EE 459/611: Smart Grid Economics, Policy, and Engineering

Lecture 2: Common and Renewable

Generation Basics and Costs,

Market Economy

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Fall 2020

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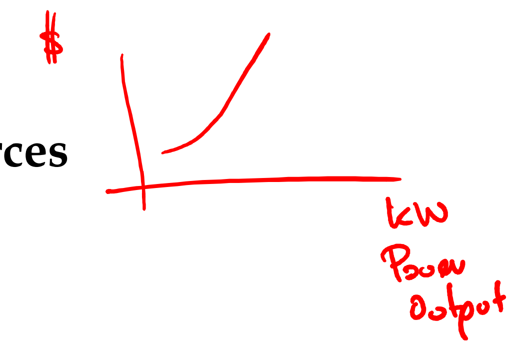
Goals

- **Characteristics of Power Generation (Input/output)**
  - Hydro
  - Coal
  - Solar
  - Wind



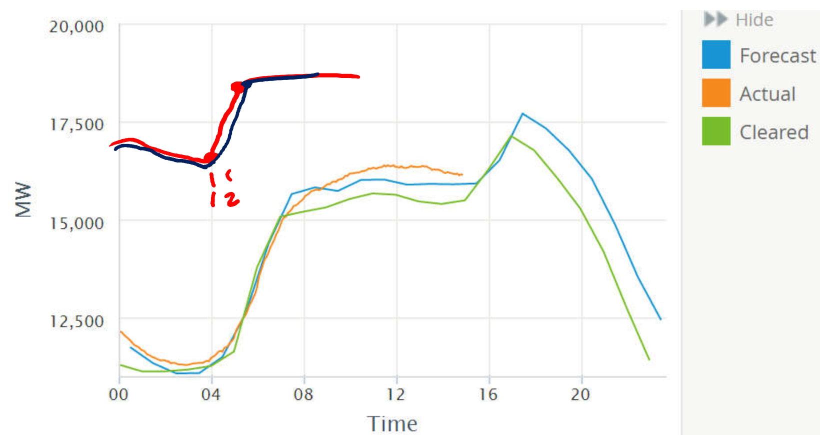
- **Understand the cost associated with each of these sources**

- **Electricity Markets**

Hydroelectric Power Plants

- Hydro electric power is the largest renewable energy source
- Produces around 16 % of the world's electricity
- 25 countries rely on hydro for 90% of their electricity (99.3% in Norway)
- **Advantages**
  - Good load following capability (minute level)
  - Dams can be used to store energy for days to years, how?
  - Startup can be quickly (thermal plants/coal can take hours to start)

Niagara Power Plant*



Hydroelectric Power Plants

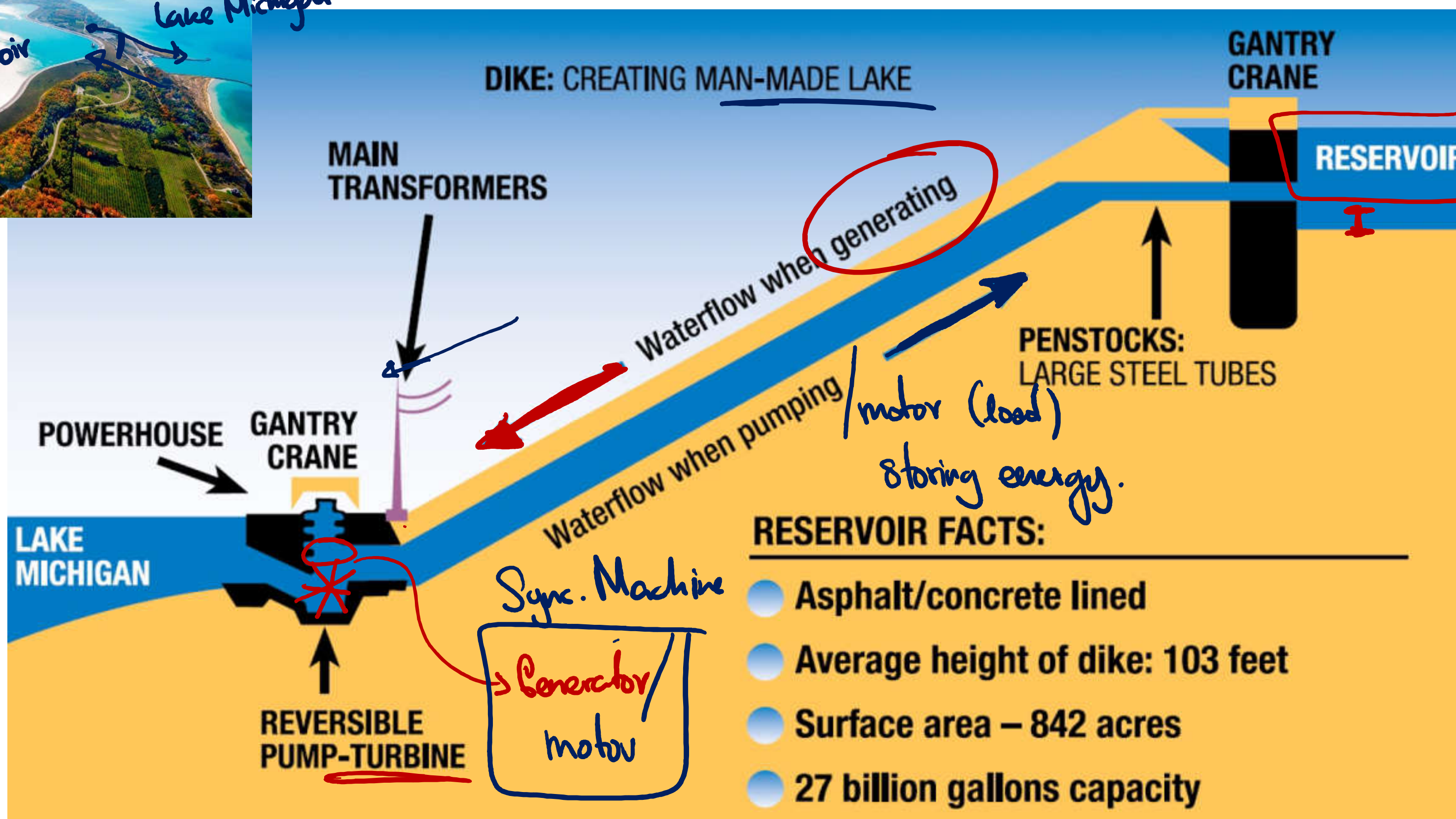
- **Disadvantages**
  - Emissions from the construction of hydropower, water sitting in reservoirs and the decomposition of materials
  - Spatial and visual footprint

- Important to take into account <u>environmental</u> and <u>social impacts</u>

Niagara Power Plant*

Hydroelectric Power Plant Operation

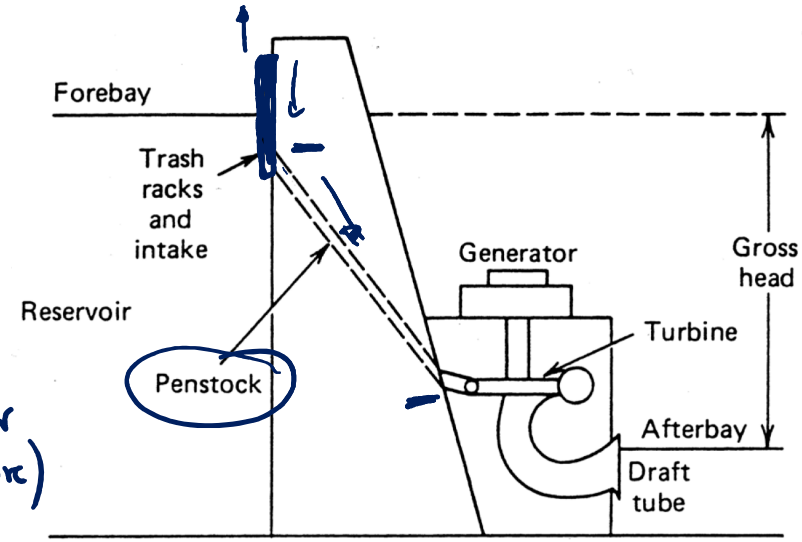
- Water flow when pumping, generator turns into a motor to consume power (typically at night)

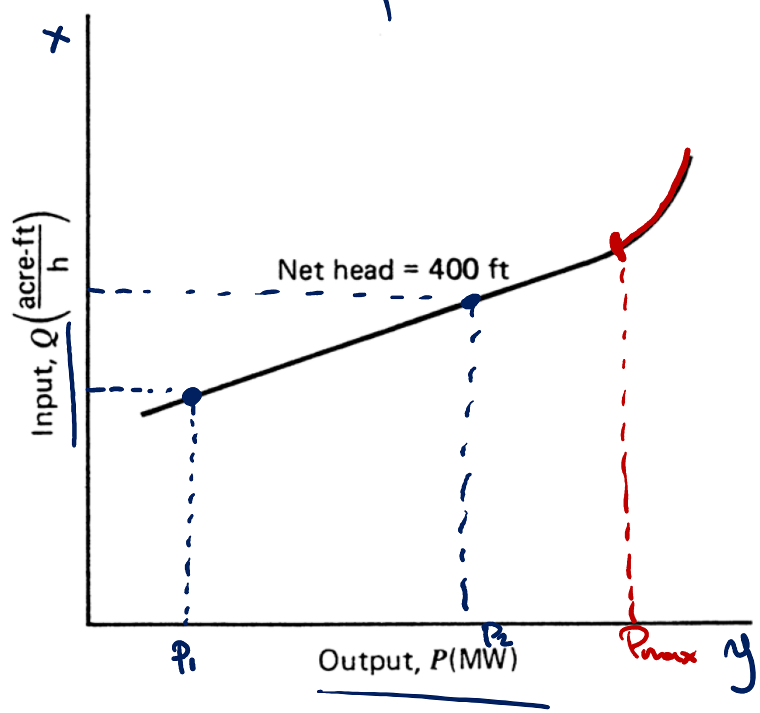


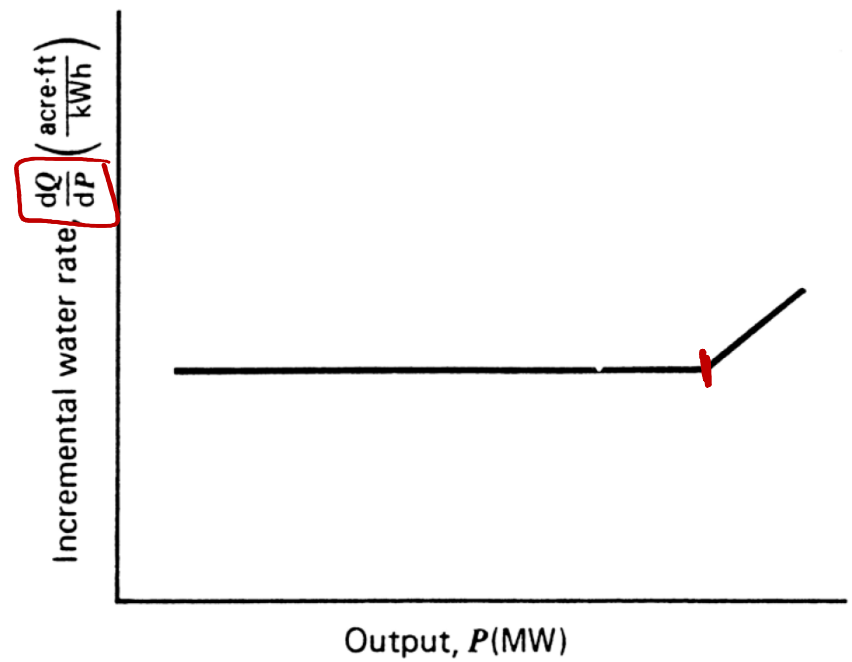
Luddington Pumped Storage Plant

Hydroelectric Power Plant Input/Output Characteristics

- **Input:** volume of water per unit time
- **Output:** electrical power

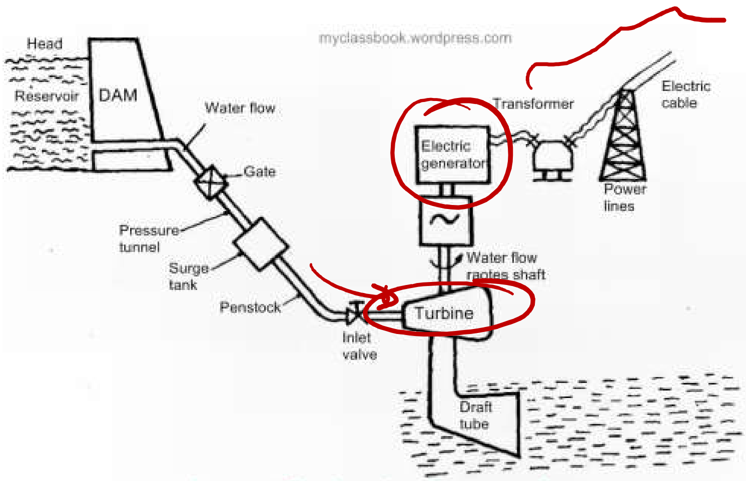




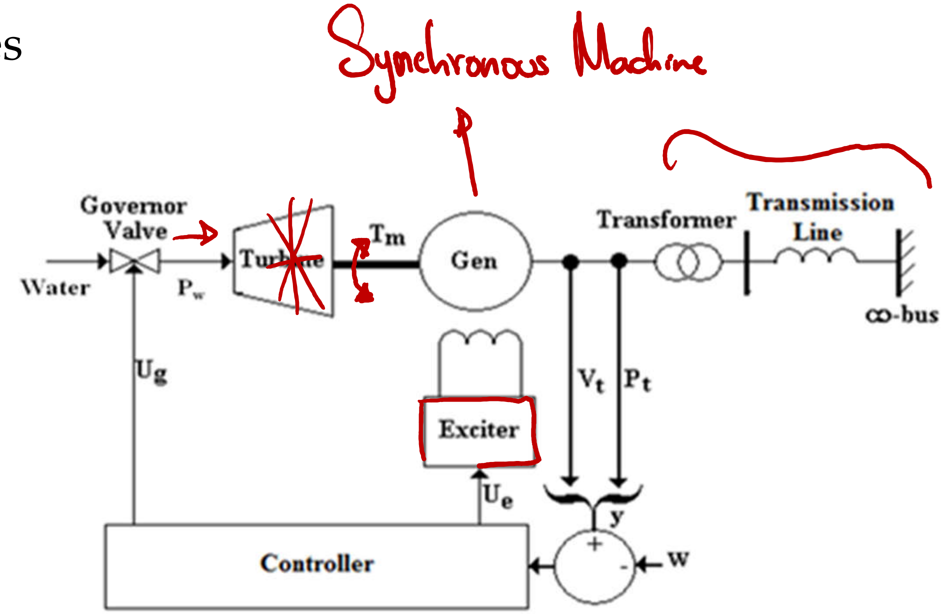


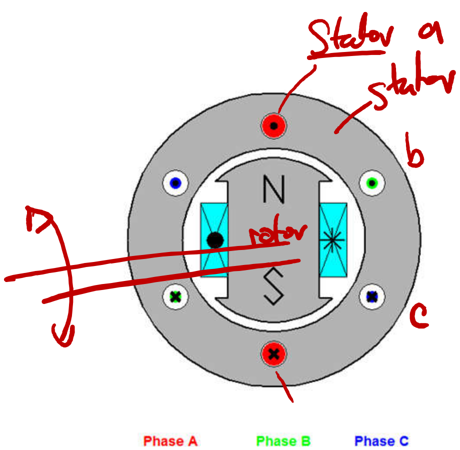
Hydroelectric Power Plant Operation

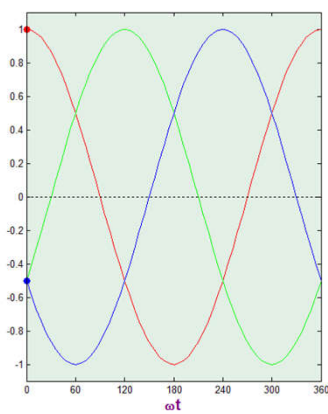
- Recall three phase electric machines



Layout of hydro electric power plant







- **Example Matlab model:** power_turbine

Hydroelectric Power Plant Costs

- What are the costs related to the operation of hydro power?
  - Investment cost ✓
  - Maintenance costs ✓
  - * ~~Fuel costs~~ (coal, natural gas)

- **Levelized Cost of Electricity (LCOE):** net preset value of unit cost of electricity over lifetime of asset

$$\text{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (\$/\text{MWh})$$

t: unit time (years)
n: max life (100 years)
I: investment cost
M: maintenance cost
r: revenue
F: fuel cost
E: energy (MWh)

(more) ≥ more return

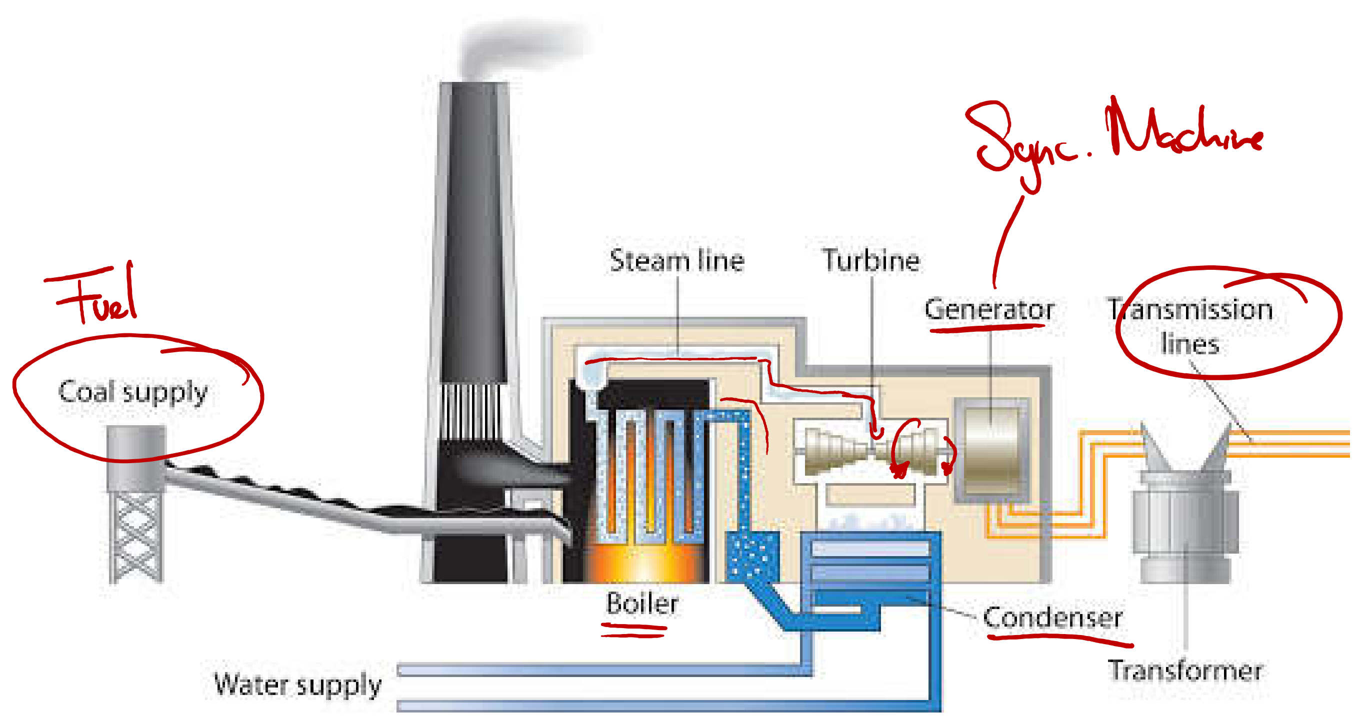
(less) ≤ lower return
loss

For hydro LCOE ≈ 36 $/MWh

- For hydro power plant the LCOE is relatively low

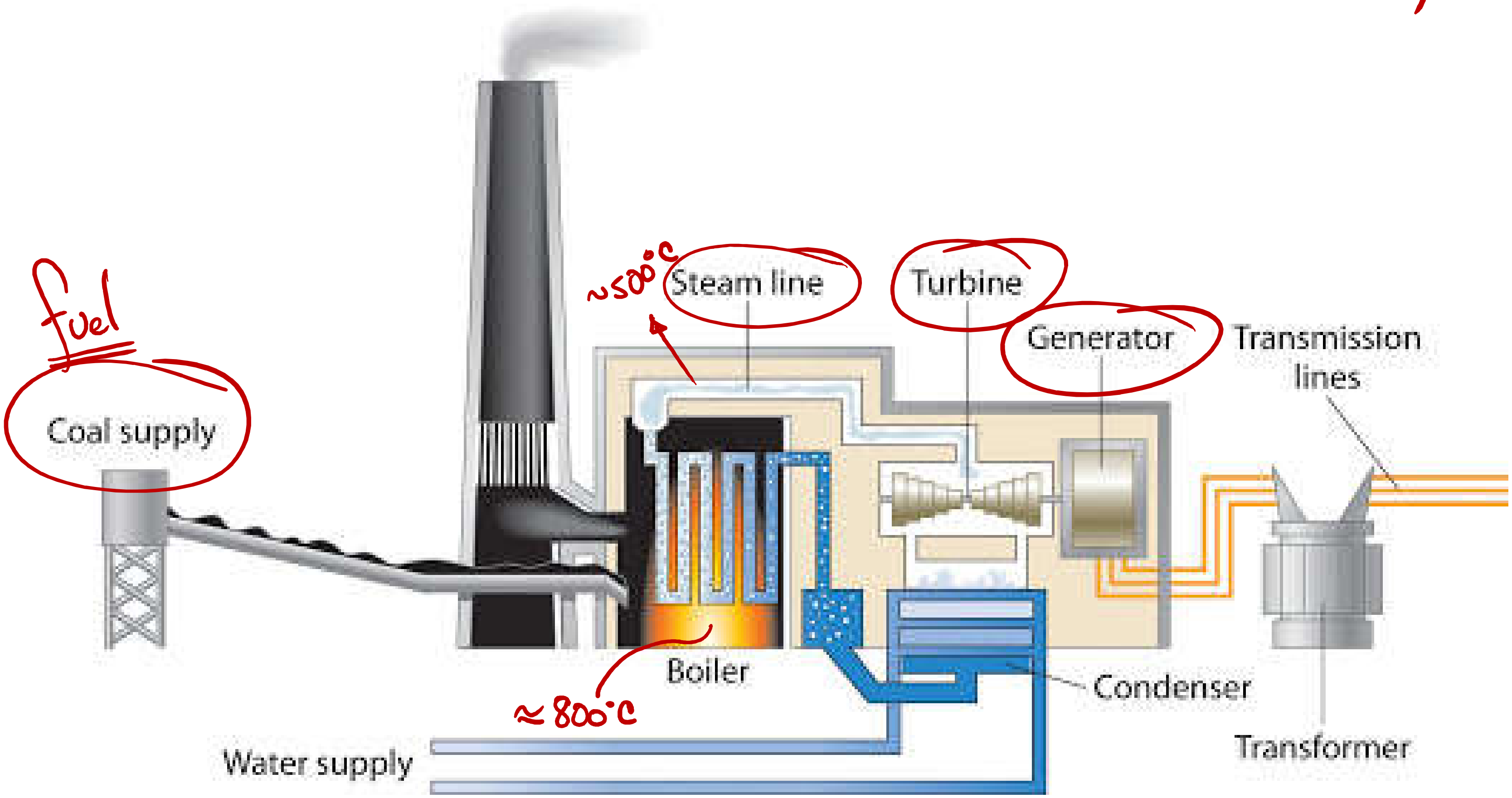
Coal Power Plant (Thermal Plant)

- Coal power plants operate by burning coal to generate steam
- The **steam** is then used to rotate the turbines
- **Condenser** is needed to turn the steam back into water
- Similar to hydro, the turbine rotates a generator to produce electricity



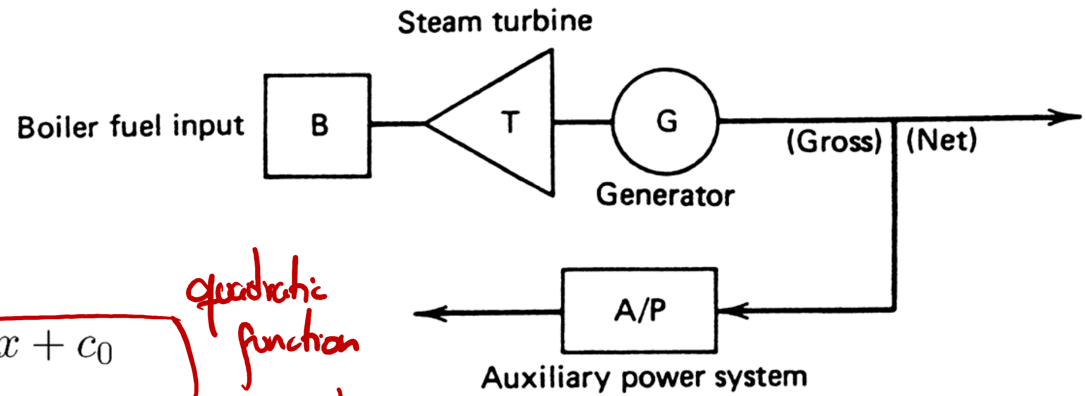
Coal Power Plant – Thermal Stress

- Turning it off/on causes large thermal stress on the boiler, steam lines, and auxiliary components **(damaging)**
- Hence, cost of turning off/on is higher (is used in Planning (day ahead) Unit Commitment)

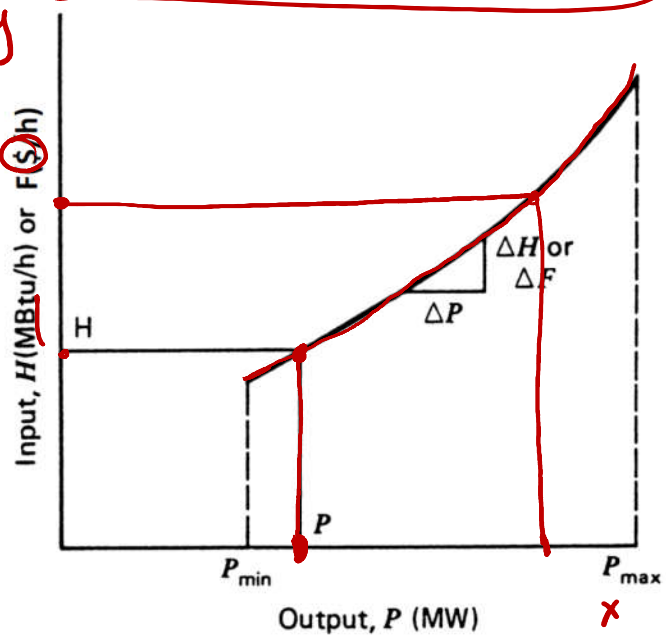


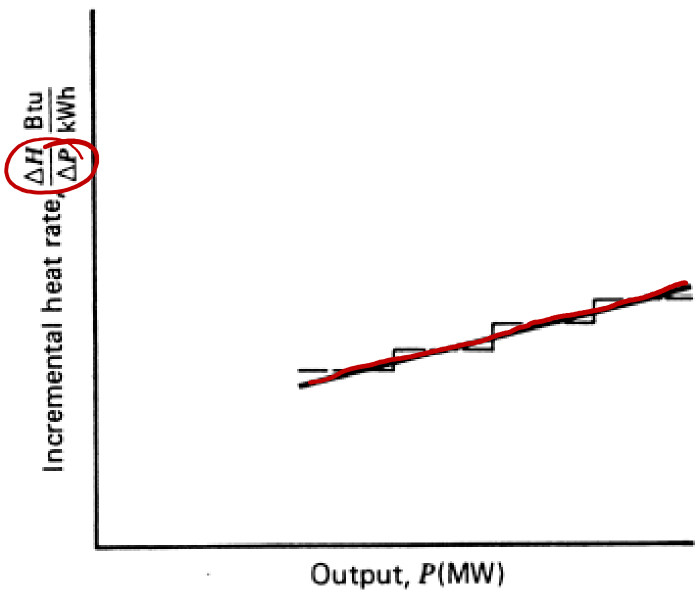
Coal Power Plant Input / Output Characteristics

- **Input** characteristics are typically given as BTU/h (heat/hour) or ($/hour)
- **Output** is typically given as the **net electrical** power output



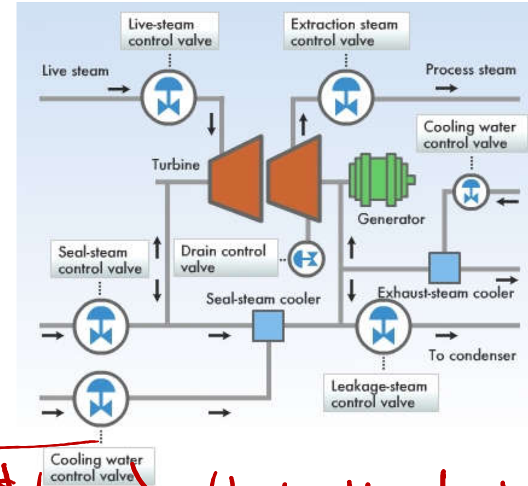
$$f(x) = c_2 x^2 + c_1 x + c_0$$





Coal Power Plant I/O Multiple Steam Valves

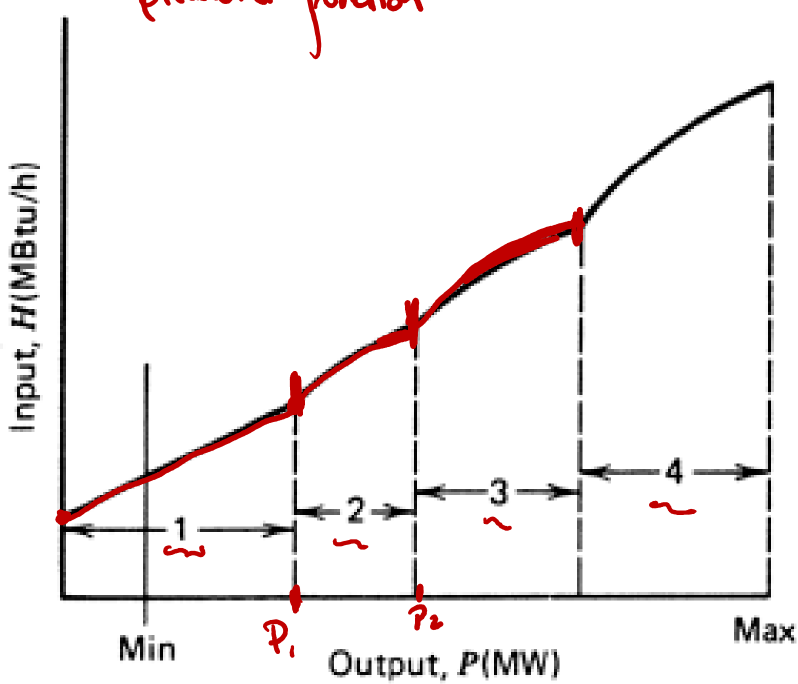
- A steam turbine can have multiple steam valves
- The input/output characteristics are a combination as more valves open

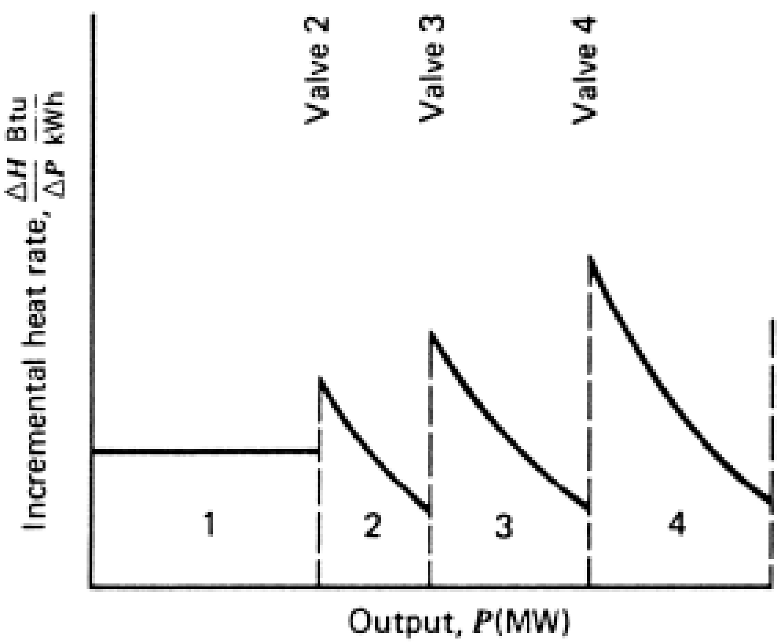


$$\text{Cost}(P) = \begin{cases} (\#1) & P_0 \le P \le P_1 \\ (\#2) & P_1 \le P \le P_2 \\ \vdots & \end{cases}$$

piecewise function

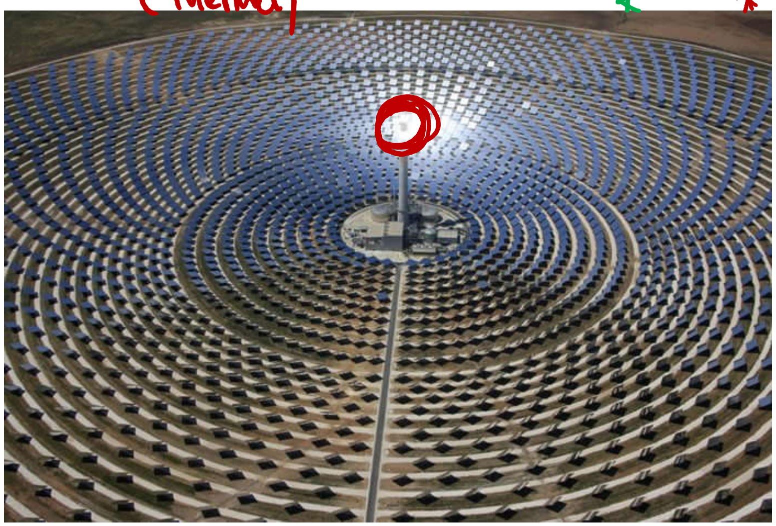
$LCOE_{coal} \approx 80\ \$/MWh$ (higher than hydro)





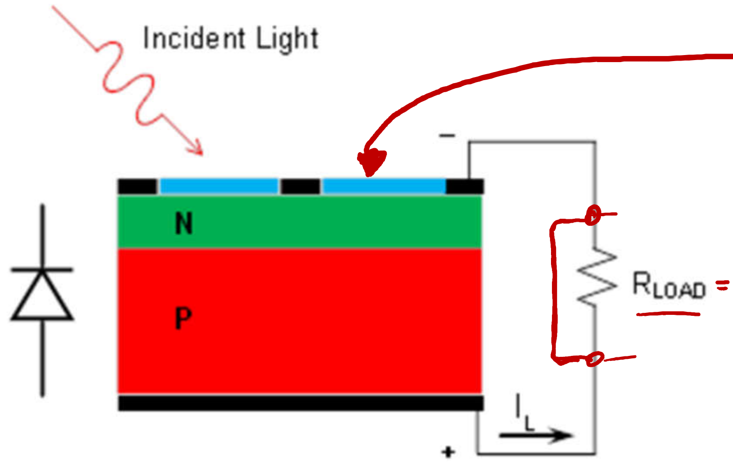
Solar Energy

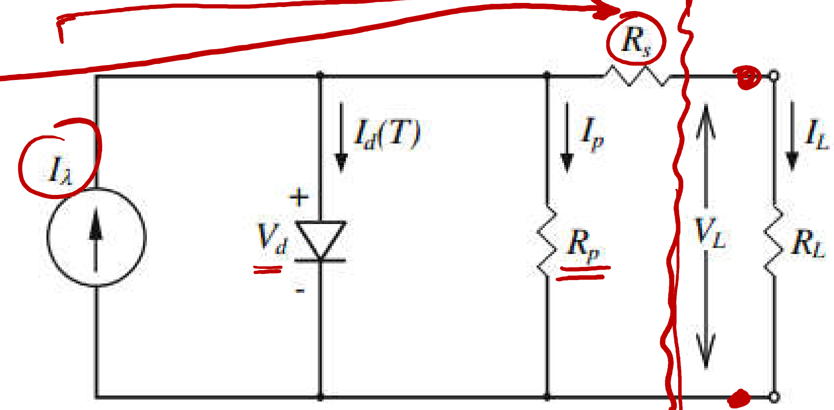
- Solar energy: thermal and electrical
- Quick to install
- Modular
- Quiet and static
- No pollution
- Portable
- Match with daytime loads



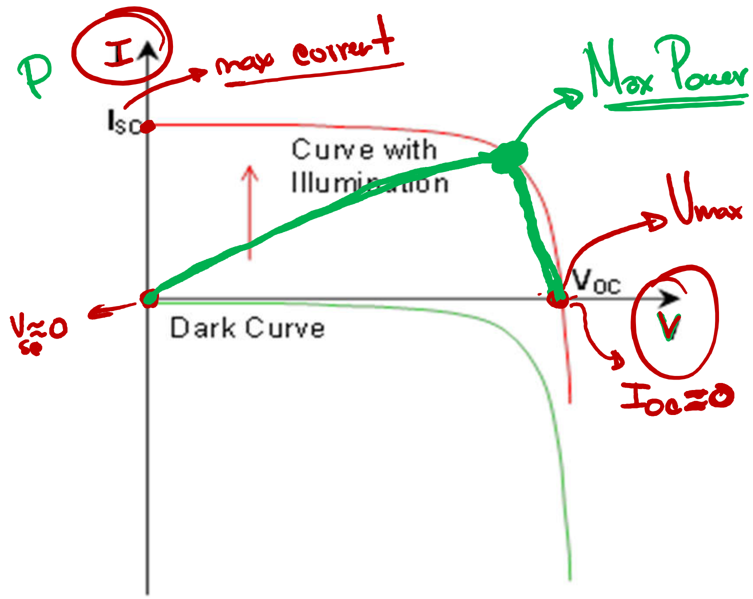
- Solar energy in US: 3.0-7.0 kWh/(m^2-day)
- Solar energy in Arizona: 5.0-5.5 kWh/(m^2-day)
- Solar irradiance is measured in W/m^2
- Integrate irradiance over a period of time→ solar irradiation (energy), in the unit of Wh/m^2
- Efficiency of solar radiation to heat, vapor, then electricity: 50-74%
- Efficiency of solar light directly into electrical energy (Photovoltaic): 3~30%

Photovoltaic Cell and I-V Curve





$$I_L = I_\lambda - I_s(e^{qV_d/\eta kT} - 1) - V_d/R_p$$



I_d: Ideal diode equation (internal diode current with a bias voltage)

$$I_d = I_s(e^{qV_d/\eta kT} - 1)$$

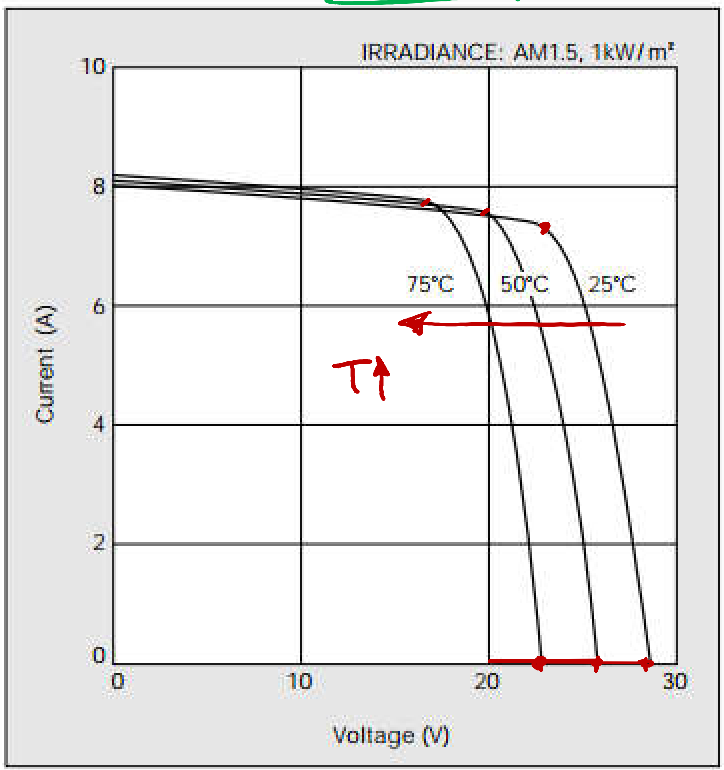
I_λ: photo current

I_p: shunt current

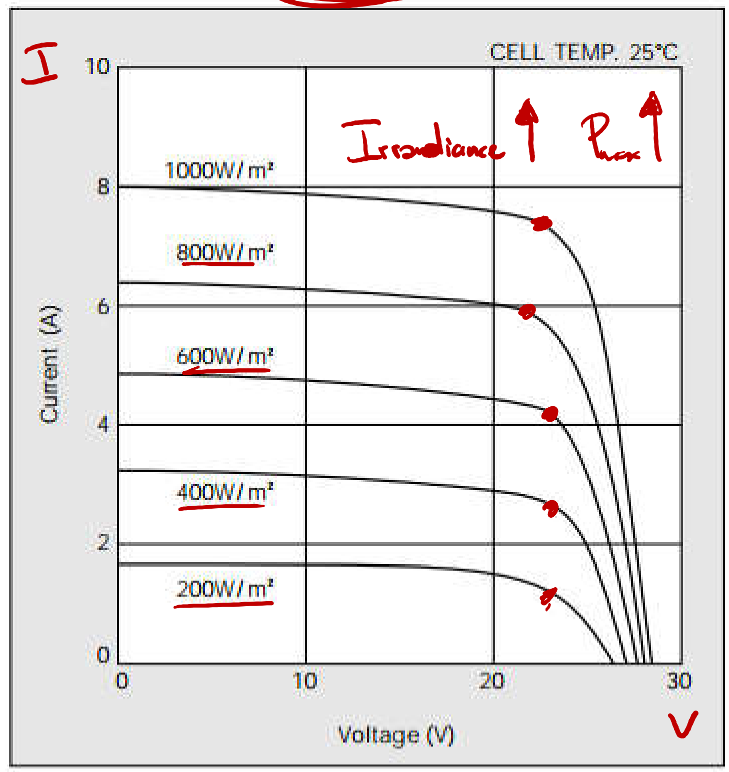
Source: *https://wiki.analog.com/university/courses/eps/photovoltaic*

Dependence on Temperature and Irradiance

Current-Voltage characteristics of Photovoltaic Module KC170GT at various cell temperatures



Current-Voltage characteristics of Photovoltaic Module KC170GT at various irradiance levels



Photovoltaic Power Plant Costs

- The majority of the costs are due to:
  - **Capital costs:** one time expenses including purchase and installation
  - **Operation and maintenance**

~~Fuel~~

$LCOE_{PV} \approx 80 \$/MWh$

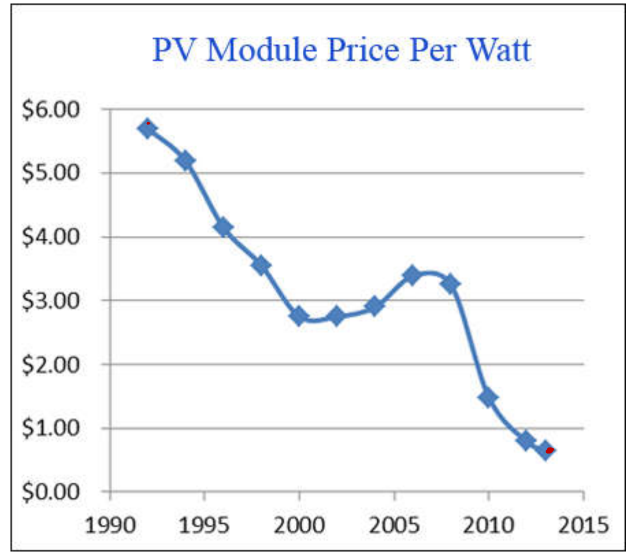
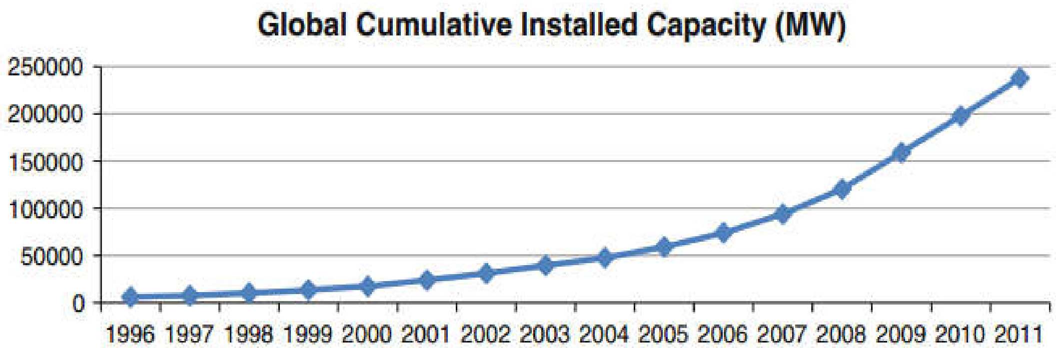


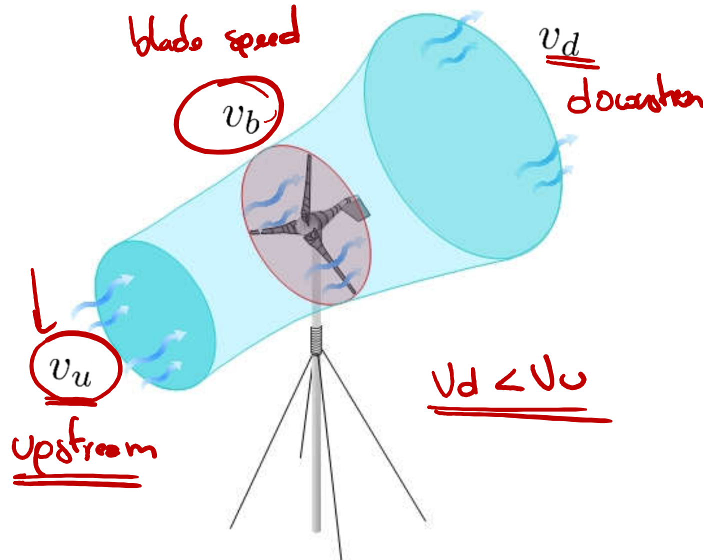
Table 1 – Costs for Electric Generating Technologies

Technology Type	Mean installed cost ($/kW)	Installed cost Std. Dev. (+/- $/kW)	Fixed O&M ($/kW-yr)	Fixed O&M Std. Dev. (+/- $/kW-yr)	Variable O&M ($/kWh)	Variable O&M (+/- $/kWh)	Lifetime (yr)	Lifetime Std. Dev. (yr)	Fuel and/or water cost ($/kWh)	Fuel and/or water Std. Dev. ($/kWh)
PV <10 kW	$3,897	$889	$21	$20	n/a	n/a	33	11	n/a	n/a
PV 10–100 kW	$3,463	$947	$19	$18	n/a	n/a	33	11	n/a	n/a
PV 100–1,000 kW	$2,493	$774	$19	$15	n/a	n/a	33	11	n/a	n/a
PV 1–10 MW	$2,025	$694	$16	$9	n/a	n/a	33	9	n/a	n/a

http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

Wind Power





Kinetic energy in the wind: $E = \frac{1}{2} m v^2$

$E_u = \frac{1}{2} m V_u^2 \quad E_d = \frac{1}{2} m V_d^2 \Rightarrow E_b = E_u - E_d = \frac{1}{2} m (V_u^2 - V_d^2) = \frac{1}{2} m V_b^2$

The power in the wind is the first derivative of kinetic energy: $E = \int P\,dt$

$$P_b = \frac{d(E_u - E_d)}{dt} = \frac{1}{2}\frac{dm}{dt}(v_u^2 - v_d^2) \qquad \frac{dm}{dt} = \rho A \frac{v_u - v_d}{2}$$

(mass is not constant; mass flow rate; density of air; cross sectional area of blades)

Define the following: $\lambda = \frac{v_d}{v_u}$, then: $\lambda < 1$

$$P_b = \frac{1}{2}\rho A \left(\frac{v_u + \lambda v_u}{2}\right)(v_u^2 - \lambda^2 v_u^2) = \frac{1}{2}\rho A v_u^3 \left[\frac{1}{2}(1+\lambda)(1-\lambda)\right]$$

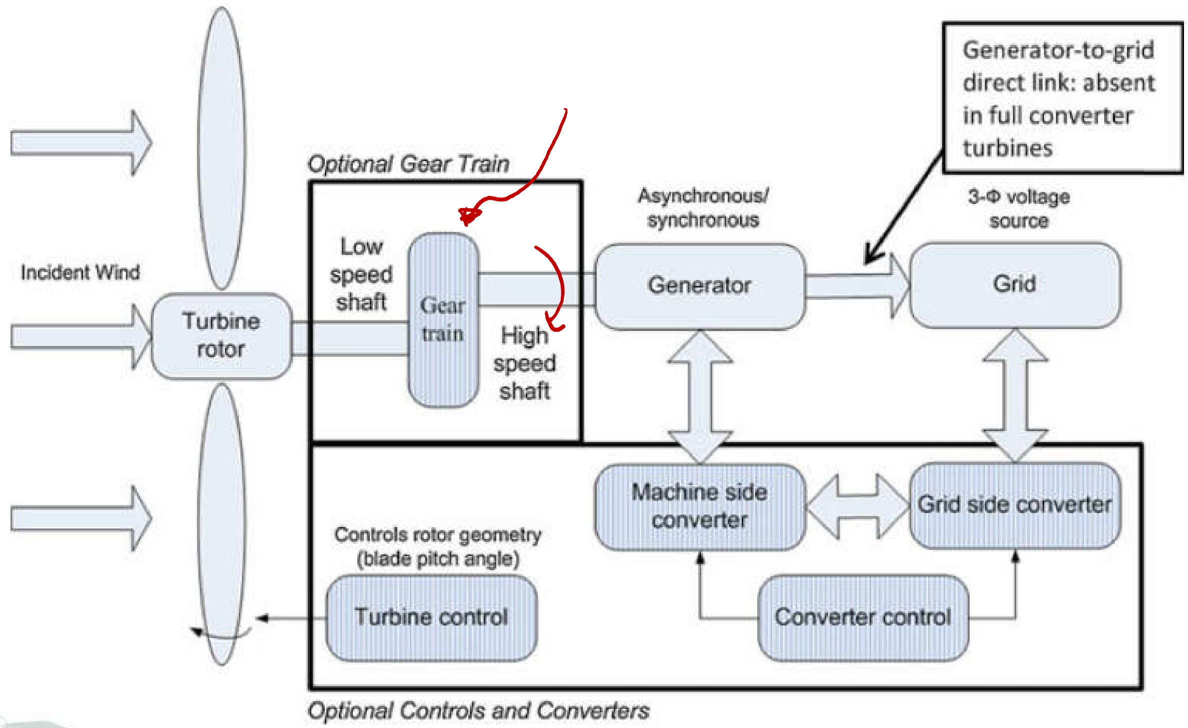
C_p = rotor efficiency ≤ 0.593

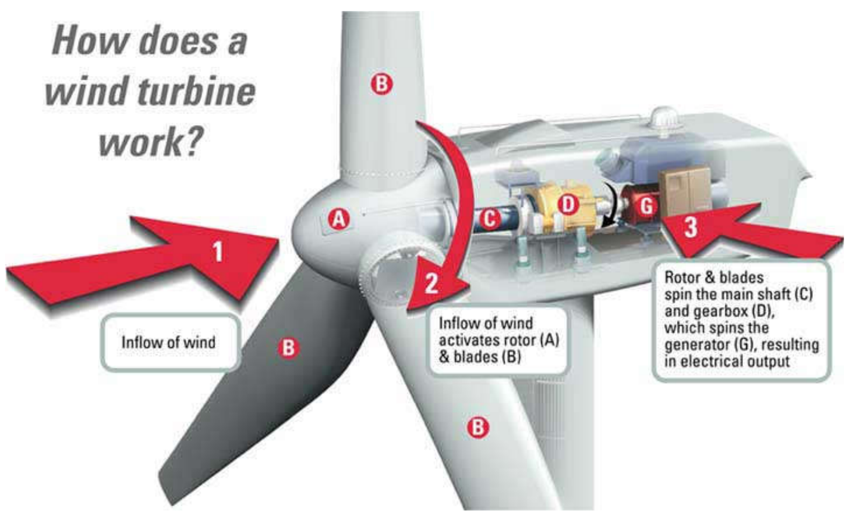
An ideal wind turbine cannot extract more than 0.593 of P_{air}. A real rotor extracts even smaller amount of power

Wind Power Generation

Different types of wind turbines according to generation technology:

- Fixed speed wind turbines
- Variable speed wind turbines
- Doubly fed induction generator turbines
- Full converter wind turbines



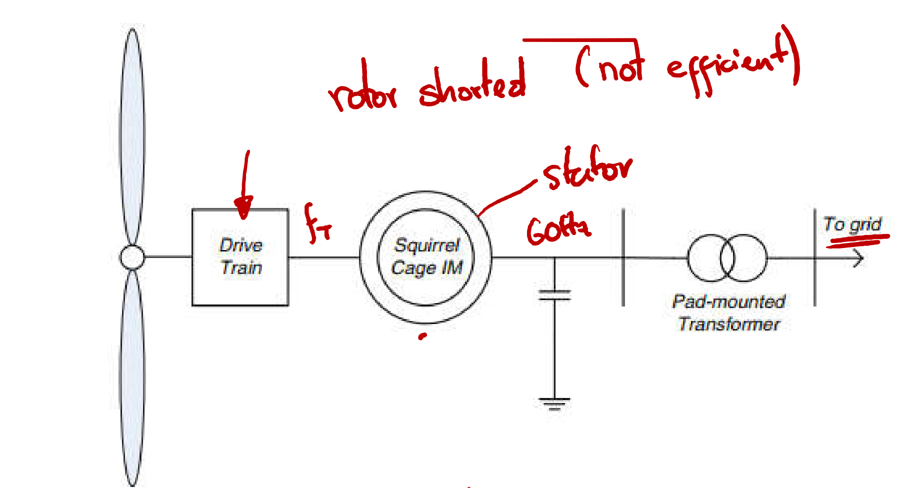


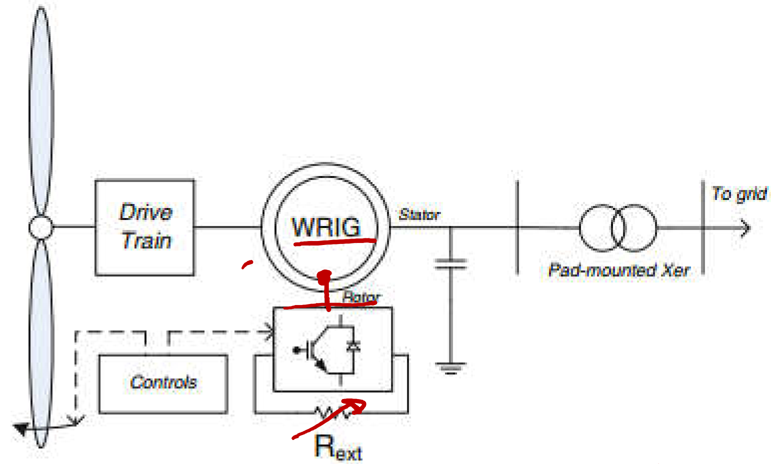
http://www.ecoplanetenergy.com/all-about-eco-energy/overview/wind/

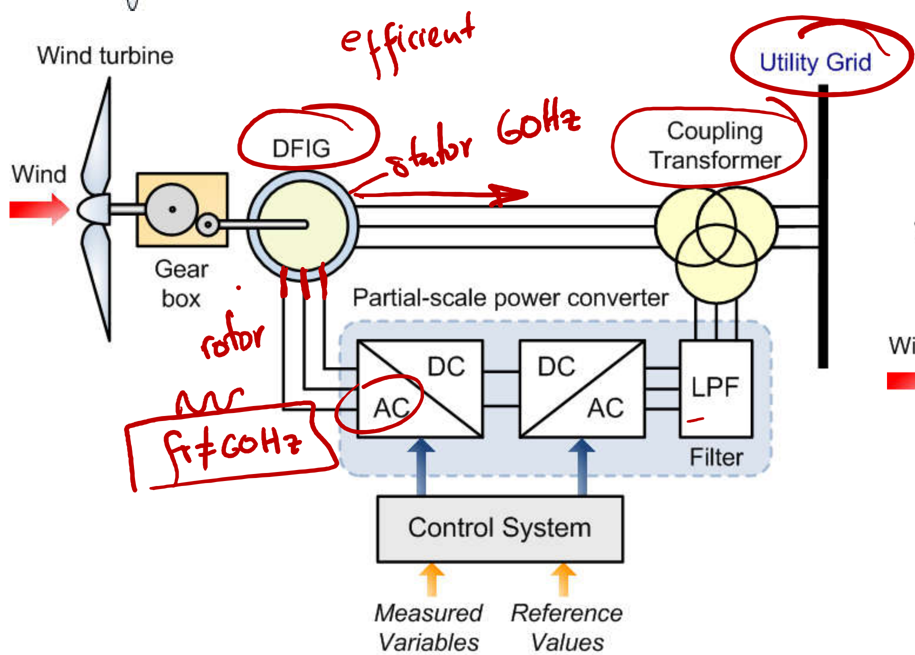
- The generator is always ac generator
- The frequency of generator output power depends on the speed of wind turbine
- The frequency does not (in most cases) match grid frequency
- To connect to grid, ac/dc+dc/ac
- For dc transmission: ac/dc

Source: *Power Electronics for Renewable and Distributed Energy Systems, by Chakraborty, Sudipta; Simões, Marcelo G.; Kramer, William E.*

Wind Power Grid Connection







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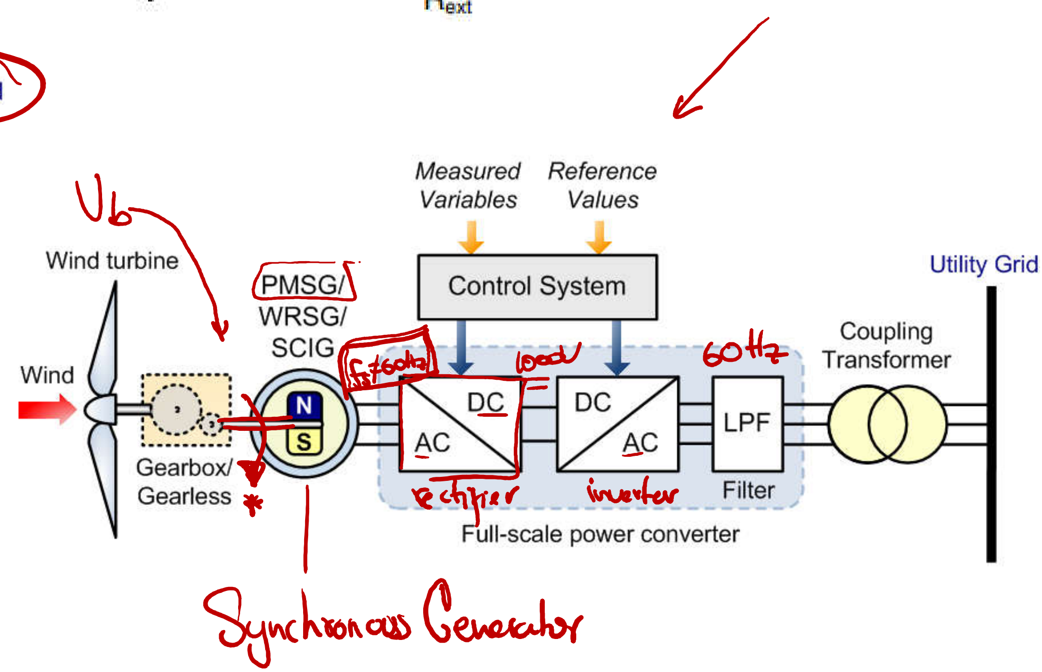

Source 2:http://www.intechopen.com/books/wind-farm-technical-regulations-potential-estimation-and-siting-assessment/technical-and-regulatory-exigencies-for-grid-connection-of-wind-generation

Wind Power Costs

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Wind <10 kW	$7,645	$2,431	$40	$34	n/a	n/a	14	9	n/a	n/a
Wind 10–100 kW	$6,118	$2,101	$35	$12	n/a	n/a	19	5	n/a	n/a
Wind 100–1000 kW	$3,751	$1,376	$31	$10	n/a	n/a	16	0	n/a	n/a
Wind 1–10 MW	$2,346	$770	$33	$16	n/a	n/a	20	7	n/a	n/a

http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

Stochastic Opt. Problem

LCOE wind (ground) = 40 $/MWh

LCOE wind (offshore) = 122 $/MWh

Outline

- **Characteristics of Power Generation (Input/output)**
  - Hydro
  - Coal
  - Solar
  - Wind

- **Understand the cost associated with each of these sources**

- **Market Economy** (History)

Market Economy Overview

- Introduction to the fundamental concepts of economics in power systems:
  - Traditional regulated environments ≤ 1990s
  - De-regulated environments ≥ 1990s

Regulated Electric Companies

- The US was originally structured to have **"regulated"** electric companies (also known as **microregulated**)
- Managed by the state and the federal government at a micro-decision level

- Utility (with approval from state and government) controls all aspects of electricity supplied:
    - Generation
    - Transmission
    - Distribution
    - Retail/consumers

Regulated Environment

- The federal and state governments control the **profit margin** allowed by utility and its share holders

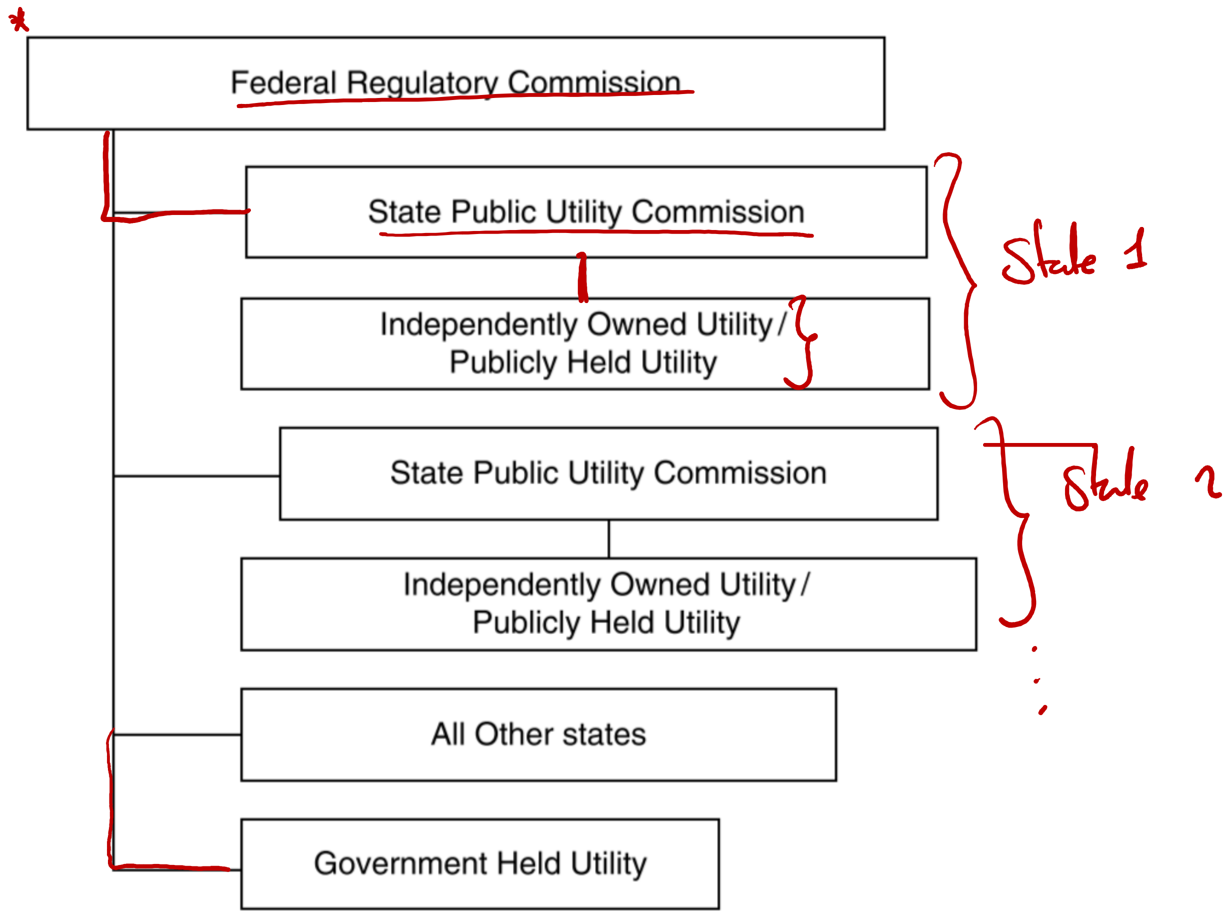


FIGURE 2.1 Regulated industry structure.

Regulated Environment

- Investor owned utilities (IOUs) are private for-profit companies granted **monopoly** franchise for a geographic region
  - Examples: American Electric Power, National Grid, Iberdrola, etc.
  - Tariffs is regulated (avoid overcharge)

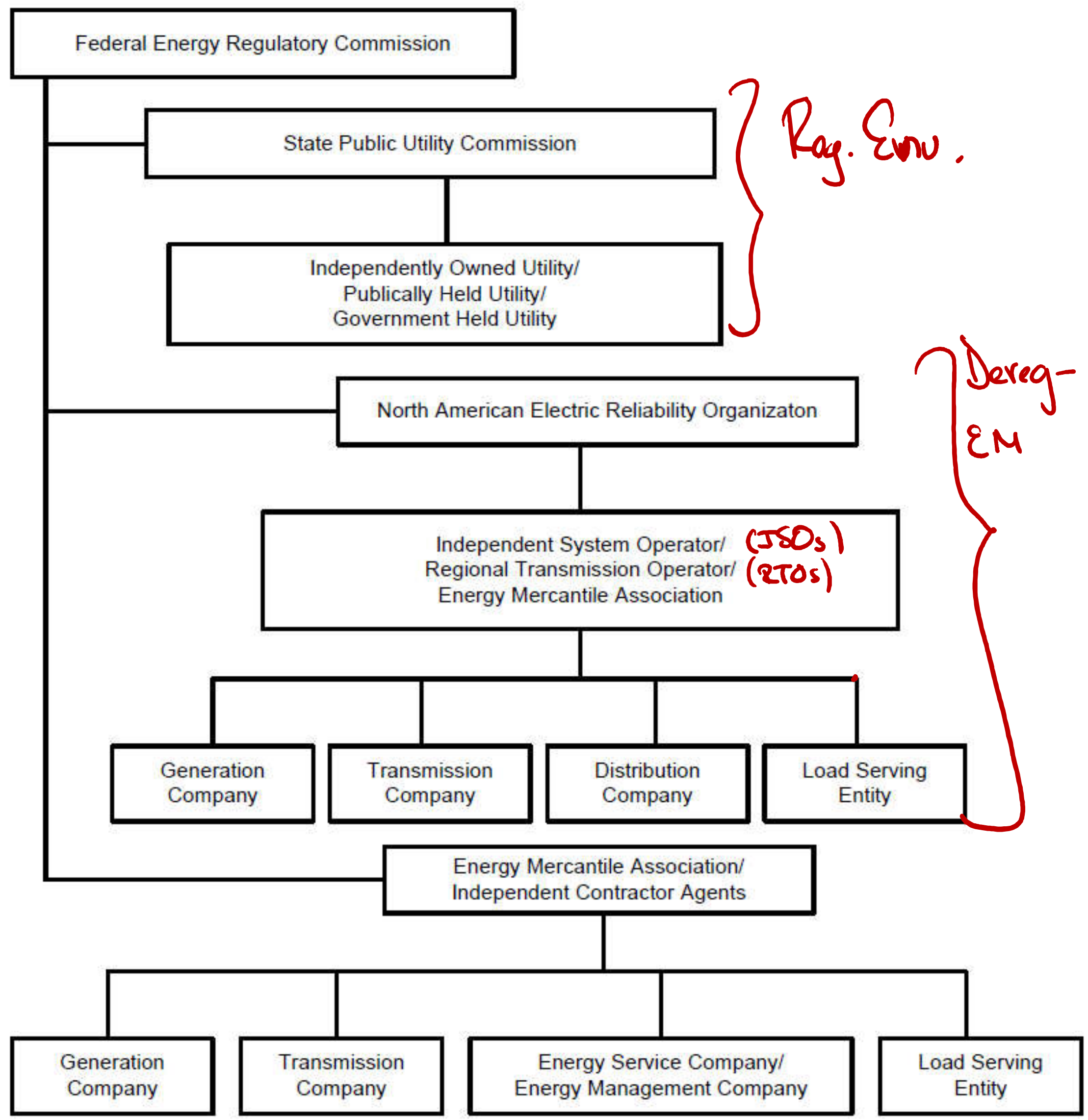
Concerns of Regulated Environments

- Customers have little influence on the price
- Limited incentive to utility to **minimize costs/rates**

- State legislators and utility regulators are now letting consumers choose among a variety of energy suppliers on the basis of competitive prices
- Leads to **deregulation/restructuring** (primarily in Generation and Retail)

Deregulated/Competitive Environments

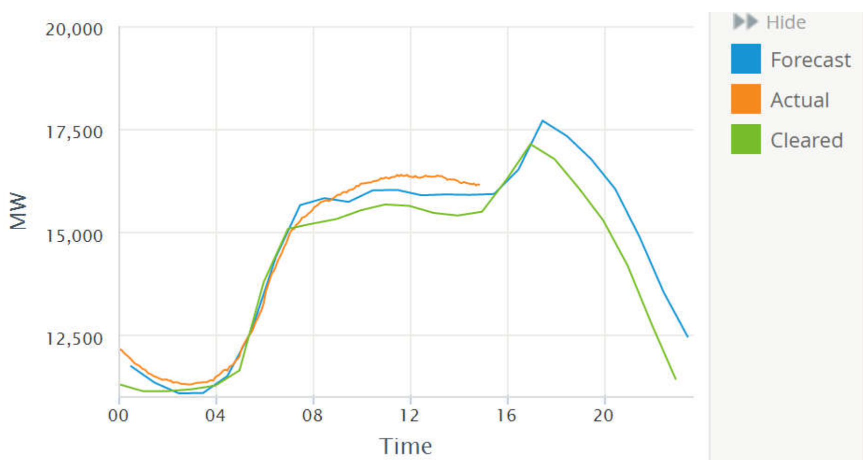
- Generation companies participate in the market to sell its power
- Loads/customers can also participate in market through Energy Service Company (ESCO) – customer is free to choose any ESCO
- This is done in the respective **Independent System Operators (ISOs)**

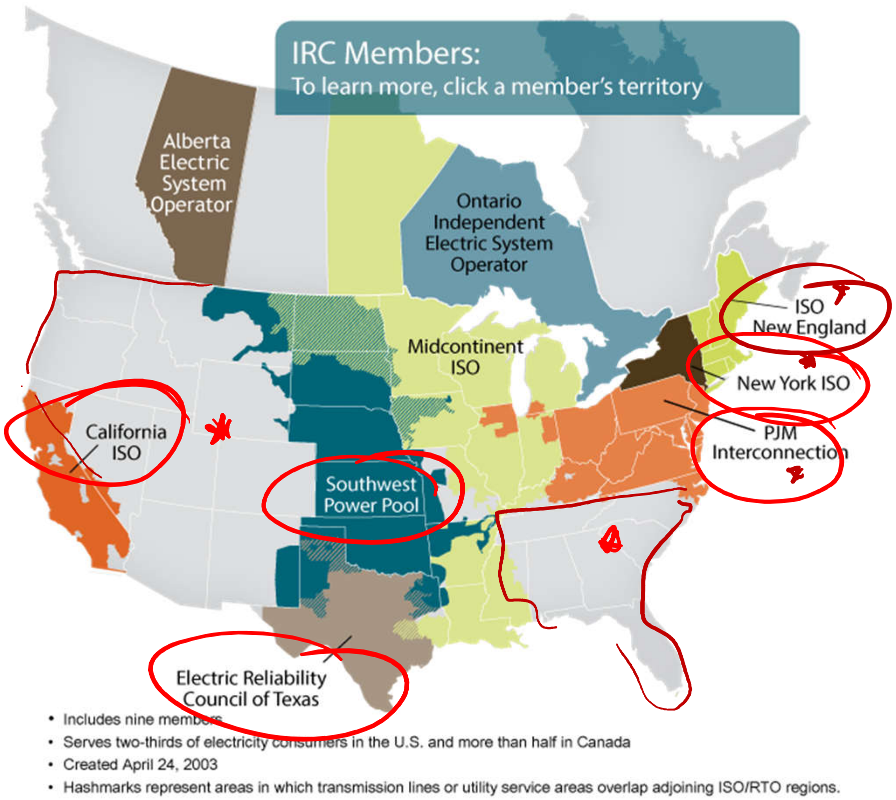


Independent System Operators

- **Day ahead scheduling process is** conducted based on bids from load entities and generator entities the **day before**
  - o An optimization process is used (LP or MIP) to "clear" the market

- Real time market scheduling is also conducted to offset imbalances





Next Topic

- **Mathematical Review**
  - Linear Algebra
  - Multivariable Calculus

Optimization Theory