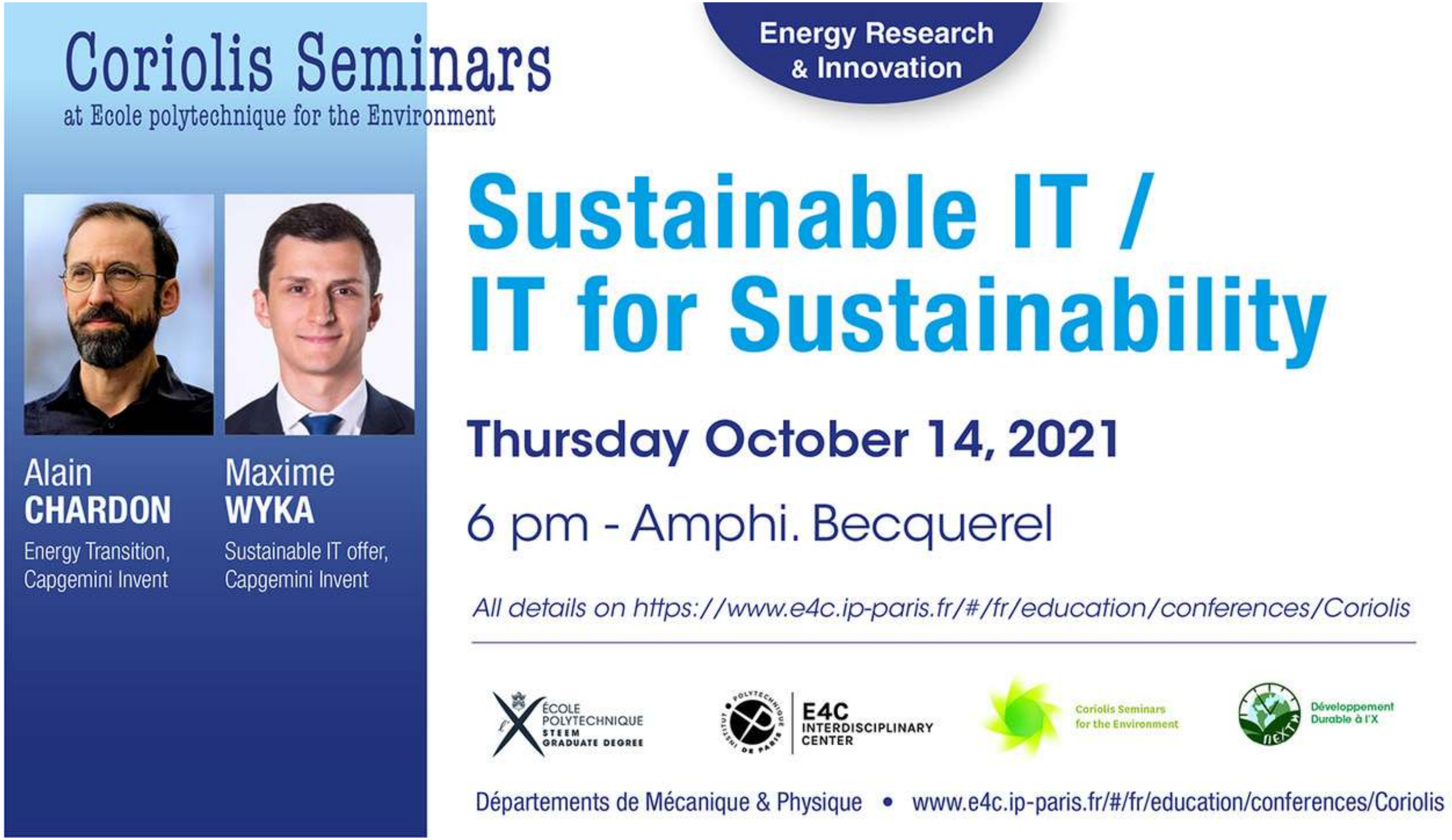
Lecture 3
Fossil fuels

PHY 555 – Energy & Environment

Erik Johnson, Mathieu de Naurois, Daniel Suchet

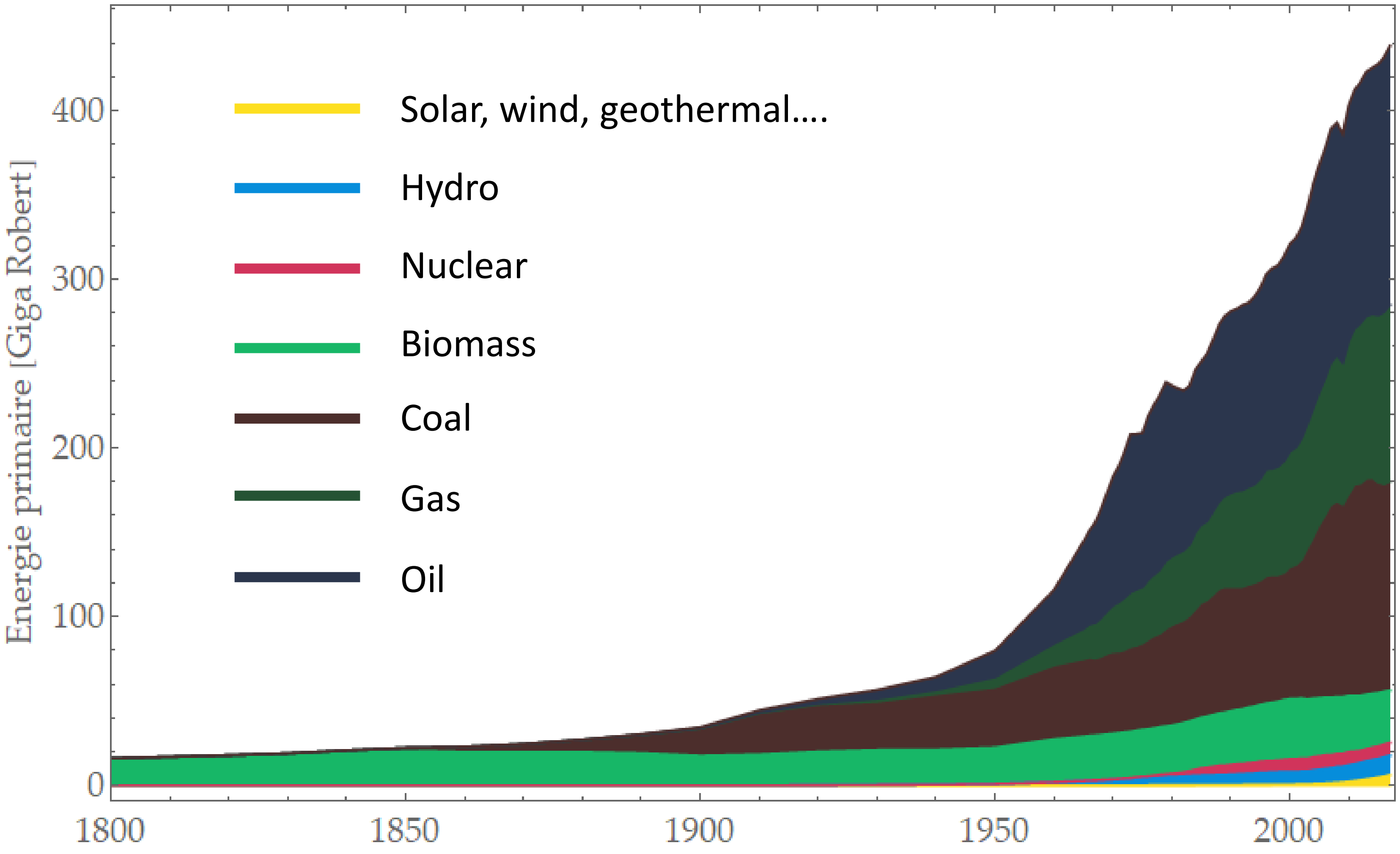
Omanobserver

Advertisment



Why discuss fossil fuel?

1. Because fossil fuels cover 85% of our primary energy

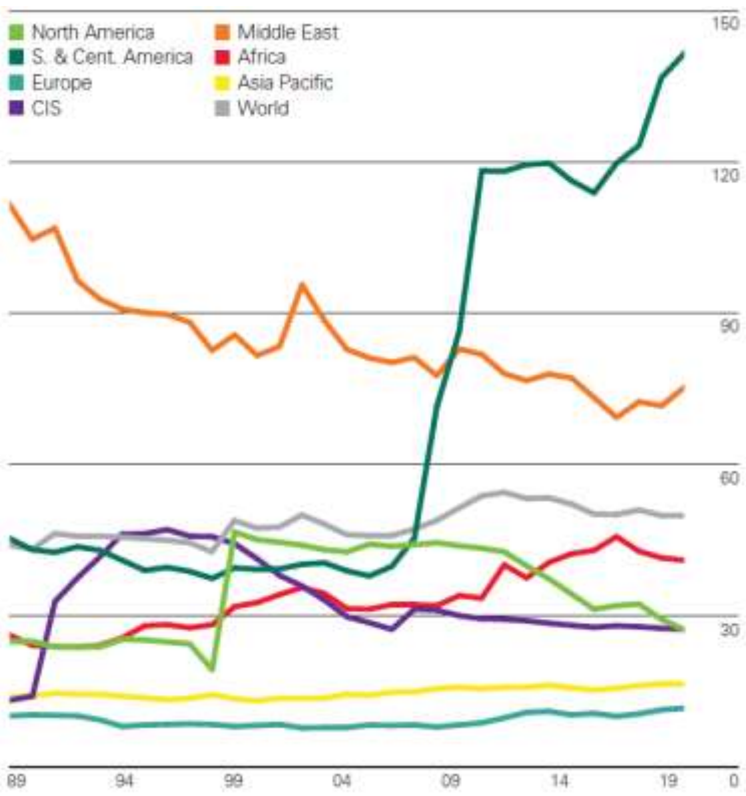


Why discuss fossil fuel?

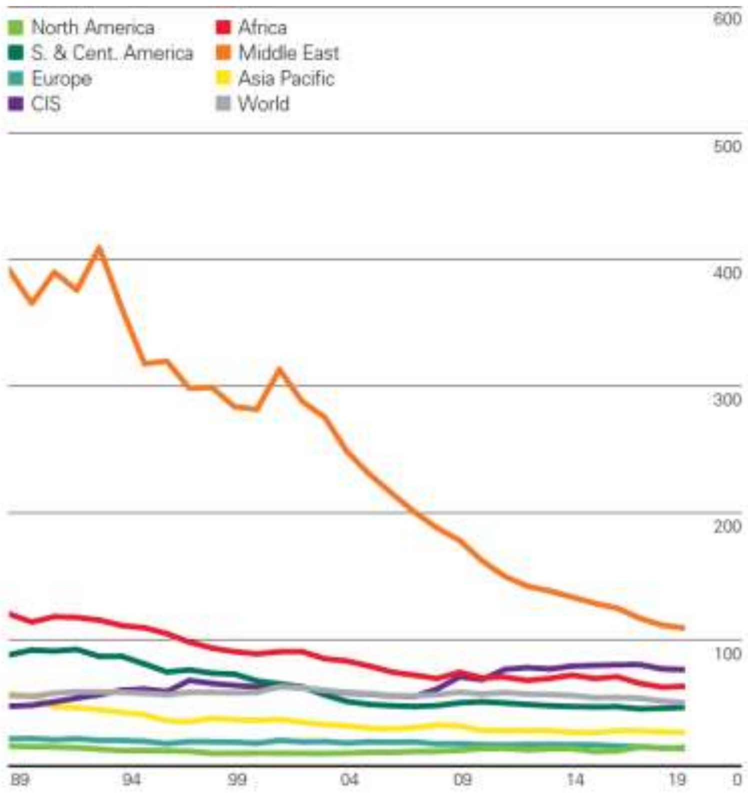
1. Because fossil fuels cover 85% of our primary energy
2. Because fossil reserves are limited

Source: BP Statistical Review of World Energy (2020)

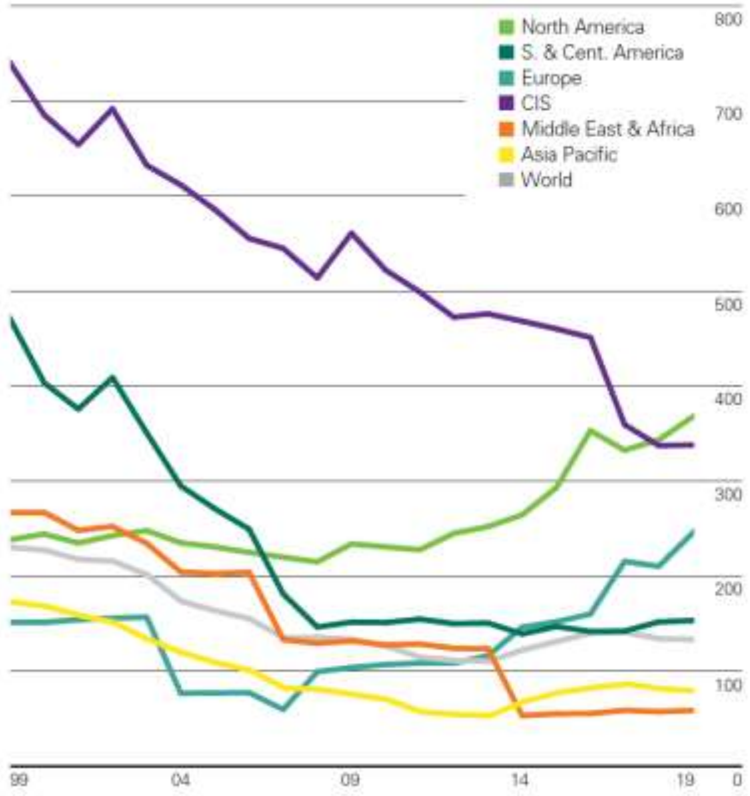
Reserve – to – production ratios



Oil : 50 years



Gas: 50 years

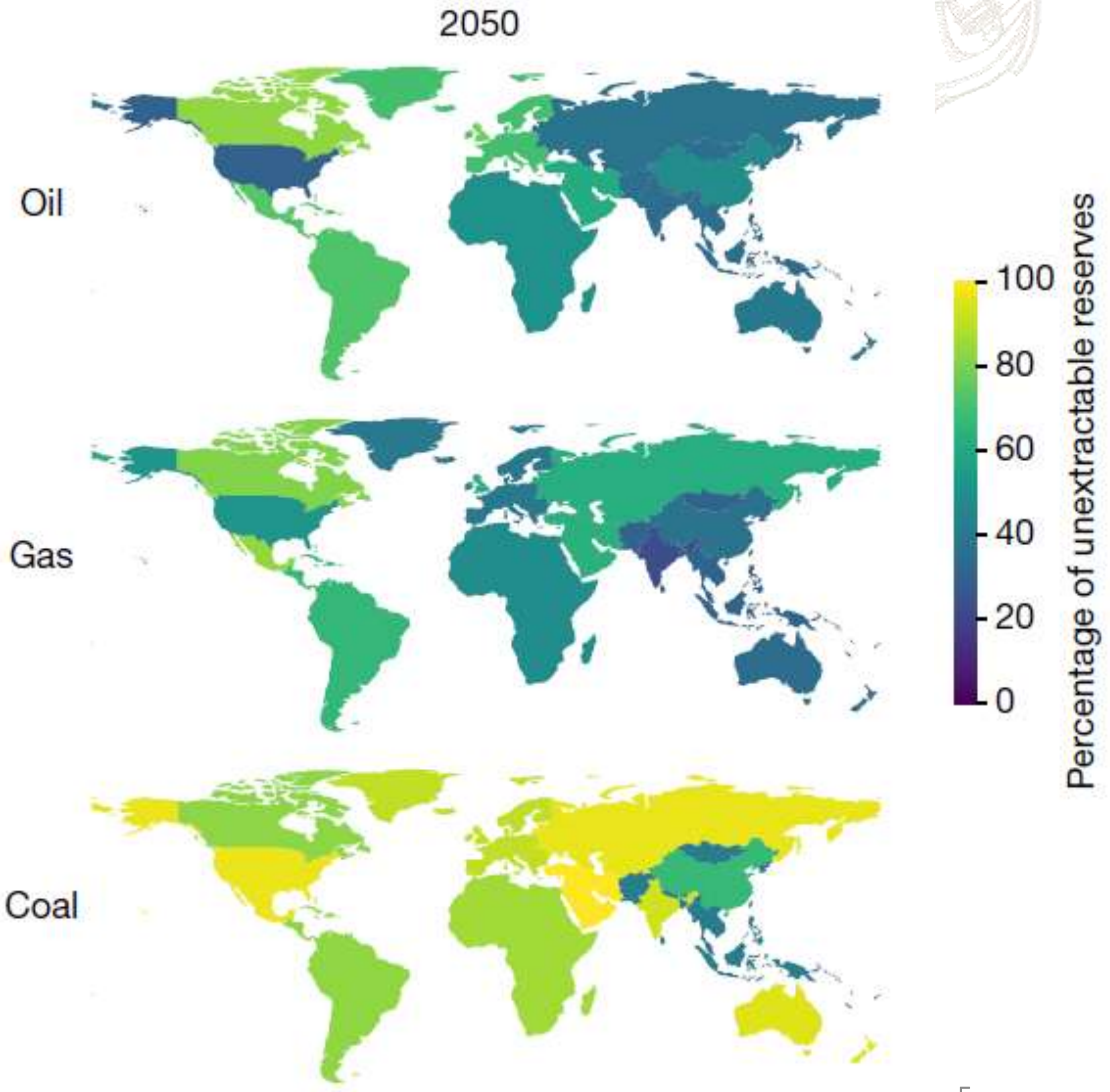


Coal: 130 years

Why discuss fossil fuel?

1. Because fossil fuels cover 85% of our primary energy
2. Because fossil reserves are limited
3. Because we'd better not reach this limit

"By 2050, we find that nearly 60 per cent of oil and fossil methane gas, and 90 per cent of coal must remain unextracted to keep within a 1.5 °C carbon budget"



Welsby et al., Unextractable fossil fuels in a 1.5 °C world, Nature (2021)

Lecture 3 Fossil fuels

What, Who, What for, Why ?

Thermo toolbox : the chemical potential

Oil, gas and coal formation: in and out the organic carbon cycle

Oil (and gas) production: conventional and unconventional sources

Oil refining: from crude oil to the gas station

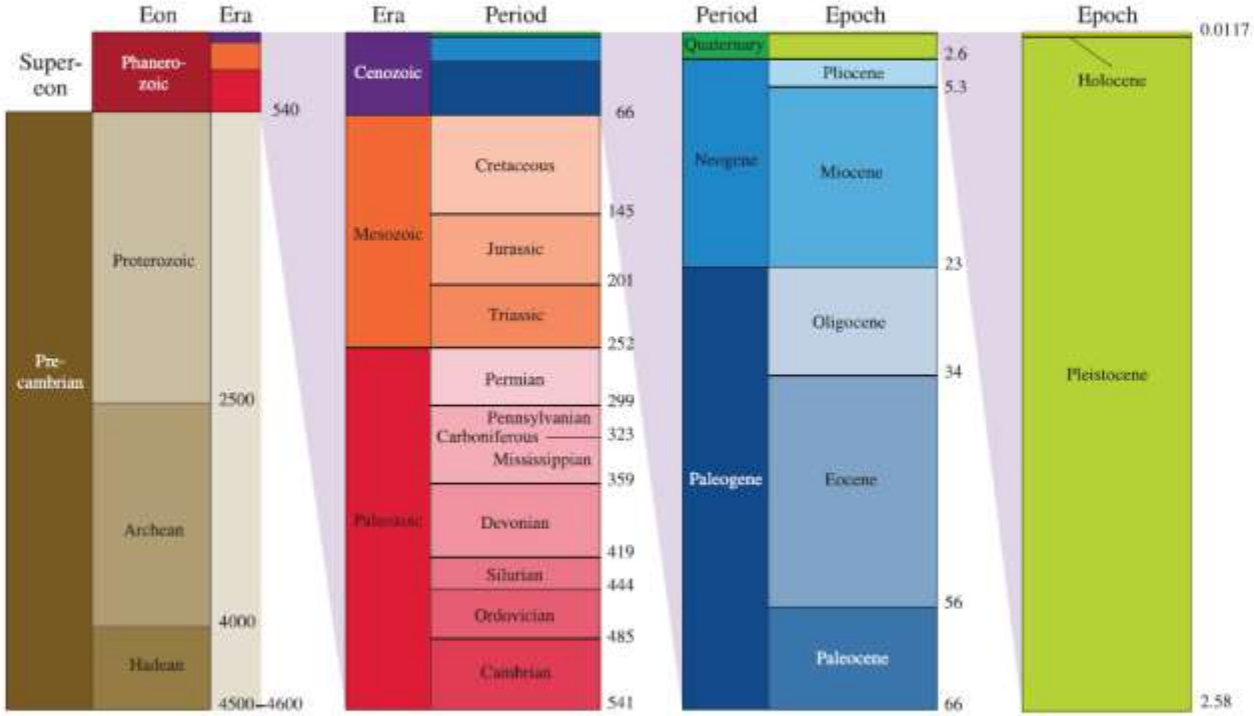
Perspectives

Dino’s juice

Table 26.2 Average Chemical Composition of Biochemicals as Compared to Petroleum.

	Elemental Composition in Weight Percent				
	C	**H**	**S**	**N**	**O**
Carbohydrates	44	6			50
Lignin	63	5	0.1	0.3	31.6
Proteins	53	7	1	17	22
Lipids	76	12			12
Petroleum	85	13	1	0.5	0.5

Source: From Hunt, J. M. (1996). Petroleum Geochemistry and Geology, *2nd edition. W. H. Freeman and Co., New York, p. 63.*

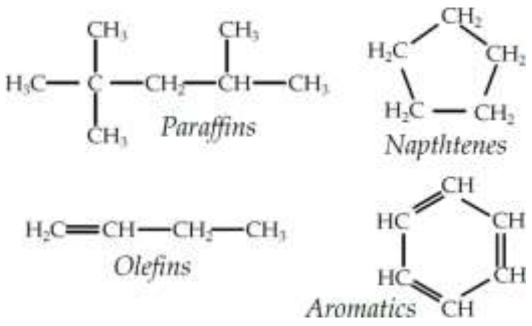


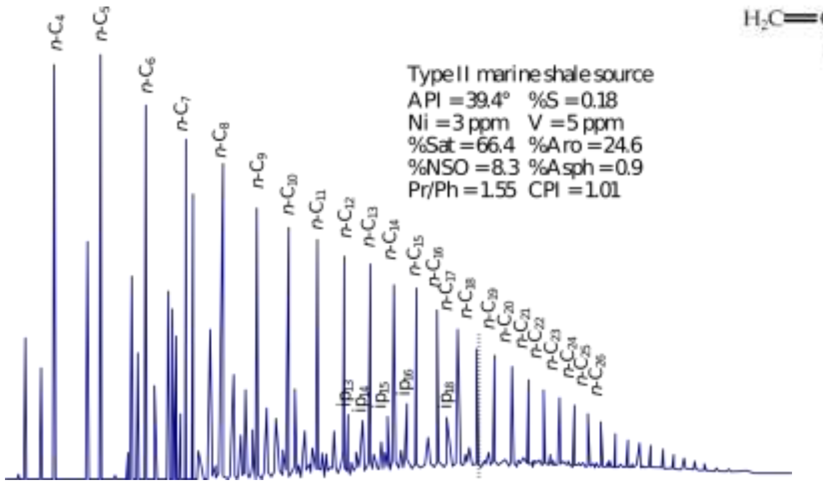
Petroleum ← lipids ← plankton ← sea environment (Mesozoic era, 66 to 252 Myr)

Coal = lower H/C ratio ← lignin ← vascular plants← terrestrial environment (Carboniferous, 320 Myr)

What? Petroleum (=crude oil)

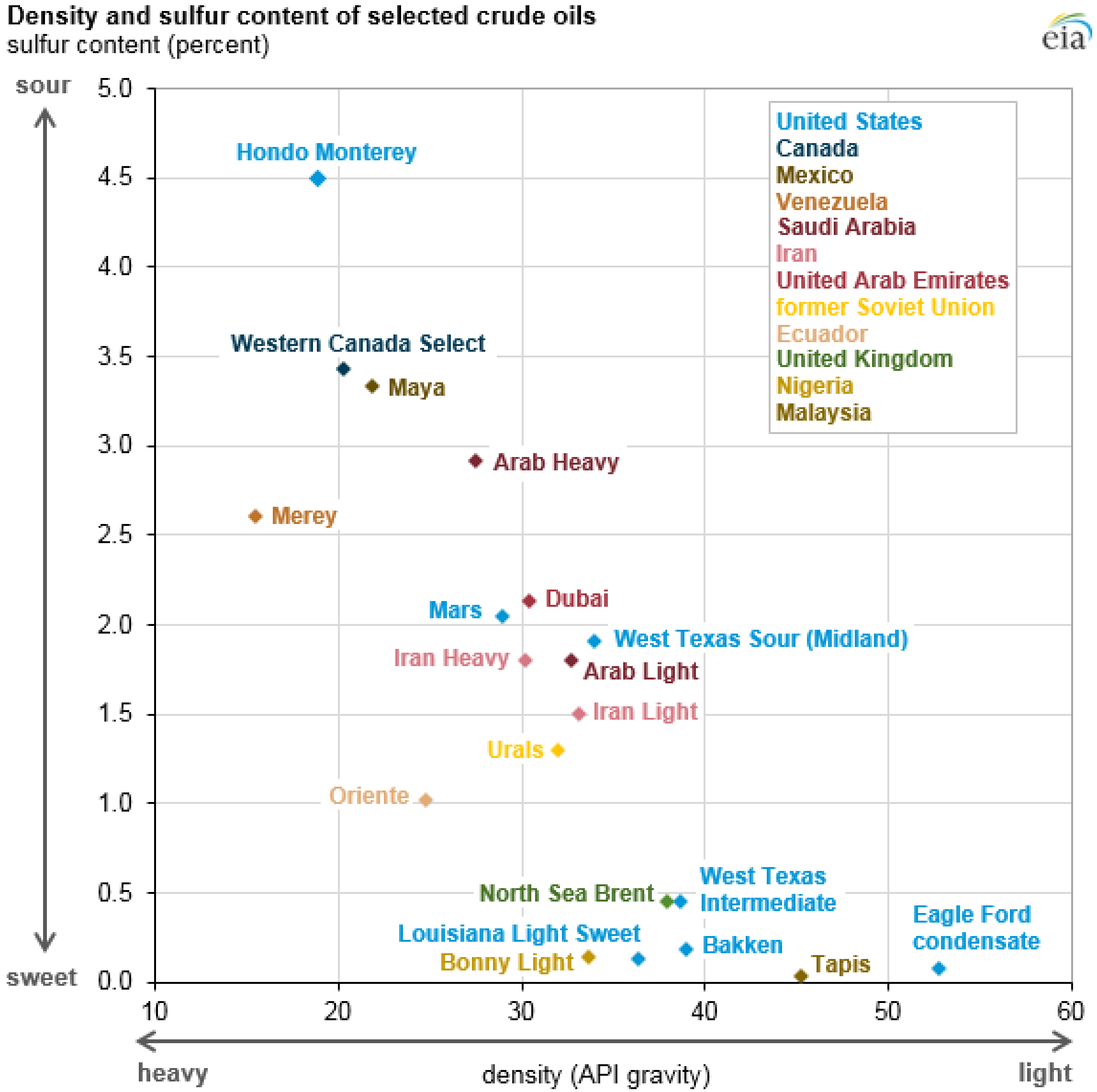
A broad mixture of hydrocarbons





Hsu, Robinson (Eds), Springer Handbook of Petroleum Technology

https://kimray.com/



Typical characterizations

Heavy versus light

$$\text{API gravity} = \frac{141.5}{\rho_{\text{oil}}/\rho_{\text{water}}} - 131.5$$

Sour versus sweet

% of sulfur content

What? Oil products

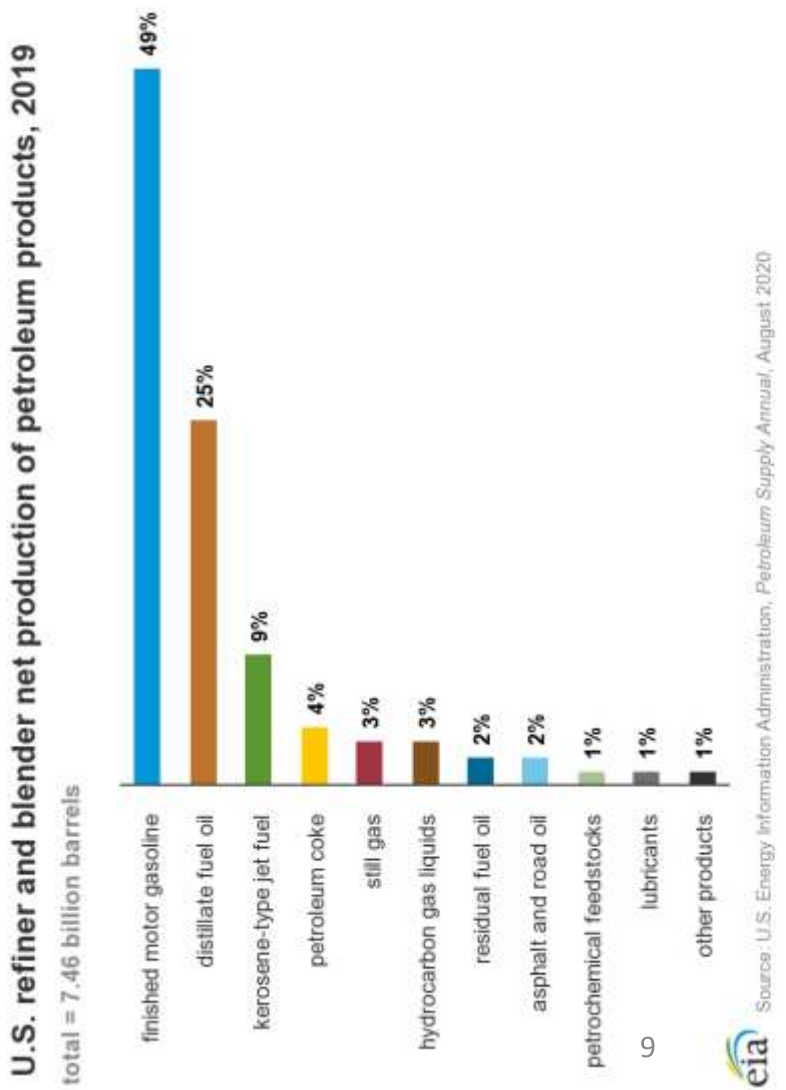
	Number of carbons	Boiling point range	Uses
Gases	1–4	0–30°C	Bottled and natural gas
Naphthas	5–10	30–180°C	Gasoline
Kerosenes	10–16	180–260°C	Kerosene for home heaters, jet fuel
Gas oils	16–60	260–350°C	Diesel fuel, feedstock for cracking
Lubricants	>60	350–575°C	Motor oil, feedstock for cracking
Fuel oil	>70	>490°C	Candles, fuel oil for ships and power stations
Asphalt	>80	>580°C	Roofing tar, road tar

Light distillates

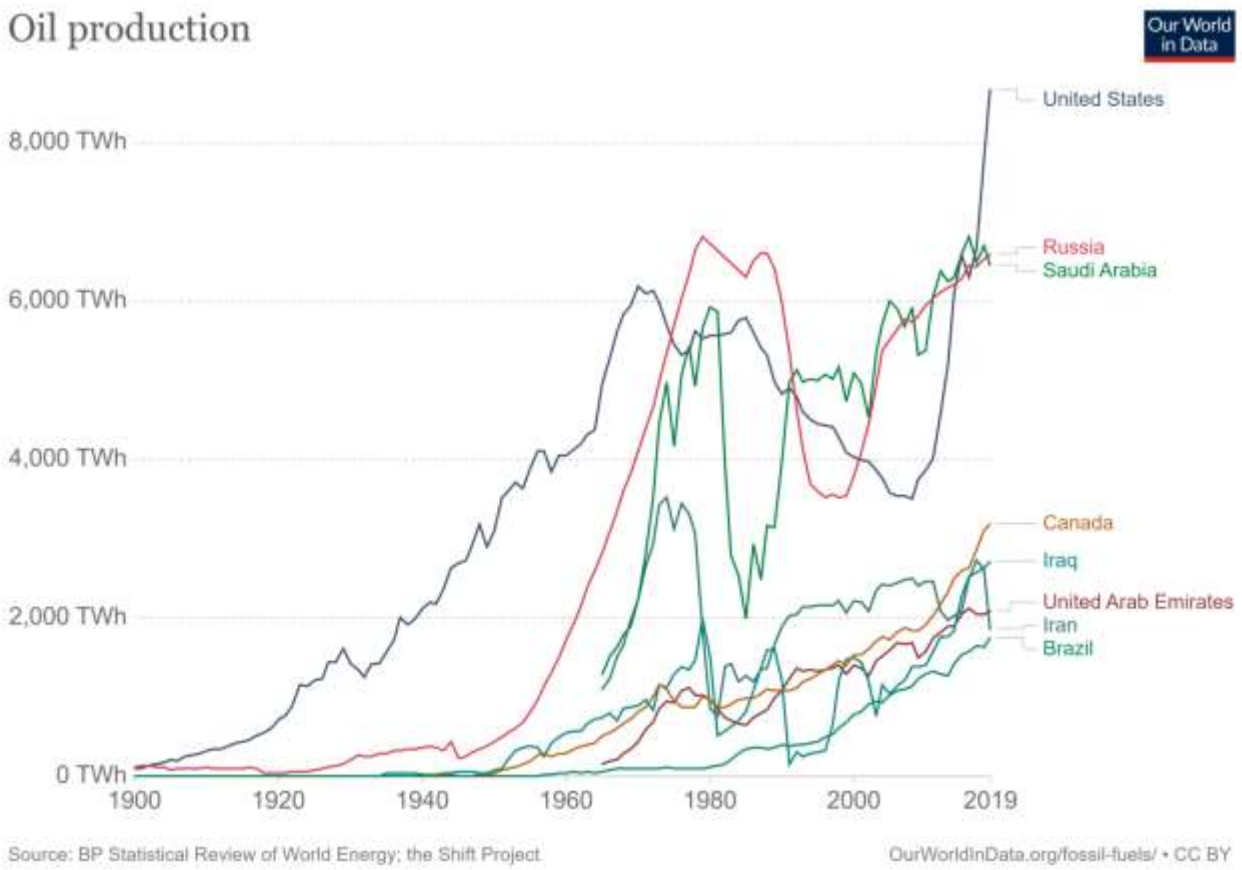
Middle distillates

Heavy distillates

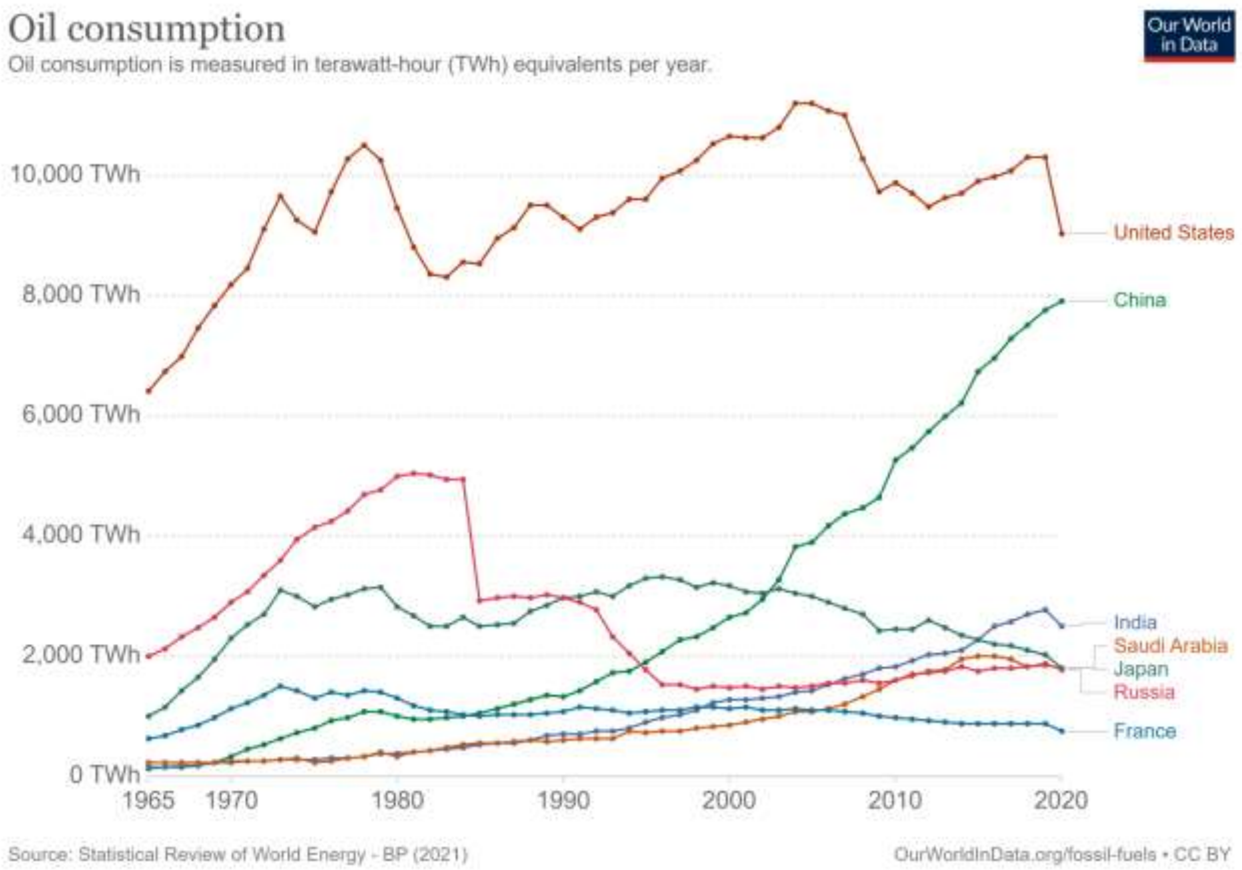
Residuum



Who? Oil



Oil production
Our World in Data
United States
Russia
Saudi Arabia
Canada
Iraq
United Arab Emirates
Iran
Brazil
8,000 TWh
6,000 TWh
4,000 TWh
2,000 TWh
0 TWh
1900
1920
1940
1960
1980
2000
2019
Source: BP Statistical Review of World Energy; the Shift Project
OurWorldInData.org/fossil-fuels/ • CC BY



Oil consumption
Oil consumption is measured in terawatt-hour (TWh) equivalents per year.
Our World in Data
United States
China
India
Saudi Arabia
Japan
Russia
France
10,000 TWh
8,000 TWh
6,000 TWh
4,000 TWh
2,000 TWh
0 TWh
1965
1970
1980
1990
2000
2010
2020
Source: Statistical Review of World Energy - BP (2021)
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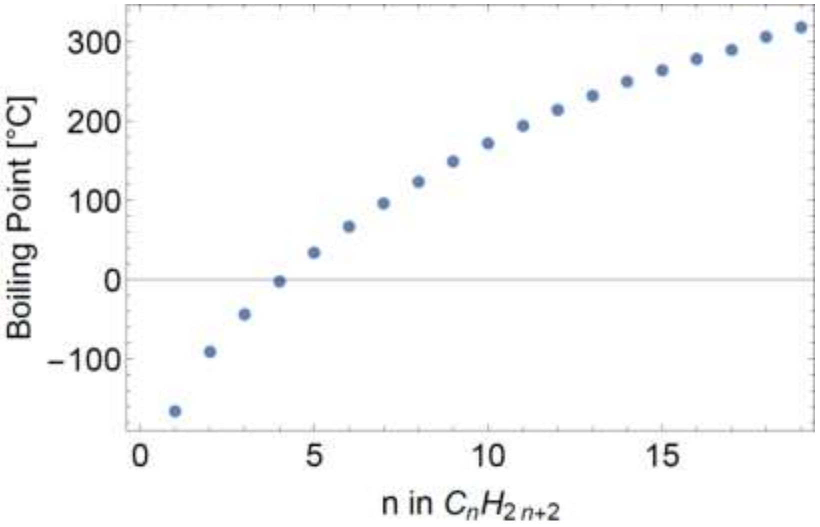
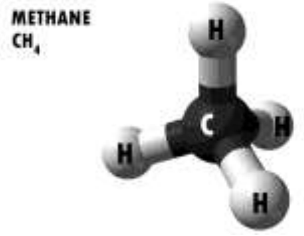
What? Gas



Light hydrocarbon (#C < 5) are gaseous at ambient (T,p)

- Natural Gas ≈ 95% Methane = CH_4

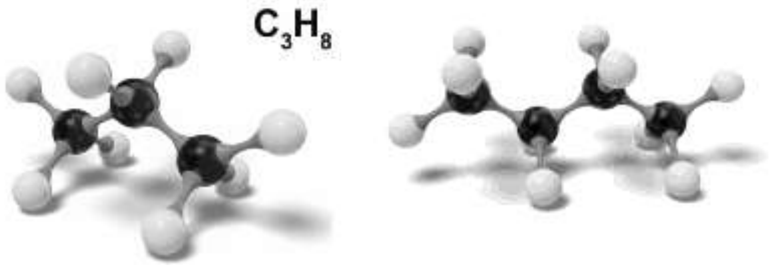


Extracted together with oil, or dedicated production

Liquified Natural Gas (LNG) : ambient p, -160°C

Compressed Natural Gas (CNG) : 200-250 bar, ambient T

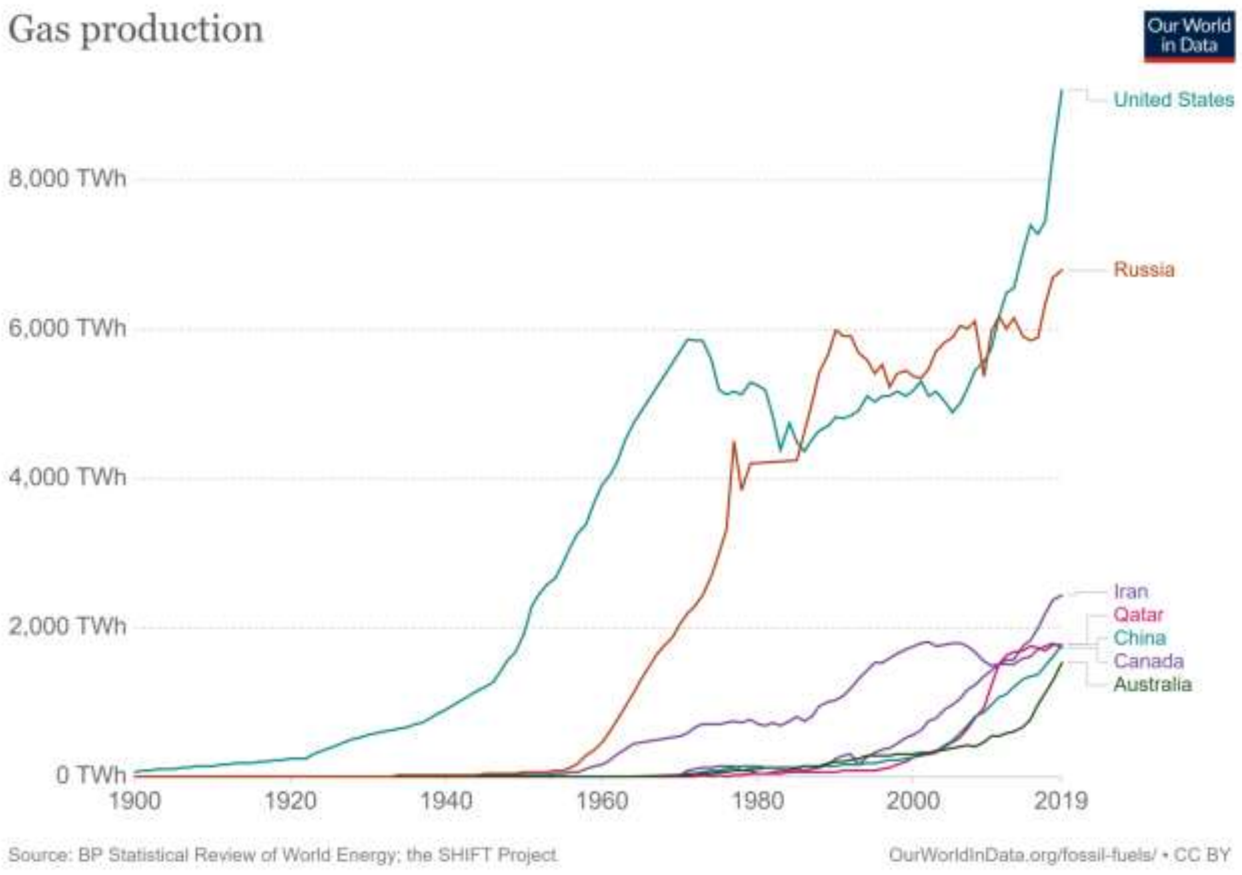
- Liquified Petroleum Gas (LPG) = propane & butane mix

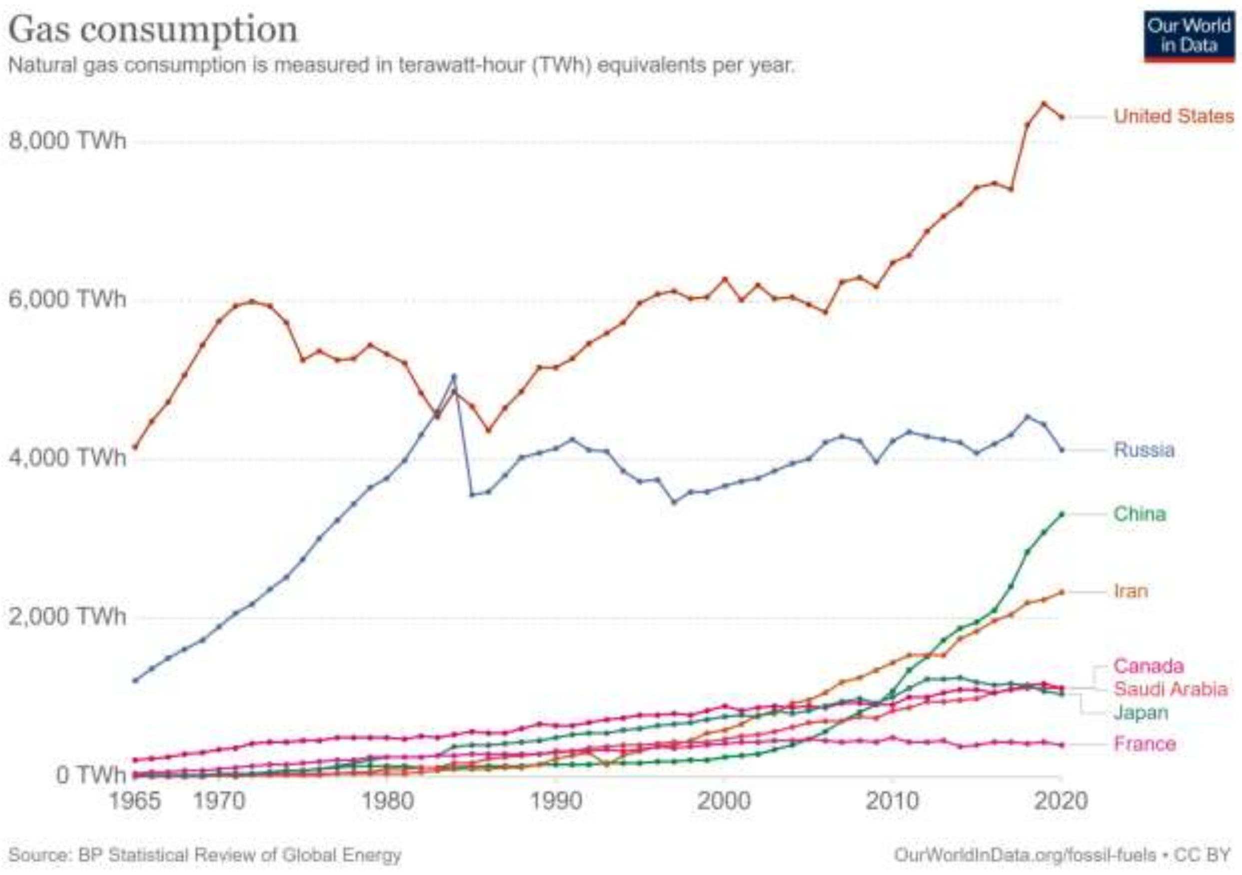


Much easier to handle: 17,5 bar ambient T

Smaller energy densities

Who? Gas


Gas production
Our World in Data
United States
Russia
Iran
Qatar
China
Canada
Australia
8,000 TWh
6,000 TWh
4,000 TWh
2,000 TWh
0 TWh
1900
1920
1940
1960
1980
2000
2019
Source: BP Statistical Review of World Energy; the SHIFT Project
OurWorldInData.org/fossil-fuels/ • CC BY


Gas consumption
Natural gas consumption is measured in terawatt-hour (TWh) equivalents per year.
Our World in Data
United States
Russia
China
Iran
Canada
Saudi Arabia
Japan
France
8,000 TWh
6,000 TWh
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2,000 TWh
0 TWh
1965
1970
1980
1990
2000
2010
2020
Source: BP Statistical Review of Global Energy
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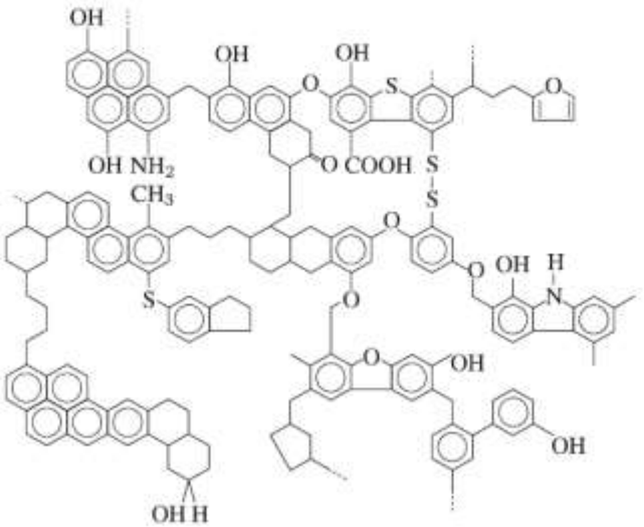
What? Coal



Peat [=tourbe]

Carbon content 50%, energy density 10-20 MJ/kg

Lignite

Carbon content 60-80%, energy density 20 MJ/kg

Bituminous coal [=houille]

Carbon content 80-90%, energy density 30 MJ/kg

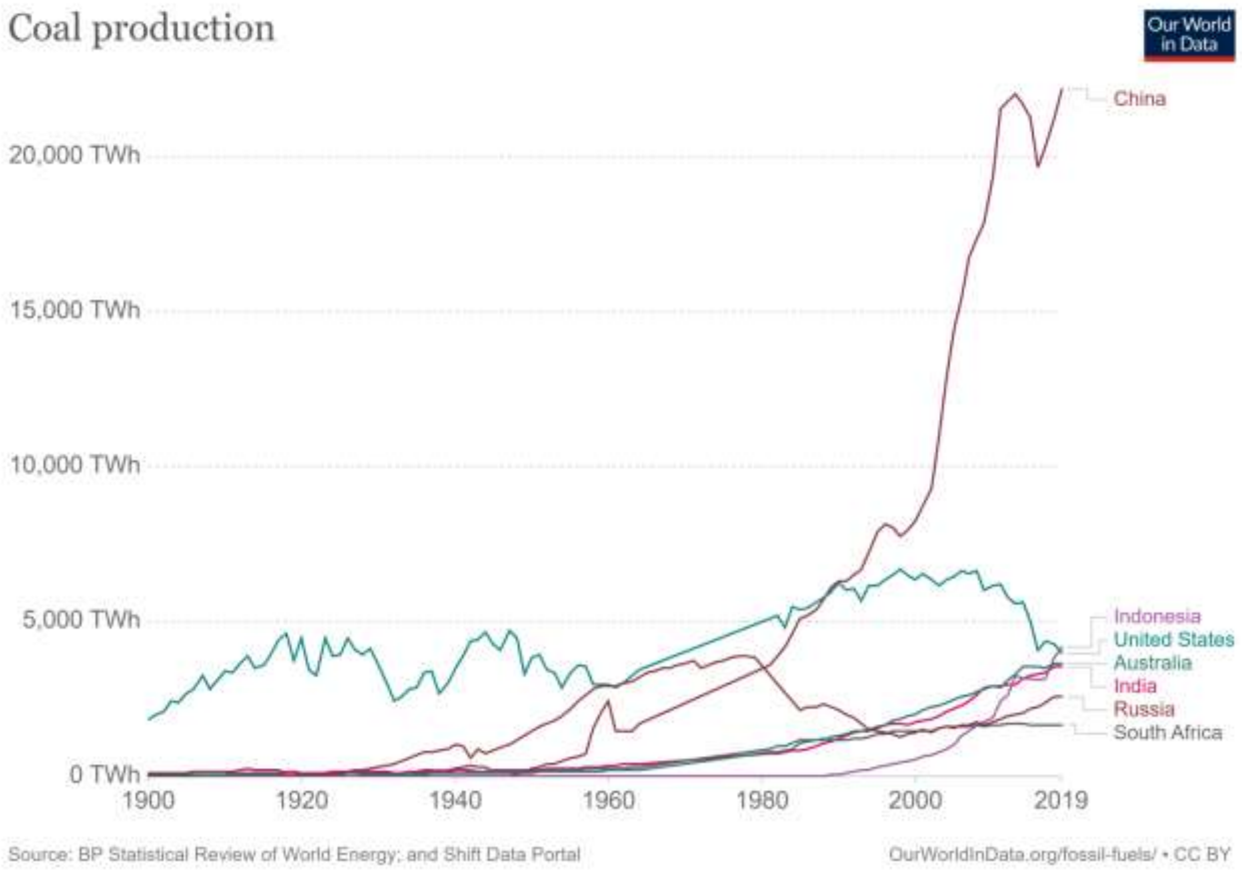
Coking coal

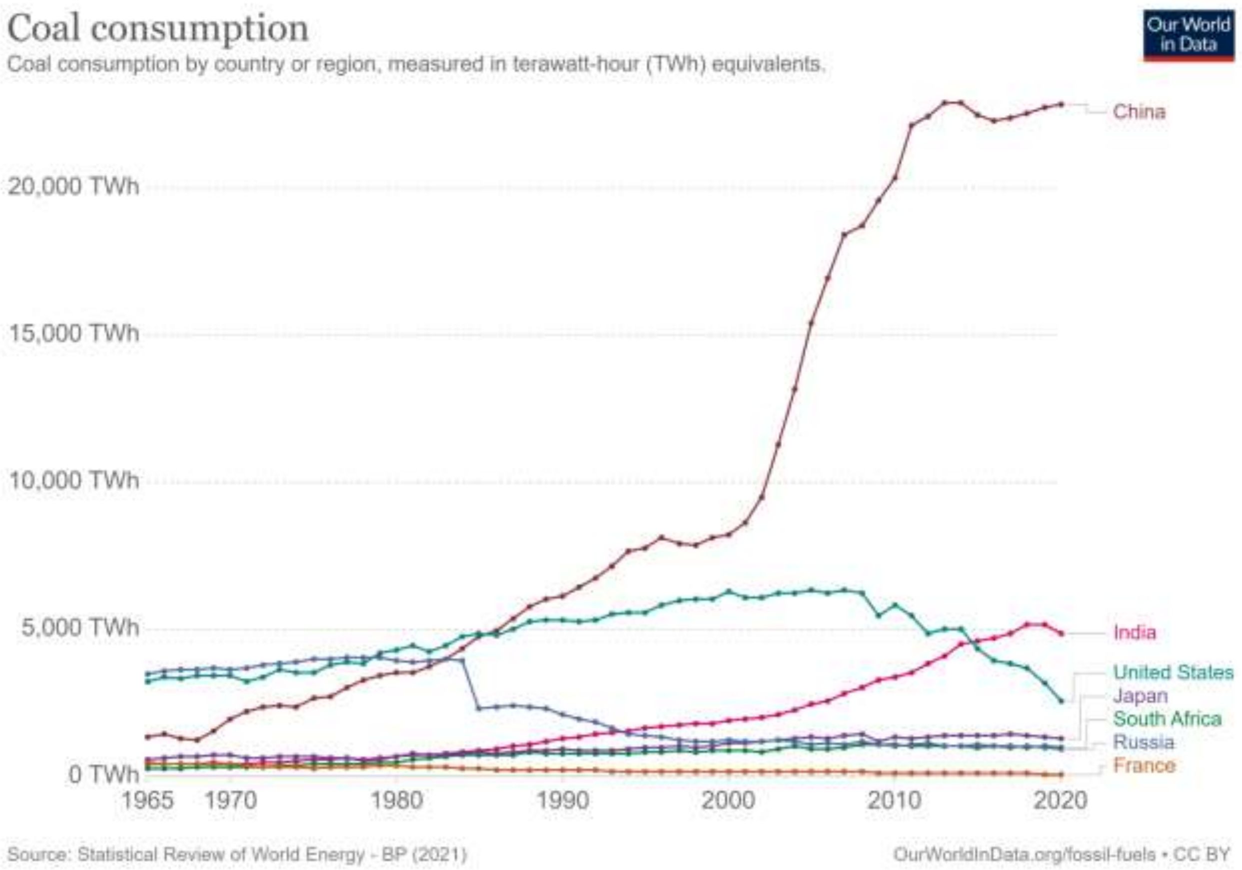
Used to produce coke by pyrolysis → industrial applications

Anthracite

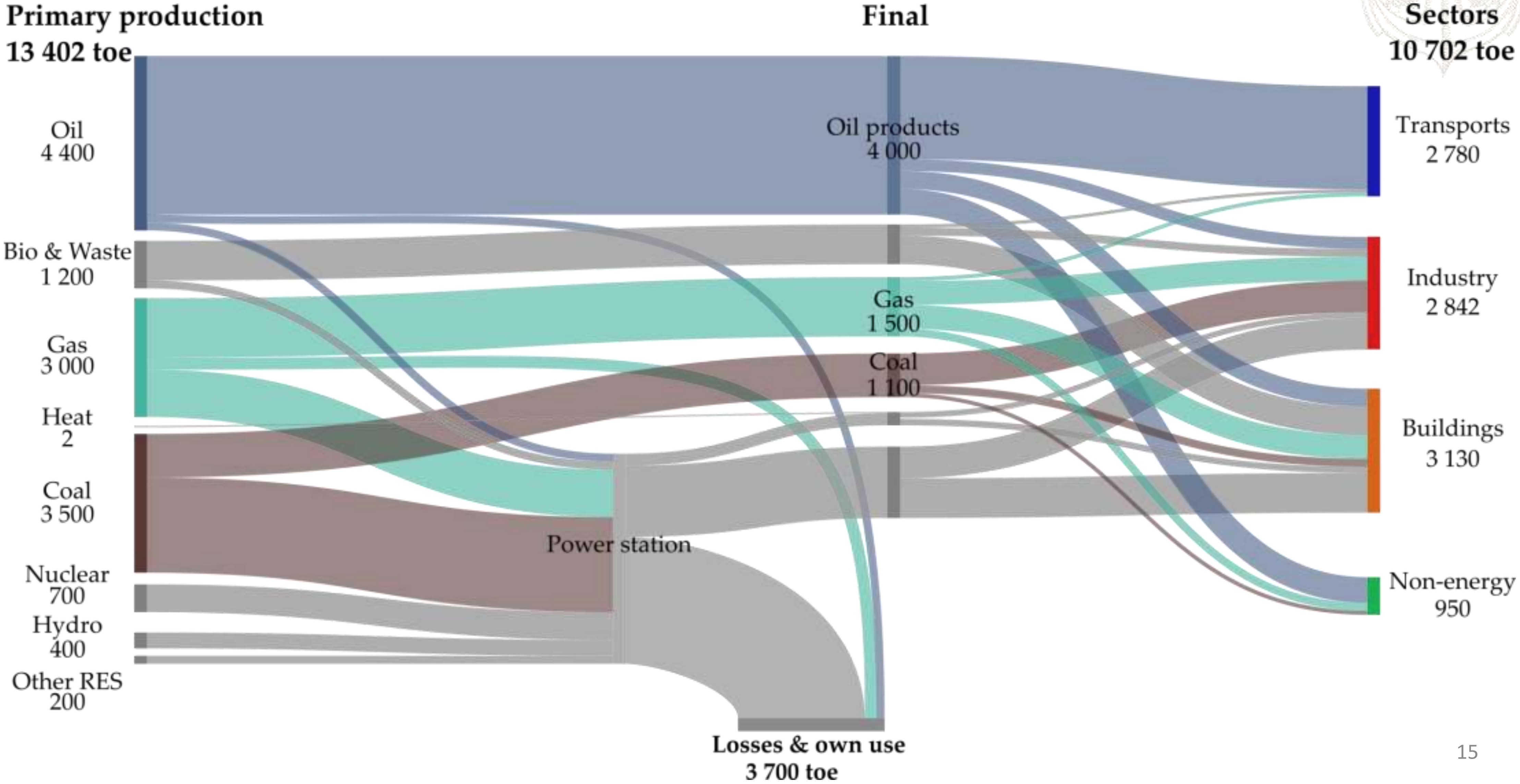
Carbon content 98%, energy density 36 MJ/kg

Who? Coal


Coal production
Our World in Data
China
20,000 TWh
15,000 TWh
10,000 TWh
5,000 TWh
0 TWh
Indonesia
United States
Australia
India
Russia
South Africa
1900
1920
1940
1960
1980
2000
2019
Source: BP Statistical Review of World Energy; and Shift Data Portal
OurWorldInData.org/fossil-fuels/ • CC BY

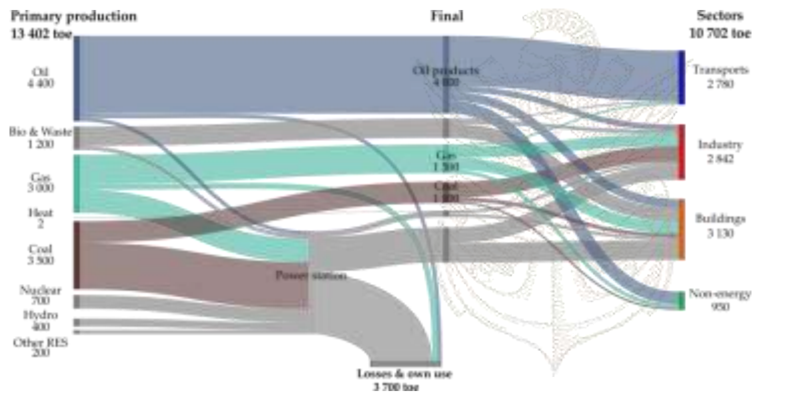

Coal consumption
Coal consumption by country or region, measured in terawatt-hour (TWh) equivalents.
Our World in Data
China
20,000 TWh
15,000 TWh
10,000 TWh
5,000 TWh
0 TWh
India
United States
Japan
South Africa
Russia
France
1965
1970
1980
1990
2000
2010
2020
Source: Statistical Review of World Energy - BP (2021)
OurWorldInData.org/fossil-fuels • CC BY

What for?



Primary production
13 402 toe
Final
Sectors
10 702 toe
Oil
4 400
Bio & Waste
1 200
Gas
3 000
Heat
2
Coal
3 500
Nuclear
700
Hydro
400
Other RES
200
Oil products
4 000
Gas
1 500
Coal
1 100
Power station
Losses & own use
3 700 toe
Transports
2 780
Industry
2 842
Buildings
3 130
Non-energy
950

What for?



Primary production
13 402 toe
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Bio & Waste
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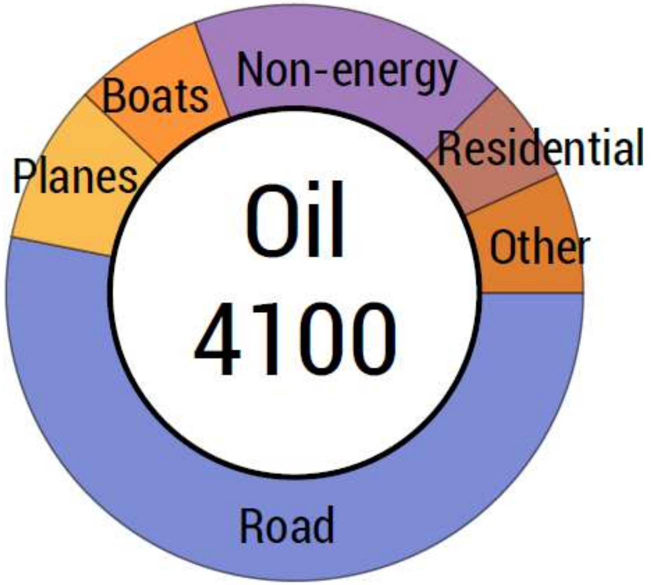
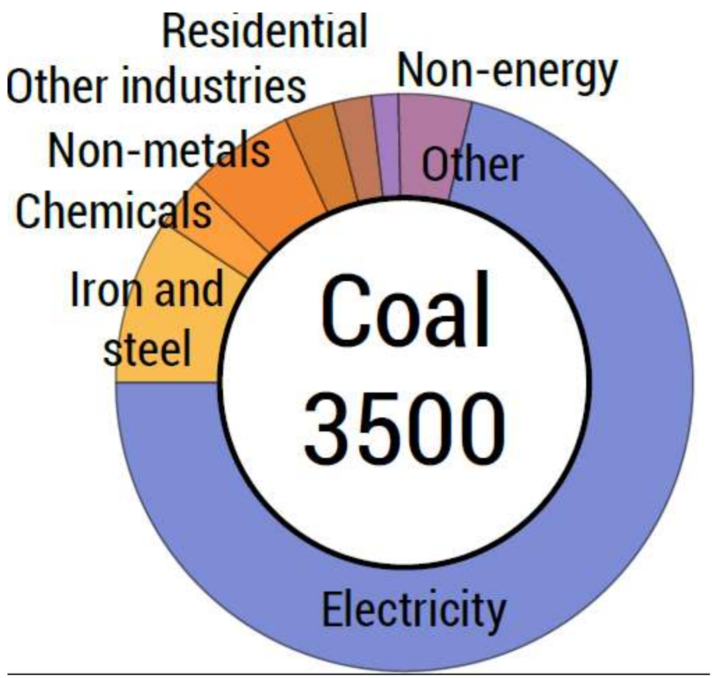
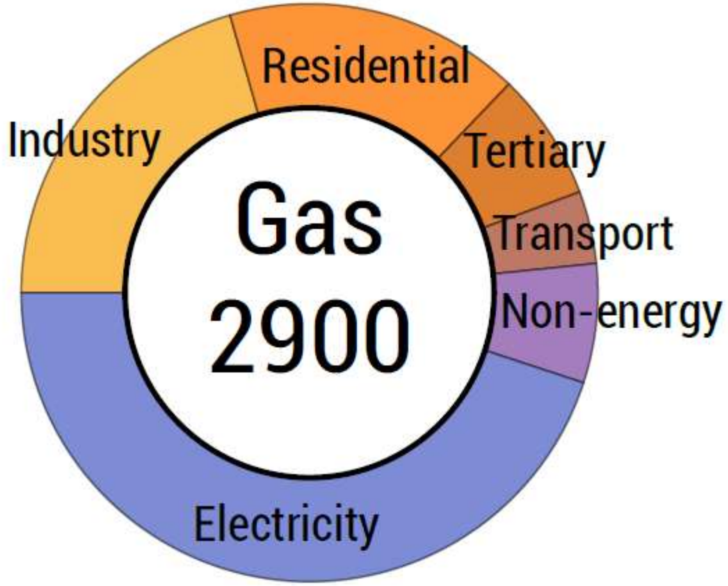


Oil
4100
Non-energy
Boats
Planes
Residential
Other
Road



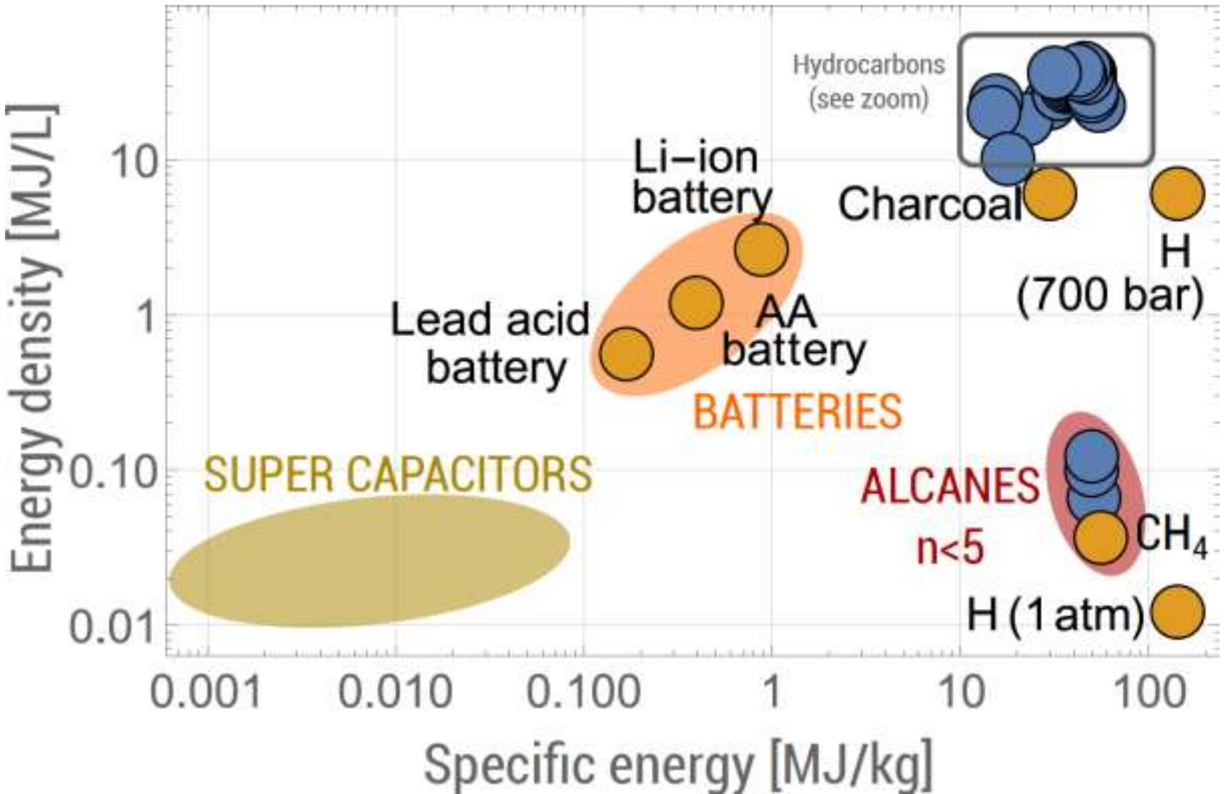
Coal
3500
Residential
Other industries
Non-energy
Non-metals
Other
Chemicals
Iron and steel
Electricity

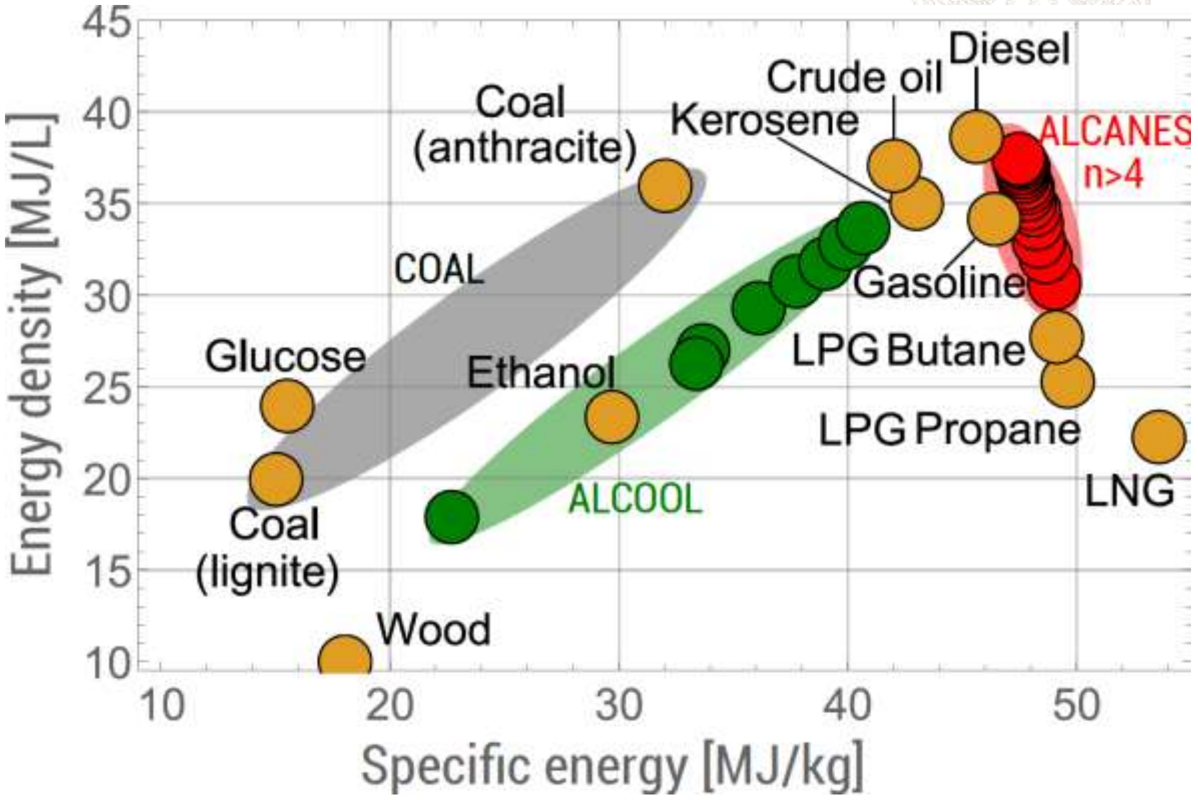


Gas
2900
Residential
Industry
Tertiary
Transport
Non-energy
Electricity

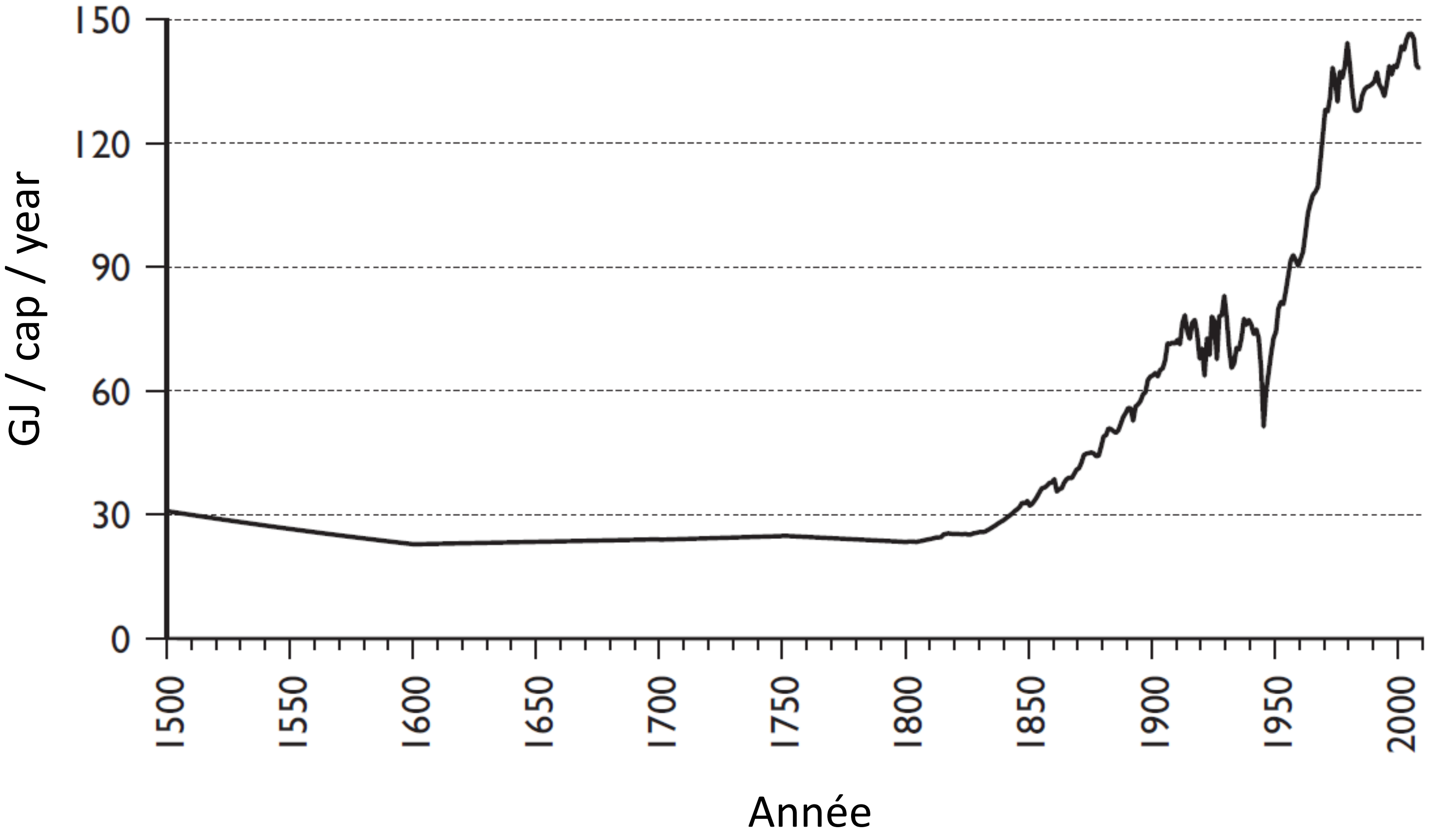
Why? Energy density

Fossil fuels
=
solar energy accumulated over millions of year
released in a second





Why? Energy availability



For 1€,
30 000 J

For 1€,
30 000 000 J

Source Astrid Kander et al, *Power to the People* (2013)

Lecture 2 Fossil fuels

What, Who, What for, Why ?

Thermo toolbox : the chemical potential

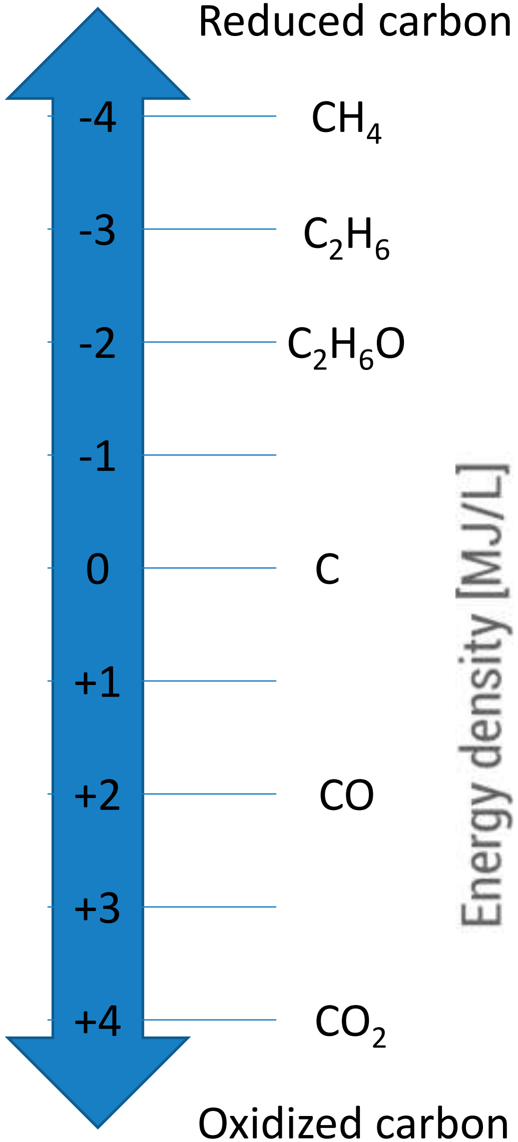
Oil, gas and coal formation: in and out the organic carbon cycle

Oil (and gas) production: conventional and unconventional sources

Oil refining: from crude oil to the gas station

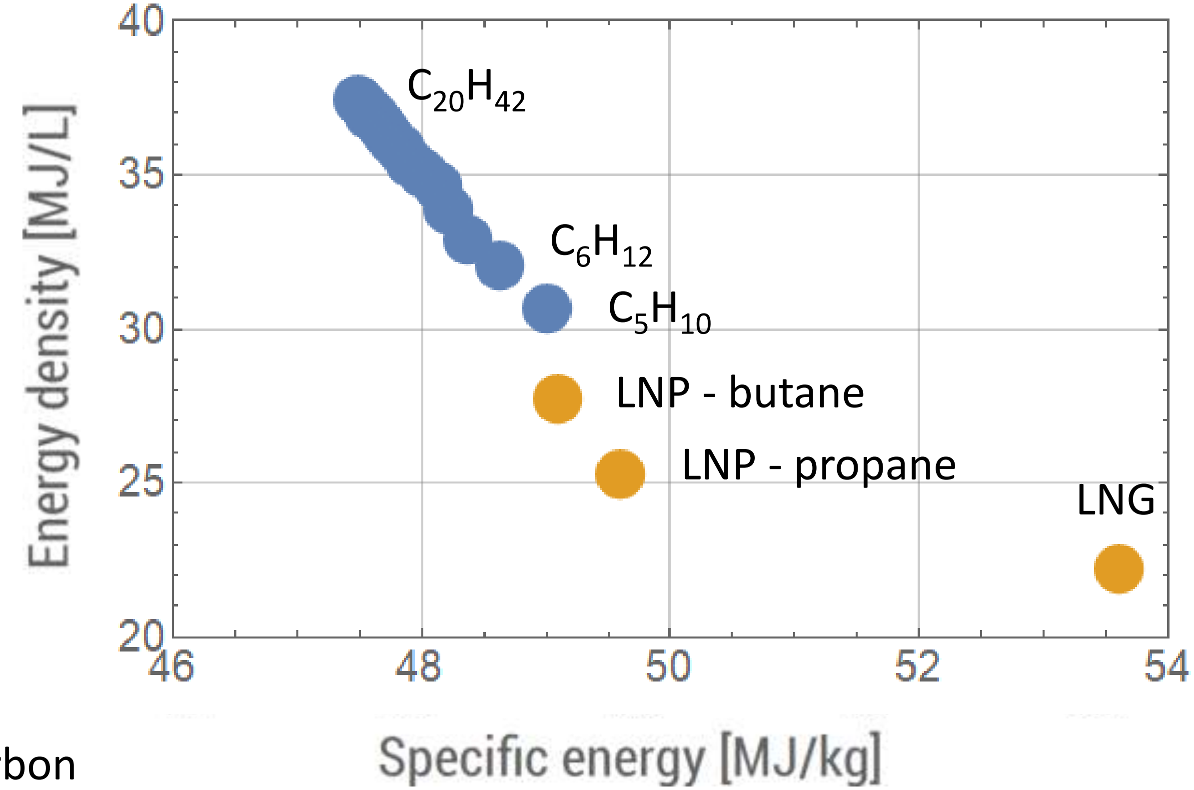
Perspectives

Combustion: redox reaction



$$C_nH_mO_p + \left(n + \frac{m}{4} - \frac{c}{2}\right) O_2 \rightarrow nCO_2 + \frac{m}{2} H_2O$$

Combustion = carbon oxidation from reduced form to CO_2



Largest energy per carbon atom

= most reduced carbon = CH_4

→ also per MJ/kgCO2, per MJ/kg

Problem :

gas → very small density (kg/L)

LNG → heavy logistics (T,p)

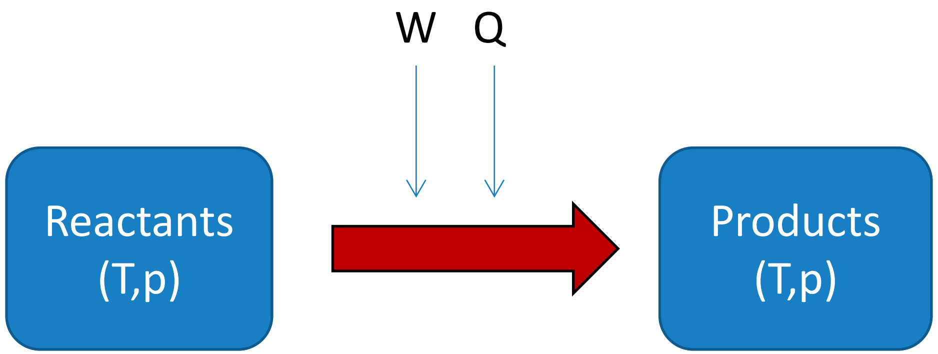
Heavier hydrocarbons

→ less MJ/#C (MJ/kg, MJ/kgCO2)

→ much larger density (liquid)

Combustion: Hess' law

How to estimate the released energy?



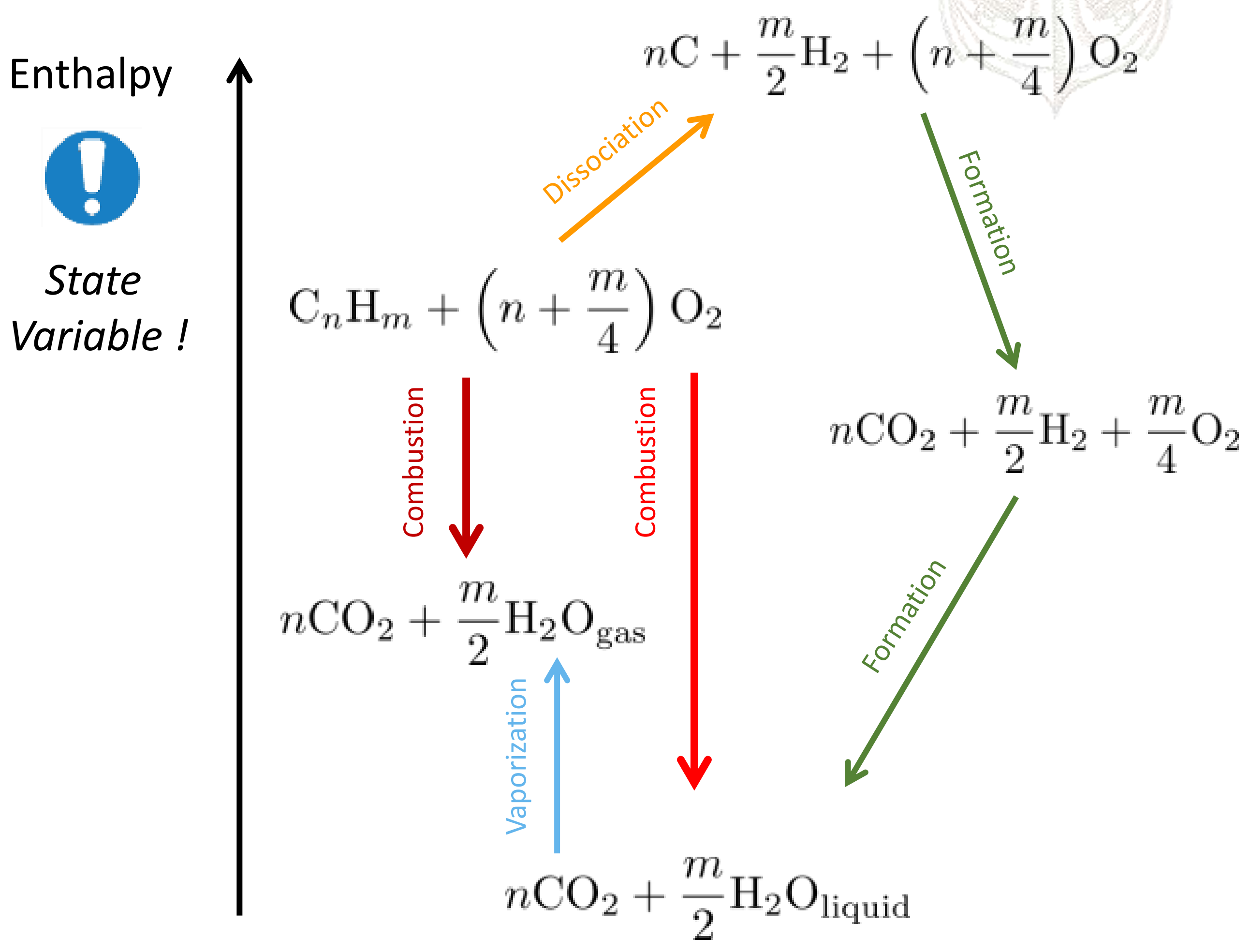
$$\Delta H = Q = H_{\text{prod}} - H_{\text{react}}$$

$\Delta H < 0$ Exothermal

$\Delta H > 0$ Endothermal

Lower heating value: water vapour still gaseous

Higher heating value: condensed water vapour



$$\Delta_{\text{comb}}H_{\text{HHV}} = \underbrace{-\Delta_f H\left(C_nH_m\right) + n\Delta_f H\left(CO_2\right) + \frac{m}{2}\Delta_f H\left(H_2O\right)}_{\Delta_{\text{comb}}H_{\text{LHV}}} + \frac{m}{2}\Delta_{\text{liq}}H\left(H_2O\right)$$

Nature's nature

General idea

Take a system out of equilibrium with the environment (T,p,µ…),
Let it relax towards environmental conditions (dead state),
Collect work along the ride !

What is the spontaneous evolution?

Energy? Some spontaneous reactions are endothermal (ex: water evaporation)

Entropy? Some spontaneous reactions decrease entropy (ex: $2H_2+O_2 \rightarrow 2H_2O$)

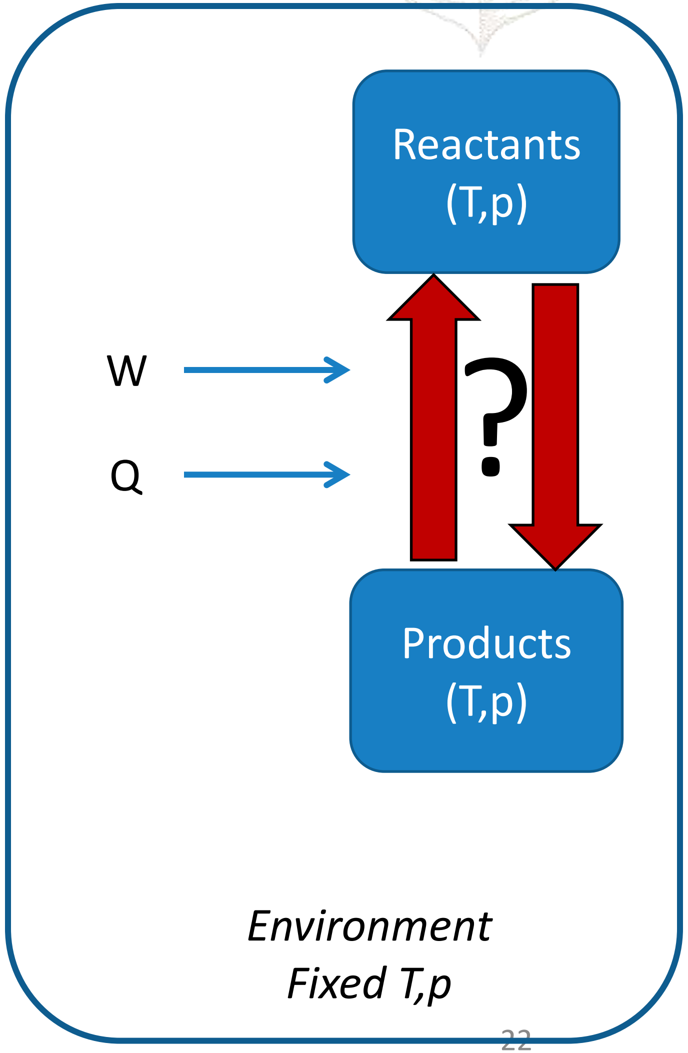
Global entropy must increase

$$dS_{\text{tot}} = dS_r - \frac{dH_r}{T} \geq 0$$

Spontaneous evolution:

$$dG_r = dH_r - TdS_r \leq 0$$

Lazy *Sloppy*



Gibbs energy and chemical potential

Josiah Willard Gibbs

Gibbs (Free) Energy $$G(N,T,p) = H - TS = N\,\mu(T,p)$$

- Thermo identity

$$dG = -SdT + Vdp + \mu dN$$

- What is μ ?

''Energy required to add a particle'' **at fixed S and V** !

$$\mu = \left(\frac{\partial U}{\partial N}\right)_{S,V} = \left(\frac{\partial F}{\partial N}\right)_{T,V} = \left(\frac{\partial G}{\partial N}\right)_{T,p} = -T\left(\frac{\partial S}{\partial N}\right)_{U,V}$$

μ for particle exchange ↔ T for energy exchange

Two major consequences

$$G(N,T,p) = H - TS = N\,\mu(T,p)$$

1 For a closed system at fixed (T,p),

spontaneous evolution = minimize G

Application $\Delta G = (\mu_2 - \mu_1)\Delta N$

Particles flow spontaneously from high μ to low μ

Two systems exchanging particles reach the same μ

μ for particle exchange ↔ T for energy exchange

Application	$\Delta H < 0$	$\Delta H > 0$
$\Delta S > 0$	Always	At high temperatures
$\Delta S < 0$	At low temperatures	Never

2 Maximal recoverable heat: $-\Delta H$

Maximal recoverable work: $-\Delta G = -\Delta H + T\Delta S$

! $-\Delta G > -\Delta H \text{ if } \Delta S > 0$

System drains heat from environment

The many lives of μ

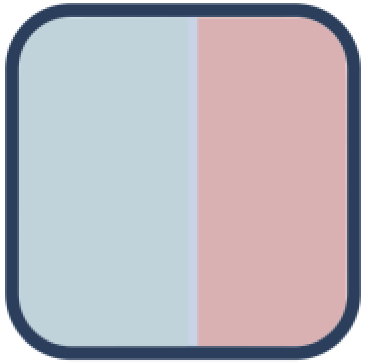
Pure body

$\mu_{A,0}(T,p)$

Gibbs Duhem relation

$$d\mu = -sdT + vdp$$

Non reacting mixture



$\mu_A(T,p,x)$

$\mu_B(T,p,x)$

Activity

$$\mu_i = \mu_{i,0} k_B T \log x_i$$

Chemical reaction

$$a\,\mu_A(\xi) + b\,\mu_B(\xi) = c\,\mu_C(\xi) + d\,\mu_D(\xi)$$

Law of mass action

Equilibrium displacement
(Van’t Hoff, Le Chatelier…)

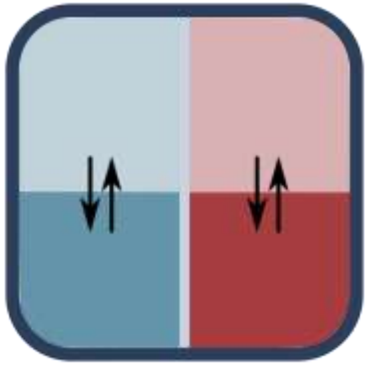
Phase change

$\mu^{\mathrm{gas}}_{A,0}(T,p) = \mu^{\mathrm{liq}}_{A,0}(T,p)$

Clapeyron relation

$$\frac{dp_{\mathrm{sat}}}{dT} = \frac{\Delta_{\mathrm{vap}} H}{T \times (v_{\mathrm{gas}} - v_{\mathrm{liq}})}$$

Binary system



$\mu_A^{gas}(T,p,x_A^g) = \mu_A^{liq}(T,p,x_A^l)$

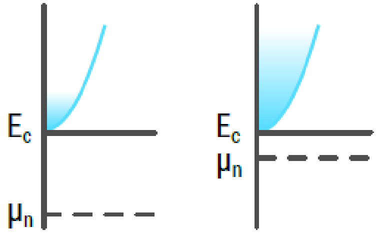
$\mu_B^{gas}(T,p,x_B^g) = \mu_B^{liq}(T,p,x_B^l)$

Binary diagram

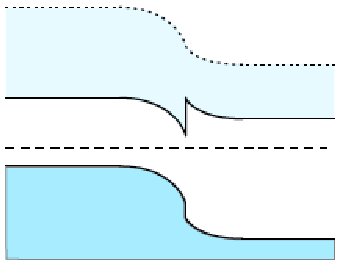
The many (many) lives of μ

Carriers density

$$n = N_c \exp\left(\frac{\mu_n - E_C}{k_B T}\right)$$

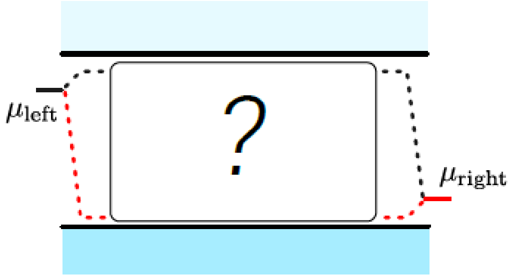


Band alignement



Voltage

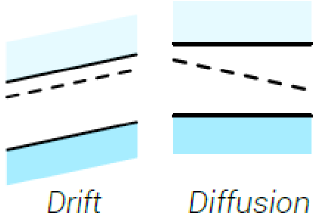
$$qV = \mu_{\text{left}} - \mu_{\text{right}}$$



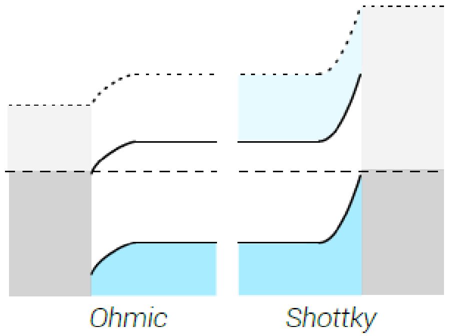
Chemical potential (~ Fermi level) in a semi conductor

Current

$$\mathbf{J}_n = -en\mu_{\text{mob}}\nabla\mu_n$$

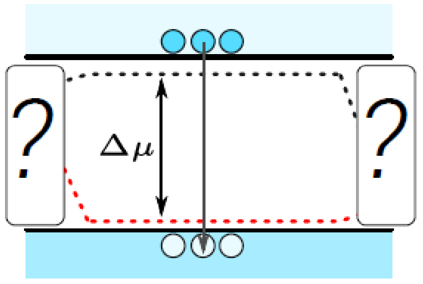


Contact



Photoluminescence

$$\text{PL}(E) = C \times \frac{A(E)E^2}{\exp\left(\frac{E-\Delta\mu}{k_B T}\right) - 1}$$



Lecture 3 Fossil fuels

What, Who, What for, Why ?

Thermo toolbox : the chemical potential

Oil, gas and coal formation: in and out the organic carbon cycle

Oil (and gas) production: conventional and unconventional sources

Oil refining: from crude oil to the gas station

Perspectives

Fossil fuel formation - outline

Step1 Turn atmospheric CO2 into biomass

Plankton *Plants*

Step2 Prevent biomass from oxidizing back to CO2

Sediments *Peat*

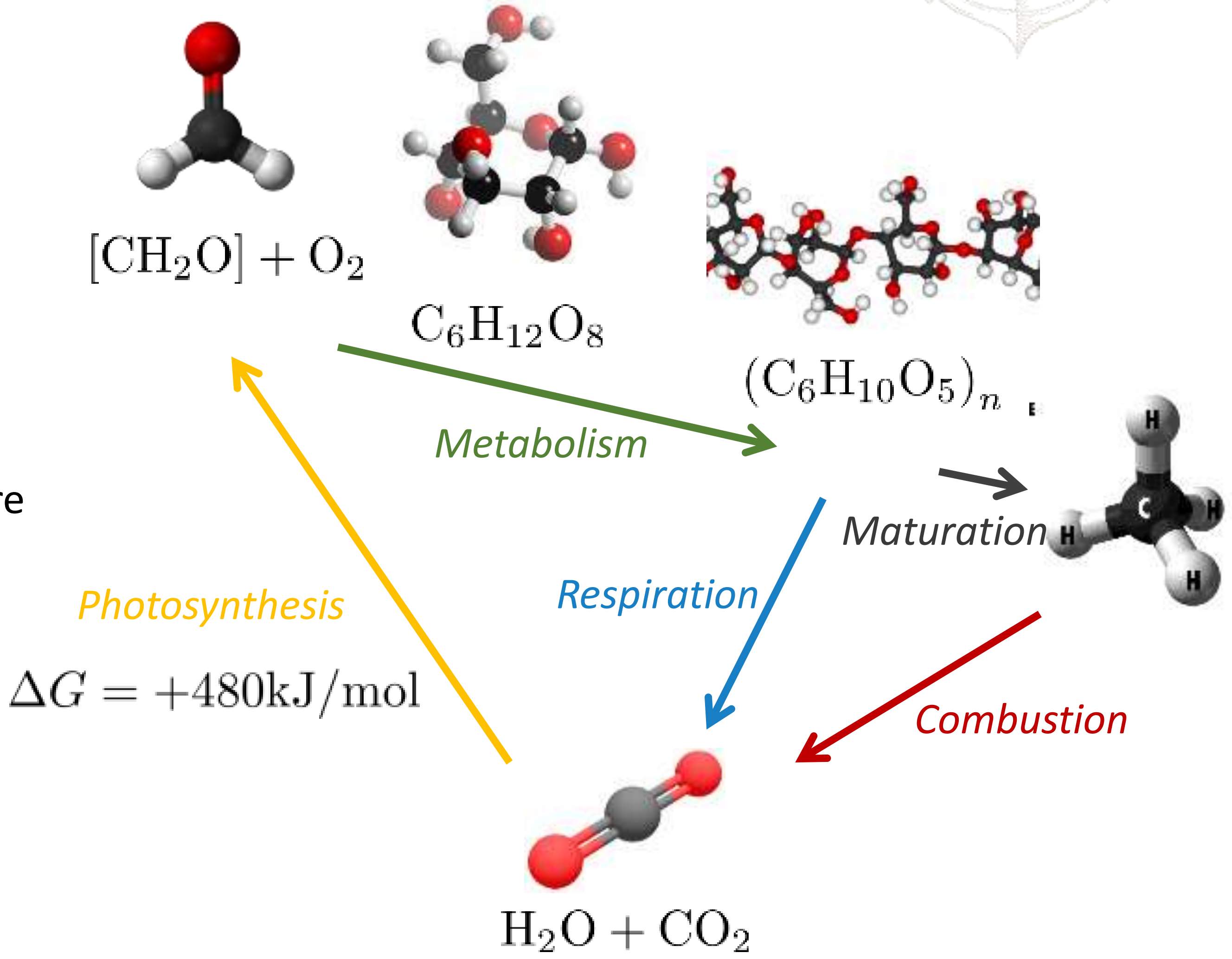
Step3 Let biomass mature at high temperature and pressure

Source rock *Coal*

Step4 Migrate to a trap

Reservoir rock -

Step5 Extraction



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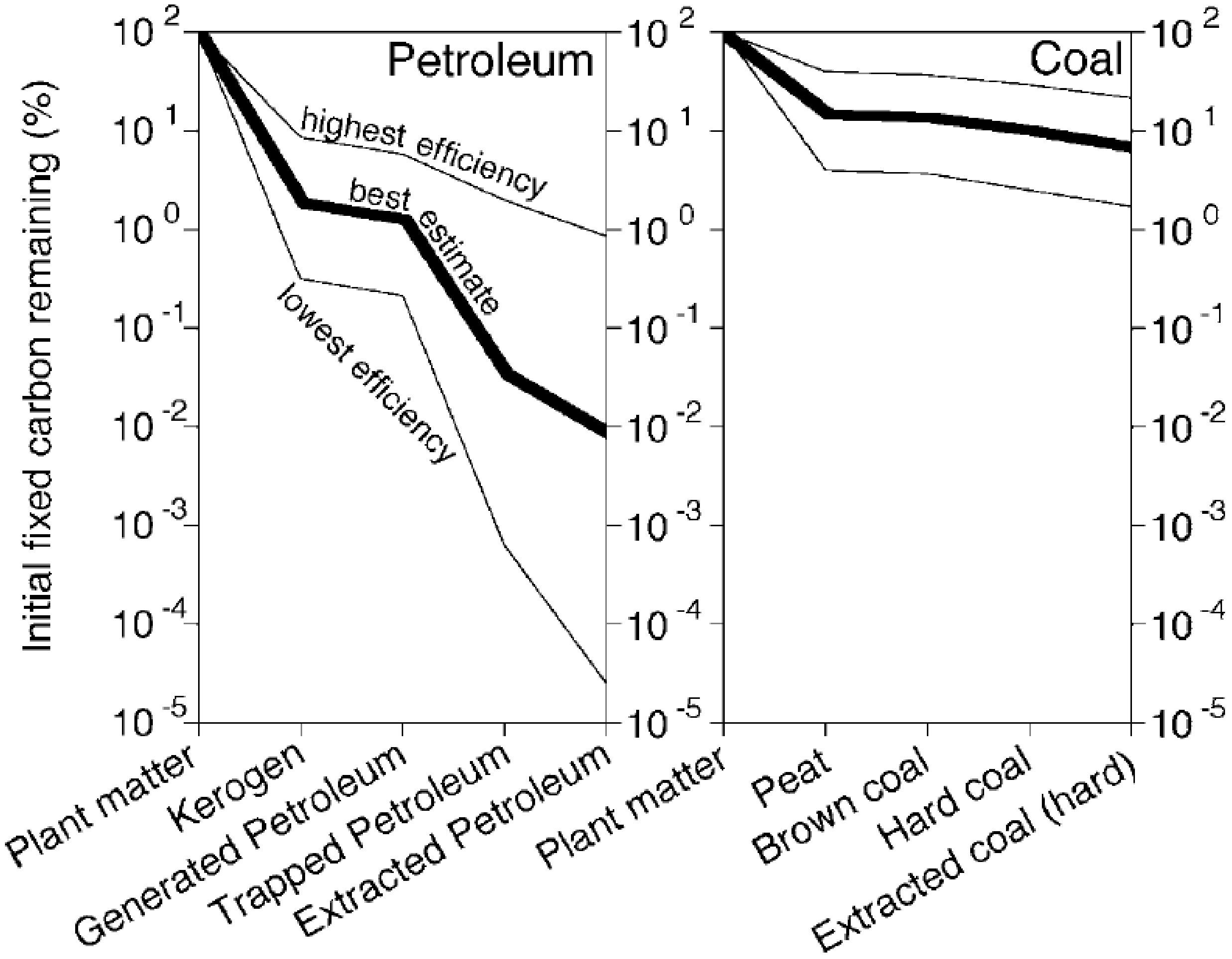
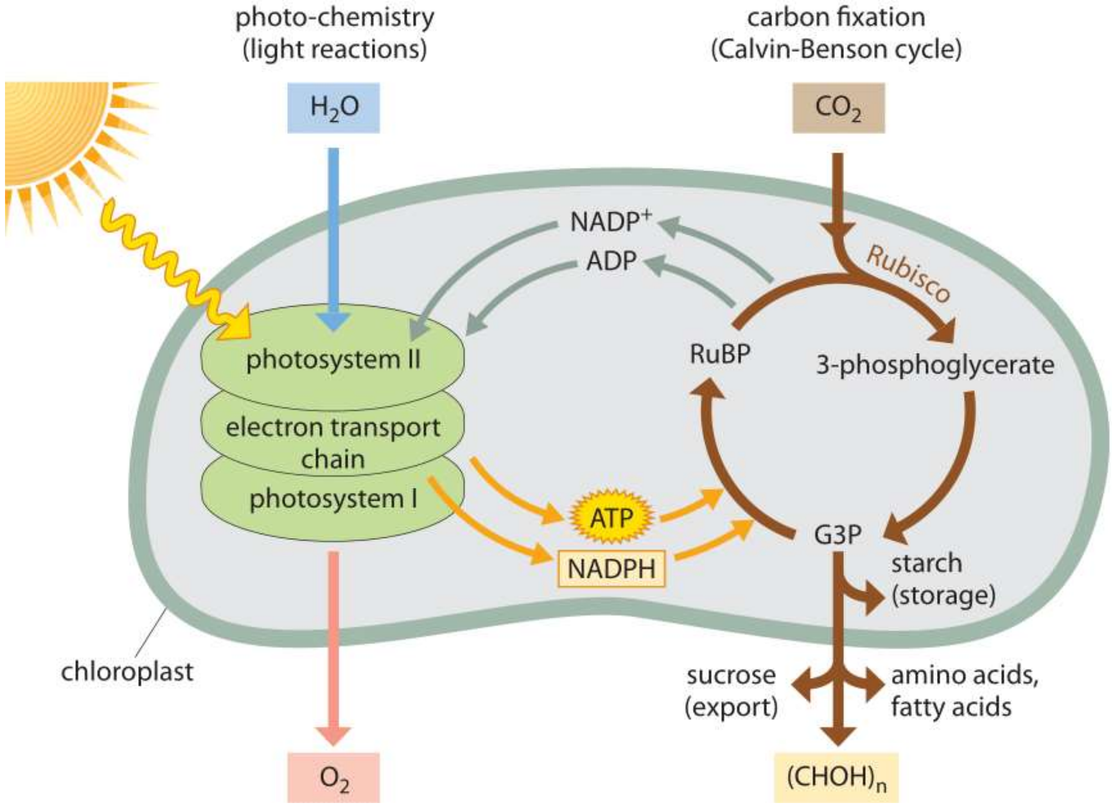
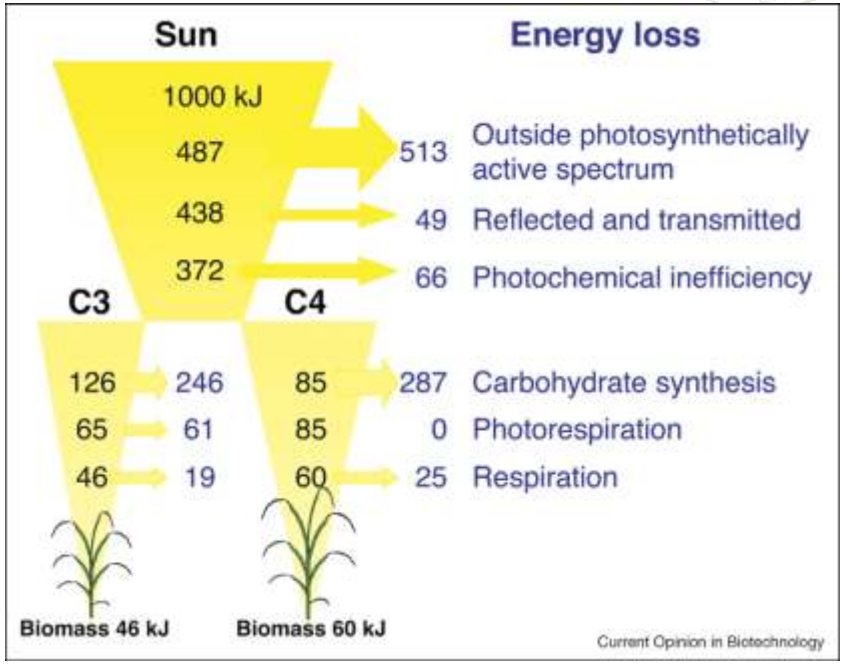


Burning Buried Sunshine: Human Consumption of Ancient Solar Energy, J. Dukes Climatic Change volume 61, pages31–44 (2003)

Photosynthesis: carbon cycle's engine





Zhu et al. Current Opinion in Biotechnology 2008, 19

Light + H_2O → 2H + energy + ½ O_2

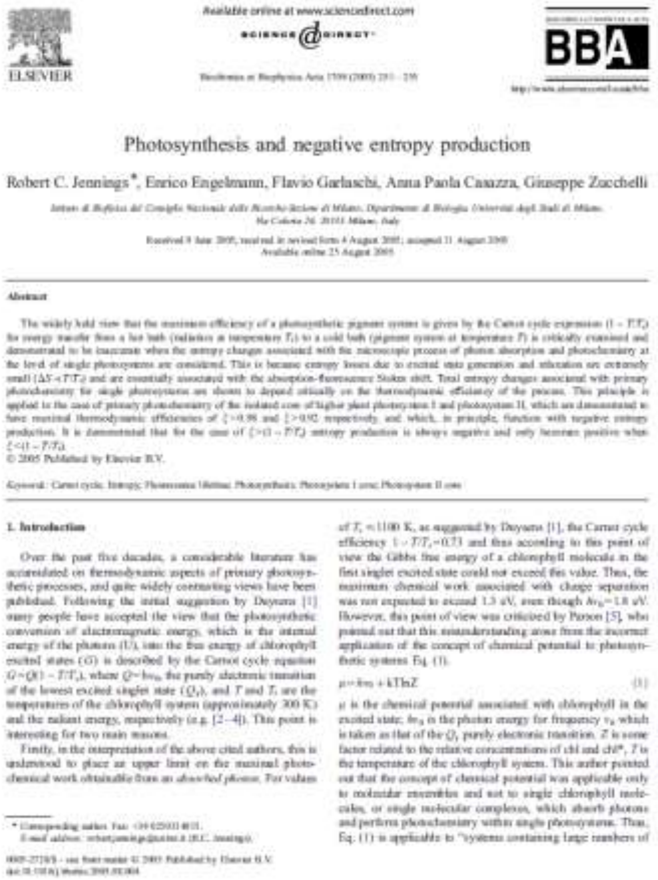
4H + CO_2 + energy → CH_2O + H_2O x3 or x4

~ 8 red photons per CO_2 molecule

Overall efficiency (light to chemical energy) : 0.1-1%

→ Power density : 1 W/m²

Thermo clash – round 1


Available online at www.sciencedirect.com

SCIENCE @ DIRECT

BBA

Photosynthesis and negative entropy production

Robert C. Jennings*, Enrico Engelmann, Flavio Garlaschi, Anna Paola Casazza, Giuseppe Zucchelli

[…]the Carnot cycle concept for photosynthetic energy conversion is based on the assumption that the second law of thermodynamics is necessarily applicable to photosystem function. […] If the overall quantum efficiency is high enough, negative or zero entropy changes are able to be contemplate

Thermo clash – round 2


Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

BBA

Review

Commentary on: "Photosynthesis and negative entropy production" by Jennings and coworkers

Jérôme Lavergne

[…] the authors ignore the statistical essence of the problem. There is no justification for excluding the interaction of matter with light from common thermodynamics: the theory of black body emission, which was at the origin of the quantum revolution, was precisely elaborated to meet this demand.

Another precursor of second law violation in photosynthesis, according to Jennings, is Parson [6], who would have argued against "the incorrect application of the concept of chemical potential to photosynthetic systems" . This is again an obvious misunderstanding of what this author really said. Parson was by no means an opponent to the application of chemical potential in this field.

Thermo clash – round 3


Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

BBA

Rapid report

Reply to "Commentary on Photosynthesis and Negative Entropy Production by Jennings and coworkers" by J. Lavergne

R.C. Jennings, A.P. Casazza, E. Belgio, F.M. Garlaschi, G. Zucchelli

It is argued that the chemical potential analogy does not provide useful information on the thermodynamics of photosystems, as the thermodynamic efficiency of an absorbed quantum is not considered. […]

At high thermodynamic efficiencies, primary photochemistry can, in principle, violate the Second Law of Thermodynamics

Thermo clash – round 4


Robert C.

Reply to

Available online at www.sciencedirect.com

ScienceDirect

BBA

Entropy production and the Second Law in photosynthesis

Robert S. Knox, William W. Parson

Abstract

1. Introduction

2. Entropy changes associated with photoexcitation

An assertion that the primary photochemistry of photosynthesis can violate the Second Law of thermodynamics in certain efficient systems has been put forward by Jennings et al., who maintain their position strongly despite an argument to the contrary by Lavergne. We identify a specific omission in the calculation of Jennings et al. and show that no violation of the Second Law occurs, regardless of the photosynthetic efficiency.

Thermo clash – round 5


Available online at www.sciencedirect.com

ScienceDirect

BBA

Entropy consumption in primary photosynthesis

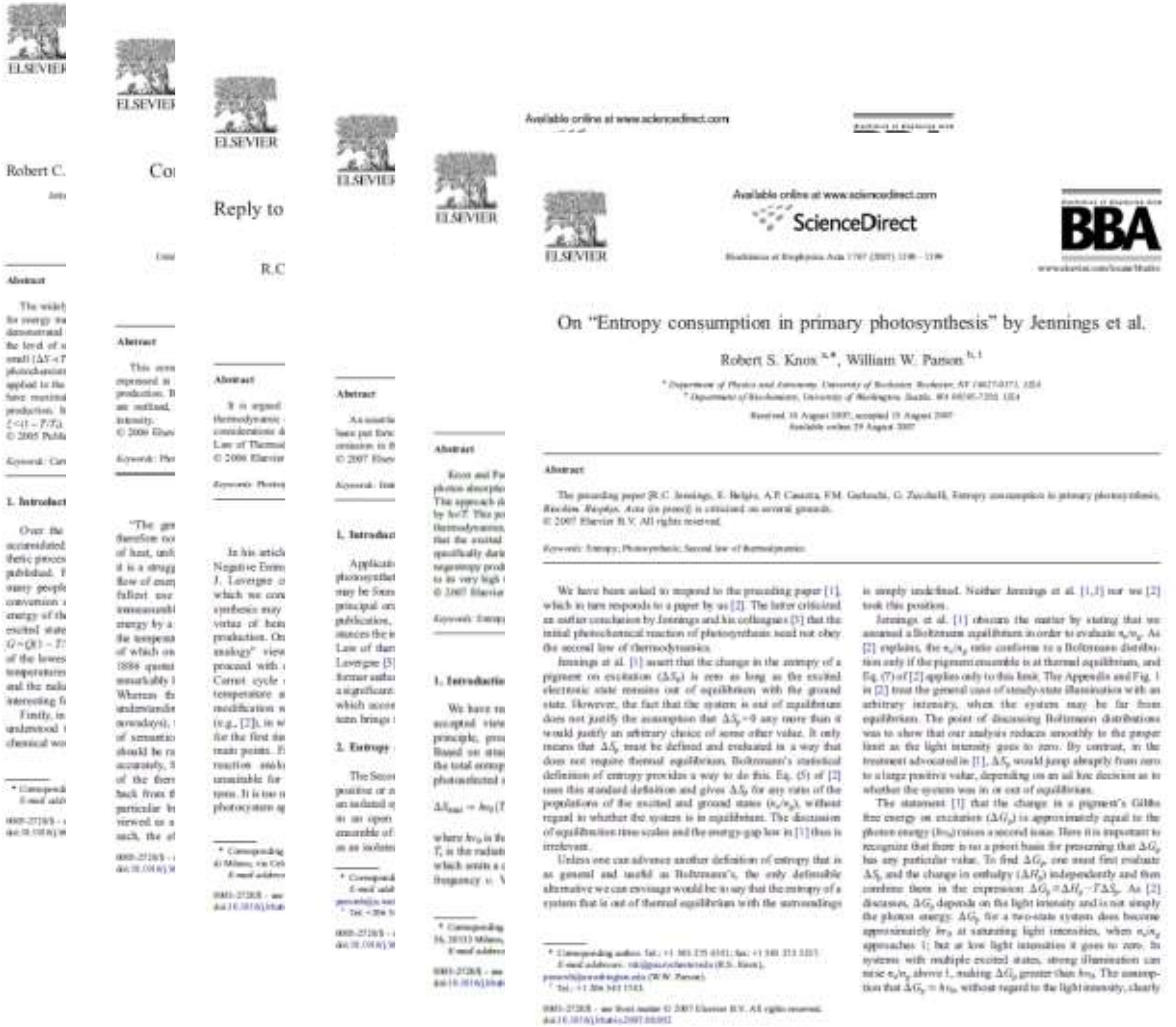
Robert C. Jennings, Erica Belgio, Anna Paola Casazza, Flavio M. Garlaschi, Giuseppe Zucchelli

Abstract

1. Introduction

our conclusions on possible negentropy production […] remain unchanged.

Thermo clash – round 6 !


Available online at www.sciencedirect.com

ScienceDirect

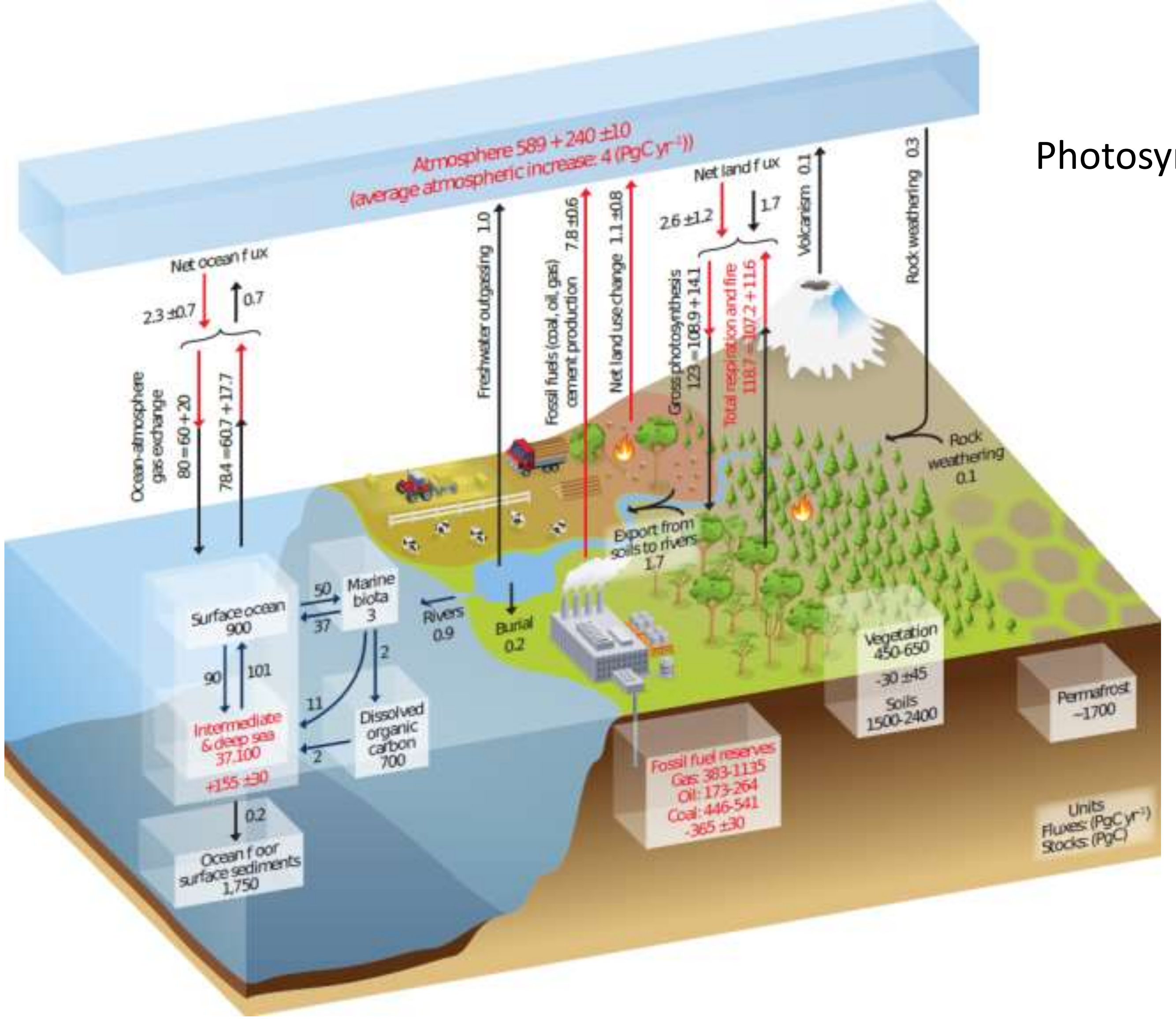
BBA

On “Entropy consumption in primary photosynthesis” by Jennings et al.

Robert S. Knox a,*, William W. Parson b,1

The preceding paper is criticized on several grounds. […] Jennings et al. [1] wrongly claim that their conclusions are “in agreement with” certain earlier papers (their references [5] and [9]), including one written by one of the present authors.

From the atmosphere to the atmosphere



Organic matter

Photosynthesis

Respiration
Degradation

CO_2

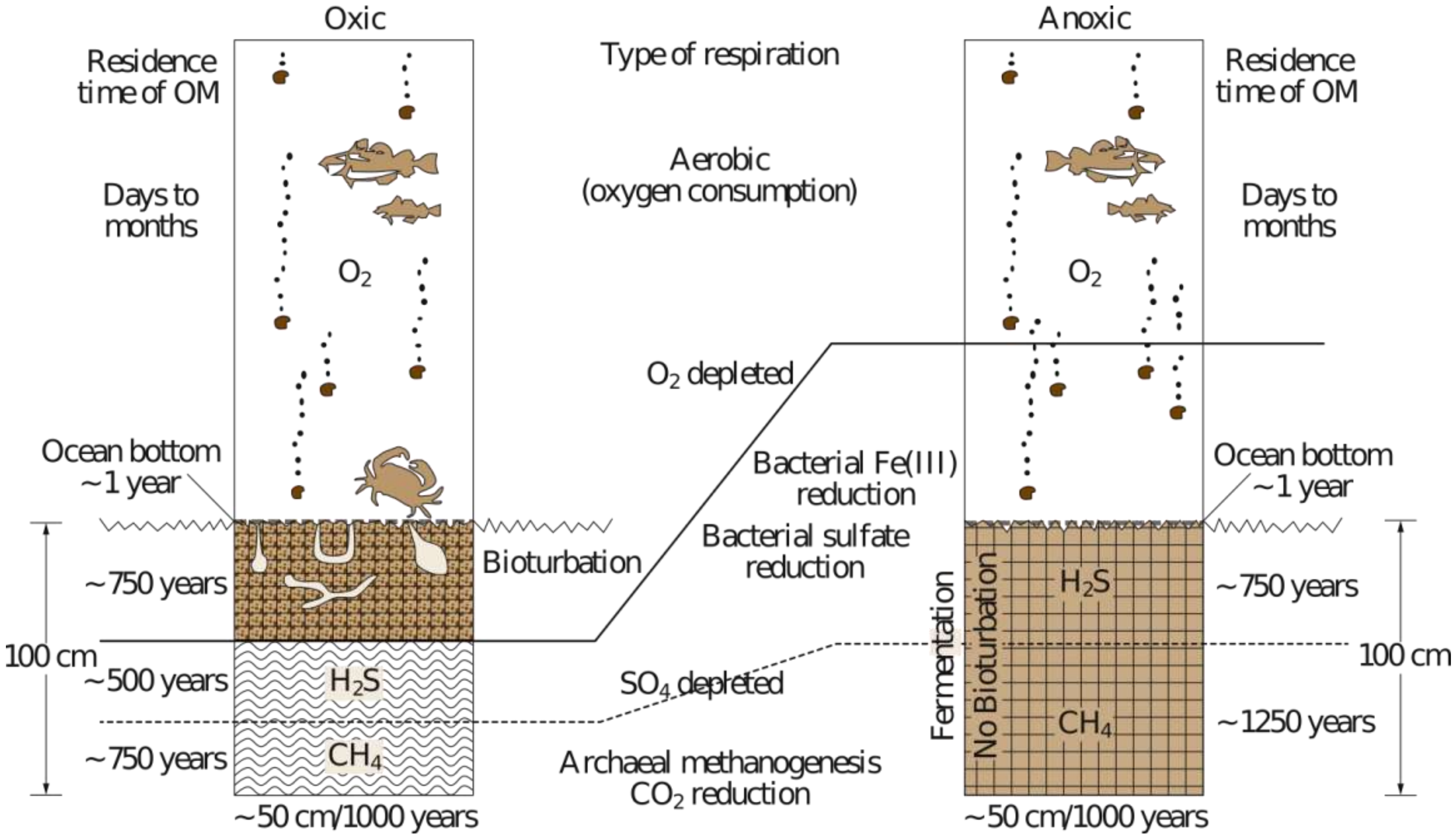
Photosynthesis requirements:

- Sunlight
- Water
- CO_2
- Nutriments

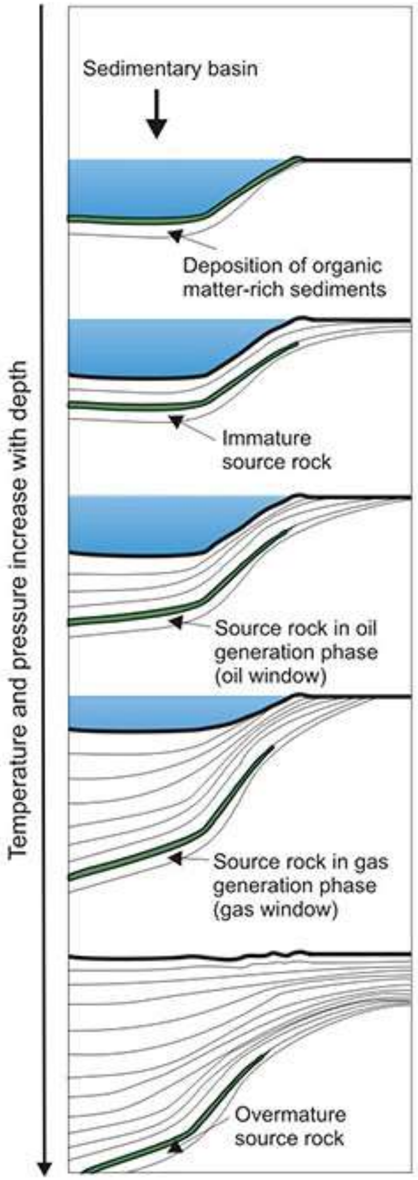
Surface waters close to shore

Adequate land areas

Escaping the carbon cycle



Burial rate ~ 1 cm/century



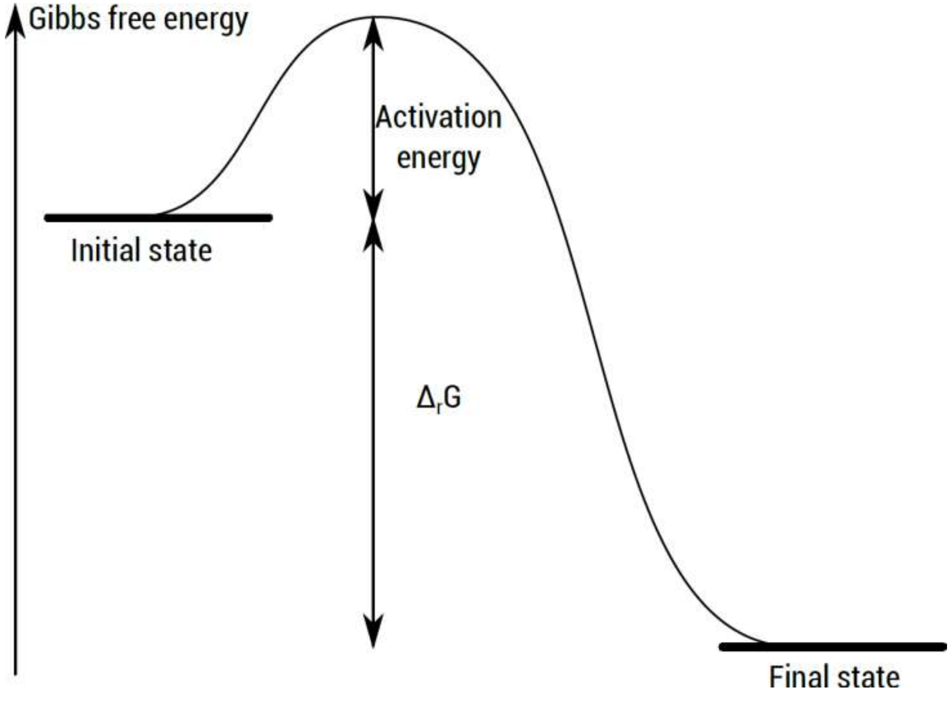
infolupki.pgi.gov.pl/

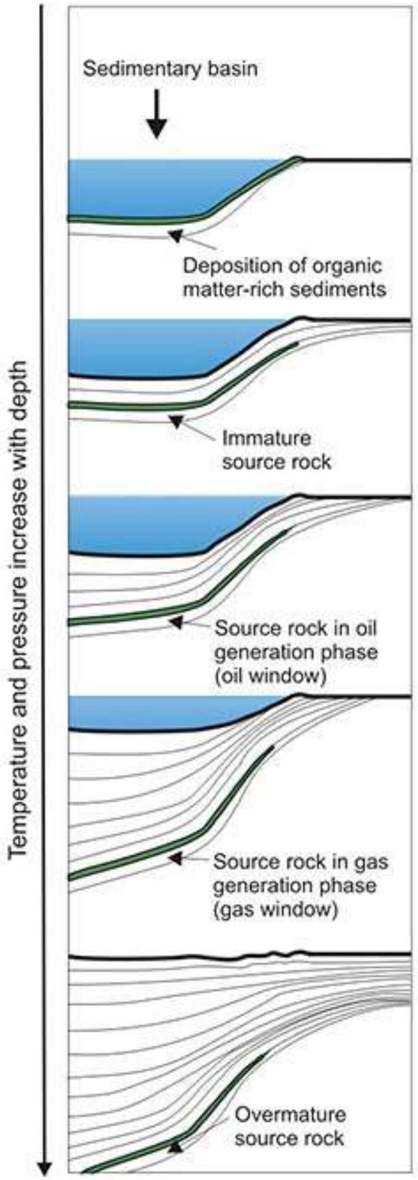
Maturation – oil & gas

Burial rate ~ 1 cm/century

Increasing pressure (100 bar/km)
& temperature (15-50 K/km)

- Displace chemical equilibriums
- Accelerate thermal clock





infolupki.pgi.gov.pl/

Maturation – oil & gas

Diagenesis — (Mostly) biotic degradation of organic matter into kerogen

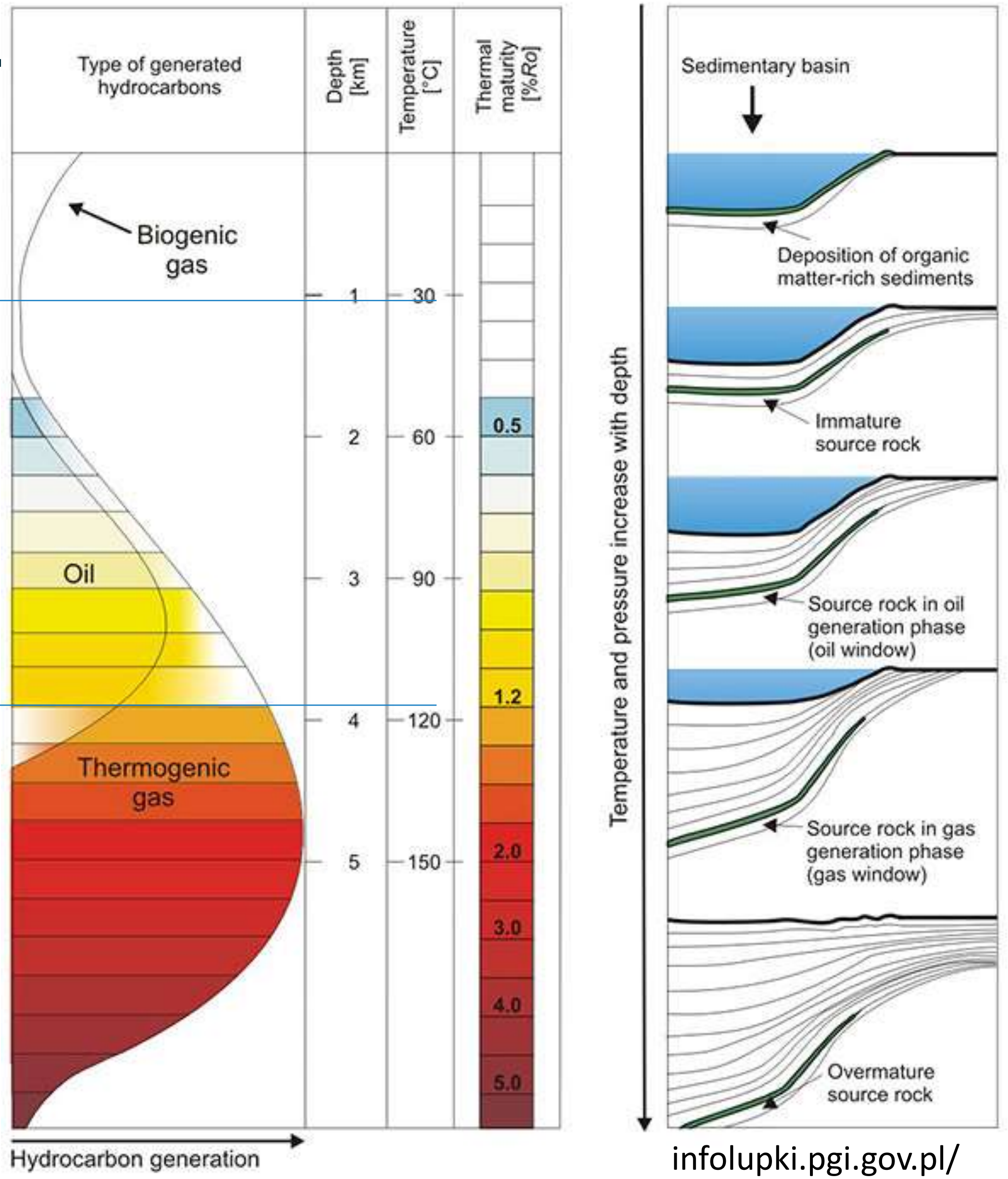
Catagenesis — Thermal degradation of kerogen into hydrocarbons

O → H_2O S → H_2S N → N_2

Metagenesis — Further carbonisation → graphite

Organic matter → kerogen → hydrocarbons in a source rock

Total Organic Carbon [%]	< 0.5	<1	<2	<4	>4
Source rock quality	Poor	Fair	Good	Very good	Excellent



infolupki.pgi.gov.pl/

Maturation – oil & gas

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Catagenesis	Thermal degradation of kerogen into hydrocarbons $O \rightarrow H_2O$ $S \rightarrow H_2S$ $N \rightarrow N_2$
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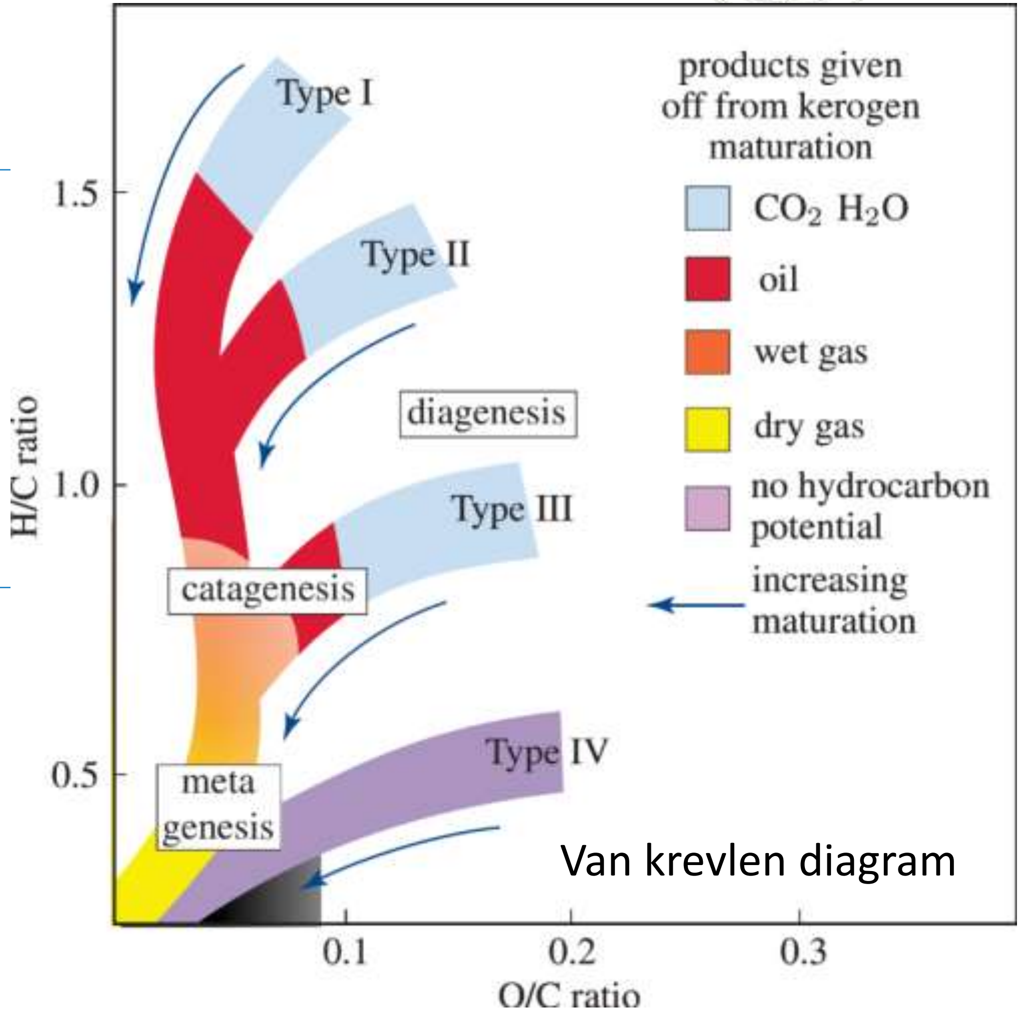
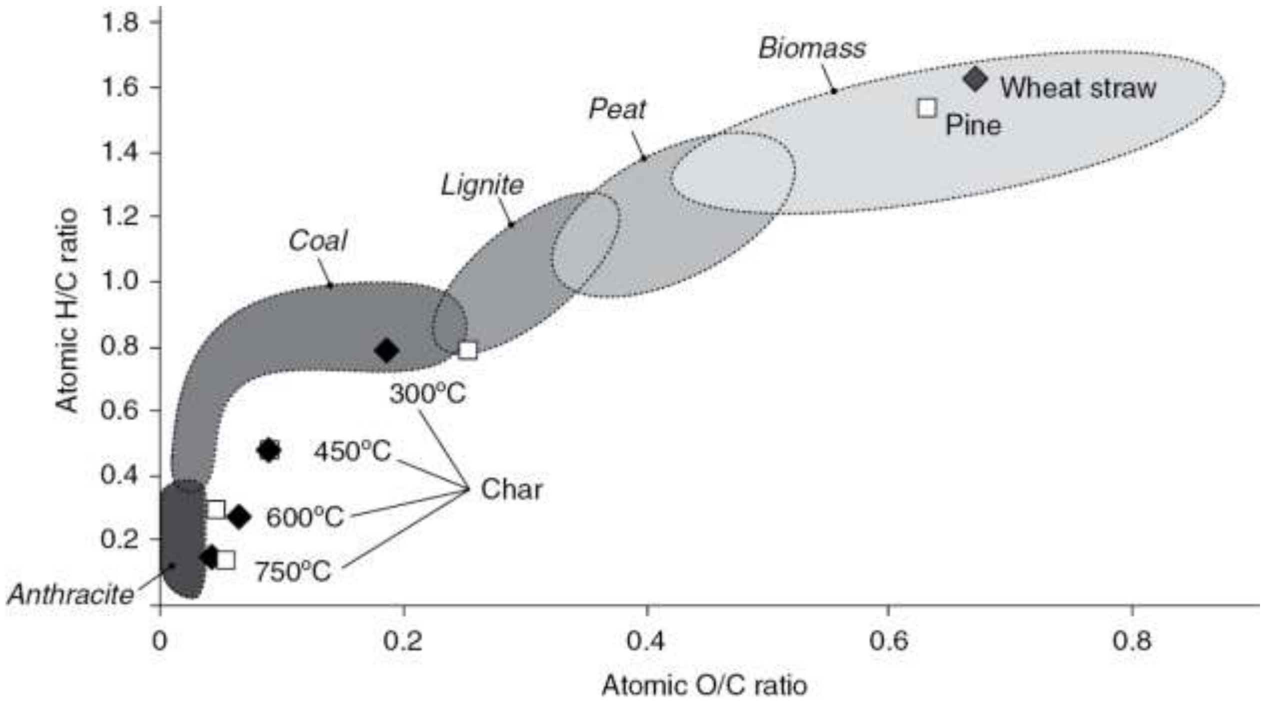
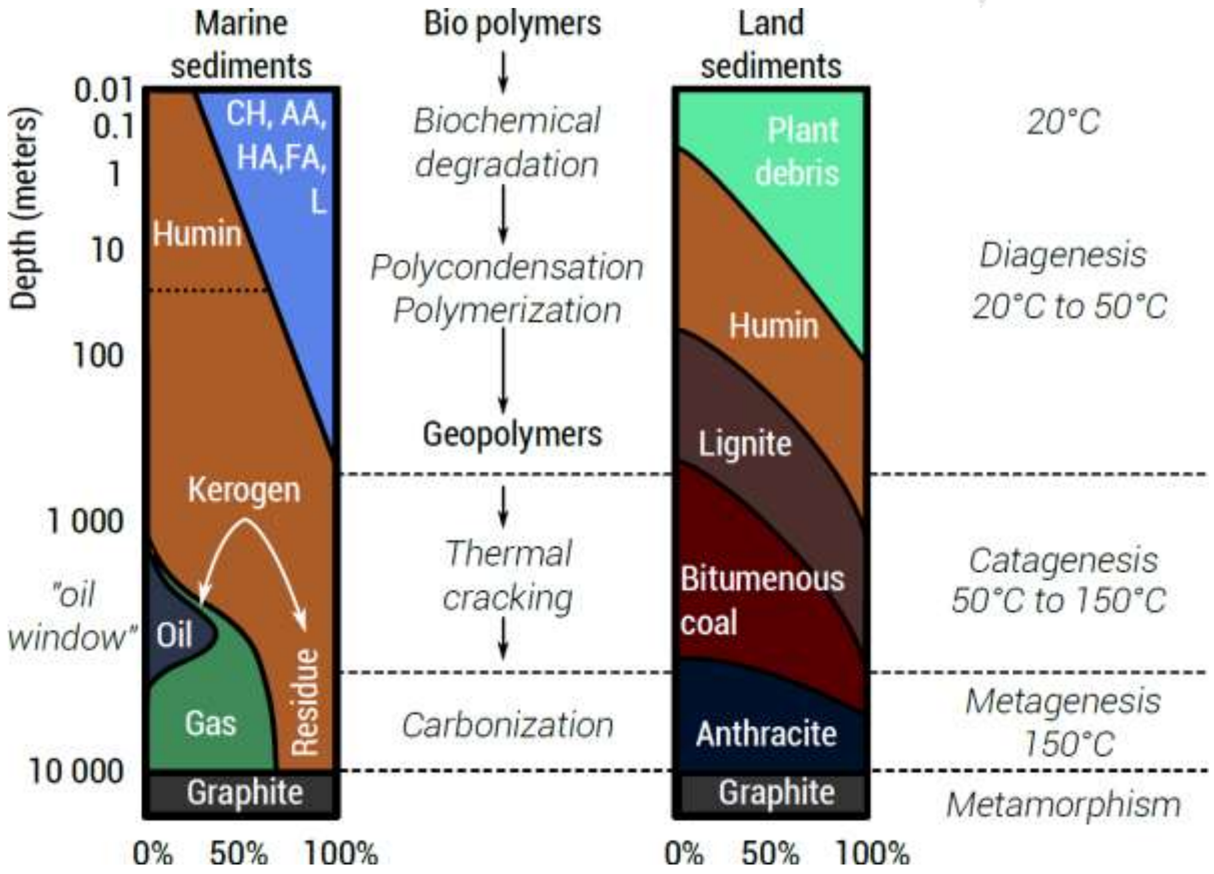


Van krevlen diagram

Maturation – coal & gas

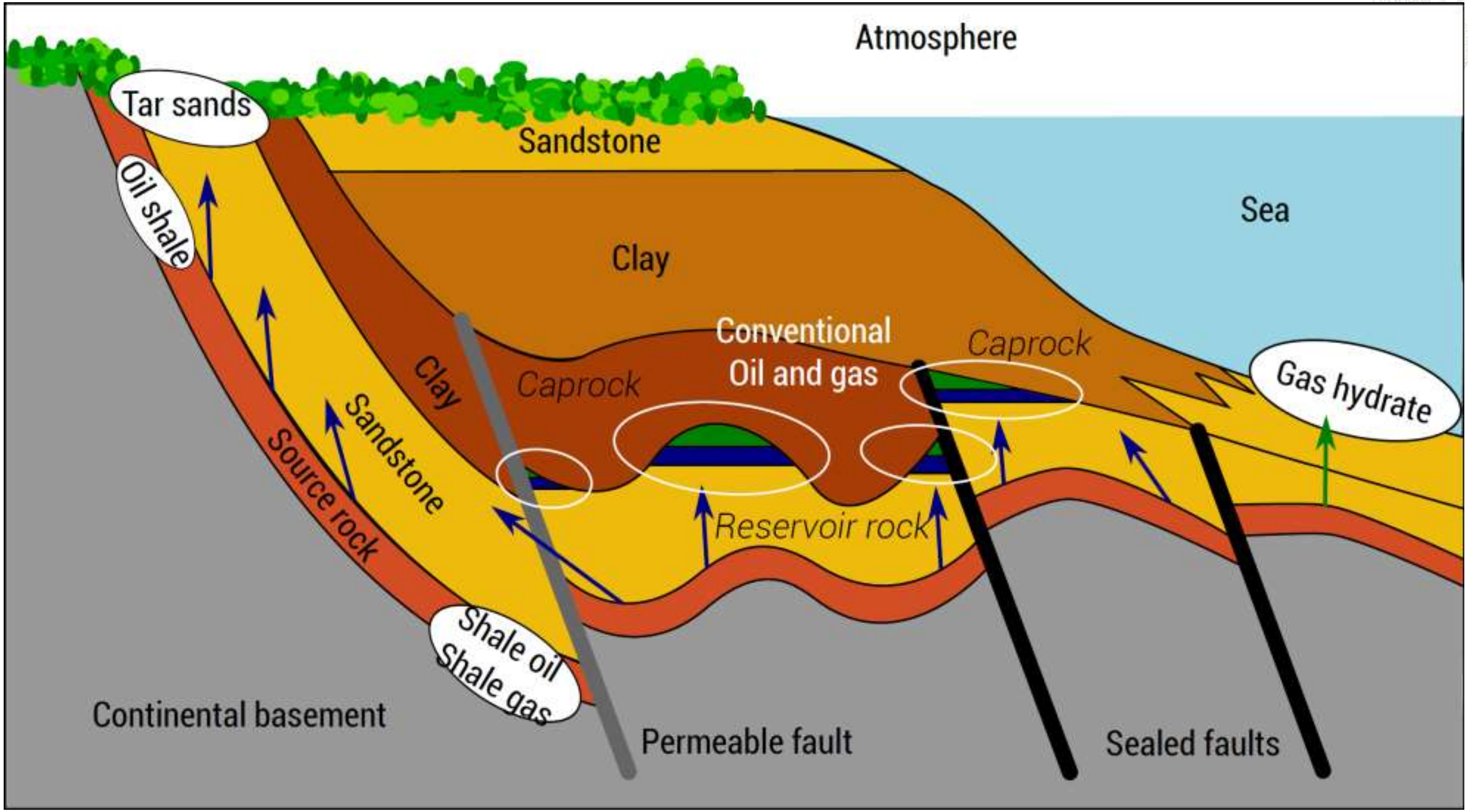
Similar story for coal:





Gas is formed together with coal → firedamp [=grisou]

Migration



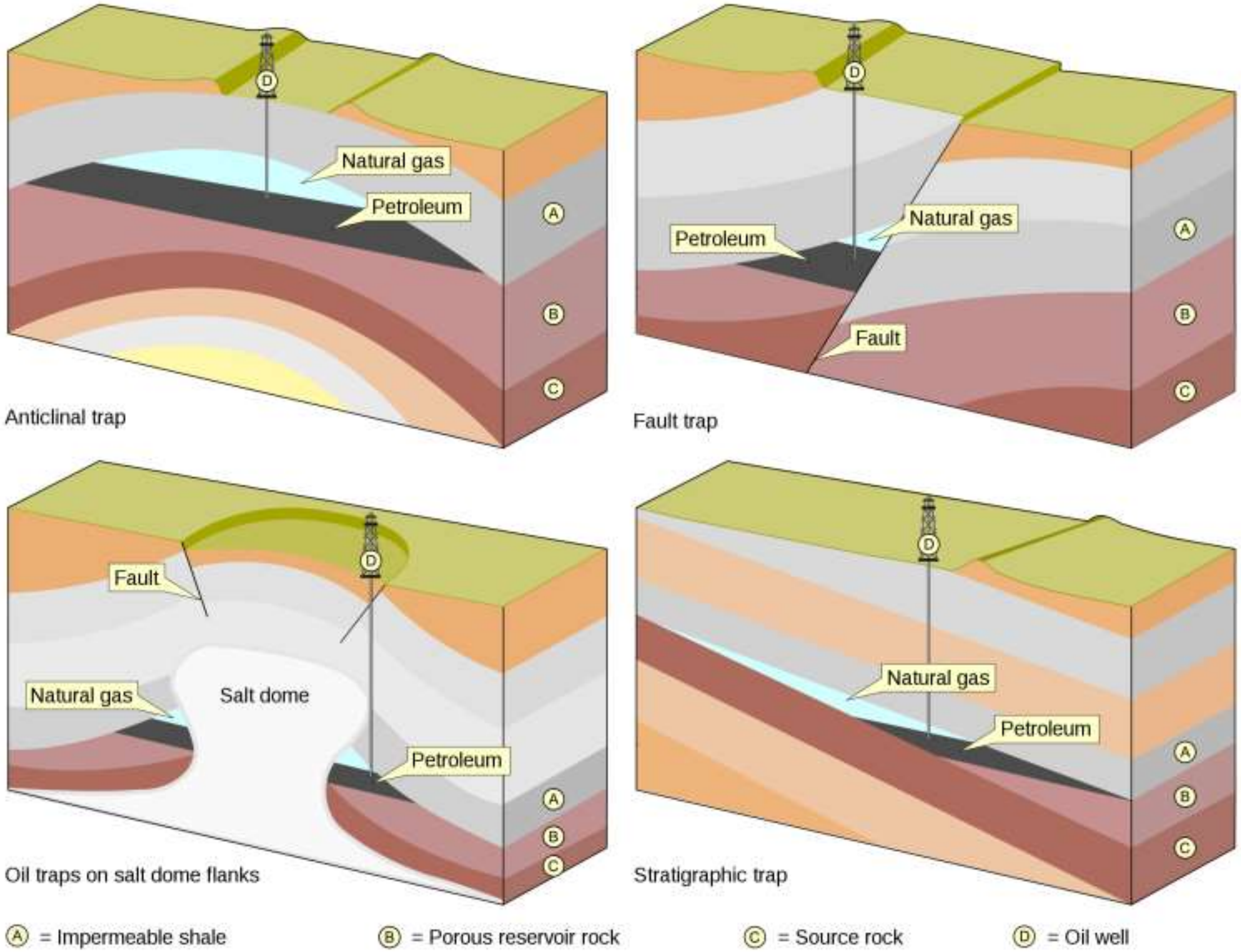
Atmosphere
Tar sands
Sandstone
Sea
Oil shale
Clay
Conventional
Oil and gas
Caprock
Caprock
Clay
Sandstone
Gas hydrate
Source rock
Reservoir rock
Shale oil
Shale gas
Continental basement
Permeable fault
Sealed faults

It’s a trap

Sometimes gas without oil

Water !

Resource vs reserve



Lecture 2 Fossil fuels

What, Who, What for, Why ?

Thermo toolbox : the chemical potential

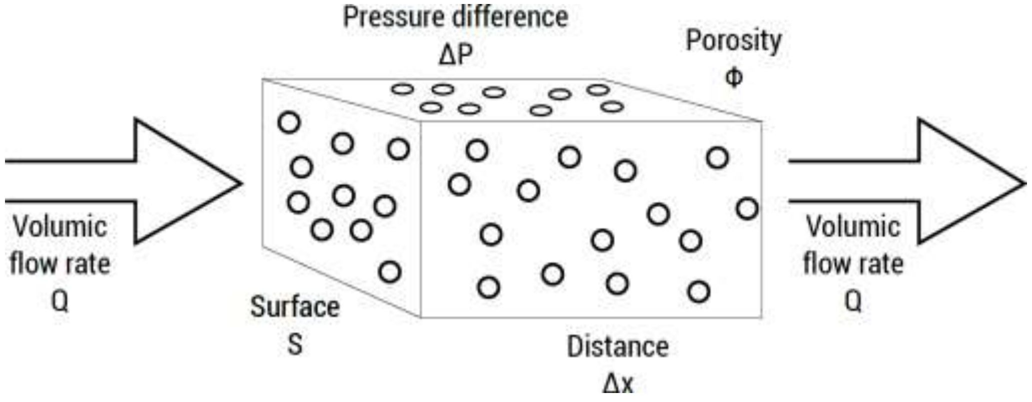
Oil, gas and coal formation: in and out the organic carbon cycle

Oil (and gas) production: conventional and unconventional sources

Oil refining: from crude oil to the gas station

Perspectives

Conventional oil

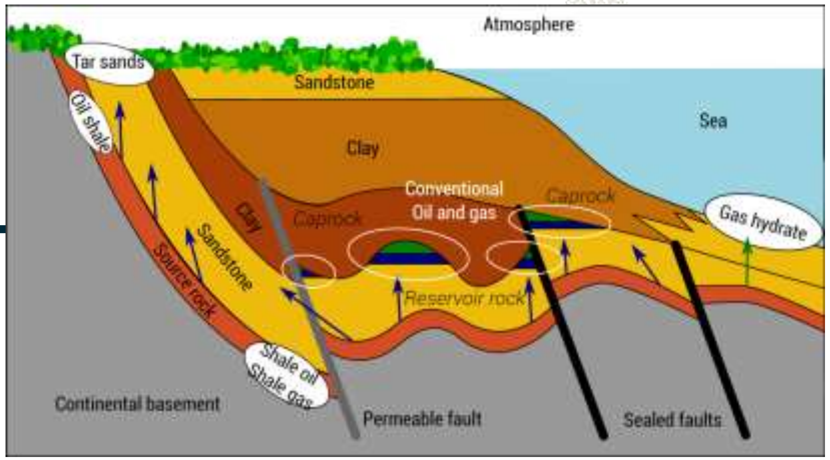


Porosity

$$\phi = \frac{\text{Empty volume}}{\text{Total volume}}$$

Permeability (Darcy's law)

$$Q = k \times \frac{S}{\eta}\frac{\Delta p}{\Delta x}$$

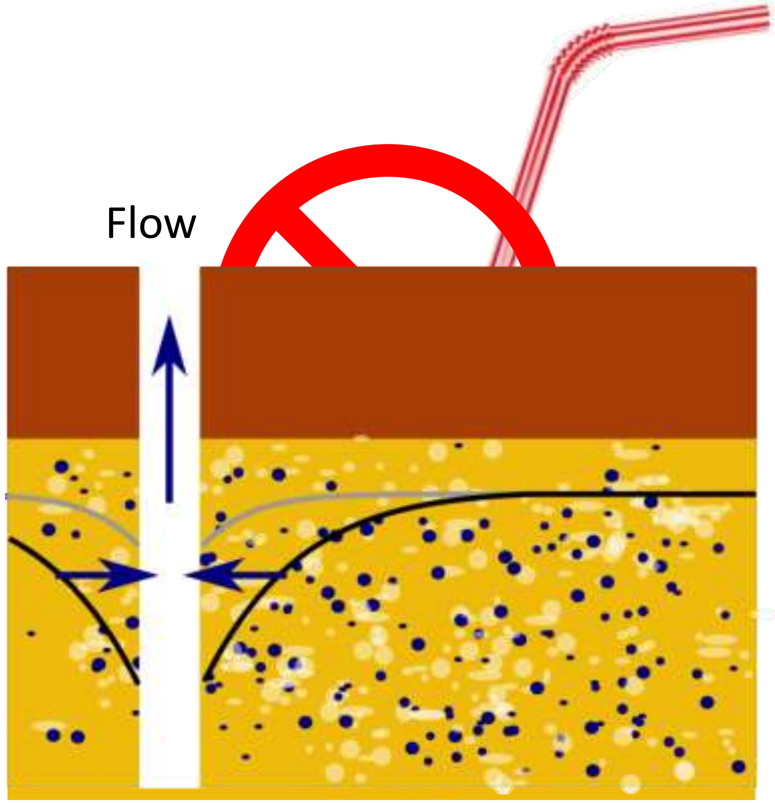


Drill a well → pressure gradient → oil flow

(to bring the oil up, push, don't pull !)

Oil flow → decrease pressure gradient

$$\partial_t p = \frac{k}{\bar{\chi}\eta}\Delta p \quad \Rightarrow \quad R(t) \sim 4\sqrt{\frac{k}{\bar{\chi}\eta}t}$$



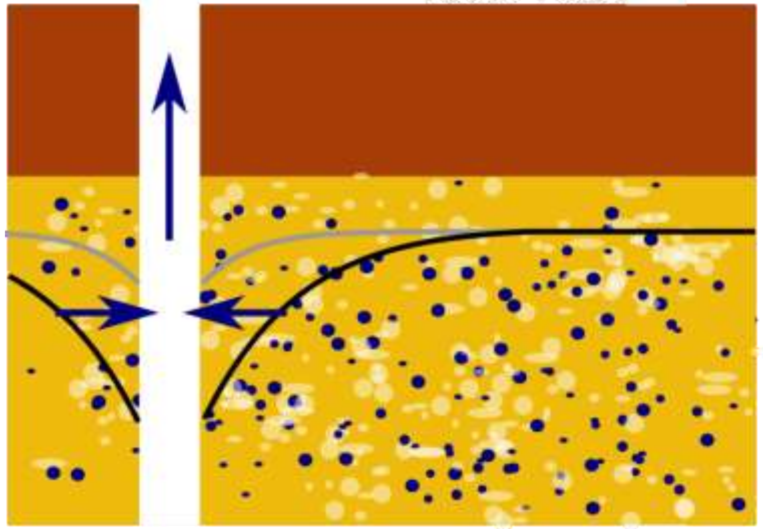
Consequences

Darcy's law

$$Q = k \times \frac{S}{\eta}\frac{\Delta p}{\Delta x}$$

Pressure relaxation

$$R(t) \sim 4\sqrt{\frac{k}{\bar{\chi}\eta}t}$$



Competition between wells

Don't drill too close to the neighbour !

Exploitation phases

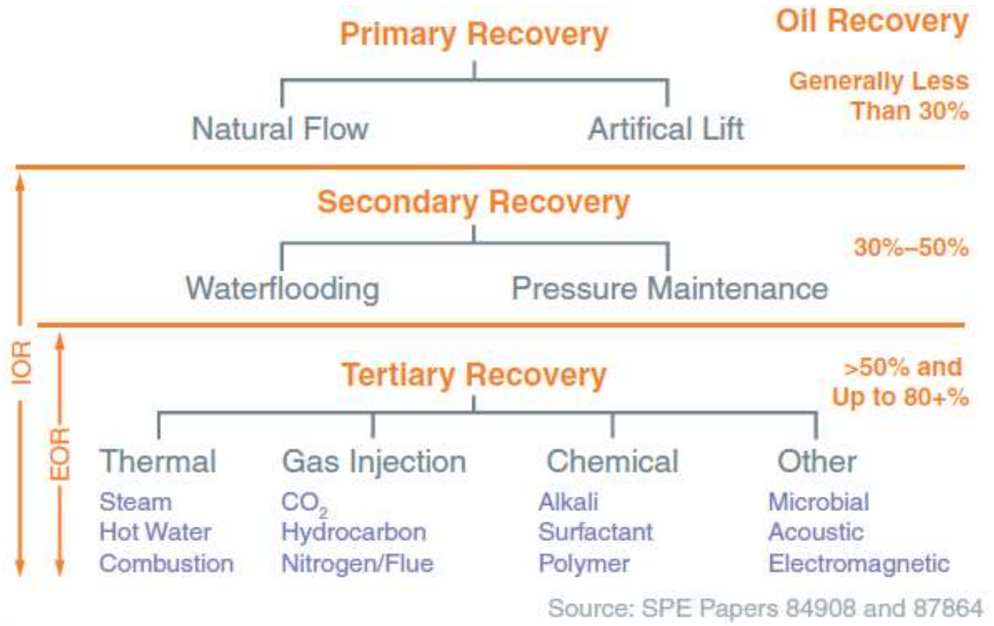


Fig. 2—Defining improved oil recovery (IOR) and enhanced oil recovery (EOR).

100% recovery is impossible

Unconventional petroleum

Shale oil = tight oil [pétrole de shiste, de roche mère]
Shale gas [gaz de schiste]

Fracture low permeability source rocks to recover hydrocarbons

≠

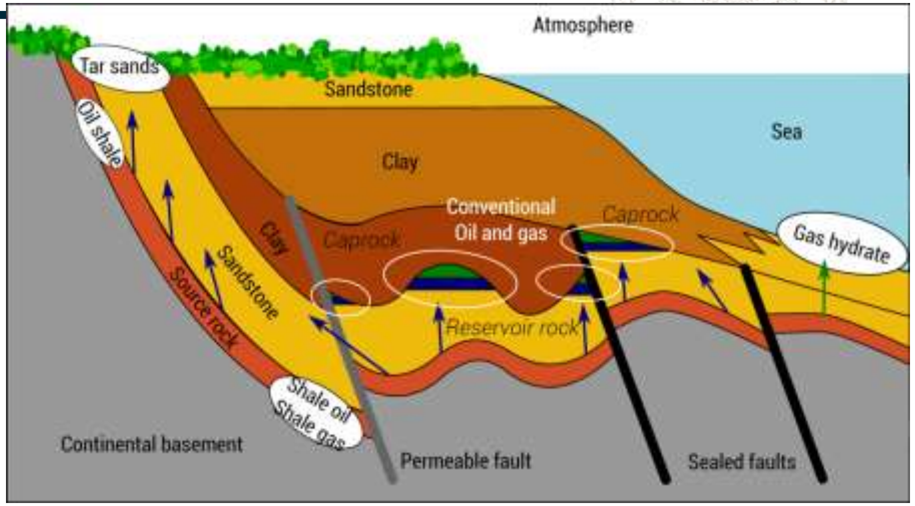
Oil shale [schistes bitumineux] → oil shale oil [huile de schiste].

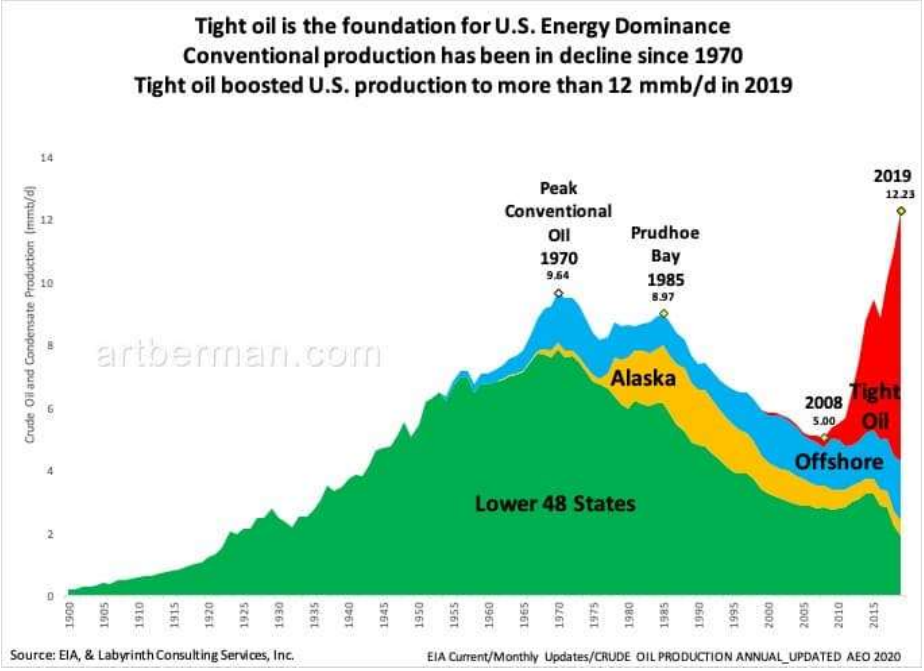
Immature source rock, requires treatement to process kerogen into synthetic fossil fuels.

Fracking techniques?

Energy return on investment?

Economic viability?





Lecture 3 Fossil fuels

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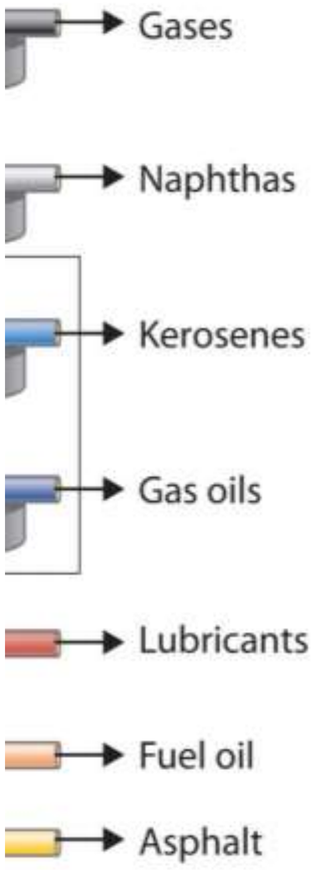
Refining oil – what, why?

Crude oil in, oil products out



Costly and complicated operation
(15% of industry consumption in the US !)

Why bother?

Specific properties for specific applications

You can eat everything but the oink

Application: diesel and gasoline (1/2)

Otto cycle efficiency (see next lecture)

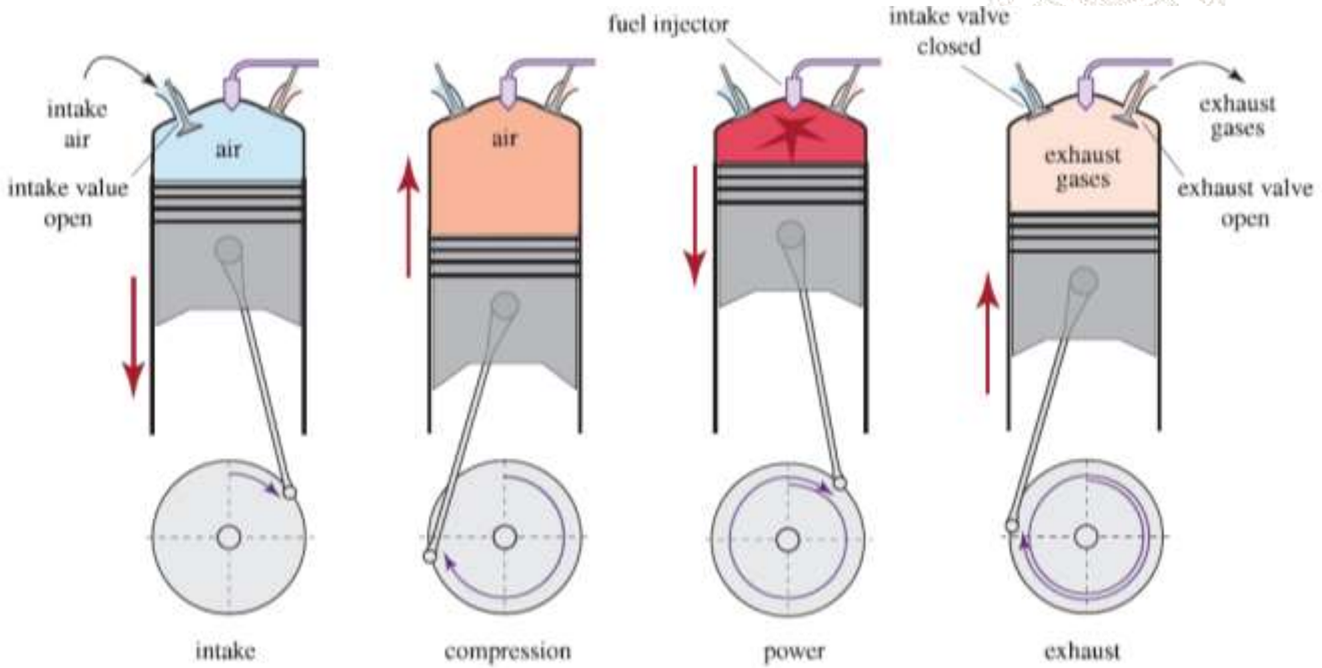
$$\eta = 1 - \frac{1}{r^{\gamma - 1}}$$

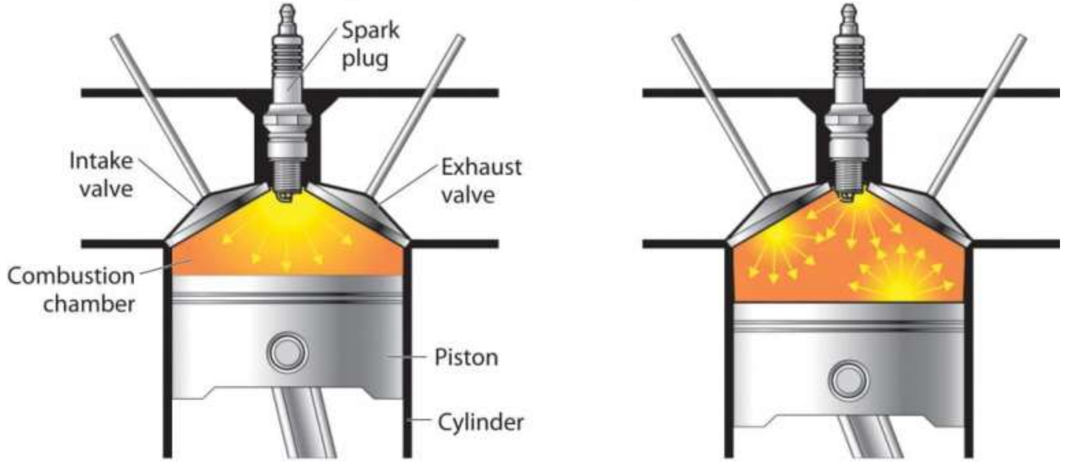
compression ratio

Higher compression ratio

→ more work recovered from fuel

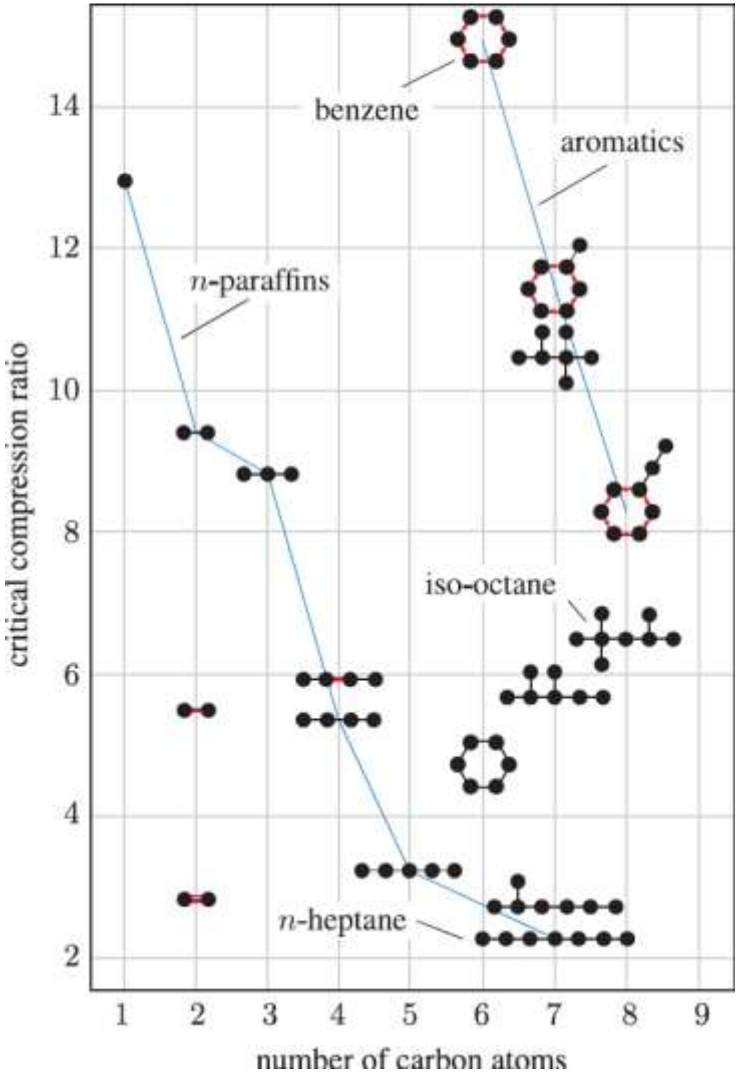
Problem: self ignition (knocking)





(a) Normal combustion **(b) Premature combustion**

Application: diesel and gasoline (2/2)

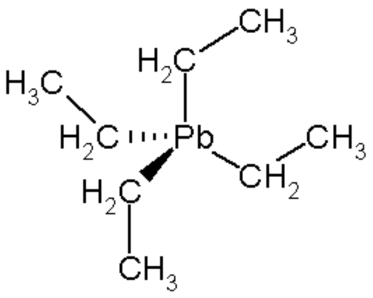


Jaffe, Taylor, The Physics of energy

Knock resistance: Octane Number

0 = n-heptane   100 = iso octane

- Don't compress too much (if your car don't need so much power)
- Select fuels with high critical compression ratio
  Iso octane, aromatics
- Add antiknock agent

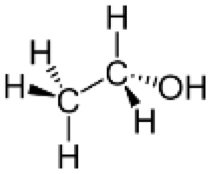


Tetraethyllead

Banned due to toxicity

Unleaded fuels

[=sans plomb]

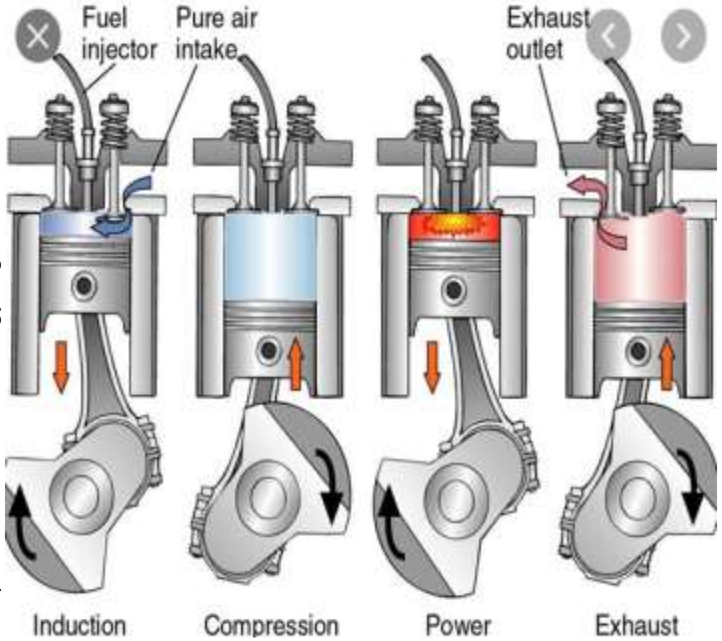


Ethanol

Ethanol / gasoline mix :

$$x\,21.2 + (1-x)35\,[\mathrm{MJ/L}]$$

- Self ignition proof design



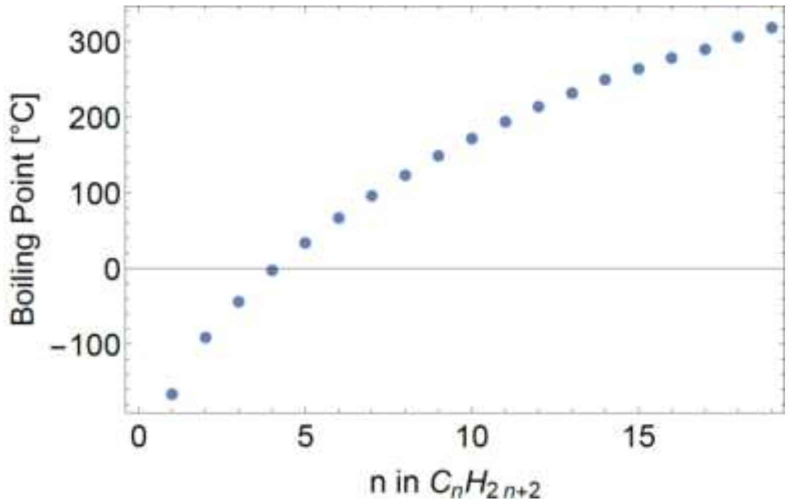
https://www.ammoniaenergy.org/

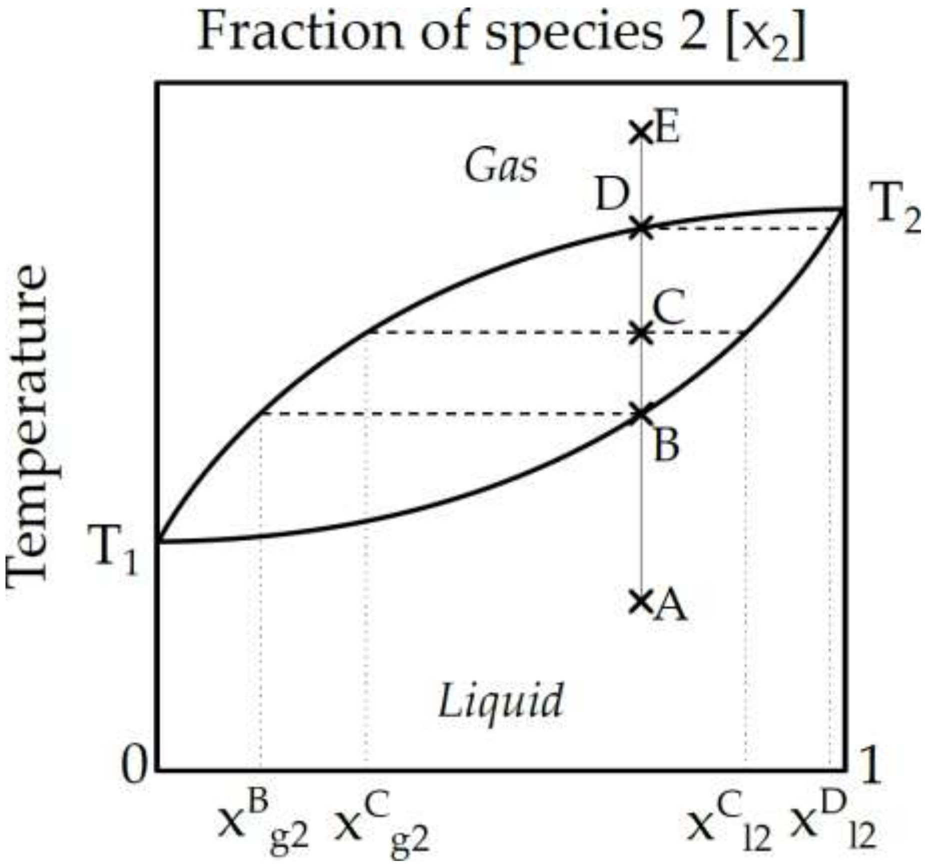
Application: diesel and gasoline (2/2)

- Don’t compress too much (if your car don’t need so much power)
- Select fuels with high critical compression ratio
- Add antiknock agent
- Self ignition proof design

Boiling a mixture

Different hydrocarbons have different boiling temperatures → Distillation





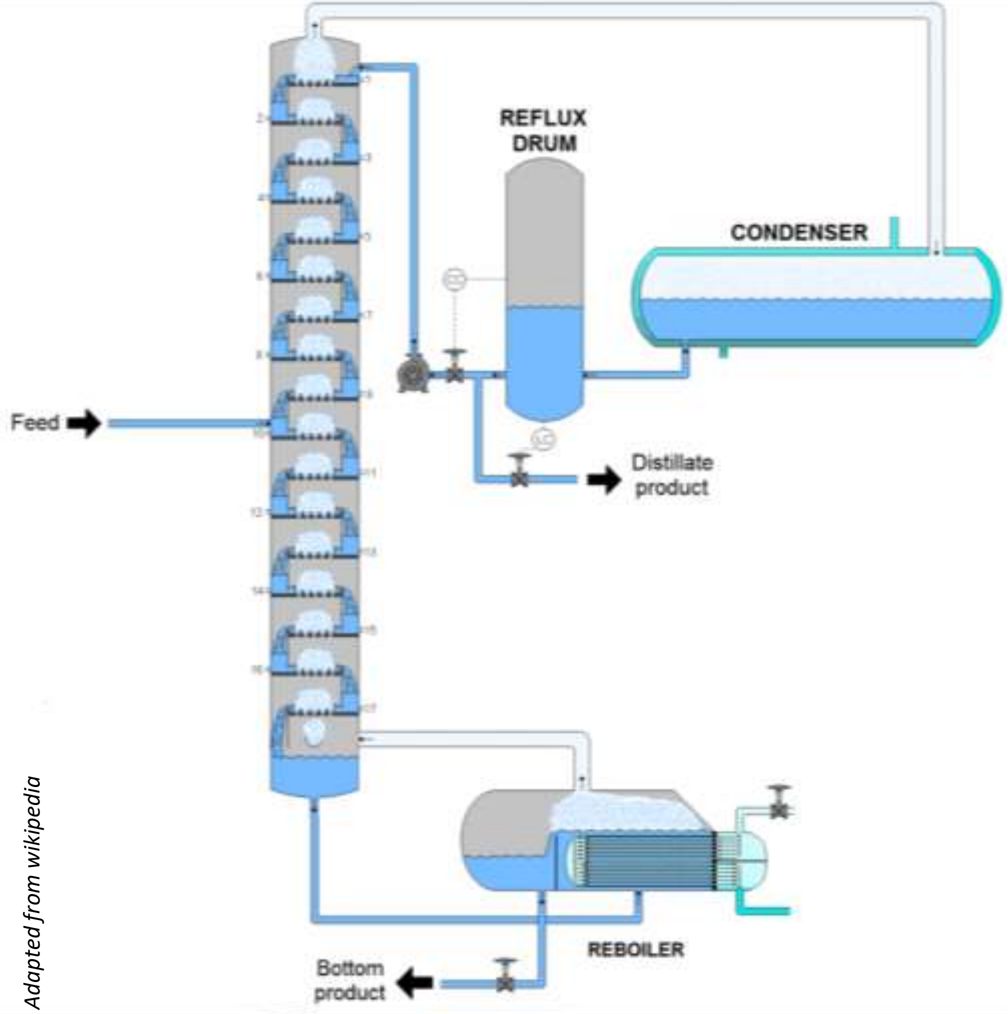
(calculated from chemical potentials !)

A: Heat up a mixture of species 1 and 2
with two different boiling temperatures (T1 < T2)

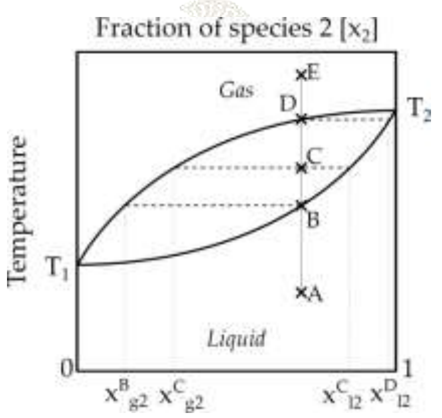
B: The mixture starts boiling.
The first bubble of gas is enriched in species 1

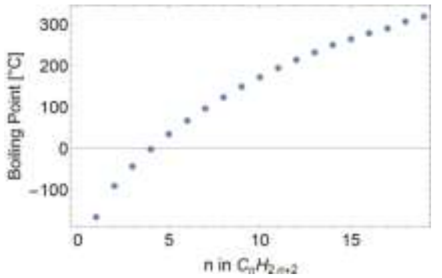
D: All the mixture turned into a gas.
The last droplet is enriched in species 2

Distillation - principle



Adapted from wikipedia





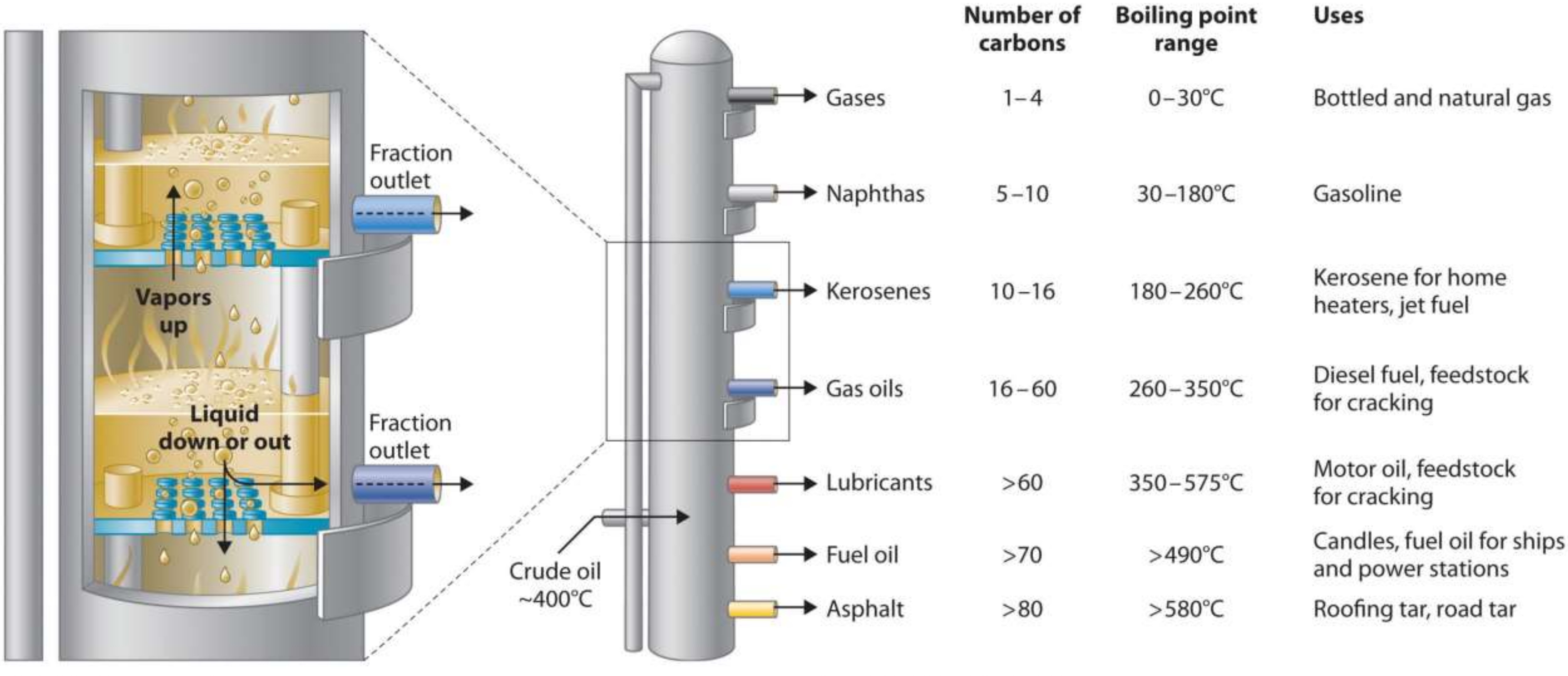
Introduce pre heated feedstock of crude oil

At a given tray

- Gas phase enriched in lighter species
  → moves up to the next tray
- Liquid phase enriched in heavier species
  → falls down to the previous tray

Cuts @ given locations
⇔ given temperatures
⇔ given compositions

Distillation tower



(a) Petroleum distillation tower **(b) Petroleum fractions**

Source : https://chem.libretexts.org/

Refining chemistry

Cracking / polymerization

Turn large / small chains into small / large chains

Change an oil product into another

Reforming

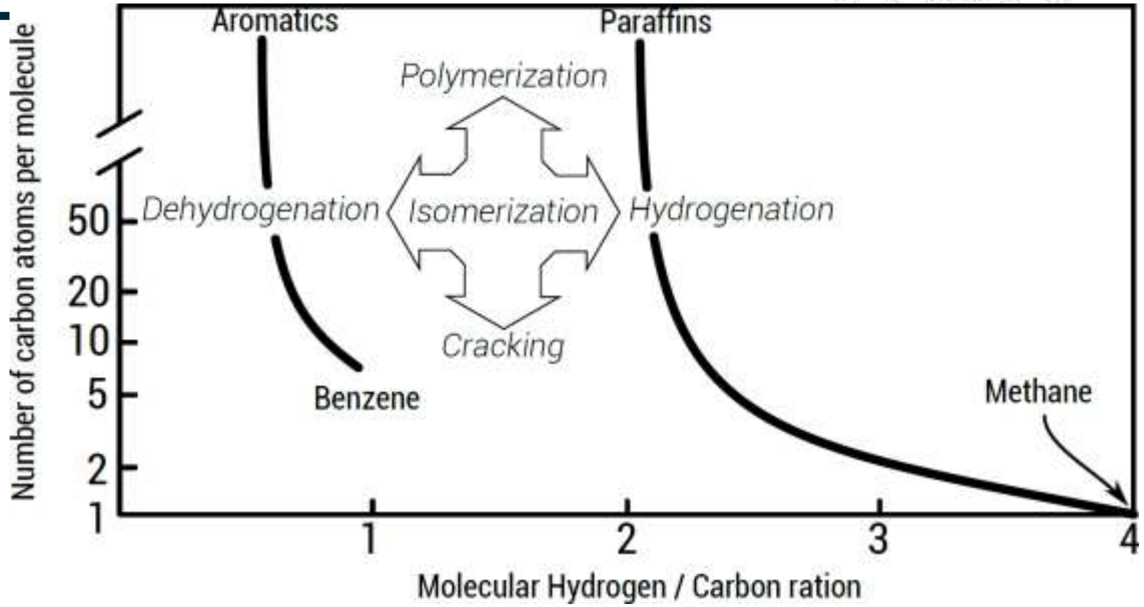
Create double bonds → produces H

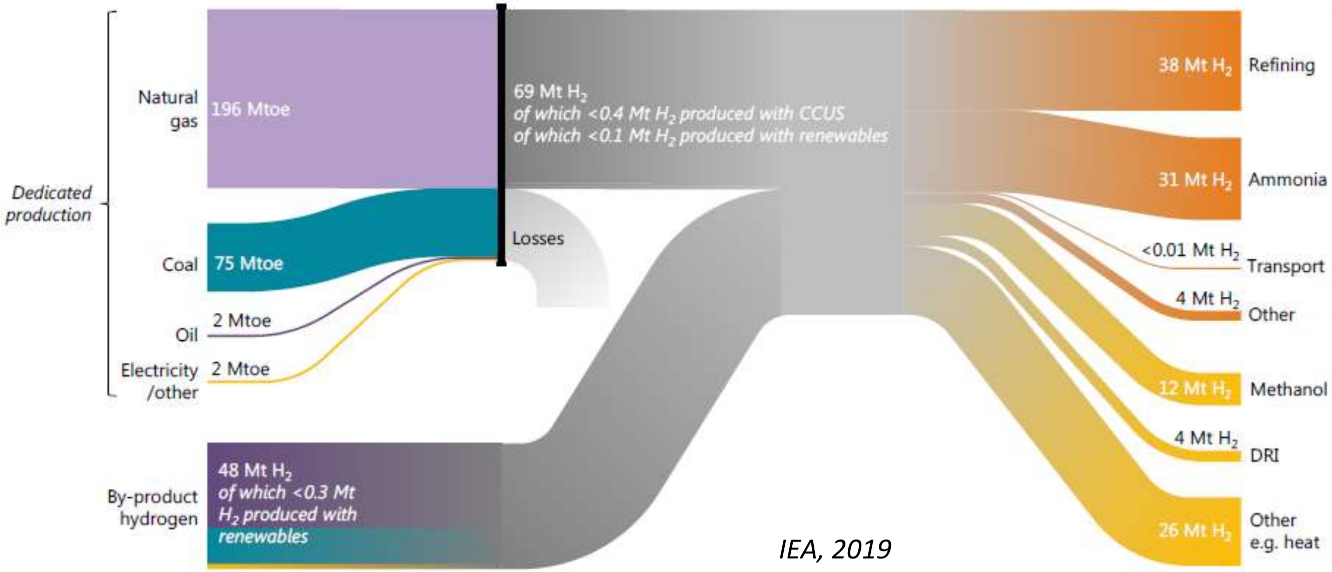
Increase octane number

Purifying

Separate different molecules

Remove heteroatoms (N,S) → requires H



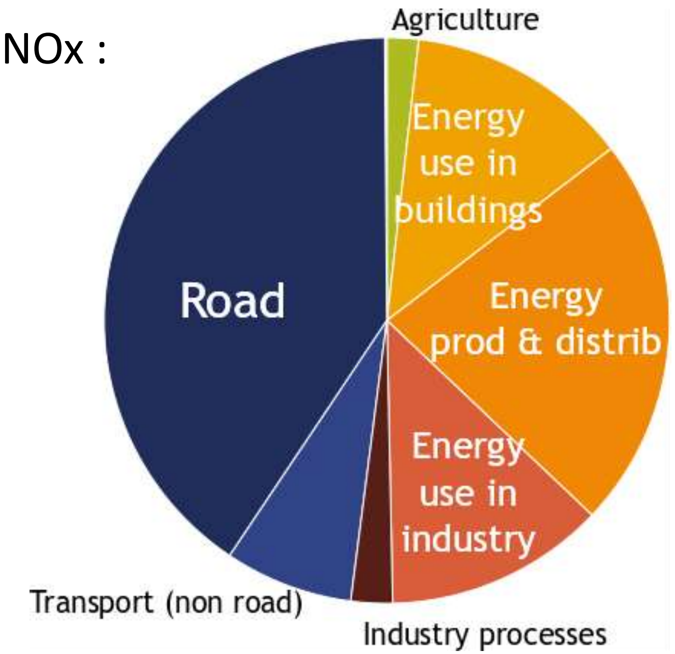


IEA, 2019

Nitrogen and sulfur oxides

SOx : fossil fuels combustion

NOx :



European Environment Agency

NOx + volatile compounds + sunlight
Ground-level Ozone (Smog)

Acid rain

NOx + ammonia
Particles

Water Quality Degradation
Eutrophication

Global warming
GWP N_2O = 250

Toxic chemicals

Fog

Lecture 3 Fossil fuels

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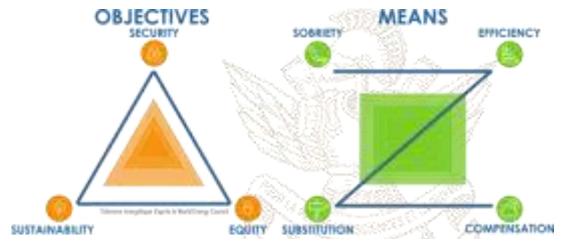
Perspectives

Alternatives to fossile fuels?

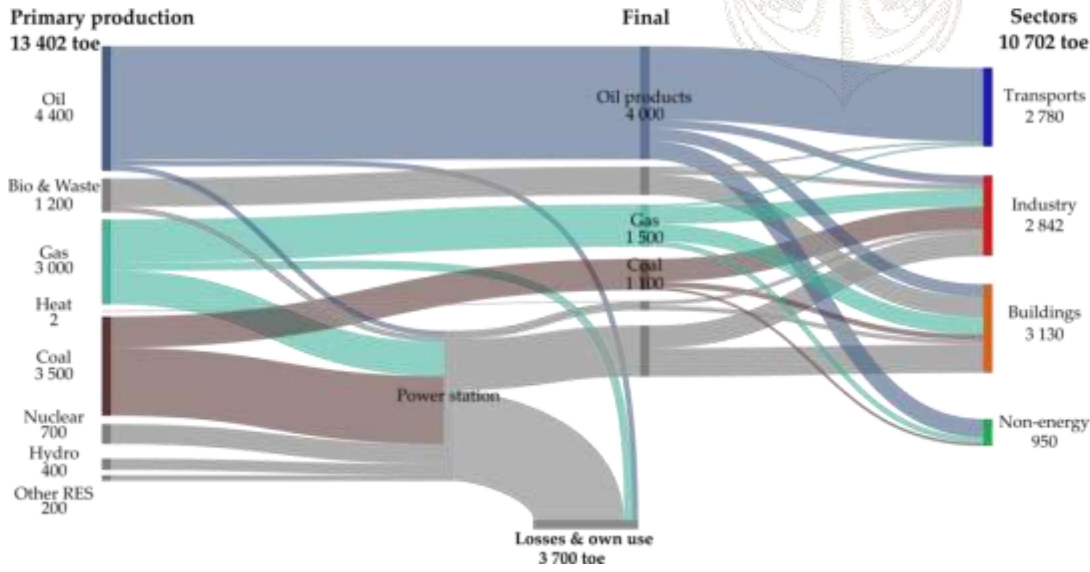


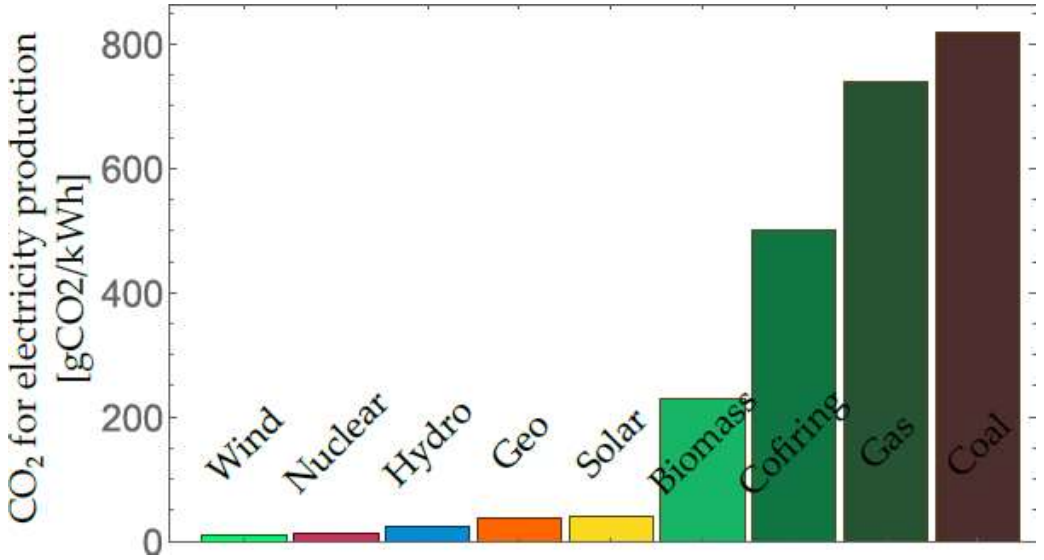
Restraint — Yes !

Compensation — CCS (PC 3)

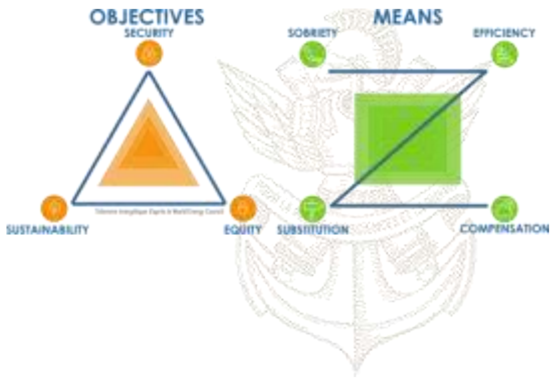
Efficiencies
- Lecture 4 (heat engines)
- Lecture 8 (heating)

Substitution
- Electricity (lectures 5,6,7,9)
- Heating (lectures 8)
- Transport (lecture 9)



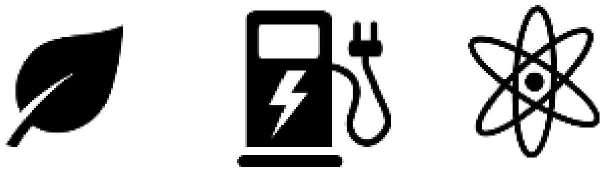


Alternative fuels



Biomass based	Conventional 1st generation	(Edible) crops → Bioethanol, biodiesel
	Advanced 2nd, 3rd generation	Non competing with food & feed Residue, municipal wastes, used cooking oil, algae…
Electricity based	Electric battery	(loaded with low carbon electricity !)
Hydrogen based	Fuel cell	Hydrogen flow to electricy current
	Amnonia	Hydrogen combined with atmo nitrogen
	e-fuels	Hydrogen to reduce CO_2 into hydrocarbon

Alternative questions



Technical specificities?

power density, freezing point…

Costs?

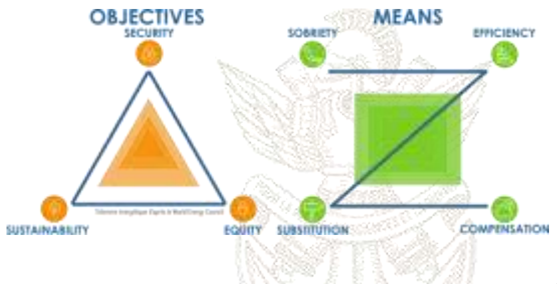
Overall efficiency, feedstock availability…

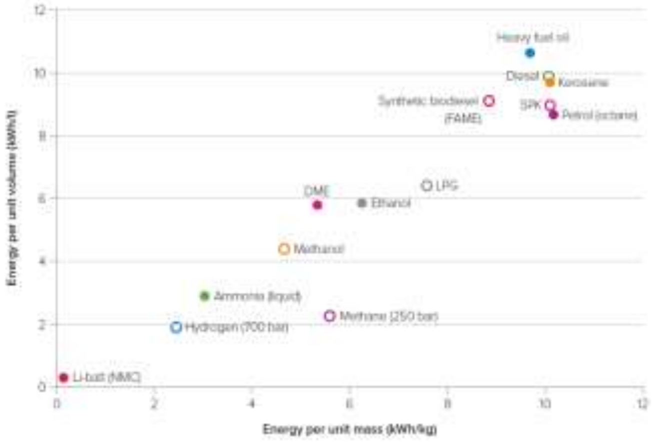
Supply chain?

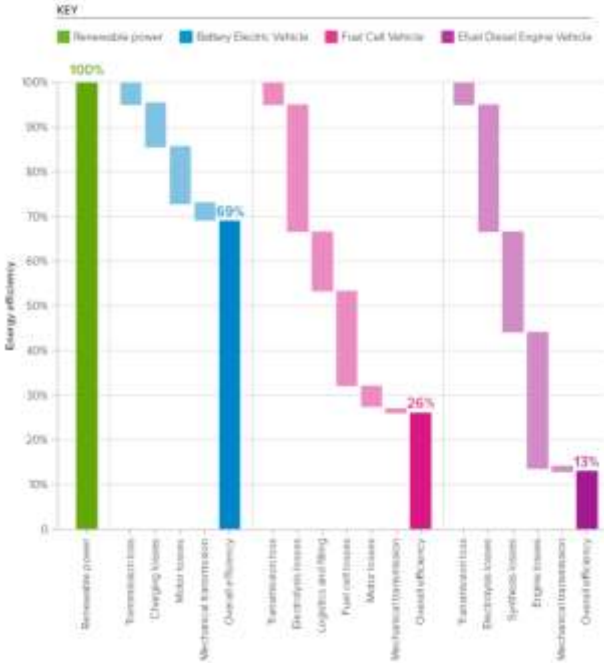
Compatible with current infrastructures?

Environmental impacts?

Sustainability besides CO_2

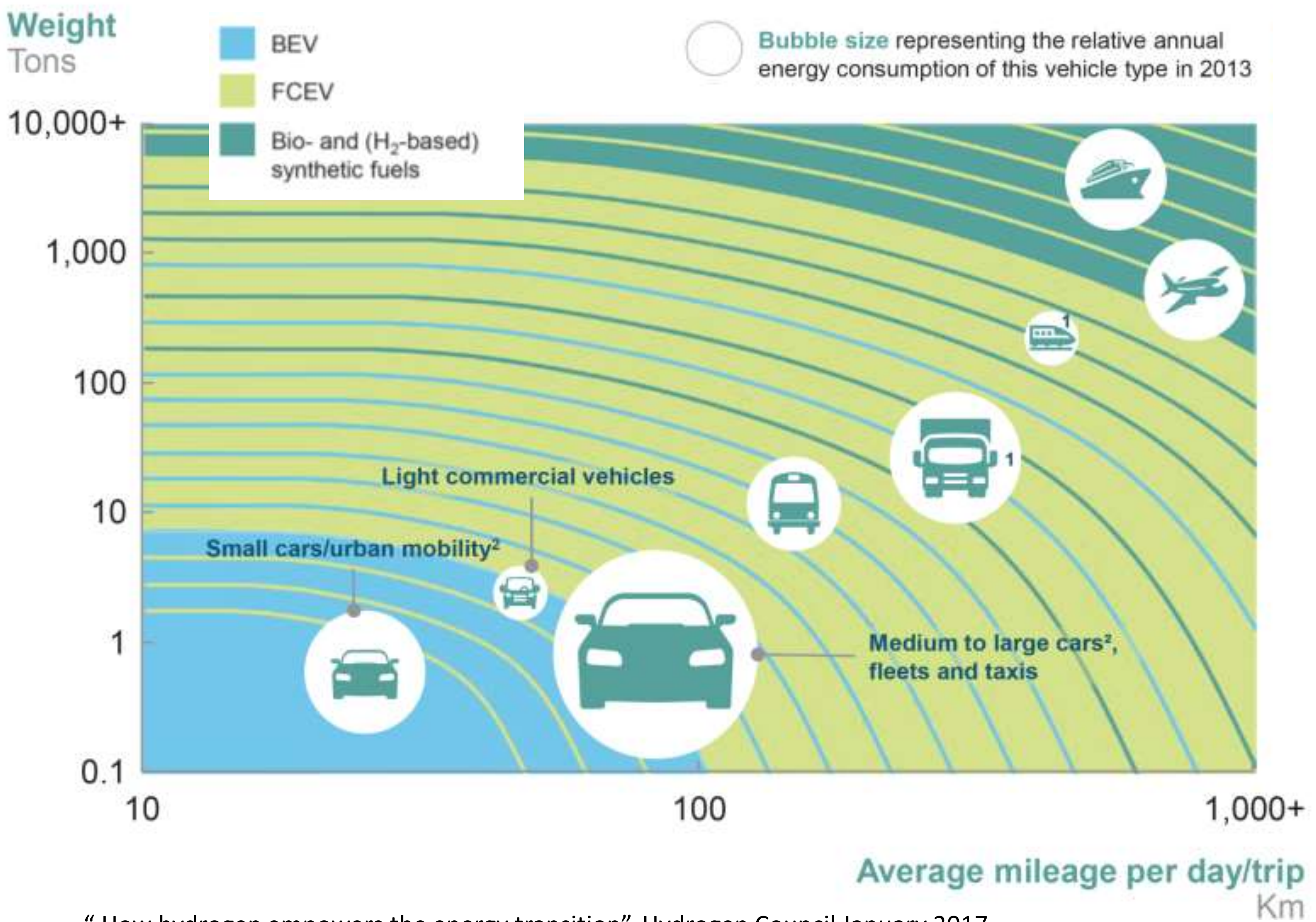






The Royal Society (2019), *Sustainablesyntheticcarbonbasedfuels for transport*

The right fuel for the right transport



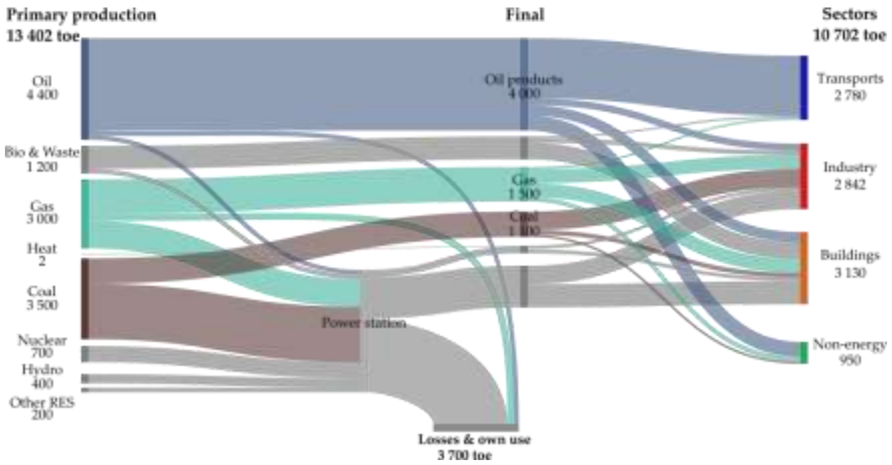
Vehicle and duty cycle compatibility		Synthetic efuels	Biomethane	Hydrogen	Electricity
City car			CNG		
Long distance car			CNG		
Urban van			CNG		
Heavy-duty truck			LNG		
Aviation	Short haul				
	Long haul				
Marine	Short journey		LNG		
	Long journey		LNG		

The Royal Society (2019), *Sustainablesyntheticcarbonbasedfuels for transport*

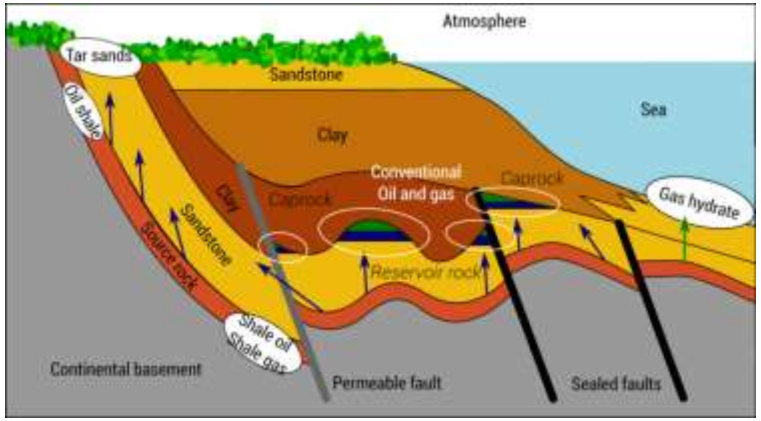
" How hydrogen empowers the energy transition", Hydrogen Council January 2017

Take home message

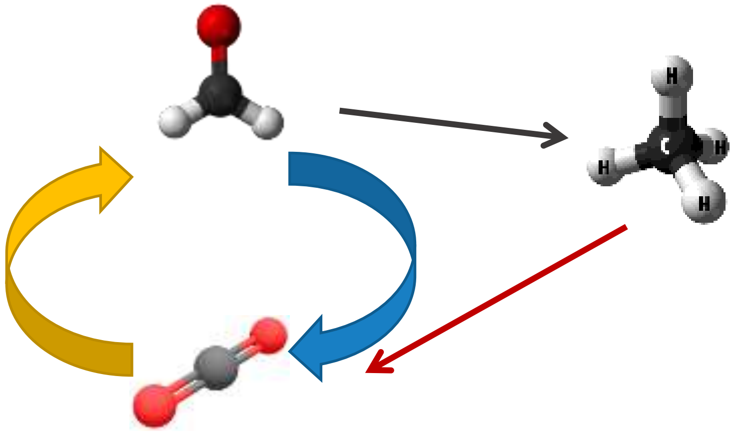
Oil, coal and gas: what, why?



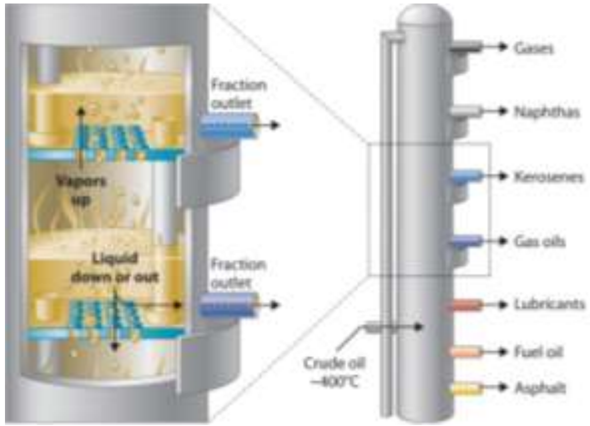
Basic petroleum vocabulary



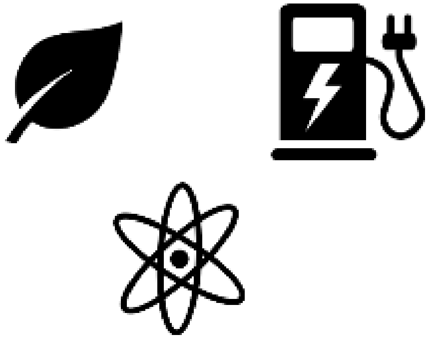
In and out the organic carbon cycle



Refining 101



Alternative fuels



It's all about the chemical potential !

$$G(N,T,p) = H - TS = N\,\mu(T,p)$$