Power Generation Economics & Management

"Power-Generation Systems"

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Outline

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  - **Sensibility analysis**
  - **Investment**
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  - **Structure**
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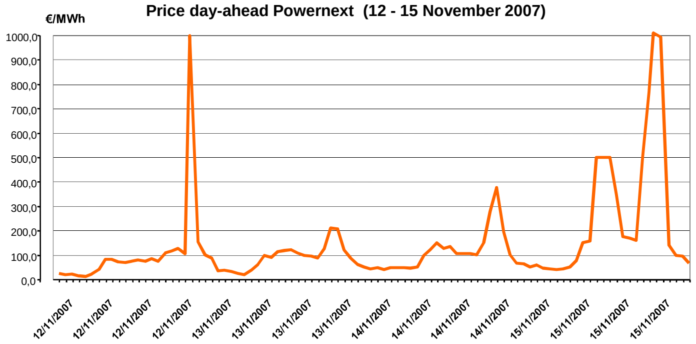
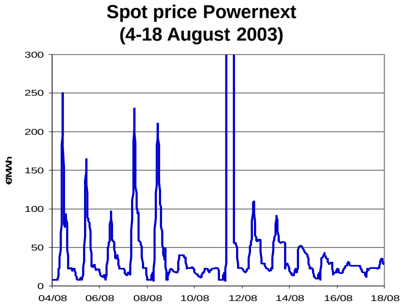
  - **Regulation**

Electricity specificities

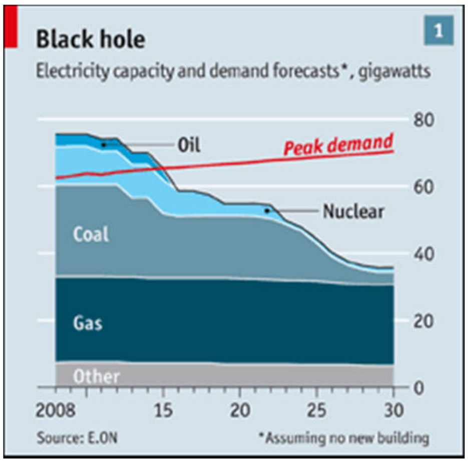


Huge volatility !



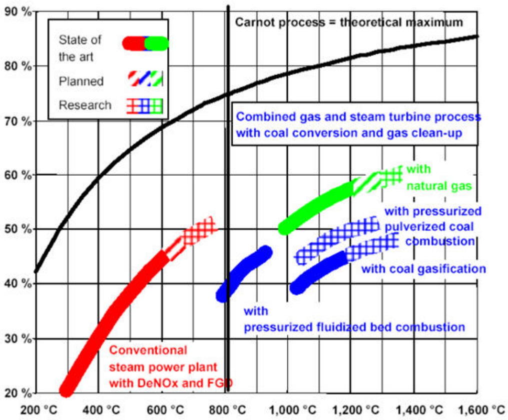
In UK, 20GW will disappear before 2015

The looming electricity crunch - **"Dark days ahead"**
Aug 6th 2009 from *The Economist* print edition



Electricity specificities

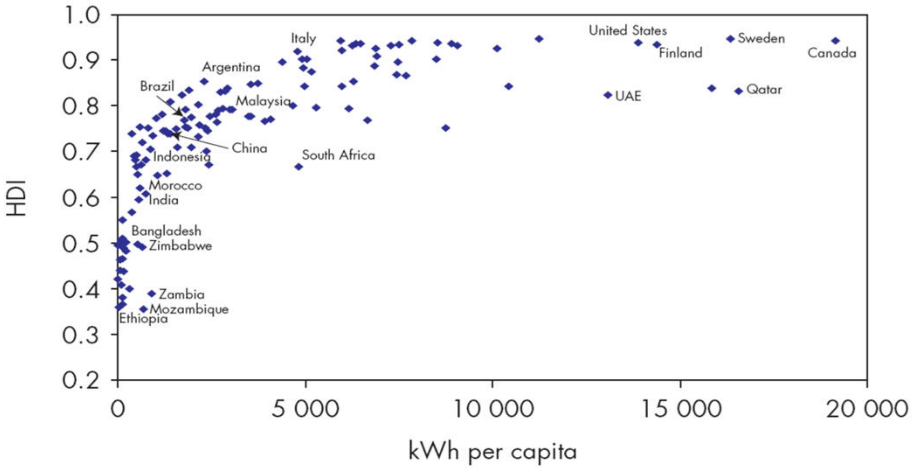
- It is a noble energy that is convertible into all forms of energy.
- There is a loss of efficiency in its production (Carnot principle).
- It does not generate pollution at the user level, although there is a potential danger.
- Its transport is expensive and meets specific physical laws (Kirchhoff).
- Its storage is difficult.



Socio-political characteristics of the electricity

- **Less than 2% of national GDP but essential to economic activity.**
- **Associated with a certain idea of progress ("Socialism is the Soviets plus electricity" - Lenin).**
- **The political debate on its status (service or industry?) Is not closed.**
- **States still intervene in the sector:**
  - **Heavy investments made,**
  - **Innovations are very slow, requiring too much R & D.**
  - **The potential economies of scale also encourage concentrations.**
  - **Constraints in terms of resources are very important.**

HDI (Human Development Indicators) & electricity consumption



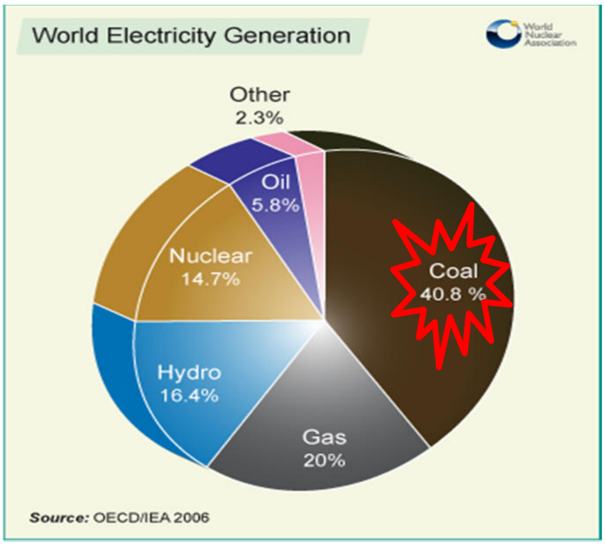
Source: WEO - IEA analysis

Environmental issues

Electricity sector is a major GHG contributor and is likely to be relatively convenient sector to be targeted, given its concentration among a number of large emitters and the fact that it is heavily regulated in most parts of the world.

Around 35% of total US emissions comes out of electricity generation.

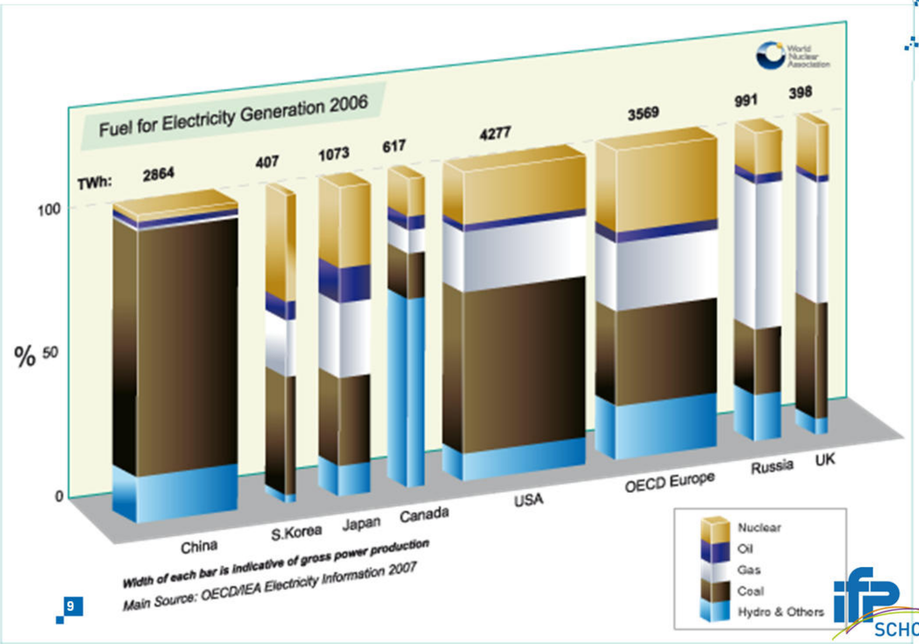
Share of different resources used in the world electricity generation in 2006



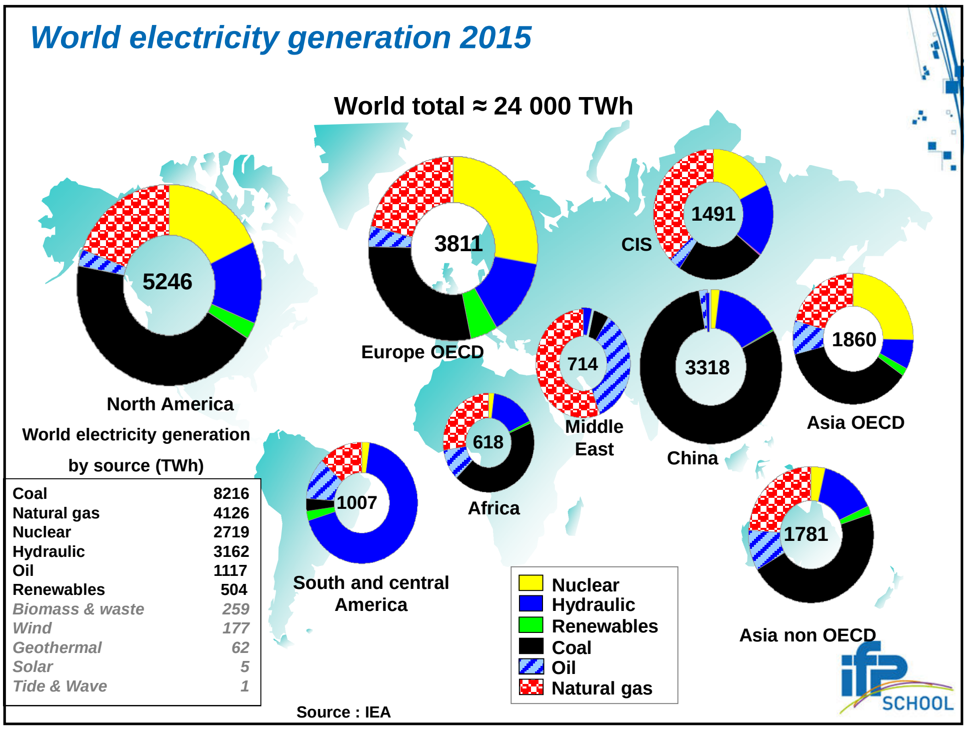
Source: OECD/IEA 2006

Total (in 2006) = 18 921 TWh

Share of different resources used in the world electricity generation in 2006 for each country



Width of each bar is indicative of gross power production
Main Source: OECD/IEA Electricity Information 2007



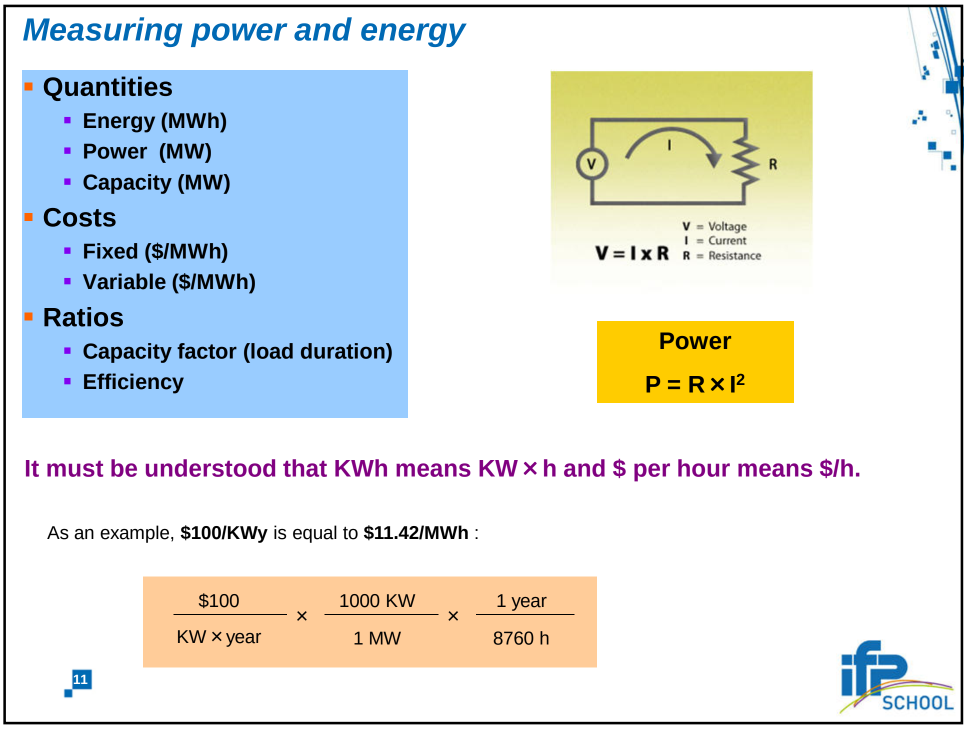
World electricity generation 2015

World total ≈ 24 000 TWh

World electricity generation by source (TWh)

Coal	8216
Natural gas	4126
Nuclear	2719
Hydraulic	3162
Oil	1117
Renewables	504
Biomass & waste	*259*
Wind	*177*
Geothermal	*62*
Solar	*5*
Tide & Wave	*1*

Source : IEA



Measuring power and energy

- **Quantities**
  - **Energy (MWh)**
  - **Power (MW)**
  - **Capacity (MW)**
- **Costs**
  - **Fixed ($/MWh)**
  - **Variable ($/MWh)**
- **Ratios**
  - **Capacity factor (load duration)**
  - **Efficiency**

$V = I \times R$

V = Voltage
I = Current
R = Resistance

Power

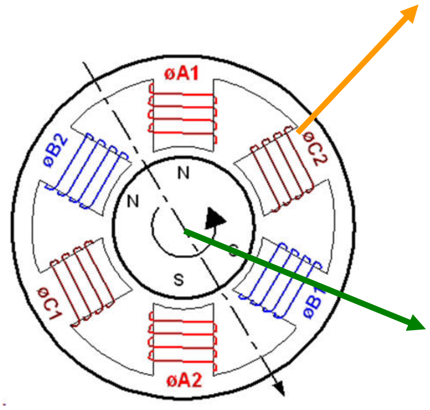
$P = R \times I^2$

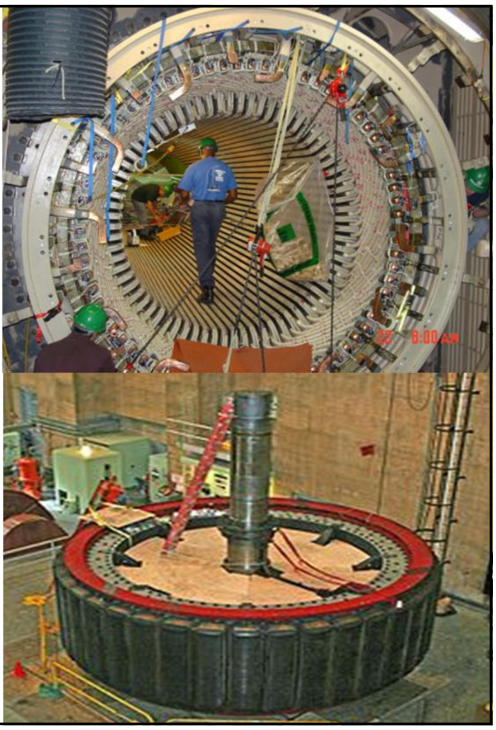
It must be understood that KWh means KW × h and $ per hour means $/h.

As an example, **$100/KWy** is equal to **$11.42/MWh** :

$$\frac{\$100}{KW \times year} \times \frac{1000\ KW}{1\ MW} \times \frac{1\ year}{8760\ h}$$

3-phase generator





Voltage levels

Three main duties for different levels of voltage :

- **Interconnections and transmission**
  - **400 KV or even higher in some countries**
    - e.g. 745 KV for 6000 MW of power transmitted over 1000 Km
- **Regional networks**
  - **225 – 90 – 63 KV**
- **Distribution**
  - **20 KV & 110 - 400 V**

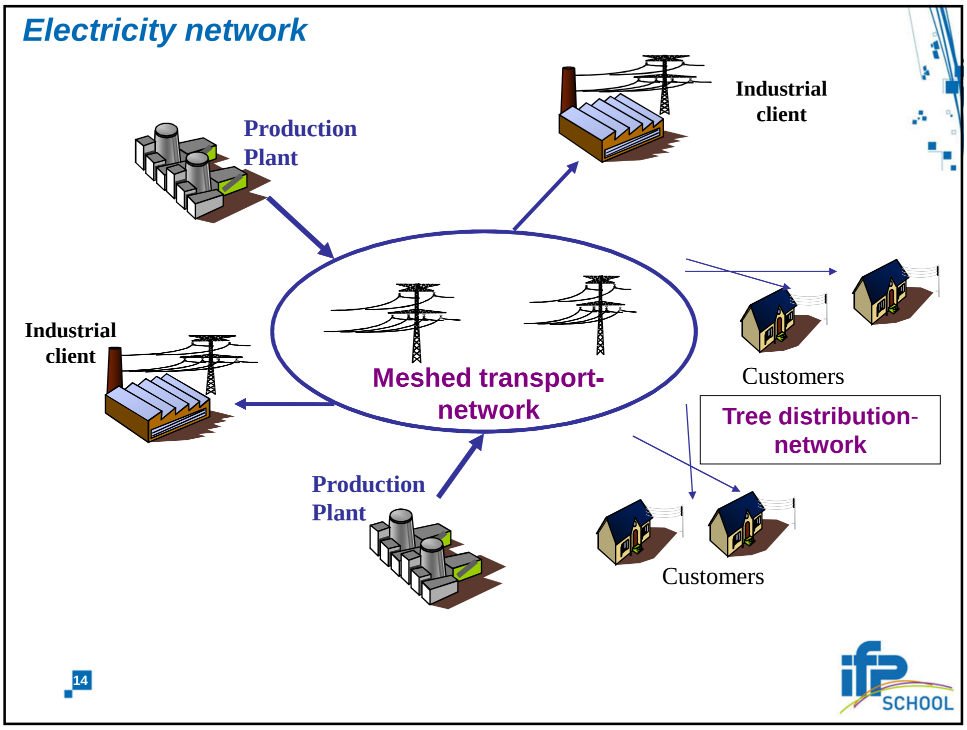
DC connections:

400 KV:* *3000-6000MW over 2000 Km (overhead) &

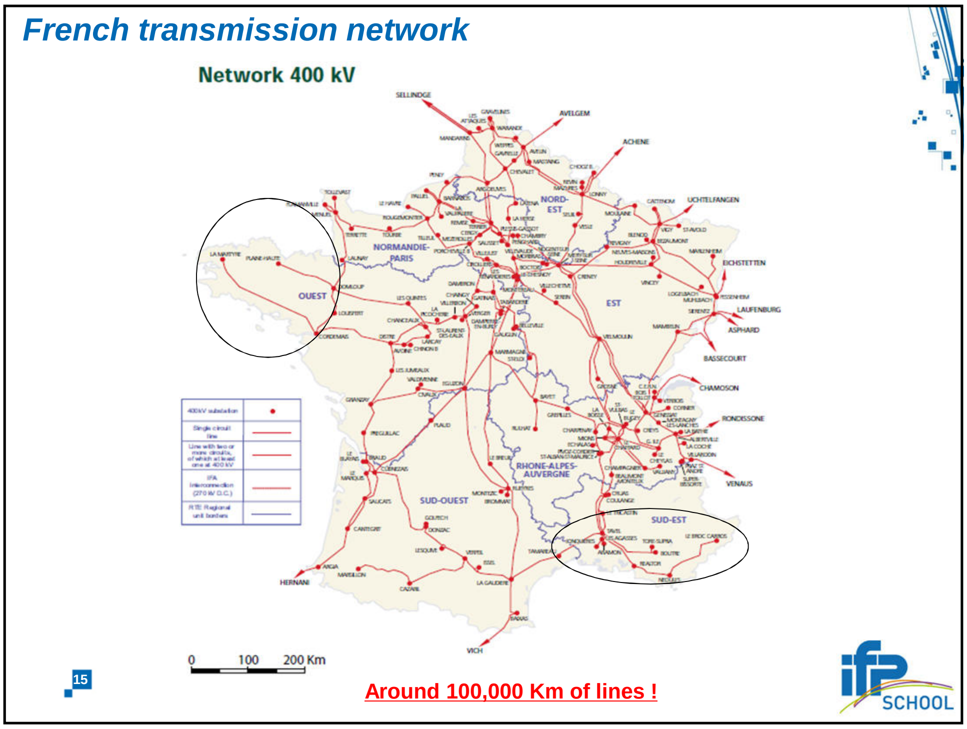
500-2000 MW over 30-600 KM (submarine/underground).

Generation:

1 KV to 25 KV due to the insulation constraints in generator.



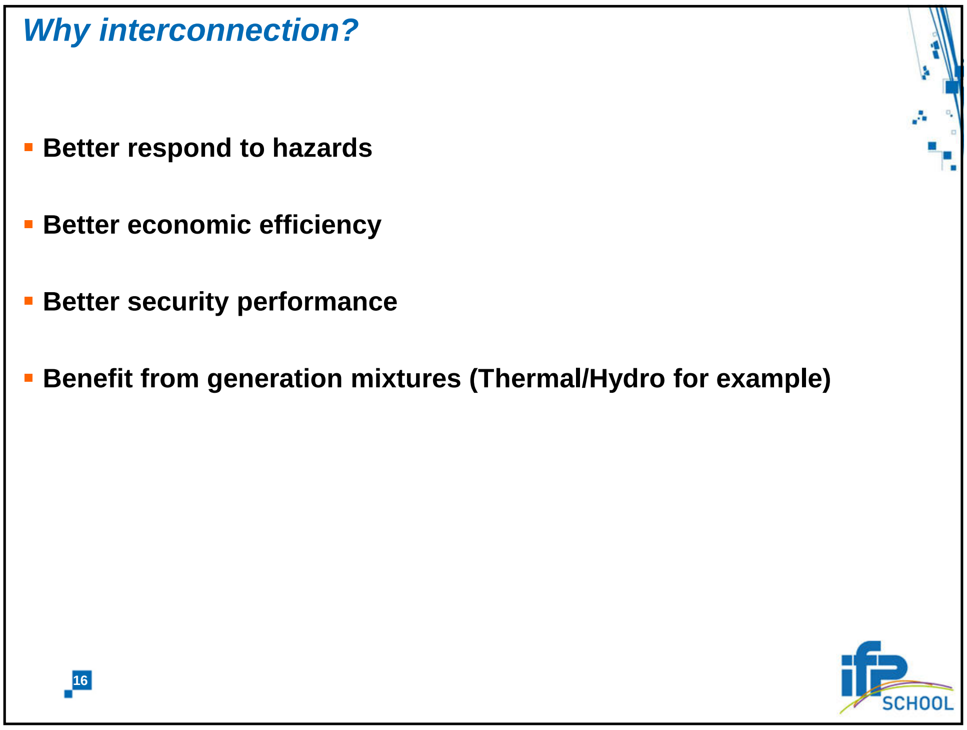
Electricity network



French transmission network

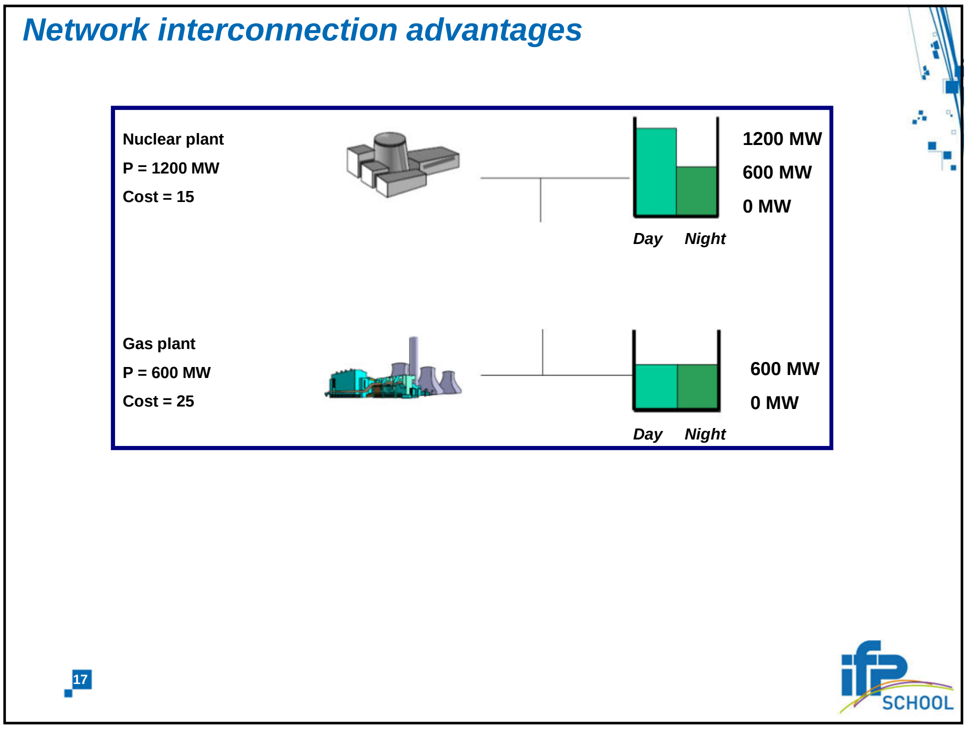
400kV substation	●
Single circuit line	—
Line with two or more circuits, of which at least one at 400 kV	—
IFA Interconnection (270 kV D.C.)	—
RTE Regional unit borders	—

Around 100,000 Km of lines !



Why interconnection?

- Better respond to hazards
- Better economic efficiency
- Better security performance
- Benefit from generation mixtures (Thermal/Hydro for example)

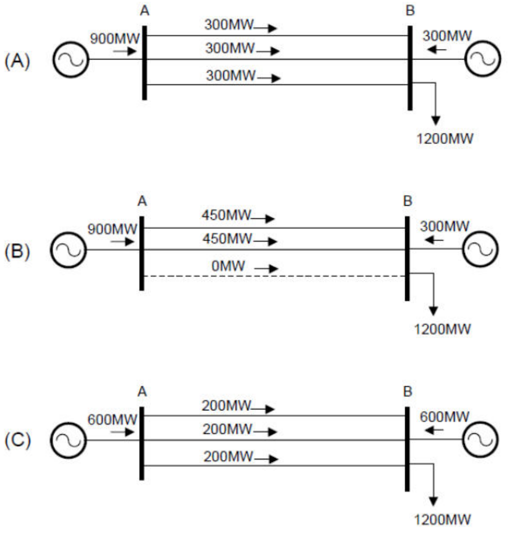


Network interconnection advantages

Nuclear plant
P = 1200 MW
Cost = 15

Gas plant
P = 600 MW
Cost = 25

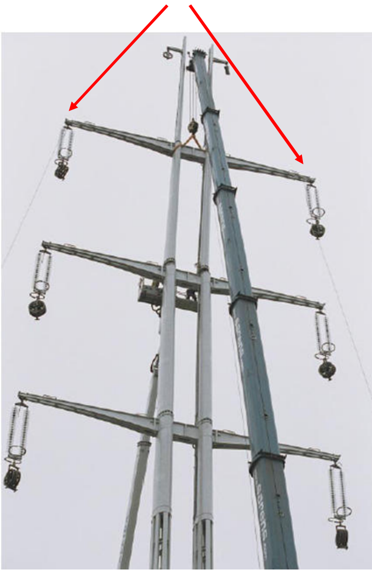
Security criteria (N-1)

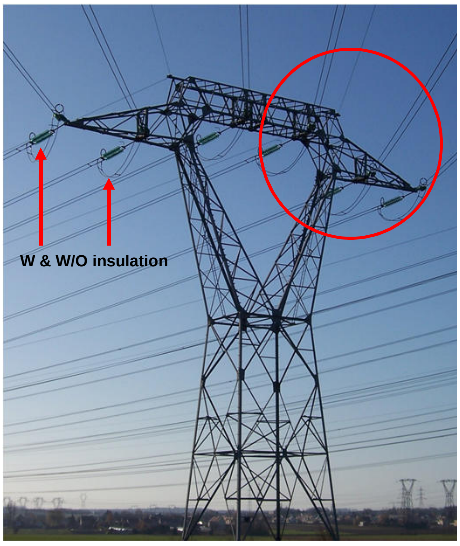


Line capacity: 400MW

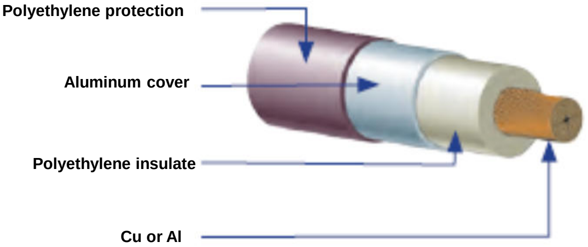
Pylons

Two 3-phase circuits





Underground cable

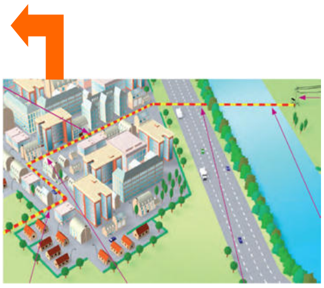


Polyethylene protection

Aluminum cover

Polyethylene insulate

Cu or Al



Advantages :

Reduction of harmful electric field (cancer), visual aspects,...

Costs :

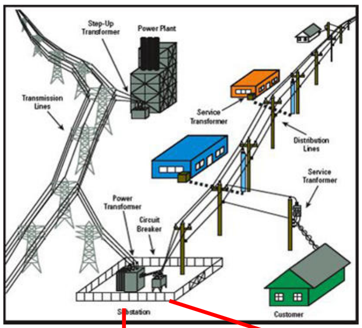
400 KV 7-15 times more than overhead lines, 225 KV 3-5 times, 63 and 90 KV 1.5-3 times

Materials :

Cable with synthetic insulate (polyethylene or nitrogen with 10% SF6)

Superconductors cooled with liquid nitrogen (future project)

Substations

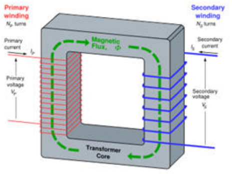


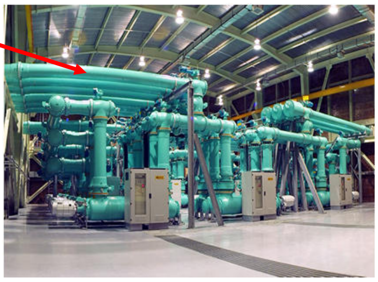
Main functions:

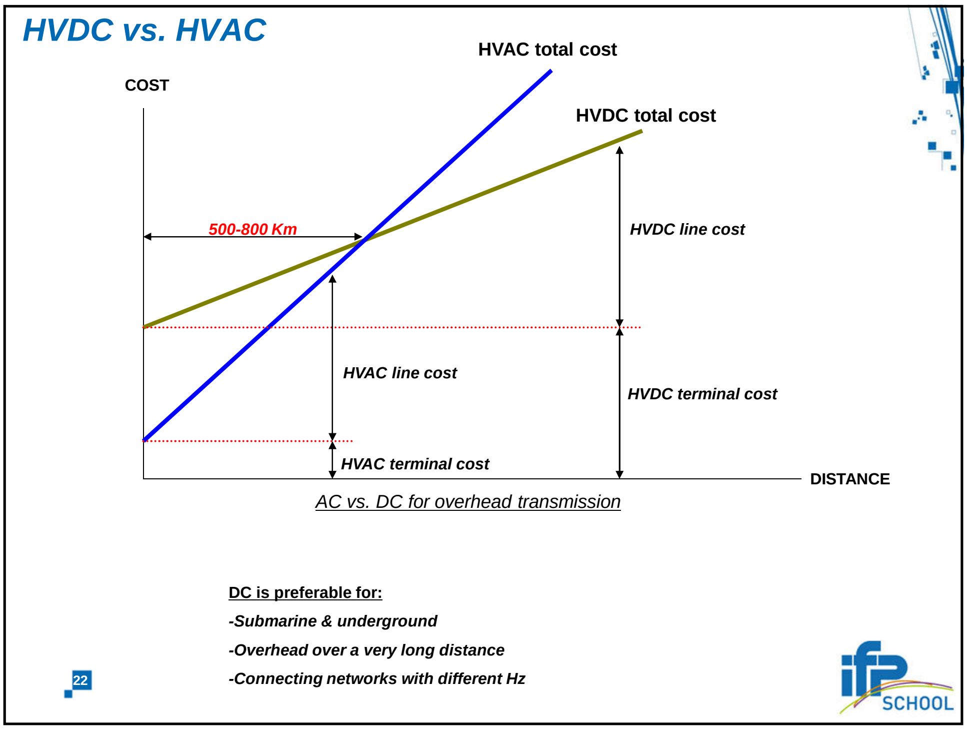
-Allow to connect / disconnect the different elements

-Switch energy to different directions

-Shelter transformers







HVDC vs. HVAC

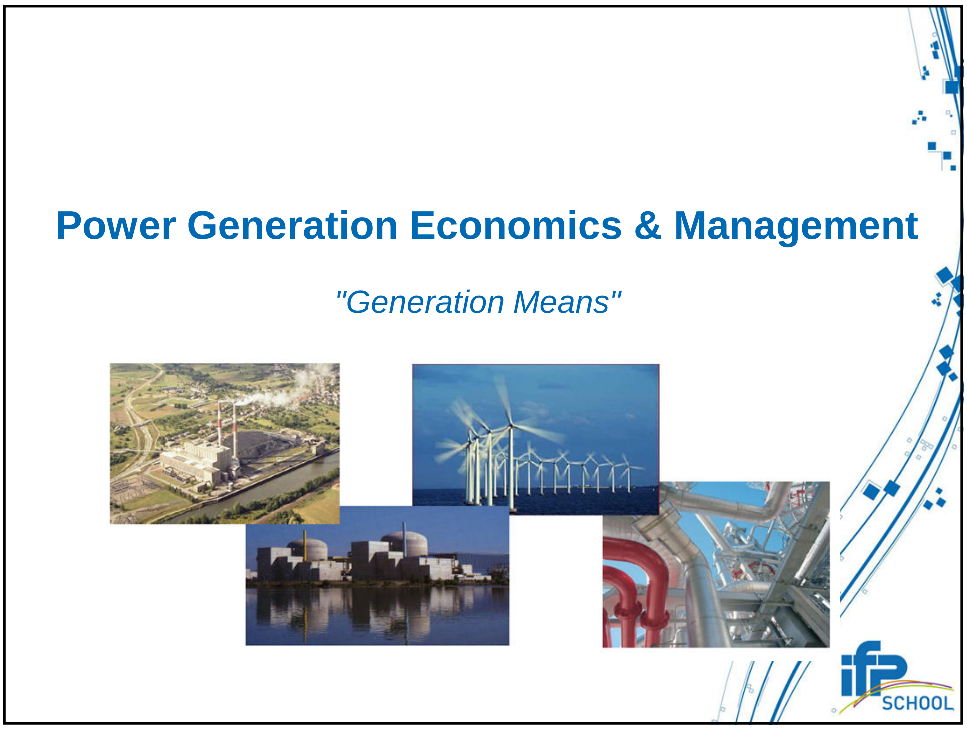
AC vs. DC for overhead transmission

DC is preferable for:

-*Submarine & underground*

-*Overhead over a very long distance*

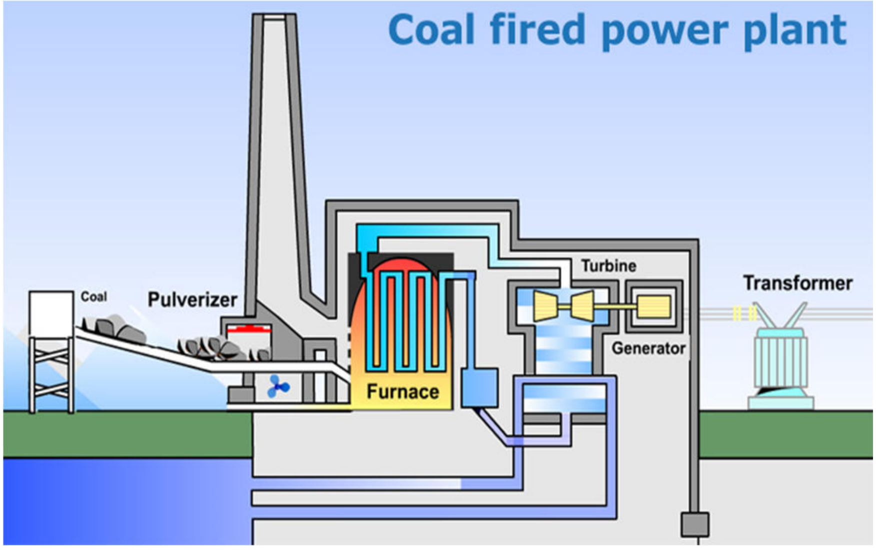
-*Connecting networks with different Hz*



Power Generation Economics & Management

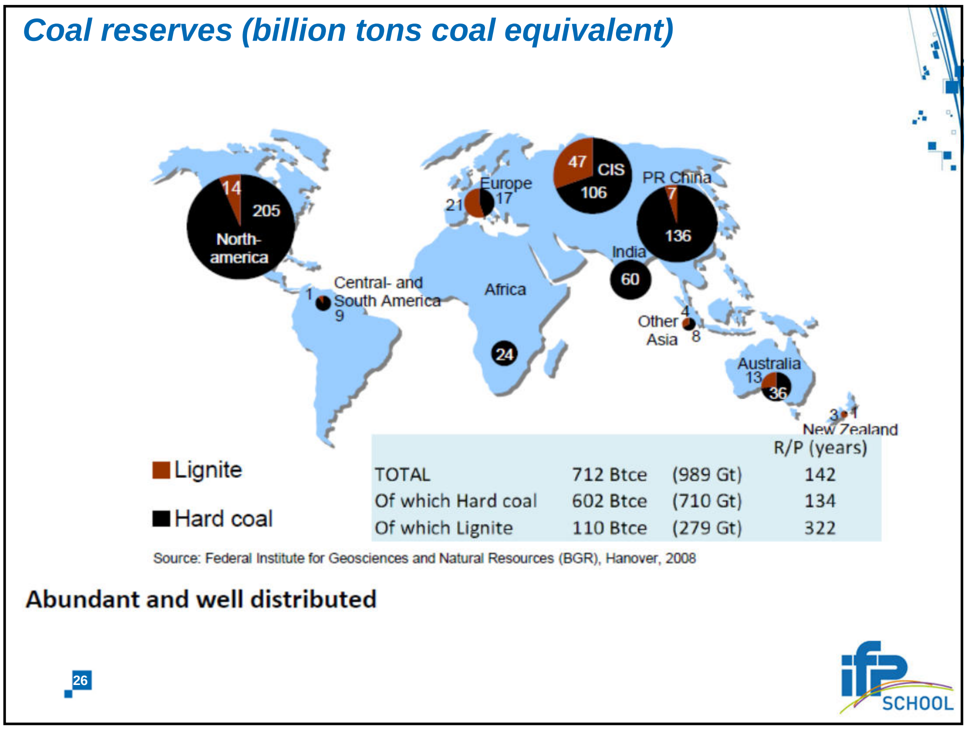
"Generation Means"

Coal power plant



Coal power plants

- Old and mature technology
- Abundant supply (more than 200 years of reserves)
  - geographically distributed (without cartel),
  - relatively cheap.
- About 50% of plants in Germany, U.S., Japan, Russia
- Majority of the plants put into service in China, India, etc. ...
- The market has recently developed:
  - 17 Mt were traded in 1979
  - 589 Mt in 2007
  - 820 Mt in 2017 provided



Coal reserves (billion tons coal equivalent)

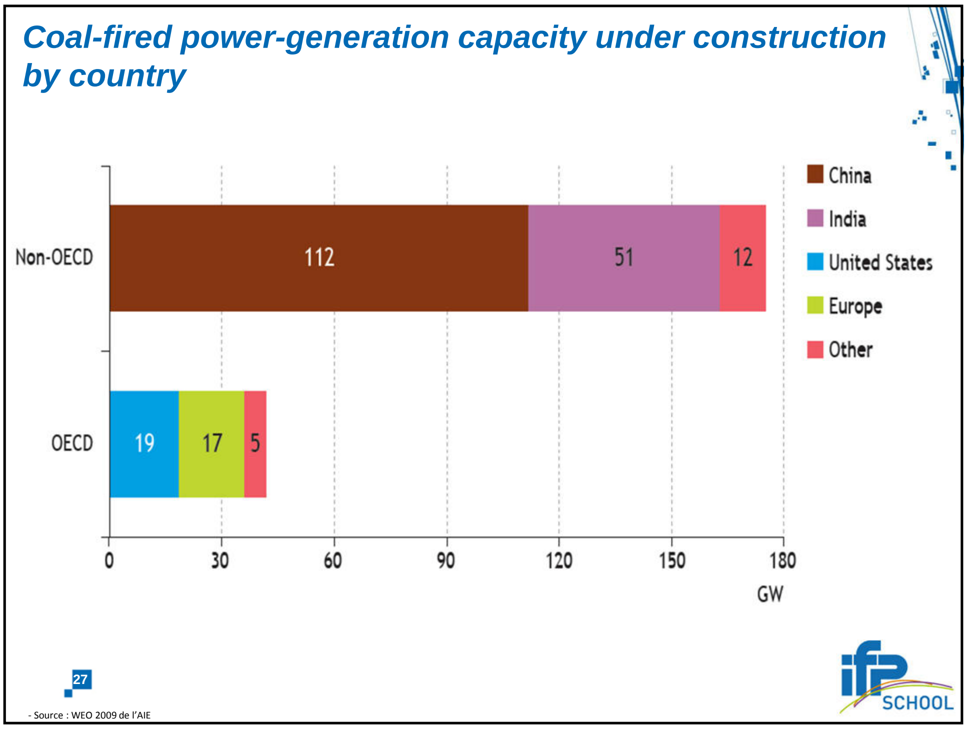
■ Lignite

■ Hard coal

			R/P (years)
TOTAL	712 Btce	(989 Gt)	142
Of which Hard coal	602 Btce	(710 Gt)	134
Of which Lignite	110 Btce	(279 Gt)	322

Source: Federal Institute for Geosciences and Natural Resources (BGR), Hanover, 2008

Abundant and well distributed



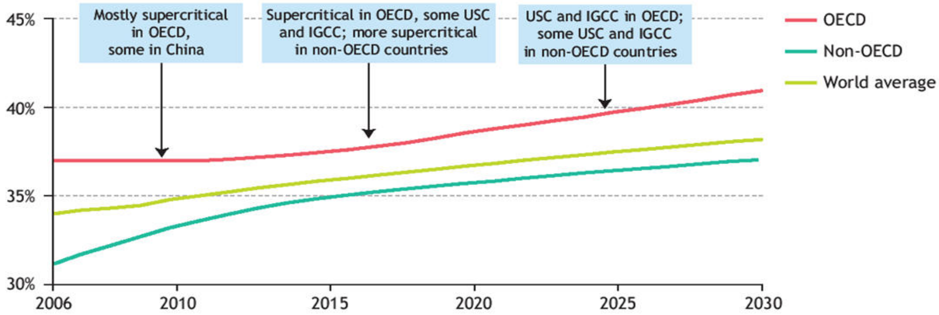
Coal-fired power-generation capacity under construction by country

- Source : WEO 2009 de l'AIE

Supercritical cycles

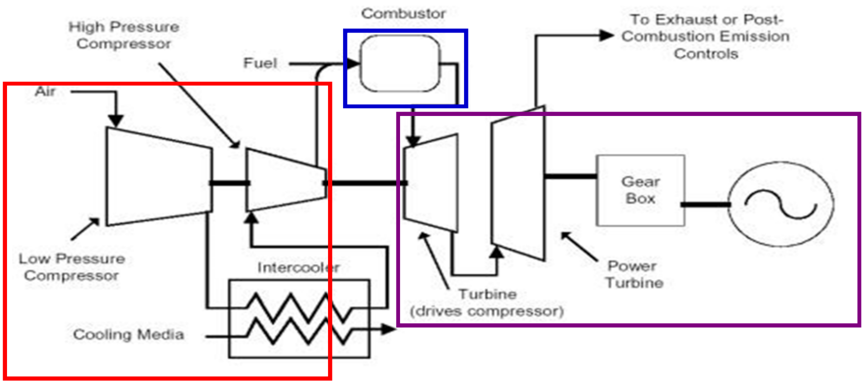
High temperature competition :

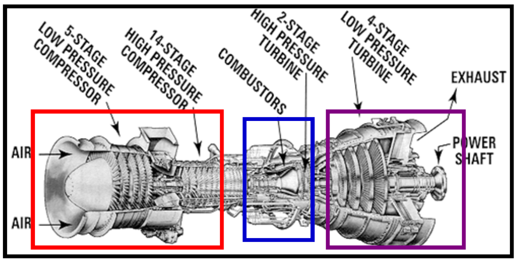
- Subcritical cycle P < 180 bar T < 570° C
  - Efficiency 41 %
- Supercritical P ~ 250 bar T ~ 570° C
  - Efficiency 43 %
- Advanced Supercritical P ~ 300 bar T ~ 590° C
  - Efficiency 45 %
- Ultra supercritical P ~ 400 bar T ~ 700° C
  - Efficiency 50 %

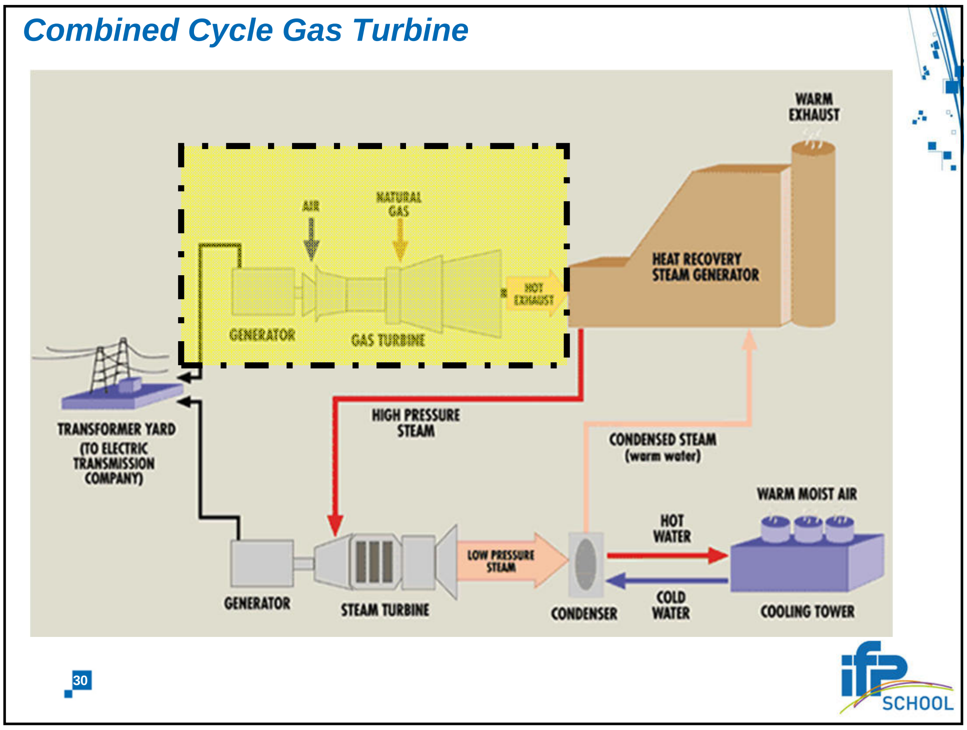


Note: Average efficiency of installed coal-fired capacity. USC refers to ultrasupercritical steam conditions. IGCC refers to integrated gasification combined cycle.

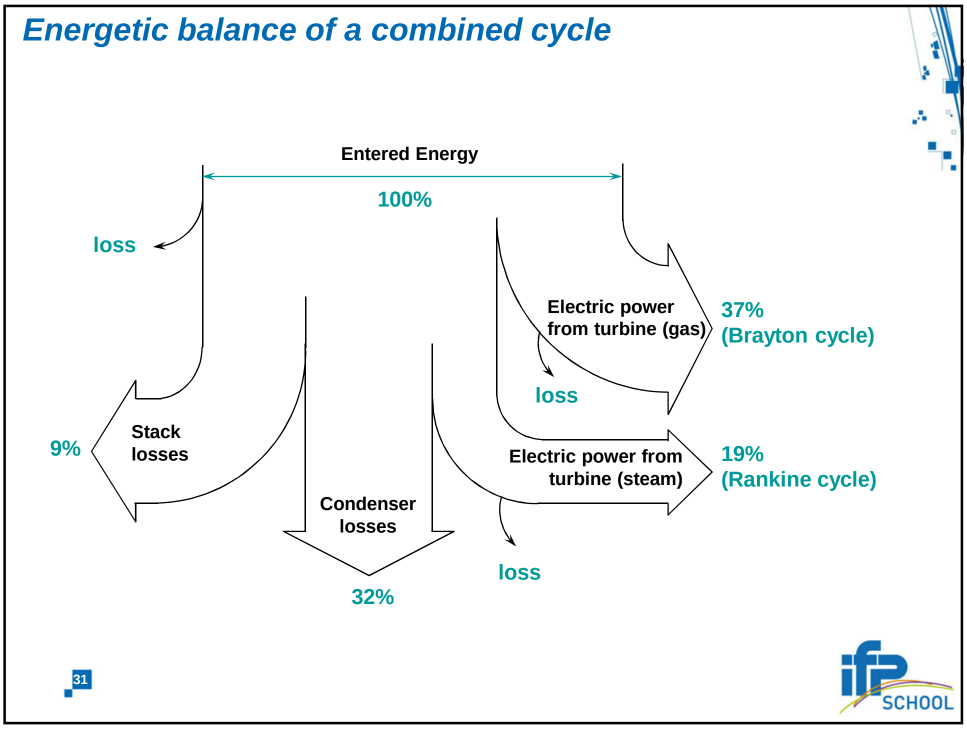
Gas Turbine







Combined Cycle Gas Turbine



Energetic balance of a combined cycle

Entered Energy

100%

loss

Electric power from turbine (gas)

37% (Brayton cycle)

loss

9%

Stack losses

Electric power from turbine (steam)

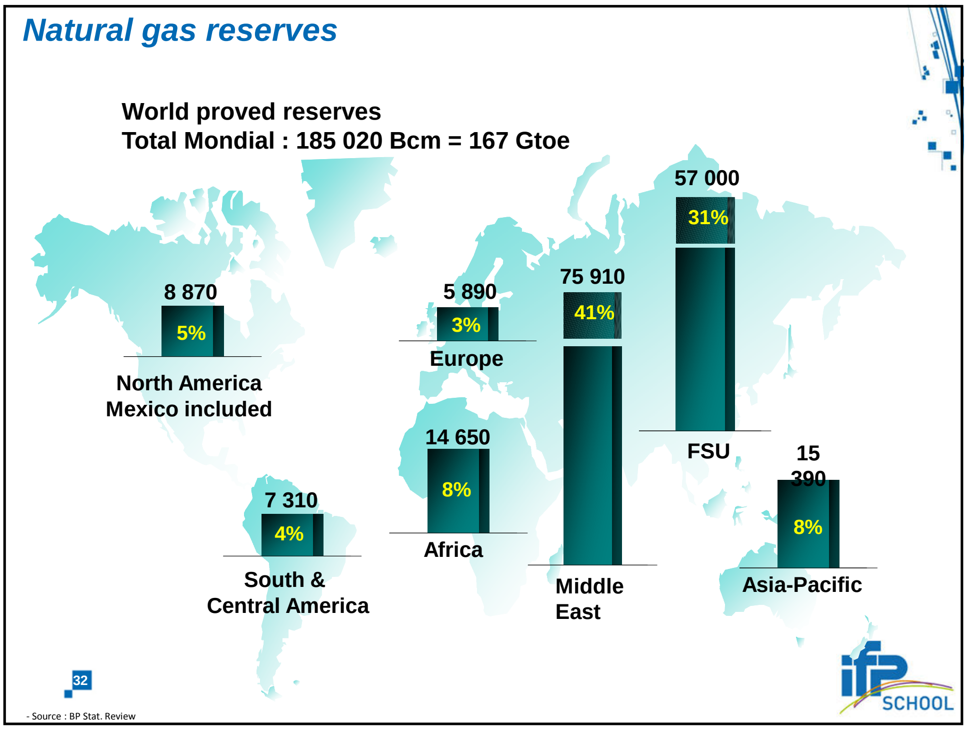
19% (Rankine cycle)

Condenser losses

loss

32%

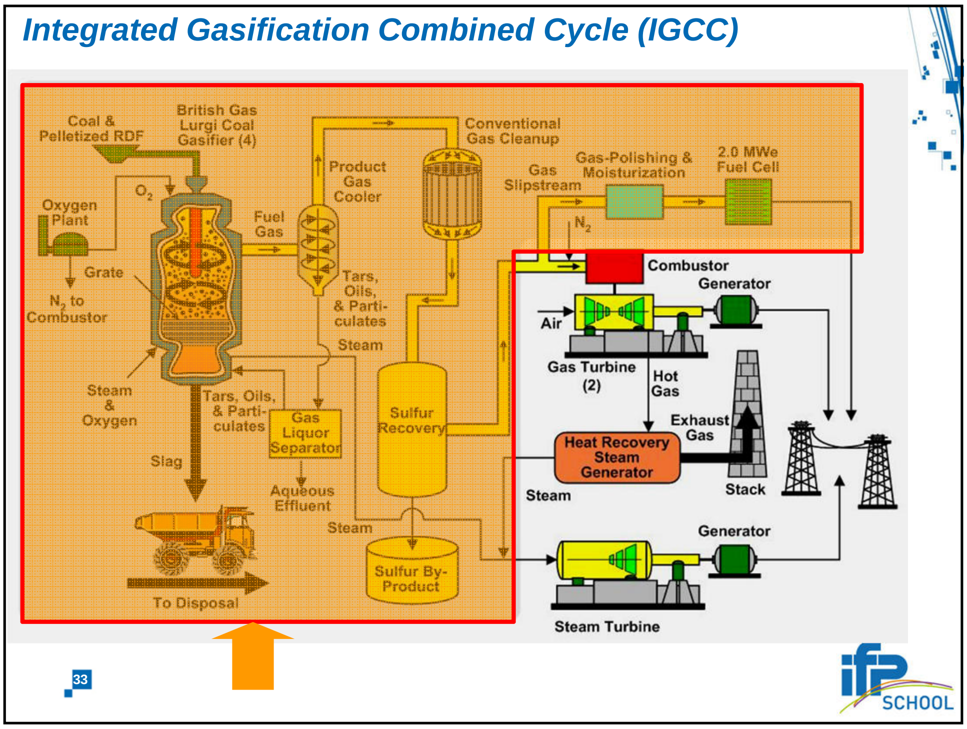
Natural gas reserves



World proved reserves
Total Mondial : 185 020 Bcm = 167 Gtoe

- Source : BP Stat. Review

Integrated Gasification Combined Cycle (IGCC)



IEA Study

Carbon Capture and Storage

International Energy Agency

2009-2010

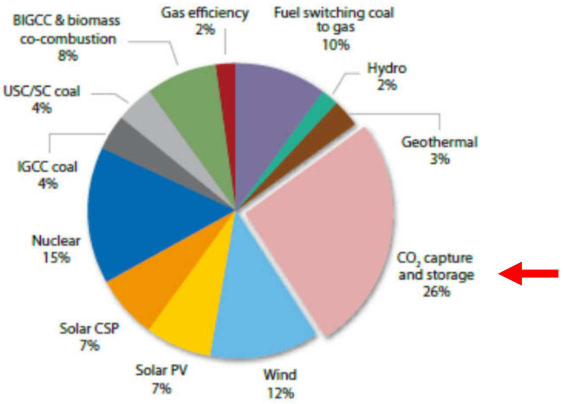
IEA Study

- In power generation, one quarter of the necessary CO2 reduction is attributable to CCS.
- Coal-based and gas-based electricity generation accounts for three quarters of power generation in 2050 compare to two-third in 2005.

*Share of power generation in CO2 emissions:

2005 : 41%

2050 : 44%

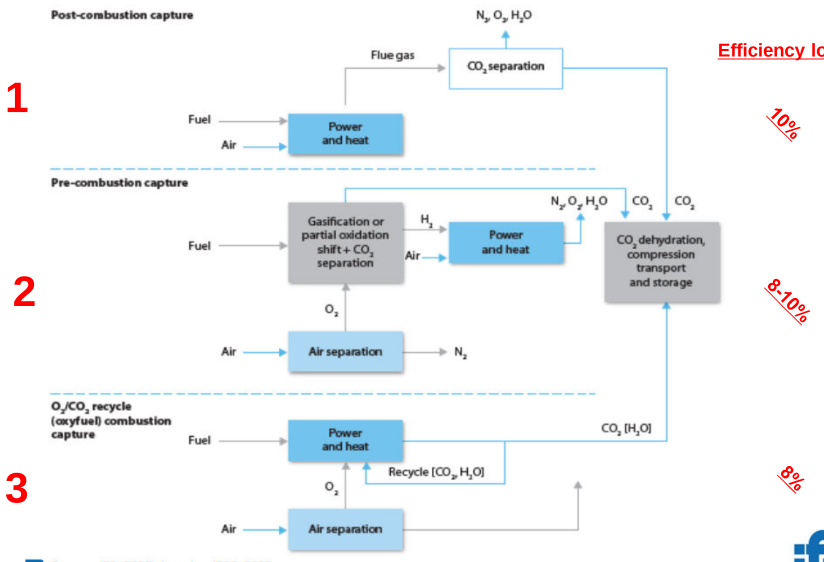


Reduction in CO2 emissions in power sector in 2050, by technology area

IEA Study

CO2 capture processes

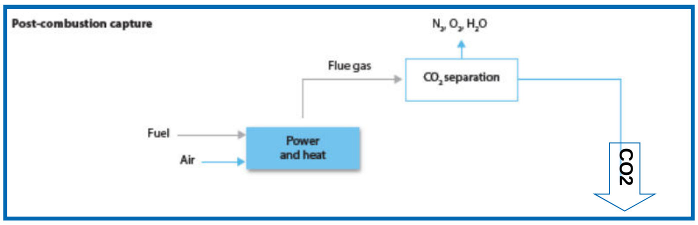
Efficiency lost:



Sources: IEA, 2008b based on IPCC, 2005.

IEA Study

Post-combustion process



-CO2 is captured from flue gases that contain 4% to 8% of CO2 by volume for natural gas-fired power plants, and 12% to 15% by volume for coal-fired power plants.

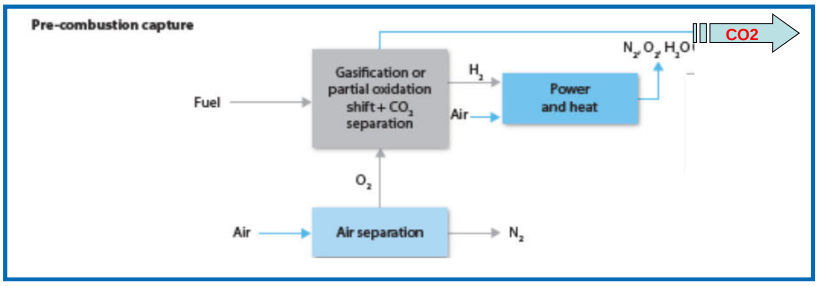
-Separation of CO2 from the flue gas is done by a chemical absorption process (with amine-based solvents such as MonoEthanolAmine) and has been applied in industry on a commercial scale for decades.

We should recover the CO2 from the solvent with a minimum energy penalty and at an acceptable cost.

Challenge!!!

IEA Study

Pre-combustion process



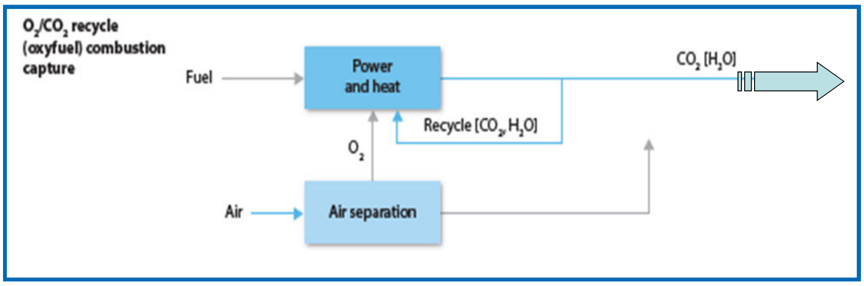
-CO2 is separated from the fuel before burning it. The process can be used for variety of fuels. In the case of solid or liquid fuels, it has first to be gasified before reacting with O2 and steam and then further processed in a shift reactor to produce a syngas (H2 and CO2).

Efficiency penalties are associated with the energy used for shift reaction and the O2 generation and also the energy necessary for gasification of solid or liquid fuels.

Challenge!!!

IEA Study

Oxy-combustion process



-This process involves the removal of nitrogen from the air using an air separator unit (ASU) or, potentially in the future membranes. Fossil fuel is then combusted with near-pure O2 using recycled flue gas to control the combustion temperature.

R&D developments are focusing on reducing the necessary energy for O2 provision.

Challenge!!!

Transport and Storage

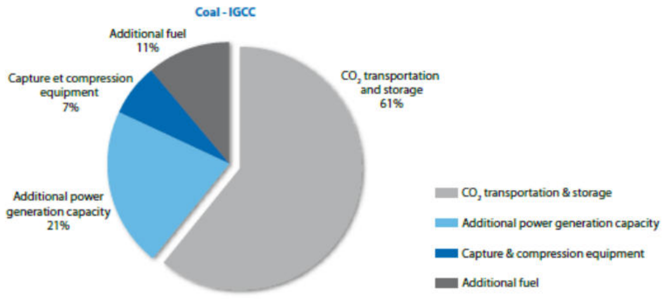
- The Co2 has to be transported from capture plants to the storage sites.
- It can be transported by pipelines, ships and road tankers.
- For large quantities, a pipeline is the most cost-effective means of transportation.
  - Exactly like a gas pipeline (diameter & flow rate issues) but more corrosive.
  - Lower cost for transporting compare to natural gas for example, due to the liquid or supercritical state of CO2 (with a density 10 to 100 times higher than that of natural gas).

e.g. :

Transport cost of CO2 can vary between USD 2/t CO2 to USD 6/t CO2 over 100 km per year for a CO2 quantity of 2 Mt, Which correspond roughly to the amount of CO2 produced by a 400 MW coal plant in a year. Scale effects can reduce it to even USD 2/tCO2.

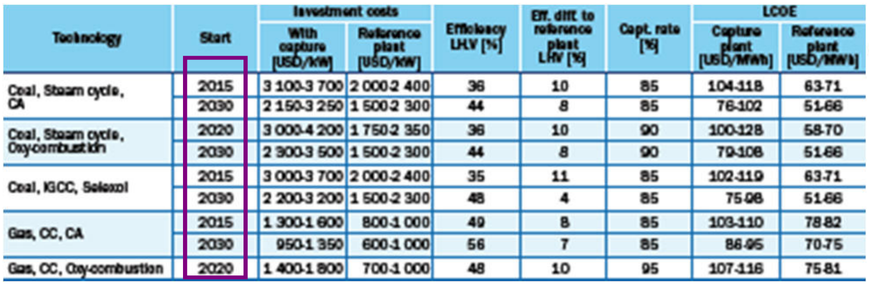
Cost of capturing CO2 in the power sector

- The steps of CO2 capturing, transporting and storing determine the overall costs of CO2 capture and storage from a power plant.



Cost components of the capture costs for a coal power plant

Techno-economic characteristics of power plants with carbon capture



Technology	Start	Investment costs		Efficiency LHV [%]	Eff. diff. to reference plant LHV [%]	Capt. rate [%]	LCOE	
		With capture [USD/kW]	Reference plant [USD/kW]				Capture plant [USD/MWh]	Reference plant [USD/MWh]
Coal, Steam cycle, CA	2015	3 100-3 700	2 000-2 400	36	10	85	104-118	63-71
	2030	2 150-3 250	1 500-2 300	44	8	85	76-102	51-66
Coal, Steam cycle, Oxy-combustion	2020	3 000-4 200	1 750-2 350	36	10	90	100-128	58-70
	2030	2 300-3 500	1 500-2 300	44	8	90	79-108	51-66
Coal, IGCC, Selexol	2015	3 000-3 700	2 000-2 400	35	11	85	102-119	63-71
	2030	2 200-3 200	1 500-2 300	48	4	85	75-98	51-66
Gas, CC, CA	2015	1 300-1 600	800-1 000	49	8	85	103-110	78-82
	2030	950-1 350	600-1 000	56	7	85	86-95	70-75
Gas, CC, Oxy-combustion	2020	1 400-1 800	700-1 000	48	10	95	107-116	75-81

CA : Chemical Absorption, **CC :** Combined-Cycle, **IGCC :** Integrated Gasification Combined-Cycle

So far, no power plant with CO2 capture operates on a commercial scale!!!

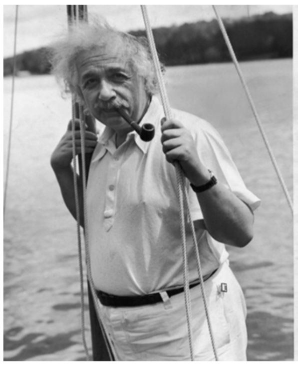
R & D Technologies

- **Air Capture**
  - *collecting CO2 from ambient air*
- **Biomass Co-firing**
- **The HyPr-Ring Process**
  - *Japan, H2*
- **The ZECA Process**
  - *Los Alamos National Laboratory, H2*
- **Hybrid Combustion Gasification Chemical Looping Coal Power Technology**
  - *ALSTOM*
- **the Calcium looping Process**
  - *DOE*
- **Fuel Flexible Process**
  - *General Electric*
- **Coal Direct Chemical Looping Reforming Process & Syngas Redox Process**
- **Membrane**
- **Etc.**

Retrofitting issue?

Power Generation Economics & Management

"Nuclear Energy"



How powerful it is!

How many wind power installations to replace one Nuclear power plant?
Same thing in terms of surface for photovoltaic panels?

Uranium has a very high energy density compare to the other fuels.

under current techniques for producing energy:

One tone of Uranium = 10000 & 16000 tones of Oil

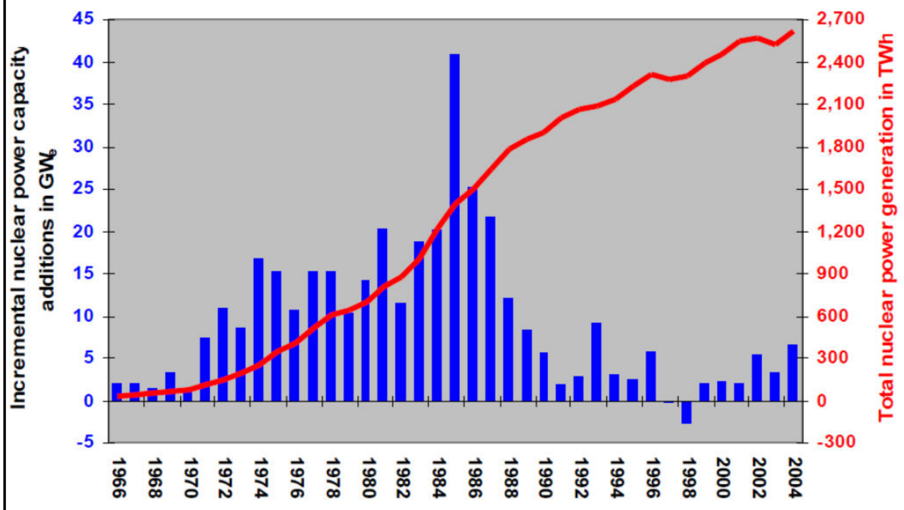
Unfortunately it was first introduced by military actions!

Little Boy & Fat MAN in 1945

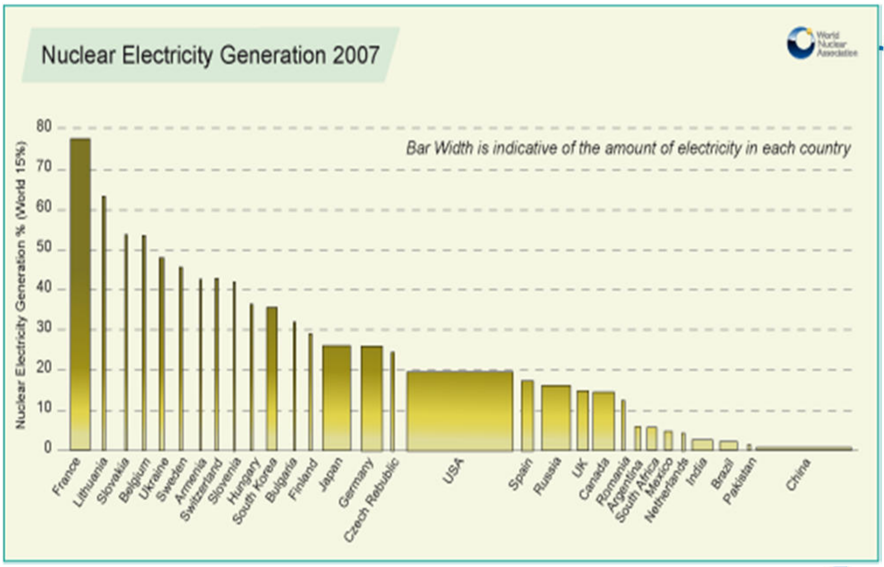
Nuclear energy trend

- An unfortunate birth (1945, Hiroshima)
- Very rapid development after the second war with commercial reactors in the early 1960s
- An almost halted in the 1980s after accidents TMI (1979) and Chernobyl (1986) but also for other reasons:
  - Improved efficiency,
  - Reduced demand
  - Overcapacities
  - Collapse of fossil fuel prices
  - Liberalization of energy markets
  - High interest rates
- A renewed motivation today (security of supply, fighting against greenhouse gases, still expensive renewable)

Growth of world generation capacity



Nuclear generation by country

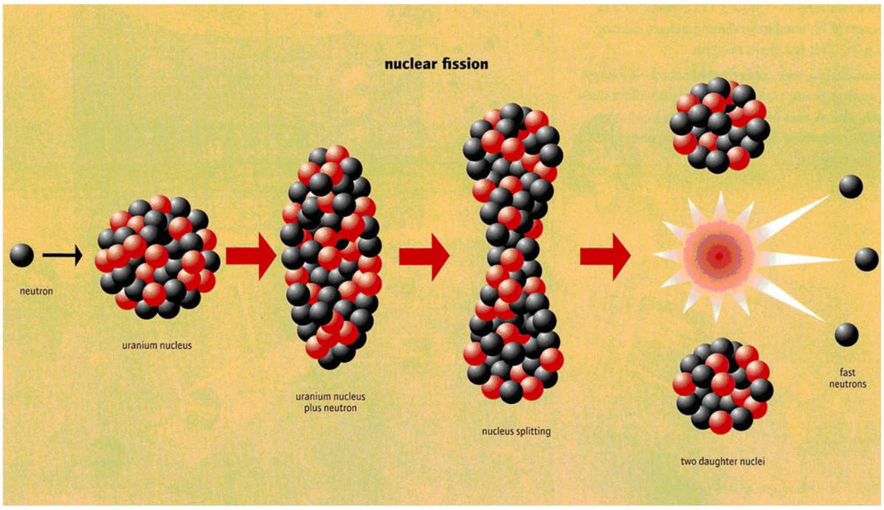

Nuclear Electricity Generation 2007

Bar Width is indicative of the amount of electricity in each country

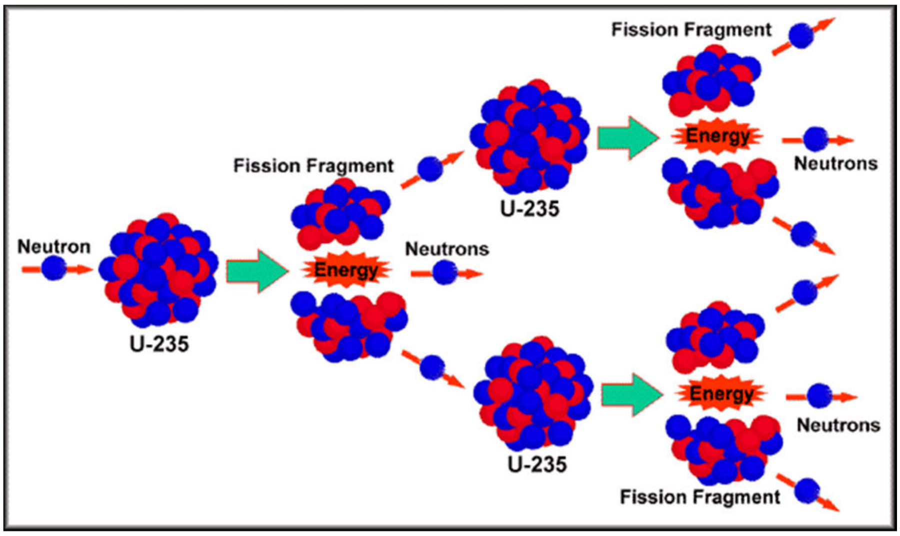
Nuclear power plants in the world

International Nuclear Safety Center at ANL, Dec 1999

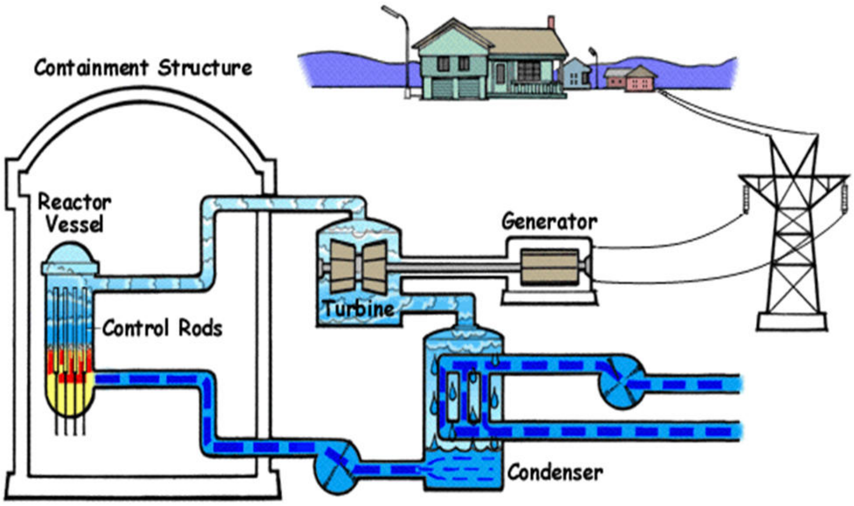
Fission



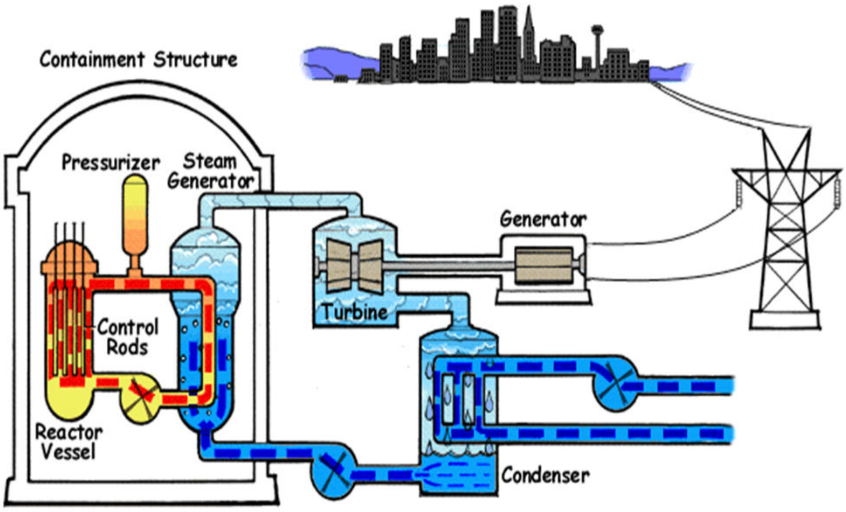
Chain reaction



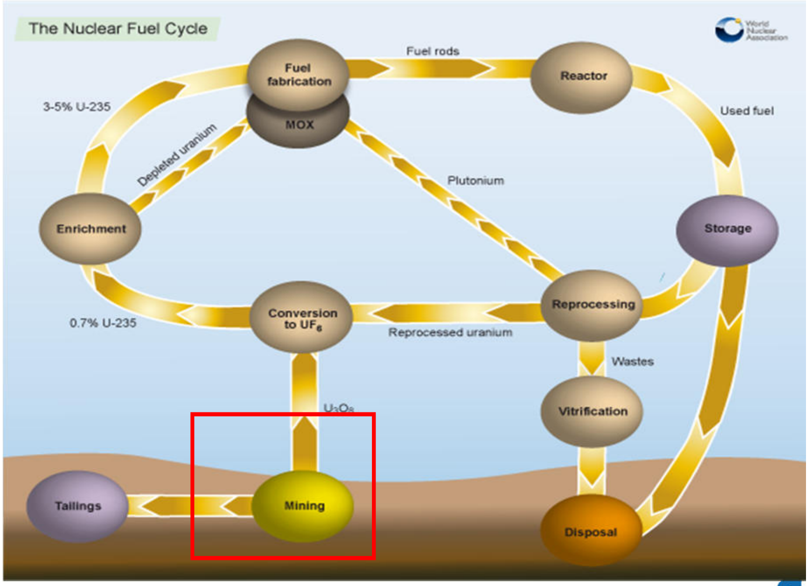
BWR reactor



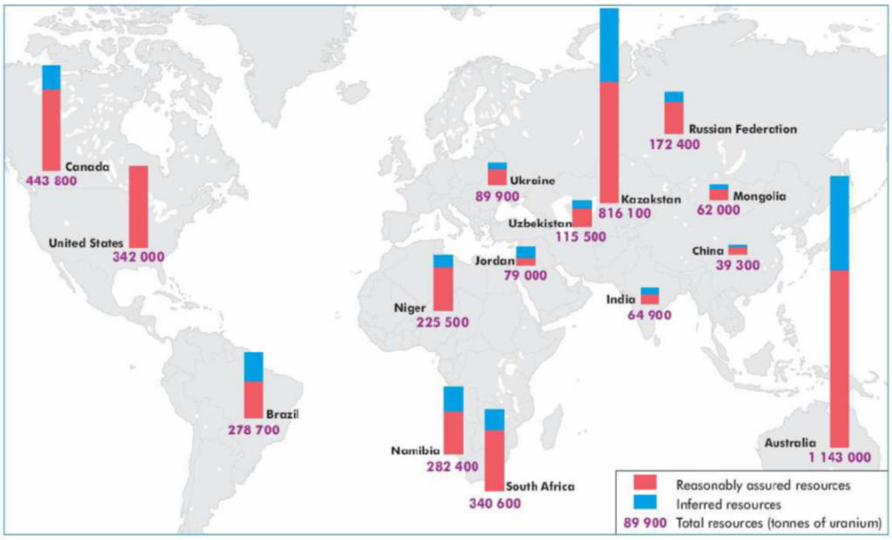
PWR reactor



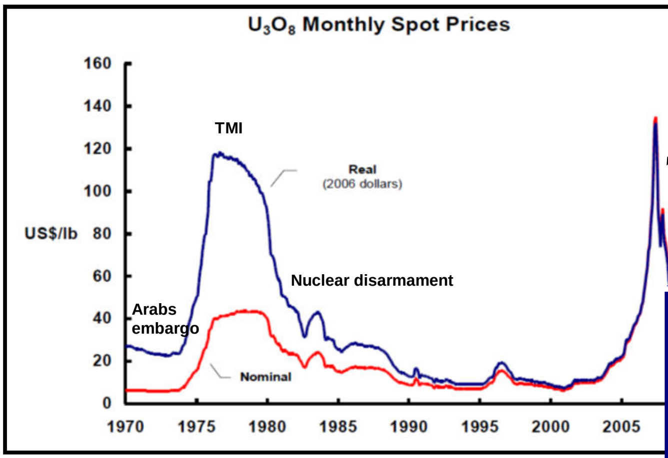
Fuel cycle



Uranium reserves (2015)



Price evolution



Perspectives
Stocks' reduction
Problems in the mines
constructions
Speculations
etc

Weekly Spot Ux U$_3$O$_8$ Price
as of August 9, 2010
Change from previous (week)

	1 US$ =	0.75577 €
U$_3$O$_8$ Price (lb)	$46.50 [+0.50]	€35.14 [+0.38]

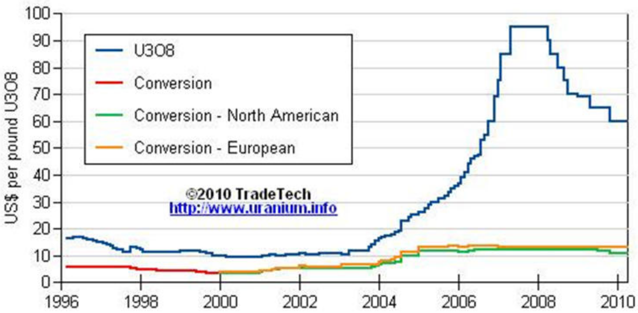
Ux Month-End Spot Prices
as of July 26, 2010
Change from previous [month]

	1 US$ =	0.77000 €
U$_3$O$_8$ Price (lb)	$46.00 [+4.25]	€35.42 [+3.27]
NA Conv. (kgU)	$10.00 [+3.00]	€7.70 [+2.31]
EU Conv. (kgU)	$9.25 [+1.50]	€7.12 [+1.16]
NA UF$_6$ Price (kgU)	$130.00 [+14.00]	€100.10 [+10.78]
NA UF$_6$ Value* (kgU)	$130.19 [+14.10]	€100.25 [+10.86]
EU UF$_6$ Value* (kgU)	$129.44 [+12.60]	€99.67 [+9.70]
SWU Price (SWU)	$153.00 [Unch.]	€117.81 [Unch.]

Only 15% of uranium is negotiated in the market and the majority of it is negotiated through long term contracts.

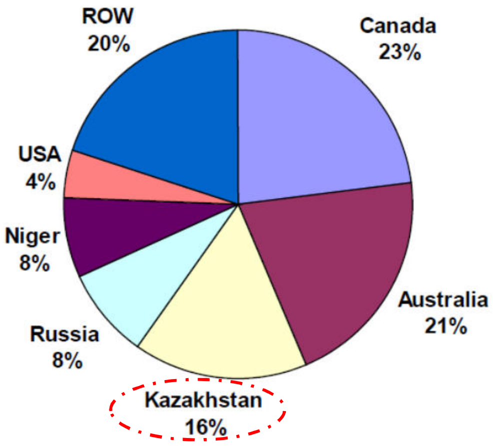
Long term contracts' price

- **Generally the details of these transaction are not available but some countries and international organizations (such as US, Australia, Euratom) publish some price indicators.**



Off course less volatile but somehow follows the same trend.

Uranium production (2007)



Total production = 41 265 tones

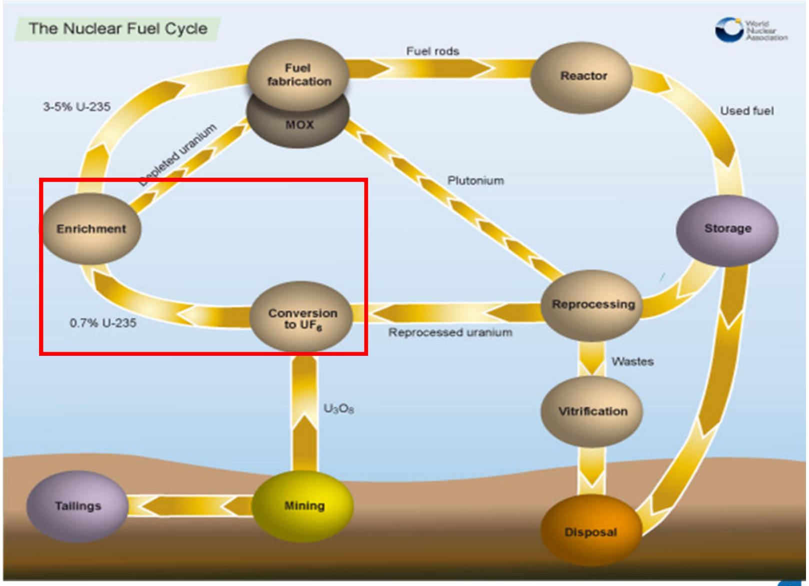
But total consumption = 67 000 tones !!!

Concentration process

Mineral

Yellow cake

Fuel cycle



Uranium conversion & enrichment

25% of the world enrichment

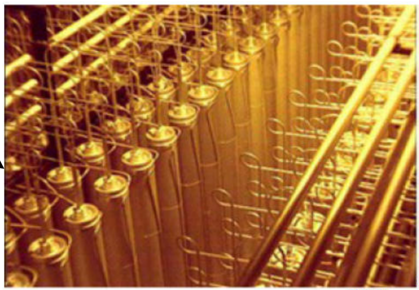
Gaseous diffusion enrichment

Conversion

Yellow cake to UF6 (gas state)

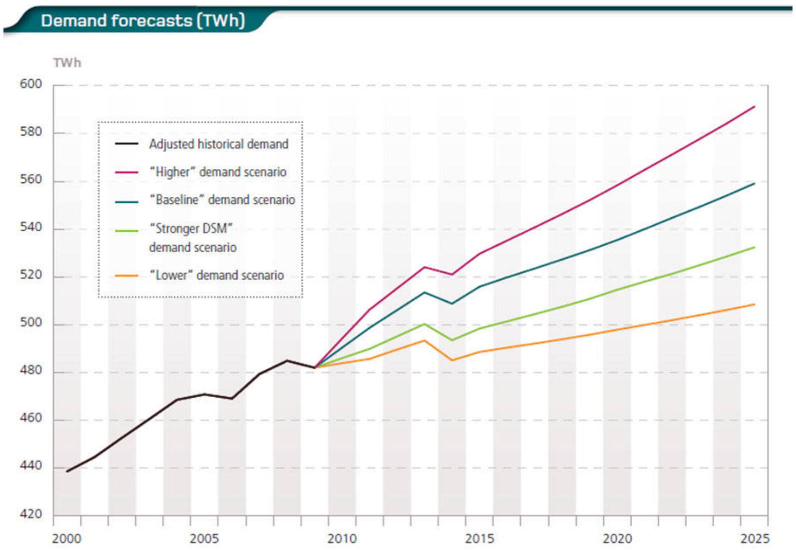
Centrifuge enrichment

George Besse Plant (Eurodif)

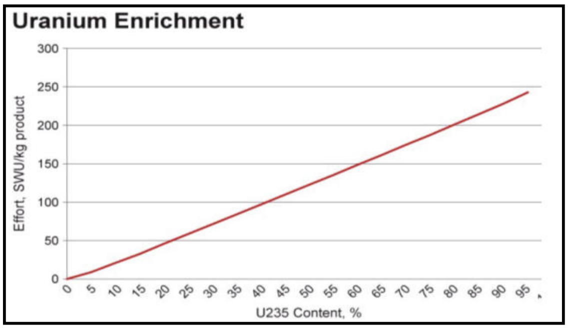


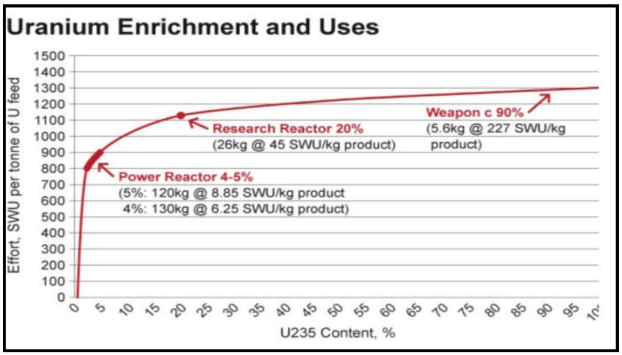
URENCO Plant

Demand forecast

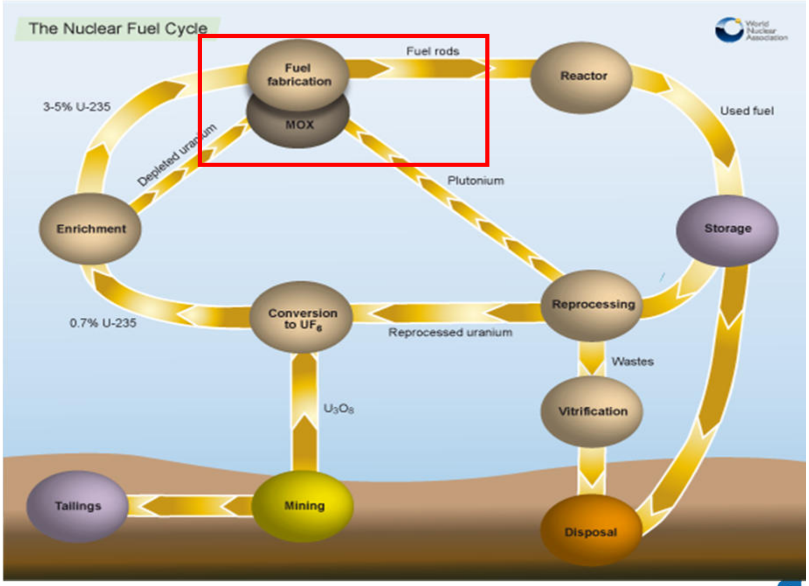


SWU & enrichment uses

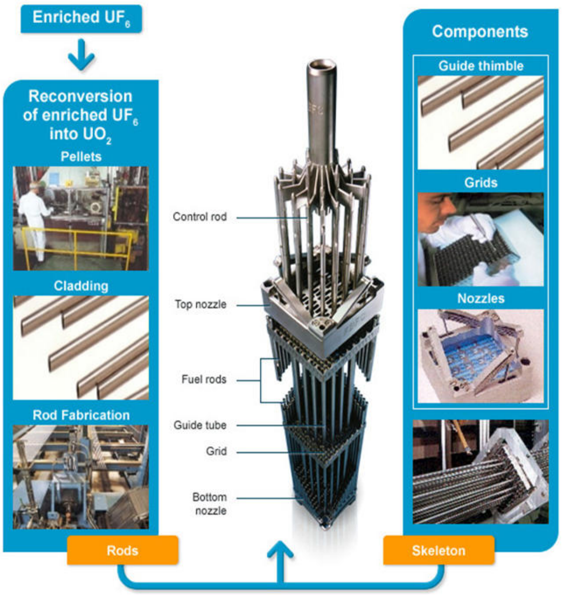




Fuel cycle



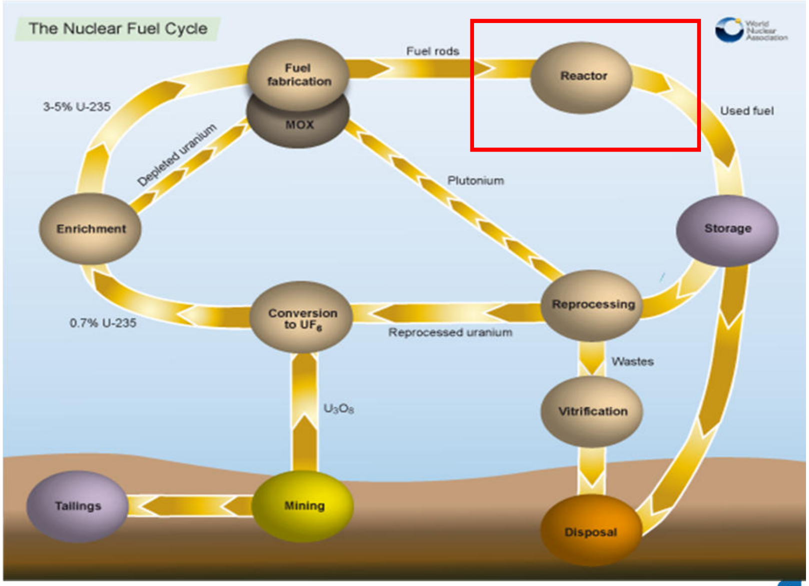
Fuel fabrication



Pellets & rods

Source: AREVA

Fuel cycle



Principle elements of a nuclear plant

- **Fuel** that undergoes fission.
- **Moderator** that slows down the speed of neutrons and maintain the chain reaction.
- **Coolant** which transmits the heat generated in the reactor and at the same time cooling of reactor.
- **Fuel, moderator and coolant vary according to the reactors' types. It is the combination of these three elements which defines the type of the nuclear power.**

Different types of reactor

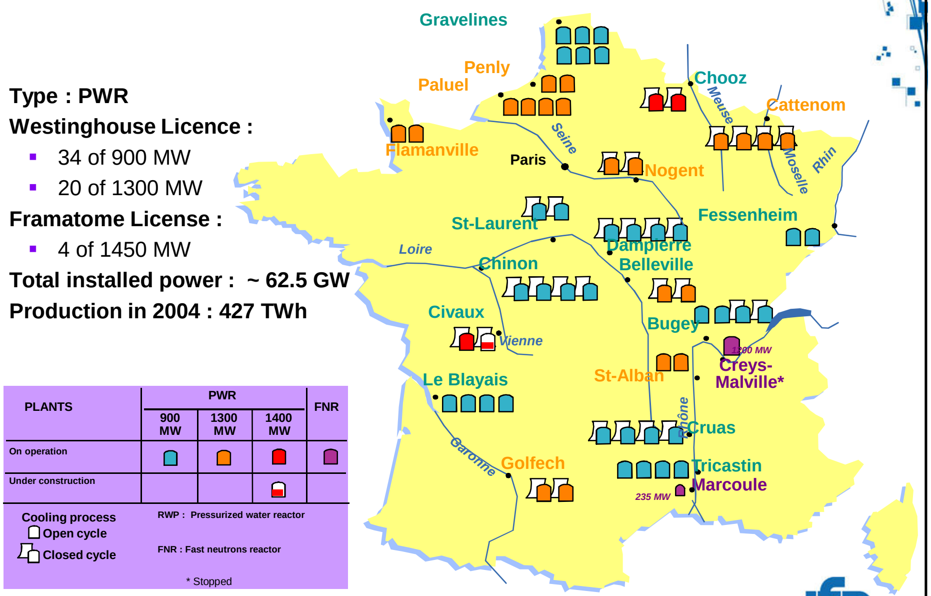
	Fuel	Moderator	Coolant			Spent Fuel Reprocessing	Steam Cycle Efficiency	Main Economic and Safety Characteristics
			Heat extraction	Outlet temp.	Pressure			
Magnox	Natural uranium metal (0.7% U^{235}) Magnesium alloy cladding	Graphite	Carbon dioxide gas heated by fuel raises steam in steam generator	360°C	300 psia	Typically within one year, for operational reasons	31%	Safety benefit that coolant cannot undergo a change of phase. Also ability to refuel whilst running gives potential for high availability
AGR	Uranium dioxide enriched to 2.3% U^{235} Stainless steel cladding	Graphite	Carbon dioxide gas heated by fuel raises steam in steam generator	650°C	600 psia	Can be stored under water for tens of years, but storage could be longer in dry atmosphere	42%	Same operational and safety advantages as Magnox but with higher operating temperatures and pressures., leading to reduced capital costs and higher steam cycle efficiencies
PWR	Uranium dioxide enriched to 3.2% U^{235} Zirconium alloy cladding	Light Water	Pressurised light water pumped to steam generator which raises steam in a separate circuit	317°C	2235 psia	Can be stored for long periods under water giving flexibility in waste management	32%	Low construction costs resulting from design being amenable to fabrication in factory-built sub-assemblies. Wealth of operating experience now accumulated world wide. Off load refuelling necessary
BWR	Uranium dioxide enriched to 2.4% U^{235} Zirconium alloy cladding	Light Water	Pressurised light water boiling in the pressure vessel produces steam which directly drives a turbine	286°C	1050 psia	As for PWR	32%	Similar construction cost advantages to PWR enhanced by design not requiring a heat exchanger, but offset by need for some shielding of steam circuit and turbine. Off load refuelling necessary
CANDU	Unenriched uranium dioxide (0.7% U^{235}) Zirconium alloy cladding	Heavy water	Heavy water pumped at pressure over the fuel raises steam via a steam generator in a separate circuit.	305°C	1285 psia	As for PWR	30%	Good operational record but requires infrastructure to provide significant quantities of heavy water at reasonable costs.
RBMK	Uranium dioxide enriched to 1.8% U^{235}	Graphite	Light water boiled at pressure, steam used to drive a turbine directly	284°C	1000 psia	Information not available	31%	Information not available but operated in considerable numbers in the former USSR. Believed in the West to be inherently less safe

Nuclear power plants in commercial operation

Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
→ Pressurised Water Reactor (PWR)	US, France, Japan, Russia, China	265	251.6	enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	86.4	enriched UO_2	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	44	24.3	natural UO_2	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	UK	18	10.8	natural U (metal), enriched UO_2	CO_2	graphite
Light Water Graphite Reactor (RBMK)	Russia	12	12.3	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Japan, France, Russia	4	1.0	PuO_2 and UO_2	liquid sodium	none
Other	Russia	4	0.05	enriched UO_2	water	graphite
	TOTAL	441	386.5			

French nuclear power plants

- **Type : PWR**
- **Westinghouse Licence :**
  - 34 of 900 MW
  - 20 of 1300 MW
- **Framatome License :**
  - 4 of 1450 MW
- **Total installed power : ~ 62.5 GW**
- **Production in 2004 : 427 TWh**



PLANTS	PWR			FNR
	900 MW	1300 MW	1400 MW	
On operation	🟦	🟧	🟥	🟪
Under construction			🟥	

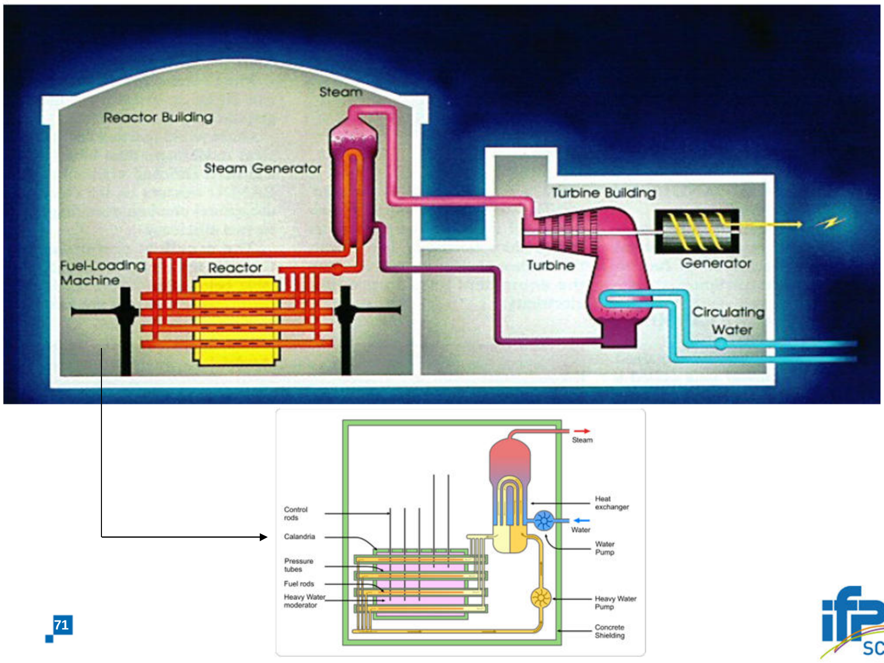
Cooling process
☐ Open cycle
☐ Closed cycle

RWP : Pressurized water reactor

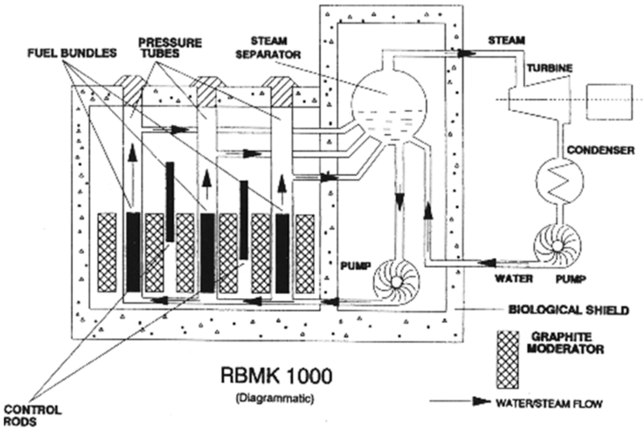
FNR : Fast neutrons reactor

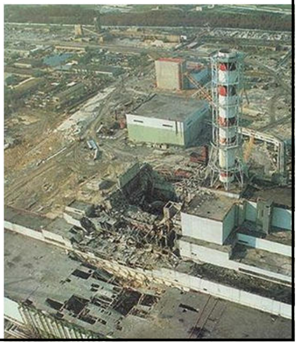
* Stopped

CANDU reactor

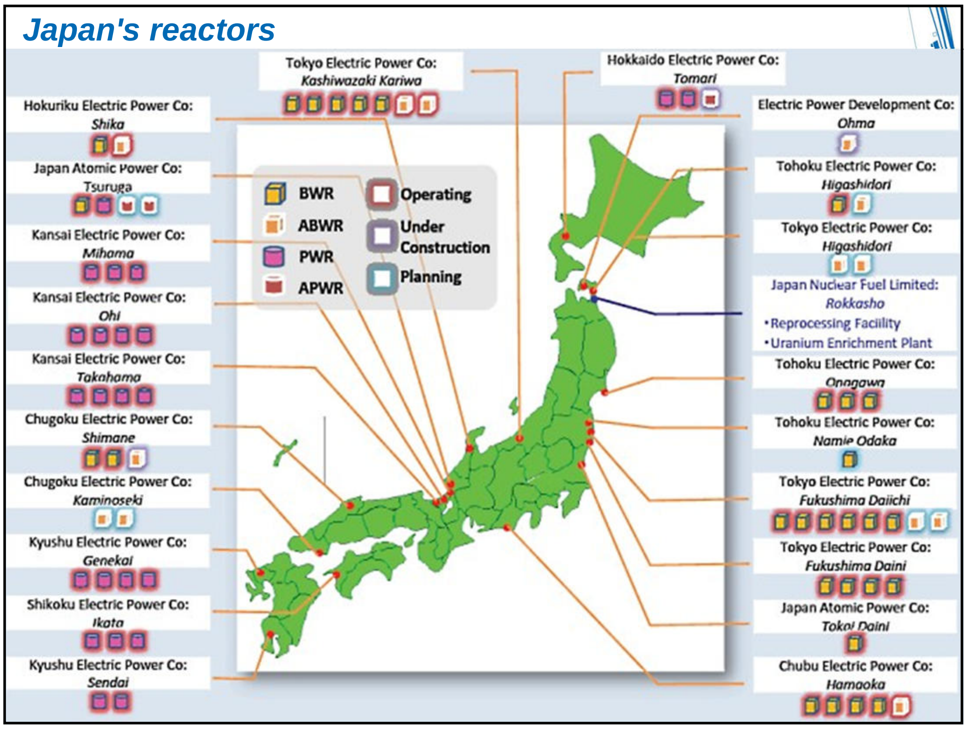


RBMK reactor!

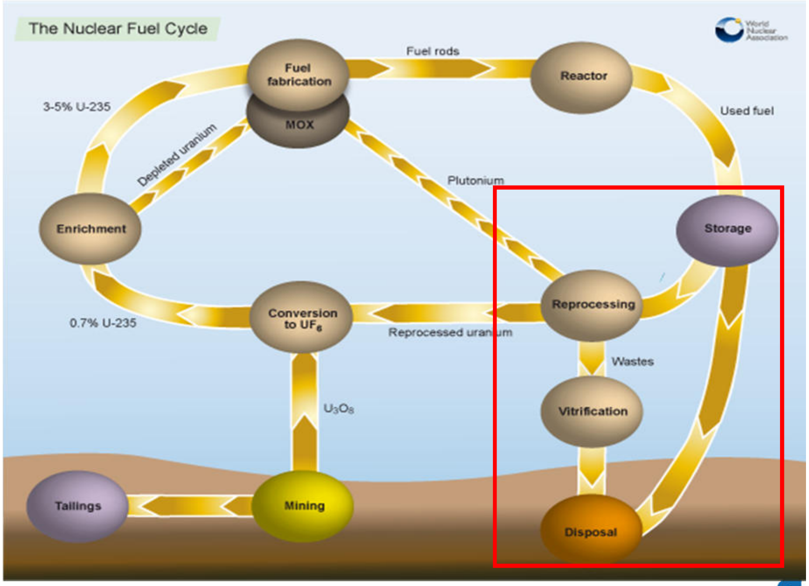




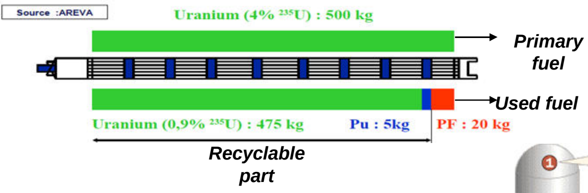
Japan's reactors

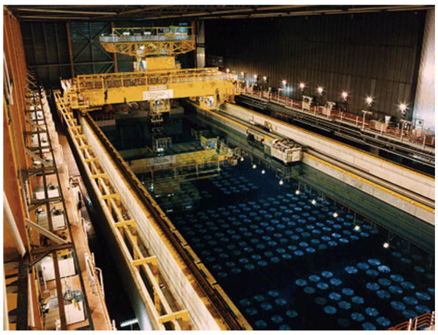


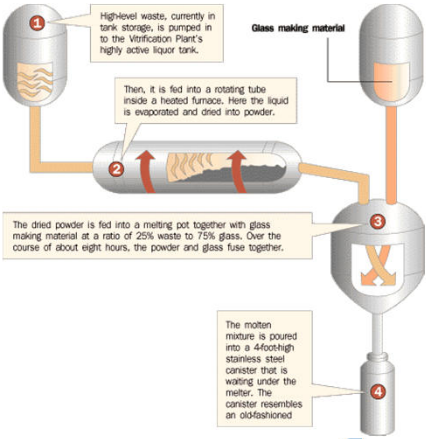
Fuel cycle



Nuclear wastes







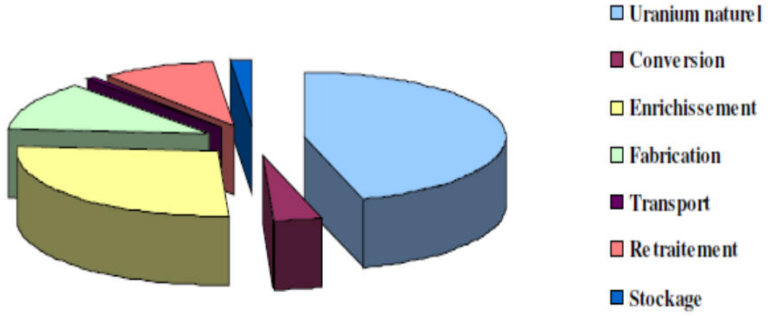
High-level waste, currently in tank storage, is pumped in to the Vitrification Plant's highly active liquor tank.

Then, it is fed into a rotating tube inside a heated furnace. Here the liquid is evaporated and dried into powder.

The dried powder is fed into a melting pot together with glass making material at a ratio of 25% waste to 75% glass. Over the course of about eight hours, the powder and glass fuse together.

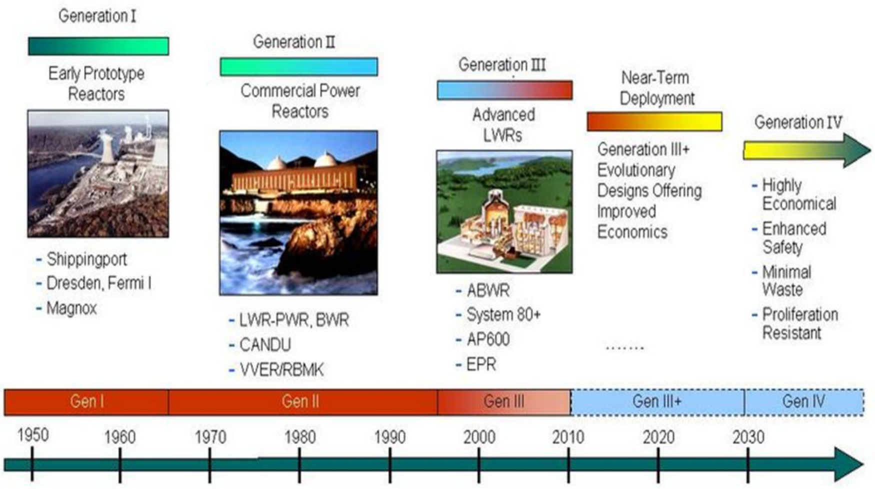
The molten mixture is poured into a 4-foot-high stainless steel canister that is waiting under the melter. The canister resembles an old-fashioned

Fuel cost decomposition for EPR (DGEC 2008)

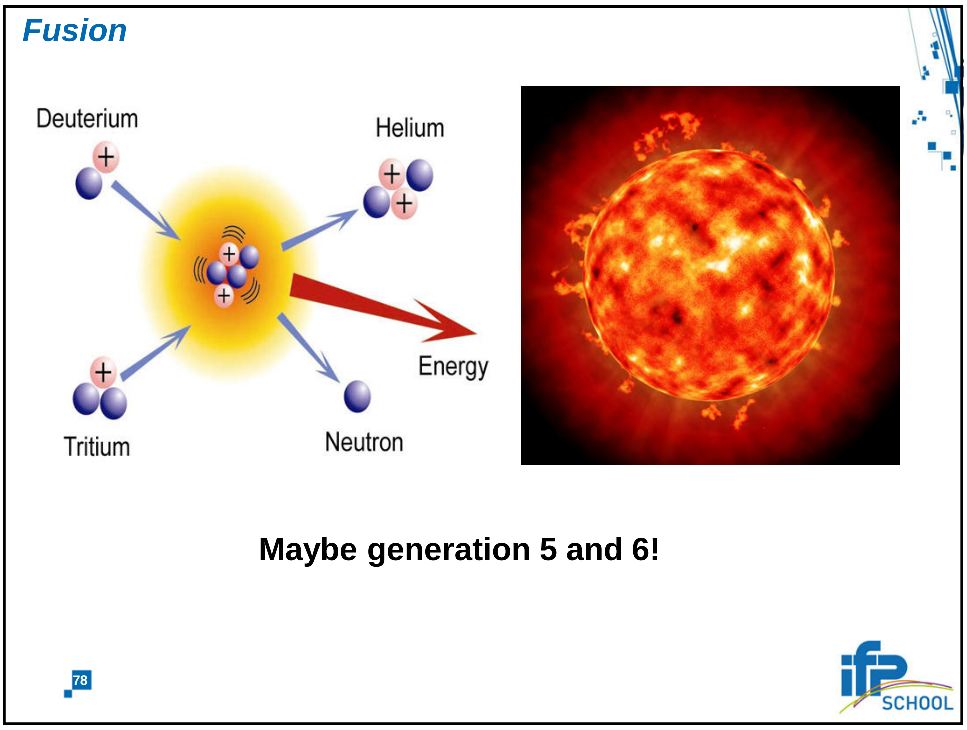


Décomposition du coût du combustible nucléaire (actualisation à 8% sauf pour l'aval du cycle)

Different reactor's generations

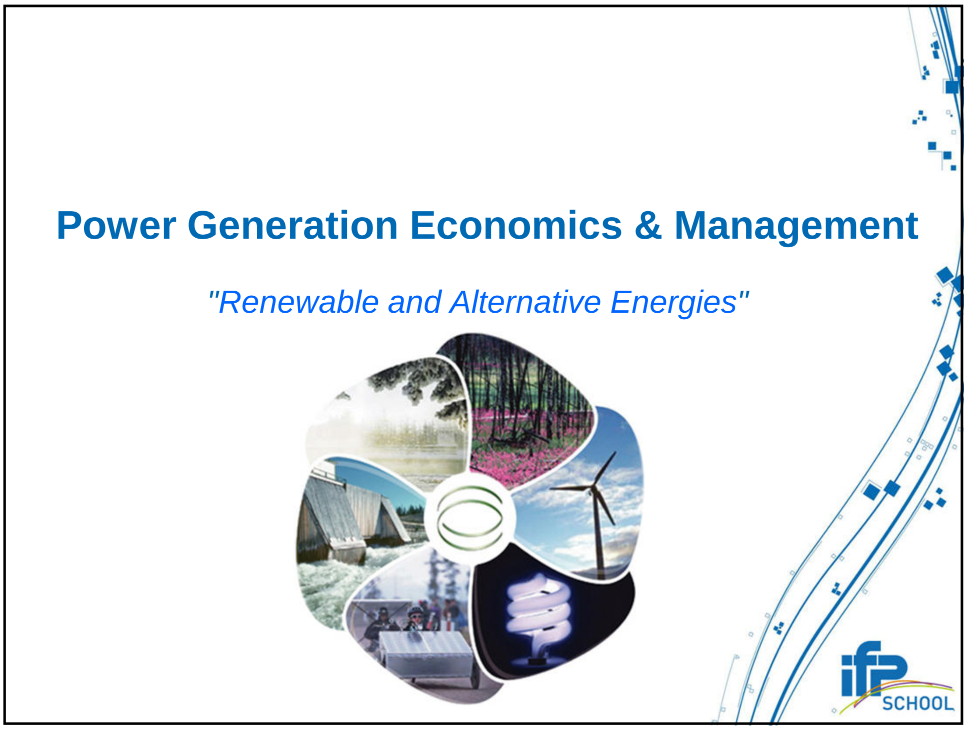


Fast neutron reactors



Fusion

Maybe generation 5 and 6!



Power Generation Economics & Management

"Renewable and Alternative Energies"

Renewable Energies – Overview

- The resources are considerable (for some of them: e.g. solar)
- Attractive: greenhouse effect, cost of fossil fuels, energy independence
- Some are intermittent (wind, solar)
- Large potential to become more competitive position via innovation, economies of scale, development of new materials, etc.
- Major companies now involved in renewables – will improve credibility, financability and will accelerate further R&D activities
- Still many opportunities for small companies to grow via innovation

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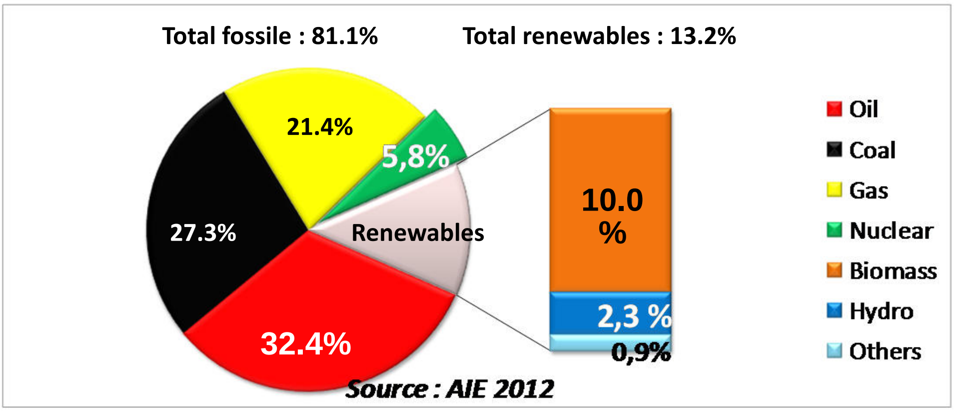
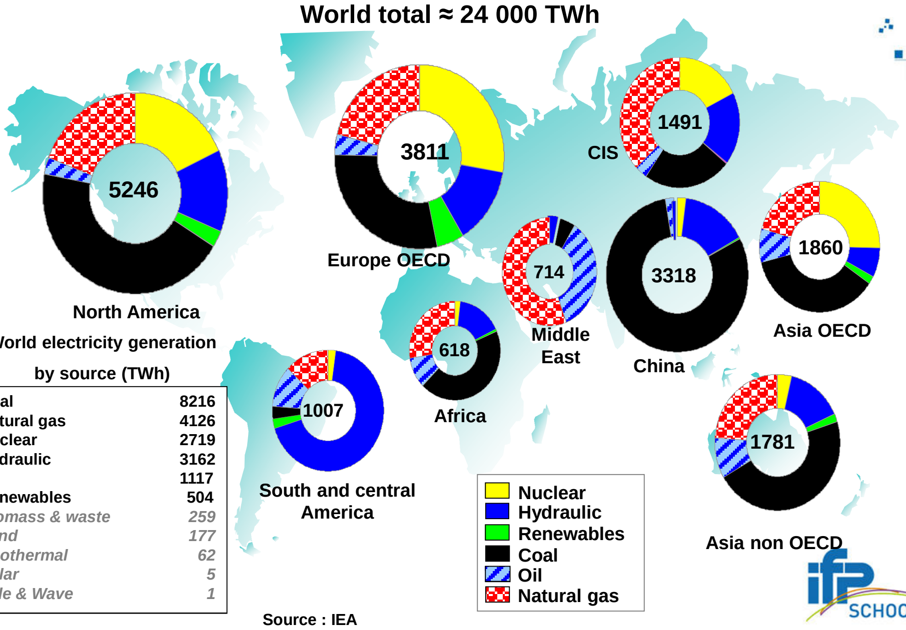
Share of renewable in world total primary energy supply (2015)



Source : AIE 2012

World electricity generation 2015

World total ≈ 24 000 TWh

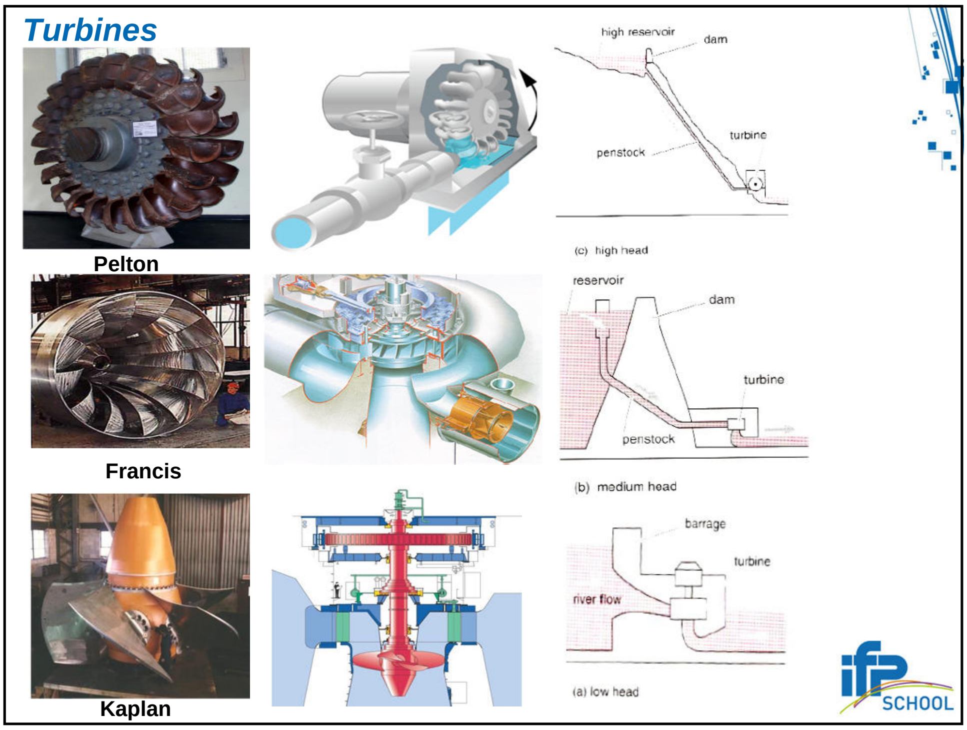


World electricity generation by source (TWh)

Coal	**8216**
Natural gas	**4126**
Nuclear	**2719**
Hydraulic	**3162**
Oil	**1117**
Renewables	**504**
Biomass & waste	*259*
Wind	*177*
Geothermal	*62*
Solar	*5*
Tide & Wave	*1*

Source : IEA

Hydroelectricity

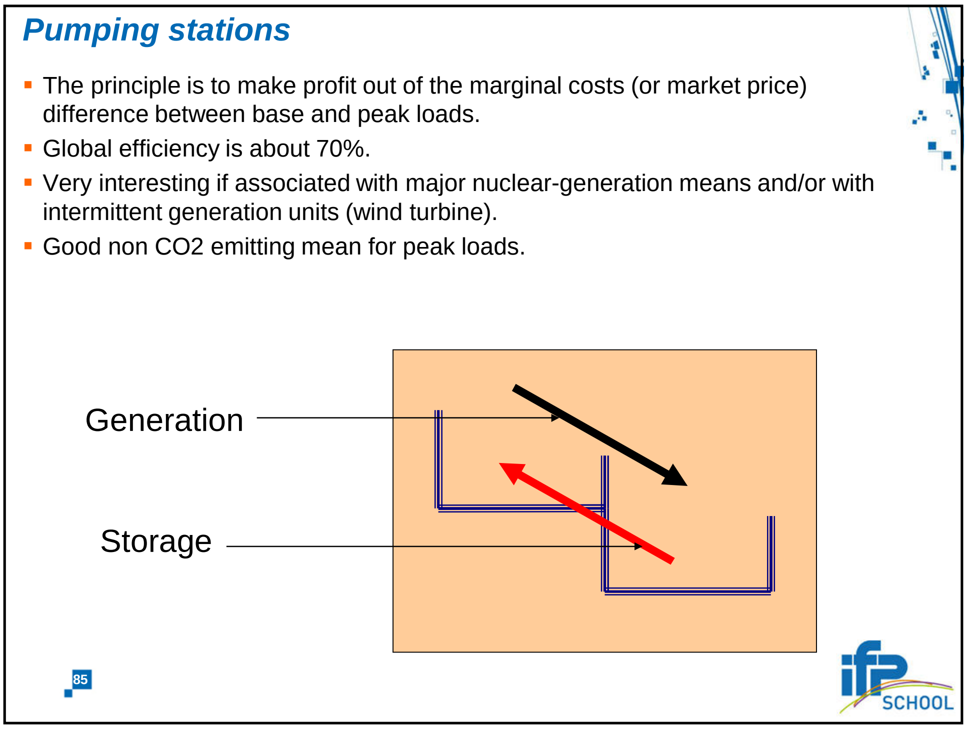


Turbines

Pelton

Francis

Kaplan



Pumping stations

- The principle is to make profit out of the marginal costs (or market price) difference between base and peak loads.
- Global efficiency is about 70%.
- Very interesting if associated with major nuclear-generation means and/or with intermittent generation units (wind turbine).
- Good non CO2 emitting mean for peak loads.

Generation

Storage

Hydro Electric Power

- Hydropower
  - 16% of all power generation
  - >90% of all renewable power generation

- 40 000 dams in the world
  - China, USA, Canada, Brazil, Russia, Norway...

- 300 MW on average
  - Three Gorges Dam: largest hydro project 18 GW - Will supply 10% of China’s power

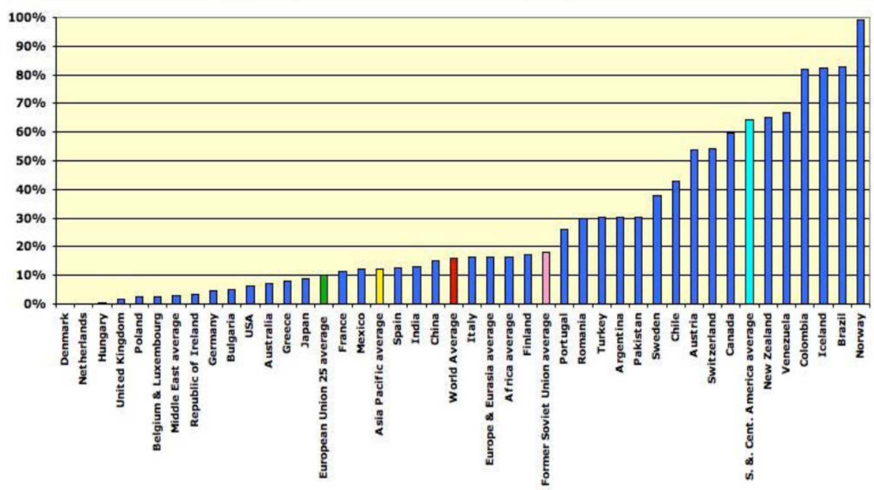
- Normally run as “base load”

- Pumped storage for “peaking”

- Provides irrigation

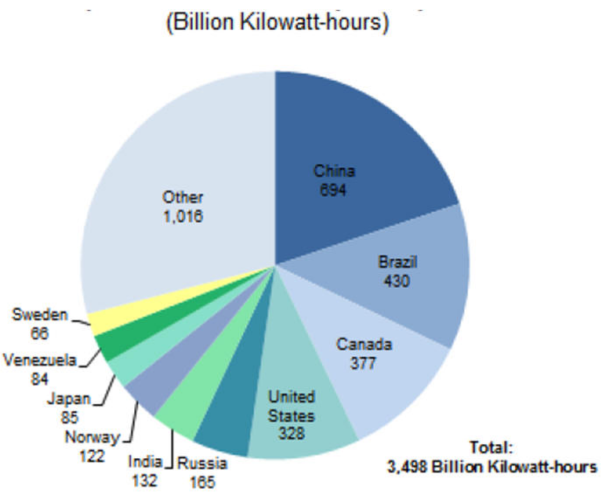
Hoover Dam
Nevada, USA

% of Hydroelectricity in the power generation of the country



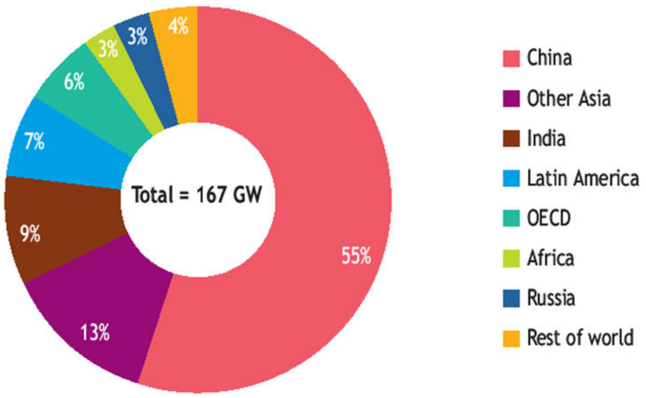
Source: BP Statistical review, 2015

Hydroelectric power generation by Countries

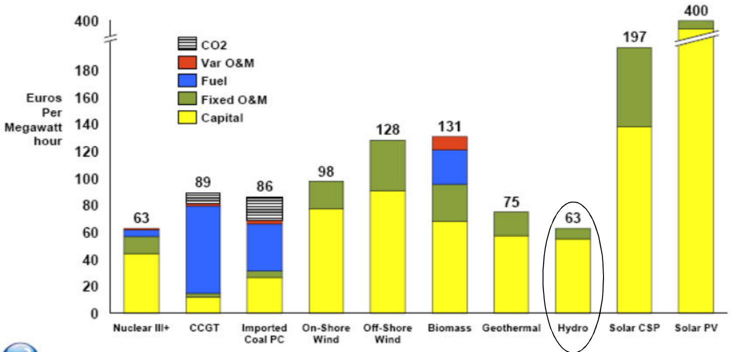


Source: BP Statistical review, 2015

Hydroelectric projects under construction in 2014



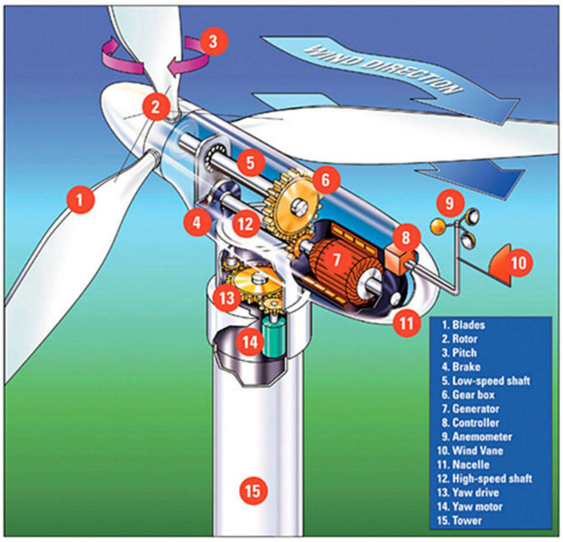
Generating Costs



Source: Cambridge Energy Research Associates.
Note: Nuclear II+ = Generation III plus; CCGT: Combined Cycle Gas Turbine; PC: Pulverized Coal; CSP: Concentrated Solar Power; PV: Photovoltaic
Fuel prices used: gas Eurocents 3.2 per kilowatthour; coal: $135 per tonne; CO_2: €22 per tonne
Overnight capital costs per kilowatt used: €3,060 for nuclear, €746 for CCGT, €1,665 for PC, €1,400 for onshore wind, €2,300 for offshore wind CERA_Template_MMDD08

Wind Power

Wind turbines



Wind power (Pw) :

$0.5 \rho V^{3}$ watts per m^2

The maximum power that can be extracted is 0.593 Pw. This quantity is referred to as the Betz limit.

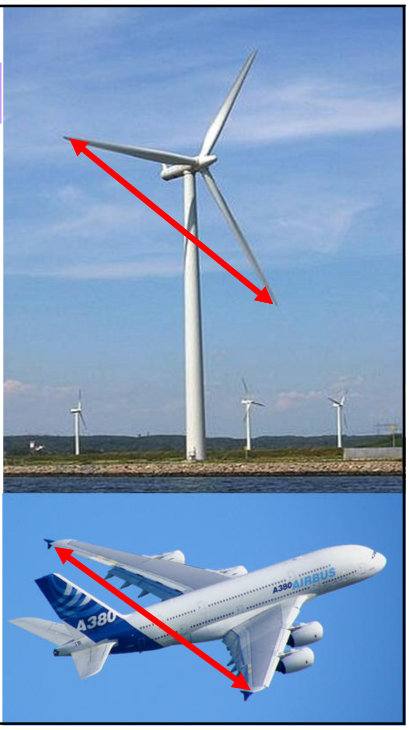
Wind turbines (2.7 MW)

***Load-factor* : all the energy generated divided by the full capacity over a period of time.**

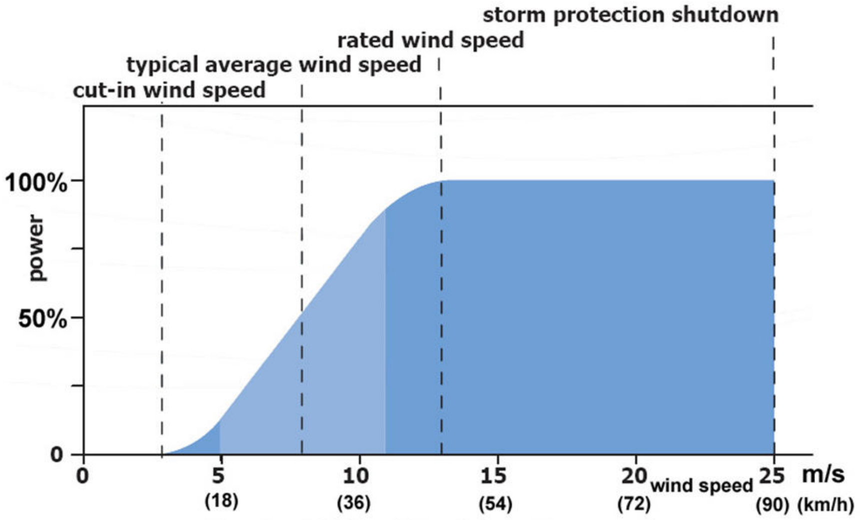
Load factor of a wind turbine : 18 to 35 %

Typically :

- stopped 30% of the time (not enough wind)
- 60% under its rated load
- 10% near its rated load

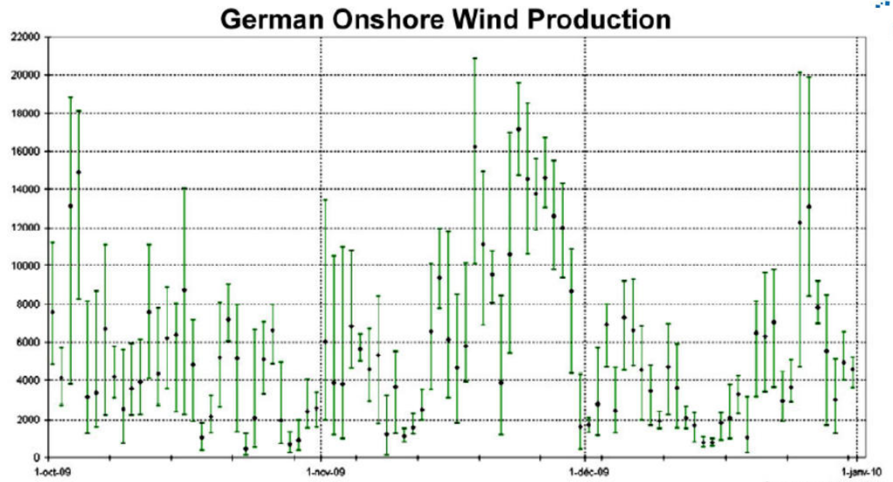


Power curve

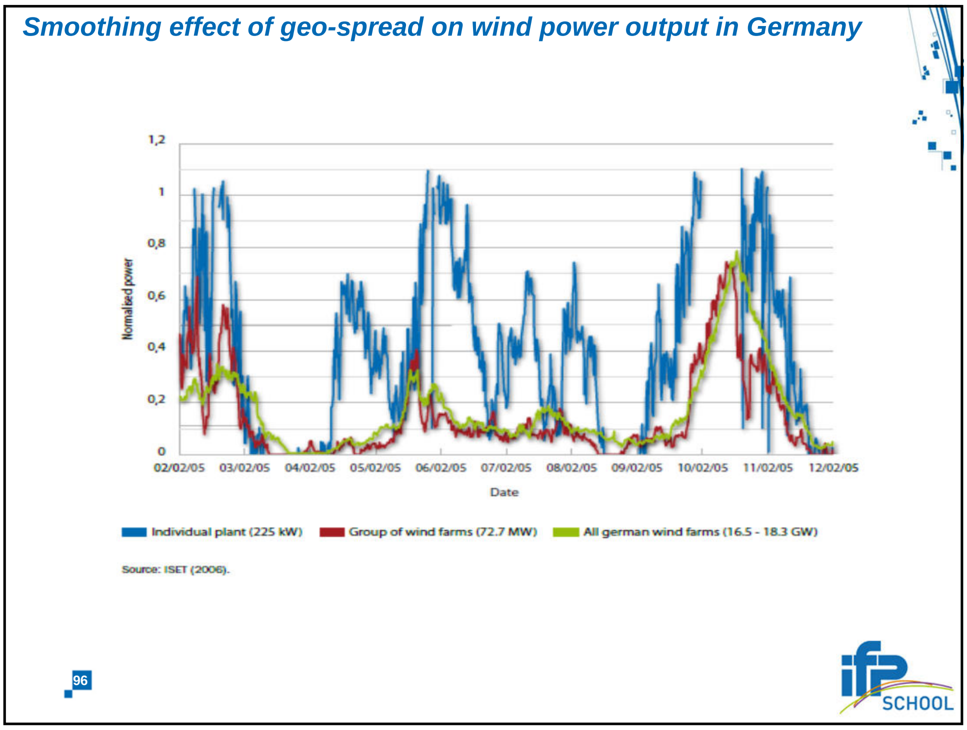


Typical Wind Turbine Power Curve

Power generation variation by a wind farm

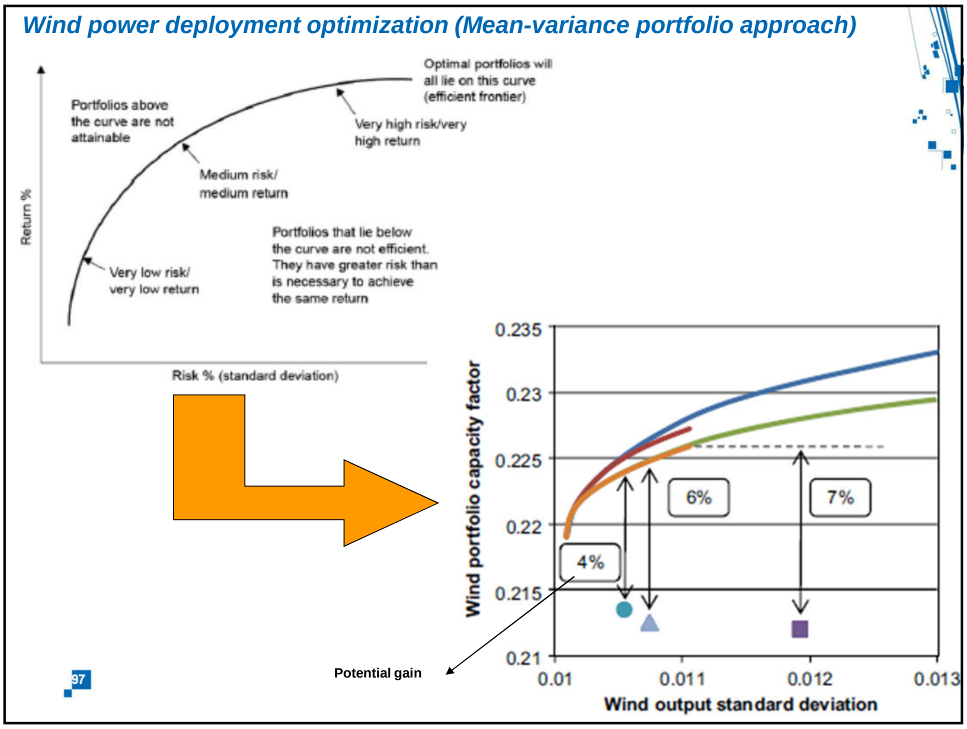


Source : BDEW



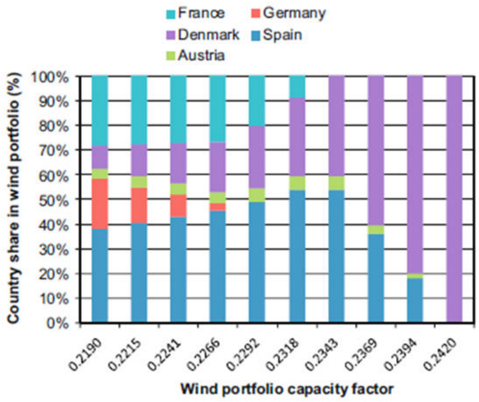
Smoothing effect of geo-spread on wind power output in Germany

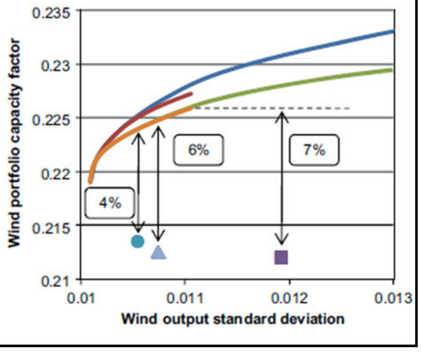
Source: ISET (2006).



Wind power deployment optimization (Mean-variance portfolio approach)

Wind power deployment optimization (MVP approach)





Feed-in-tariff (or premium) with locational component or a European green certificates trading scheme which would integrate these geographic portfolio effects.

Support schemes and Market design (e.g. in Europe)

Feed-in Tariff

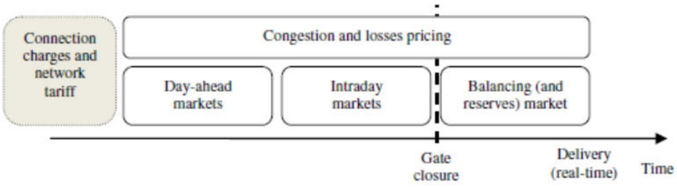
Guarantees a fixed price for the total wind energy amount fed into the grid.

Feed-in Premium

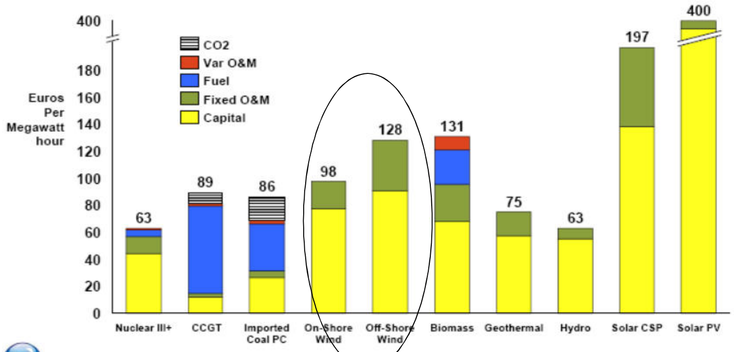
Under this scheme, producers receive the elec. market price and a fixed regulated premium.

Green Certificate

Based on the level of renewable generation obligation imposed on suppliers.



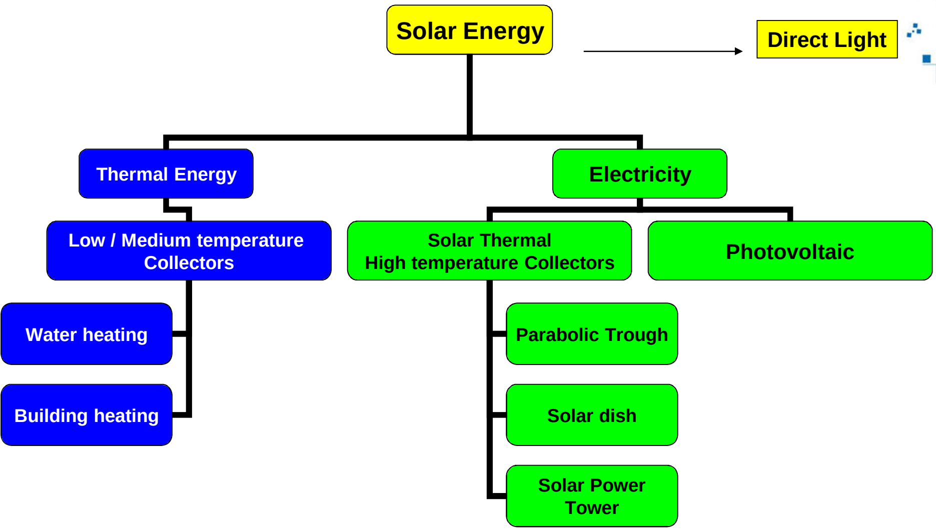
Generating Costs



Source: Cambridge Energy Research Associates.
Note: Nuclear II+ = Generation III plus; CCGT: Combined Cycle Gas Turbine; PC: Pulverized Coal; CSP: Concentrated Solar Power; PV: Photovoltaic
Fuel prices used: gas Eurocents 3.2 per kilowatthour; coal: $135 per tonne; CO_2: €22 per tonne
Overnight capital costs per kilowatt used: €3,060 for nuclear, €746 for CCGT, €1,665 for PC, €1,400 for onshore wind, €2,300 for offshore wind CERA_Template_MMDD08

Solar

Conversions of solar energy

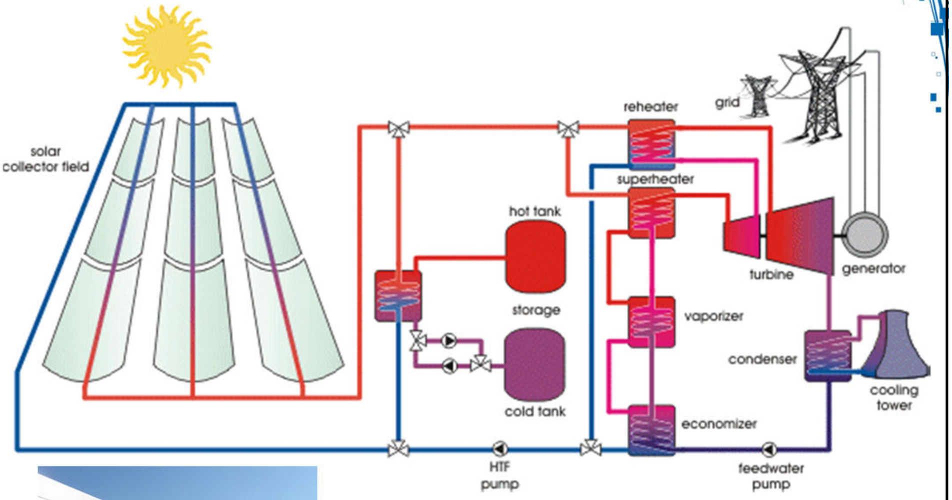


Solar Energy

Direct Light

- **Thermal Energy**
  - **Low / Medium temperature Collectors**
    - **Water heating**
    - **Building heating**
- **Electricity**
  - **Solar Thermal High temperature Collectors**
    - **Parabolic Trough**
    - **Solar dish**
    - **Solar Power Tower**
  - **Photovoltaic**

Solar thermal power plant



Concentration solar power plant

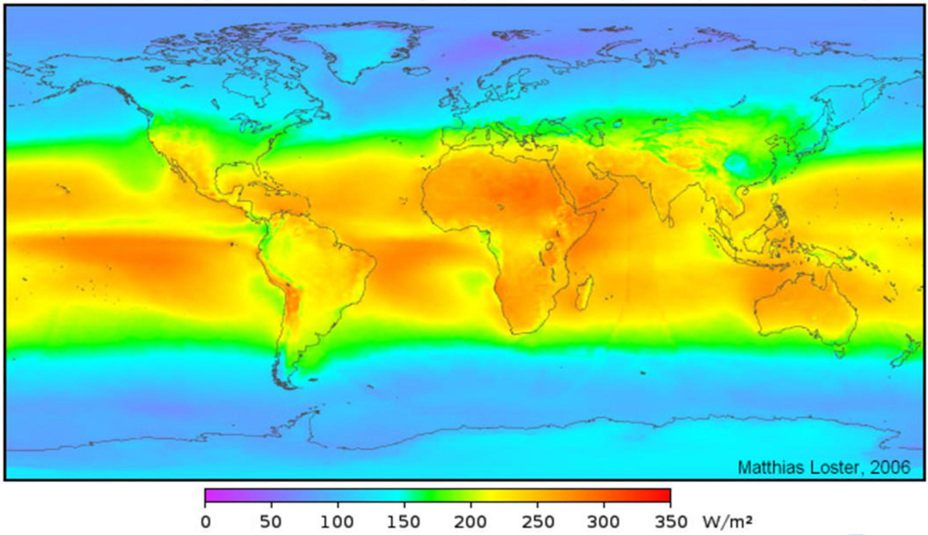
11 MW Sanlucar (near Seville) thermal solar power plant in Spain

In operation since 2007

Steam 40 bars, 250° C, storage capacity : 1 h

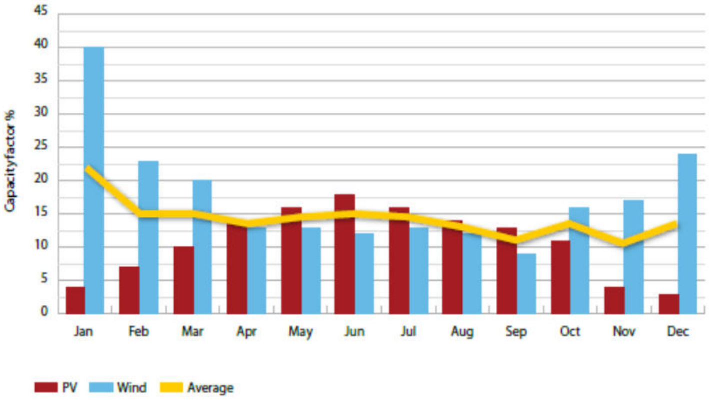
Potential of solar energy

Max electric power delivered by a photovoltaic panel (10% efficiency)

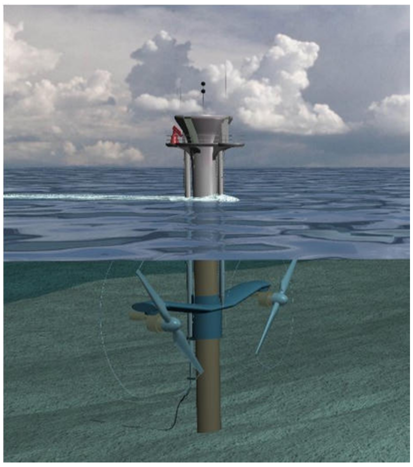


Matthias Loster, 2006

Monthly capacity factors for wind and PV, Germany, 2015



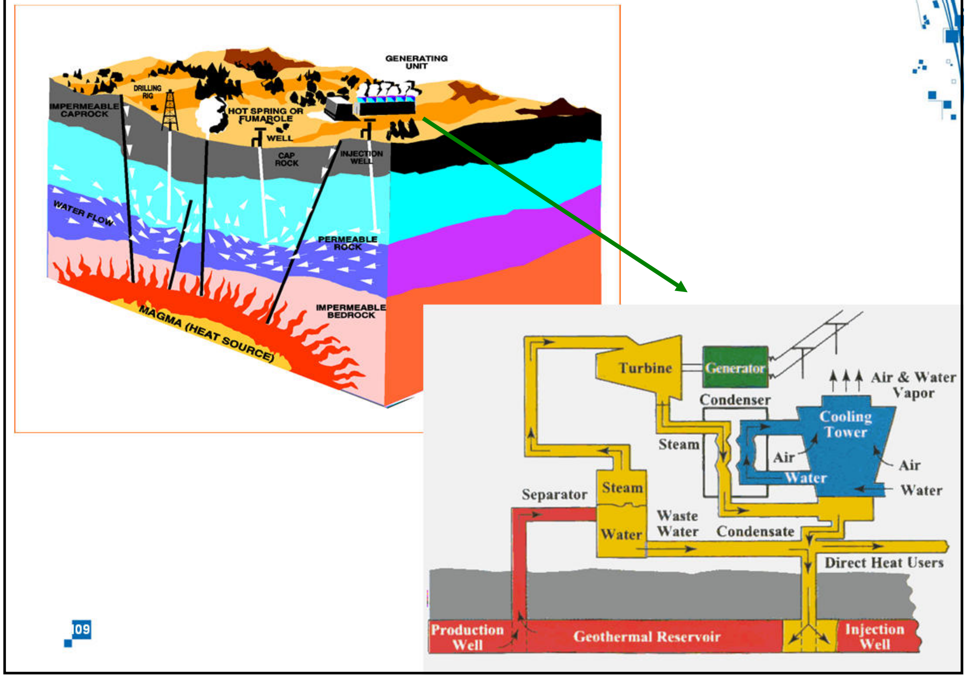
Geothermal and Sea energy



Geothermal and sea energy

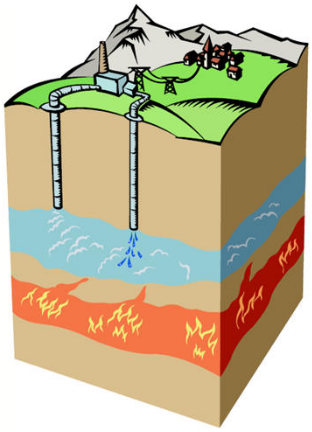
- Geothermal energy
- Tidal / current energy
- Wave energy
- Osmotic energy
- Ocean (temperature gradient energy)

Geothermal energy



Geothermal Power Generation

- **10 GW installed worldwide**
- **Used in 21 countries, usually where have high geological activity:**
  - **USA 2.2 GW**
  - **Philippines 1.9 GW**
  - **Italy 0.8 GW**
  - **Indonesia 0.6 GW**
- **Base-load power generation**
- **Clean energy – does not produce CO2**
- **Cost competitive with fossil fuels**
- **Enormous resource base worldwide**
  - **Especially if use deep drilling techniques**
- **Long term growth capability**
- **Increased focus of late**
- **Provides energy security/diversification**



Tidal power / Marine current power

- Tidal barrage
  - **Rance river : 240 MW**
  - **Annual production: 600 GWh (since 1966)**
- Tidal stream systems
  - **Relatively new technology**
  - **Prototype units around 1MW**
- Tidal lagoon
- Marine current stream generators

La Rance, France 240 MW

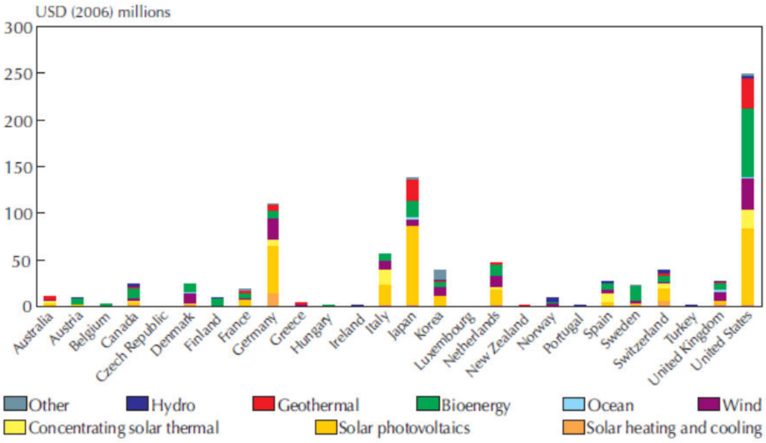
Tidal Range: 8 m

Wave Power Generation – e.g. Pelamis

Pelamis devise

- Waves are a highly concentrated energy source with regular energy availability
- Western Europe offers many excellent high energy wave sites
- Many devises under development & test
- OPD - a Scottish company:
  - Funded by government agencies & venture capital - tested the Pelamis machine off Orkney,
  - Order to build the first phase of the world's first commercial wave-farm in Portugal
  - The initial phase - 3 machines sited 5km from shore
  - Project - €8m with capacity of 2.25MW
  - Anticipate 30 more machines (20MW)

Average annual R&D budgets for renewable (1990-2014)



Average annual R&D budgets for renewable as a percentage of GDP

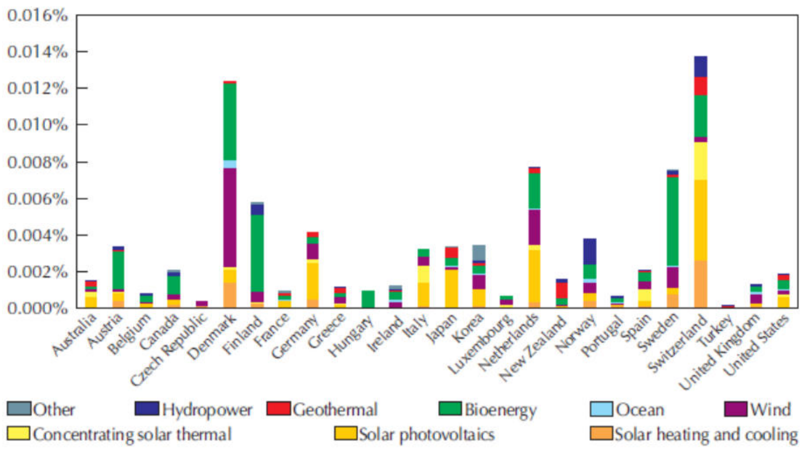
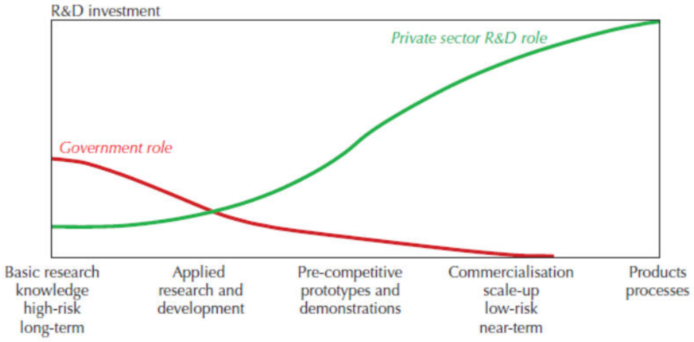
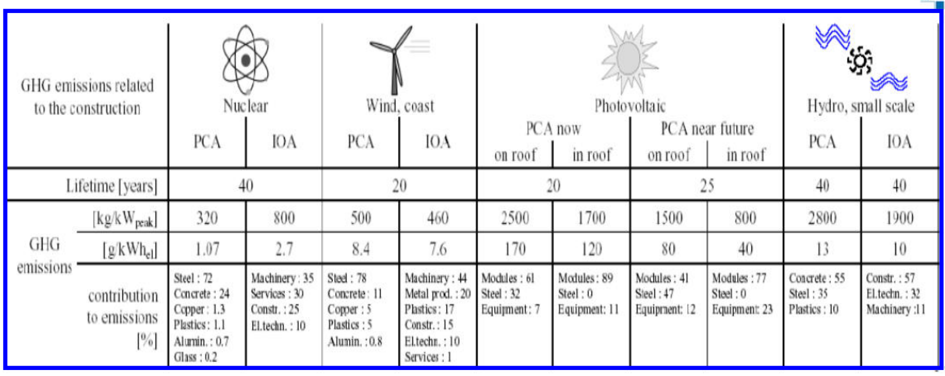


Illustration of respective government and private sector RD&D roles in phases of research over time



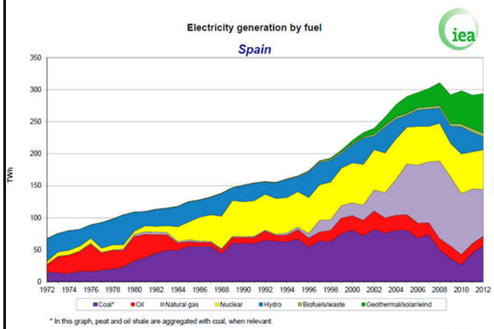
Indirect emissions of electricity generation

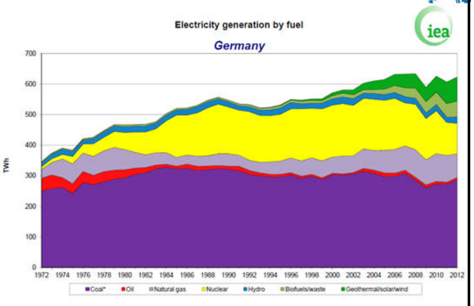


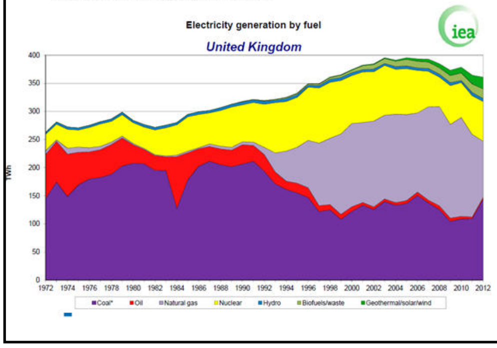
GHG emissions related to the construction		Nuclear		Wind, coast		Photovoltaic				Hydro, small scale	
						PCA now		PCA near future			
		PCA	IOA	PCA	IOA	on roof	in roof	on roof	in roof	PCA	IOA
Lifetime [years]		40		20		20		25		40	40
GHG emissions	[kg/kW$_{peak}$]	320	800	500	460	2500	1700	1500	800	2800	1900
	[g/kWh$_{el}$]	1.07	2.7	8.4	7.6	170	120	80	40	13	10
	contribution to emissions [%]	Steel : 72 Concrete : 24 Copper : 1.3 Plastics : 1.1 Alumin. : 0.7 Glass : 0.2	Machinery : 35 Services : 30 Constr. : 25 El.techn. : 10	Steel : 78 Concrete : 11 Copper : 5 Plastics : 5 Alumin. : 0.8	Machinery : 44 Metal prod. : 20 Plastics : 17 Constr. : 15 El.techn. : 10 Services : 1	Modules : 61 Steel : 32 Equipment : 7	Modules : 89 Steel : 0 Equipment: 11	Modules : 41 Steel : 47 Equipment: 12	Modules : 77 Steel : 0 Equipment: 23	Concrete : 55 Steel : 35 Plastics : 10	Constr. : 57 El.techn. : 32 Machinery :11

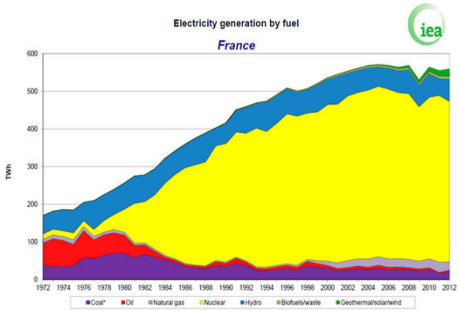
Source : University of Leuven (Belgium) - 2006

Generation utility means (Europe)

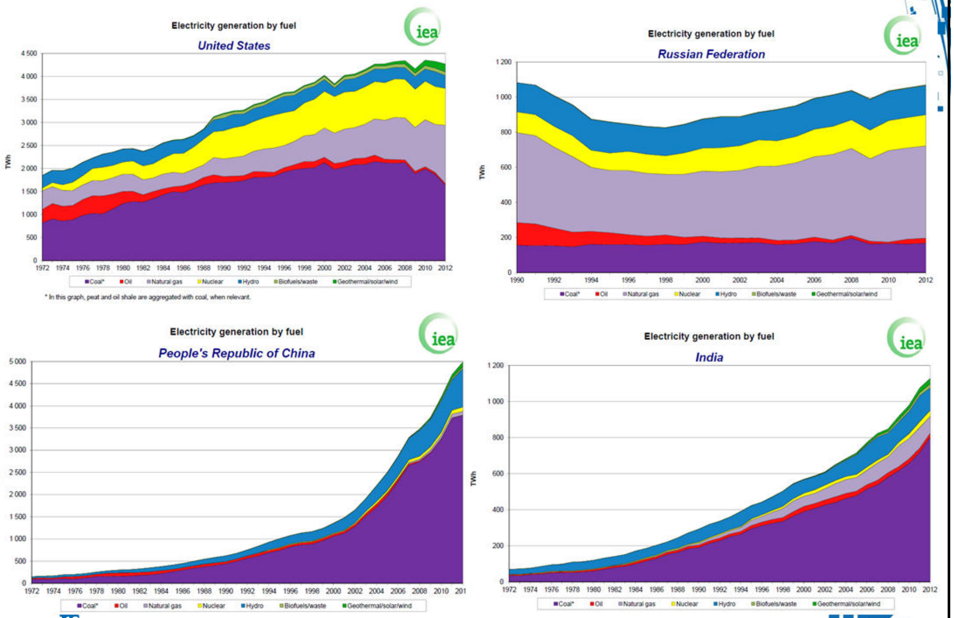




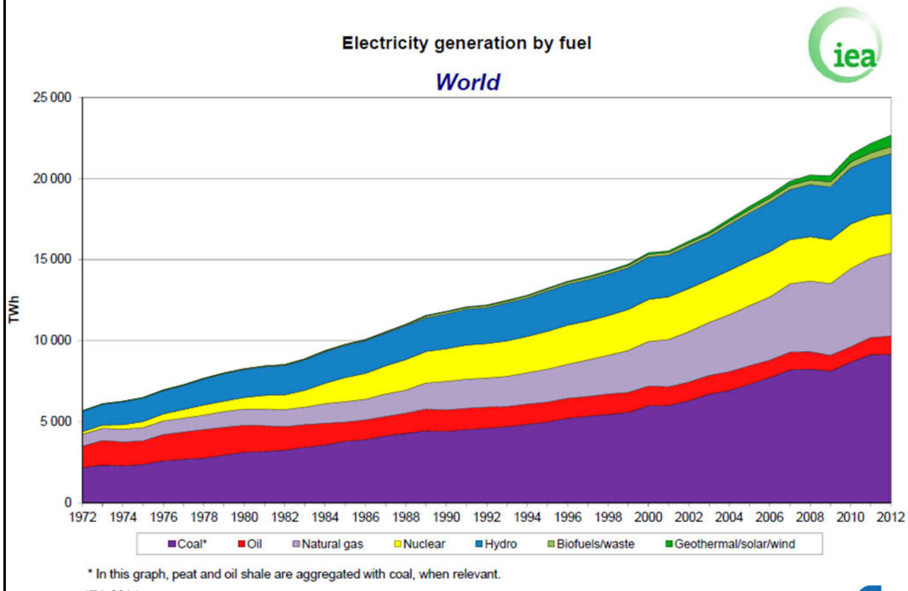




Generation utility means (US, Russia, China & India)



World electricity generation



* In this graph, peat and oil shale are aggregated with coal, when relevant.

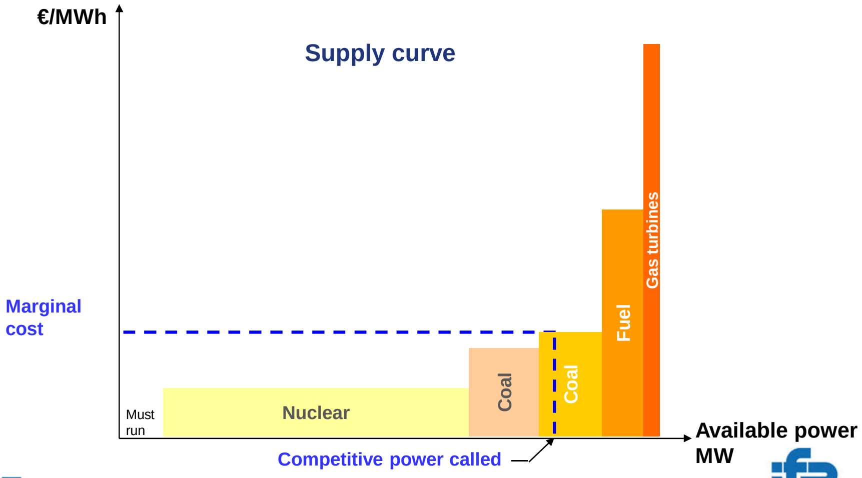
IEA 2014

Power Generation Economics & Management

"Generation Cost "

Merit Order

The "Merit Order" consists of economic ranking of the generation means in order to adjust the production to the demand at a given time.



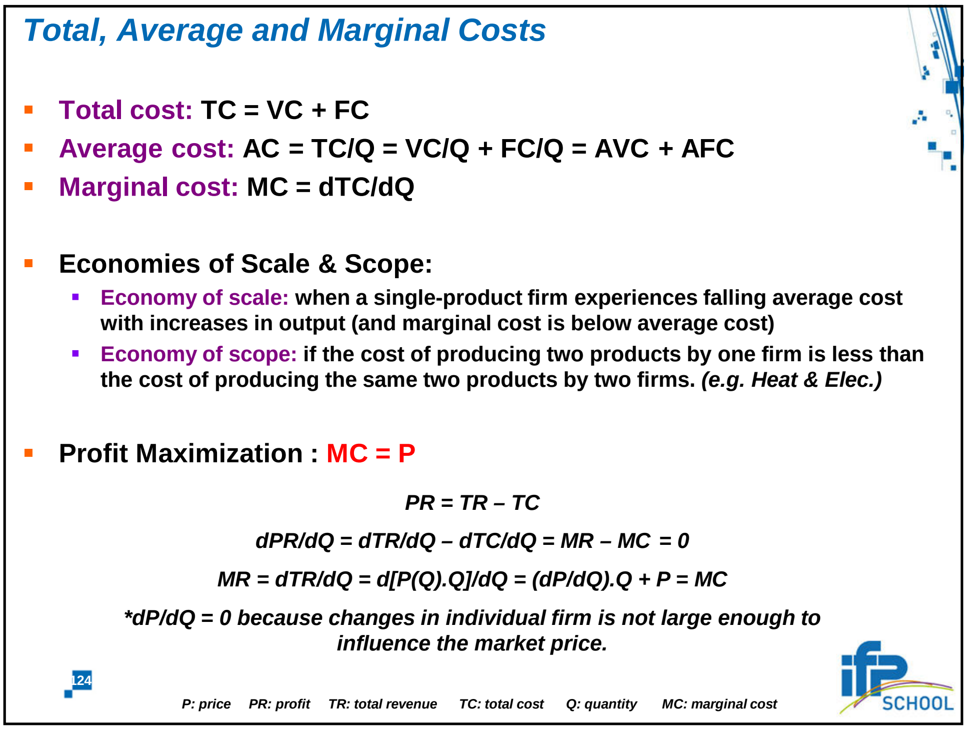
Some definitions

- **Cost ≠ Price :** **first is the Σ of expenditures and the second is the result of market equilibrium.**
- **Accounting cost ≠ Economic cost :** **first comes from financial statements but the second comes out of profitability study & opportunity cost approach.**
  - **Opportunity cost :** **the highest alternative value of all resources used in the production of a good or service.**
  - **Here we are interested in economic cost.**
- **Total cost ≠ Marginal cost :** **first includes fixed, variable, startup and no-load costs and the second is the change in total cost with a unit (KWh) increase (or decrease) in production.**

Short run vs. Long run

- ***Fixed costs*** **are fixed during some period but** ***Variable costs*** **vary by the time. We define** ***short run*** **as a period during there are some fixed costs.**

Time	Cost	Technology
very short run	**all** cost are fixed	fixed
short run	**some** costs are fixed	fixed
long run	**no** costs are fixed	fixed
very long run	**no** costs are fixed	**not fixed**



Total, Average and Marginal Costs

- **Total cost:** TC = VC + FC
- **Average cost:** AC = TC/Q = VC/Q + FC/Q = AVC + AFC
- **Marginal cost:** MC = dTC/dQ

- Economies of Scale & Scope:
  - **Economy of scale:** when a single-product firm experiences falling average cost with increases in output (and marginal cost is below average cost)
  - **Economy of scope:** if the cost of producing two products by one firm is less than the cost of producing the same two products by two firms. *(e.g. Heat & Elec.)*

- Profit Maximization : MC = P

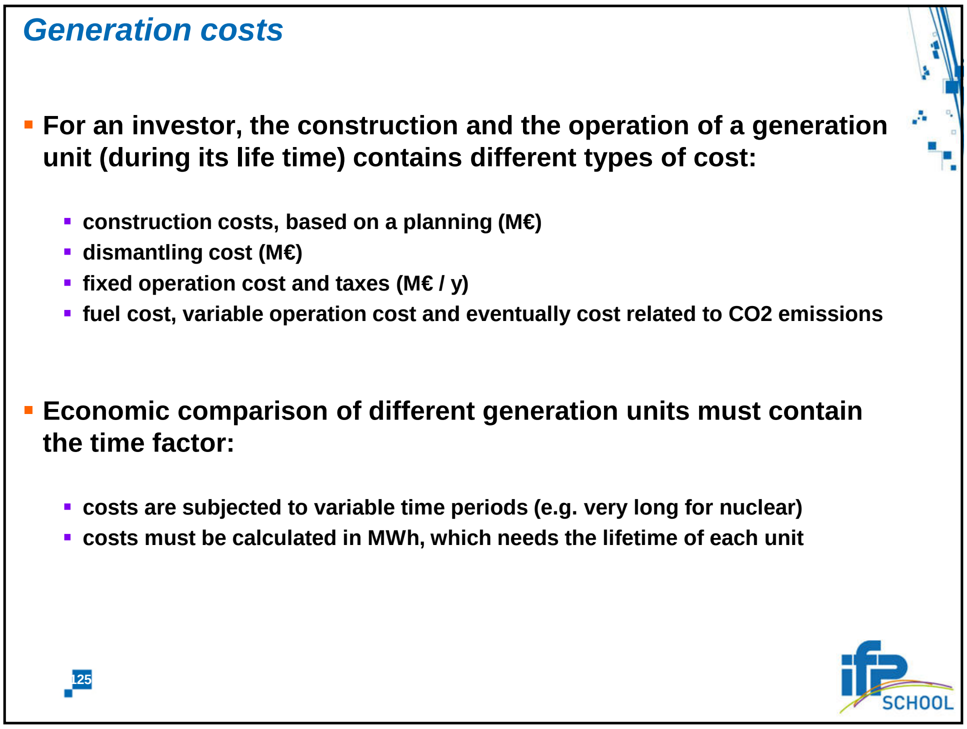
PR = TR – TC

dPR/dQ = dTR/dQ – dTC/dQ = MR – MC = 0

MR = dTR/dQ = d[P(Q).Q]/dQ = (dP/dQ).Q + P = MC

**dP/dQ = 0 because changes in individual firm is not large enough to influence the market price.*

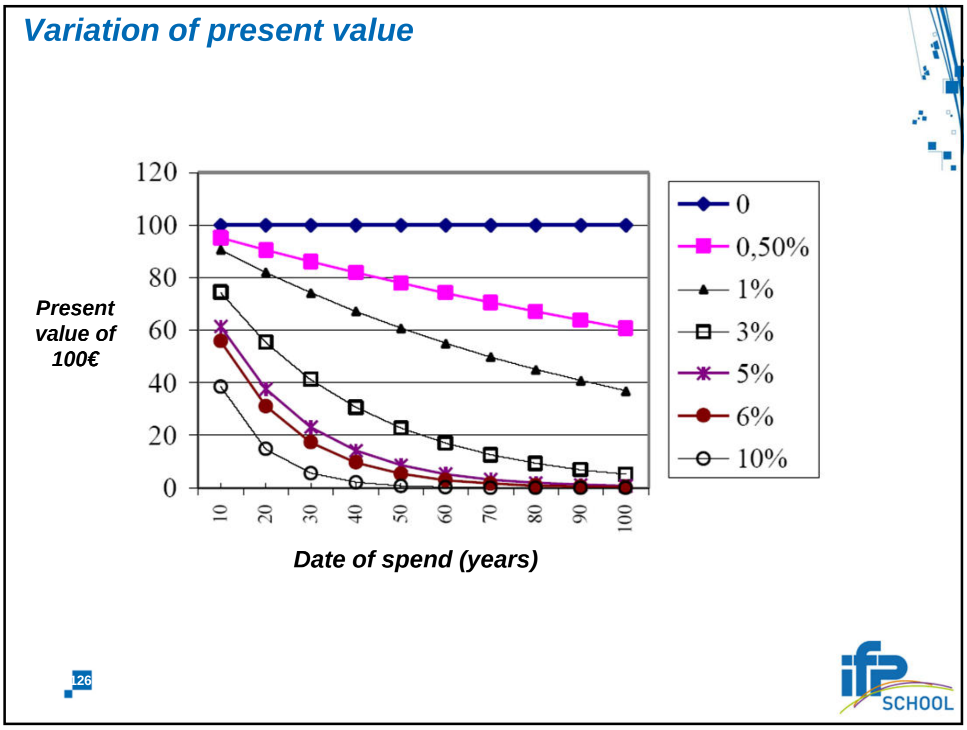
P: price PR: profit TR: total revenue TC: total cost Q: quantity MC: marginal cost



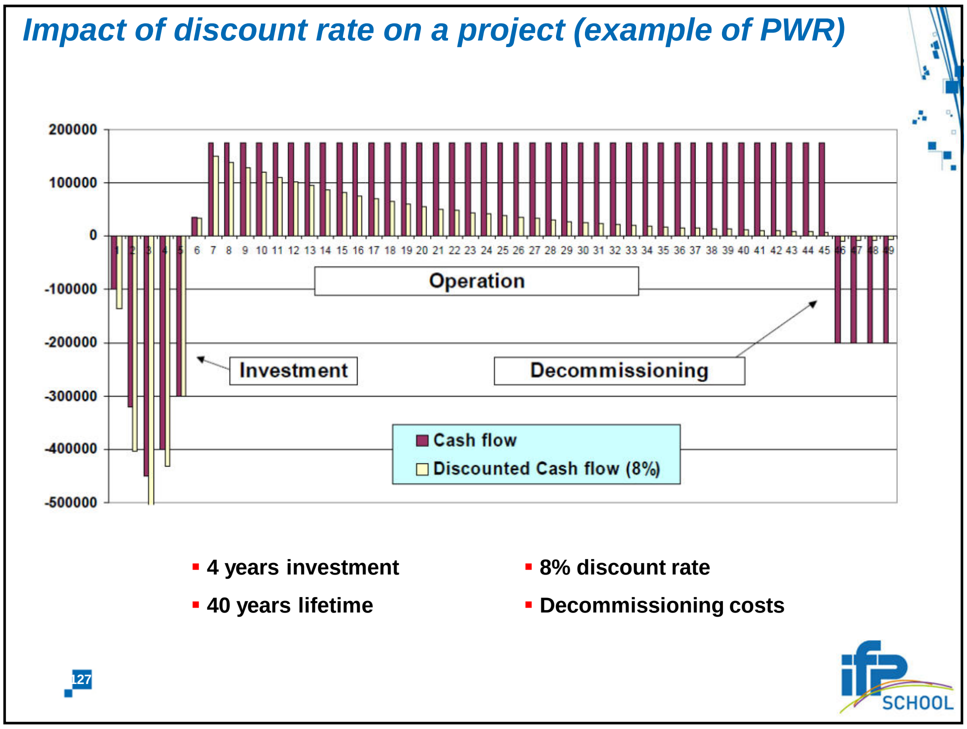
Generation costs

- For an investor, the construction and the operation of a generation unit (during its life time) contains different types of cost:
  - construction costs, based on a planning (M€)
  - dismantling cost (M€)
  - fixed operation cost and taxes (M€ / y)
  - fuel cost, variable operation cost and eventually cost related to CO2 emissions

- Economic comparison of different generation units must contain the time factor:
  - costs are subjected to variable time periods (e.g. very long for nuclear)
  - costs must be calculated in MWh, which needs the lifetime of each unit



Variation of present value



Impact of discount rate on a project (example of PWR)

- **4 years investment**
- **40 years lifetime**
- **8% discount rate**
- **Decommissioning costs**

Total cost

- **The "Overnight" cost of capacity**
  - **It is typically given in $/KW.**
  - **This is the present-value cost of the plant.**
    - For example, it might be $1050/KW for a coal plant or $350/KW for a conventional gas-turbine generator (GT).
      - ***Is it 3 times cheaper to produce electricity with GT?***
    - Assume coal costs $10/MWh of energy produced and cost of fuel for a GT comes to around $35/MWh.
      - ***Now which plant is cheaper?***
    - Now, assume that the load has duration of 25% (2190h/y) so it will have a capacity factor of 25%.
      - ***Finally which plant would be the cheapest one?***

The overnight cost concerns the Fixed costs and the fuel cost concerns Variable costs.

Total cost

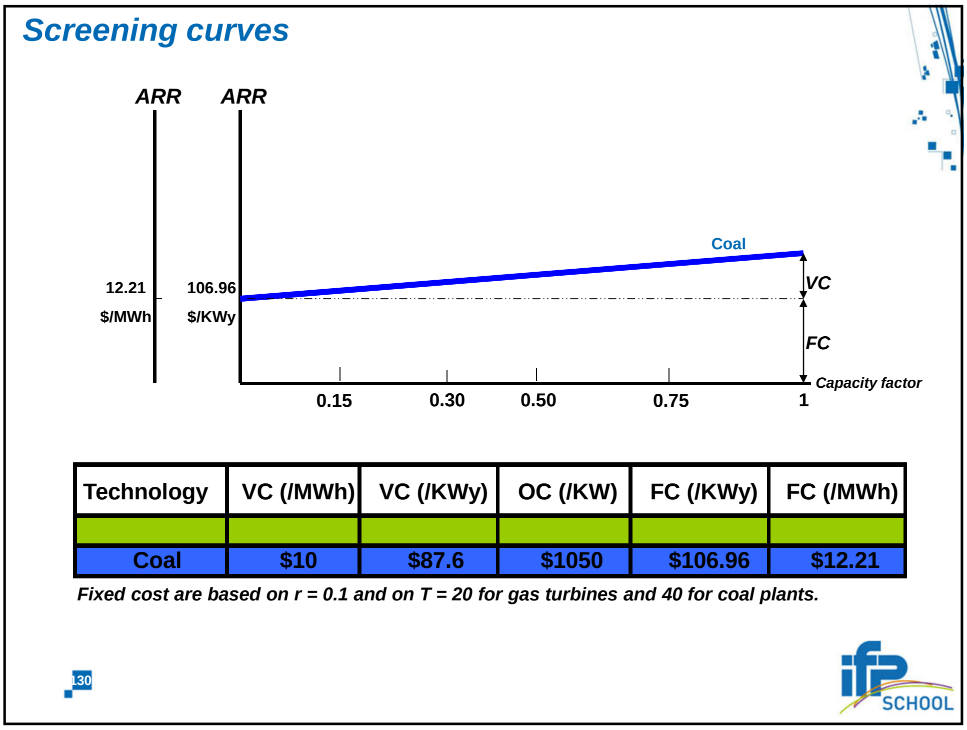
- **Identifying fixed costs**
  - **The correct fixed-cost is the overnight cost amortized (levelized) over the life of the plant.**

$$FC^* = \frac{r \times OC}{1-1/(1+r)^T}$$

**FC depends on overnight cost (OC), the discount rate (r, in % per year) and the life of the plant (T, in years).*

- **Capacity factor**
  - **The generator capacity factor is its percentage utilization which is determined by the load's duration.**

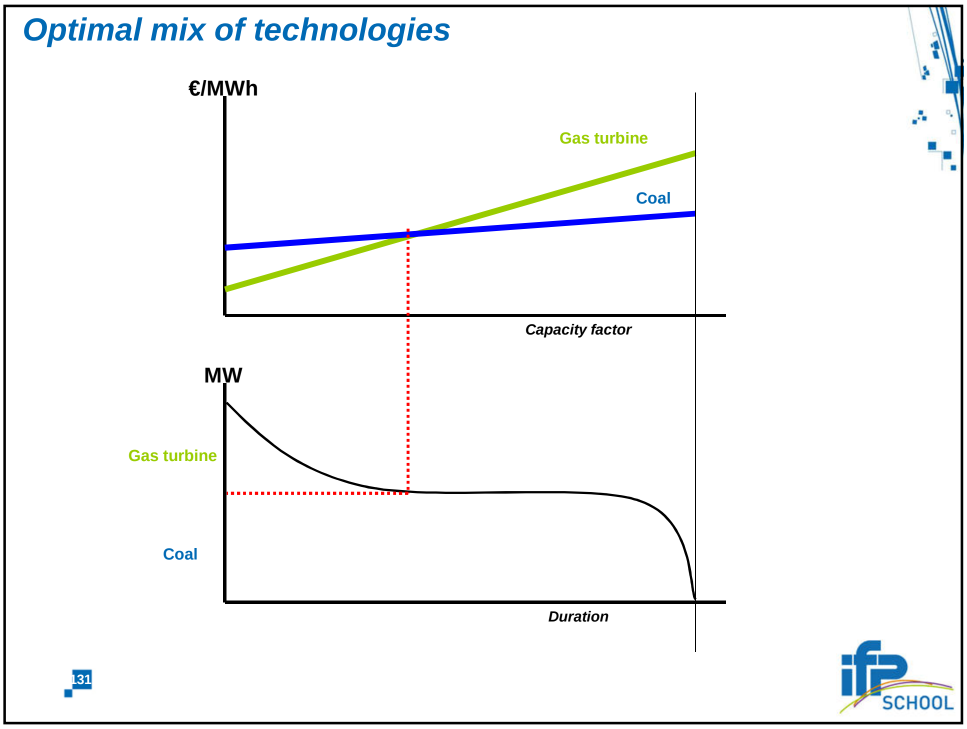
Annual Revenue Requirement (ARR) = FC + (cf × VC)



Screening curves

Technology	VC (/MWh)	VC (/KWy)	OC (/KW)	FC (/KWy)	FC (/MWh)
Coal	$10	$87.6	$1050	$106.96	$12.21

Fixed cost are based on r = 0.1 and on T = 20 for gas turbines and 40 for coal plants.



Optimal mix of technologies

Case study (plant costs & revenue, in UK)

Generation data	**Units**	**Gas**	**Coal**
Capacity	MW	375	375
Total fixed costs/yr	£m	14.83	30.49
Total variable costs	£/MWh	17.08	12.56
Base load price	£/MWh	23.50	23.50
Peaking load price	£/MWh	32.00	32.00
Base load utilization	%	55	88
Peaking utilization	%	35	35

1. What are the base and peak load profit for a year for Gas plant for the given utilization levels?

2. That level of base load utilization when the base load profit is equal to the peaking profit for gas of £2.3m/yr?

3. That level of base load utilization for coal plant resulting in zero profit?

Case study (Solution)

1. What are the base and peak load profit for a year for Gas plant for the given utilization levels?

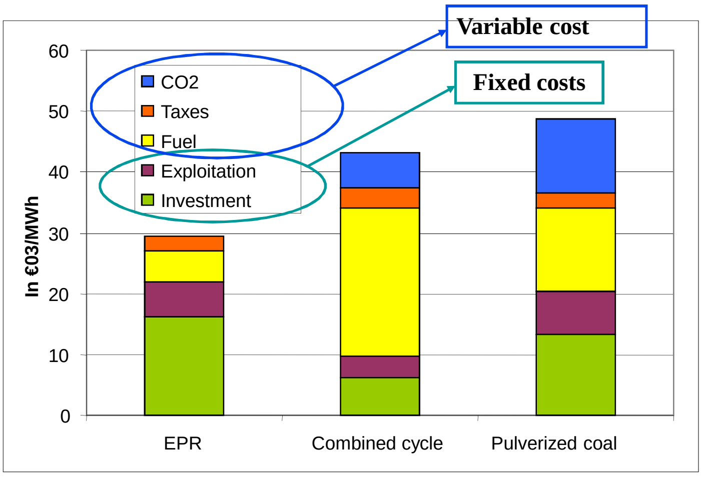
Case study (Solution)

2. That level of base load utilization when the base load profit is equal to the peaking profit for gas of £2.3m/yr?

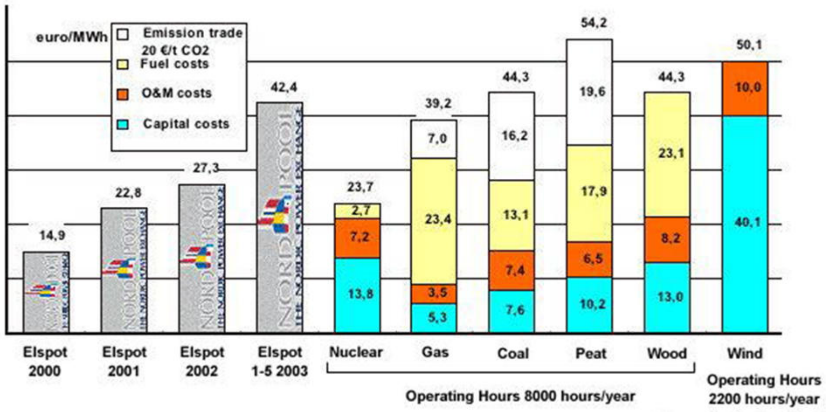
Case study (Solution)

3. That level of base load utilization for coal plant resulting in zero profit?

Generation cost structure



Finnish Study (2002-discount rate 5%)

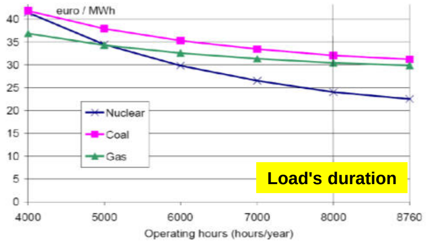


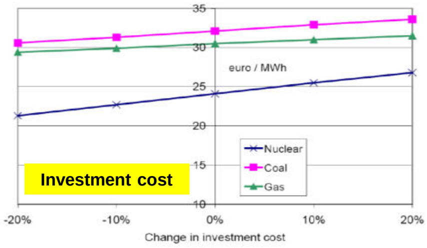
Generation Costs without investment subsidy and the return of electricity tax (wood and wind)

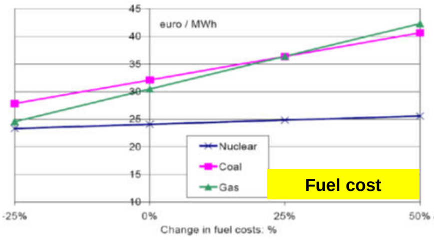
Real Interest Rate 0.5%
March 2003 Prices

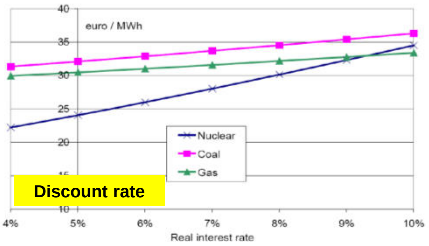
R. Tarjanne & K. Luostarinen 03.07.2003
Lappeenranta University of Technology

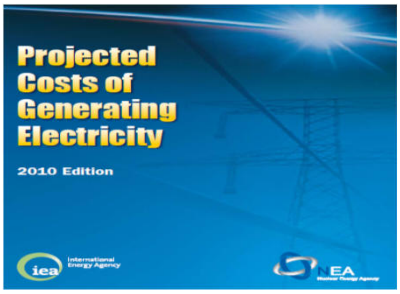
Sensibility Analysis (Comparison)











Projected Costs of Generating Electricity

2010 Edition

iea International Energy Agency

NEA Nuclear Energy Agency

Projected Cost of Generating Electricity

Nuclear Energy Agency

International Energy Agency

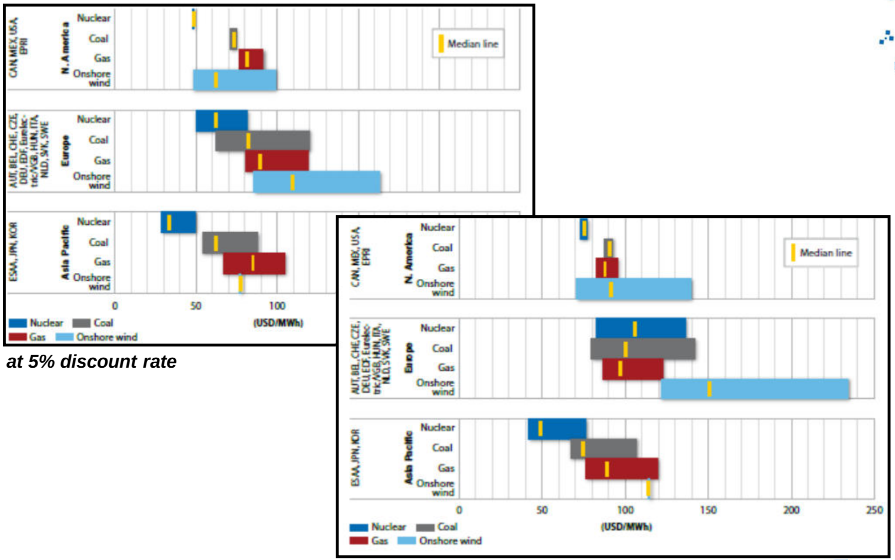
IEA study 2010

- Study includes:
  - Almost 200 power plants in OECD and non-OECD were studied
  - Power plants that could be commissioned by 2015
  - Renewable and non-renewable

- Main assumptions:
  - Real discount rates of 5% and 10%
  - Carbon price of USD 30 per tonne of CO2
  - Only financial costs were considered (neither social nor external)

- Uncertainties:
  - Future fuel and CO2 prices
  - Financing costs
  - Construction cost
  - Costs for decommissioning and storage
  - Electricity prices
  - Different energy policy contexts

Regional ranges of LCOE



at 5% discount rate

at 10% discount rate

Many other studies

Massachusetts Institute of Technology

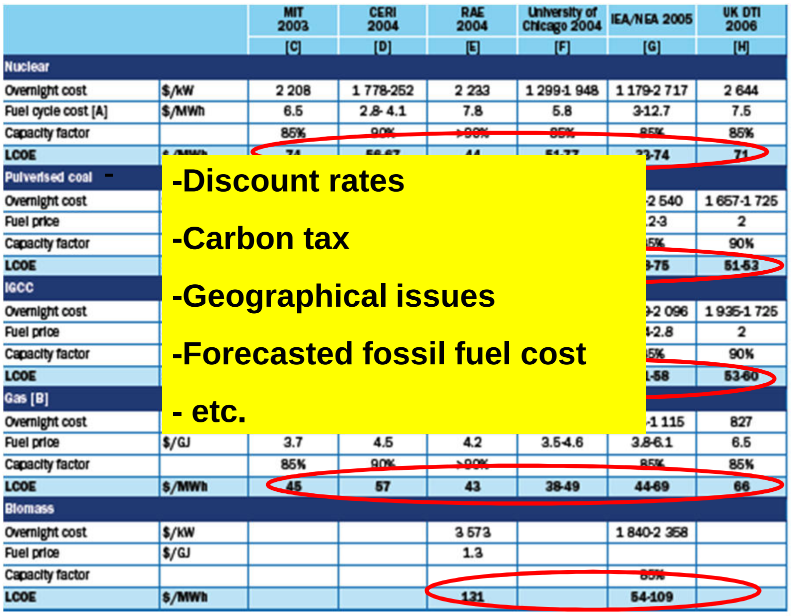
CANADIAN ENERGY RESEARCH INSTITUTE

dti

Electric Power Research Institute

The Royal Academy of Engineering

CONGRESSIONAL BUDGET OFFICE



		MIT 2003	CERI 2004	RAE 2004	University of Chicago 2004	IEA/NEA 2005	UK DTI 2006
		[C]	[D]	[E]	[F]	[G]	[H]
Nuclear							
Overnight cost	$/kW	2 208	1 778-252	2 233	1 299-1 948	1 179-2 717	2 644
Fuel cycle cost [A]	$/MWh	6.5	2.8- 4.1	7.8	5.8	3-12.7	7.5
Capacity factor		85%	90%	>90%	85%	85%	85%
LCOE	$ /MWh	74	56-67	44	51-77	33-74	71
Pulverised coal							
Overnight cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-2 540	1 657-1 725
Fuel price	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2-3	2
Capacity factor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5%	90%
LCOE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-75	51-53
IGCC							
Overnight cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-2 096	1 935-1 725
Fuel price	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-2.8	2
Capacity factor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5%	90%
LCOE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-58	53-60
Gas [B]							
Overnight cost	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1 115	827
Fuel price	$/GJ	3.7	4.5	4.2	3.5-4.6	3.8-6.1	6.5
Capacity factor		85%	90%	>90%		85%	85%
LCOE	$/MWh	45	57	43	38-49	44-69	66
Biomass							
Overnight cost	$/KW			3 573		1 840-2 358	
Fuel price	$/GJ			1.3			
Capacity factor						85%	
LCOE	$/MWh			131		54-109	

-Discount rates

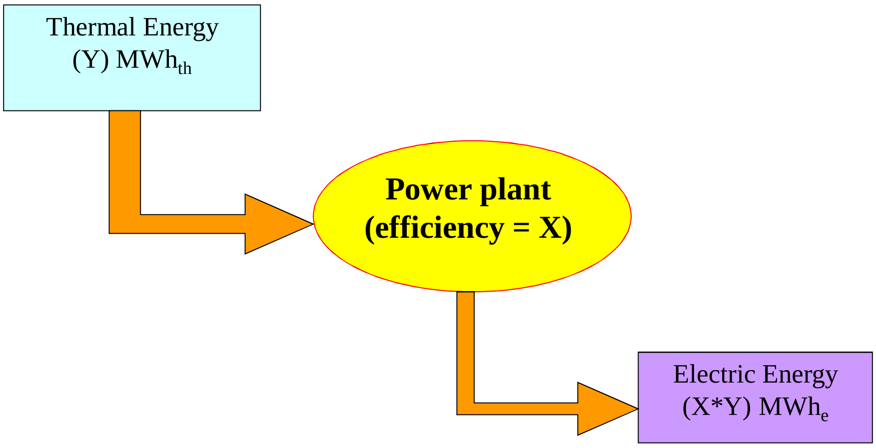
-Carbon tax

-Geographical issues

-Forecasted fossil fuel cost

- etc.

Efficiency concept



Thermal Energy
(Y) MWh_{th}

Power plant
(efficiency = X)

Electric Energy
(X*Y) MWh_e

Fuel cost calculation & efficiency impact

	Mbtu	MWh th	GJ	Nm3	bl	tep	Gcal	Tec
Mbtu	1	0,2931	1,0549	28	0,172	0,025	0,252	0,04198
MWh th	3,412	1	3,5992	95,536	0,588	0,0853	0,860	0,143
GJ	0,948	0,278	1	26,544	0,1634	0,0237	0,239	0,040
Nm3	0,03571	0,010	0,03767	1	0,0062	0,00089	0,0090	0,0015
bl	5,8	1,70	6,118	162,400	1	0,1450	1,46	0,24
tep	40	11,72	42,194	1120	6,897	1	10,08	1,68
Gcal	3,96825	1,16	4,186	111,111	0,68418	0,0992	1,00	0,17
Tec	23,82129	6,98	25,128	667	4,107	0,59553	6,00	1,00

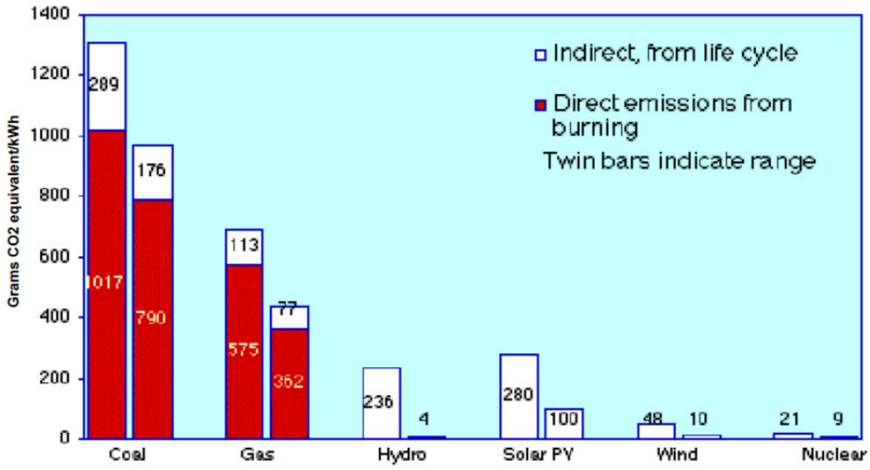
***Uranium :** around 4000 GJ/kg (1 GWh/kg) for existing PWR according to enrichment process & fuel life-time.*

What is the fuel power price in €/Mwh_e?

1€ = 1.25 $

	Coal	Gas
Efficiency	43,80%	57%
Resource	**75($/t)**	**8 ($/Mbtu)**

Power generation & GHG emissions



What's their impact on the generation costs?

Direct CO2-emissions price impact on generation cost

CO2 emissions of main primary fuels

Source IPCC	per toe	per GJ	per thermal MWh	per 1000 m3	per tonne
Coal	3,961	0,0943	0,3392		2,763
Fuel Oil	3,101	0,0738	0,2656		3,12
Natural Gas	2,333	0,0555	0,1998	2,08	2,827

**These values don't contain the emissions due to fuel-transport, leakage & etc. For example, for gas the usual number is 0.230*

What is the CO2 impact in €/Mwh$_e$?

	Coal	Gas
Efficiency	**43,80%**	**57.3%**
CO2 price	**25 (€/t)**	**25 (€/t)**

Spreads

Spark spread is the theoretical gross margin of a gas-fired power plant from selling a unit of electricity, having bought the fuel required to produce this unit of electricity. All other costs (O&M, capital and other financial costs) must be covered from the spark spread.

Dark spread (Coal)

Clean spread (CO2)

-clean spark spread

-clean dark spread

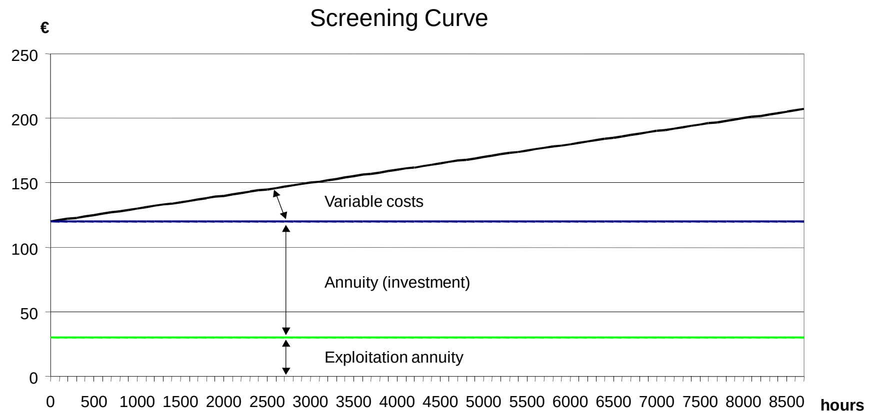
Climate spread (coal/gas)

Investment challenges

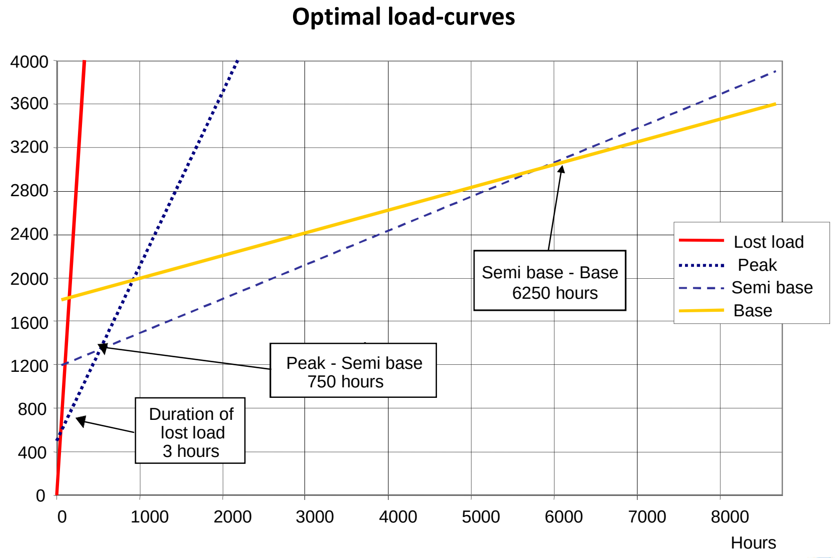
Two main approaches

- **What is the most interesting generation utility (park) structure for the country:**
  - **Global economic evaluation**
- **Adding a new power plant to the system:**
  - **Marginal economic evaluation**

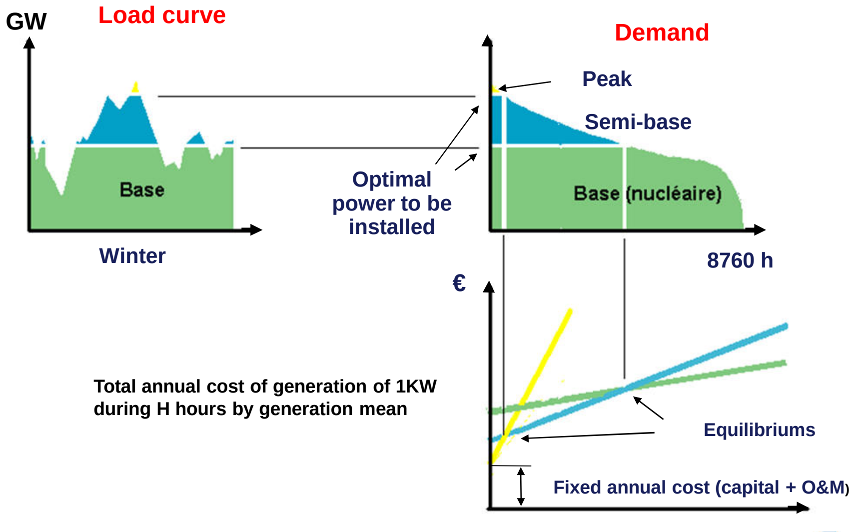
Global method



Global approach



Investment in generation



Total annual cost of generation of 1KW during H hours by generation mean

Source : W. Varoquaux

After liberalization

During monopole time : The state is at the same time the shareholder (of EDF) and the regulator. If the generation means are adapted : M.C. LT = M.C. ST

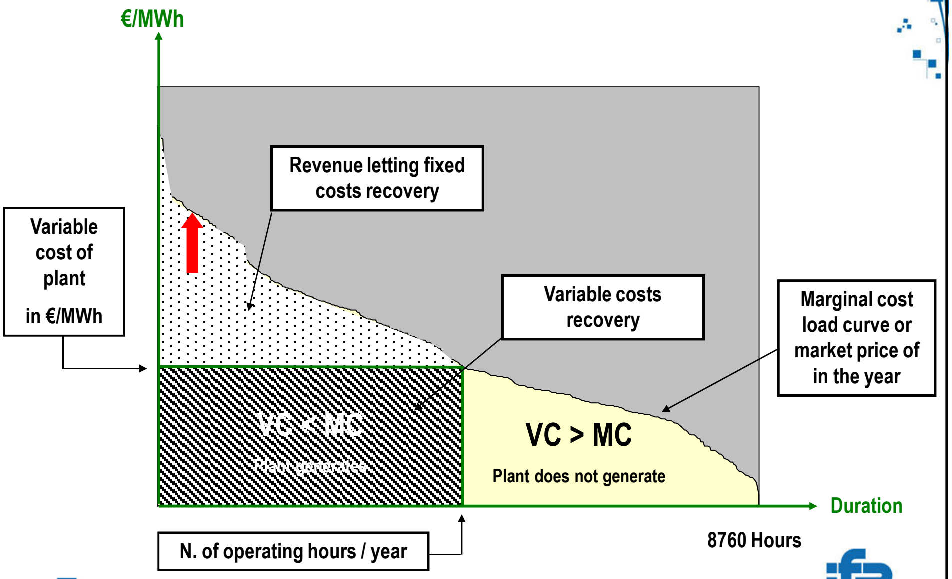
From cost minimization

$$\mathbf{MIN} \sum_{k=1}^{N} \frac{C\,in(k) + C\,op(k)}{(1+i)^{k}}$$

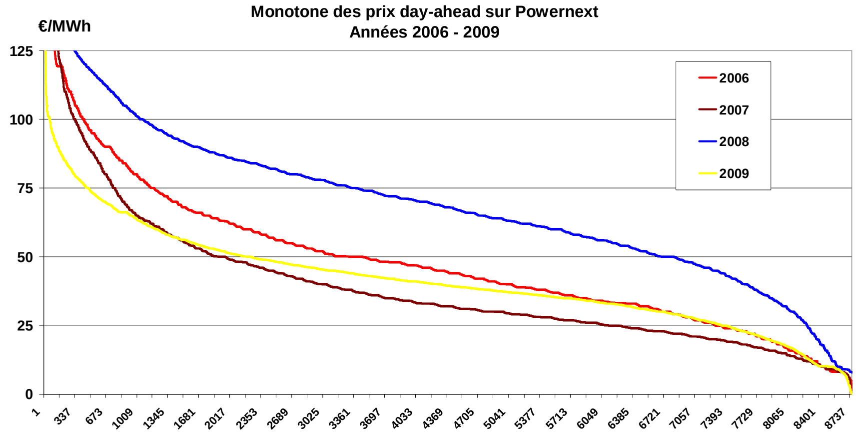
To the profit maximization

$$\mathbf{MAX}_{j} \sum_{k=1}^{D} \frac{Cashflows(j,k)}{(1+i)^{k}}$$

Marginal economic evaluation



Price replace the demand in screening curves



Do we need more investment?

- **Average rate of growth in the OECD electricity generation from 1990 until now is around 2.4%.**
- **Over the same period, total OECD consumption increased at an average annual growth rate of 2.3%.**

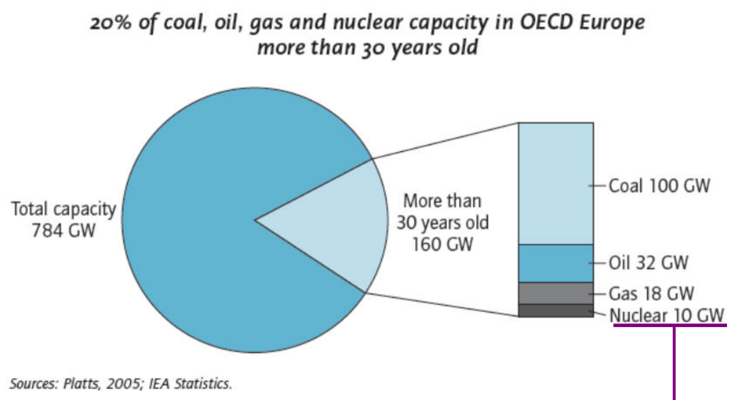
So capacity kept pace with demand !?

• At the aggregate level, yes. However, since electricity markets are regional in nature, it is more appropriate to assess generation adequacy at regional level.

• A closer look at national electricity statistics reveals that the investment picture varies considerably between countries.

• Another very important parameter is the plants ageing and retirements.

Generation plants' ageing


20% of coal, oil, gas and nuclear capacity in OECD Europe more than 30 years old

Sources: Platts, 2005; IEA Statistics.

Even if more than 90% of nuclear capacity in OECD Europe is still less than 30 years old, but 60% is older than 20 years.

Trends in Power Generation

- **Barriers toward new investment:**
  - Complicated and time-consuming processes for licensing and approval
  - Uncertainty created by the recent and ongoing transition to liberalized markets
  - Development of new technologies that change the overall energy mix
  - Lack of clarity in the policy realm regarding environmental issues

Real Option Approach

Evaluating the power investment options with uncertainty in climate policy

International Energy Agency

Electric Power Research Institute

Oxford Energy Associates

London Business School

March 2007

Real Option Approach

- **UNCERTAINTY**
  - Whether climate change policies are introduced through a price mechanism or through some other regulatory mechanism, emissions' cost must be included in the investment analysis.
  - Problem with incorporating these emission costs into financial analysis is that the ***status of climate change policy in most countries is uncertain***.
- **NPV ANALYSIS** *(drawbacks)*
  - Simple deterministic and expected NPV analysis does not take into account the uncertainties of the investment and the continuation value.
  - Profit-seeking enterprises can invest in the power plant project now if they think the ROI is high enough to match the risk, or they can postpone it to the time when they get more information of those risks.
  - **Investors have the option but not the obligation to invest in a project at a particular point in time**.

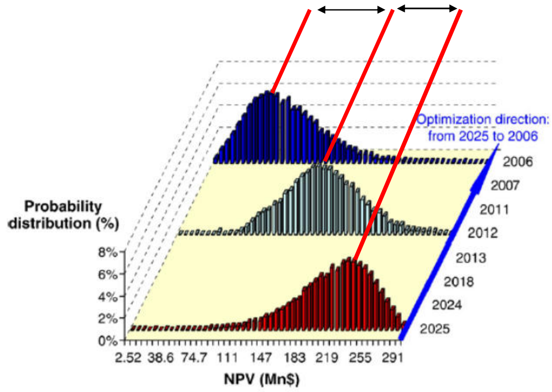
Real Option Approach

$$V_t^{\text{inv}} = \left(\sum_{n=t}^{L} d(t,n)E[B_n] \right) - K$$

$$V_t^{\text{cont}} = A_t + d(t,t+1)E[V^*_{(t+1)}]$$

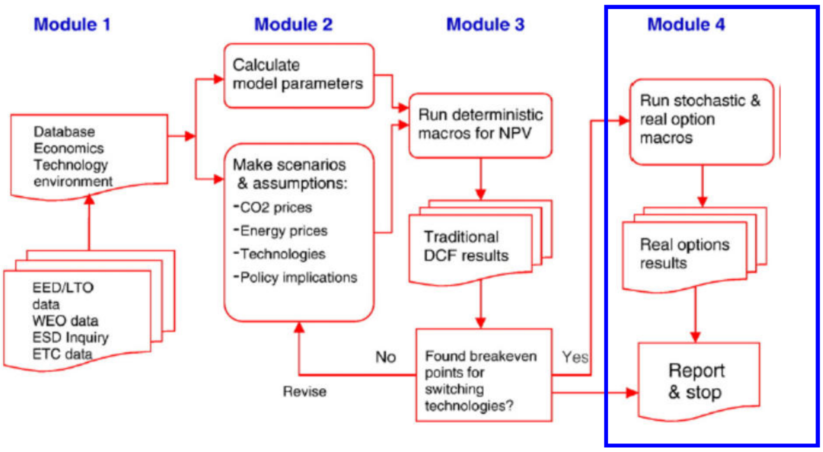
$$V_{T-1}^{\text{cont}} = A_{T-1} + d(T-1,T)\max\{E_{T-1}[V_T^{\text{inv}}],0\}$$

K: total capital
B: annual cash flow with investment
A: cash flow without investment
L: Project life-time
d (t,n): discount factor applied at time t to cash flows occurring at time n
T: one year in the future
V: optimal NPV from year t+1 until the end of the project life-time*
E: expected value



Optimization of future cash flows using real options

Model used for ROA



Module 3: $\text{NPV} = \sum_{t=1}^{T} \frac{C(P_c)_t}{(1+r)^t} - C_0$

Module 4: $\text{NPV} = \sum_{t=1}^{T} \frac{C(\text{Stochastic } \mathrm{P}_c \text{ and } P_e)_t}{(1+r)^t} - C_0$

C_0 : unit construction cost
Pc : carbon price
$C(Pc)_t$: project's cash-flow at year t

C_0 : unit construction cost
Pc & Pe : carbon prices & energy prices
$C(Stocas.\ Pc\ \&\ Pe)_t$: project's cash-flow at year t

Results & Conclusion

- *Climate policy risks can become large if there is only short time between a future climate policy and the time when the investment decision is being made.*
- *The way in which CO2 price variations feed through to electricity price variations is an important determinant of the investment risk.*
- *The government will be able to reduce investment risks by implementing* ***long term*** *climate policies rather than short term policies.*
- *Investment risks vary according to the technology being considered.*

Assumptions: **!!!**

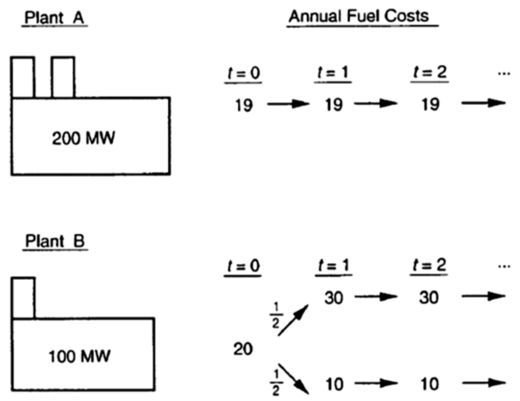
- Electricity price formation is under competitive market.
- There is no technical risk, such as uncertain costs, performance or load factor for example.

The ROA could be used to evaluate the risks associated with uncertainties in climate change policy with an ultimate view to making recommendation on how policy could be implemented to reduce investment risk.

Case study of power plant investment decision making (Scale v.s. Flexibility)

Consider a utility facing with annual demand growth of **100MW** and must add to its capacity. It can build a Coal power plant with capacity of **200MW** at the capital cost of **180M$ (Plant A)** or it can build a **100MW** Fuel-oil power plant with a CAPEX of **100M$ (Plant B)**. Yearly OPEX of plant A is equal to 19M$ for each 100MW and that of plant B is 20M$.

Discount rate of the Utility: ***10%***
Plants lifetime: Infinite
Fuel costs: constant for coal but fuel-oil will change (as it is indexed on Oil price)



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Discount rate of the Utility: ***10%***
Plants lifetime: Infinite
Fuel costs: constant for coal but fuel-oil will change (as it is indexed on Oil price)

If we make investment decision analysis for the first two years, what would be the present value of the flow of cost for Coal power unit (plant A) ?

Consider a utility facing with annual demand growth of **100MW** and must add to its capacity. It can build a Coal power plant with capacity of **200MW** at the capital cost of **180M$ (Plant A)** or it can build a **100MW** Fuel-oil power plant with a CAPEX of **100M$ (Plant B)**. Yearly OPEX of plant A is equal to 19M$ for each 100MW and that of plant B is 20M$.

Discount rate of the Utility: ***10%***
Plants lifetime: Infinite
Fuel costs: constant for coal but fuel-oil will change (as it is indexed on Oil price)

If we make investment decision analysis for the first two years, what would be the present value of the flow of cost for Fuel-oil power unit (plant B) ?

Consider a utility facing with annual demand growth of **100MW** and must add to its capacity. It can build a Coal power plant with capacity of **200MW** at the capital cost of **180M$ (Plant A)** or it can build a **100MW** Fuel-oil power plant with a CAPEX of **100M$ (Plant B)**. Yearly OPEX of plant A is equal to 19M$ for each 100MW and that of plant B is 20M$.

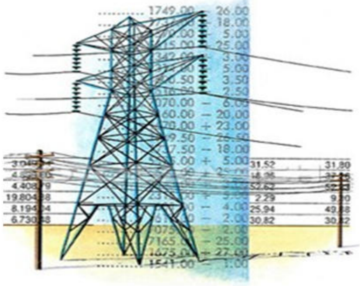
Discount rate of the Utility: ***10%***
Plants lifetime: Infinite
Fuel costs: constant for coal but fuel-oil will change (as it is indexed on Oil price)

If we consider the flexibility of Fuel-oil units and make investment decision analysis according to the oil price variation, what would be the present value of the flow of cost for our energy system (whether Plant A or B or even both!)?

What is the value of this flexibility?

Power Generation Economics & Management

"Electricity Market"



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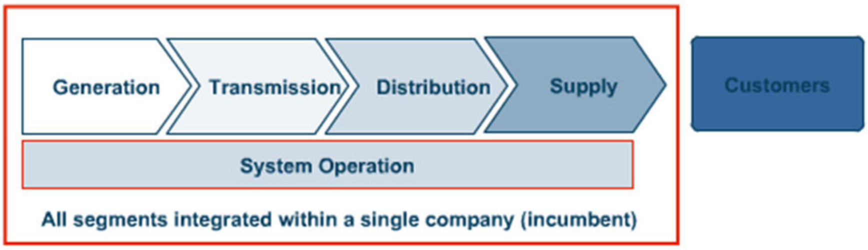
Outline

- **Vertically integrated company**
- **Electricity market liberalization**
- **Unbundling models**
  - **Single buyer**
  - **Pools**
  - **Wholesale competition**
  - **Retail competition**
  - **European model**
- **Market time-line**
- **Market, system and transmission operators**

Vertically integrated company


Generation
Transmission
Distribution
Supply
Customers
System Operation
All segments integrated within a single company (incumbent)

Unbundling models

- Unbundling using ring-fencing rules setting requirements for:
    - Accounting separation
    - Functional separation
    - Company's behavior
    - May be extended towards legal separation
- Full ownership unbundling
    - New entity in charge of network and operation activities with separate ownership control
- Independent system operator
    - Sourcing out the SO functions under separate ownership

Advantages and disadvantages of full ownership unbundling

- Removes incentives to discriminate competing generators
- Removes potential cross-subsidies between regulated network and competitive businesses
- Prevents from charging excessive network tariffs
- Increases transparency and efficiency of regulation

- Efficiency loss in coordination of planning between generation and transmission investments
- Loss of synergies (e.g. shared services) and high transaction costs
- Lower credit ratings for the unbundled companies and probably higher cost of capital
- Increase of the complexity of regulatory framework

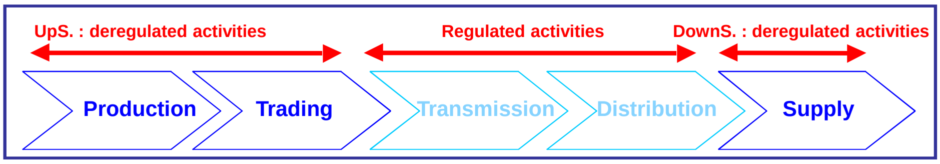
The "Textbook Model" for Restructuring and Competition

- Privatization
- Vertical separation
- Horizontal restructuring (adequate number of generators e.g.)
- Independent system operator (network stability & facilitate competition)
- Markets and trading arrangements
- Access to the transmission network
- Unbundling of retail tariffs & access to the distribution network
- Arrangement for supplying customers until retail competition is in place
- Independent regulatory agencies (with enough power & information)
- Provision of transition mechanism (supportive mechanisms)

International development of wholesale electricity markets

Electricity market liberalization in Europe

- **February 19 in 1999 :**
  - **Competition in electricity generation**
  - **Third access to the transmission system**
  - **Accounts separation** *(avoid cross-subsidies)*
  - **Market opening (clients can chose their supplier)**
    - in July 2004, non-residential clients
    - In July 2007, total opening



UpS. : deregulated activities

Regulated activities

DownS. : deregulated activities

Production **Trading** **Transmission** **Distribution** **Supply**

Actors in the electricity market

- **Market Participants**
  - **Producer (generator)**
  - **Trader**
  - **Supplier**
  - **Consumer**
- **Market Facilitators**
  - **Transmission system operator**
  - **Market operator**
  - **Distribution system operator**

Services in the electricity market

Energy (MWh)

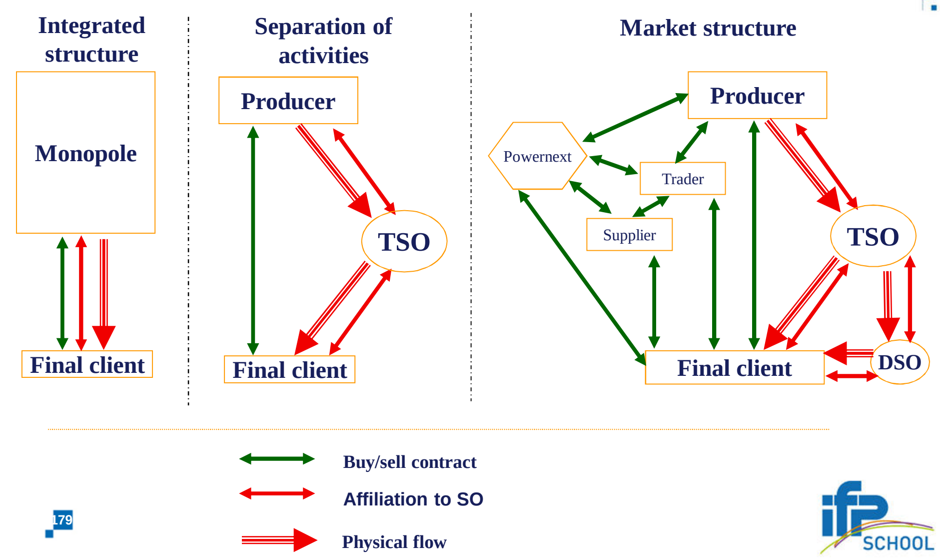
Generation capacity (MW)

Transport capacities

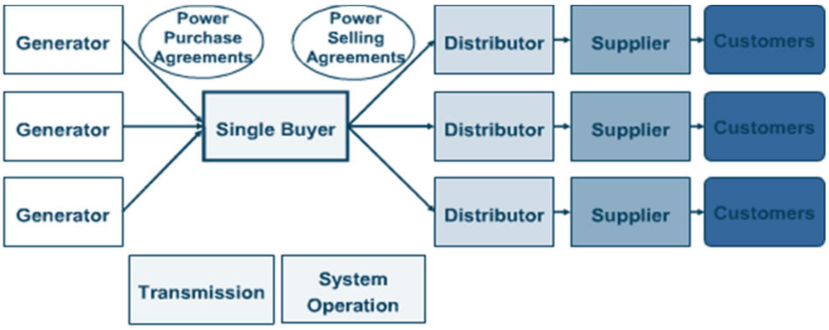
System/Ancillary services

A market structure to replace the integrated monopoly

-The end users can choose their suppliers but are fed by the network.
-The opening of the market introduced through the proliferation of contractual relations.

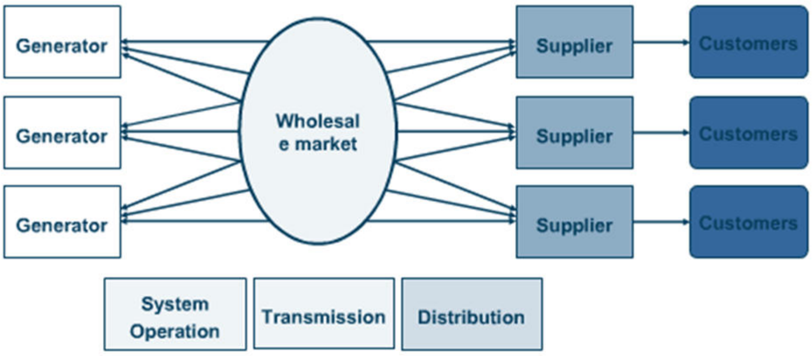


Single buyer model



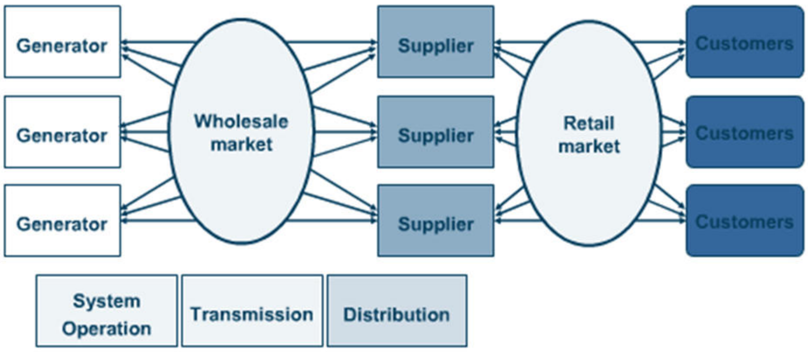
Generator
Generator
Generator
Power Purchase Agreements
Power Selling Agreements
Single Buyer
Distributor
Distributor
Distributor
Supplier
Supplier
Supplier
Customers
Customers
Customers
Transmission
System Operation

Wholesale competition



Generator
Generator
Generator
Wholesale market
Supplier
Supplier
Supplier
Customers
Customers
Customers
System Operation
Transmission
Distribution

Retail competition



Generator

Generator

Generator

Wholesale market

Supplier

Supplier

Supplier

Retail market

Customers

Customers

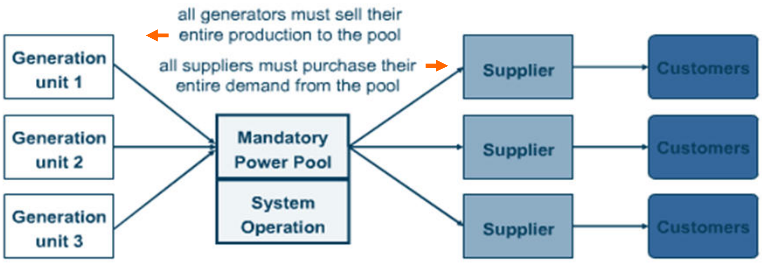
Customers

System Operation

Transmission

Distribution

Power pool



all generators must sell their entire production to the pool

all suppliers must purchase their entire demand from the pool

Generation unit 1

Generation unit 2

Generation unit 3

Mandatory Power Pool

System Operation

Supplier

Supplier

Supplier

Customers

Customers

Customers

Transmission

Distribution

OPTIONAL

Financial: CFD

Physical: Bilateral contracts

Contracts for Differences

Example: (UK pool's CFD)

*Assume that a generator bids into the pool a price for the day of **£27/MWh**.*

*The average pool marginal price is calculated to be **£30/MWh** so the generator is selected to run.*

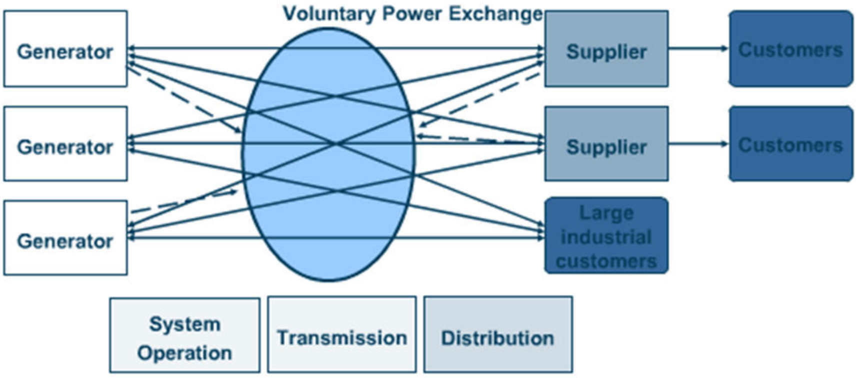
*The supplier places a CFD with the generator for a fixed 100 MW for the day at a price of **£27.5/MWh**.*

What is the net price paid by the supplier?

Power pools

Cost-based power pool	Price-based power pool
Generators submit offers for their individual units at their actual or estimated variable production costs. **Pool operator ranks generating units from least to most expensive production costs (merit order).** **Clearing price is determined by the short-run marginal costs of the generating unit that clears the market.** **Cost-based pools require regulatory audits of costs.**	**Generators submit offers for their individual units at their willingness to offer.** **Offers include start-up costs and minimum and maximum MW.** **Pool operator ranks engineering units based on offer prices.** **Clearing price is determined by the most expensive bid offered which is needed to satisfy demand in each time interval.**
Latin American wholesale markets : Chile, Bresil, Argentina, Columbia and also South korea	*England and wells (1990-2001) and also Australia*

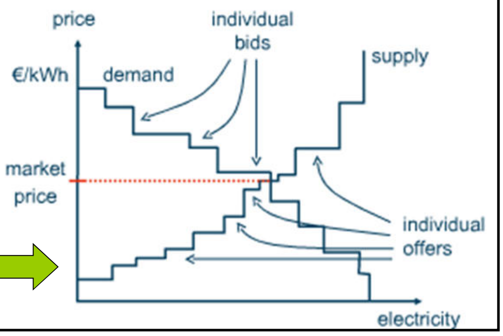
Market with bilateral trade



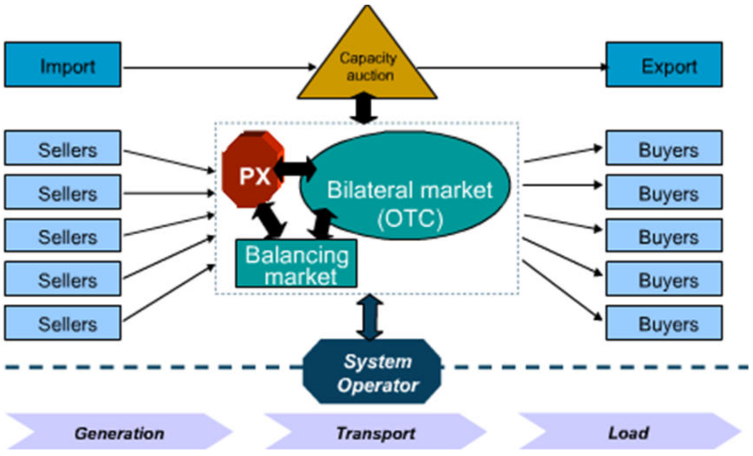
Power pools vs. power exchanges

- -All electricity traded over pool (mandatory).
- -Generators offer price-quantity pairs for the supply of electricity for each generating unit during specific time interval.
- -Pool operator forecasts demand and dispatch generating units.
- -Final production schedule of all producers is centrally determined by the pool operator.

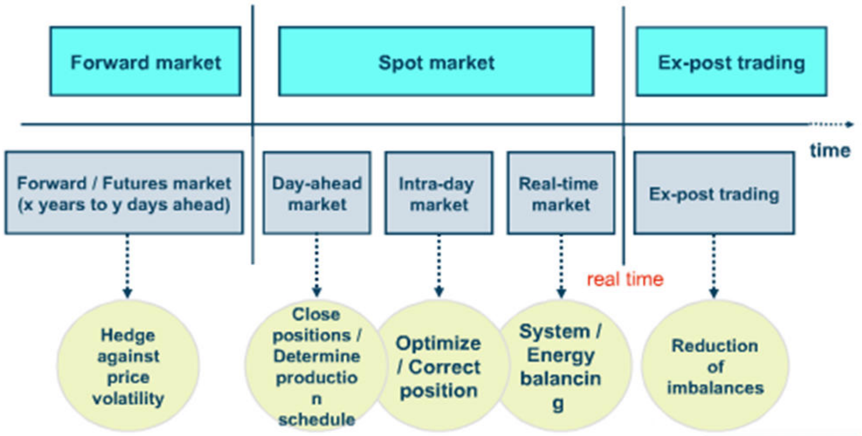
- -Organized voluntary market in addition to bilateral trading.
- -Generators submit individual price-quantity offers for the supply of electricity for different production levels and time intervals.
- -Suppliers, traders, large industrials submit individual bids for different production levels and time intervals.
- -Most expensive bid offered which is needed to satisfy demand is the market price.



Market with bilateral trade (European model)



Market timeline



Market, system and transmission operator

Market operator (MO)	System operator (SO)	Transmission operator (TO)
– Operate and/or facilitate the market – Registration of market participants – Receive bids/offers from market participants – Market clearing – Settlement and invoicing	– Operate or coordinate the system, ensure reliability and security – Real-time dispatch to balance supply and demand – Manage ancillary services to maintain system reliability – Manage congestion	– Plan, construct, maintain and own transmission lines

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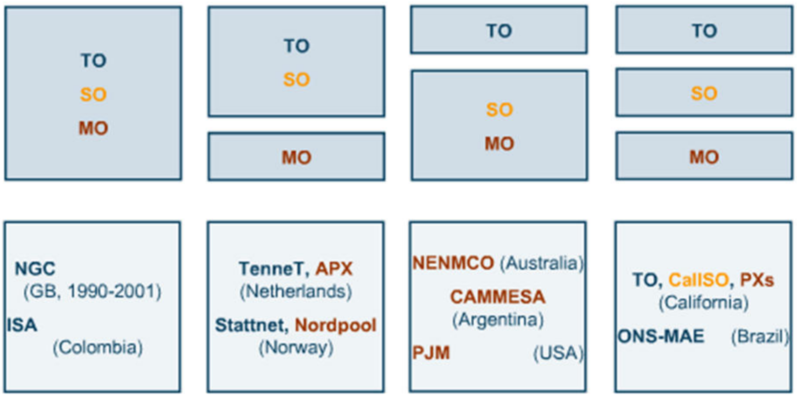
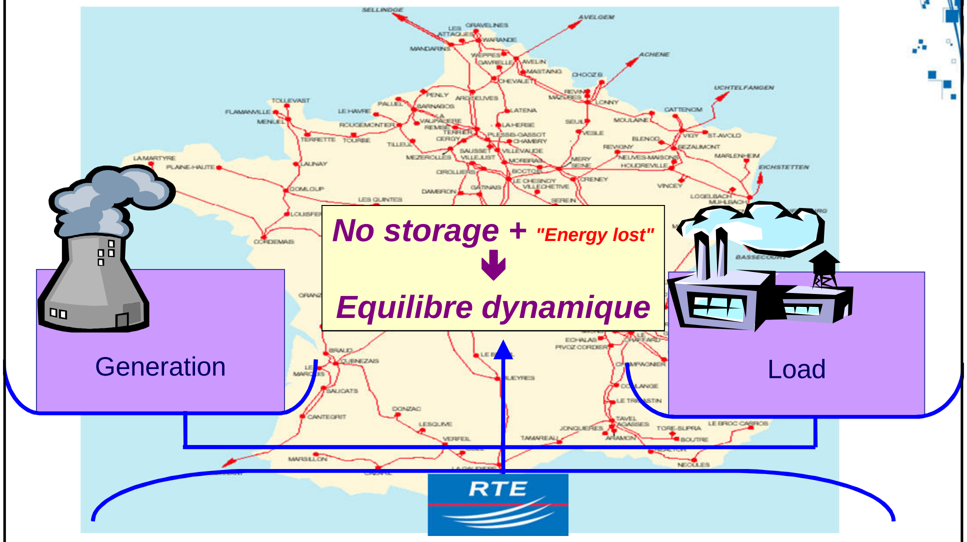
Market, system and transmission operator

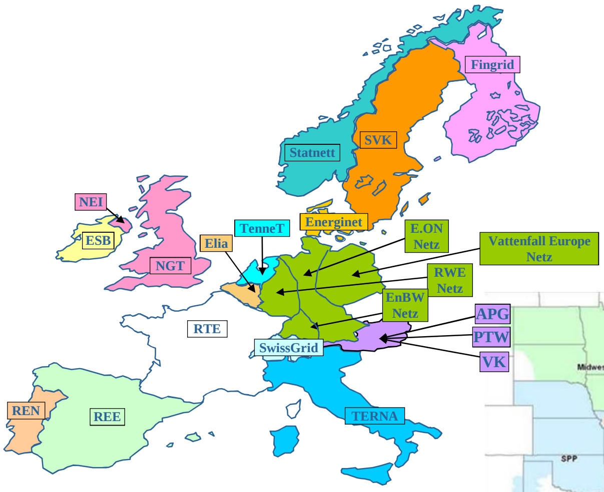


TO SO MO	TO SO MO	TO SO MO	TO SO MO
NGC (GB, 1990-2001) **ISA** (Colombia)	**TenneT**, **APX** (Netherlands) **Stattnet**, **Nordpool** (Norway)	**NENMCO** (Australia) **CAMMESA** (Argentina) **PJM** (USA)	**TO**, **CalISO**, **PXs** (California) **ONS-MAE** (Brazil)

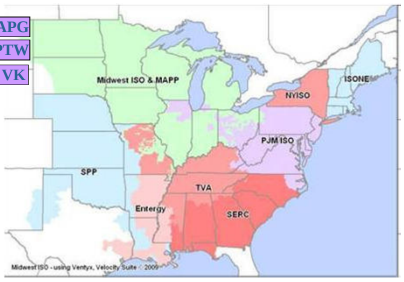
TSO



Transmission System Operators



Europe



East coast
(US)

Derivative products

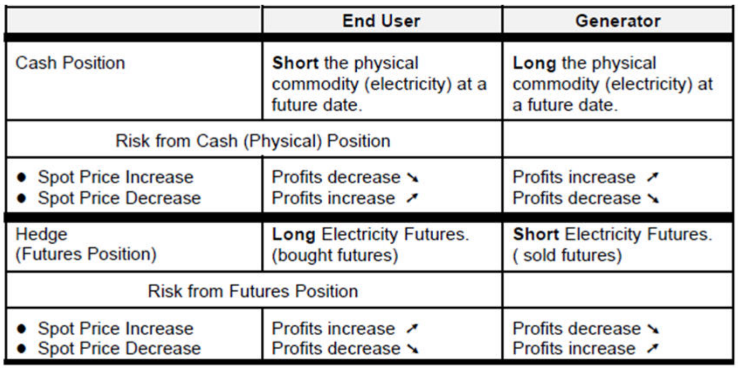
- **Forward**
  - OTC & Bilateral Contracts
  - Large flexibility (Volume, date, delivery place, quality,...)
  - Signature risk

- **Futures**
  - Power exchange
  - Standardized product
  - Clearing house

- **Options**
  - Execpt NordPool, they are exchanged in OTC market in Europe
  - **Classic** *(Plain Vanilla options)*
    - Put & Call
  - **Exotic**
    - Spread (crack spread & spark spread)
    - Barrier, basket, average strike,...

- **Swaps** *(Contract for differences)*
  - very important for energy companies (price variation vs. final detail price for end users)

Hedging strategy for generators & end-users



	End User	**Generator**
Cash Position	**Short** the physical commodity (electricity) at a future date.	**Long** the physical commodity (electricity) at a future date.
Risk from Cash (Physical) Position		
● Spot Price Increase ● Spot Price Decrease	Profits decrease ↘ Profits increase ↗	Profits increase ↗ Profits decrease ↘
Hedge (Futures Position)	**Long** Electricity Futures. (bought futures)	**Short** Electricity Futures. (sold futures)
Risk from Futures Position		
● Spot Price Increase ● Spot Price Decrease	Profits increase ↗ Profits decrease ↘	Profits decrease ↘ Profits increase ↗

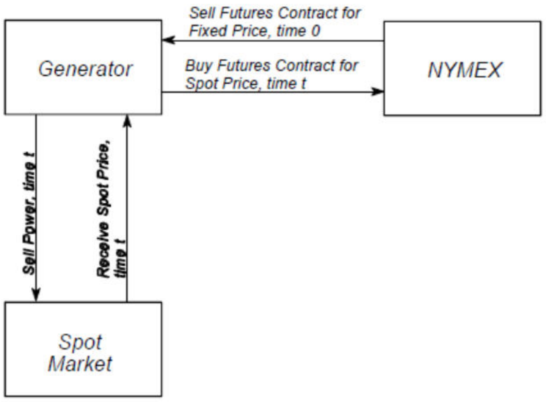
Source: Stoft, Balden,Goldman & Pickle, "Primer on Electricity Futures and other Derivatives"

Hedging example

Assume that a generator expects to sell electricity into the spot market in six months. The generator's cost of production is \$20/MWh, the current spot price is \$20/MWh, and the futures price for delivery in six months is \$18/MWh. In this instance, the generator is long electricity and will lose money if the spot price falls, will make money if the spot price increases, and will break even if the spot price remains constant.

What would be a prefect hedge for this generator?

Generator Hedging example



Obstacles to Market Development

- **Nature of the product**
    - Non storability of the product (Smeers 2004)
    - Many technical elements (transmission capacities and congestion)
- **Liquidity costs**
    - Traders hesitate to enter such a market (Newbery 2003)
    - Except for the Hedge funds (Amihud 2005)
- **Manipulation risk**
    - Not a perfect competition so the manipulation risk is high (Sikorzewski 2003)
    - Oligopolistic market (Boisseleau 2004)
- **Credit risks in the wholesale transactions**
    - Many actors are newcomers and unknown
    - Instable industrial structure (many M&As in Europe for example)
- **Competition between organized stock markets and OTC market**
    - OTC works well
    - Risky for the actors to migrate (Holder 1999)
    - Spot prices have not become a reference yet

Power Generation Economics & Management

"Modeling"

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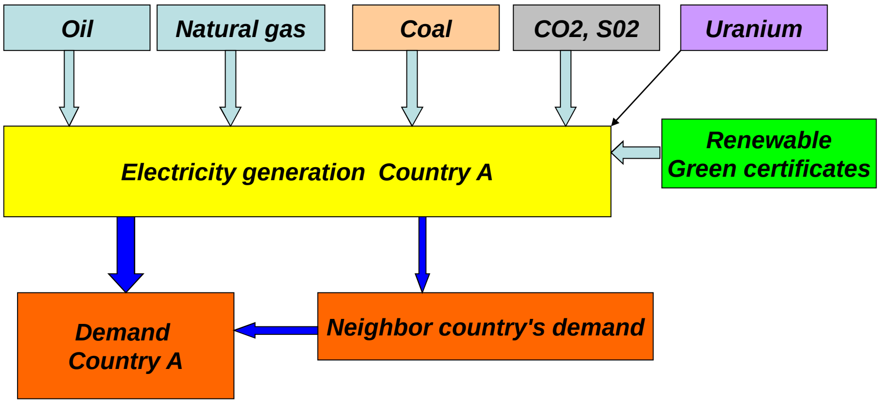
A market in interaction with many markets



Electricity price characteristics

The price of electricity is characterized by:

- **Extreme volatility,**
- **Instability of correlations between different areas of trade,**
- **And strong seasonality.**
  - It is less pronounced in Scandinavia, where the proportion of hydraulic electricity allows smoothing of production costs.

The electricity prices are often analyzed using econometric time series models. Generally **ARCH** type (*cf. Campbell et al., 1997*) and may therefore represent processes whose volatility are not constant (with alternating periods, calm and turbulent).

Modeling electricity prices

- **Fundamental models**
  - **Basic model: Cost minimization under constraints**
- **Finance and econometric models**
  - **Geometric brownian motion, Mean-reversion, Jump-diffusion,**
  - **ARMA (autoregressive moving average)**
  - **GARCH (generalized autoregressive conditional heteroscedasticity)**
  - **Markov regime switching, Multifactor,...**
- **Integrated modeling approach**
  - **Fundamental and Stochastic models**
- **Modeling competition in the Electricity industry**
  - **Competition on the wholesale : Cournot-Nash**
  - **Competition on the retail : Bertrand**

Fundamental models

$$MinCt = \sum_u C_{Op,u,t} = \sum_u P_{F,u,t} h_u y_{u,t}$$

Objective function as minimization of operation costs which are determined by plant output, fuel price and heat rate.

$$\sum_u y_{u,t} \geq D_t$$

Balance of supply and demand.

$$y_{u,t} \leq K_u$$

Capacity constraint for each unit.

Transmission constraints, hydro plants specificities, ... must be considered!!!

Challenges:

Data availability (costs, capacities, demand pattern, ...)

Choice of appropriate time resolution,

Perfect competition

Finance & econometric models

Geometric Brownian motion:

$$\frac{dp}{p} = \mu dt + \sigma dz$$

Elec. price variation

stochastic: volatility

deterministic : drift (big movements)

Mean-reversion models:

$$\Delta p_t = \kappa(p_0 - p_t)\Delta t + \sigma\varepsilon\sqrt{\Delta t}$$

** The deterministic part depends on whether the price is currently above or below the equilibrium price.*

It can also be presented in logarithm which can increases the probability of high prices.

Jump-diffusion models:

Empirical studies shows that Elec. price is not always normally distributed & strong price jumps are very probable.

$$dp = \mu p dt + \sigma_0 p dz + \sigma_s p \Phi dq$$

Poisson process: probability of jumps in a given time interval dt.

The size of the jumps depends on the standard deviation σ and a normally distributed stochastic variable.

$$dp = \kappa(p_0 - p)dt + \sigma_0 p dz + \sigma_s p \Phi dq$$

Finance & econometric models

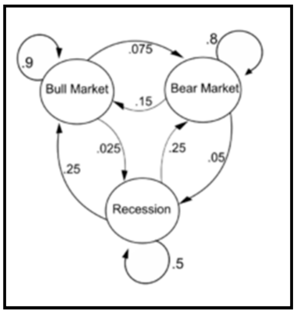
Autoregressive models : (AR1, ARMA, ARCH, GARCH,...)

$$Y_t = \beta_0 + \beta_1 Y_{t-1} + \gamma_1 X_{t-1} + u_t$$

$$\sigma^2{}_t = \alpha_0 + \alpha_1 u_t{}^2 + ... + \alpha_p u^2{}_{t-p} + \phi_1 \sigma^2{}_{t-1} + ... + \phi_q \sigma^2{}_{t-q}$$

Markov switching regime:

We introduce different regimes in order to be able to model various changes for the global trend.



Modeling competition in the electricity industry

Besides price uncertainty, the strategies of the competitors also affect the decision of electric utilities.

Whole sale competition Vs. retail competition:

The competition on the retail market is quite different from the wholesale competition in that the firms are usually setting their sales prices and not the quantities sold. Equivalency of price (**Bertrand**) and quantity (**Cournot**).

e.g. : p1 = p2 = P(q1 + q2)

Π1 = q1(P(q1 + q2) − c)

$$\frac{\partial \Pi_i}{\partial q_i} = \frac{\partial P(q_1+q_2)}{\partial q_i}.q_i + P(q_1+q_2) - \frac{\partial C_i(q_i)}{\partial q_i} = 0$$

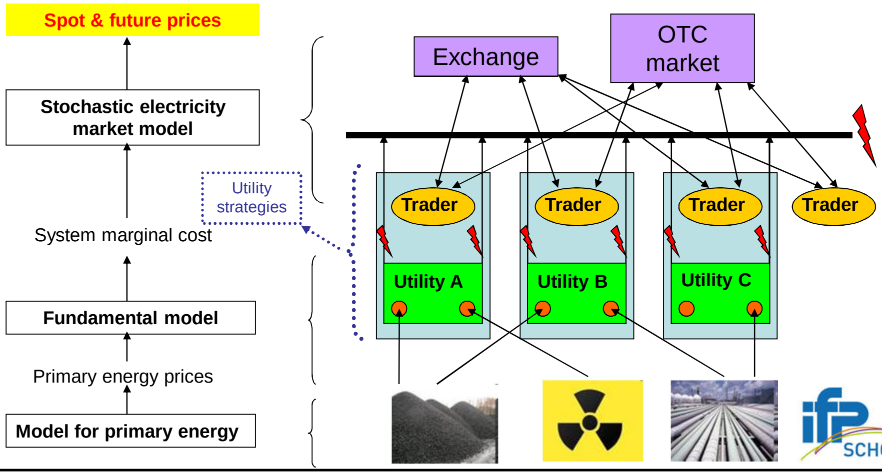
In most analysis, the entire focus is on the wholesale market and the inter-linkage between wholesale and retail markets is so far hardly analyzed.

Integrated modeling approach

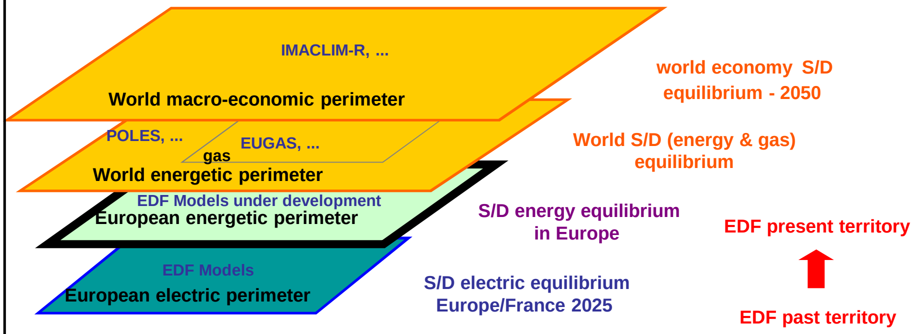
The previous discussion of fundamental and financial models for electricity price modeling has pointed at the relative strengths and weaknesses of both approaches.

Therefore an integrated model is proposed, which combines fundamental and finance type models.

More precisely, it uses the price established by a fundamental model as equilibrium price for a mean-reversion stochastic model.



Position of different models used by a utility (e.g. EDF)



IMACLIM-R, ...

World macro-economic perimeter

POLES, ...

EUGAS, ...

gas

World energetic perimeter

EDF Models under development

European energetic perimeter

EDF Models

European electric perimeter

world economy S/D equilibrium - 2050

World S/D (energy & gas) equilibrium

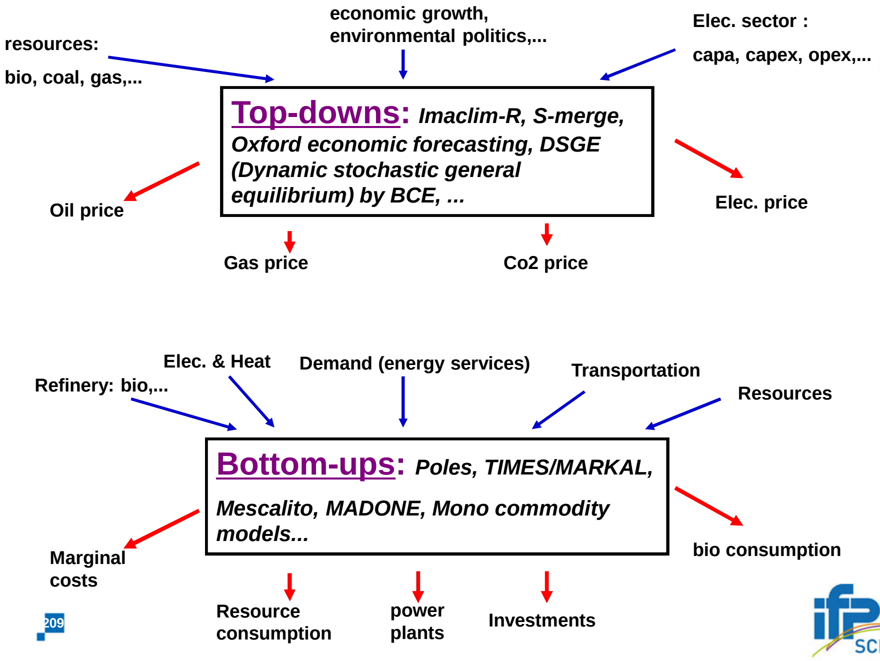
S/D energy equilibrium in Europe

S/D electric equilibrium Europe/France 2025

EDF present territory

EDF past territory

Top-down vs. Bottom-up models



resources:

bio, coal, gas,...

economic growth, environmental politics,...

Elec. sector :

capa, capex, opex,...

Top-downs: *Imaclim-R, S-merge, Oxford economic forecasting, DSGE (Dynamic stochastic general equilibrium) by BCE, ...*

Oil price

Elec. price

Gas price

Co2 price

Refinery: bio,...

Elec. & Heat

Demand (energy services)

Transportation

Resources

Bottom-ups: *Poles, TIMES/MARKAL, Mescalito, MADONE, Mono commodity models...*

Marginal costs

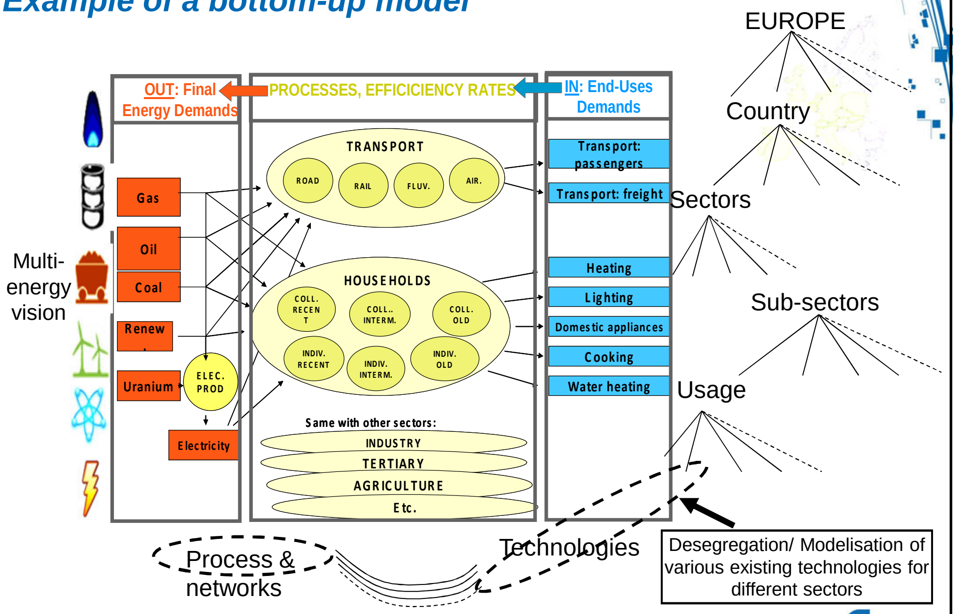
bio consumption

Resource consumption

power plants

Investments

Example of a bottom-up model



EUROPE
Country
Sectors
Sub-sectors
Usage

Multi-energy vision

Gas
Oil
Coal
Renew.
Uranium
ELEC. PROD
Electricity

OUT: Final Energy Demands
PROCESSES, EFFICIENCY RATES
IN: End-Uses Demands

TRANSPORT
ROAD
RAIL
FLUV.
AIR.

HOUSEHOLDS
COLL. RECENT
COLL.. INTERM.
COLL. OLD
INDIV. RECENT
INDIV. INTERM.
INDIV. OLD

Same with other sectors:
INDUSTRY
TERTIARY
AGRICULTURE
Etc.

Transport: passengers
Transport: freight
Heating
Lighting
Domestic appliances
Cooking
Water heating

Process & networks
Technologies

Desegregation/ Modelisation of various existing technologies for different sectors

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Power Generation Economics & Management

"Regulation & Deregulation"

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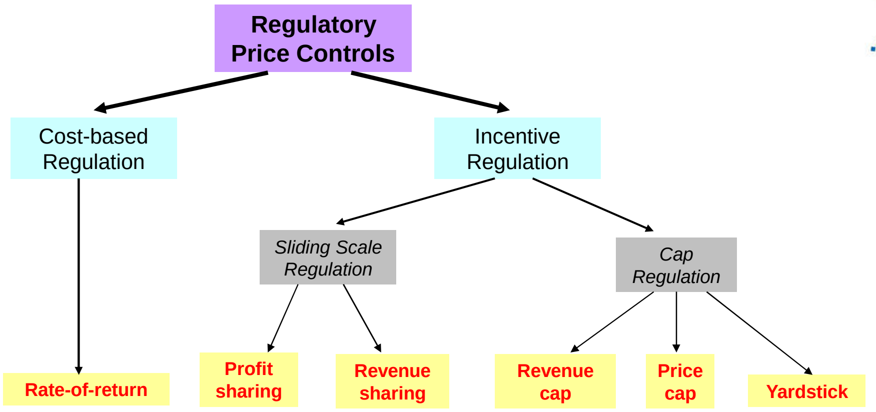
Outline

- **Major price control models**
  - **Cost-based regulation**
  - **Incentive regulation**
    - Cap
    - Sliding
- **Comparison of different models**
  - **Rate of return**
  - **Revenue/Profit sharing**
  - **Revenue cap**
  - **Price cap**
  - **Yardstick**

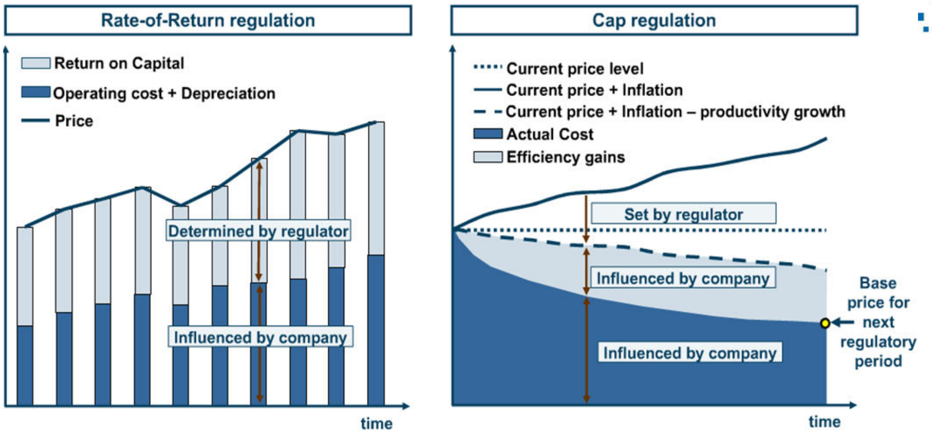
Major price control models



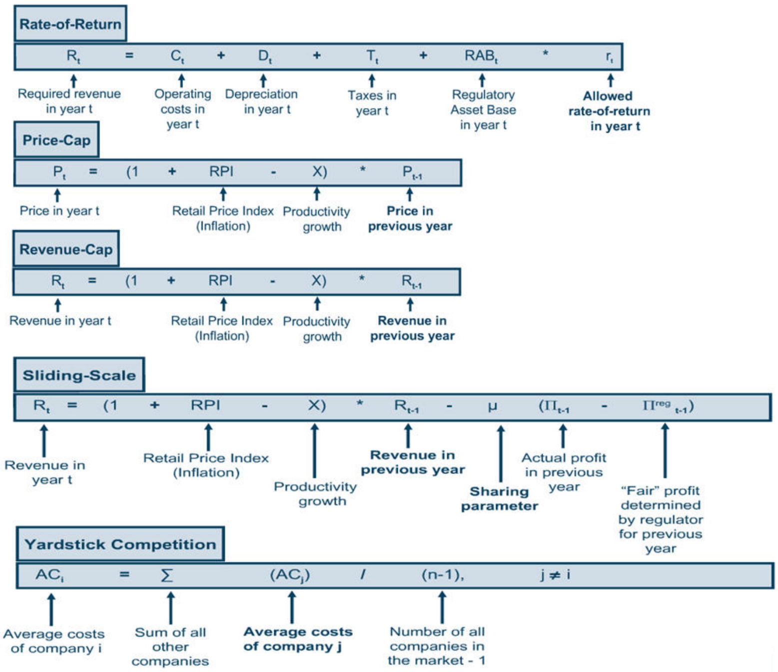
In practice also cases where

- **elements of different regimes are applied simultaneously**
- **different regimes are applied for different services of the same company**

Rate-of-return vs. Cap regulation



Regulatory formulas



Rate-of-Return

$$R_t = C_t + D_t + T_t + RAB_t * r_t$$

Price-Cap

$$P_t = (1 + RPI - X) * P_{t-1}$$

Revenue-Cap

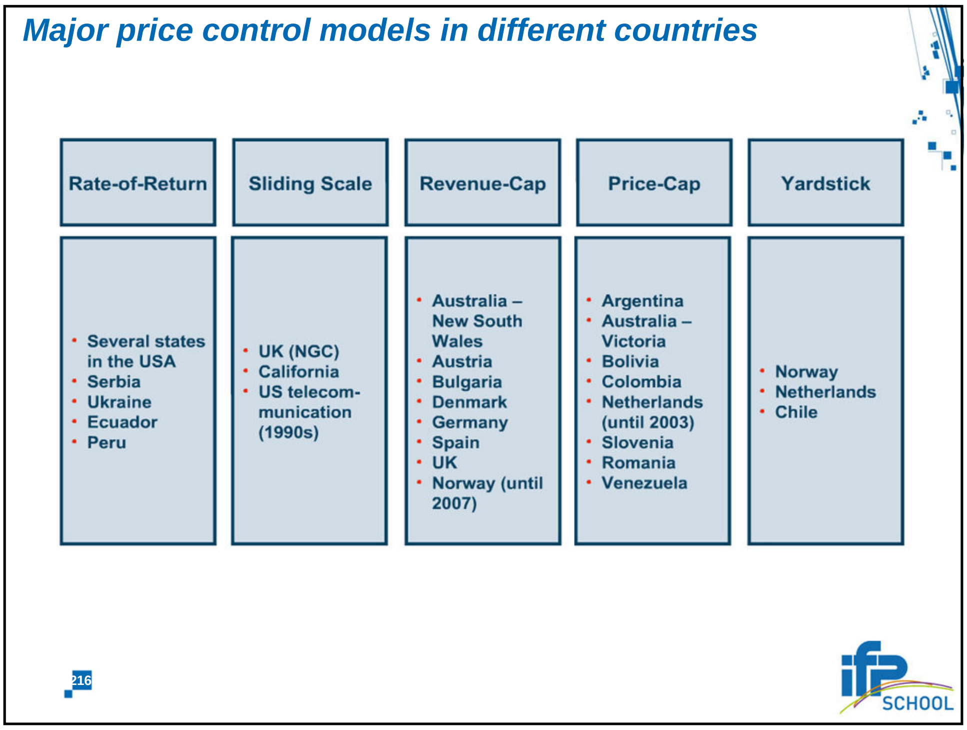
$$R_t = (1 + RPI - X) * R_{t-1}$$

Sliding-Scale

$$R_t = (1 + RPI - X) * R_{t-1} - \mu (\Pi_{t-1} - \Pi^{reg}{}_{t-1})$$

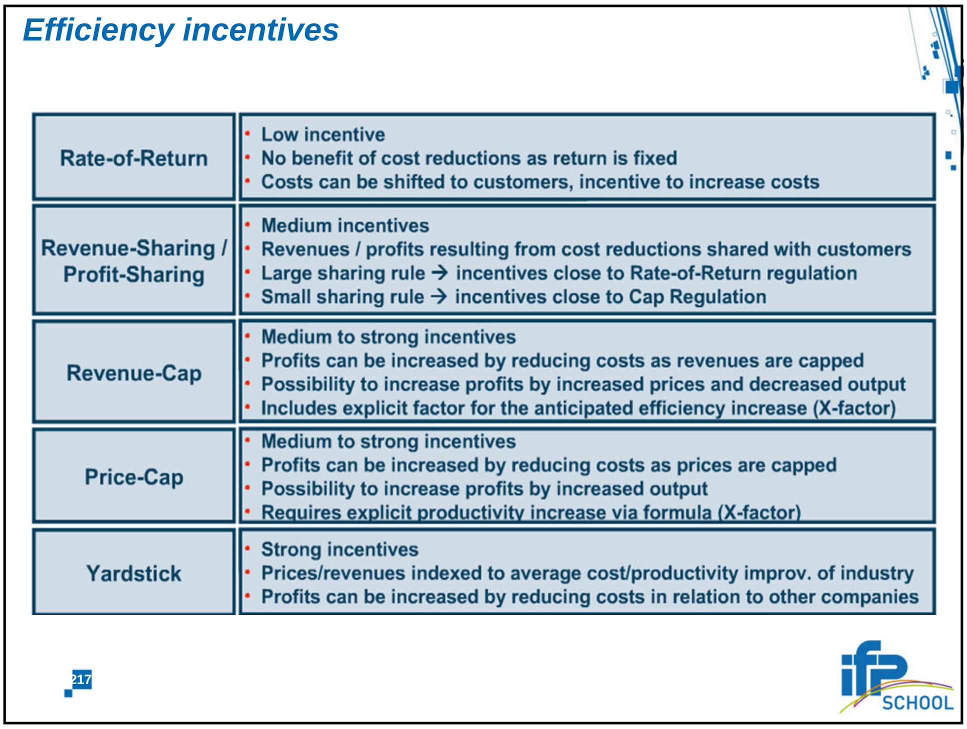
Yardstick Competition

$$AC_i = \sum (AC_j) / (n-1), \quad j \neq i$$



Major price control models in different countries

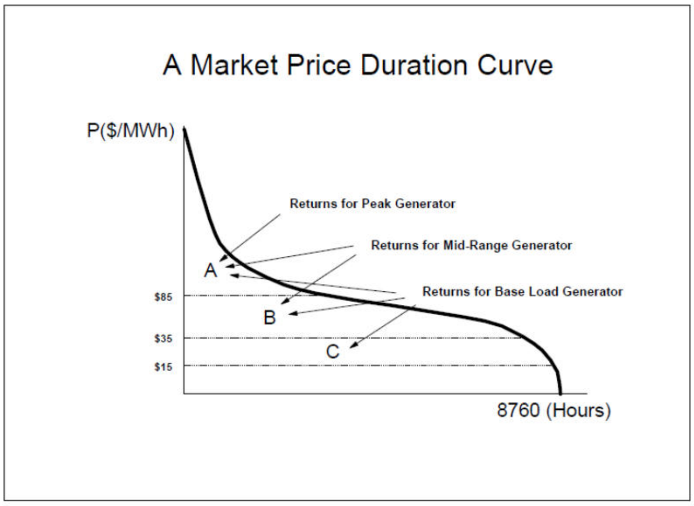
Rate-of-Return	Sliding Scale	Revenue-Cap	Price-Cap	Yardstick
Several states in the USA Serbia Ukraine Ecuador Peru	UK (NGC) California US telecommunication (1990s)	Australia – New South Wales Austria Bulgaria Denmark Germany Spain UK Norway (until 2007)	Argentina Australia – Victoria Bolivia Colombia Netherlands (until 2003) Slovenia Romania Venezuela	Norway Netherlands Chile



Efficiency incentives

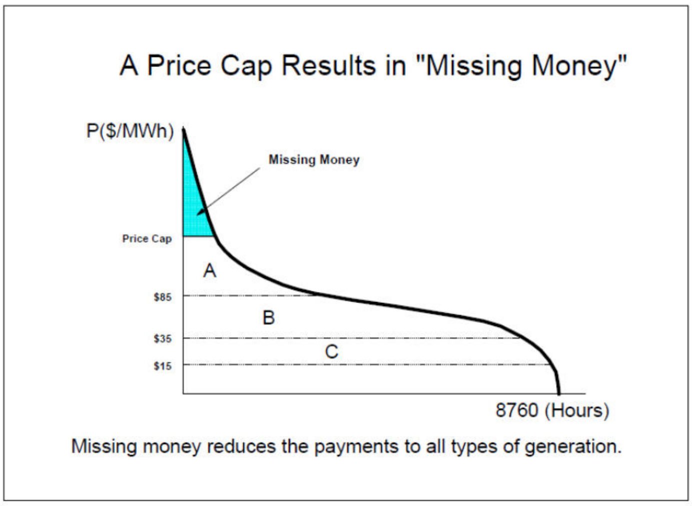
Rate-of-Return	Low incentive No benefit of cost reductions as return is fixed Costs can be shifted to customers, incentive to increase costs
Revenue-Sharing / Profit-Sharing	Medium incentives Revenues / profits resulting from cost reductions shared with customers Large sharing rule → incentives close to Rate-of-Return regulation Small sharing rule → incentives close to Cap Regulation
Revenue-Cap	Medium to strong incentives Profits can be increased by reducing costs as revenues are capped Possibility to increase profits by increased prices and decreased output Includes explicit factor for the anticipated efficiency increase (X-factor)
Price-Cap	Medium to strong incentives Profits can be increased by reducing costs as prices are capped Possibility to increase profits by increased output Requires explicit productivity increase via formula (X-factor)
Yardstick	Strong incentives Prices/revenues indexed to average cost/productivity improv. of industry Profits can be increased by reducing costs in relation to other companies

Energy-only market design


A Market Price Duration Curve

Source: William W. Hogan, John F. Kennedy School of Government, Harvard University

Energy-only market design


A Price Cap Results in "Missing Money"

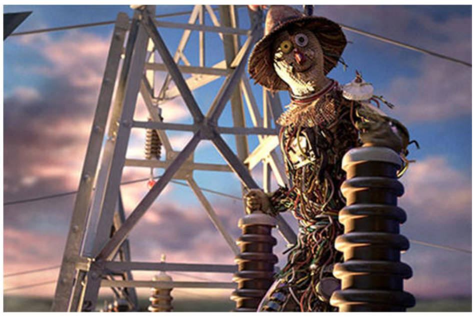
Missing money reduces the payments to all types of generation.

Source: William W. Hogan, John F. Kennedy School of Government, Harvard University

Appendix

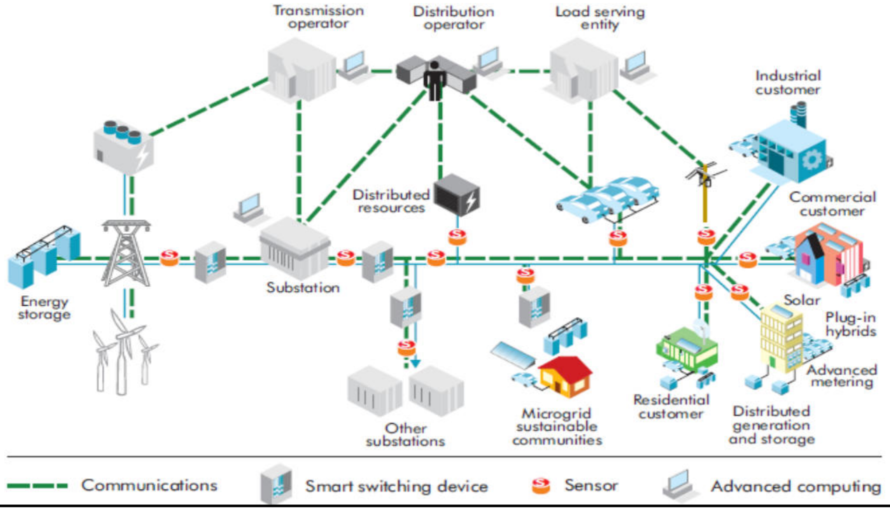
- Smart Grids
- Interconnections

Smart Grids



What is a smart grid?

- A smart grid is an electricity network that uses **digital technology** to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users.
- Such grids will be able to co-ordinate the needs and capabilities of all **generators**, **grid operators**, **end users** and electricity market stakeholders in such a way that it can optimise asset utilisation and operation and, in the process, minimise both costs and environmental impacts while maintaining system reliability, resilience and stability.



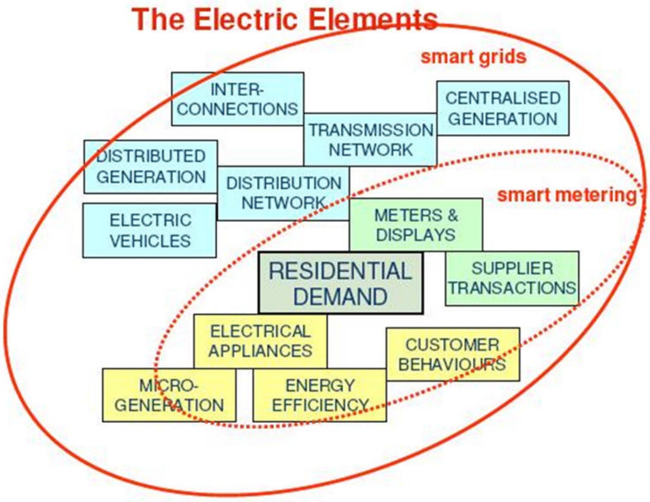
Smart grids

- **EUROPE**
  - **A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it –generators, consumers and those that do both- in order to efficiently deliver sustainable, economic and secure electricity supply.**
    - Source: European Technology Platform *smart grids*
- **USA**

A smart grid :

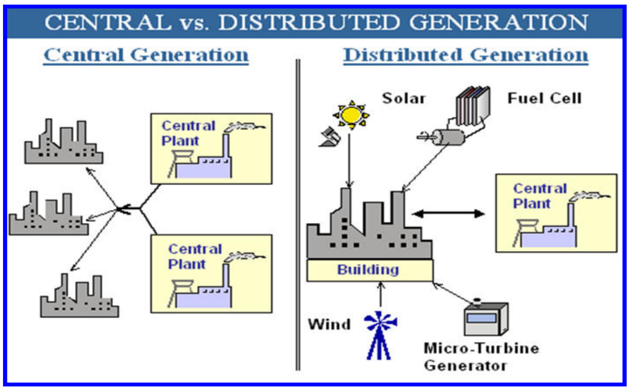
- **is self healing,**
- **enables active participation of consumers,**
- **operates resiliently against attack and natural disaster,**
- **accommodates all generation and storage options,**
- **enables introduction of new products, services and markets,**
- **optimizes asset utilization and operate efficiently, provide power quality for digital economy.**
  - Source: US Department of Energy

Smart grids & metering



Distributed Generation

- **Distributed generation can be defined as a source of electric power connected to the distribution network or the customer site.**
  - This approach is fundamentally distinct from the traditional central plant model for energy generation and delivery. The wide development of DG requires a thorough examination of all technical and non-technical aspects of an increased use of renewable energy resources and other decentralized generation units in distribution networks.



Micro-Grids

- **Micro-Grids are small electrical distribution systems that connect multiple customers to multiple distributed sources of generation and storage. Micro-grids are typically characterized by multipurpose electrical power services to communities with populations of up to 500 households with overall energy demands of up to several thousand kWh per day, and are connected via low-voltage networks.**
  - These hybrid systems have the potential to provide reliable power supply to <u>remote communities</u> where connection to transmission supply is uneconomical.
  - A number of demonstration projects have been undertaken in the <u>Greek islands</u> using this type of system.

Opportunities & barriers

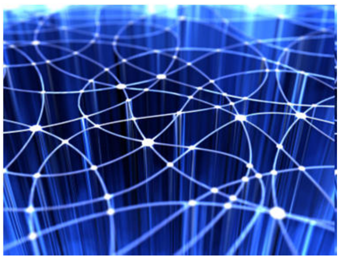
Opportunities:

-Environmental concerns
-Deregulation of the electricity market
-Diversification of energy sources/energy autonomy
-Energy efficiency

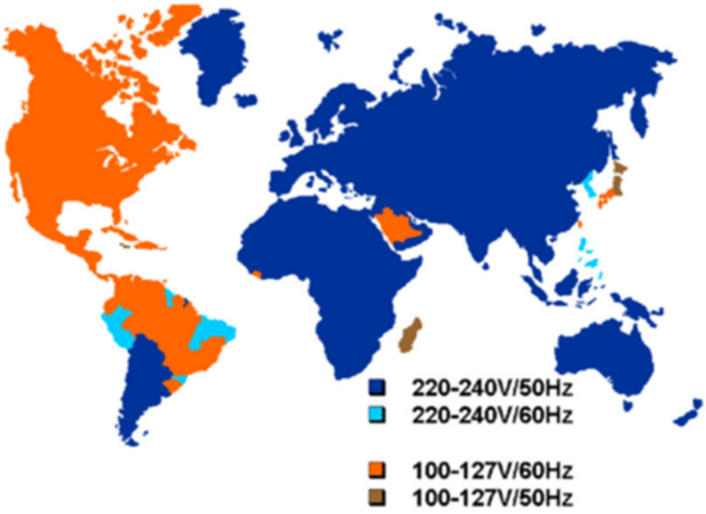
Barriers:

-Technical constraints, such as design procedures, limitations on rural network capacity, lack of interconnection standards, power quality,...
-Market, regulatory and tariffs challenges

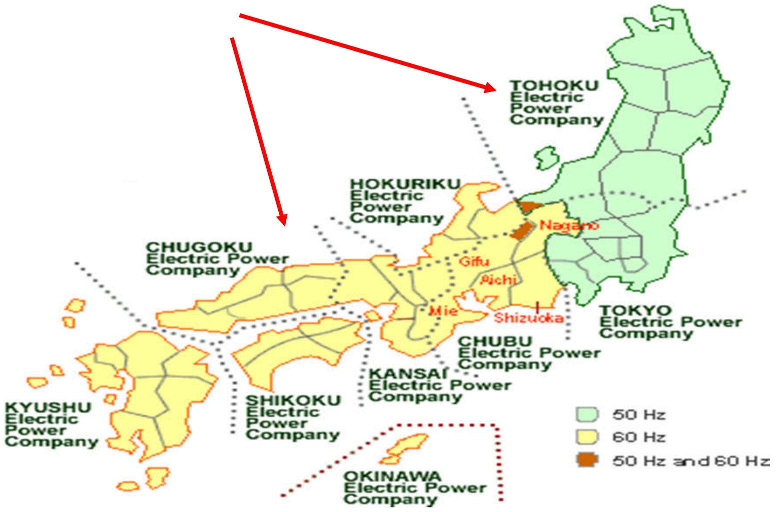
Networks' Interconnections



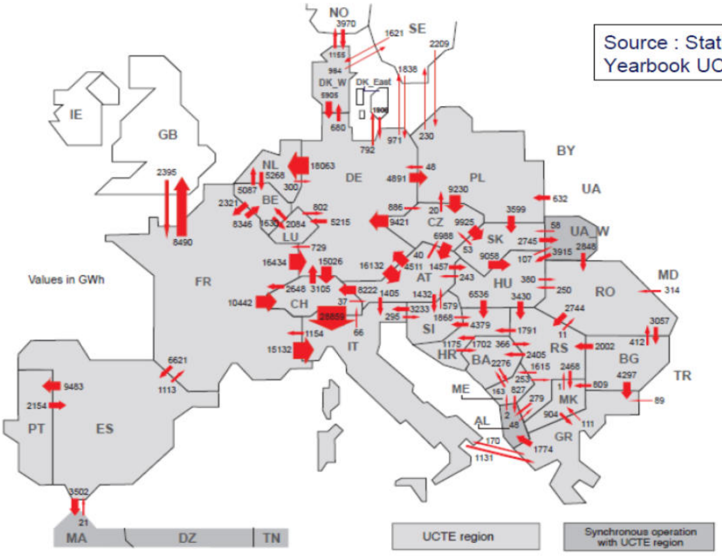
V & Hz in different zones



Japan's frequency zones

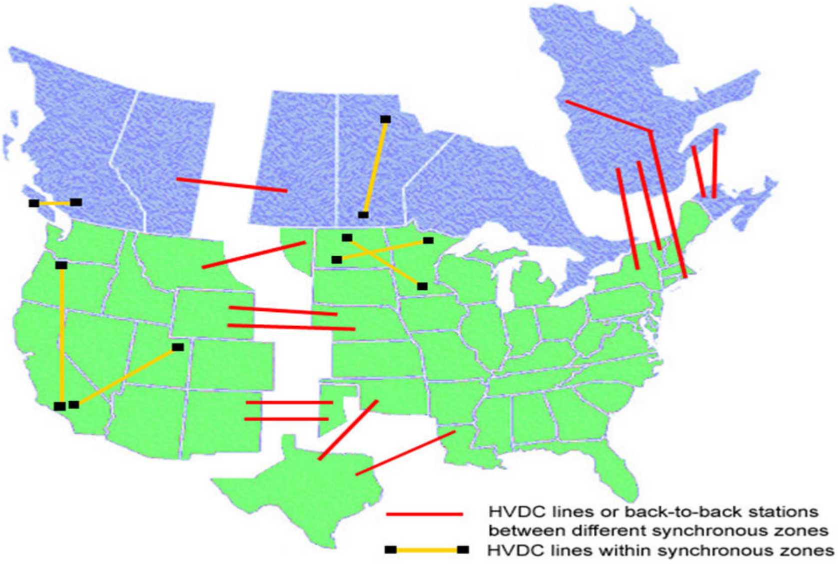


Electric flow (GWh) in European interconnected network



Source : Statistical Yearbook UCTE 2007

North American network structure



Frequency control

Why?

-Current quality

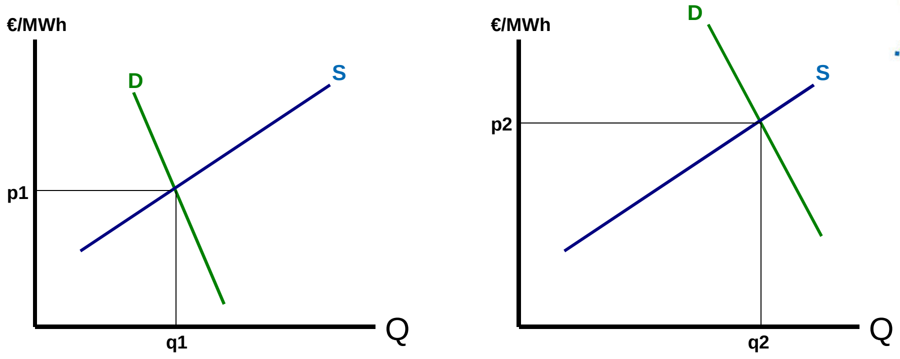
-Network equipment and specially transformers

-Transmission between countries

- **Primary control**
  - **For each generator**
  - **Playing with valves and rotary velocity**
- **Secondary control**
  - **At a larger scale**
  - **Compensate primary control imperfections**

Voltage control also !

Example of interconnection



P1=65€/MWh & P2= 85€/MWh

"FRANCE"

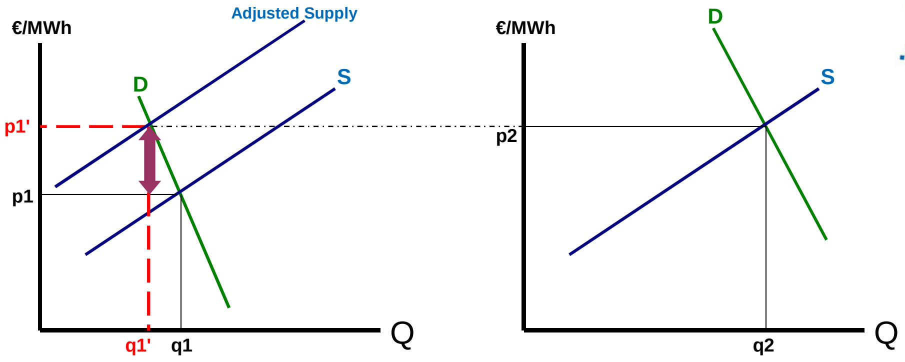
"GERMANY"

What is the generation rent for the French producer during peak load? (Transfer from French consumer to French producer)?

Hypothesis:

-Two countries are perfectly interconnected and there is no congestion.

Example of interconnection

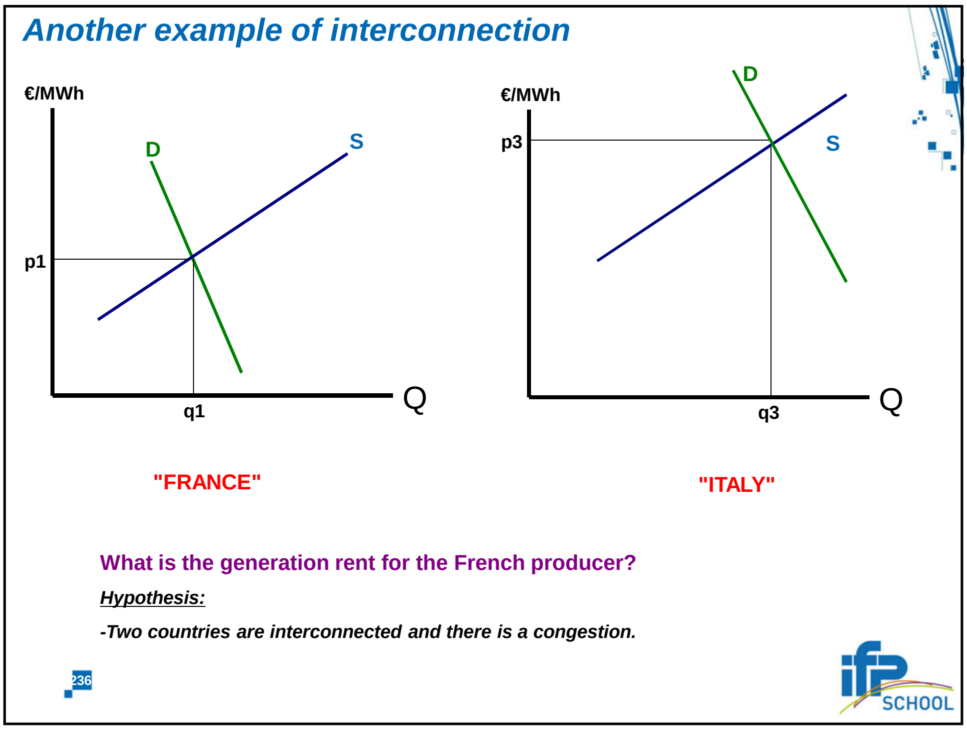


P1=65€/MWh & P2= 85€/MWH

"FRANCE"

"GERMANY"

Generation rent = $q_1' \cdot (P_1'-P_1) = 20q_1'$

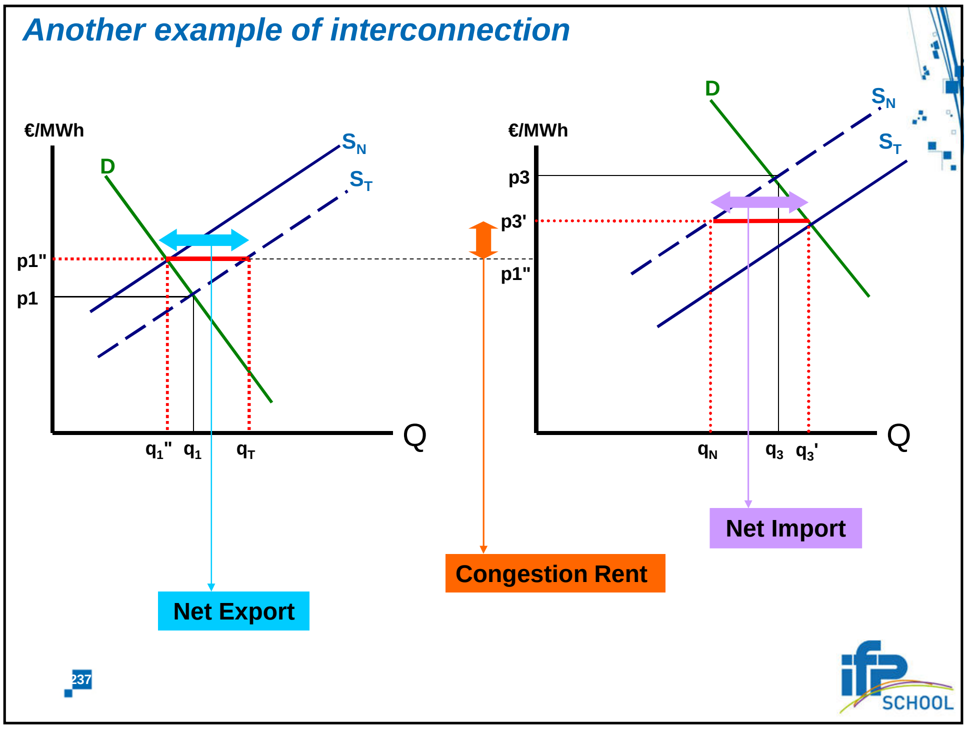


Another example of interconnection

What is the generation rent for the French producer?

Hypothesis:

-Two countries are interconnected and there is a congestion.



Another example of interconnection