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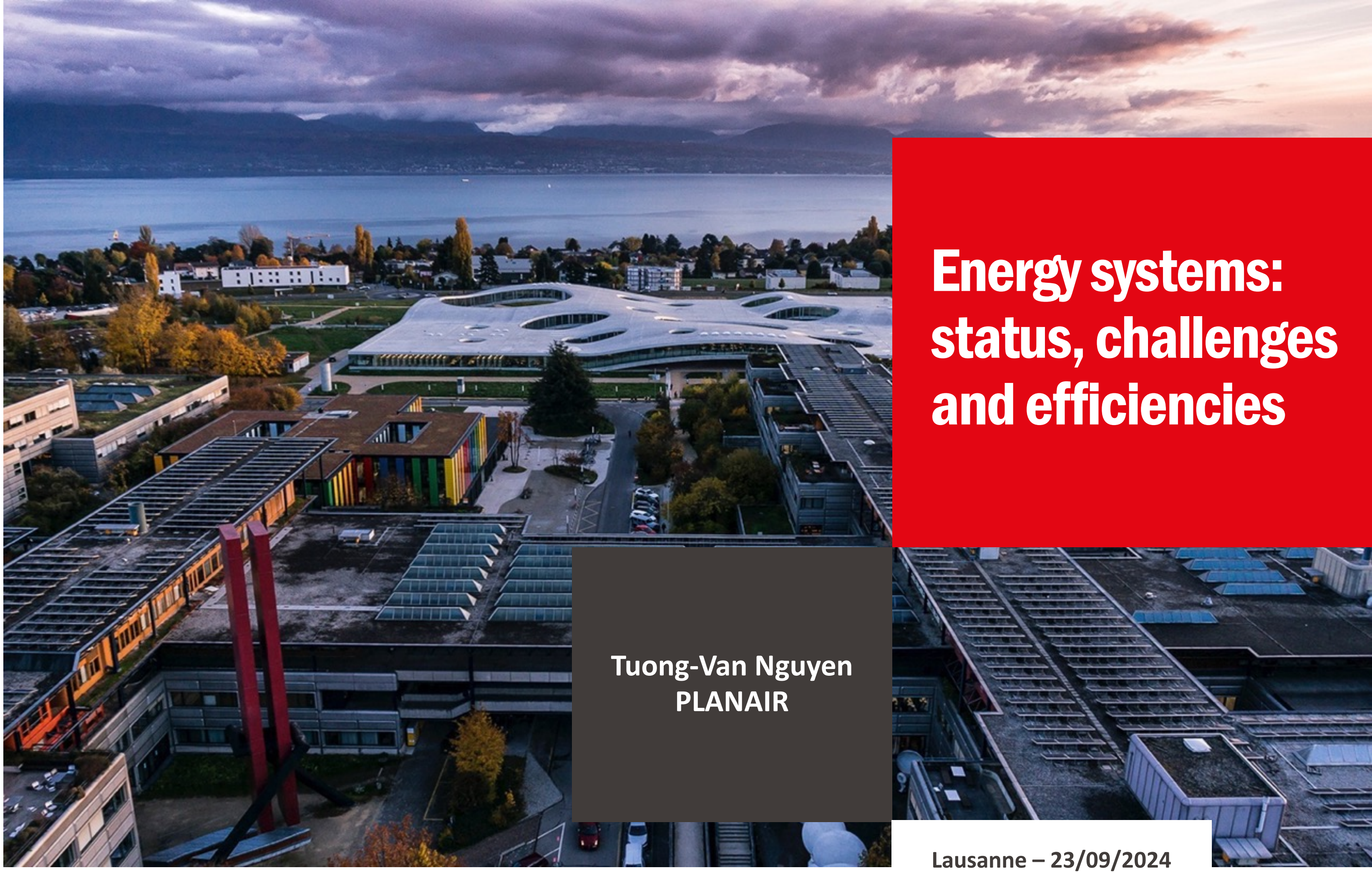

Energy systems: status, challenges and efficiencies

Tuong-Van Nguyen
PLANAIR

Lausanne – 23/09/2024

École
polytechnique
fédérale
de Lausanne

Schedule

ENERGY SYSTEM, MODELS, POLICIES

Week	Date	Topic	Lecturer
1	09/09	Introduction / What is an energy system?	FM / TVN
2	23/09	Energy system: status, challenges and efficiencies	TVN
3	30/09	Rankine cycles	TVN
4	07/10	Combustion / Brayton cycles	FM
5	14/10	Coal / CCS	FM
6	28/10	Nuclear / Cogeneration	TVN
7	04/11	Heat pumps / Geothermal	TVN
8	11/11	Solar	FM
9	18/11	Wind / Hydro	FM
10	25/11	Biomass	TVN
11	02/12	Storage	TVN
12	09/12	Fuel cells & Hydrogen	JVH
13	16/12	Energy strategy / Final wrap-up	GG / FM / TVN

FM = Francois Maréchal, **TVN** = Tuong-Van Nguyen, **JVH** = Jan Van Herle, **GG** = Gianfranco Guidati

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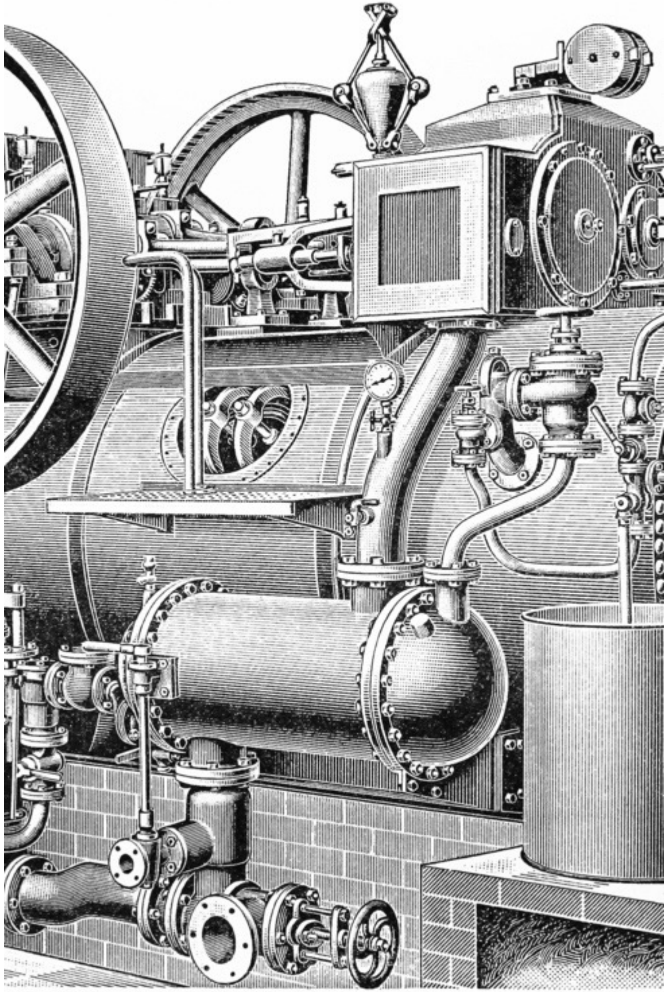
Goals

- **Explain** the status and challenges related to the energy transition and future energy systems
- **Use** different metrics to compare energy systems (costs, efficiencies, areas)
- **Calculate** the maximum efficiency an energy conversion system can reach



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Recall from Lecture #1

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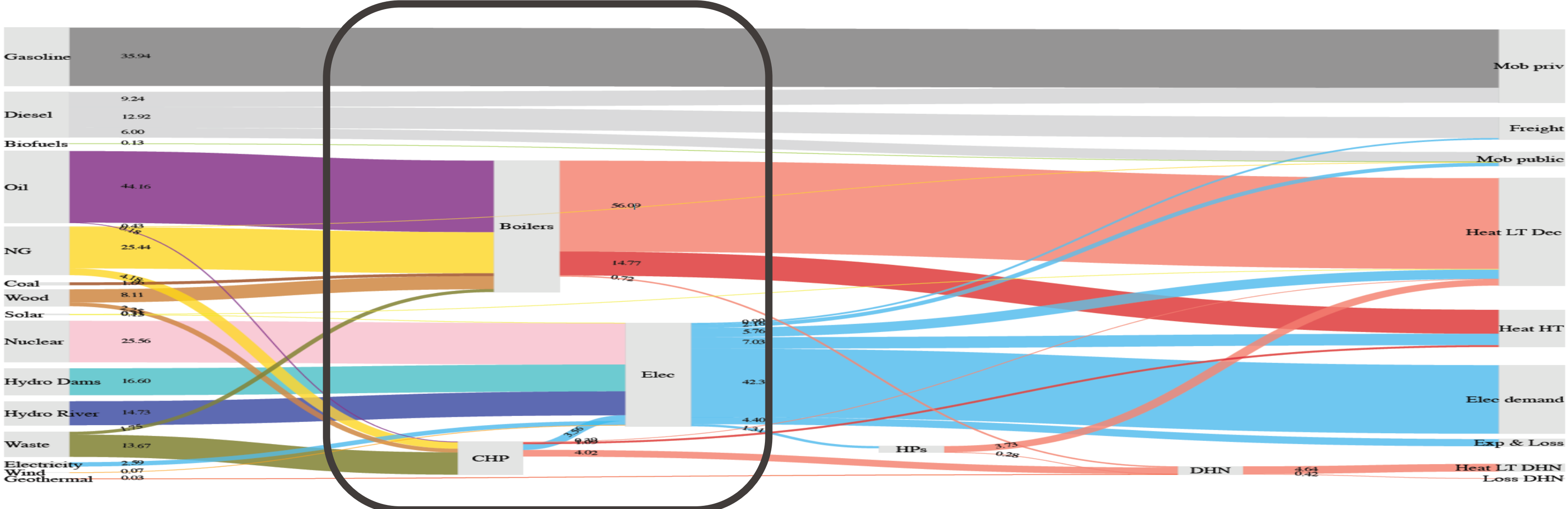
Energy systems

Production **Conversion** **Delivery** **Use**



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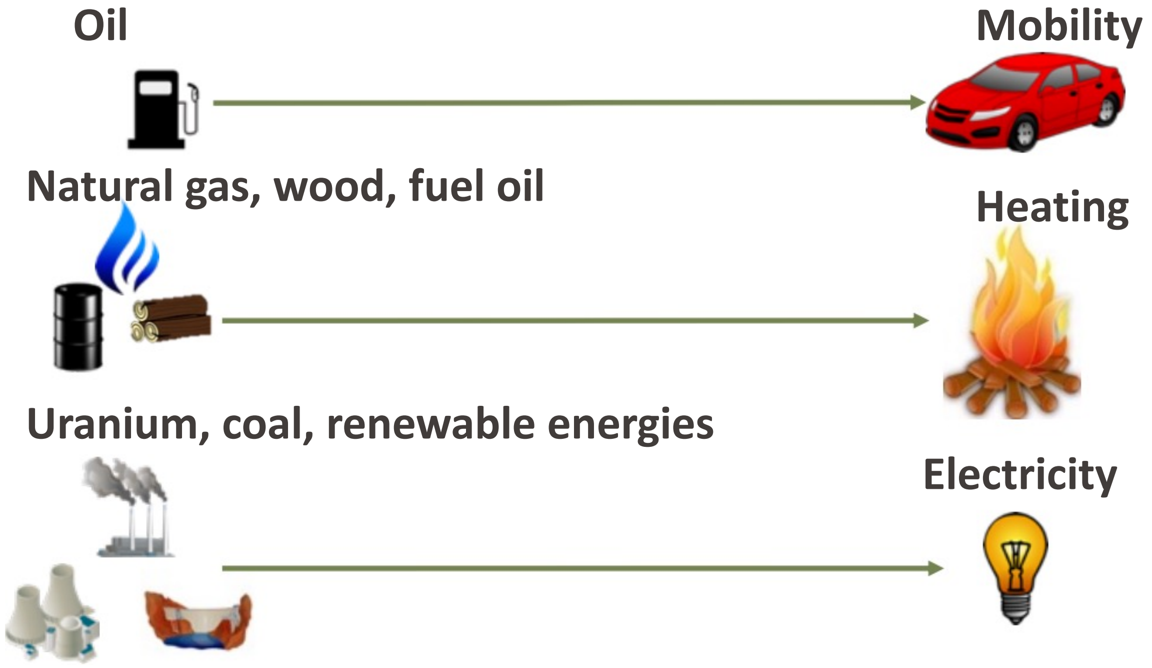
The energy system - *before*

- Until now, every resource has its own **use**!
- Possible if there is no resource **limitation**



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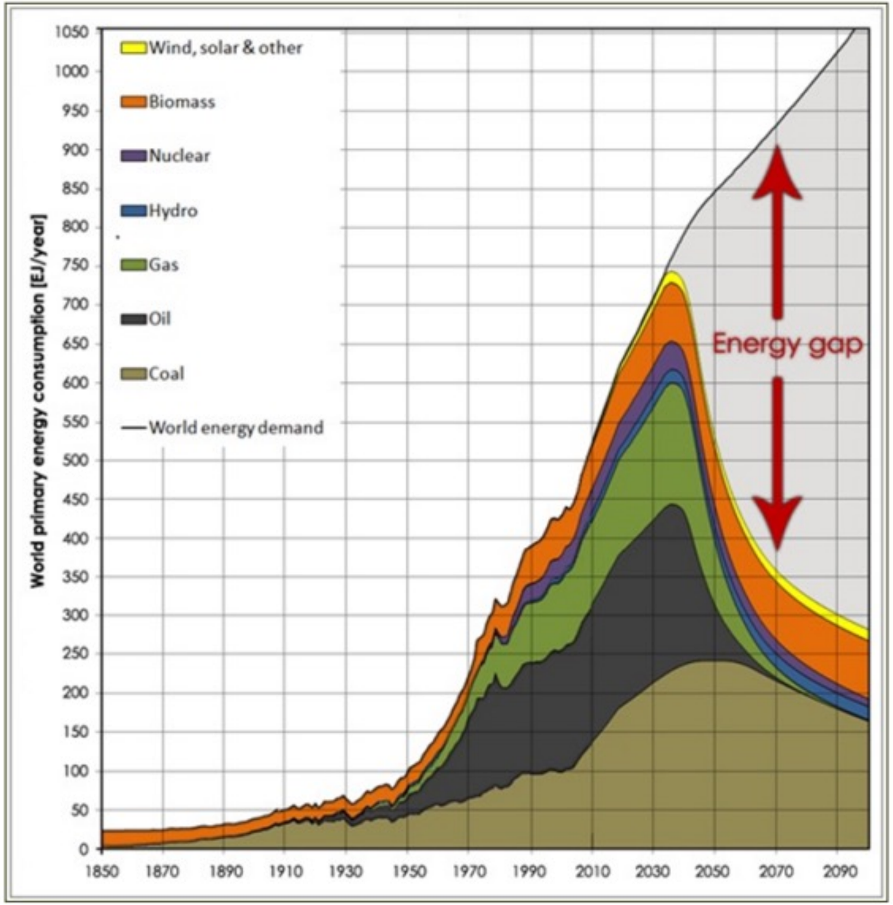
The energy system - *in the future?*



As our economy **grows**, so does our energy consumption

We need to **reduce** our demand for fossil fuels to curb global warming **and ensure our energy security**

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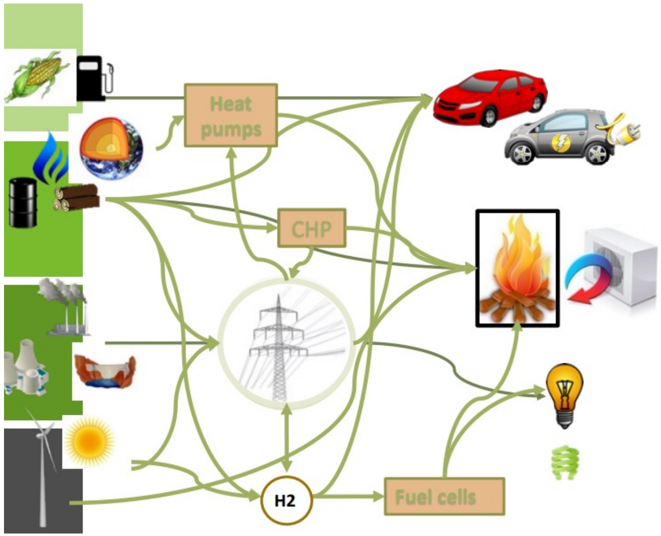
The energy system - *in the future?*

<u>4 **key trends** :</u>

- Exploitation of **new fossil resources**
- **Diversification of fossil fuel and material** supplies
- Integration of **renewable energies** and electrification
- **Reducing our demands, decoupling from growth**



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Energy system: status and challenges

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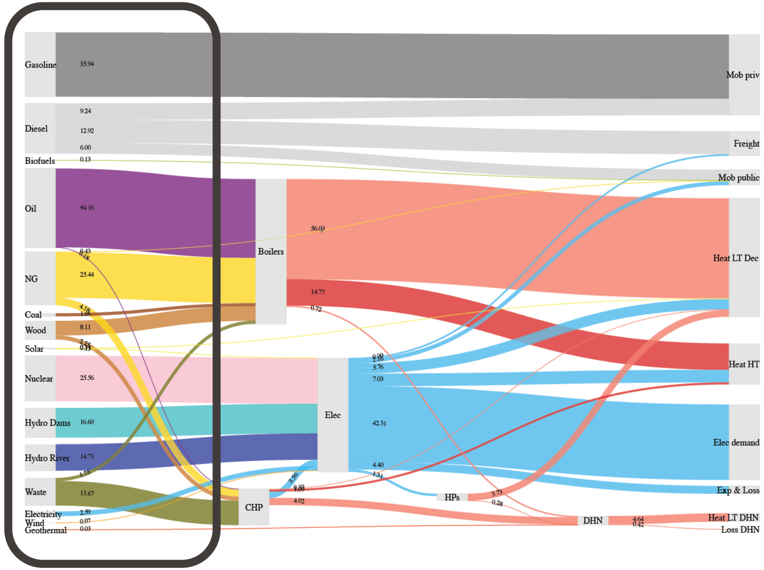

The ”energy” challenge

Resources vs. Reserves

Renewables vs. non-renewables

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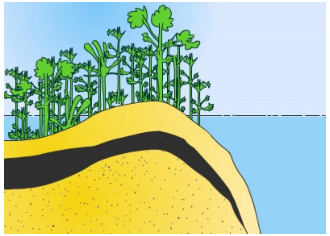
Energy resources
– Renewables vs. Non-renewables

- **Non-renewable**

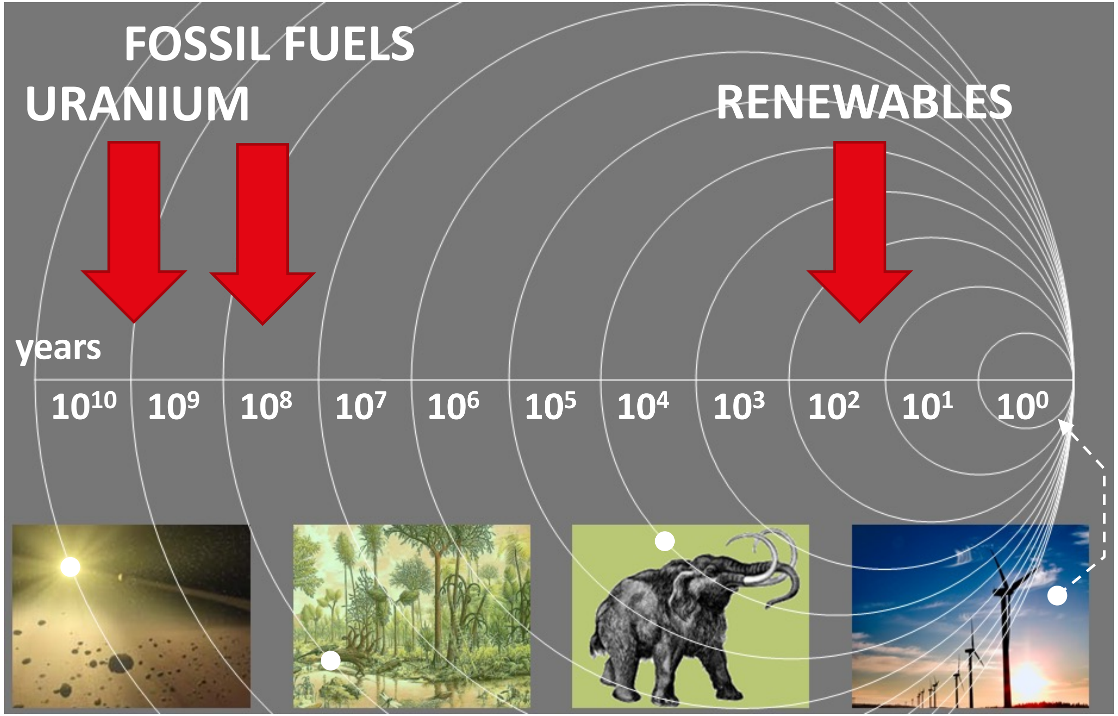
Consumption

<< Generation



100-400 mil years

“Bank analogy”



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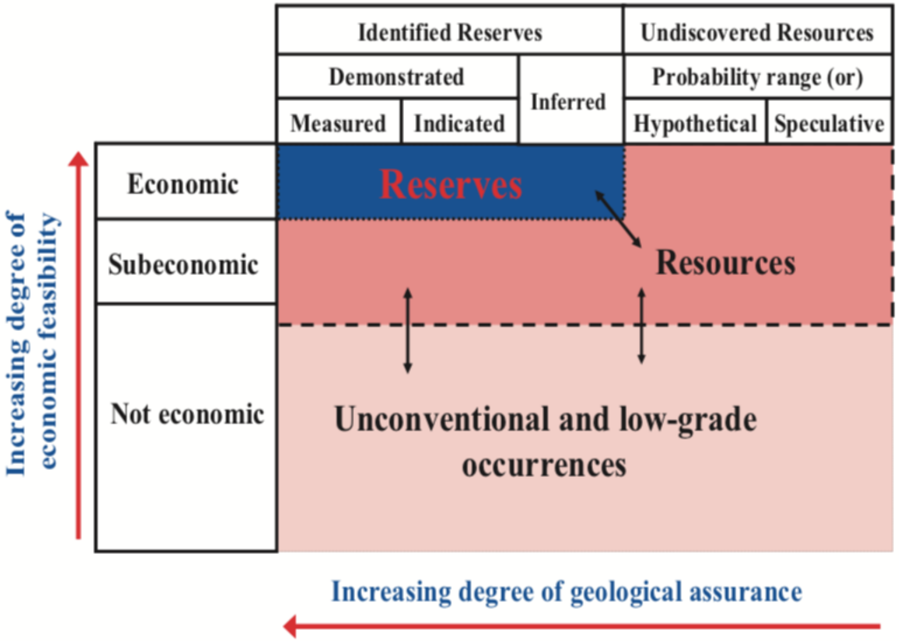
Energy resources
– Reserves & Resources

+ Certainty & economic producibility

- **Reserves** = can be recovered in the future
- **Resources** = detected, cannot yet be recovered profitably
- **Unconventional** = not economic or not feasibly recoverable



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Given the current global reserves and production rates, how many years still of coal, oil and gas?

A. < 20 years
B. 20-50 years
C. 50-100 years
D. > 100 years

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Energy resources
– Fossil fuel reserves

	Historical production through 2005	Production 2005	Cumulative extraction GEA scenarios 2005–2100	Reserves	Resources	Additional Occurrences
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
Conventional oil	6 069	147.9	6 600–10 000	4 900–7 610	4 170–6 150	
Unconventional oil	513	20.2	2–470	3 750–5 600	11 280–14 800	> 40 000
Conventional gas	3 087	89.8	7 900–11 900	5 000–7 100	7 200–8 900	
Unconventional gas	113	9.6	180–8 500	20 100–67 100	40 200–121 900	> 1 000 000
Coal	6 712	123.8	3 300–16 500	17 300–21 000	291 000–435 000	
Conventional uranium[b]	1 218	24.7	1 520–28 500	2 400	7 400	
Unconventional uranium[c]	n.a.	–			4 100	> 2 600 000

(a) The data reflect the ranges found in the literature; the distinction between reserves and resources is based on current (exploration and production) technology and market conditions. Resource data are not cumulative and do not include reserves.

(b) Reserves, resources, and occurrences of uranium are based on a once-through fuel cycle operation. Closed fuel cycles and breeding technology would increase the uranium reserve and resource dimensions 50–60 fold. Thorium-based fuel cycles would enlarge the fissile-resource base further.

(c) Unconvential uranium occurrences include uranium dissolved in seawater

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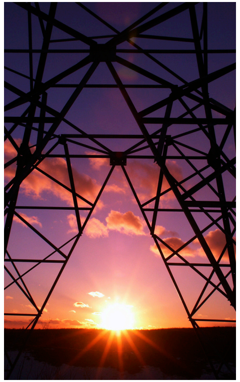
Energy resources
– Fossil fuel reserves

"The stone age did not end because the world ran out of stones, and **the oil age will not end because we run out of oil**"

- Don Huberts, Shell





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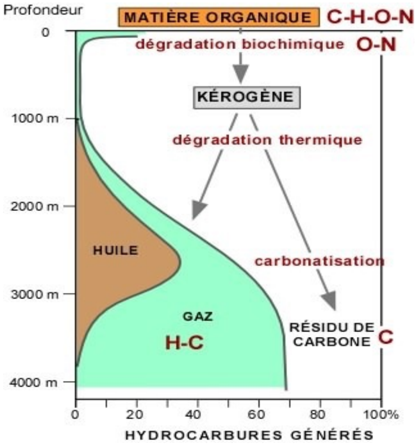
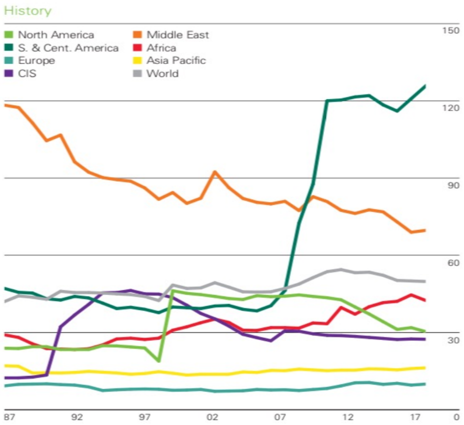
Energy resources
– Oil

- Reserve/production ratio ≈ **50** years
- “Peak debate” (2040?)
- Fossilized organic materials





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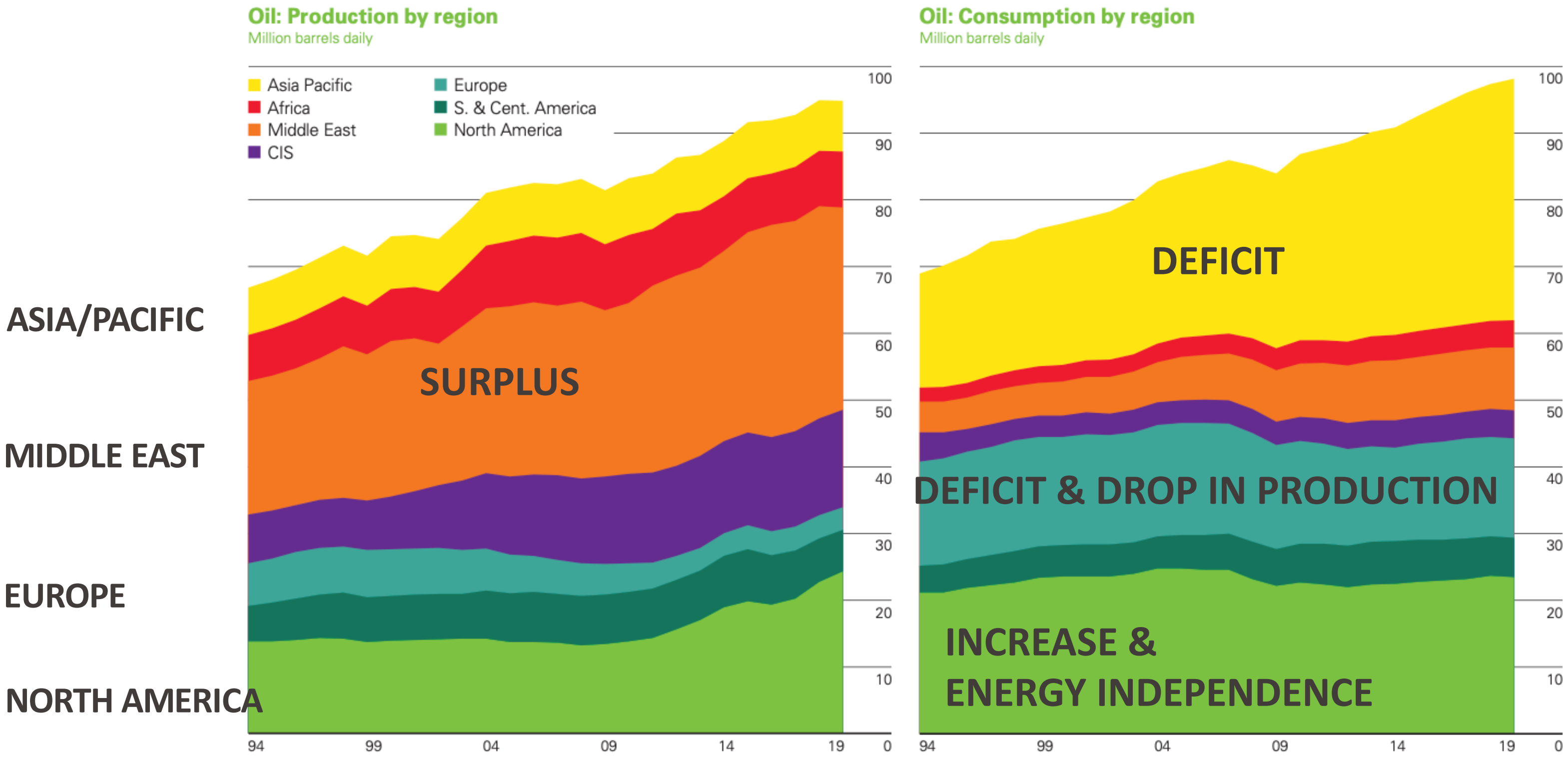
Energy resources
– Oil



Source: Statistical Review of World Energy (2020)

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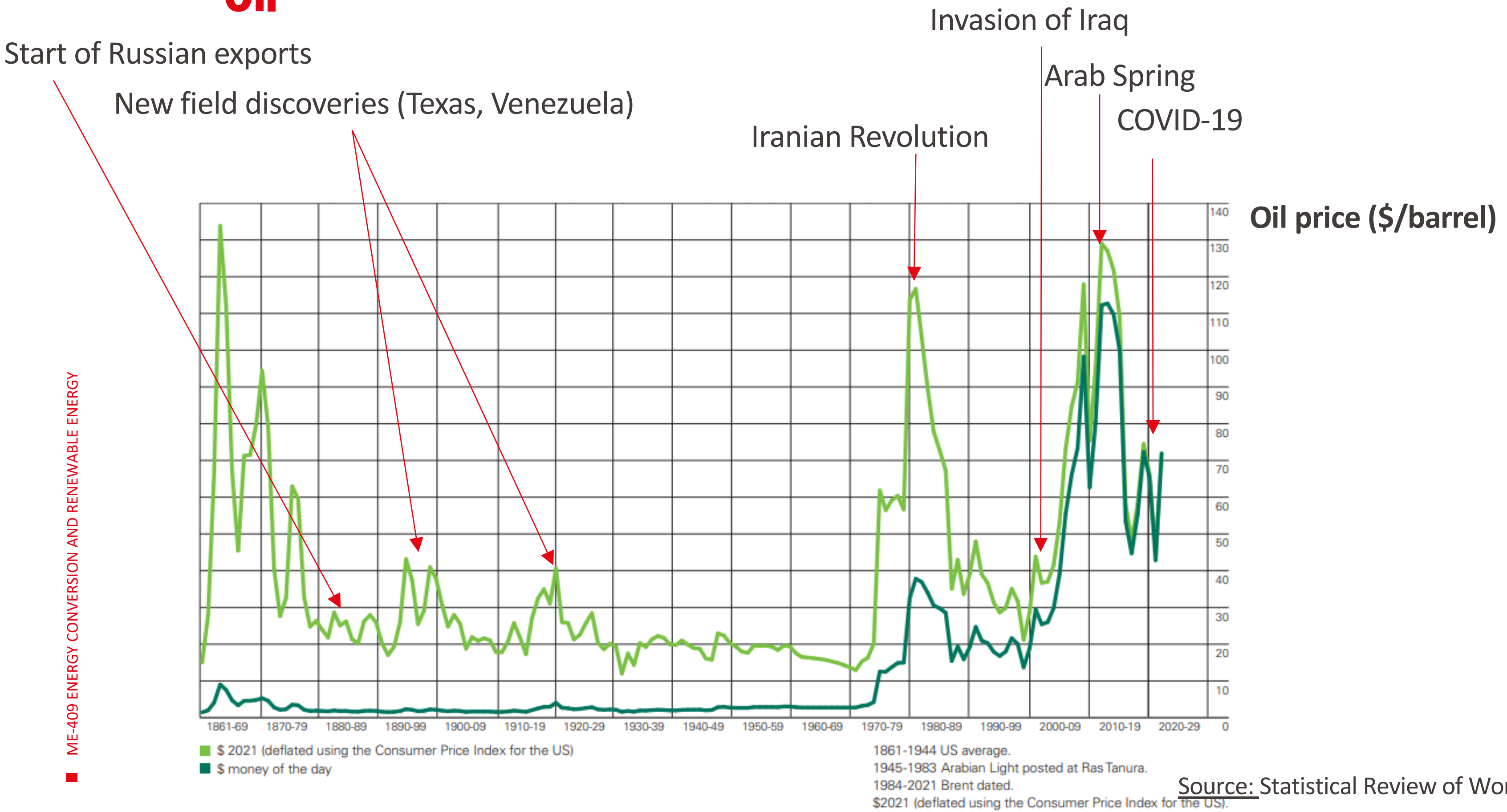
Energy resources
– Oil



Source: Statistical Review of World Energy (2022)

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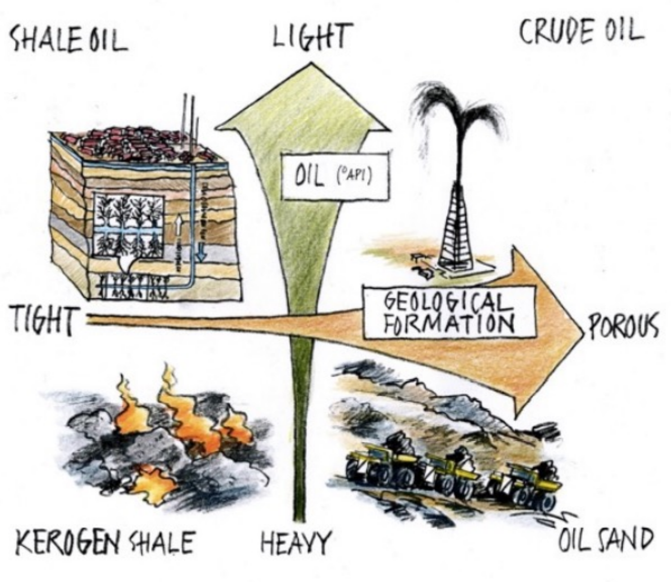
Energy resources
– Non-conventional oil resources

- More difficult operating conditions and greater environmental/economic risks
- Currently not economically interesting to extract?



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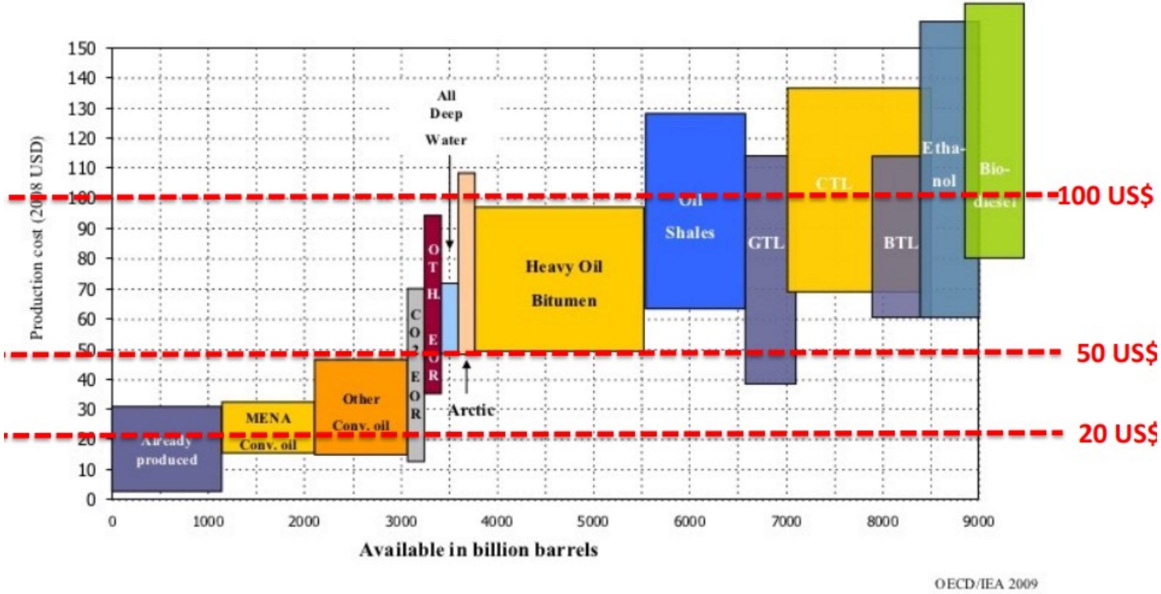
Energy resources
– Non-conventional oil resources

- The higher the **price of oil…**
  - The more competitive **renewable resources** are
  - As well as **non-conventional resources** (as in the USA)!



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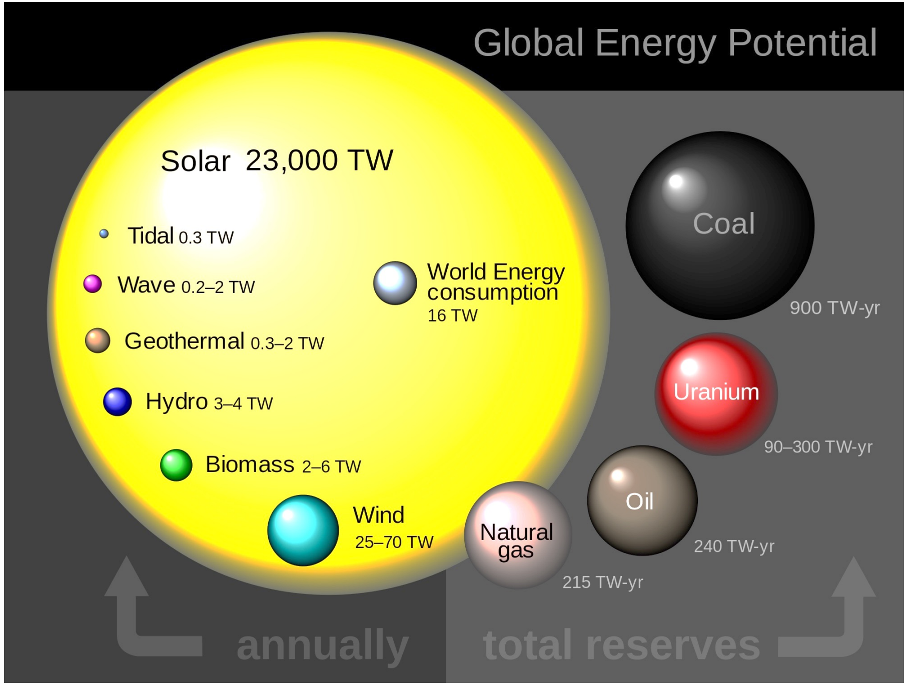
Energy resources
– Comparison

- We have by far enough resources – fossil fuel depletion is not an issue



Perez et al., 2009, "A Fundamental Look At Energy Reserves For The Planet"

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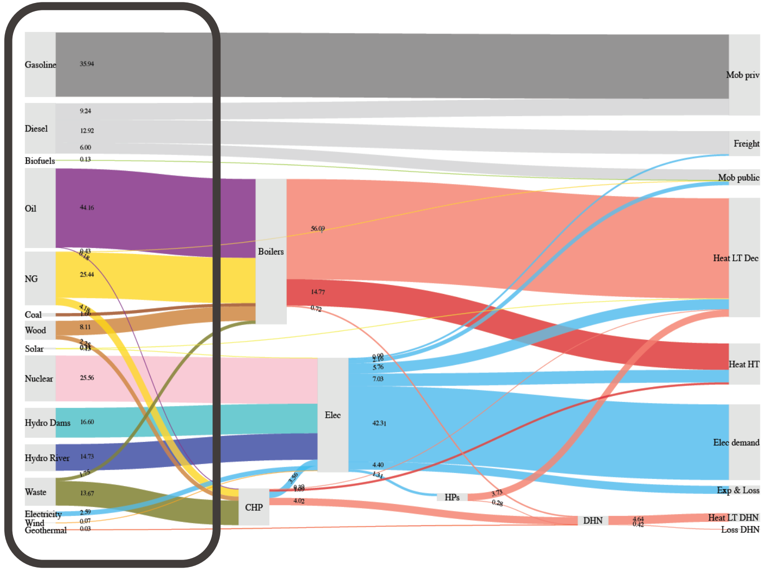

The ”material” challenge

Material requirements

Supply chains

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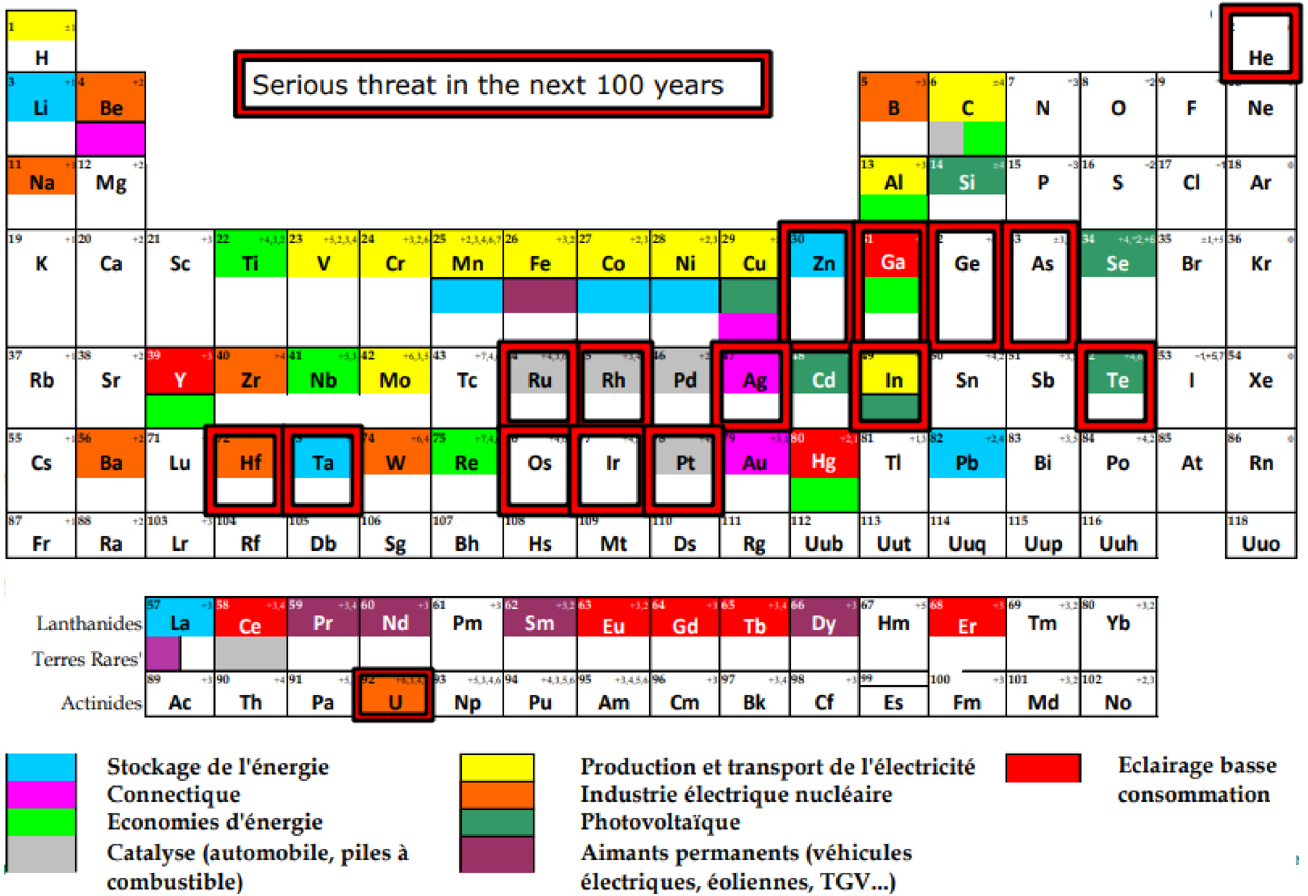
Which of these energy resources require rare earths?

A. Fossil (gas, coal)
B. Wind
C. Solar
D. Nuclear

Materials requirements



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Materials requirements

Rare earths (17 elements)

- Not necessarily rare
- Supply risk
- Increasing use

e.g. Neodymium, Dysprosium

(synchronous generators - offshore wind power)

Rare metals

- Low abundance metals

e.g. Indium (PV CIGS)

Critical materials

- Strategic sourcing

Ex: Silicon (PV), Copper (PV/wind/geothermal), Silver (PV), Tellurium (PV)

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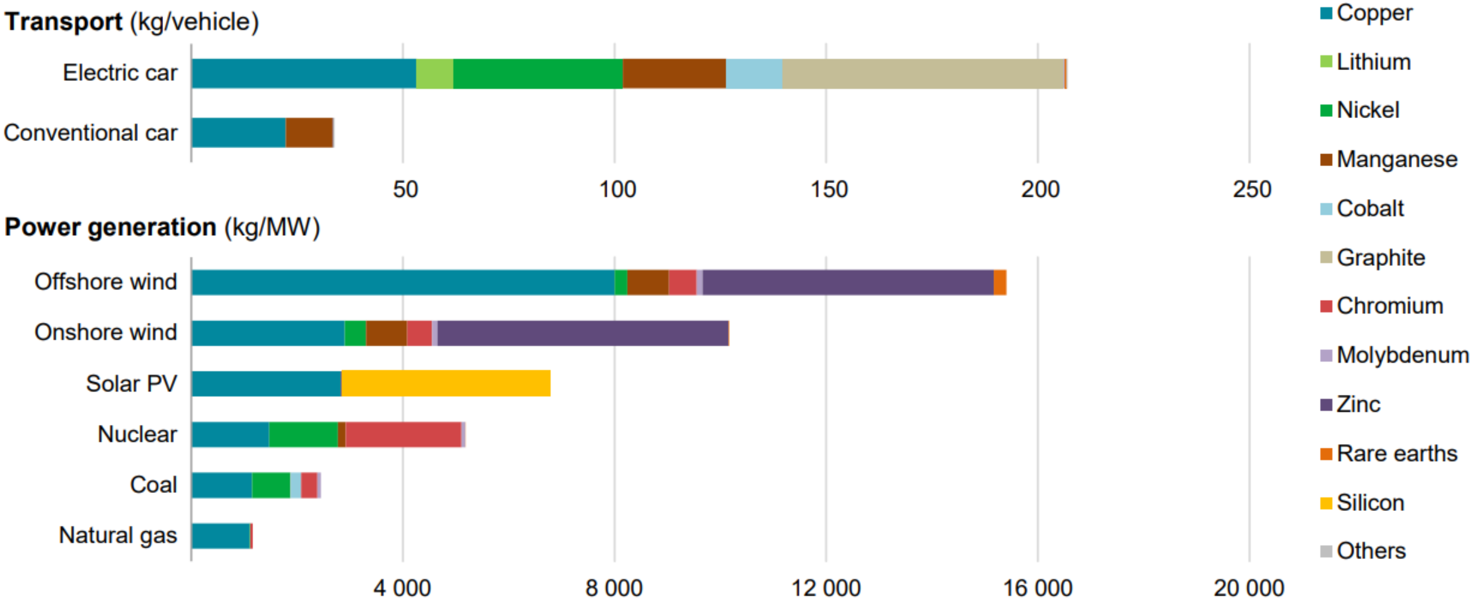
Materials requirements

- Developing wind power, solar energy and electric vehicles
- On the other hand - **few impacts** caused by hydroelectricity and bioenergy



Source: International Energy Agency - The role of critical minerals in clean energy transitions (2020)

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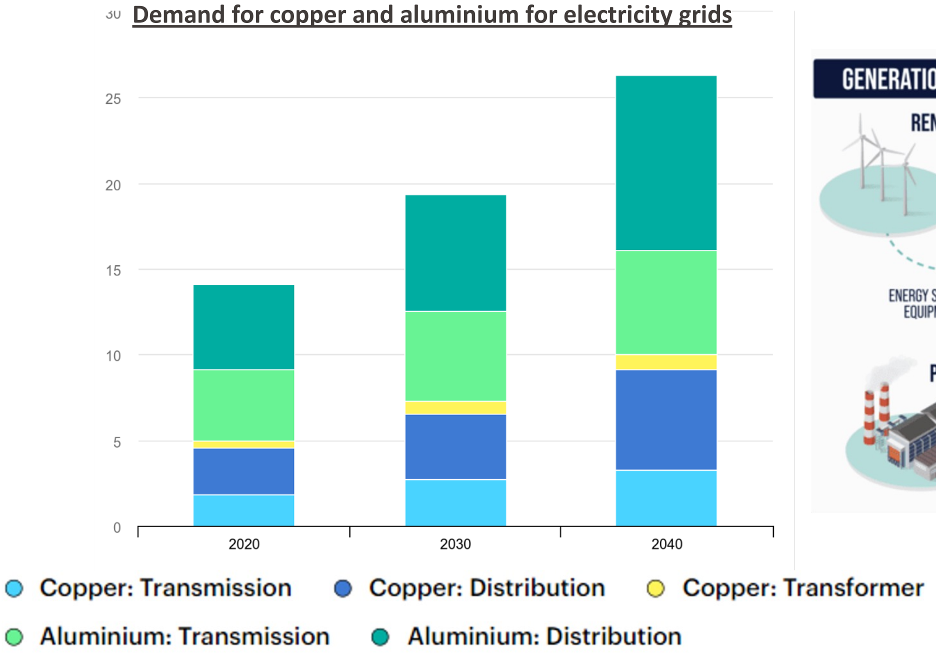
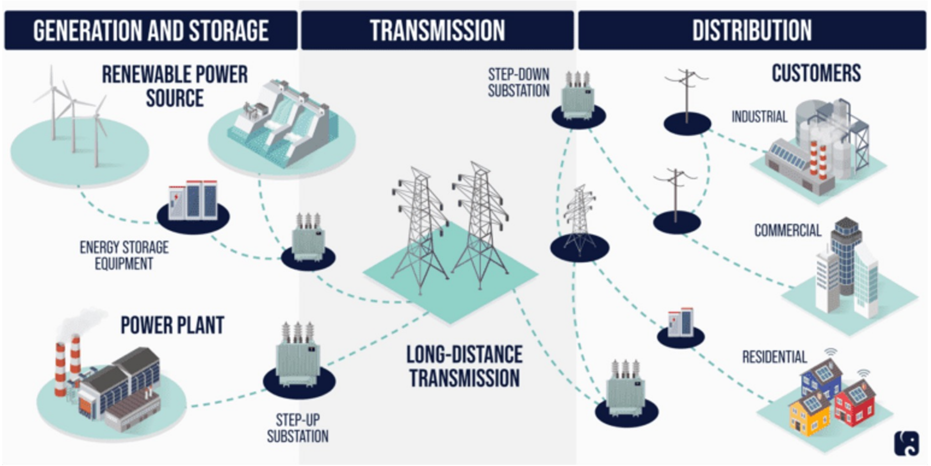
Cases: aluminium and copper

- Extensive use of copper in all solutions
- Demand often underestimated, as grid development is often not taken into account





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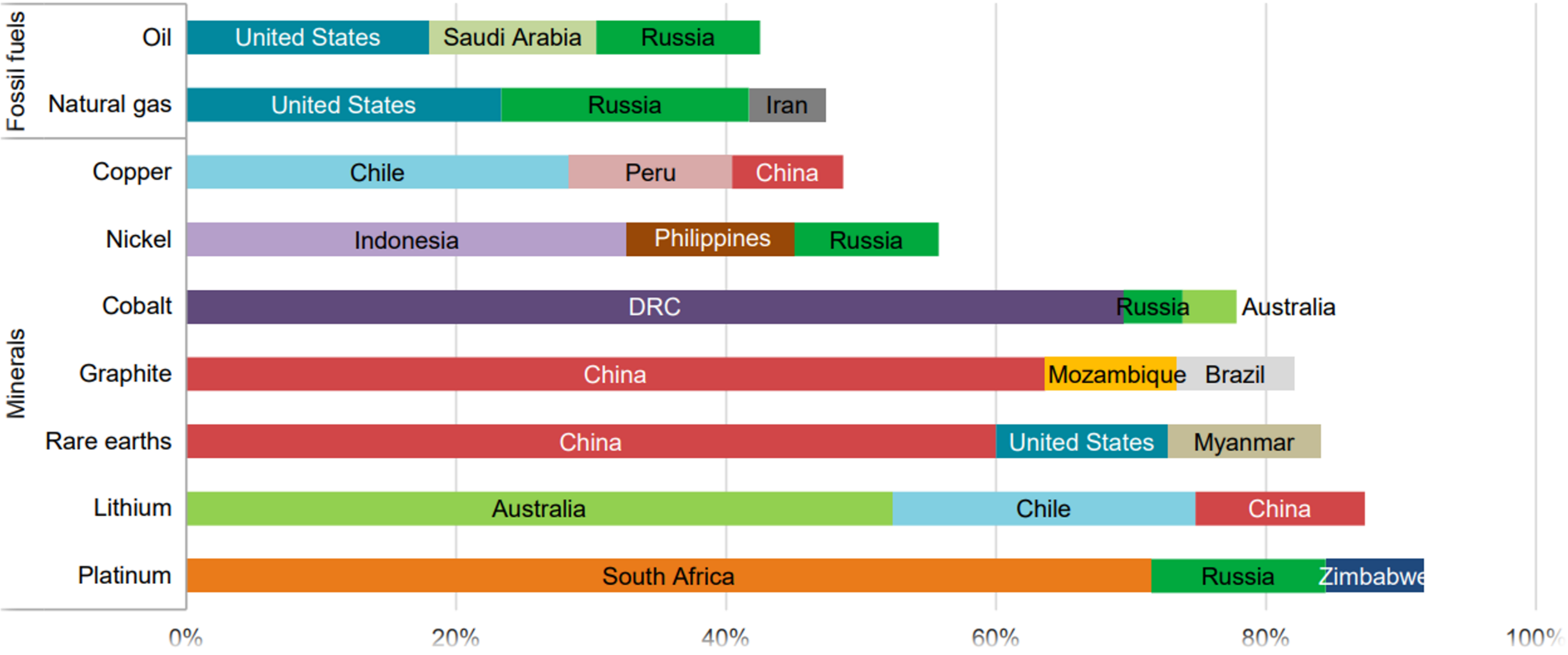
Supply & processing chains

Share of top three producing countries in total production for selected minerals and fossil fuels, 2019



Source: International Energy Agency - The role of critical minerals in clean energy transitions (2020)

- More geographically concentrated reserves of materials!

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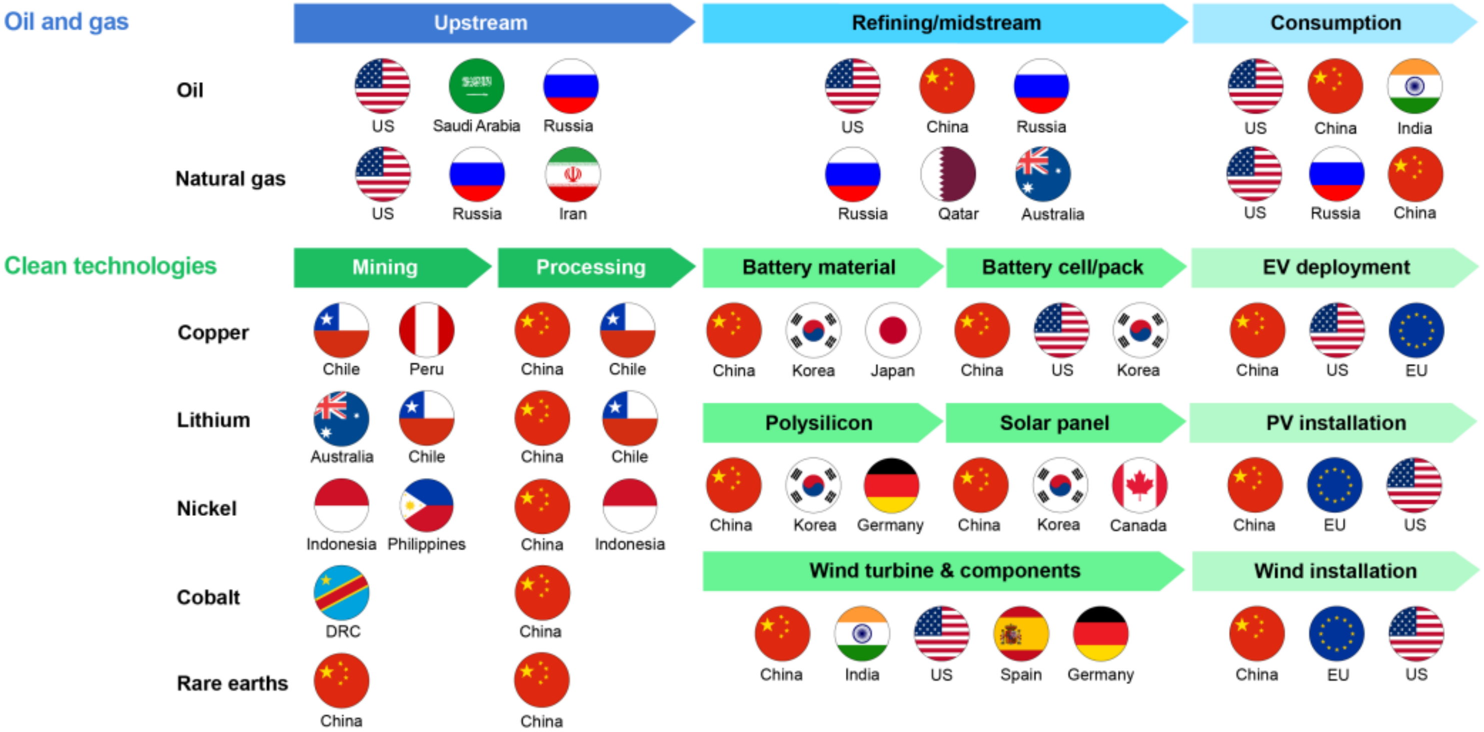
Supply & transformation chains

- **Less** diversified chains - China is a key player for rare earths and manufacturing!



Source: International Energy Agency - The role of critical minerals in clean energy transitions (2020)

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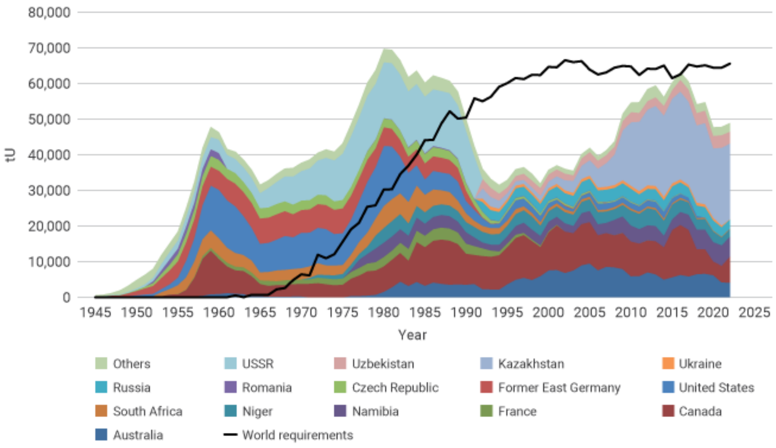
Supply & transformation chains

- Similar situation for conventional **nuclear fuels**
- Major uranium-producing countries: Kazakhstan, Canada and Australia
- Major enrichment countries: Russia (Rosatom), France/Germany/USA (Orano & Urenco), China
- Thorium: development in India?



Source: OECD-NEA, IAEA, World Nuclear Association

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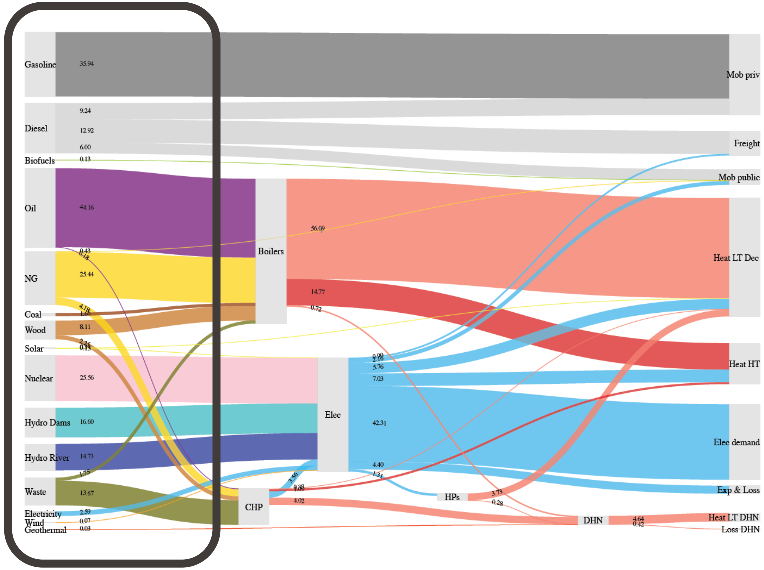
The ”cost” challenge



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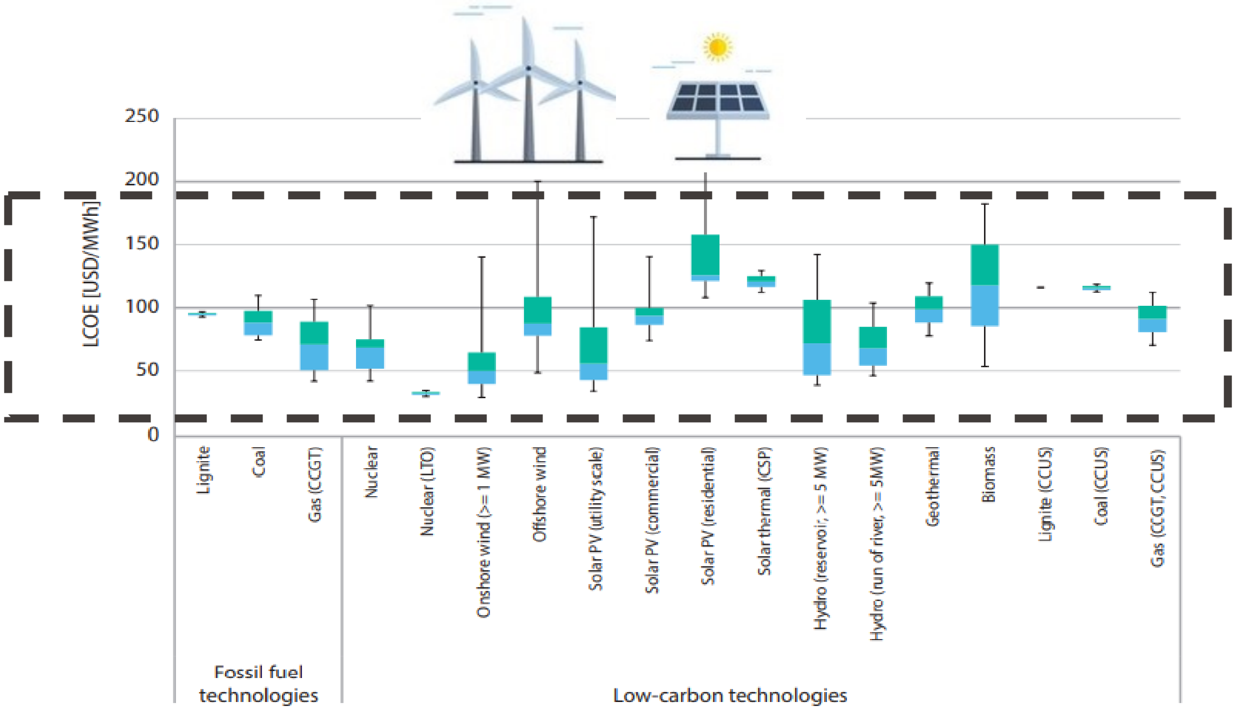
Costs of low-carbon technologies (LCOE)

- Cost of electricity generation (Levelised Cost of Electricity)



Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

Source: International Energy Agency - Projected Costs of Generating Electricity (2020)

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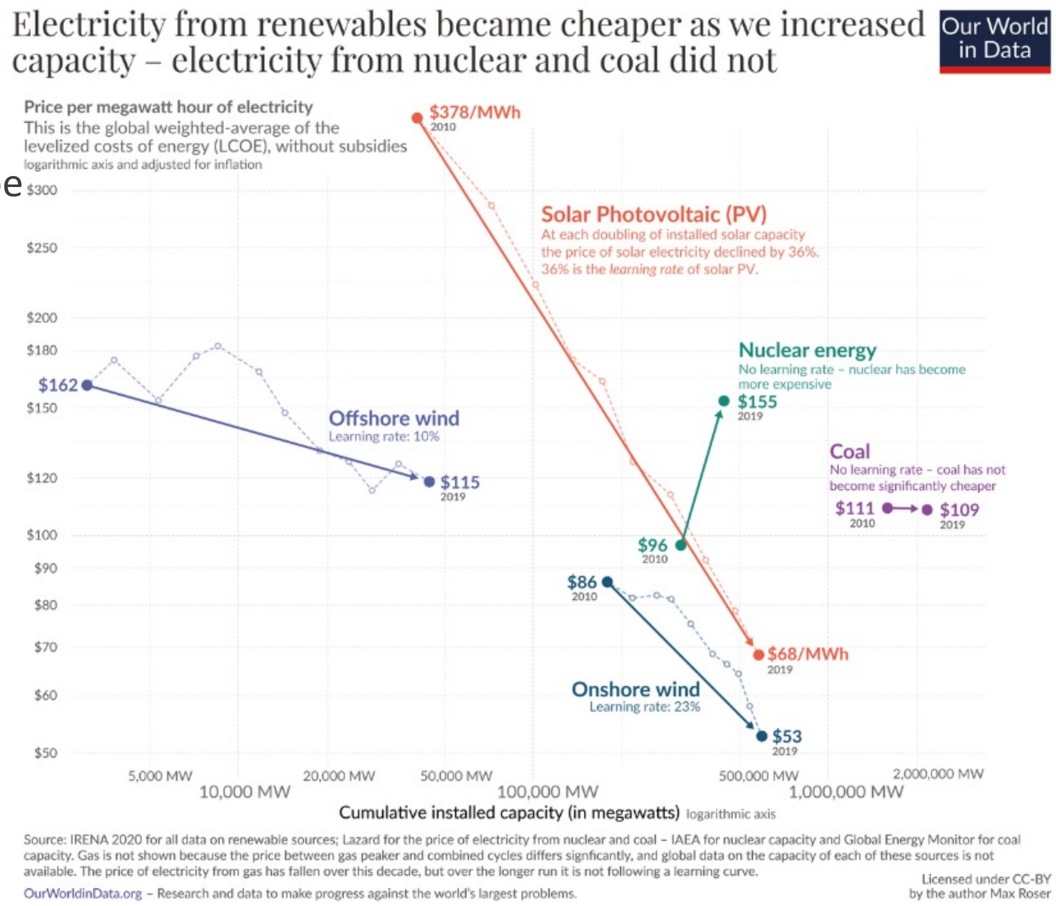
Costs of low-carbon technologies (LCOE)

- These costs depend on the installed capacity and the type of energy.
- Some renewable energies have only recently become competitive!



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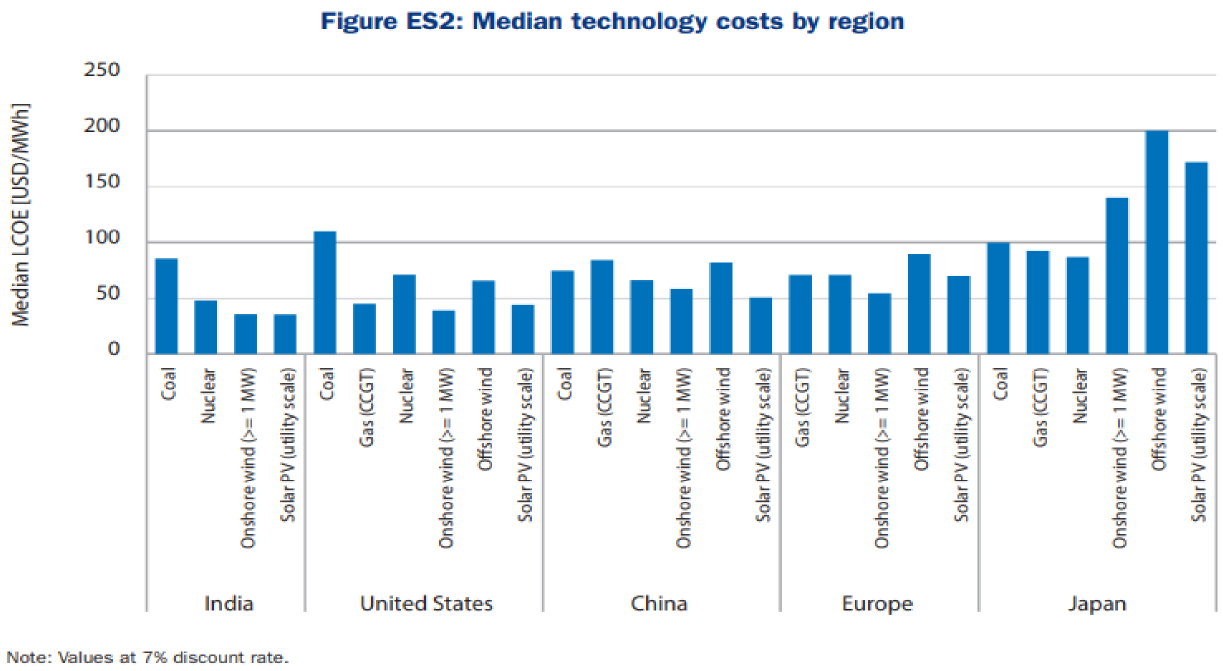
Costs of low-carbon technologies (LCOE)

- In 2020, renewables were **competitive** in Europe, but not in Japan!
- Example: median cost of producing electricity in India, USA, China and Europe



Source: International Energy Agency - Projected Costs of Generating Electricity (2020)

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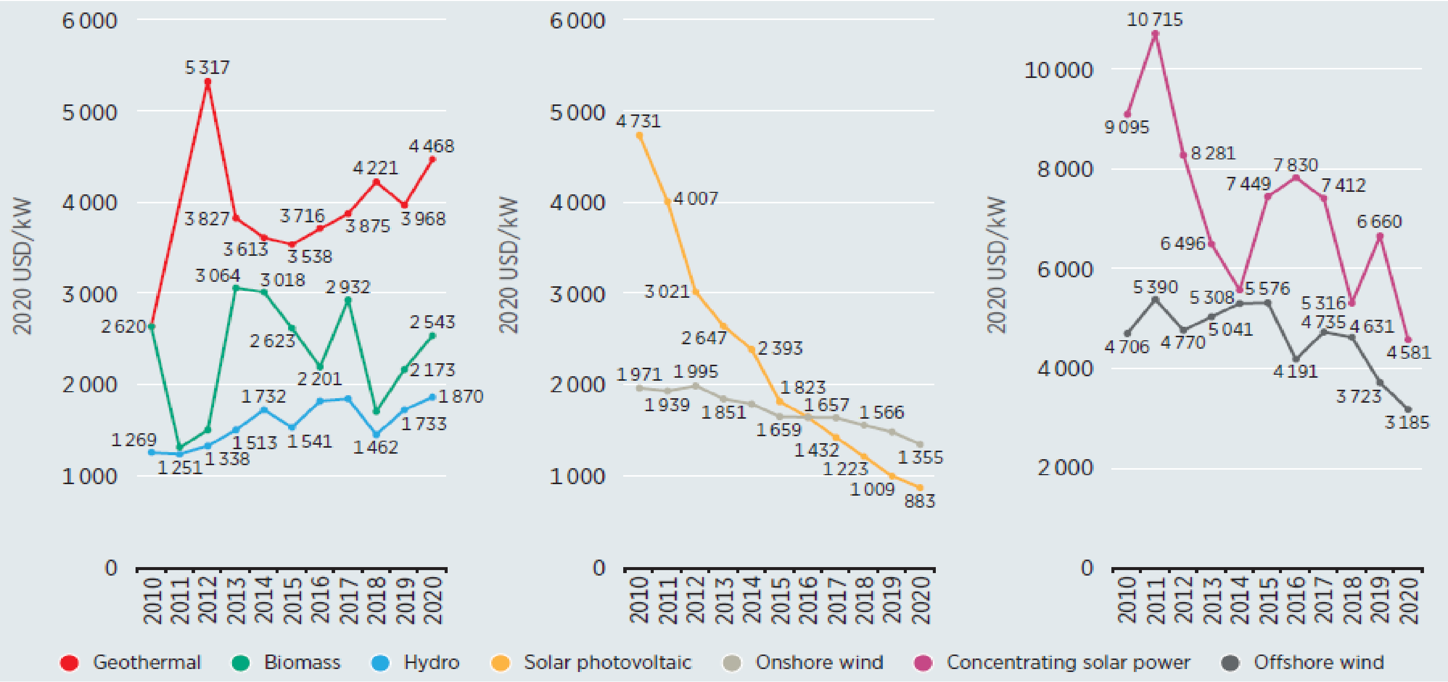
Costs of low-carbon technologies (investment)

- **Investment costs : PV, hydro and onshore wind** least expensive to invest in



Source: IRENA - Renewable Power Generation Costs in 2020

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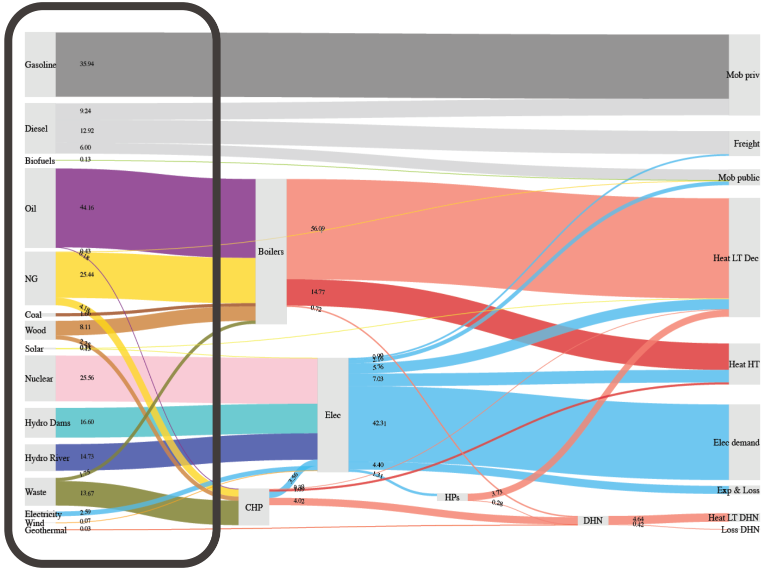
The "energy and power density" challenge



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If Swizerland was to satisfy all its energy needs with only solar energy, how much surface would be required?

A. 10-20% of the Swiss total area
B. 40-60%
C. 80-100%
D. More than 100% (energy needs to be imported!)

Renewables require large areas

bioethanol ~ **(0.05→0.15)** W/m^2
wind ~ **(2→10)** W/m^2
hydro ~(10→15) W/m^2
solar ~ (5→20) W/m^2

Solucar Solar Complex
Sanlúcar la Mayor, Spain
5x50MW

barrage hydro
Tarbela, Pakistan
250km^2, ~3.5GW

Foote Creek Wind Farm
Wyoming (USA)
41MW

Eggebek Solar Park
Allemagne
83MW

A corn field in
Switzerland

A Swiss citizen would need…

Average power use of a Swiss citizen = 3.2 kW/p

$$\frac{\text{Swiss area} = 41'285\ \text{km}^2}{\text{Swiss population} \sim 8'400'000\ \text{p}}$$

➔ **Area per capita ~ 4’915 m²/p**

➔ *(1 rugby field ~ 8’400 m²)*

A Swiss citizen would need…

Average power use of a Swiss citizen = 3.2 kW/p

$$\frac{\text{bioethanol } 3.2\text{kW/p}}{0.5\text{W/m}^2} = 6'400 \text{ m}^2\text{/p}$$

$$\frac{\text{Swiss area} = 41'285 \text{ km}^2}{\text{Swiss population} \sim 8'400'000 \text{ p}}$$

➔ **Area per capita ~ 4'915 m²/p**

➔ *(1 rugby field ~ 8'400 m²)*

A Swiss citizen would need…

Average power use of a Swiss citizen = 3.2 kW/p

windmills
3.2kW/p
$2.2W/m^2$
=
$\sim 1'455 m^2/p$

Swiss area = $41'285 \text{ km}^2$

Swiss population ~ 8'400'000 p

→ **Area per capita ~ $4'915 \text{ m}^2/p$**
→ *(1 rugby field ~ $8'400 \text{ m}^2$)*

A Swiss citizen would need…

Average power use of a Swiss citizen = 3.2 kW/p

Solar PV

$$\frac{3.2\text{kW/p}}{5\text{W/m}^2} = 640\ \text{m}^2\text{/p}$$

$$\frac{\text{Swiss area} = 41'285\ \text{km}^2}{\text{Swiss population} \sim 8'400'000\ \text{p}}$$

➔ **Area per capita ~ 4'915 m^2/p**

➔ *(1 rugby field ~ 8'400 m^2)*

A Swiss citizen would need…

Average power use of a Swiss citizen = 3.2 kW/p

bioethanol	windmills	Solar PV	Concentrated solar
$\frac{3.2kW/p}{0.5W/m^2}$	$\frac{3.2kW/p}{2.2W/m^2}$	$\frac{3.2kW/p}{5W/m^2}$	$\frac{3.2kW/p}{20W/m^2}$
=	=	=	=
6'400 m^2/p	~1'455 m^2/p	640 m^2/p	160 m^2/p

$$\frac{\text{Swiss area} = 41'285\ km^2}{\text{Swiss population} \sim 8'400'000\ p}$$

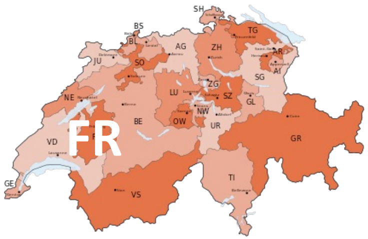
➔ **Area per capita ~ 4'915 m^2/p**

➔ *(1 rugby field ~ 8'400 m^2)*

A Swiss citizen would need…

Average power use of a Swiss citizen = 3.2 kW/p

bioethanol	windmills	Solar PV	Concentrated solar
$\frac{3.2kW/p}{0.5W/m^2}$	$\frac{3.2kW/p}{2.2W/m^2}$	$\frac{3.2kW/p}{5W/m^2}$	$\frac{3.2kW/p}{20W/m^2}$
=	=	=	=
$\frac{6400m^2/p}{4915m^2}$	$\frac{\sim 1455m^2/p}{4915m^2}$	$\frac{640m^2/p}{4915m^2}$	$\frac{160m^2/p}{4915m^2}$
=	=	=	=
~1.3×CH	**~0.30×CH**	**~0.13×CH**	**~0.033CH**



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GROUP QUESTION (2 ppl., 5-10 mins)

Switzerland has an installed capacity of 300 MW (electric) of natural gas plants, producing at full load only 27% of the time (8’760 hours). 1 kWh of electricity from natural gas ⇔ 420 g CO_2/kWh.

- How many MW of PV panels are required to replace them (capacity factor of 15%) ?
- How much surface (solar – 5 W/m²) is needed ?
- How much CO_2 is saved per year ? 1 kWh of electricity from solar PV ⇔ 18 g CO_2/kWh.

https://app.wooclap.com/ME409/questionnaires/66f11364f18a641fcd19053d

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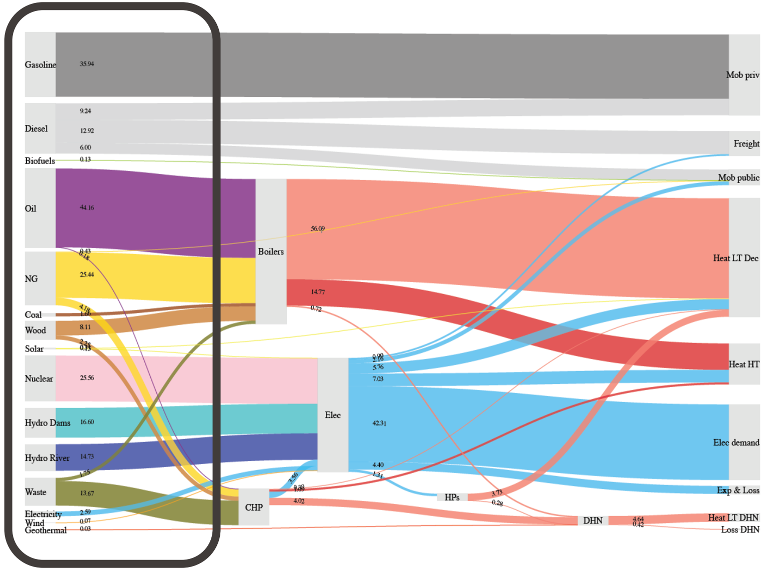

The "efficiency" challenge

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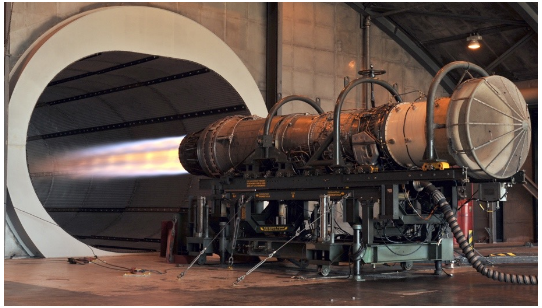
Energy conversion

- The concept of **energy efficiency** : what you want / what you consume
- Example of a **power plant** :
  - What we want = power, electricity
  - What we consume = nuclear fuel, coal, natural gas
- Example of a **heating system** :
  - What we want = heat
  - What we consume = wood, gas, oil



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Which of the following electricity production technologies present the highest energy efficiency?

A. Gas-fired plants
B. Solar photovoltaics
C. Hydroelectric dams
D. Nuclear power plants

Energy conversion

- **Thermodynamics**
  = **transformations of energy**

- **Industrial revolution : empirical** foundations + observations

- **Four** main principles
  - Can energy be **created from nothing**?
  - Do all forms of energy have the same “value” ? How much electricity can we produce at best?

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Energy system: efficiencies

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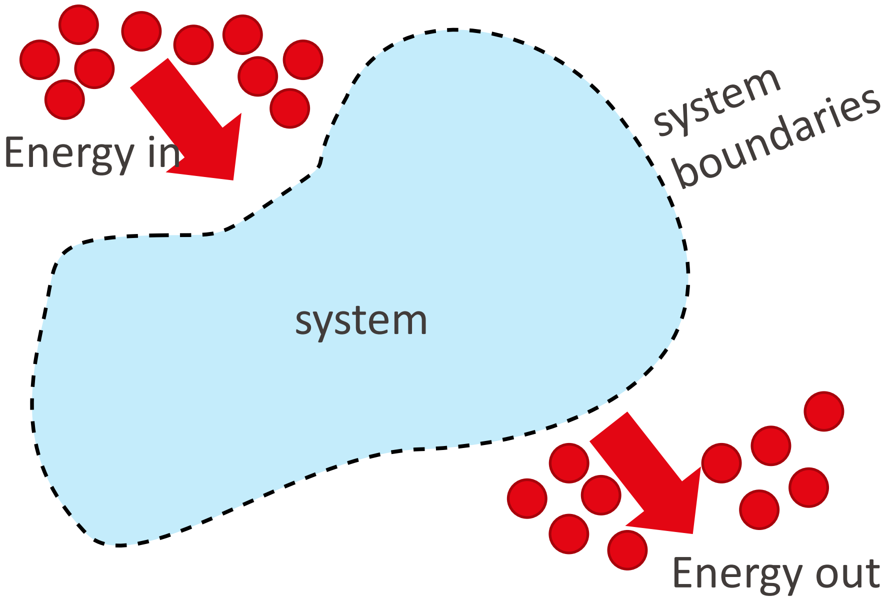
First principle
– Energy conservation

- *Applying thermodynamics to energy systems…*
- *You can't win. Energy is **conserved**, neither created nor destroyed.*



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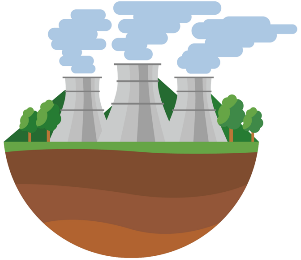
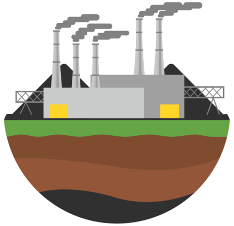
First principle
– Energy for heat and mechanical engines



NUCLEAR

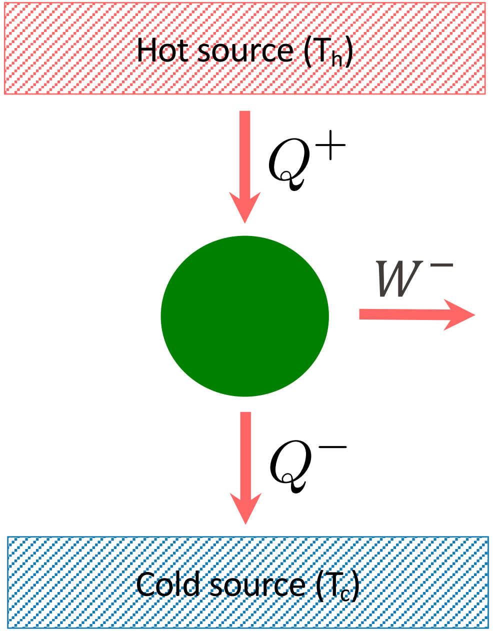
$$\eta_I = \frac{W^-}{Q^+} = \frac{\text{Power output}}{\text{Nuclear fuel energy}}$$

$$\eta_I = \frac{W^-}{W^+} = \frac{\text{Power output}}{\text{Wind kinetic energy}}$$



COAL

$$\eta_I = \frac{W^-}{Q^+} = \frac{\text{Power output}}{\text{Coal chemical energy}}$$



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Examples :
The Mühleberg nuclear power plant, the Bouchain gas power plant

Nominal **thermal output** of reactor: 1097 MW(th)
Gross electrical output: 372 MW(e)
Auxiliary electrical consumption (pumps, etc.): 17 MW(e)
Required area (infrastructure, mining, plant): 1.55 km^2

$$\eta_I = \frac{W^-}{Q^+} = \frac{\text{Net power output}}{\text{Nuclear fuel energy}}$$

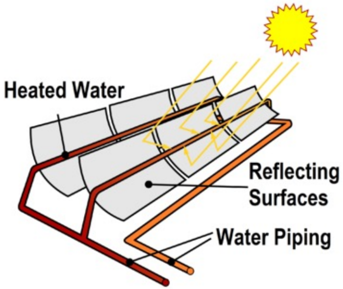
Nominal **thermal output** of reactor: 1140 MW(th)
Net electrical output: 701 MW(e)
Required area (infrastructure, mining, plant): 1.46 km^2

$$\eta_I = \frac{W^-}{Q^+} = \frac{\text{Net power output}}{\text{Gas consumption}}$$

First principle

– First-law efficiency for heat production technologies

$$\eta_I = \frac{Q^-}{W^+} = \frac{\text{Heat output}}{\text{Electricity input}}$$



$$\eta_I = \frac{Q^-}{Q^+} = \frac{\text{Heat output}}{\text{Solar radiation}}$$

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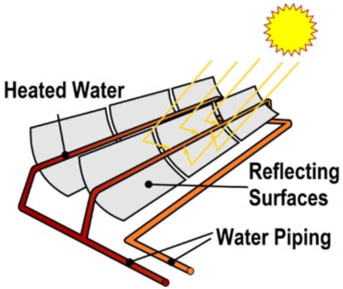
Examples : Electric heaters and solar collectors

For a basic electric heater with a footprint area

Nominal thermal output: 12 kW (th)

Nominal electricity consumption: 13 kW

- $\eta_I = \frac{Q^-}{W^+} = \frac{\text{Heat output}}{\text{Electricity input}}$



For a solar thermal collector with a footprint area of 20 m²

Nominal heat output: 14 kW (th)

Solar radiation : 20 kW

- $\eta_I = \frac{Q^-}{Q^+} = \frac{\text{Heat output}}{\text{Solar radiation}}$

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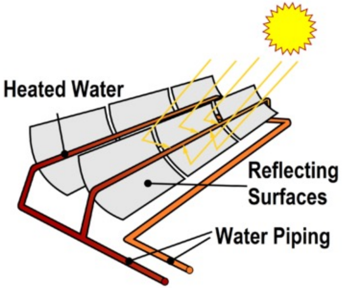
GROUP QUESTION (2 ppl., 5-10 mins)

Determine, for the 4 examples given before, their **energy efficiencies (%) AND power densities (W/m²)**.

Please answer at this link:

https://app.wooclap.com/ME409/questionnaires/66f11364f18a641fcd19053d



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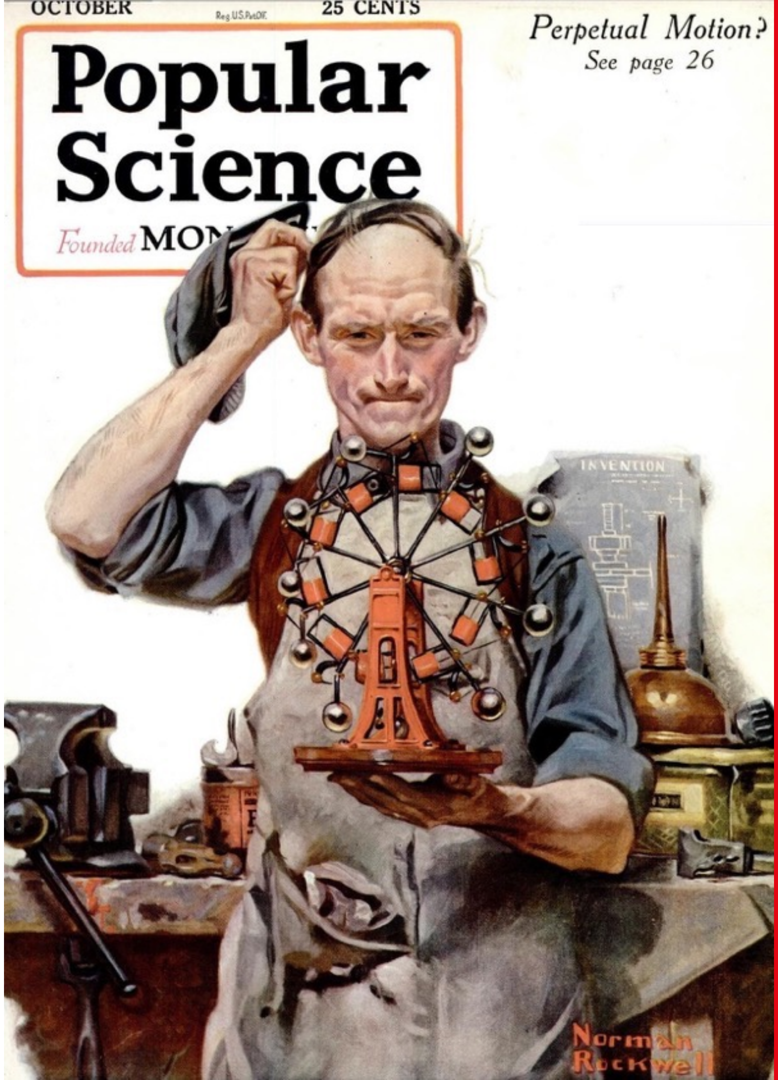

Second principle

Can we produce as much work as we get heat?

How valuable is heat compared to electricity?

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Comparison of energy efficiencies

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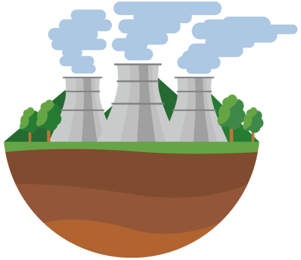
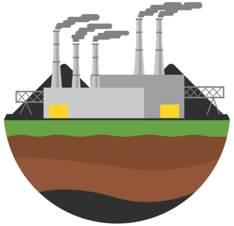


$$\eta_I = \frac{W^-}{Q^+} = \frac{\text{Power output}}{\text{Nuclear fuel energy}} \approx 30\text{-}35\%$$

$$\eta_I = \frac{W^-}{Q^+} = \frac{\text{Power output}}{\text{Gas chemical energy}} \approx 35\text{-}60\%$$



$$\eta_I = \frac{W^-}{Q^+} = \frac{\text{Power output}}{\text{Coal chemical energy}} \approx 35\text{-}40\%$$

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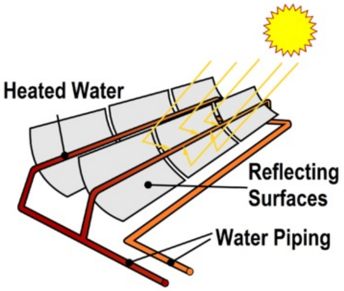
Comparison of energy efficiencies



$$\eta_I = \frac{Q^-}{Q^+} = \frac{\text{Heat output}}{\text{Solar radiation}} \approx 70\text{-}80\%$$

$$\eta_I = \frac{W^-}{W^+} = \frac{\text{Power output}}{\text{Water potential and kinetic energy}} \approx 80\text{-}90\%$$

$$\eta_I = \frac{W^-}{W^+} = \frac{\text{Power output}}{\text{Wind kinetic energy}} \approx 20\text{-}40\%$$

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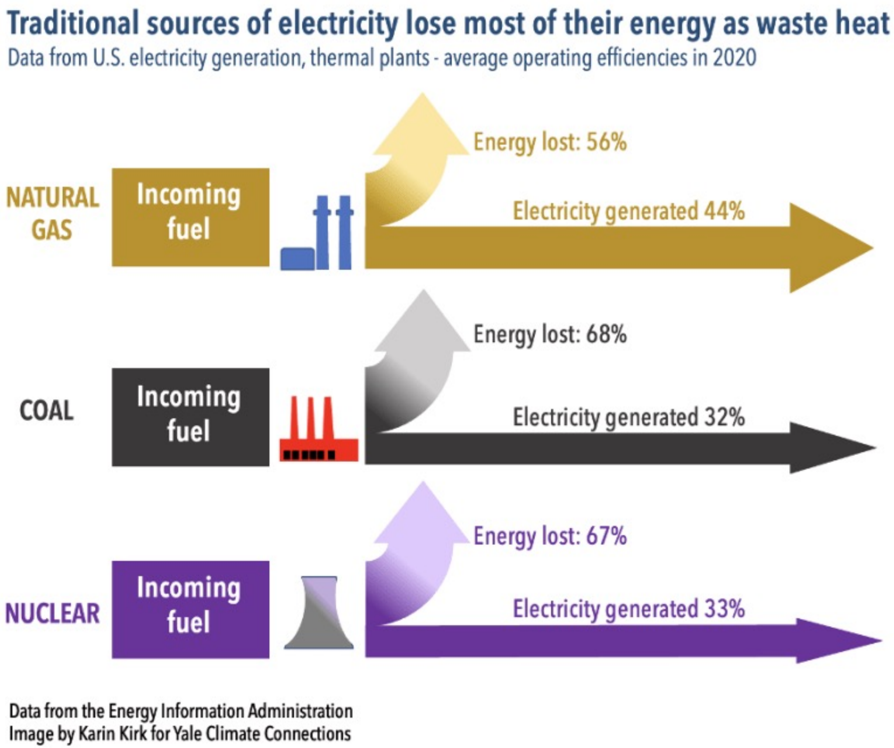
Comparison of energy efficiencies

- Difficult to compare **different energy conversion plants**
- **Heat-to-electricity devices** have lower energy efficiencies

- How can these efficiencies be improved?
- How can we best compare energy conversion plants?



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Second principle
– An explanation for these differences

- **Impossible** to get as much power **out** as heat **in** from a given power plant
- Entropy generation ⇔ 100% efficiency is not achievable
- So… what is the maximum reachable efficiency?

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Second principle
– Carnot efficiency θ

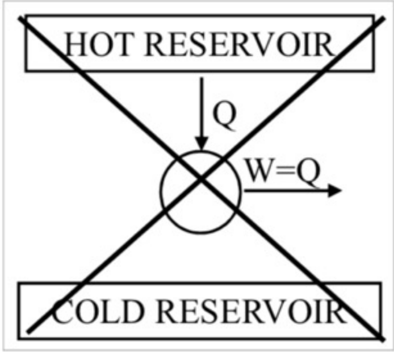
- Not all heat can be converted into electricity (heat has a lower «value»)
- On the contrary, all electricity can be converted into heat (high «value»)
- The limit is Carnot.

Ambient temperature (Kelvin)

- $\theta = (1 - \frac{T_0}{T_Q})$

Heat transfer temperature (Kelvin)

Carnot factor = ”maximum theoretical efficiency”



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Second principle
– Carnot efficiency θ

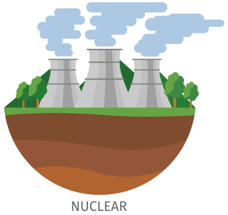
- $\theta = \left(1 - \frac{T_0}{T_Q}\right)$

High T_Q
= high value of heat

- $\theta = \left(1 - \frac{15 + 273.15}{300 + 273.15}\right)$

T = 300°C

Uranium: 100 MJ



Electricity: 35 MJ

T = 15°C

Heat to the river: 65 MJ

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Second principle
– The concept of eXergy

Exergy – the ”useful work potential” = *how much electrical or mechanical work can be produced from a given energy source in ideal conditions?*

- For mechanical and electrical flows : exergy = energy = **W**
- For fuels : exergy ≈ higher heating value (**HHV**)
- For heat : exergy = energy × Carnot factor $(1 - \frac{T_0}{T_Q})$ = $\mathbf{Q}\times\boldsymbol{\theta}$

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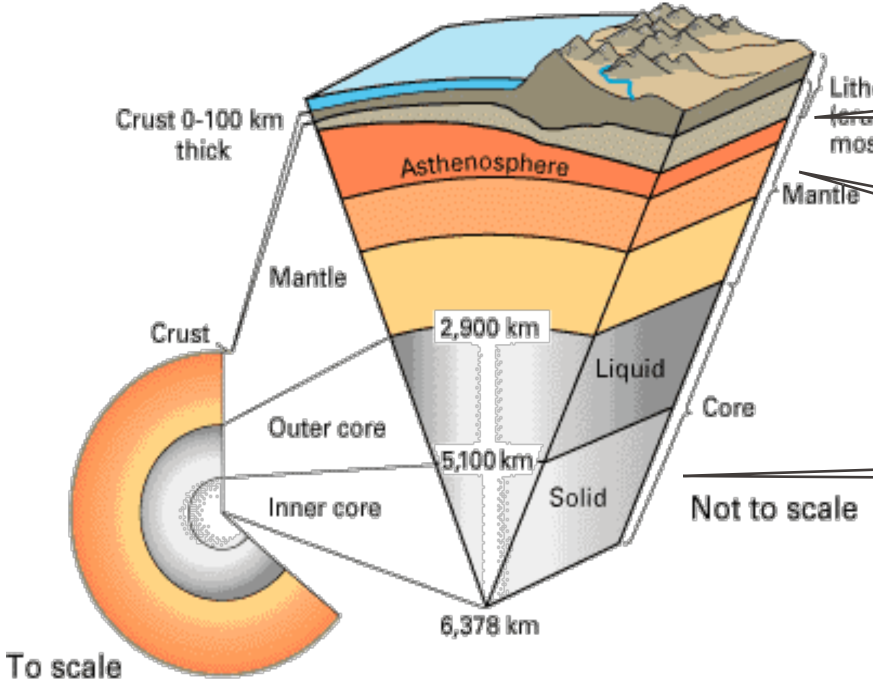
Second principle
– The concept of eXergy

Exergy – **an indication of the value of different energy forms**

For heat : exergy = energy × Carnot factor $(1 - \frac{T_0}{T_Q})$ = $\mathbf{Q \times \theta}$



3 km

$\theta = 1 - \frac{298}{423} = 30\%$

10 km

$\theta = 48\%$

$\theta = 96\%$

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Second principle
– Second-law efficiency η_{II}

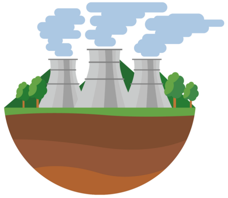
- Second-law efficiency η_{II}

$$\eta_{II} = \frac{\text{what you get}}{\text{what you would get in the } \textbf{ideal} \text{ case}}$$

- High second-law efficiencies = *small margin of improvement*

100 MJ

Uranium



35 MJ

Electricity

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Second principle

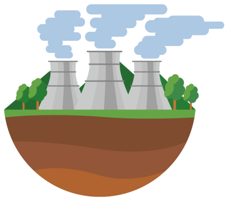
– Second-law efficiency – examples η_{II}

- Second-law efficiency for heat engines η_{II}

$$\eta_{II} = \frac{W^-}{Q^+\theta}$$

"Value of heat" = **Carnot factor**

What you pay = **fuel energy**



- Second-law efficiency for heat production from electricity η_{II}

$$\eta_{II} = \frac{Q^-\theta}{W^+}$$

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Example 1 : the Mühleberg nuclear power plant

For a power plant producing only **electricity**
Nominal **thermal output** of reactor: 1097 MW(th)
Gross electrical output: 372 MW(e)
Auxiliary electrical consumption (pumps, etc.): 17 MW(e)
Reactor temperature : 300°C
River temperature : 11°C

$$\boldsymbol{\theta} = \left(1 - \frac{T_0}{T_Q}\right)$$

$$\eta_{II} = \frac{W^-}{\boldsymbol{Q^+\theta}}$$

GROUP QUESTION (2 ppl., 5-10 mins)

Determine, for the 2 examples given before (gas power plant and electric heater), their maximum (Carnot) **AND second-law efficiencies**.

Please answer at this link:

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Example 2 : The Bouchain gas power plant (FR)

Nominal **thermal output** of reactor: 1140 MW(th)
Net electrical output: 701 MW(e)
Gas combustion temperature : 1590°C
Ambient temperature : 15°C

$$\eta_I = \frac{W^-}{\boldsymbol{Q^+}} = \frac{\text{Power output}}{\text{Gas consumption}}$$

$$\boldsymbol{\theta} = \left(1 - \frac{T_0}{T_Q}\right)$$

$$\eta_{II} = \frac{W^-}{\boldsymbol{Q^+\theta}}$$

Example 3 : A basic electrical heater

For a heat production technology

- Nominal thermal output: 12 kW (th)
- Nominal electricity consumption: 13 kW
- Heater temperature : 45°C
- Ambient temperature : 15°C

$$\boldsymbol{\theta} = \left(1 - \frac{T_0}{T_Q}\right)$$

$$\eta_{II} = \frac{\boldsymbol{Q^-\theta}}{\boldsymbol{W^+}}$$

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Production

Conversion

Delivery

Use

Conclusion

Take-home message

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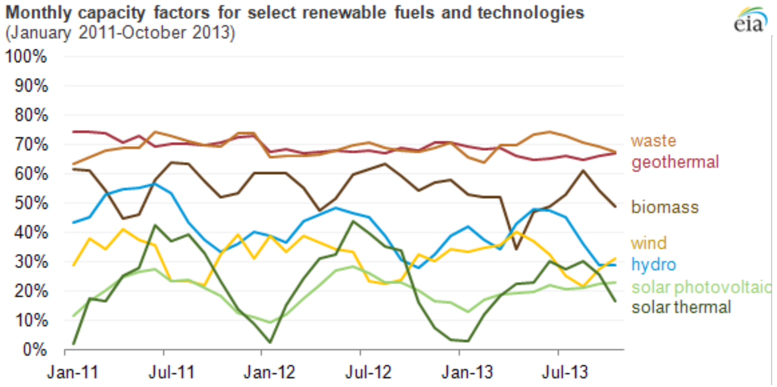
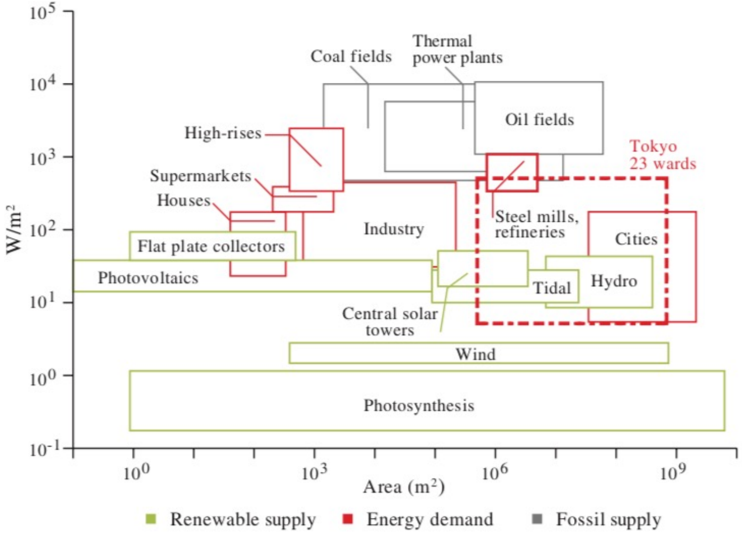
Take-home message

- **First-law efficiency** : simple and widely used energy metric.
- **Carnot factor :** measure of the maximum efficiency that can be reached, or value of heat
- **Second-law efficiency :** how ideal is my system? Can it be improved?





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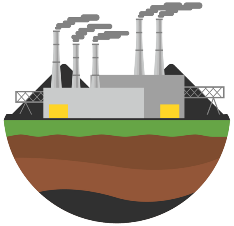
Important formulas



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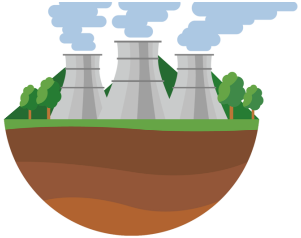

NUCLEAR

BIOMASS

Calculate :

- First-law efficiency η_I
- Carnot factor $\boldsymbol{\theta}$
- Second-law efficiency η_{II}

$$\eta_I = \frac{W^-}{\boldsymbol{Q}^+}$$

$$\boldsymbol{\theta} = \left(1 - \frac{T_0}{T_Q}\right)$$

$$\eta_{II} = \frac{W^-}{\boldsymbol{Q}^+\boldsymbol{\theta}}$$

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Questions?

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