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# Basic Understanding of the Electricity Sector

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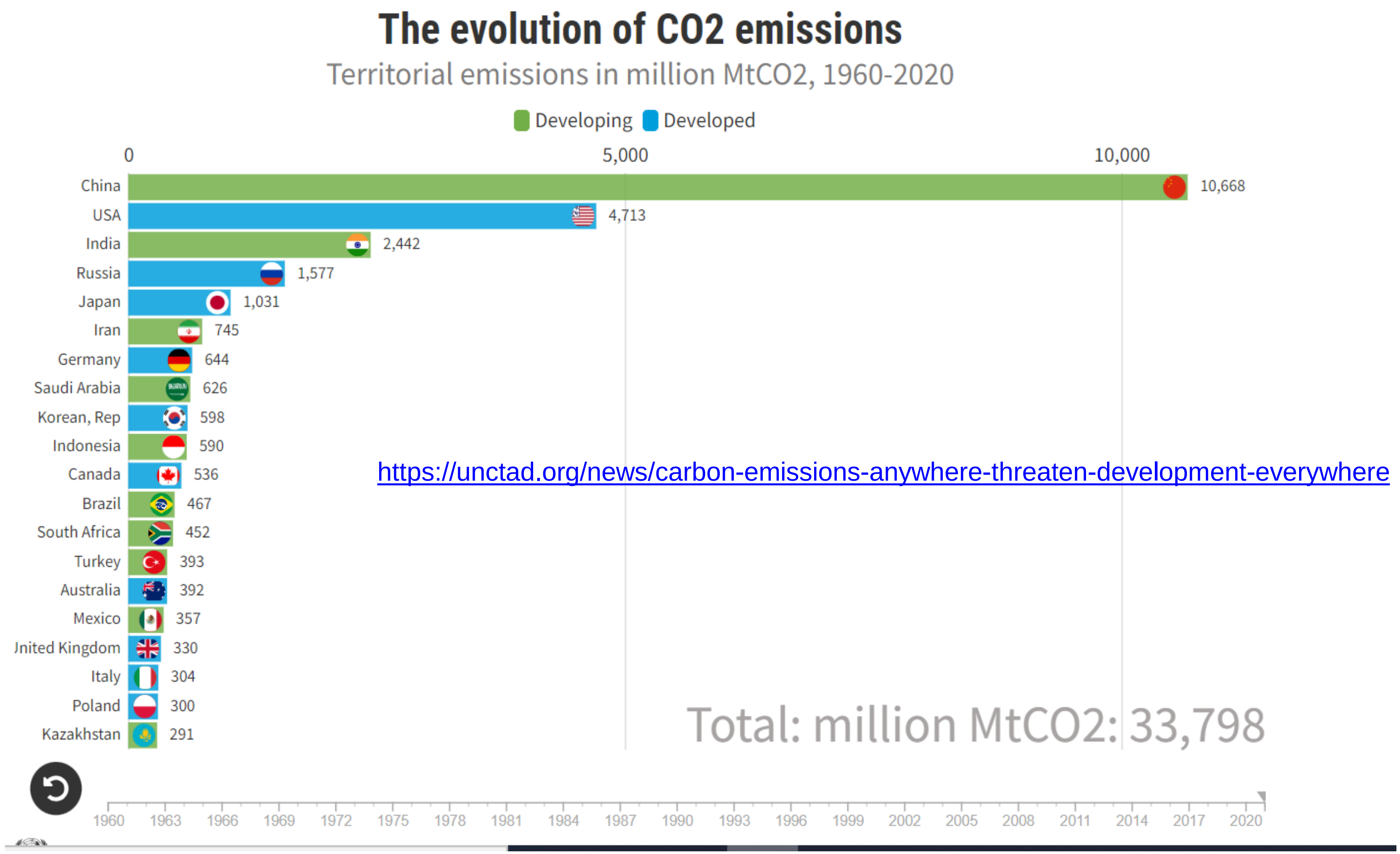
# POWER SECTOR ISSUES IN DEVELOPING COUNTRIES….

# Decarbonization challenge



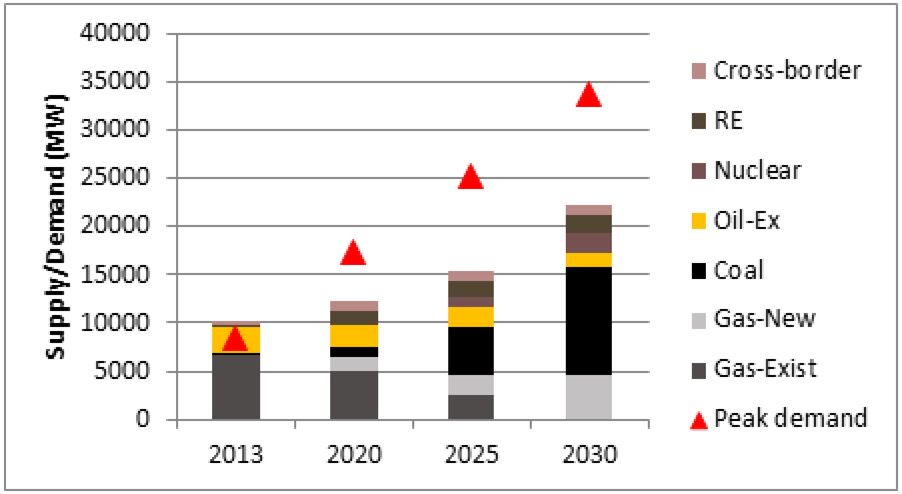

https://unctad.org/news/carbon-emissions-anywhere-threaten-development-everywhere

**Very serious reductions in coal capacity needed**

# Lack of access to electricity

- **700 million people** does not have electricity.
- 20 countries in Asia and Africa account for 70% of the population without access.
- Will require **$45bn/year investment** – five times current investment.
- Lack of adequate generation capacity backed up with sufficient fuel is a big problem in several countries even with current low level of access.
- Bangladesh faces 16% peak deficit but by 2030, the peak deficit may be over 40% if they cannot mobilize enough generation capacity.

**Projected demand-supply gap in Bangladesh**

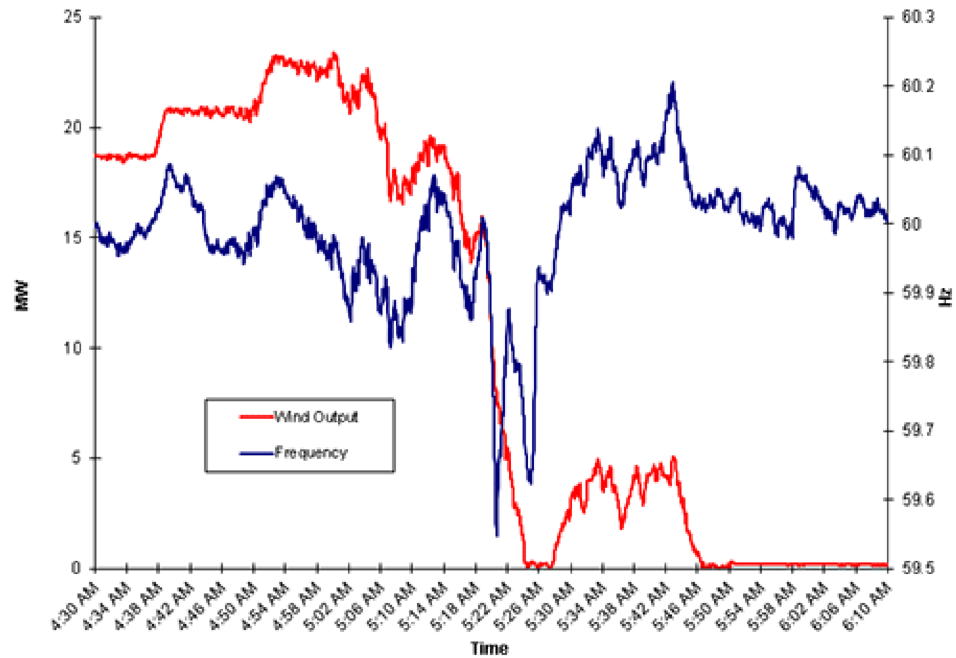



**Massive investment needed**

# Poor operational performance

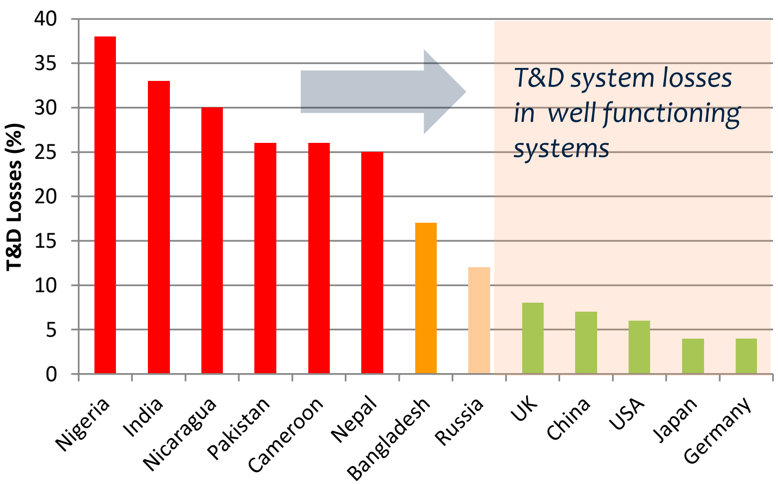
- **Weak transmission system** – lack of a strong HV transmission backbone
- **Poorly designed and maintained distribution network** – very long, LV feeders with low power factor pumps
- **Very high auxiliary consumption in power stations** (e.g., > 11% in some Asian countries)
- **Poor maintenance of generation and transmission →** high forced outage rates
- High penetration of intermittent renewables in a weak transmission system leads to **significant frequency excursions** → low utilization of wind in particular in some countries

**Example of wind variability and the effect on a frequency**



# Real-life power system

## Technical and "Non-technical" losses in Developing Countries is a Major Issue

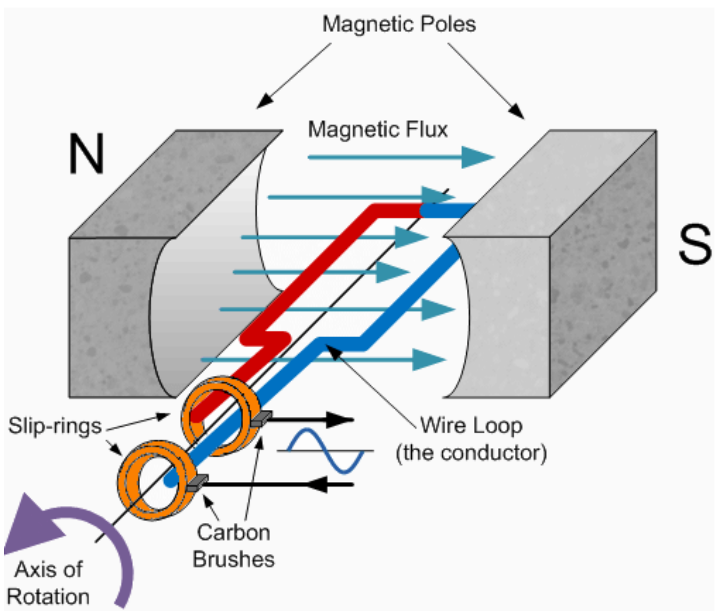



Source: Central Electricity Authority, India

- High losses in developing nations is primarily due to theft of power, but poorly designed T&D system (e.g., long low voltage rural feeders) and poor O&M practices contribute to it
- T&D losses have been > 30% in some countries on average and there are areas with > 50% losses
- Efficient benchmark for T&D depends on the distribution of generation and load but should be below 10%, e.g., China despite its massive system has achieved 7% - remainder of the losses is "commercial" / "non-technical that account vast majority of losses in some countries (e.g., the red/orange bars in the plot)

# *ELECTRICITY BASICS*

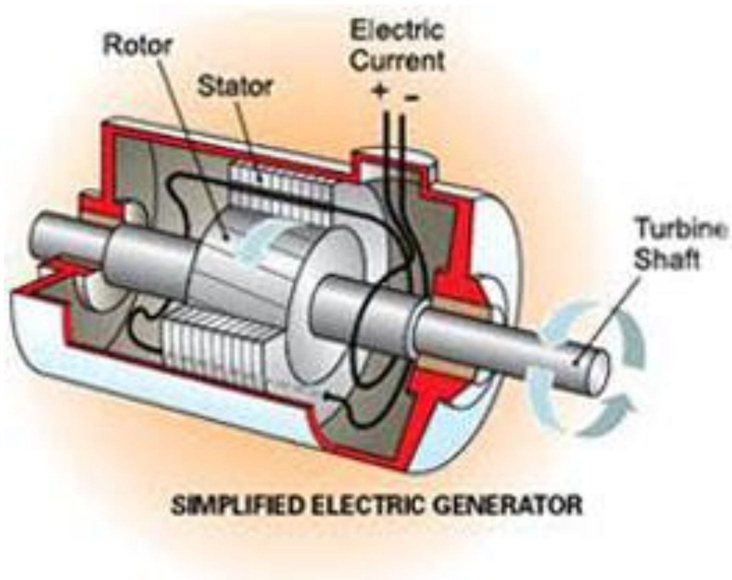
# How is electricity generated?




- Electrical energy is **secondary energy** source i.e., it requires conversion from other sources of energy – power stations produce electricity by converting kinetic (or mechanical) energy of a rotating mass [“turbine”] into electrical.
- A “generator” uses rotation of a conductor (“rotor”) in between two magnetic poles (“stator” to free up electrons on the conductor to create electrical current.

- At the other end of a transmission line, an electric “motor” performs the opposite task of converting electrical energy into mechanical energy!

# How is electricity generated?




*Parts of a typical electricity generator: Rotor stator, turbine shaft*

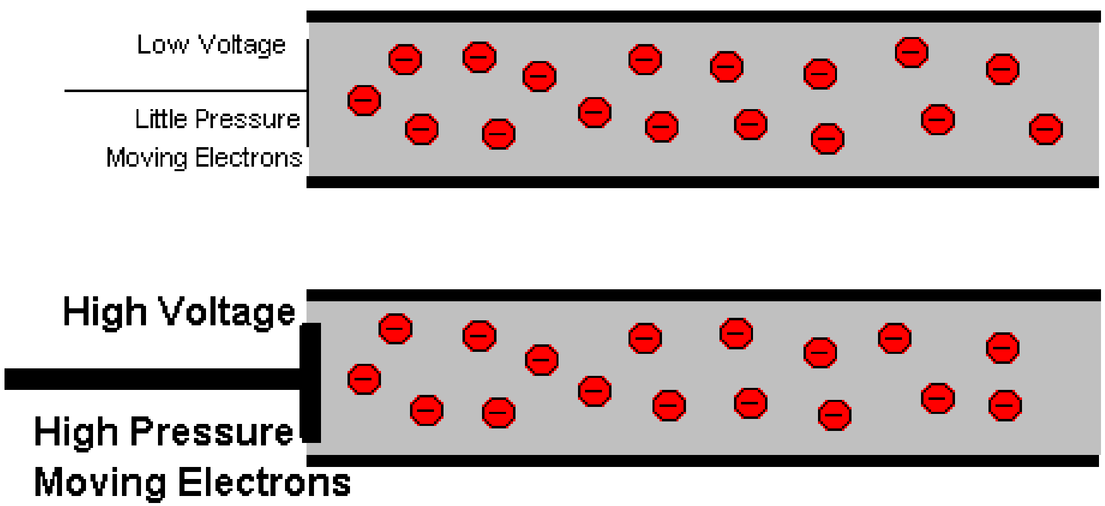
Lets watch the following video to see this in "action":

https://www.youtube.com/watch?v=AmWEs5CTQ3Q

# Key concepts: Voltage (V)

Voltage is electromotive force. It is the force or push on electrons in the circuit

- It is referred to as potential difference
- Has the potential to do work, but does nothing by itself
- It's measured in **Volts** (V or E)

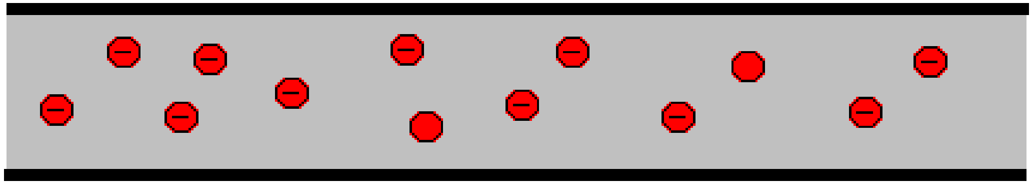



Note: The # of electrons is the same

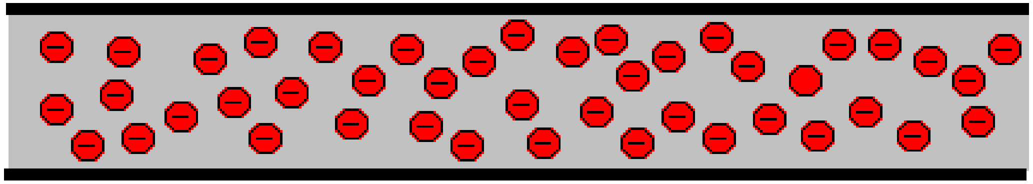
# Key concepts: Current (I)

Current is the amount of electricity that flows in the circuit

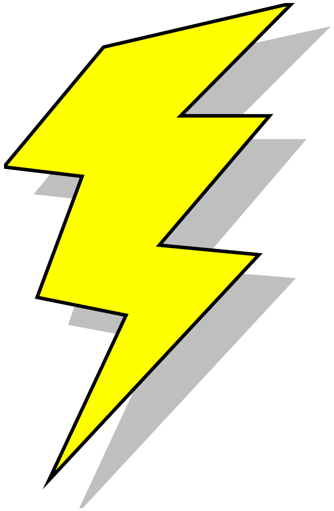
- Current is measured in **amperes** or amps (I)
- The more current, the higher the amps
- Pushed and pulled by voltage
- Produces heat



Few Electrons Flowing = Low Amps



Many Electrons Flowing = High Amps

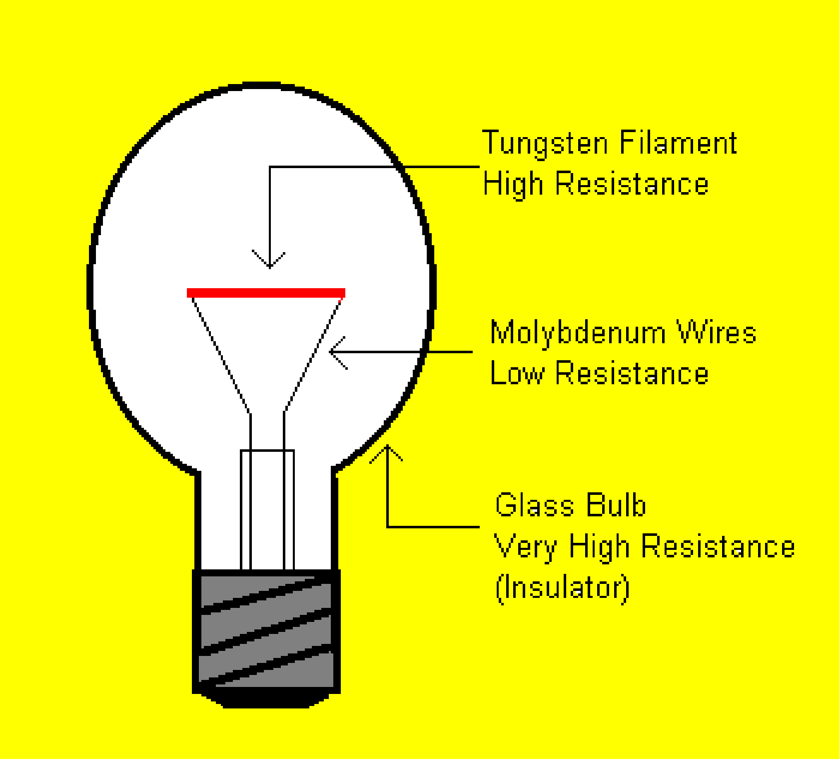


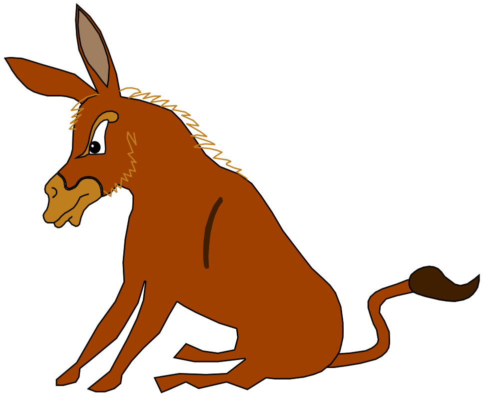
Lightning is current flowing through air

# Key concepts: Resistance (R)

Resistance is the opposition to current flow in the circuit

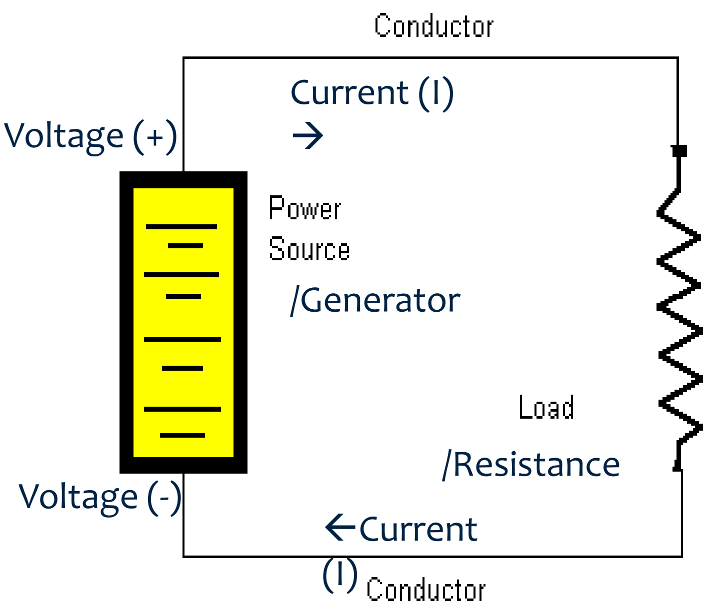
- Resistance is measured in **Ohm** (Ω)

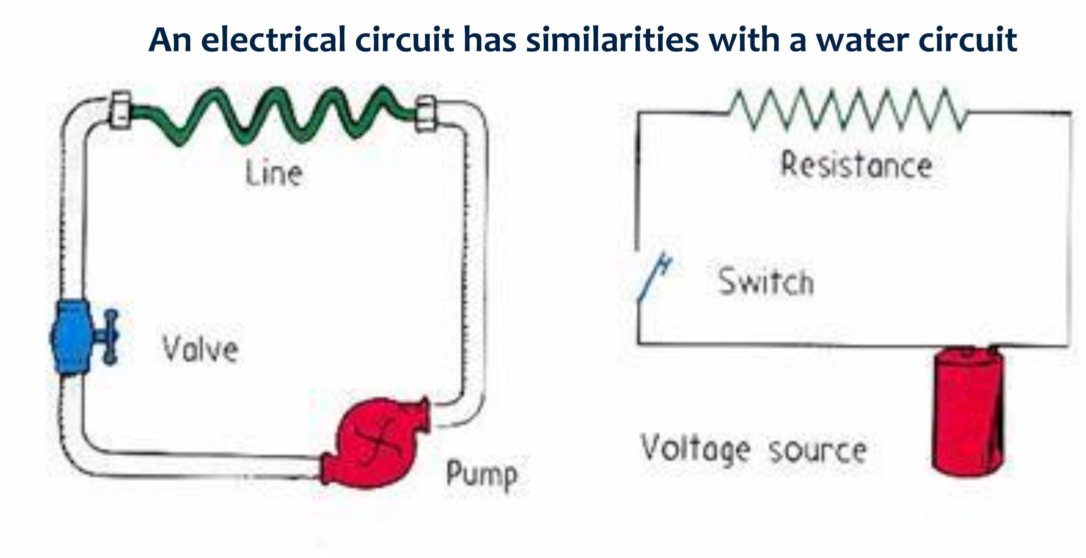


# Key concepts: Circuits

- Path of electricity in a loop with current flow driven by the voltage drop across the circuit.
- If the loop is "broken" (e.g., with a switch turned off), there is no flow – analogous to a water circuit.



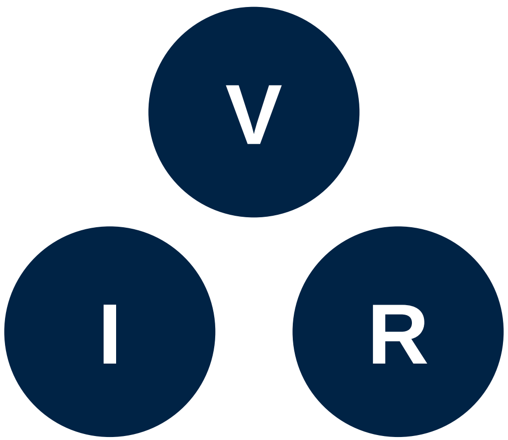



# Key concepts: Power (P) and Energy (E)

| | Power (P) | Energy (E) |
|---|---|---|
| Definition | • Instantaneous rate of consumption or production (analogous to "speed")<br><br>**Power = Voltage x Current** | • Adding up power over time, i.e., MW x Hours (MWh)<br>• Total work done (analogous to distance covered)<br><br>**Energy = Power × Time** |
| Unit | • Watts = Amps x Volts (W)<br>• kW = 1 x $10^3$ Watt<br>• MW = 1 x $10^6$ Watt<br>• GW = 1 x $10^9$ Watt | • Joule = 1 Watt-second (J)<br>• kWh = kilo Watt hour (3.6 x $10^6$ J)<br>• Btu* = 1055 J; 1 MBtu=0.292 MWh |

# Physical laws: Ohm's law

Ohm's law relates the three most fundamental electricity parameters




- V= Voltage
- I = Current
- R= Resistance

$$V = I * R$$

- Greater the resistance, one needs to apply more force to get the same amount of flow
- Voltage = Current x Resistance

$$I = V / R$$

- Amount of current that can be pushed through a conductor depends on resistance and voltage
- Current = Voltage / Resistance

$$R = V / I$$

- Greater distance means increased resistance
- Resistance = Voltage / Current

# Physical laws: Kirchhoff's laws

- Kirchhoff's Current Law:
  - **Sum of currents entering and leaving a point/node must be equal**
  - This is very similar to physical balance in any other network e.g., water

- Kirchhoff's Voltage Law:
  - Sum of potential differences, i.e., voltages around a loop is zero
  - The physical law of energy conservation (i.e., energy/charge can neither be created or destroyed) applied to an electrical network
  - In a meshed network (with "many loops") this law governs how power flows among different parts of the network may be interrelated with each other – distinguishes power network from other networks where flows may be independently controllable

# Power losses ($I^2R$)

- Let's combine the following two relationships:

  $P = V \times I$ and

  $V = I \times R$; to get

  $P = I \times I \times R = I^2R$

- **What does it mean?**

  Power is the voltage drop around a circuit and the flow it generates

  Voltage drop on the other hand is the resistance times the flow

  Power that is "spent" or "lost" in the resistance is proportional to the square of the current/flow, i.e., current doubles → losses quadruple

- **Implications:**

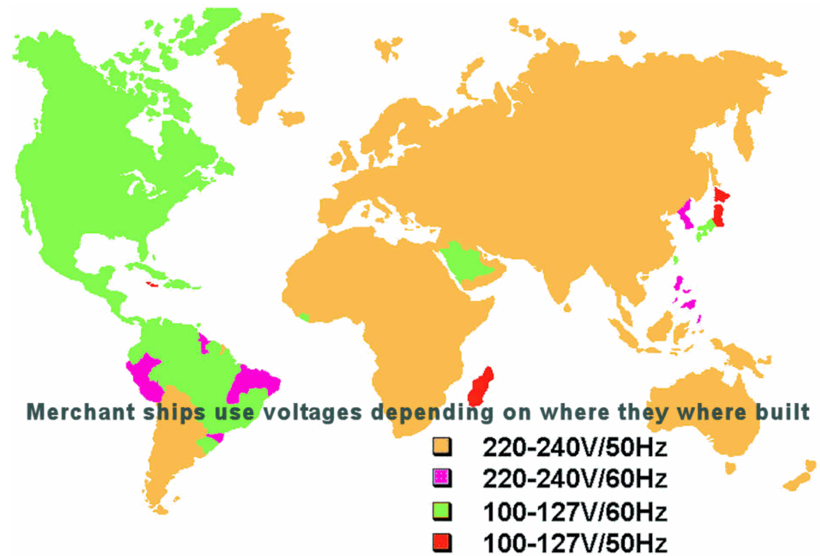
  Losses can be disproportionately high on "low voltage" lines because current will be high on such lines → hence the case for high voltage transmission

  The conductor material matters too with better conductors → lower resistance

# Key concepts: frequency (f)

- AC current requires two things: (a) magnetic poles and (b) rotation of a coil. Frequency of a power system refers to the number of oscillations of AC, i.e., how many cycles of AC is produced in one rotation of the turbine
- For example, 3000 revs per min for a 2 pole generator produces 50 cycles per second
- More generally, **N = 120f/P** where N is the number of rotation of turbine/alternator; f is frequency and P is the number of poles
- Frequency is measured in Hertz (Hz) – 50 Hz and 60 Hz are the common systems

Voltage/frequency across the globe

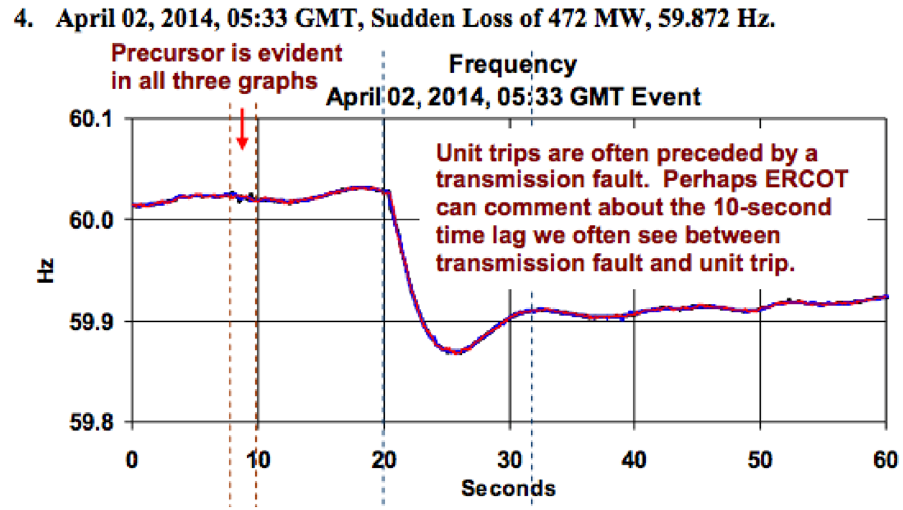


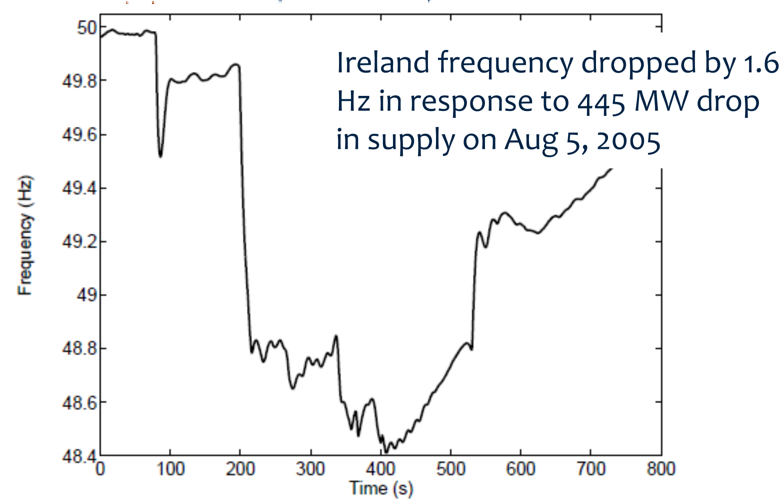

Source: Wikipedia

# Key concepts: frequency (f)

- Frequency changes every millisecond as either load or generation changes because the mechanical input (from turbine)  and electrical output (load) do not match
  - If mechanical > electrical, f ↑
  - If mechanical < electrical f ↓
- Power system control is mostly about keeping frequency within a tolerable bandd because at the load end motors might stall if the frequency is too high/low
- Frequency fluctuation is a function of how big the system and the "inertia" of generators – smaller systems need more ready to go reserve power to counter fluctuations

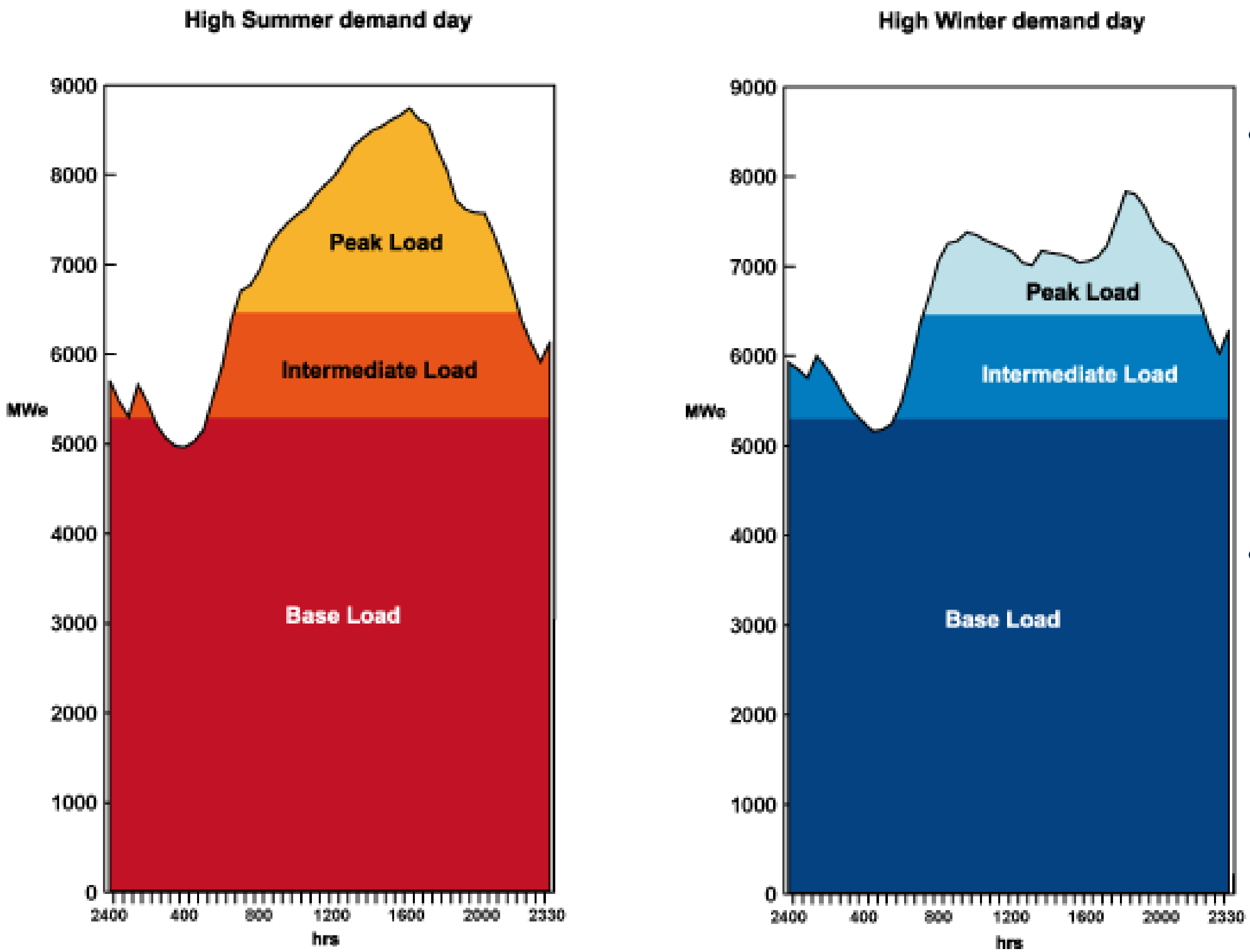
**Large interconnected System: ERCOT**



# Key concepts: load curves

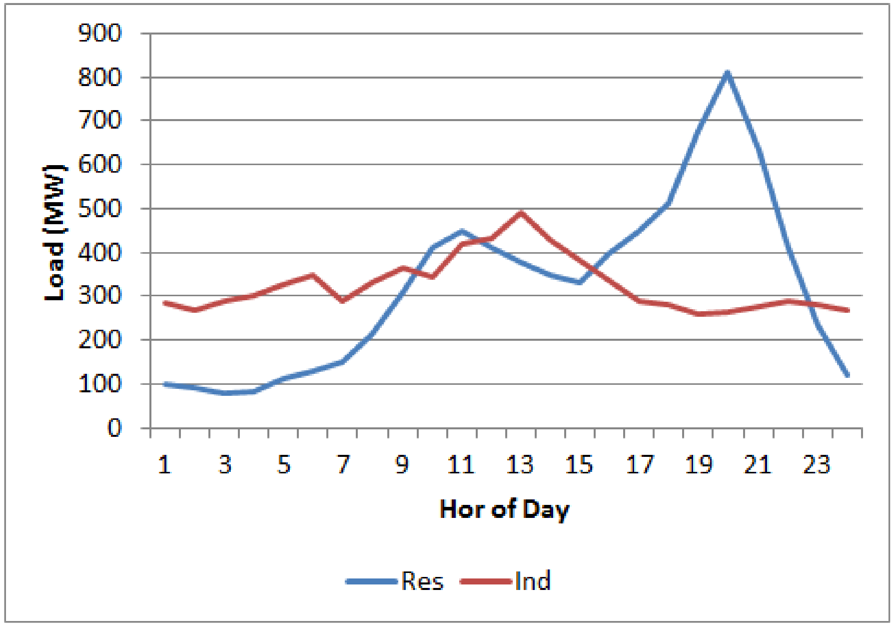
**Load curves for typical electricity grid**




- Load curve represents rate of power consumption for different parts of the day at an aggregate level for the system
- Varies across seasons, type of consumers, geography

# Load factor

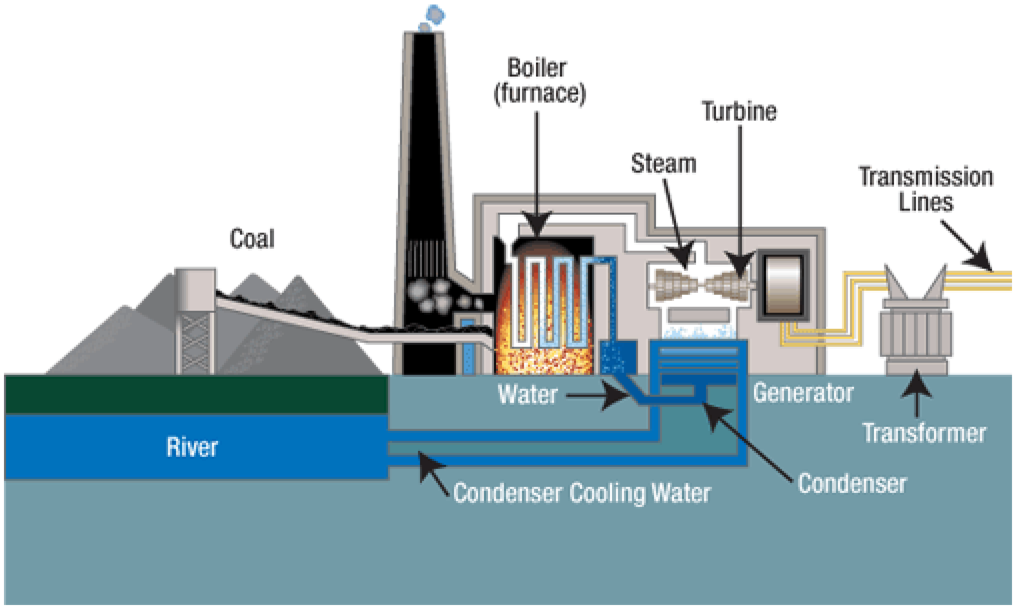
- Peak load grows faster than average and off-peak load.
- Load factor = Ratio of average load to the peak load (daily/monthly/annual).
- Residential load factor is well below 1 as the peak load consumption from air-conditioners/heaters may be higher than average/off-peak load.
- Large industrial loads with 24X7 production may be flat and a load factor closer to 1.
- Low load factor poses a problem because low utilization peaking plants are needed.




- Both residential (Res) and industrial (Ind) load curves above have the same daily energy requirement
- The former has a load factor of 0.4 compared to 0.66 for the latter – and requires 300 MW (or 60%) more peaking capacity

# *LET'S DISCUSS EACH OF THE GEN, TRANS, DIST AND LOAD IN A BIT MORE DETAIL*

# Coal-fired power generation

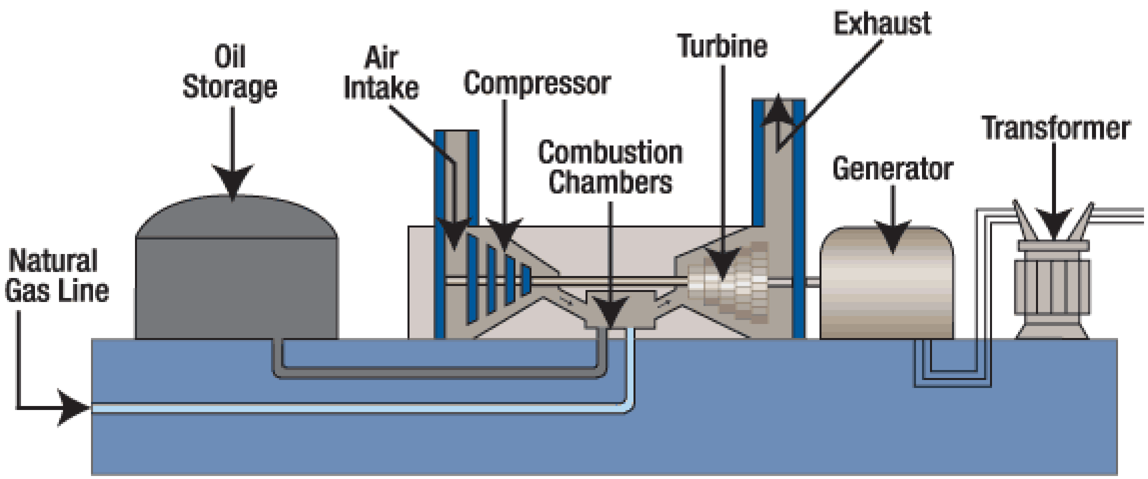


# Coal-fired power station


**Puttalam Power Station in Sri Lanka**

# Gas-fired power generation

## Combustion Turbine Power Plant



# Generation - renewable

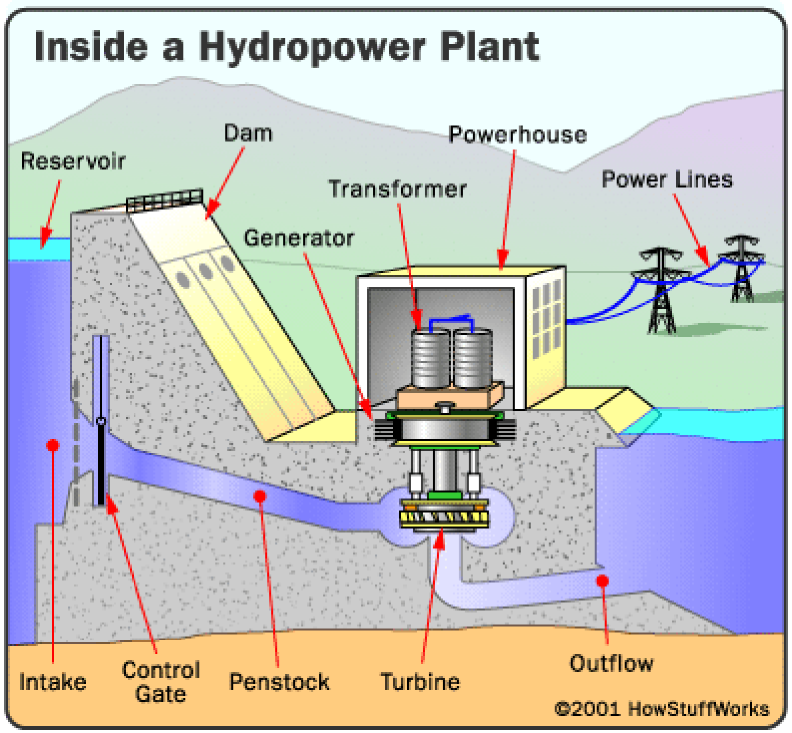
**Hydro electric**

**Wind**

Solar

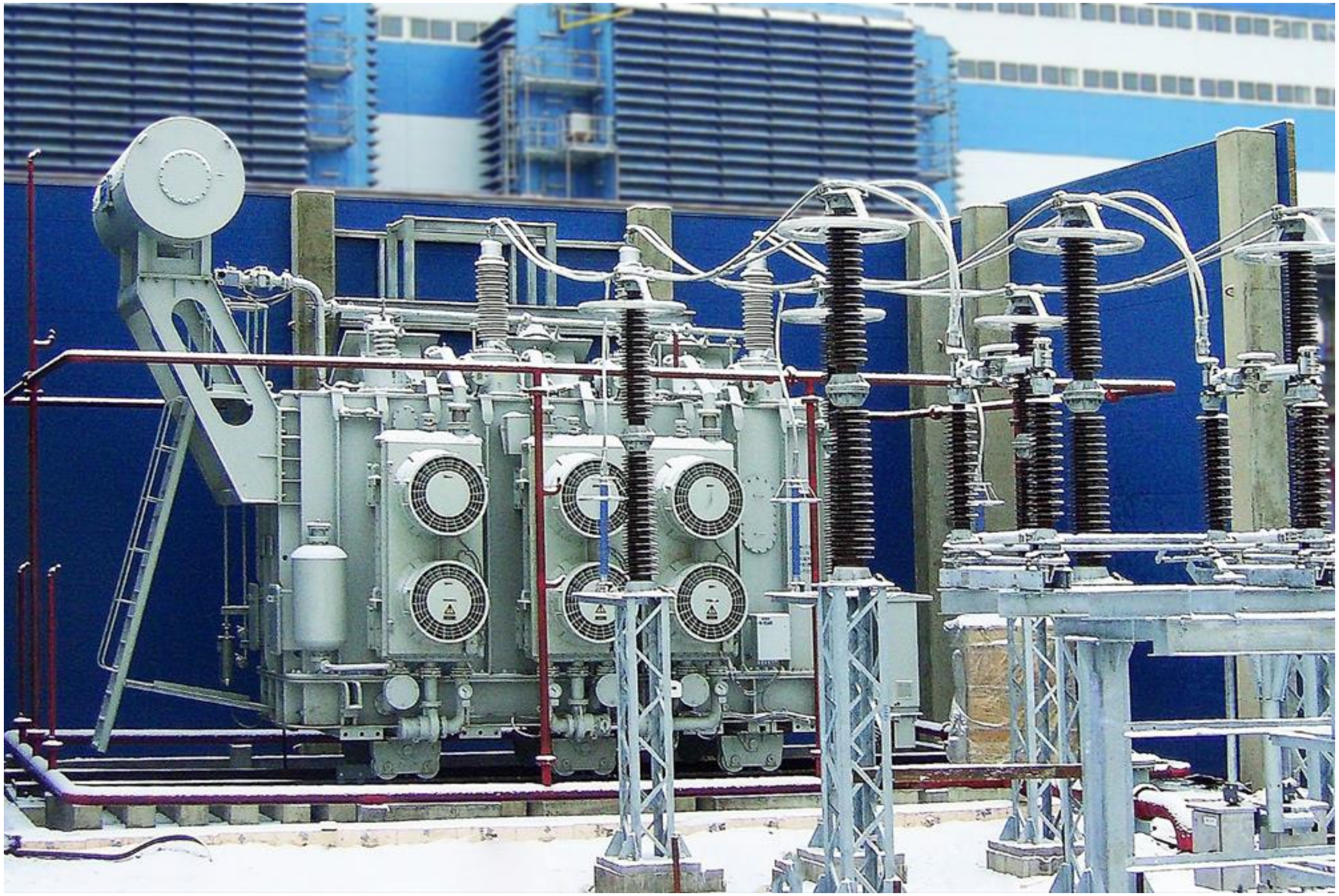
**Geothermal**

# Hydro electric power plant




**Sultan Mahmud Power Station, Malaysia**

# Generator step-up transformer



**Generator Step-up Transformer Next To A Power Station**
**(250MVA 15KV/110KV)**

Source: ZaporozhTransformator

# Power plant switch yard

**Switch Yard Next To A Power Plant**
**(10.5KV/275KV, 168MVA station)**

Source: Camie Blogspot

# High voltage transmission line

**500 KV/3500MW AC transmission line**
**(Southern California Edison)**

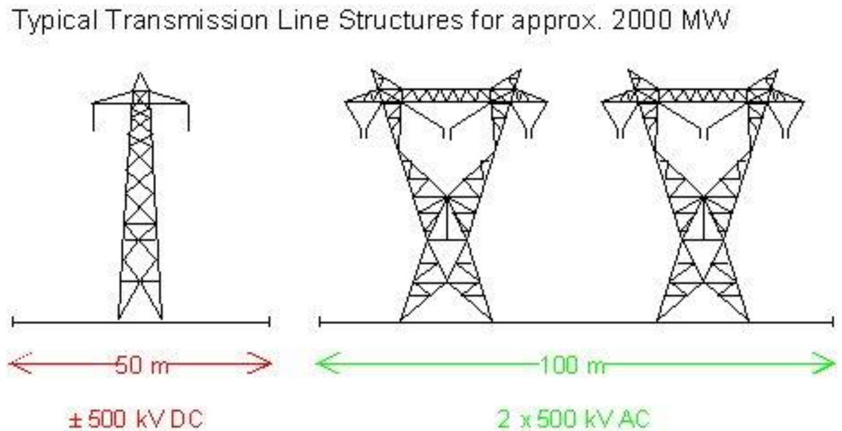
**765 KV/5000MW AC transmission line**
**(American Electric Power)**

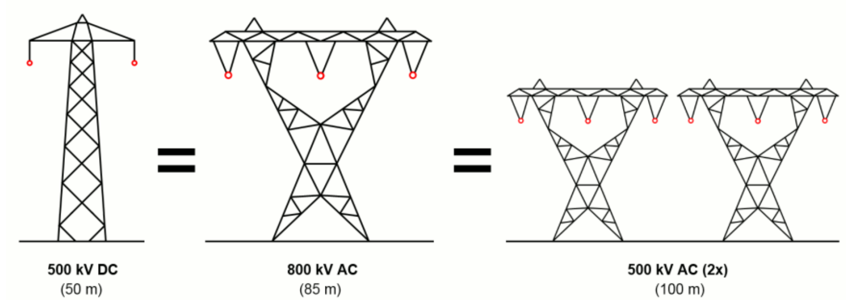
Source: SCE; AEP

# High voltage DC (HVDC) systems

**Benefits:**

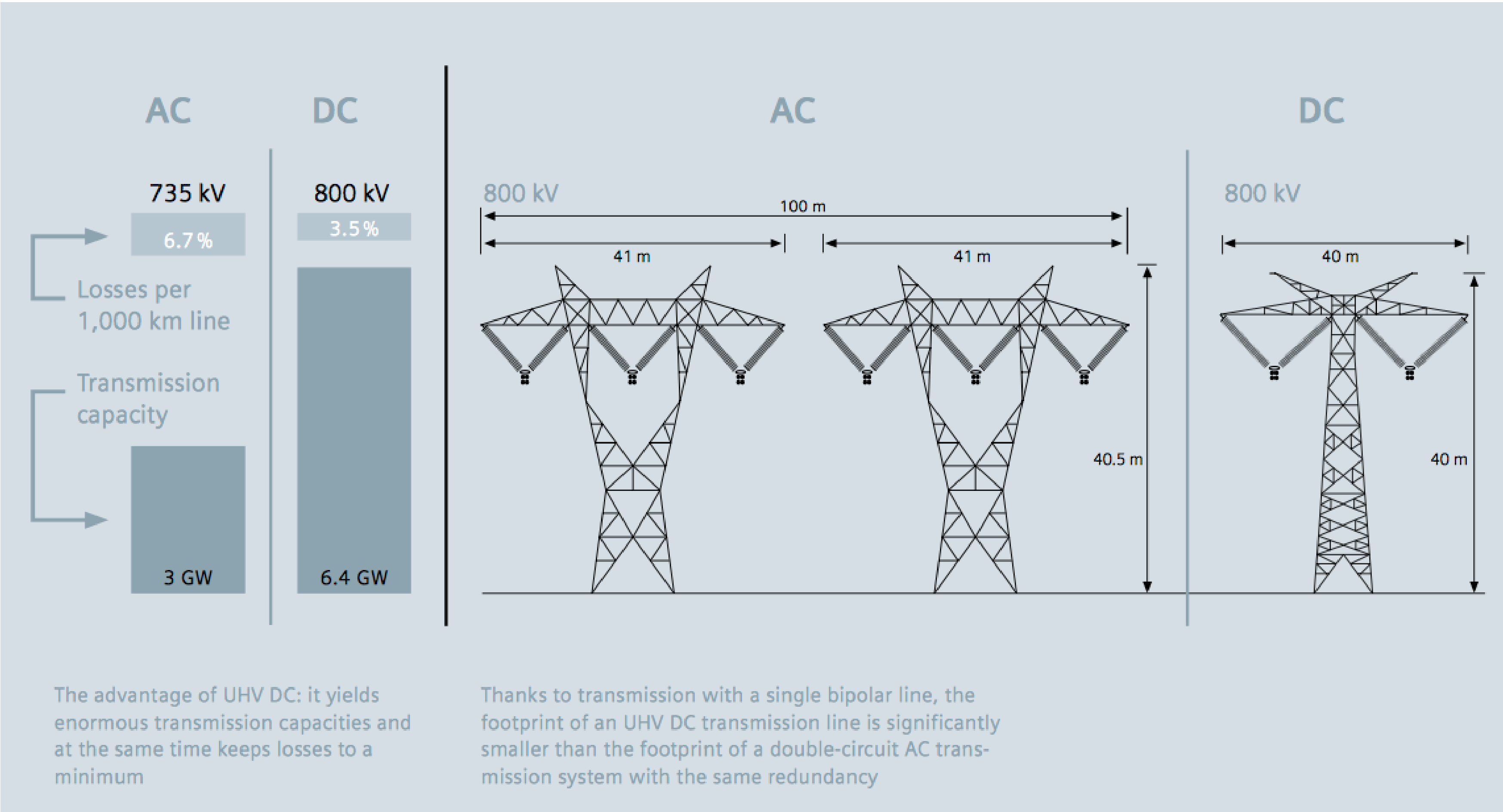
- HVDC transmission lines can deliver large bulk of power over longer distances with less electrical losses than an equivalent AC transmission line (under 3%).
- HVDC enables the intertie between systems that use different voltages and/or frequencies
- HVDC facilitates power flow between unsynchronized AC transmission systems and thereby increasing overall system stability
- HVDC can easily interface variable/intermittent renewable energy sources such as large scale wind and solar to the main AC grid with reduced instability
- HVDC can deliver lower costs due to the reduced conductoring (one less line) as well as reduced tower footprint and narrower right-of-way



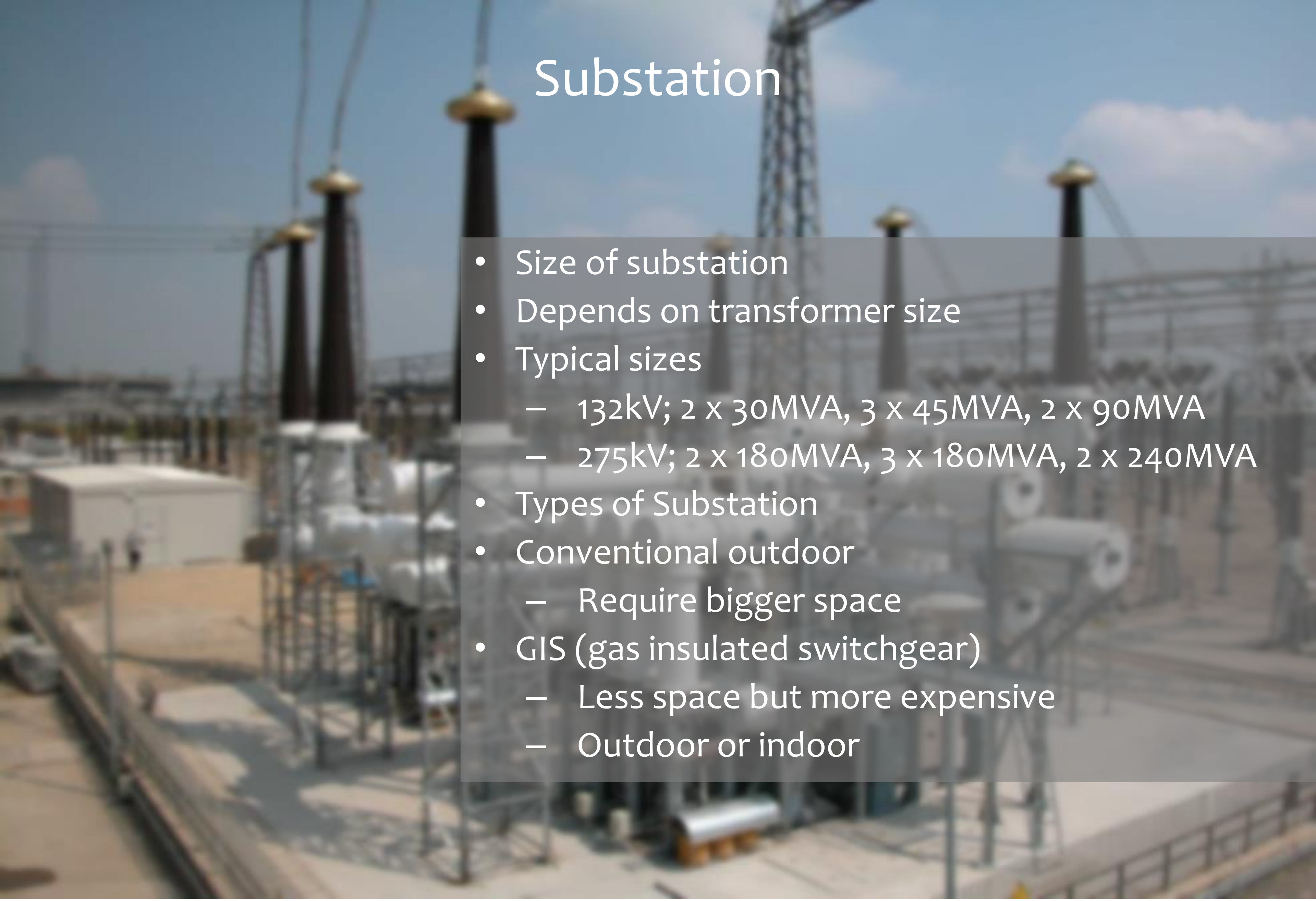




SOURCE: SIEMENS

# AC vs. DC transmission



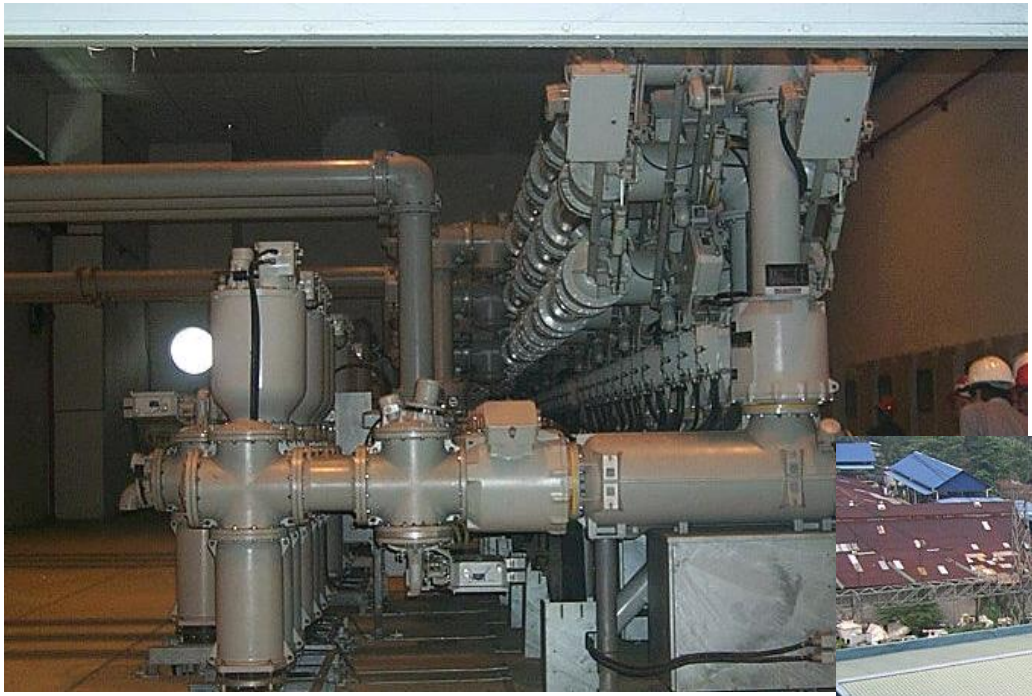

Source: www.siemens.com/energy/uhvdc



# Substation

- Size of substation
- Depends on transformer size
- Typical sizes
  - 132kV; 2 x 30MVA, 3 x 45MVA, 2 x 90MVA
  - 275kV; 2 x 180MVA, 3 x 180MVA, 2 x 240MVA
- Types of Substation
- Conventional outdoor
  - Require bigger space
- GIS (gas insulated switchgear)
  - Less space but more expensive
  - Outdoor or indoor

# Gas insulated substation



# Substation components

- **Transformer:** high→ low voltage
- **Circuit Breaker / Switch Gear Isolator Switches:** useful in isolating faults so that the rest of the power system can perform normally
- **Busbar:** Strips of conductors that connect the transformer with other elements in the S/S
- **Insulators**
- Protection Relay and Control Equipment

**Transformer**

**Circuit breaker**

# Substation components

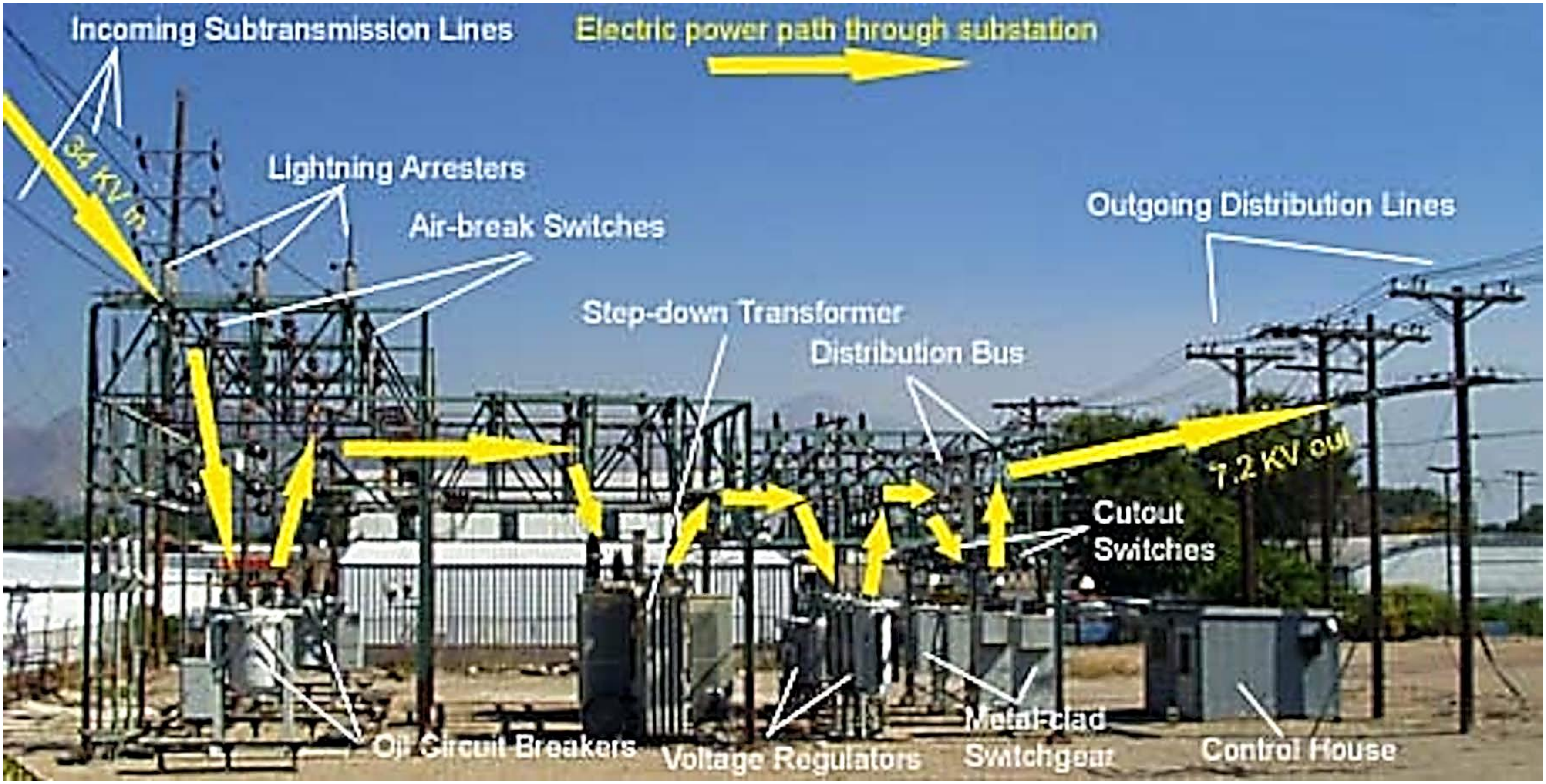
420 kV gas insulated switchgear

Insulators – ceramic or polymer separate conducting parts

# Distribution

- **Distribution lines**
- **Distribution Intakes** (33kV, 22kV)
- **Distribution Substations** (22kV, 11kV, 6.6kV)
  - Indoor substation
  - Outdoor substation
  - Pole mounted substation
  - Compact substation
  - Underground substation
- **Transformer capacity**
  - 100kVA, 300kVA, 500kVA, 750kVA and 1000kVA

# Distribution substation




**Path Of electric power In a substation**

Part 2

# 3. Power system functions

# We are going to discuss….

Planning, operation and market functions definitions

- **Planning** – issues, tasks and a planning case study for Bangladesh – what issues it dealt with, what was the outcome and were there unresolved issues
- **Operation** – what does it involve, discuss one of the new challenges around dealing with intermittency
- **Electricity market** – introductory discussions on genesis, objective, design choices and a case study for Philippines

# Power system functions

- **Planning**: covers addition and retirement of generation, transmission and distribution capacity over the next 20-30 years, i.e., when, how much, what type and where capacity should be added to meet demand taking into account retirement of existing facilities and load growth

- **Operation:** deals with efficient usage of existing facilities on a day to day basis under "normal" operating conditions. Also deals with keeping the system secure in real-time and efficient management of contingency events e.g., rapid response to a major generation or transmission line outage event through increasing/decreasing generation

- **Market functions:** Many countries around the world have started real-time/day-ahead electricity markets wherein sellers (generation companies) and buyers (distribution/retail companies) can offer/bid for generation. A market operator as an independent body manages the buying/selling (or "market clearing") functions which is often separate from the system operation role

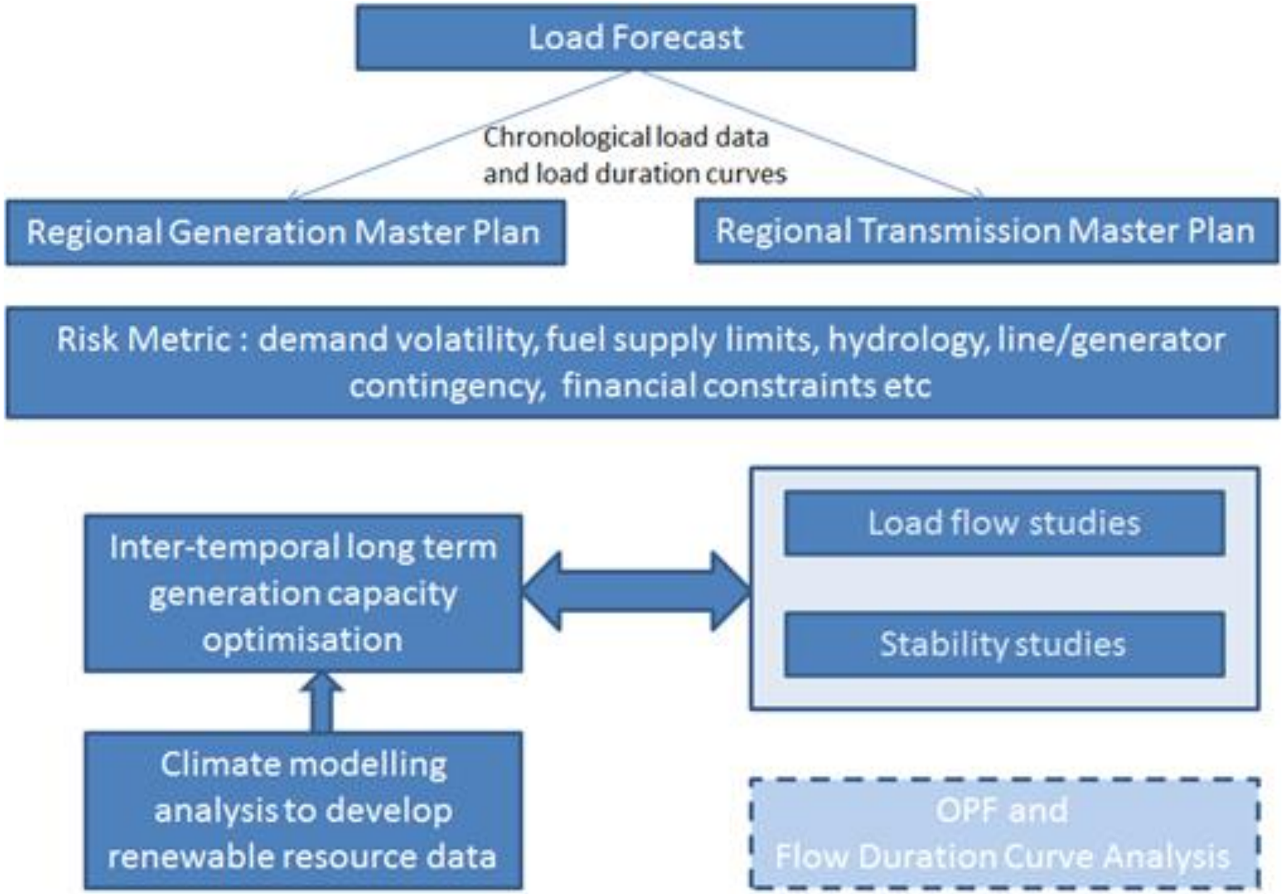
# Planning

- **Generation planning**: **Generation mix** taking into account multiple and often conflicting objective is paramount, e.g., least-cost, most secure and environmentally sustainable may have significant trade-off

- **Transmission and distribution planning:** Follows generation to ensure sufficient transmission capacity (at high voltage levels > 100 kV) is put in place to evacuate generation and meet demand – again multiple objectives apply from cost, security, social/environmental impact (associated with right-of-way)

- **Market outlook:** Market operators also put out outlooks, statement of opportunities that include demand forecasts, when supply may fall short of demand and hence indicative "opportunities" that exist for new investors to build new generation capacity – these functions have effectively replaced planning counterparts in regulated utilities, although generation decisions are not in the purview of market operator

# Planning function: components



# Planning process

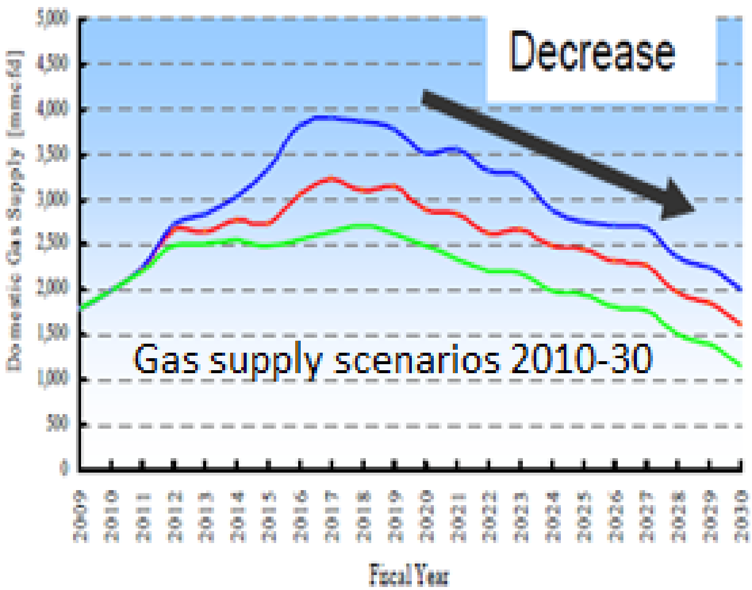
- Survey of demand
- Assessment of economic development

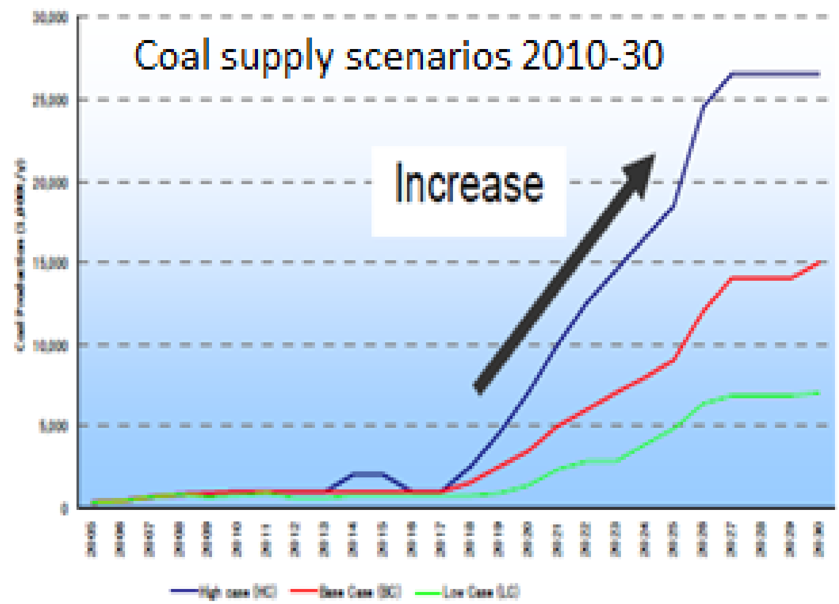
} Demand forecast

- Assessment of primary energy supply resources
- Policy considerations e.g., fuel diversification, renewable target, carbon reduction, electricity for all, fuel/power subsidies, etc
- Generation planning
- Transmission planning

# Planning issues: Bangladesh

- Planning studies from 2010 recognises gas supply constraint and emphasises fuel diversification needs



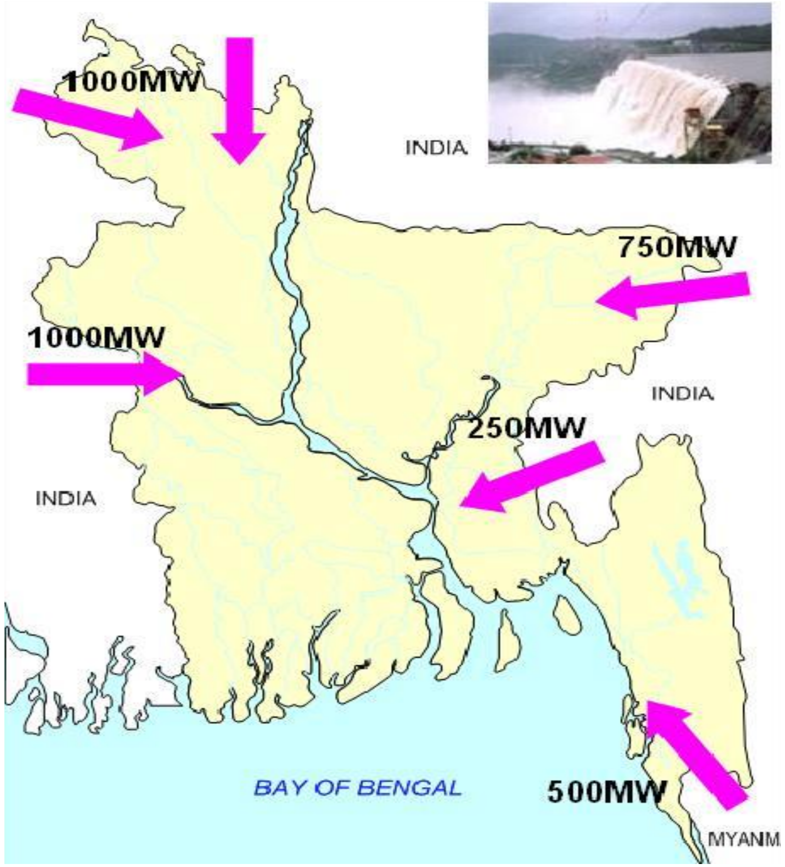




Red line: Base demand , Green line: Low demand, Blue line: High demand

Source: Bangladesh PSMP, 2010

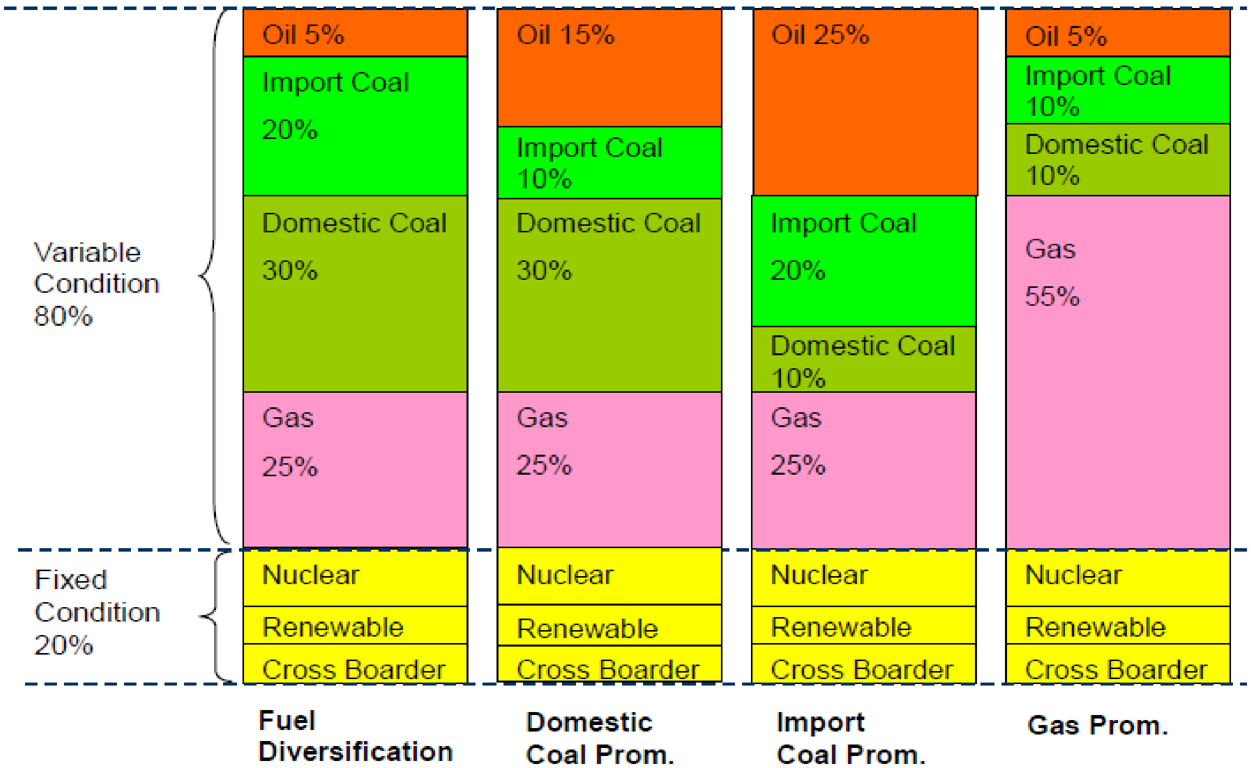
# Planning issues : Bangladesh

Significant cross-border trading opportunities exist (but limited recognition)



# Planning output : Bangladesh

- Generation planning output comprises alternative development paths
- **Fuel diversification scenario** is chosen as the optimal strategy




Source: Bangladesh PSMP, 2010

# Power system operation

- **Dispatch generation:** available generation resources are utilized in the best possible manner by using the cheaper resources as much as possible before resorting to more expensive generators ("merit order dispatch") – *functionality moved to a Market Operator in markets*

- **System monitoring:** Collects data in real-time through SCADA (Supervisory Control and Data Acquisition) system, processes and analyzes data

- **Maintain system security:** ensure flows on transmission limits are observed within tolerable limits, frequency is within stipulated limits, voltages are within stipulated limits, the system can withstand the loss of a critical component (e.g., the largest source of generation is suddenly lost)

# Operations: managing demand-supply imbalance

- Events following generation shortages:

  (1) Demand response
  (2) Voltage reduction (brown out)
  (3) Load shedding
  (4) Blackout

- The idea is to keep on reducing load until system frequency and voltages are back within tolerable limits

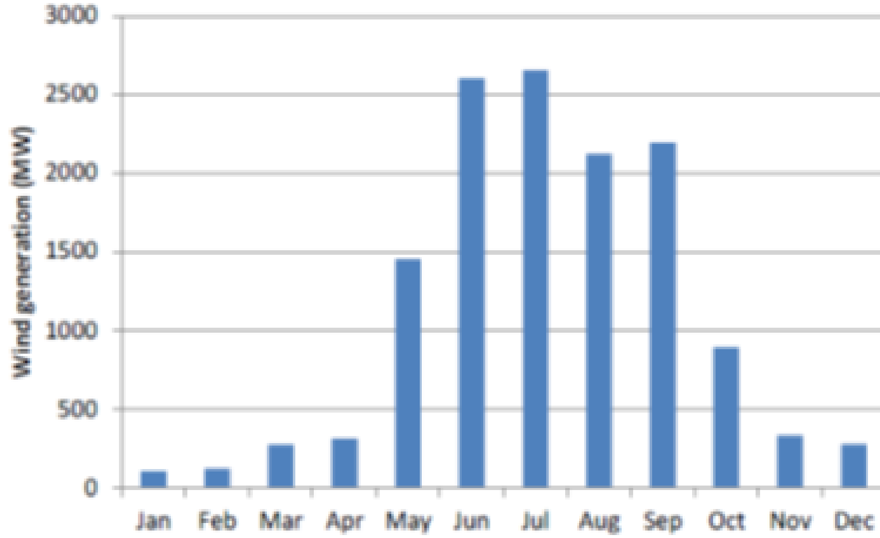
# Operations: new challenges is to deal with high volume of intermittent renewables

- High penetration of intermittent generation serves an important objective but also makes power system operation more challenging.
- The control center needs to respond instantly to the power needs in the service territory while the generation is intermittent.
- Intermittency and variability are as much a seasonal issue as it is at a daily scale or minute-by-minute or on a second-by-second management of power system

# Power system operations

## New challenges – seasonal variability of renewables

**Wind generation in Southern India during evening peak period in 2011**



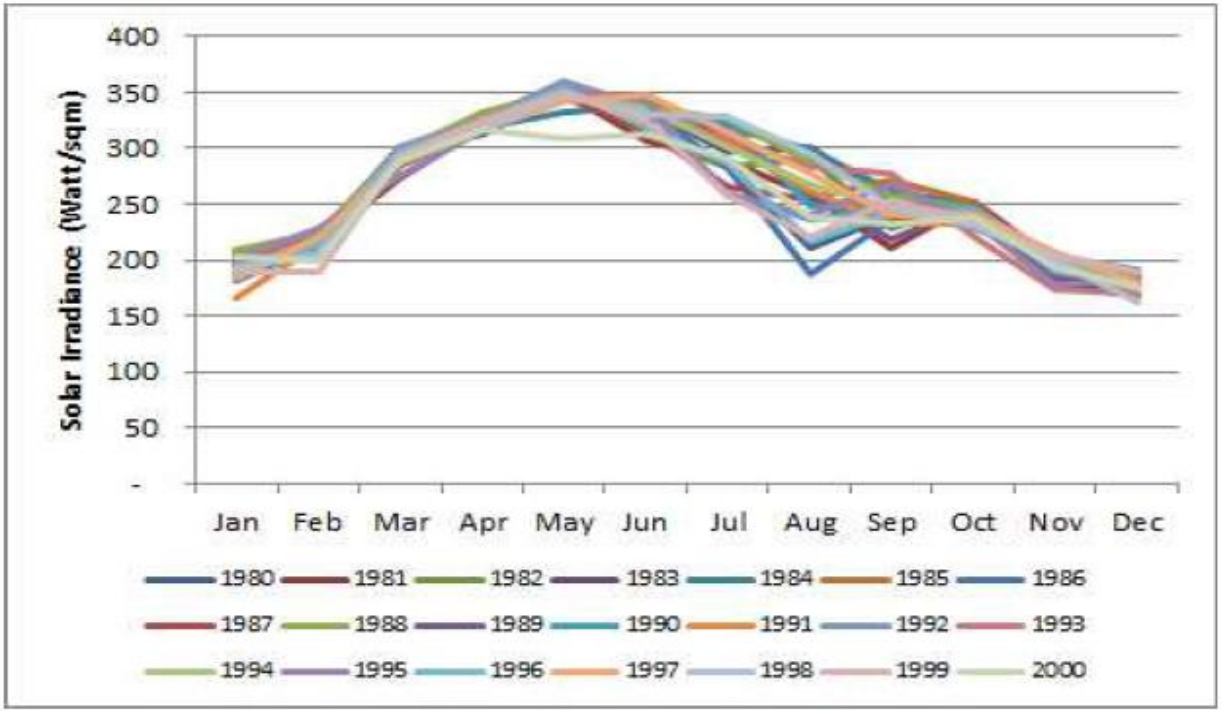

- **Significant seasonal variability** in wind in some countries.
- Southern India had more than 5000 MW of installed capacity in 2011 but little of it was available during evening peak, winter months and also Spring/early summer March-April – since there is not enough peaking capacity available some Southern states faced massive power cuts.

Source: Compiled from Regional Load dispatch Centre Data for 2011

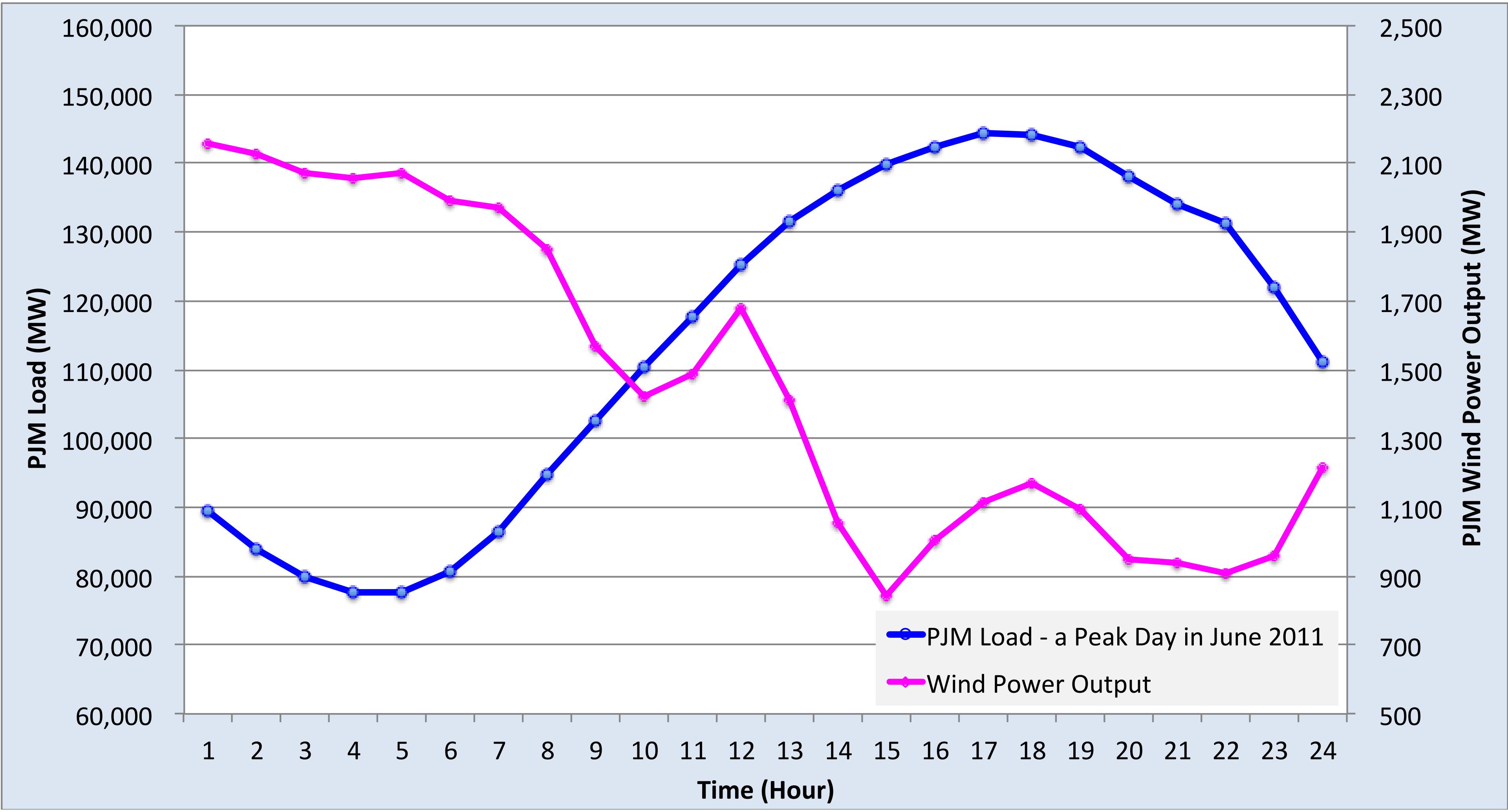
# Power system operations

## New challenges – seasonal variability of renewables

**Solar irradiance variability in Rajasthan (India) over 1980-2000**



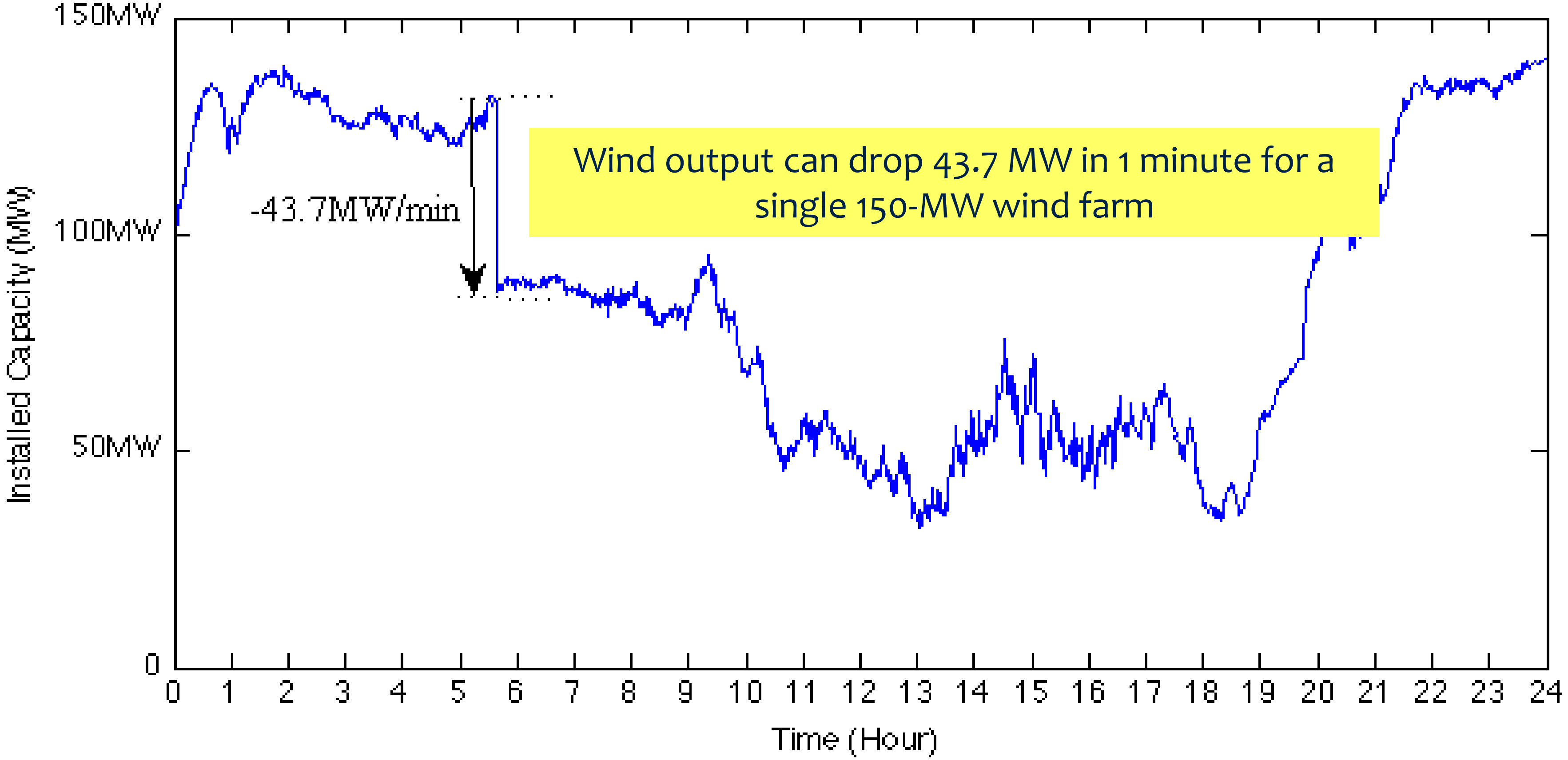
# Operation: intermittency on a daily timescale




Source: http://www.pjm.com/markets-and-operations/ops-analysis.aspx

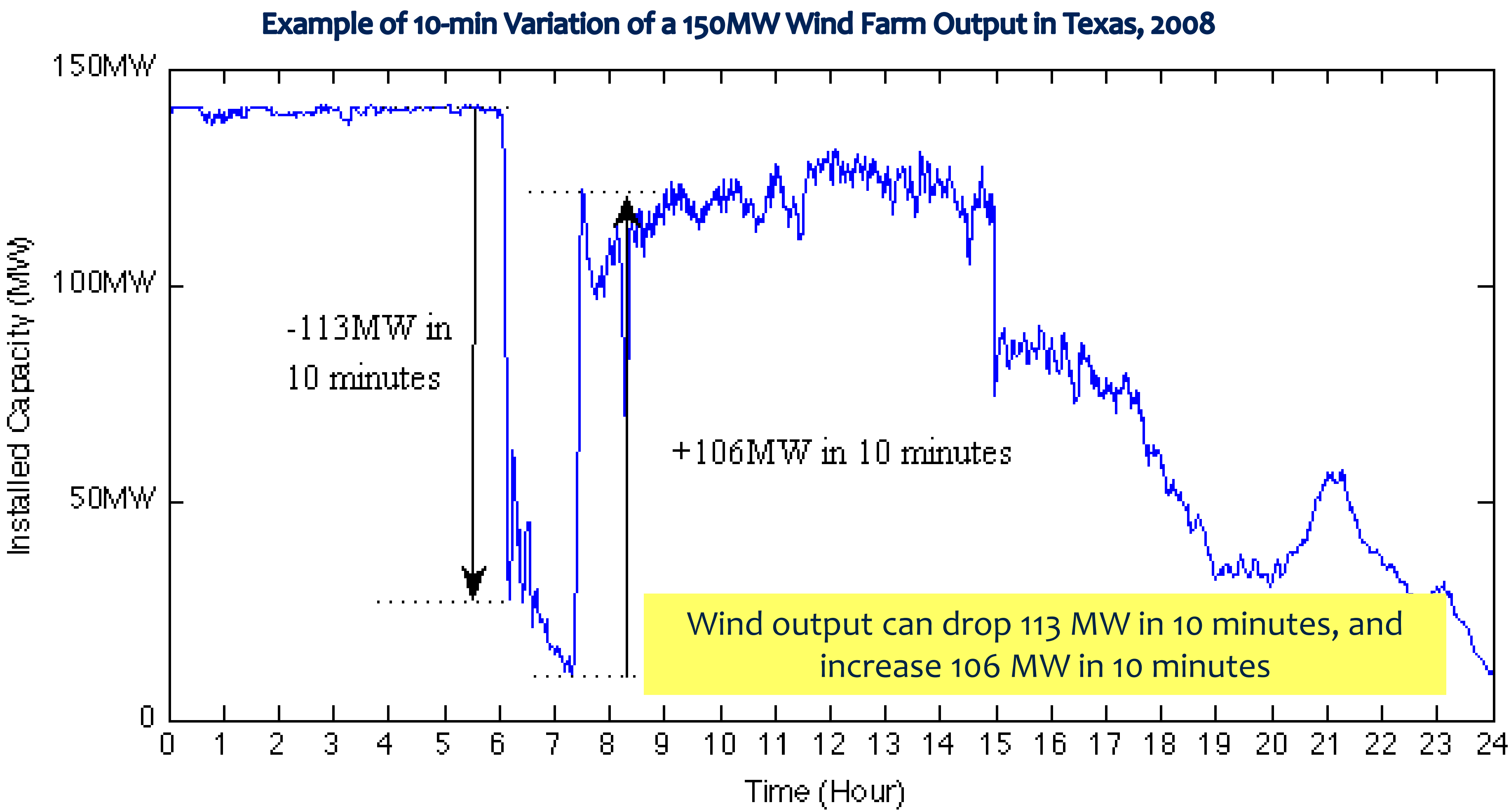
# Operation: intermittency – minute-by-minute

**Example of 1-minute Variation of a 150MW Wind Farm Output in Texas, 2008**




Source: NREL

# Operation: intermittency – minute-by-minute




Source: NREL

# Operation: how do we counter intermittency

Intermittency means demand-supply imbalance at a far greater scale which will impact on frequency and voltage – it must be managed either by changing generation, or through brown outs or shedding load:

- **More capacity**: more peaking capacity, more reserve injected into the system, or more interconnection

- **Storage:**
  - Batteries
  - Pumped storage hydro
  - Compressed air energy storage (CAES)

- **Smarter controls**: so that generation and load can be controlled in real-time efficiently → "smart grid"

# Operation of the Smart Grid

- It make the grid smarter, safer, reliable and more cost-effective using advanced sensors, communication technologies and distributed computing. Three core components of it are:

  **(1) Intelligence**

  **(2) Two-way communication**

  **(3) Real-time monitoring and control**

# Application of the Smart Grid

- Renewables integration
- Demand response application
- Peak load reduction
- Remote meter reading and billing
- Transformer/Switchgear loading
- Service monitoring and recovery

# Electricity markets

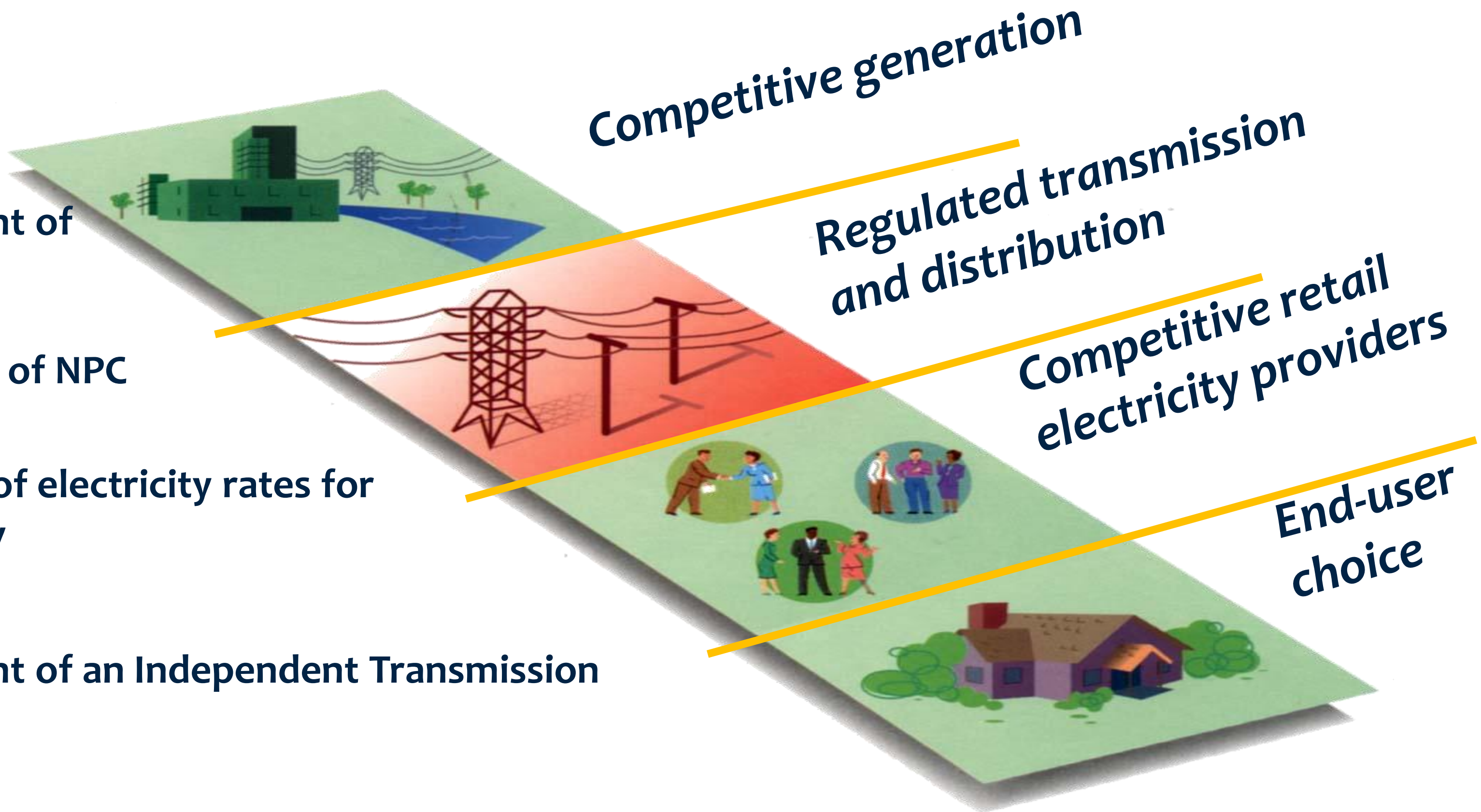
- Started with Chile followed by the British Power Pool in 1990
- Often motivated by the need for the government to privatize generation
- Economic objectives: higher competition, more price transparency → efficient investment
- Trend of deregulation and electricity market at least to separate generation and create a competitive market is commonplace
- Several developing countries have also initiated markets
- Other countries have plan to introduce markets in the near future

# Electricity markets

- Different schools of thoughts on how it should be designed, structured and operated
- Contract carriage model with a balancing market vs mandatory pool
- Nodal/zonal/single price spot markets
- Capacity and energy vs energy-only market
- With and without day ahead market
- With and without ancillary services co-optimized
- Market and system operation separate or integrated
- No universally agreed “rights” or “wrongs” about the design choices

Image source: www.originenergy.com.au

# Philippines electricity market: industry structure



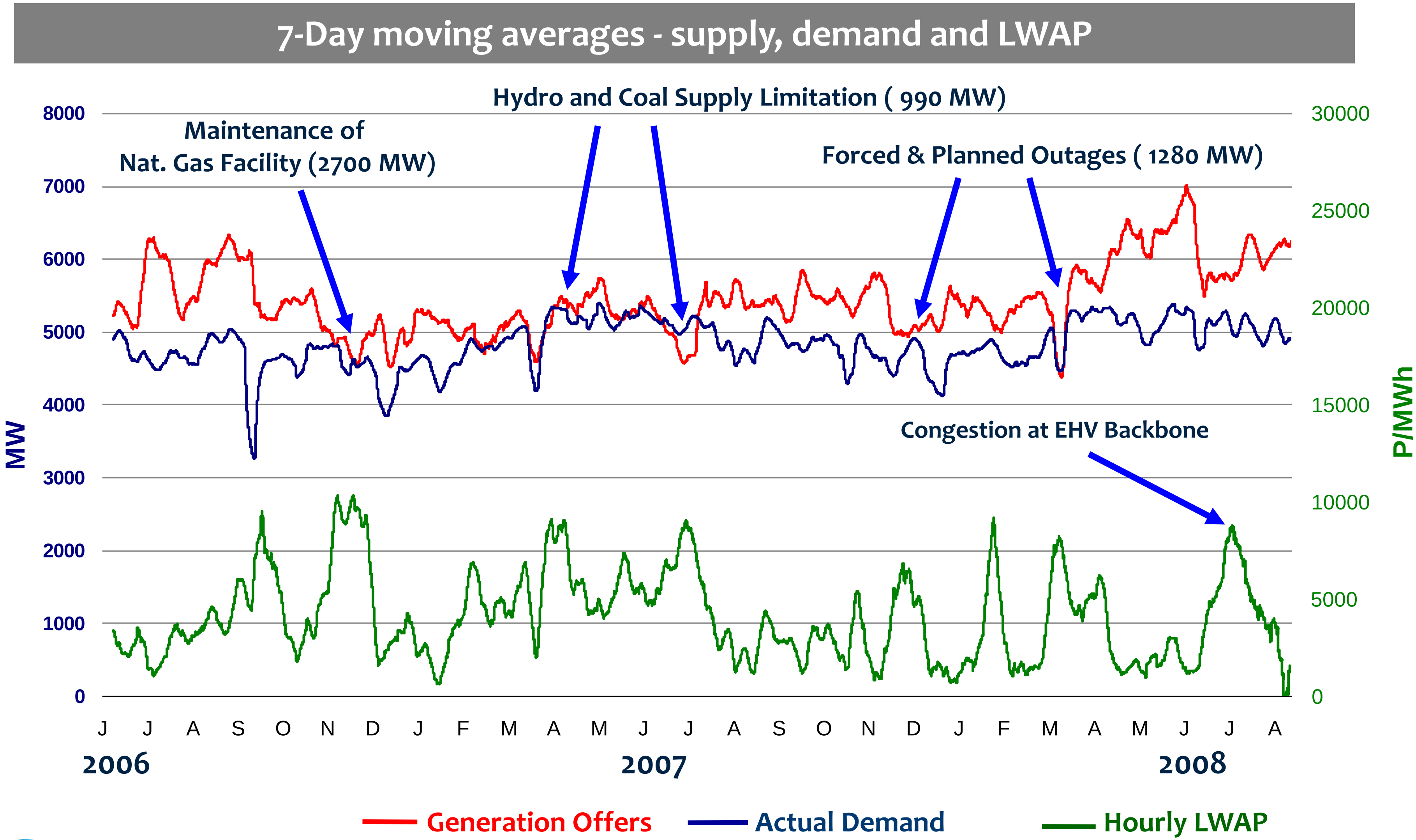

- Establishment of WESM
- Privatization of NPC
- Unbundling of electricity rates for transparency
- Establishment of an Independent Transmission Company
- Open Access of distribution network and retail competition

Source: L.A. Holopainen and M R. Pangilinan –Presentation at APEX Conference

# Philippines market design

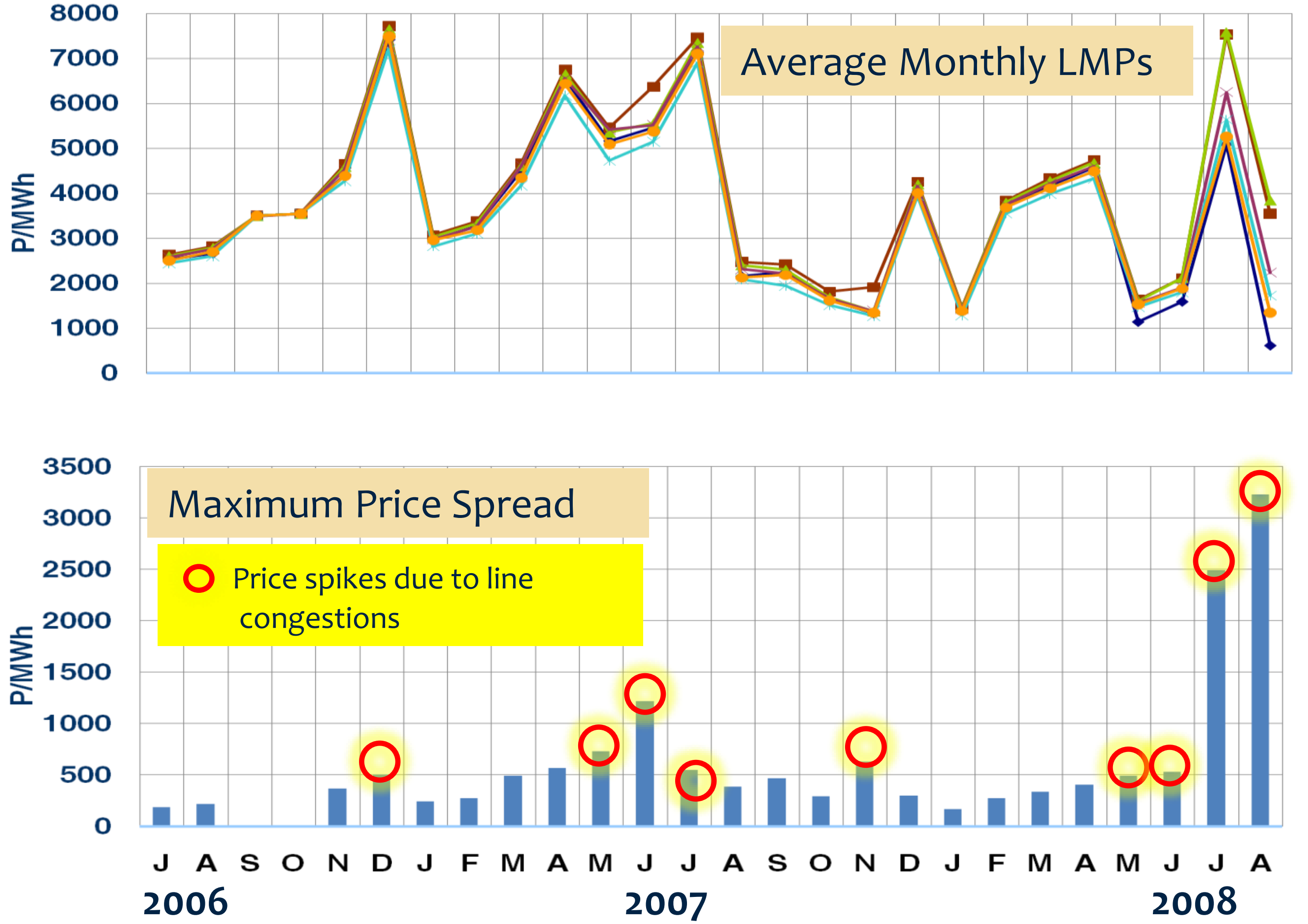
- Gross Pool: All energy transactions are scheduled through the market
- Net Settlement: Bilateral Contract quantities transacted in the pool can be settled outside of the market
- Locational/Nodal Marginal Spot Pricing: Marginal price computed at each node or location to reflect transmission loss and / or congestion
- Reserve Co-Optimization: Reserve and energy offers are scheduled at the same time
- Demand Bids: Customers' choice to buy energy lower than a specified price

# Philippines market outcomes: first three years



# Philippines market outcomes: first three years

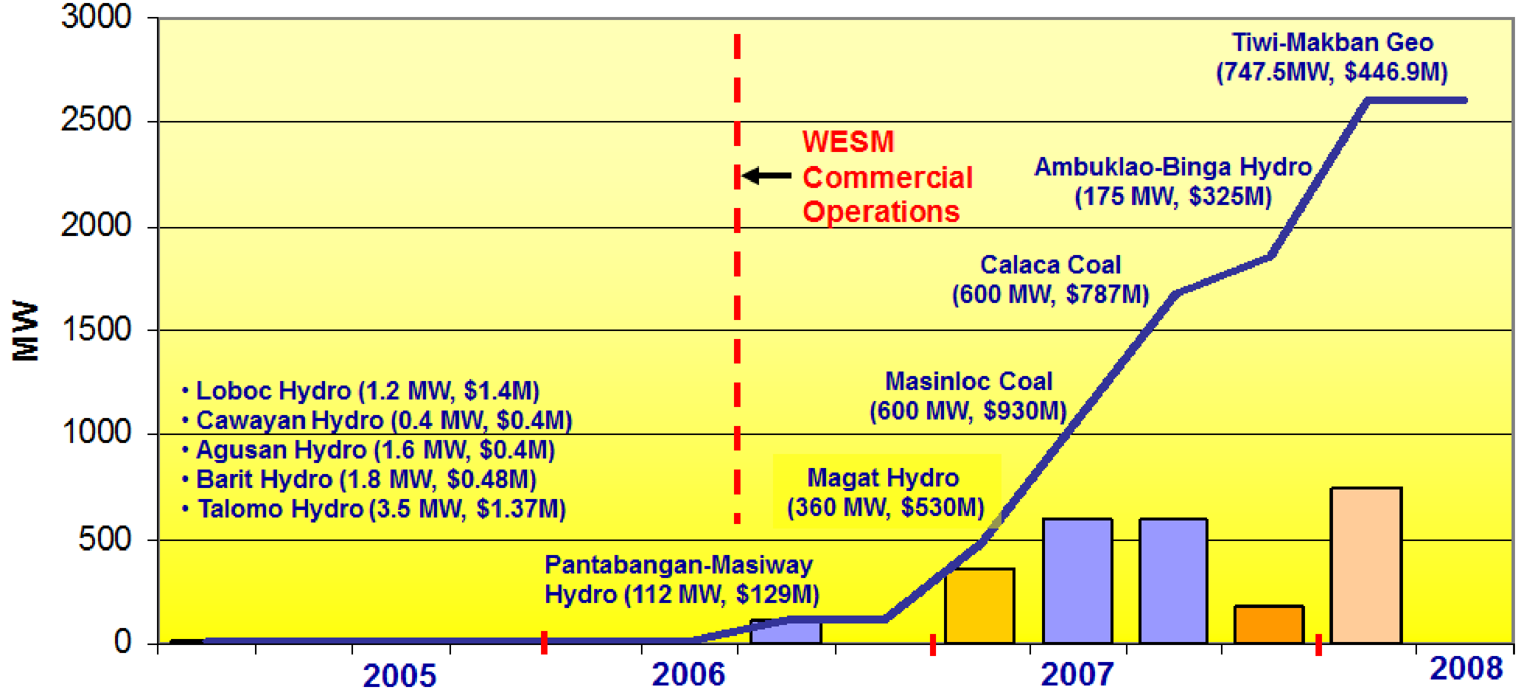
## Representative nodes: ave nodal price and max price spread


Source: WESM

# Philippines market outcomes: first three years

Significant uptake in new generation investment




Source: WESM