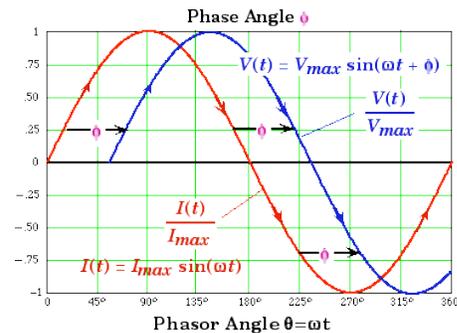
- Ohm's Law:  $I = V / R$
- Power Relationship:  $P$  (in watts) =  $V I$
- Energy:  $E = P * \text{time}$  (or  $P = E / \text{time}$ )
- Voltage Law: net voltage change is zero around any closed loop (conservation of energy)
- Current Law: net voltage change is zero around any closed loop (conservation of charge)

<http://hyperphysics.phy-astr.gsu.edu/HBASE/electric/watcir.html>

## AC Power



- More complex!
- Instantaneous electric power in AC circuit is  $P = V I$ , but these vary continuously
- Use average power:  $P_{avg} = V I \cos \phi$ 
  - $\phi$  is the phase angle between the current and the voltage,  $V$  and  $I$  are the effective or rms values of the voltage and current
  - Aka  $\cos \phi$  is the circuit's "power factor"



<http://www.ac.wvu.edu/~vawter/PhysicsNet/Topics/ACCircuit/SeriesLRC.html>

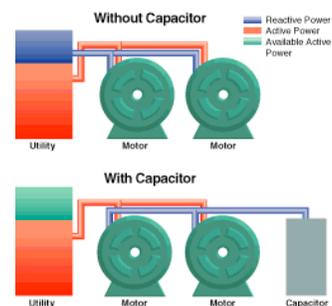
## Reactive Power

- Simple AC circuit w/source + linear load, current and voltage are sinusoidal
- IF load is purely resistive:
  - V and I reverse their polarity simultaneously
  - Direction of energy flow does not reverse
  - Only real power flows
- IF load is purely reactive:
  - V and I are 90 degrees out of phase: no net energy flow, i.e., peaks of voltage are centered at the times when the current crosses zero, and is half positive and half negative—"reactive power"
- Practical loads have resistance, inductance, and capacitance, so both real and reactive power will flow to real loads
  - Power engineers measure power use as the sum of real and reactive power Q (V amps reactive or VAR)
  - Power factor: ratio of "real power" P (watts) to "apparent power" |S| (V amps), where apparent power is the product of the root-mean-square voltage and current

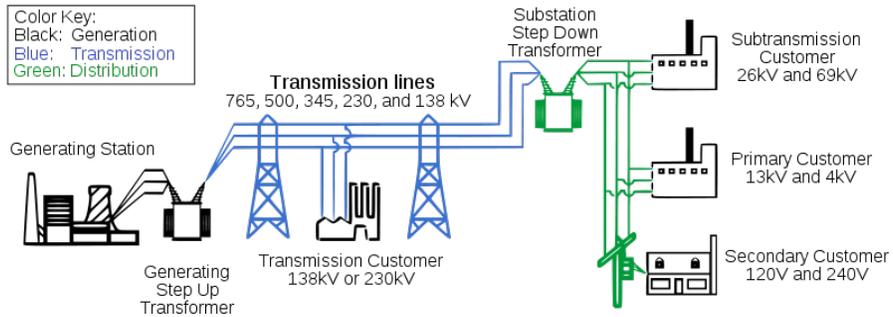
[http://en.wikipedia.org/wiki/AC\\_power](http://en.wikipedia.org/wiki/AC_power)

## Managing Reactive Power

- What is Power Factor Correction?
  - Resistive, inductive and capacitive load
  - Most loads are inductive: transformers, fluorescent lighting, AC induction motors
  - Use a conductive coil winding to produce an electromagnetic field, allowing the motor to function, e.g., wind turbines
- All inductive loads require two kinds of power to operate:
  - Active power (kwatts) - to produce the motive force
  - Reactive power (kvar) - to energize the magnetic field
- Operating power from the distribution system is composed of both active (working) and reactive (non-working) elements
  - Active power does useful work in driving the motor
  - Reactive power only provides the magnetic field
  - High transmission losses along cables and transformers
  - Large users charged for both!
- To reduce reactive power:
  - If an AC motor were 100% efficient it would consume only active power but, since most motors are only 75% to 80% efficient, they operate at a low power factor
  - Solution: capacitors



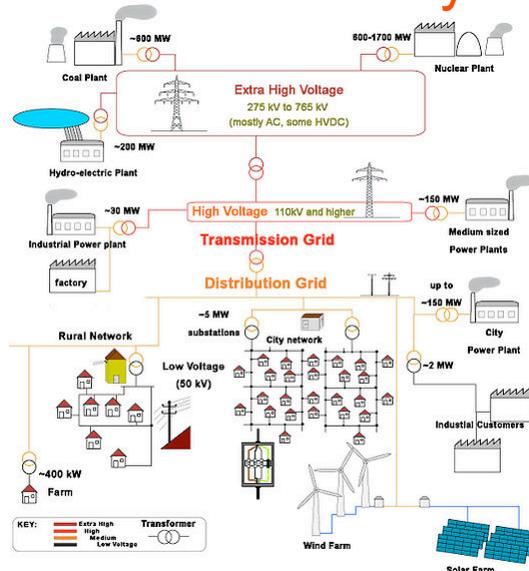
## Electrical Energy Distribution System



- **Electric power transmission:** bulk transfer of electrical energy to consumers
  - Allows distant energy sources to be connected to consumers in population centers
- **Power transmission network:**
  - Connects power plants to multiple substations near a populated area
  - **Distribution:** wiring from substations to customers

[http://en.wikipedia.org/wiki/Electric\\_power\\_transmission](http://en.wikipedia.org/wiki/Electric_power_transmission)

## Electricity Networks



- **Early days: DC distribution**
  - Difficult to scale up voltage to reduce current
  - Thick cables and short distances to reduce V losses
  - DC distribution limited to a small number of km
- **AC Distribution**
  - Transformers @ power stations raise generator voltage
  - Transformers @ substations reduce voltage
- **High V reduces line current, hence size of conductors and distribution losses**
  - More economical to distribute power over *long distances*
- **High Voltage DC (HVDC)**

[http://en.wikipedia.org/wiki/Electric\\_power\\_transmission](http://en.wikipedia.org/wiki/Electric_power_transmission)

## Proposed HVDC Lines

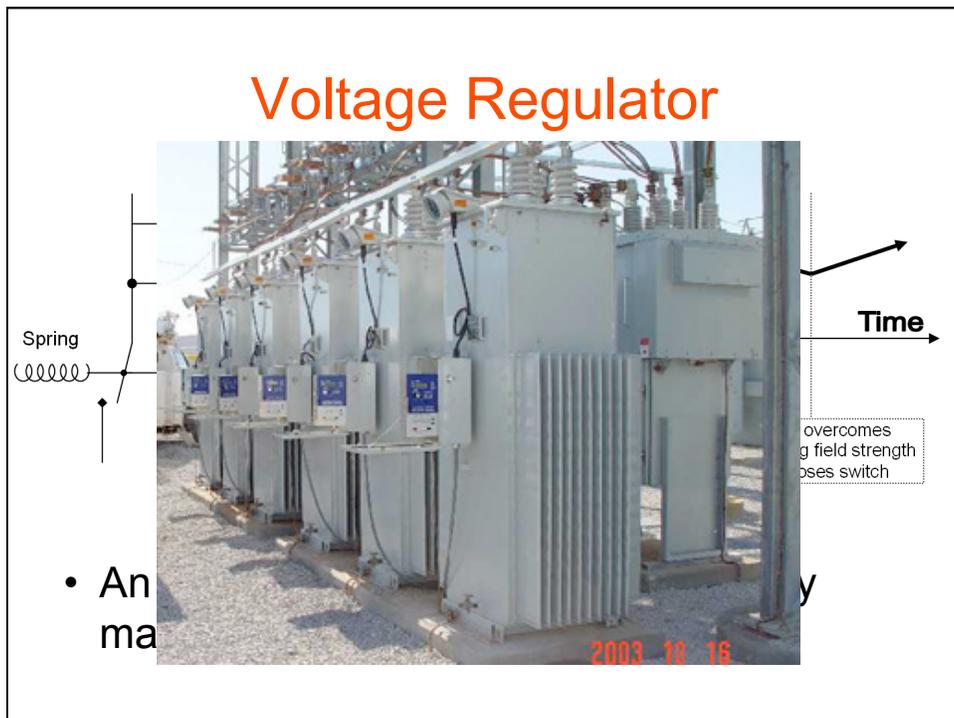
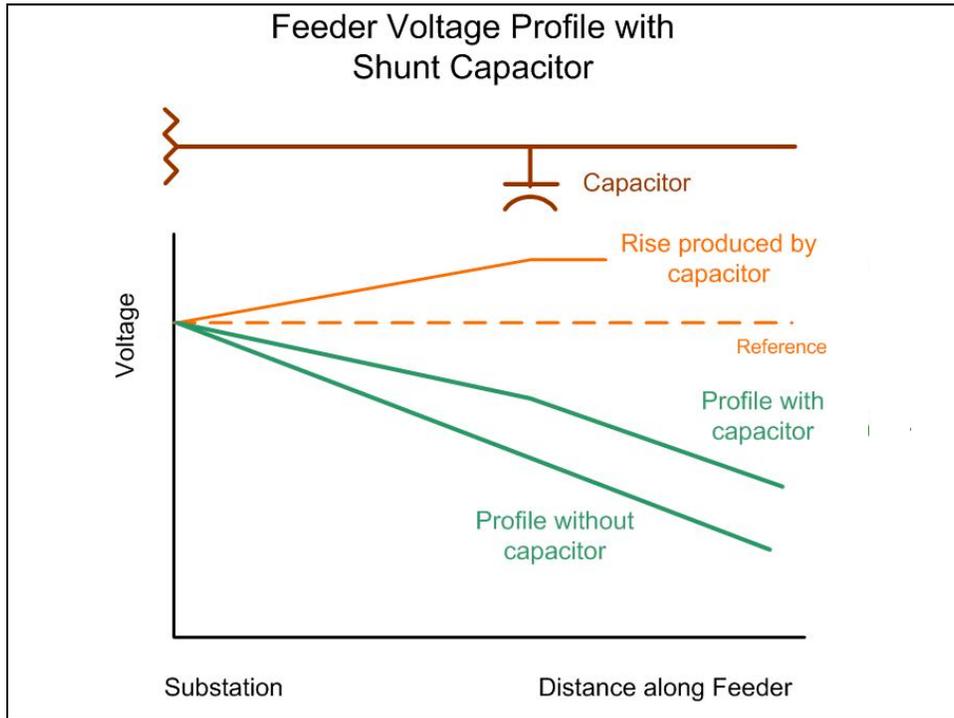


- TransCanada's Chinook Initiative
  - Connect low-cost and renewable supplies to growing markets via long distance, (HVDC) transmission line
  - Major HVDC transmission line linking low cost, environmentally attractive fossil fuelled and renewable generation with growing loads in Nevada, Arizona, and California.
- One project consists of a HVDC transmission line connecting Montana to Las Vegas.
  - Rated @ approx 3,000 MW, will cost US \$1.2 - 1.8 billion.
  - Connect clean coal and wind generation resources in Montana with growing loads in southern Nevada, Arizona, and California.
  - Extension of the line to SoCal and/or Arizona is contemplated as market conditions evolve

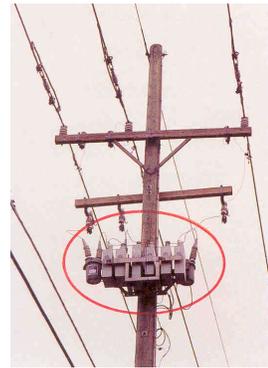
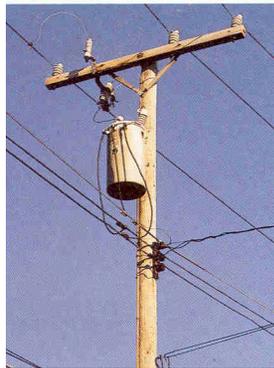
## Misc Considerations in Transmission and Distribution

- Line voltage drops between generators and loads
  - Substation transformers and voltage regulators
  - Pole top transformers
- Multiphase (typically three phase) AC service
- Phasor Measurement Units (aka Synchrophasors)/Phasor Network (aka WAMS)
  - Measure AC waveforms at various points and synchronized in time to detect when out of spec
  - Used to assess health of transmission & distribution system and drive load shedding, controlling, and balancing decisions

[http://en.wikipedia.org/wiki/Phasor\\_measurement\\_unit](http://en.wikipedia.org/wiki/Phasor_measurement_unit)



## Distribution Poles

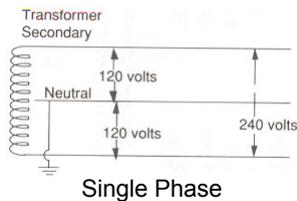


1 Phase Service Disconnects

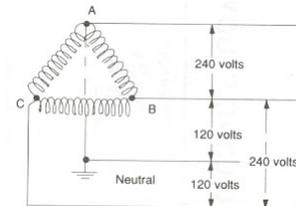
Distribution Capacitors

[http://www.energytechpro.com/Demo-IC/Basic\\_Electricity/Distribution.htm](http://www.energytechpro.com/Demo-IC/Basic_Electricity/Distribution.htm)

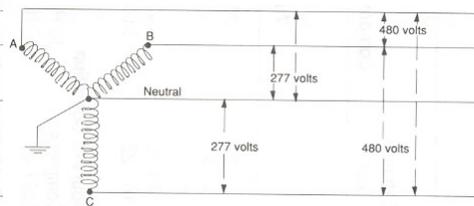
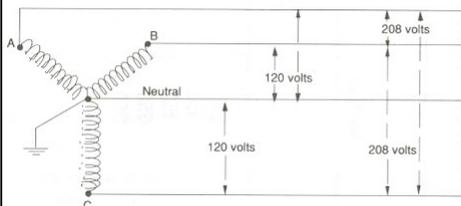
## Distribution System Wiring



Single Phase



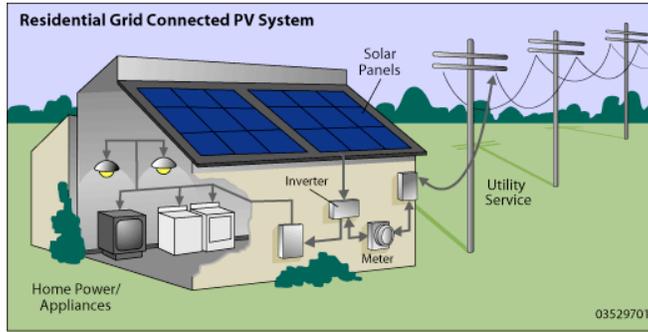
"Delta" 3 Phase/3 Conductor



"Wye" 4 Conductor distribution from substation to load to deliver higher voltages  
—actual voltages depend on transformers used

[http://www.energytechpro.com/Demo-IC/Basic\\_Electricity/Distribution.htm](http://www.energytechpro.com/Demo-IC/Basic_Electricity/Distribution.htm)

# Residential End Nodes



- Typical homes consumes on the order of 10kW per day
- Solar cells
  - Absorb sunlight to generate electricity via photoelectric effect.
  - Basic PV or solar cell typically produces only a small amount of power; PV modules range in output from 10 to 300 watts. If more power is needed, several modules can be installed on a building or at ground-level in a rack to form a PV array.
- PV arrays can be mounted at a fixed angle facing south, or can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight over the course of a day
- Grid-connected or stand alone (off-grid)

**ELECTRIC ACCOUNT DETAIL**

Service ID #: 6473535005  
 Rate Schedule: E1 TH Residential Service  
 Billing Days: 29 days

Serial	Rotating Outage Blk	Meter #	Prior Meter Read	Current Meter Read	Difference	Meter Constant	Usage
L	50	7J9066	71,585	71,862	277	1	277 Kwh

Charges

07/09/2009 - 08/06/2009

Electric Charges \$31.94

Baseline Quantity 321.90000 Kwh

Baseline Usage 277.00000 Kwh @ \$0.11531

Net Charges \$31.94

The net charges shown above include the following component(s):  
 Please see definitions on Page 2 of the bill.

Generation	\$13.47
Transmission	2.78
Distribution	9.67
Public Purpose Programs	1.63
Nuclear Decommissioning	0.08
DWR Bond Charge	1.36
Ongoing CTC	2.31
Energy Cost Recovery Amount	0.64

Taxes and Other

Energy Commission Tax \$0.06

**TOTAL CHARGES \$32.00**

Usage Comparison	Days Billed	Kwh Billed	Kwh per Day
This Year	29	277	9.6
Last Year	29	369	12.7

Rotating outage blocks are subject to change without advance notice due to operational conditions.

Generation includes charges for the portion of your energy usage provided by the Department of Water Resources (DWR) and is being collected by PG&E as an agent for DWR. DWR is collecting 8.640 cents per kWh from Bundled customers for each kWh it provides plus the Power Charge Indifference Adjustment component of the Cost Responsibility Surcharge from Direct Access and Transitional Bundled Service customers.

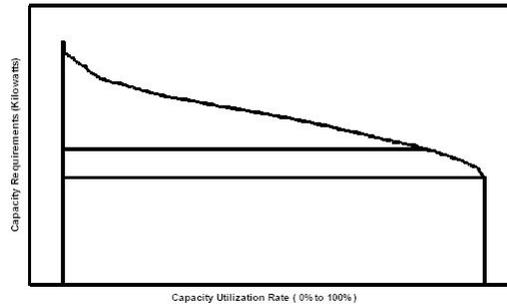
The rates shown above are applicable to bundled service customers. Direct Access and Community Choice Aggregation customers pay only a portion of these rates. Please see the appropriate rate schedule for the applicable charges.

## Randy's PGE Bill

Approx. 400 W/hr

11.5 cents per kWhr

## Load Duration Curve



Dispatch: Filling the load curve from the bottom to the top

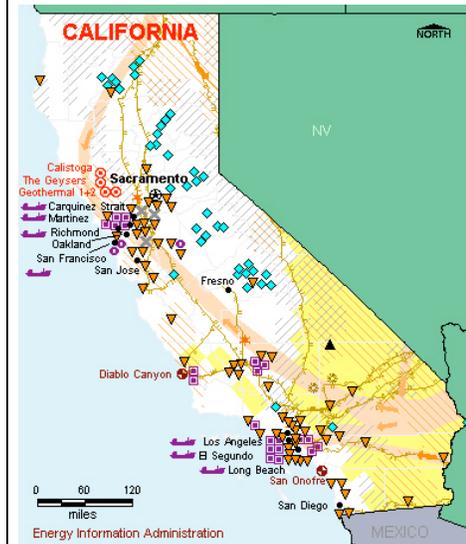
- **Load duration curve:** relationship between generating capacity requirements and capacity utilization
  - Like a [load curve](#) but the demand is ordered in descending order of magnitude, rather than chronologically
  - Shows capacity utilization requirements for each increment of load
    - Height of slice is a measure of capacity
    - Width of slice is measure of utilization rate or capacity factor
    - Product of the two is electrical energy (e.g. kilowatthours).

[http://en.wikipedia.org/wiki/Load\\_duration\\_curve](http://en.wikipedia.org/wiki/Load_duration_curve)

## Energy Supply

- Baseload power plants, which are run all the time to meet minimum power needs
  - E.g., nuclear, hydro
- Peaking power plants, which are run only to meet the power needs at maximum load (known as "peak load")
  - E.g., gas turbine
- Intermediate power plants, which fall between the two and are used to meet intermediate power loads

## California Energy Map



- California ranks 3rd in US in refining capacity and its refineries are among the most sophisticated in the world.
- California's per capita energy consumption is low, in part due to mild weather that reduces energy demand for heating and cooling.
- California leads US in electricity generation from non-hydroelectric renewable energy sources, including geothermal power, wind power, fuel wood, landfill gas, and solar power. Also a leading generator of hydroelectric power.
- California imports more electricity from other States than any other State.
- In 2000 and 2001, California suffered an energy crisis characterized by electricity price instability and four major blackouts affecting millions of customers.

[http://tonto.eia.doe.gov/state/state\\_energy\\_profiles.cfm?sid=CA](http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=CA)

## California Regional Grid



- Major distributors: PG&E, SoCal Edison, SDG&E, PCorp (North), IID (SE) + small number of small utility districts
- CAISO: California Independent System Operator

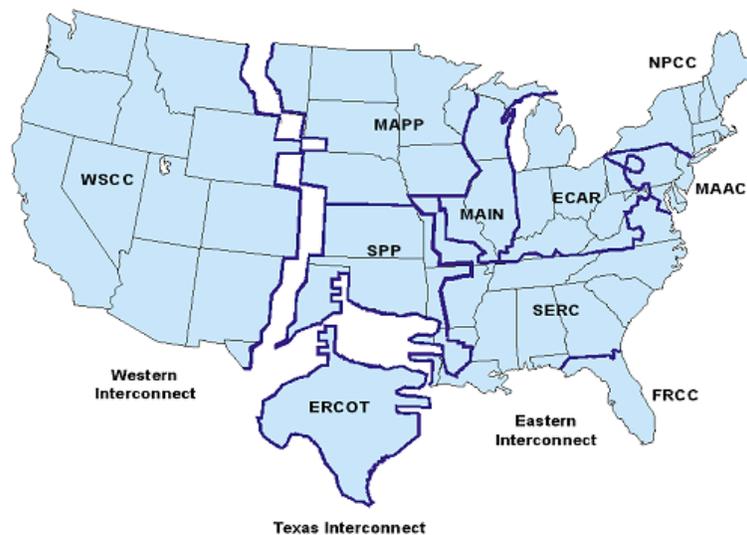
[http://projects.atlas.ca.gov/docman/index.php?group\\_id=99&selected\\_doc\\_group\\_id=111&language\\_id=1](http://projects.atlas.ca.gov/docman/index.php?group_id=99&selected_doc_group_id=111&language_id=1)

## California Regional Grid



- Long distance transmission facilities within California
- There are “hot spots” where demand cannot be met by supply due to transmission capacity bottlenecks
  - Electrical market prices are region specific

## Inter-Grid



## Inter-Grid



## Power System Performance Metrics

- Power Quality
  - Voltage, AC Frequency, Waveform
- Reliability
  - Outage frequency and duration, probabilistic measures
- Security
  - Contingency analysis

## Measures of Reliability

- **Outage: loss of power to an area**
  - Outage frequency
  - Outage duration
    - Dropouts, brownouts, blackouts
- **Loss-of-load probability (LOLP)**
  - Prob generation will be insufficient to meet demand over some specific time window
- **Loss-of-load expectation (LOLE)**
  - Expected number of days in the year when the daily peak demand exceeds the available generating capacity
- **Expected unserved energy (EUE)**
  - Measure of transmission system capacity to continuously serve all loads at all delivery points: outage/year x hrs/outage x unserved MW per outage

[http://en.wikipedia.org/wiki/Power\\_outage](http://en.wikipedia.org/wiki/Power_outage)