John Andrews & Nick Jelley

# Lecture 3:

# Energy from fossil fuels

# Proven reserves of fossil fuels

**Table 3.1** Proven reserves and R/P values for oil, gas, and coal (239.4 Gt of oil is equivalent to 1697.6 Gb)

| Region | Oil (%) | Oil R/P (y) | Gas (%) | Gas R/P (y) | Coal (%) | Coal R/P (y) |
|---|---|---|---|---|---|---|
| North America | 14.0 | 33.1 | 6.8 | 13.0 | 27.5 | 276 |
| South and Central America | 19.4 | 117.0 | 4.1 | 42.5 | 1.6 | 150 |
| Europe and Eurasia | 9.1 | 24.4 | 30.4 | 57.4 | 34.8 | 273 |
| Middle East | 47.3 | 73.1 | 42.8 | 129.5 | 3.7 | 123 |
| Africa | 7.6 | 42.2 | 7.5 | 66.4 | | |
| Asia Pacific | 2.5 | 14.0 | 8.4 | 28.1 | 32.3 | 53 |
| *World* | 239.4 Gt | 50.7 | 186.9 $Tm^3$ | 52.8 | 891.5 Gt | 114 |

*Source*: BP2016.

R/P ratio = no. of years that reserves would last if production continued at current level.

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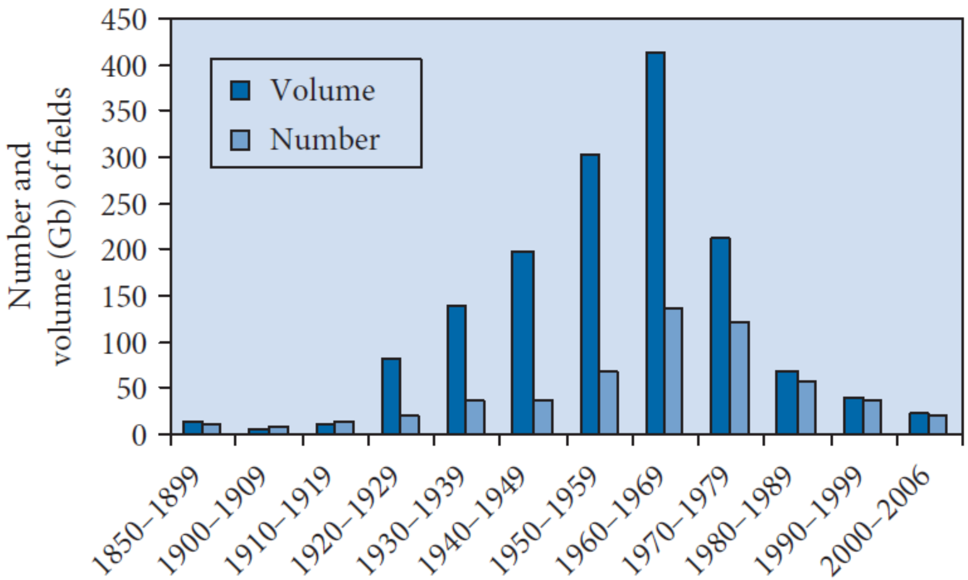
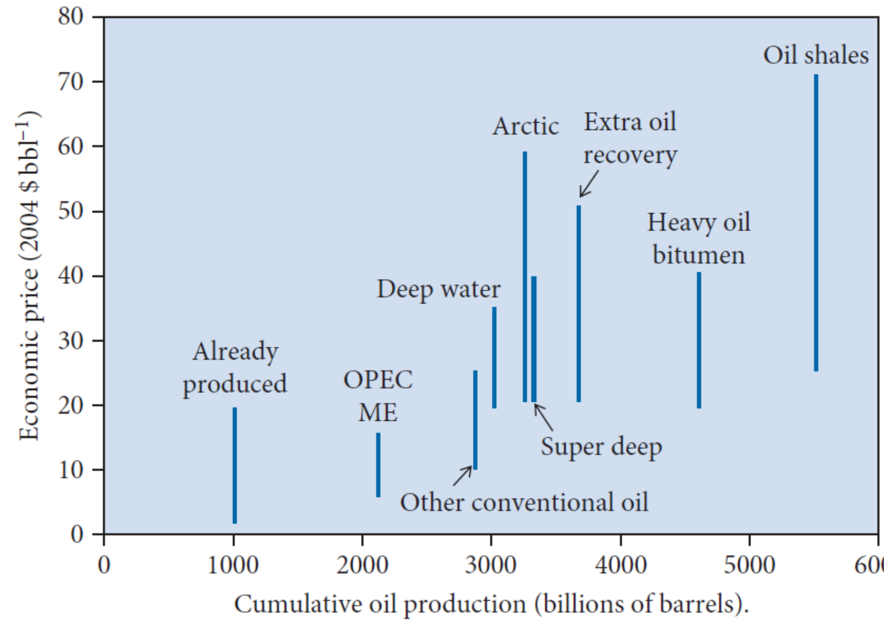
# Economics of oil and gas production




**Hubbert peak theory**: the production of **conventional** oil and gas rises as new deposits are found and extraction methods improve and falls when deposits become scarcer and more expensive to extract.

New deposits are exploited when they can compete with existing deposits

In the last 10 years the production of **unconventional** oil and gas (from shale deposits) in USA is reversing this trend.



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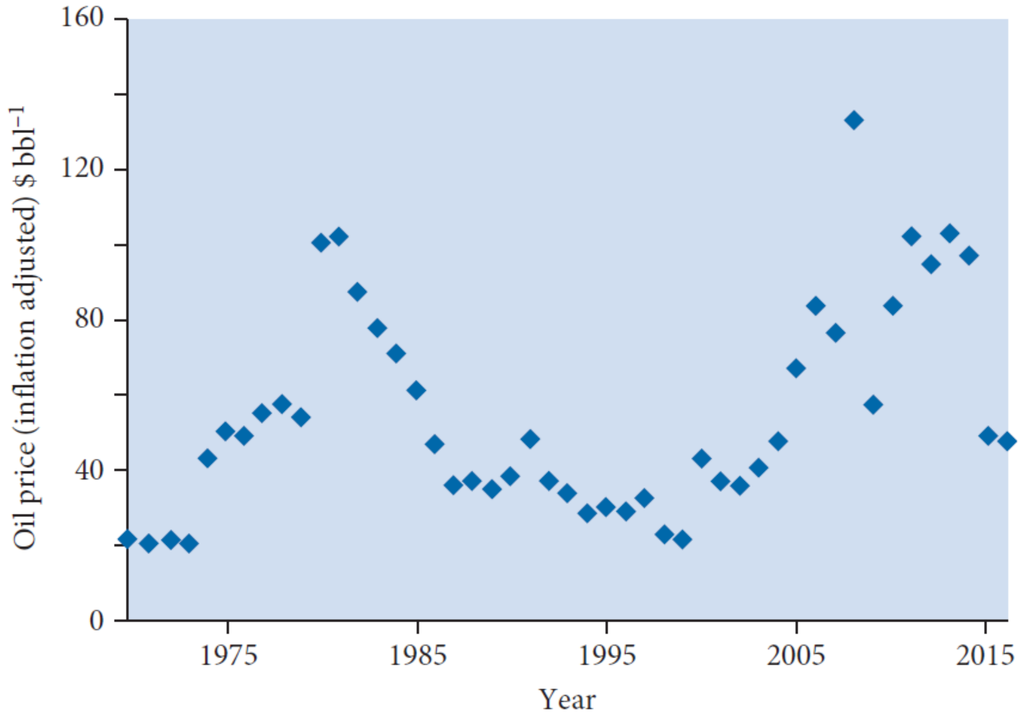
# Oil price fluctuations and alternative energy development




Price of oil is very sensitive to political pressures and wars in the Middle East. Periods of high oil prices stimulated R&D into alternative energy sources.

When prices fell back in 90s to previous levels, interest in renewables dropped

# Combustion of fossil fuels

**Methane** (in natural gas): $CH_4 + 2O_2 = CO_2 + 2H_2O$

Atomic masses H:O:C = 1:16:12 $\Rightarrow$ 16kg of methane produces 44kg of $CO_2$

**Pentane** (in oil): $C_5H_{12} + 8O_2 = 5CO_2 + 6H_2O$

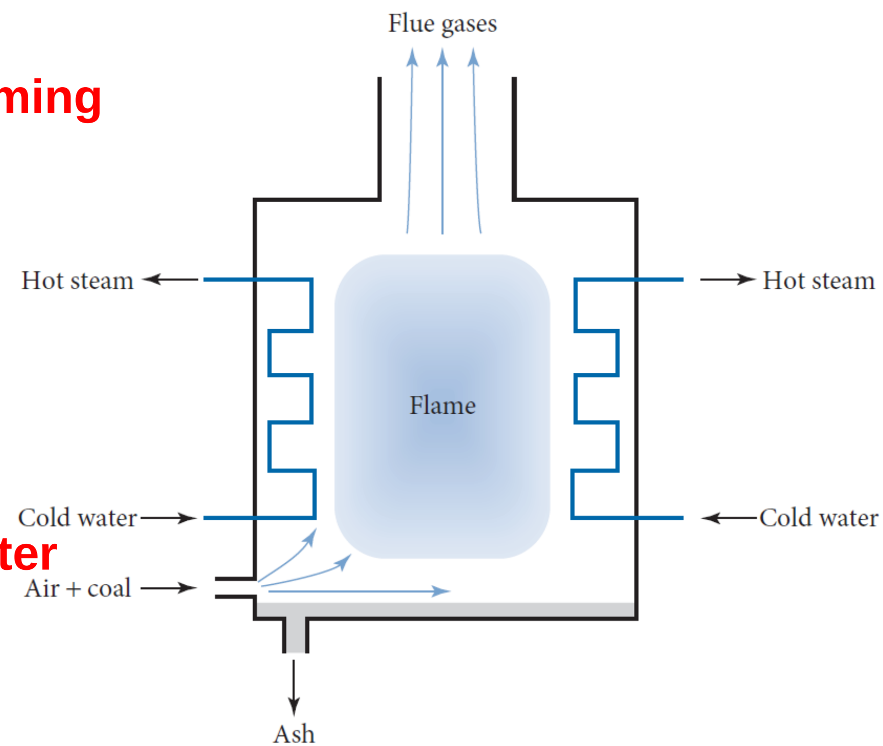
Combustion of fossil fuels releases $CO_2$ into atmosphere, which contributes to **global warming**

Sulfur in coal produces **acid rain** (damages buildings)

Airborne particulates cause **lung diseases**

Shale oil and shale gas production

- needs vast amounts of **high pressure water** which can cause **minor earthquakes**
- uses **toxic chemicals** which can **pollute groundwater**

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Andrews & Jelley: Energy Science, 3rd edition

# Higher and Lower Heating Values

- Heat of combustion = HHV

$$HHV = LHV + n \times 44 \text{ kJ mol}^{-1}$$

where *n* is number of moles water per mole of fuel.

Main contribution is relatively weak double bond in oxygen, rest from stronger O-H compared to C-H

- For compound $C_cH_hO_o$

$$HHV = -418(c + 0.3h - 0.5o) \text{ kJ mol}^{-1}$$

e.g. octane: $C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O$

$HHV = -418(8 + 18 \times 0.3) = 5601 \text{ kJ mol}^{-1}$

$LHV = HHV - 9 \times 44 = 5205 \text{ kJ mol}^{-1}$

Molecular weight 114 g so LHV = 45.7 MJ $kg^{-1}$ cf 44.4 expt

# Carbon capture and storage (CCS)

**Large scale carbon capture**, e.g. flue gas scrubbing from power plants, presents technical, economic and political challenges. Various long-term options for storage of $CO_2$ - **carbon sequestration** – are being considered, including

**geological**: in underground rock formations, e.g. old coal mines and oil fields,
**oceans**: at depths of more than 3km, where $CO_2$ liquifies
.

**Issues**

- CCS technologies are expensive and require international agreements
- $CO_2$ leakage from underground storage sites
- Sea acidification (carbonic acid)
- Only 8 full-scale CCS projects in 2012, with short timescale to demonstrate technical viability and gain international acceptance

**Example**: Sleipner CCS project (North Sea) sequesters around $10^6$ tonnes $CO_2$ per year. Seismic reflection analysis shows distribution of $CO_2$ is a stable plume trapped between layers of shale.

# Thermodynamics of steam power plants

Conventional steam power plants operate in thermodynamic cycle, involving (1) liquid water, (2) 2-phase steam-water mixture, (3) dry steam.

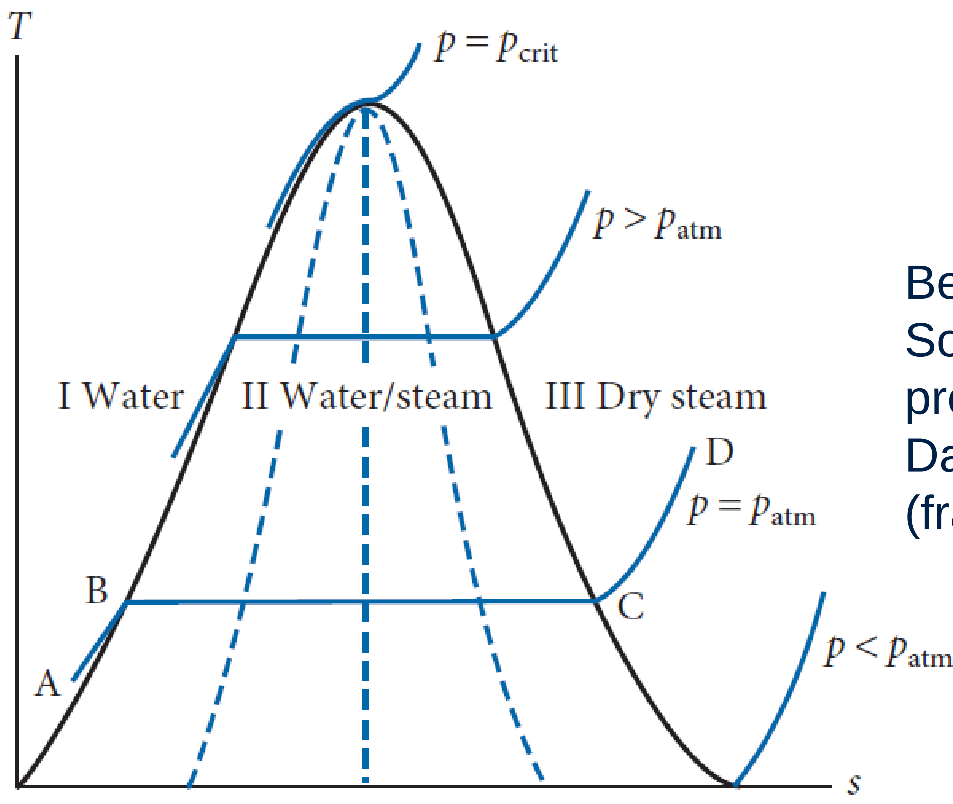
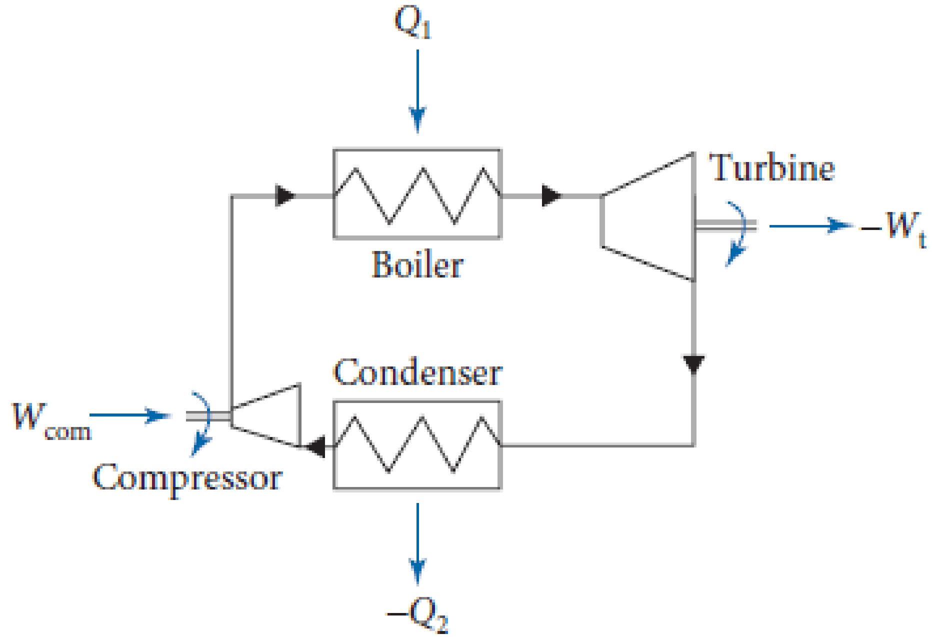



**Fig. 3.6** *T*–*s* diagram for water and steam (not to scale).

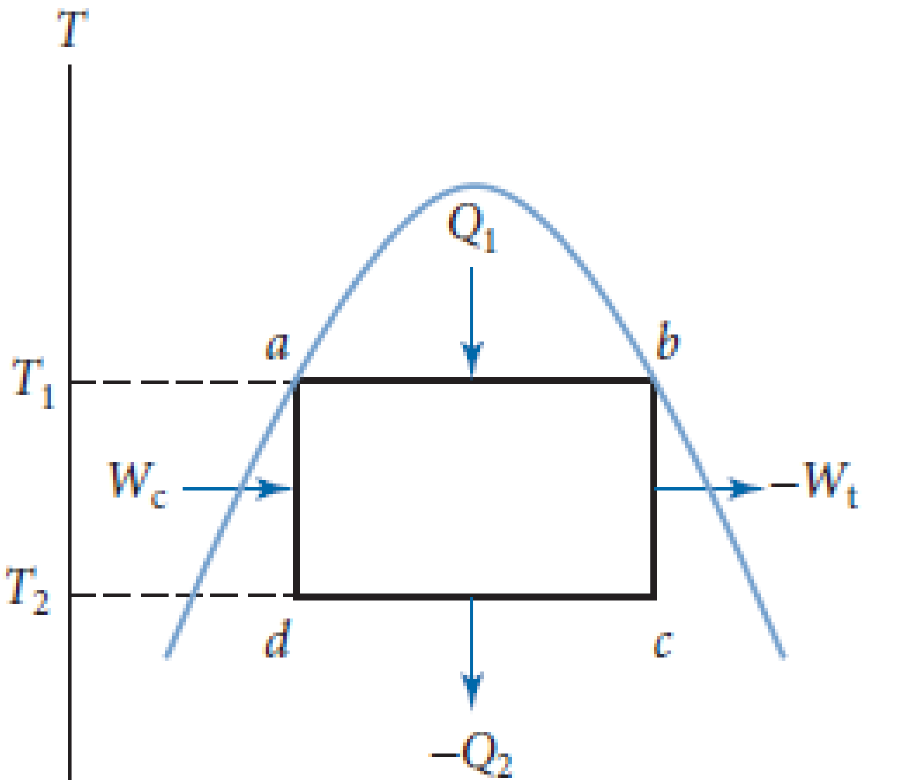
Bell-shaped curve = .phase boundary
Solid blue lines = isobars (const. pressure)
Dashed lines = const. steam quality, *x* (fraction of steam in 2-phase mixture)

# Thermal power plant




| | |
|---|---|
| **compressor** | (also known as the **boiler feed pump**) work $W_{com}$ done on the system to compress cold water from sub-atmospheric pressure to high pressure; |
| **boiler** | heat $Q_1$ added to the system to convert cold water into steam; |
| **turbine** | work $-W_t$ done by the system (i.e. by steam) on the turbine blades; |
| **condenser** | heat $-Q_2$ lost from the system to the environment in converting steam back to cold water. |

# Carnot cycle

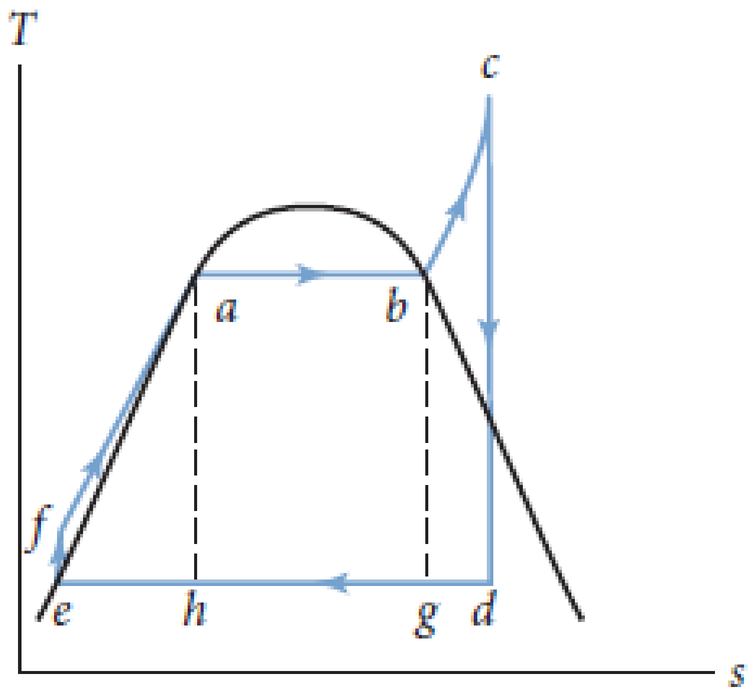


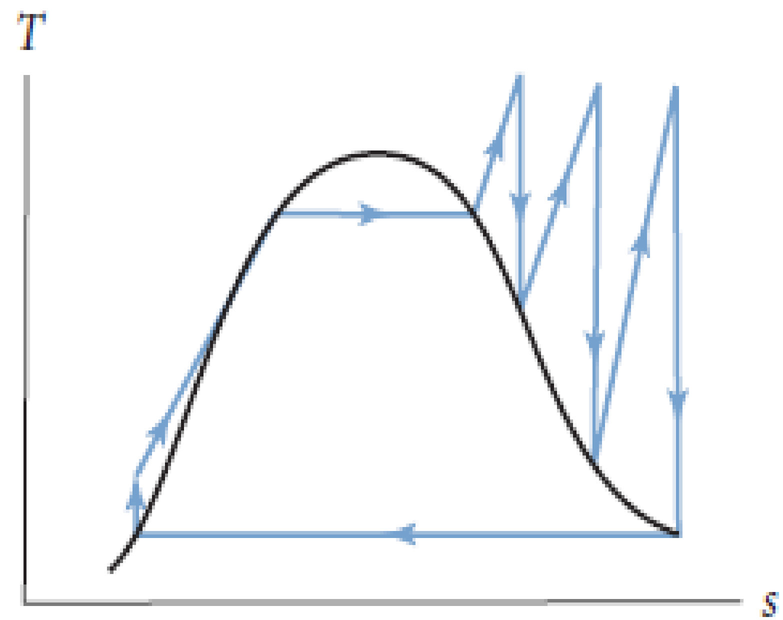

**Carnot cycle** (constant upper and lower temperatures).

Efficiency is $\eta = 1 - \dfrac{T_1}{T_2}$

Fixed upper temperature, requires cycle to be in 2-phase region, which lowers efficiency, leads to damage of turbine blades by high momentum water droplets. Also requires enormous compressor.

# Thermodynamic cycles for steam power plants
# Rankine cycle



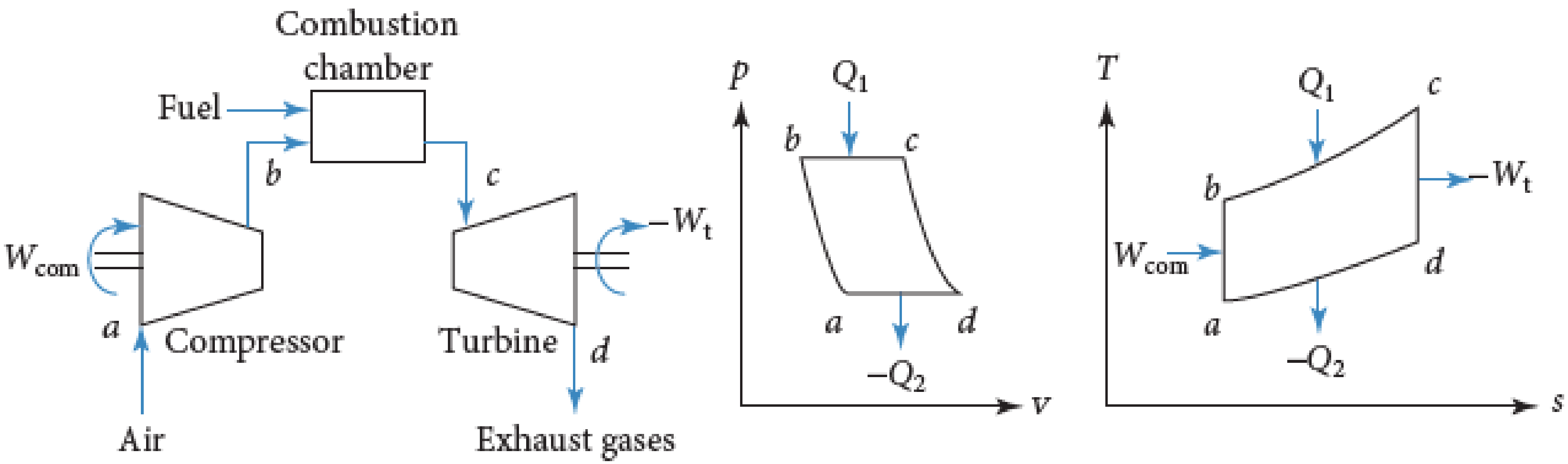

**Rankine cycle without reheat** (higher upper temperature than Carnot cycle)

Practical compressor size, but point *d* is inside 2-phase region, so high momentum water droplets not completely eliminated.

**Rankine cycle with reheat (3 reheat stages, three turbines: HP, IP, LP)**

Avoids water droplets since steam is always dry, upper temperature constrained to around 650º to avoid metallurgical damage, efficiency = 40-45%

# Gas turbine plant

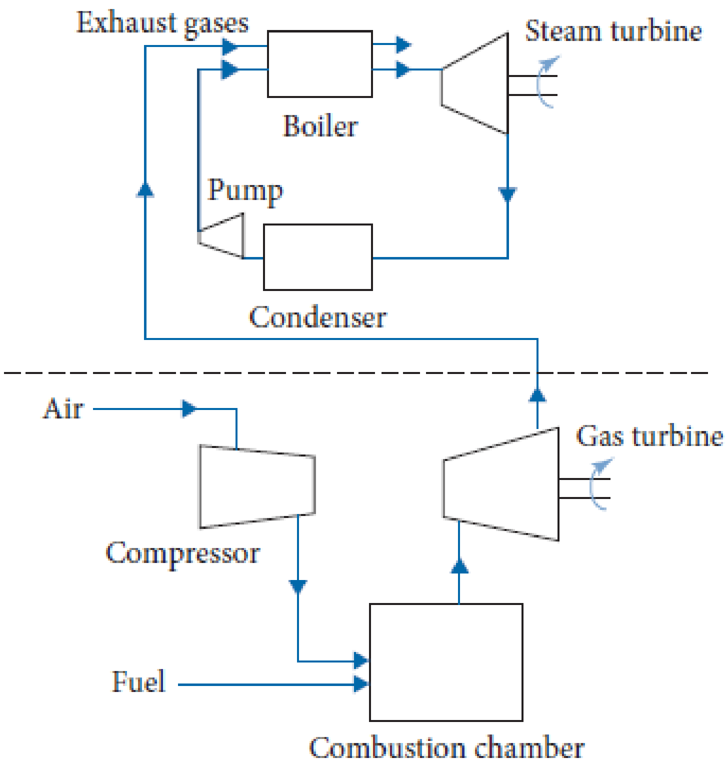



**Brayton (or Joule) cycle for gas turbine**

Upper end temperature around 1300º C (turbine blades have ceramic coating and are water-cooled).

Typical efficiency = 45%

# Combined cycle gas turbine plant (CCGT)



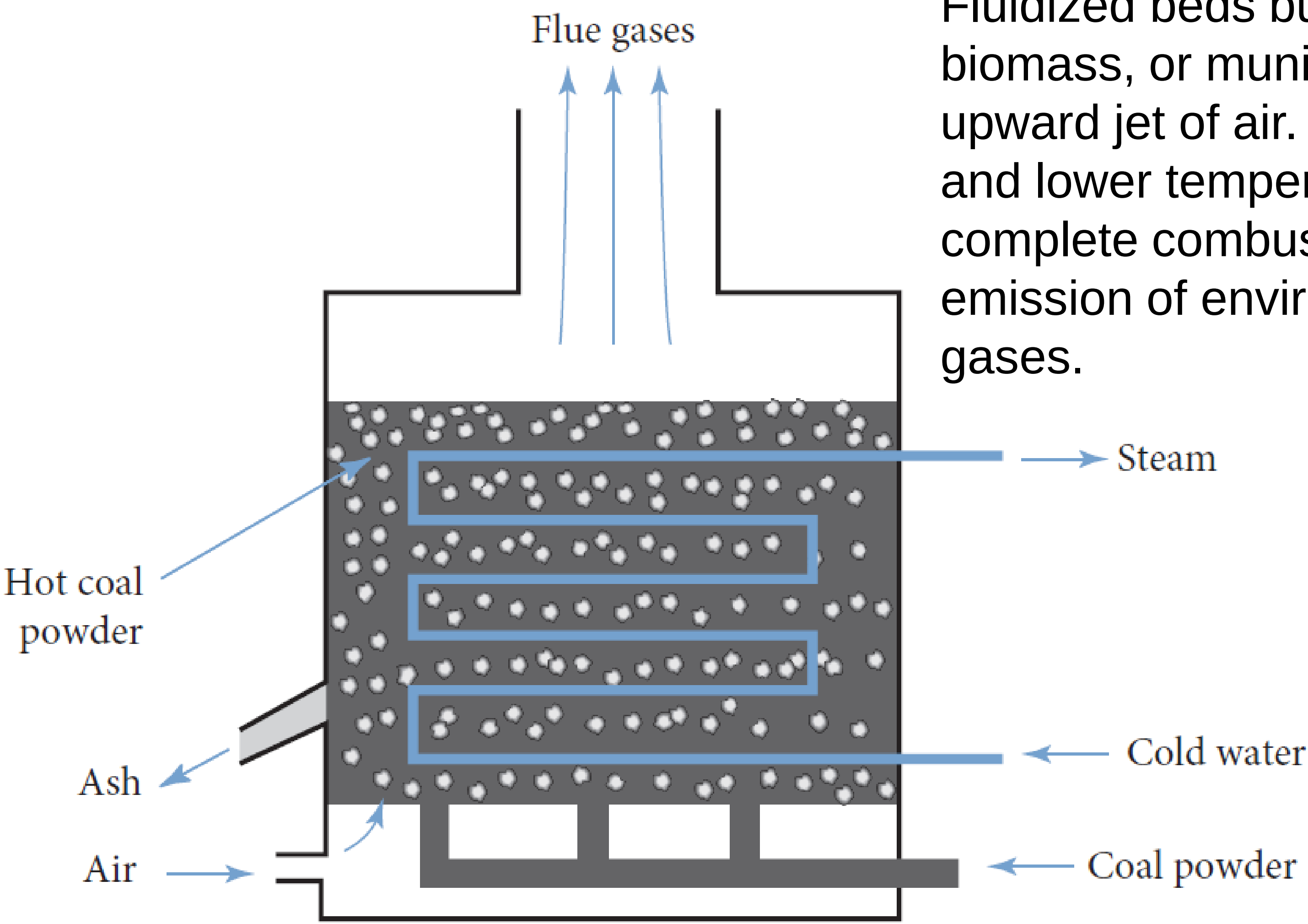

**Combined cycle**

**Trainel Kraftwerk Hamm CCGT, Germany**



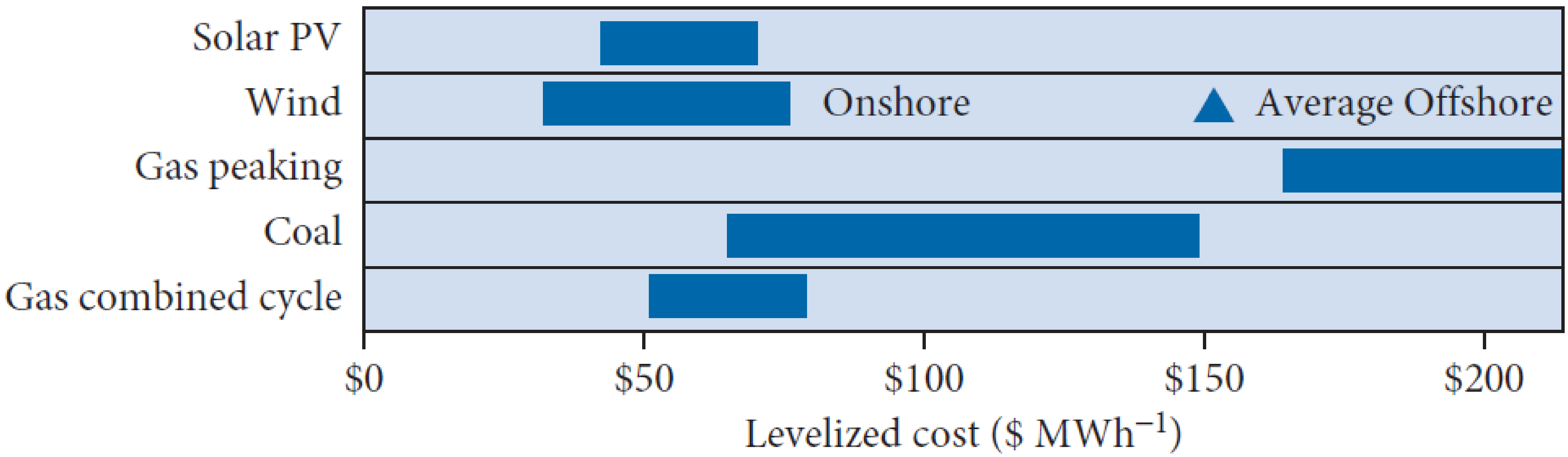
Typical efficiency = 60%, which can be increased to 80% in a combined heat and power cycle (e.g. where waste heat is used for district heating)

# Fluidized Beds




Fluidized beds burn pulverized coal, biomass, or municipal waste in upward jet of air.  Turbulent mixing and lower temperature more complete combustion reduced emission of environmentally harmful gases.

# Economics of fossil fuels




- onshore wind, solar PV are now competitive with fossil-fuel in many locations
- shale oil and gas exploitation has caused shift away from coal in USA
- shale gas will halve $CO_2$ emissions compared to coal
- India and China account for more than half of the expected 50% of growth in demand up to 2040

# Key Points

- The Rankine cycle in power plants overcomes the disadvantages of a Carnot cycle.
- Higher efficiencies can be obtained using combined cycle gas turbines which utilize the waste heat of a Brayton (or Joule) cycle in a Rankine cycle of a steam power plant.
- Fluidized beds can cope with a wide range of feedstock, produce smaller quantities of environmentally harmful gases than conventional combustion chambers, and are now commercially viable.
- It has been estimated that the proven reserves of fossil fuels will last for approximately 51 and 53 years for conventional oil and gas, respectively, and 114 years for coal. The amount of unconventional oil and shale gas approximately doubles the oil and gas reserves, but reserves are determined by limiting emissions rather than resources in the ground.
- Carbon sequestration is a potential means of storing carbon dioxide for long periods, but CCS is expensive and its impact on reducing global warming is uncertain.
- The IEA (2015) estimates that CCS from power generation and in industry could each reduce emissions in 2050 by ~3 $GtCO_2\ y^{-1}$, corresponding to ~750 GWe continuous generation (assuming an equivalence of ~0.5 $kgCO_2\ kWh^{-1}$).