For a clever use of energy: Exergy

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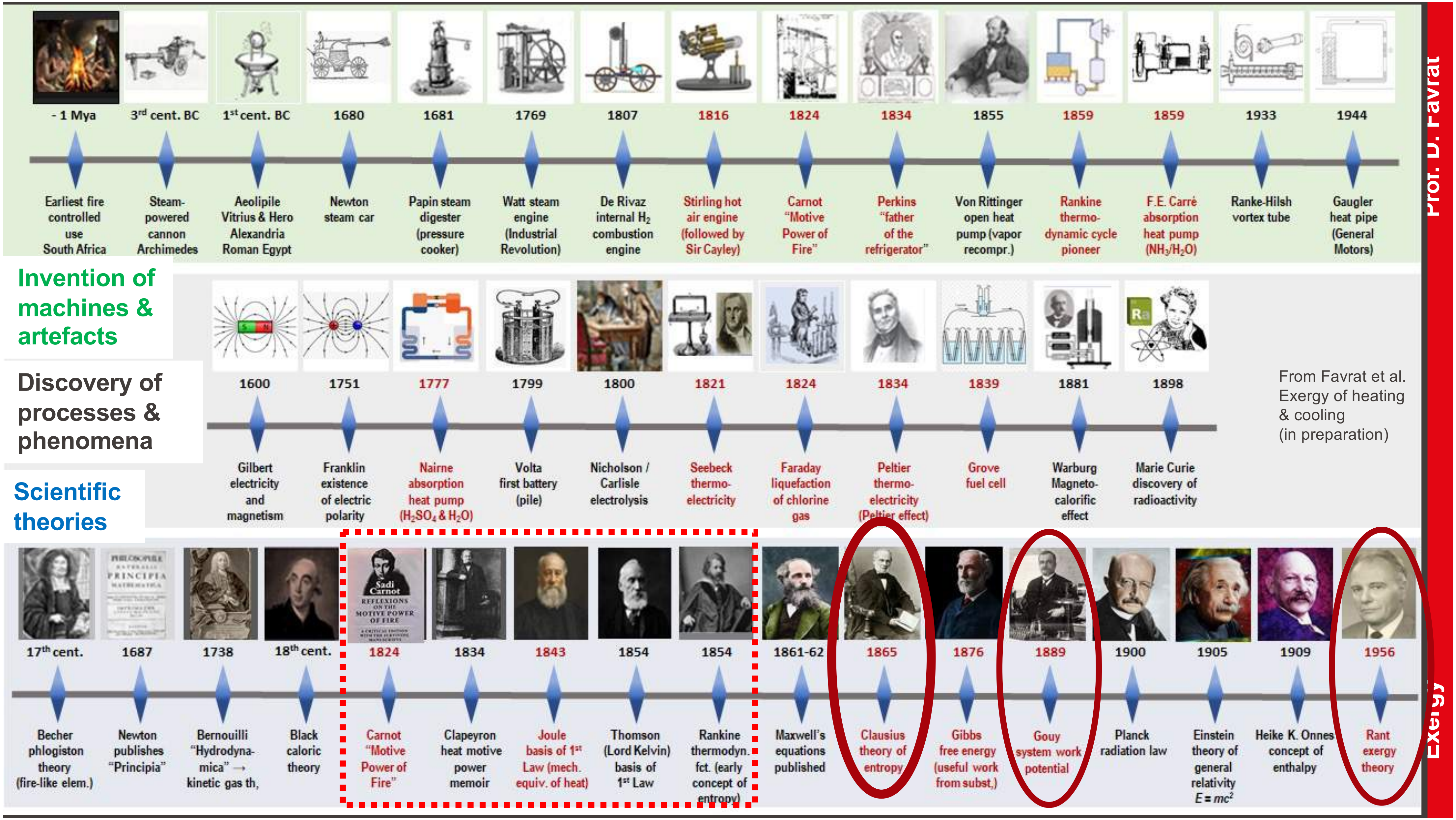
A brief historical view



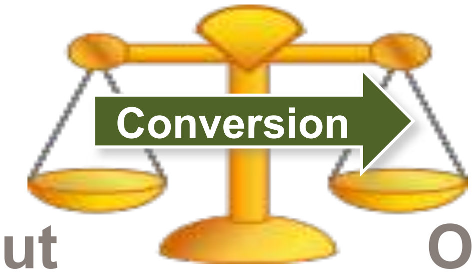
Invention of machines & artefacts
- 1 Mya
Earliest fire controlled use South Africa
3rd cent. BC
Steam-powered cannon Archimedes
1st cent. BC
Aeolipile Vitrius & Hero Alexandria Roman Egypt
1680
Newton steam car
1681
Papin steam digester (pressure cooker)
1769
Watt steam engine (Industrial Revolution)
1807
De Rivaz internal H_2 combustion engine
1816
Stirling hot air engine (followed by Sir Cayley)
1824
Carnot "Motive Power of Fire"
1834
Perkins "father of the refrigerator"
1855
Von Rittinger open heat pump (vapor recompr.)
1859
Rankine thermo-dynamic cycle pioneer
1859
F.E. Carré absorption heat pump (NH_3/H_2O)
1933
Ranke-Hilsh vortex tube
1944
Gaugler heat pipe (General Motors)
Discovery of processes & phenomena
1600
Gilbert electricity and magnetism
1751
Franklin existence of electric polarity
1777
Nairne absorption heat pump (H_2SO_4 & H_2O)
1799
Volta first battery (pile)
1800
Nicholson / Carlisle electrolysis
1821
Seebeck thermo-electricity
1824
Faraday liquefaction of chlorine gas
1834
Peltier thermo-electricity (Peltier effect)
1839
Grove fuel cell
1881
Warburg Magneto-calorific effect
1898
Marie Curie discovery of radioactivity
From Favrat et al. Exergy of heating & cooling (in preparation)
Scientific theories
17th cent.
Becher phlogiston theory (fire-like elem.)
1687
Newton publishes "Principia"
1738
Bernouilli "Hydrodyna-mica" → kinetic gas th,
18th cent.
Black caloric theory
1824
Carnot "Motive Power of Fire"
Sadi Carnot
REFLEXIONS ON THE MOTIVE POWER OF FIRE
1834
Clapeyron heat motive power memoir
1843
Joule basis of 1st Law (mech. equiv. of heat)
1854
Thomson (Lord Kelvin) basis of 1st Law
1854
Rankine thermodyn. fct. (early concept of entropy)
1861-62
Maxwell's equations published
1865
Clausius theory of entropy
1876
Gibbs free energy (useful work from subst.)
1889
Gouy system work potential
1900
Planck radiation law
1905
Einstein theory of general relativity $E = mc^2$
1909
Heike K. Onnes concept of enthalpy
1956
Rant exergy theory
Prof. D. Favrat
Exergy

"Die Energie der Welt ist konstant und die Entropie der Welt strebt einem maximum zu "

"The energy of the world is constant and the entropy of the World tends towards a maximum"

Rudolf Emmanuel Clausius (1822-1888)

In other words:
Energy can only be converted from one form into another
Like the mass it is conserved
While the entropy is increasing

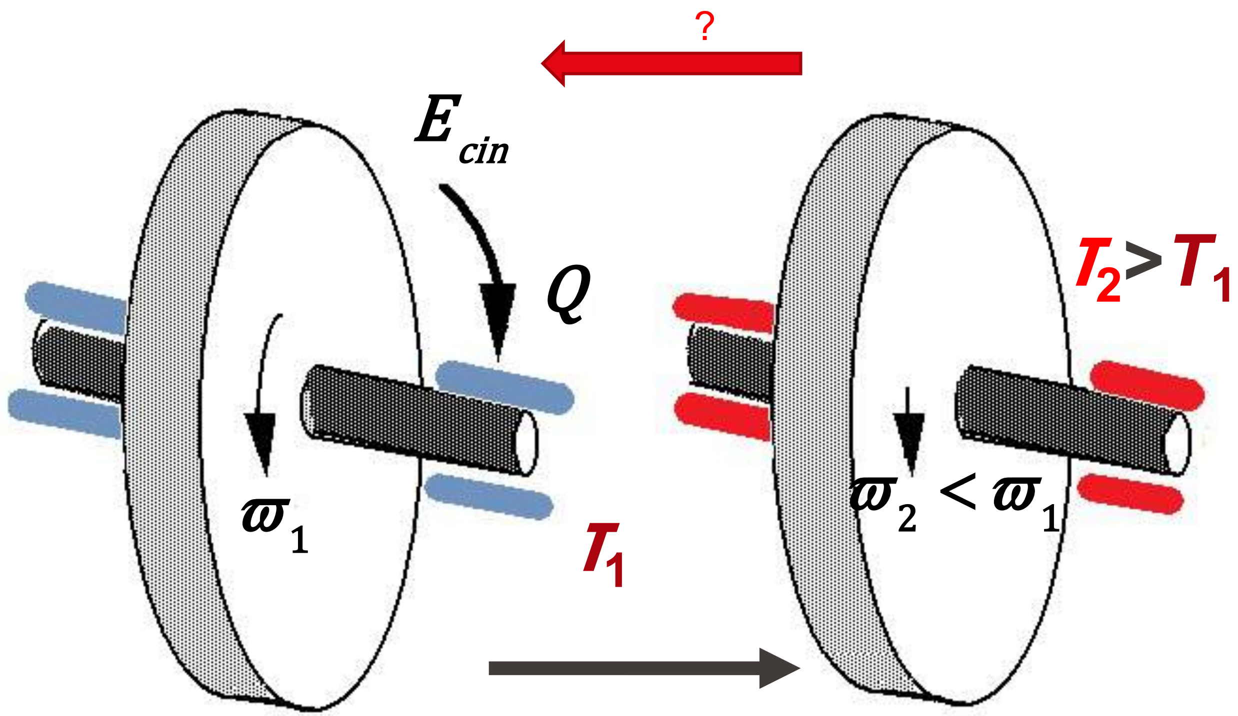


Input (mass / energy) **Output (mass / energy)**

- There is a confusion about the meaning of «energy»: Greek word "ενεργεια (containing work)

In fact the work part of energy is **exergy**

The arrow of time



The wheel slows down and stop
There is no way that it will reaccelerate without an input of work (exergy)

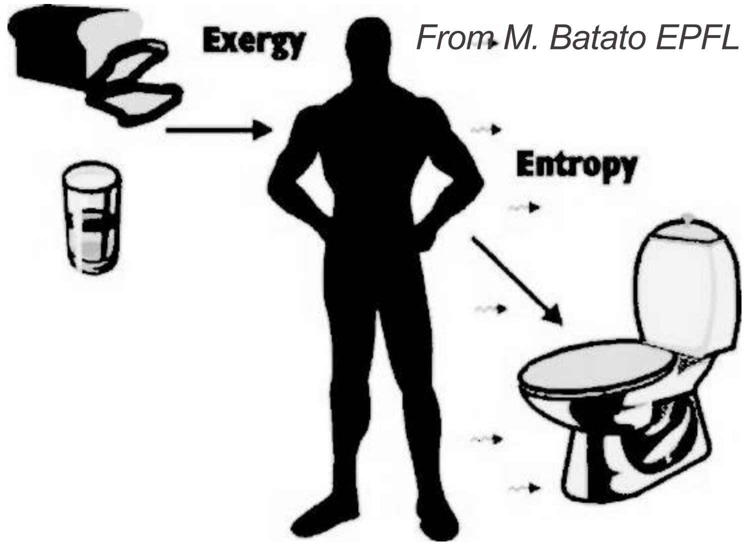
There is a degradation of mechanical energy into heat with creation of entropy

Most systems are open systems like…

us

we are all marvelous trigeneration energy systems

From M. Batato EPFL thesis, 1988

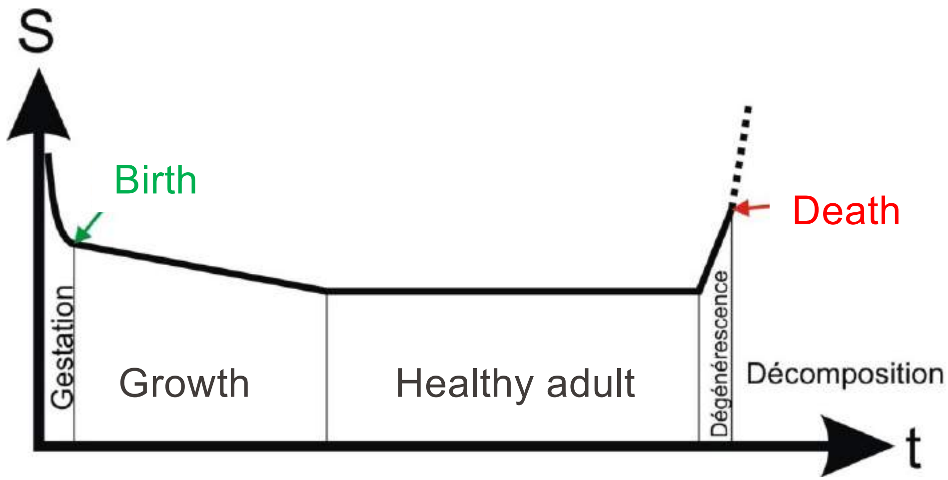


But we are not perfect !!

We generate entropy (disorder)

Did your entropy increase last year?

Was there anytime in your life that your entropy decreased ?



To keep our entropy constant, we all need a bin for entropy

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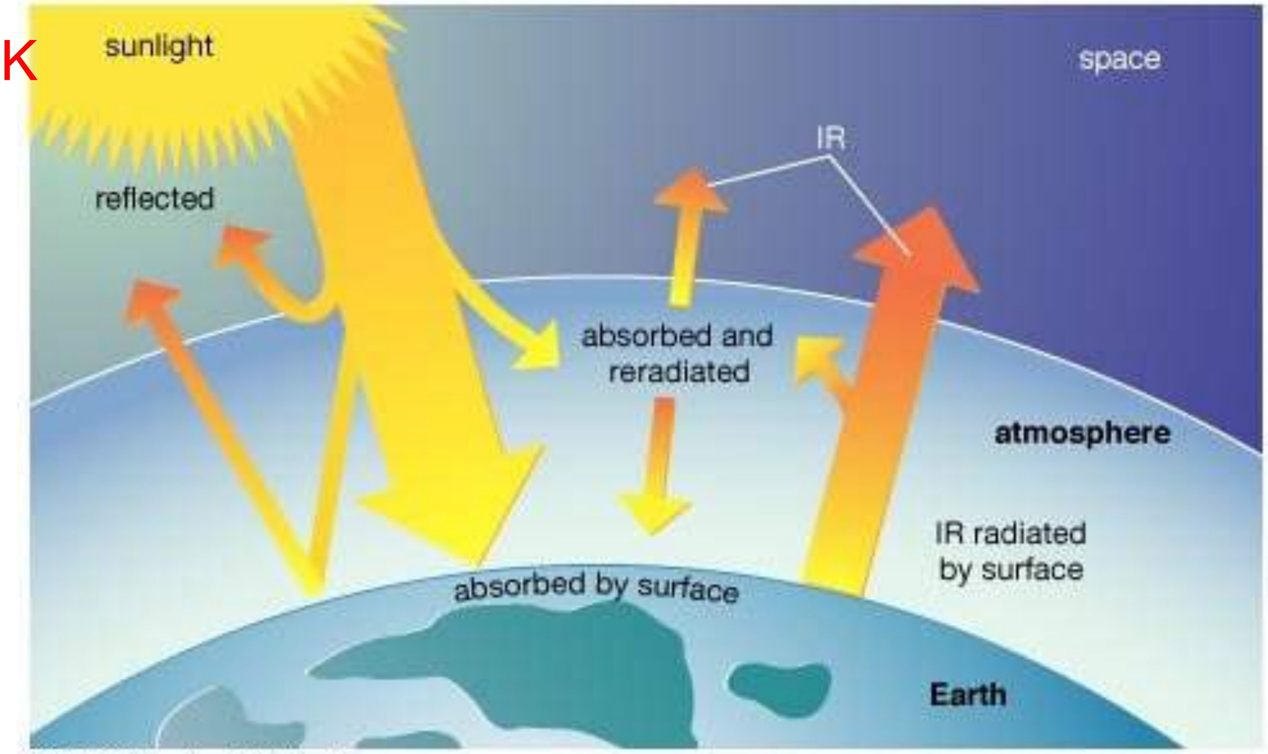
This also true for the Earth

5700 K



4K

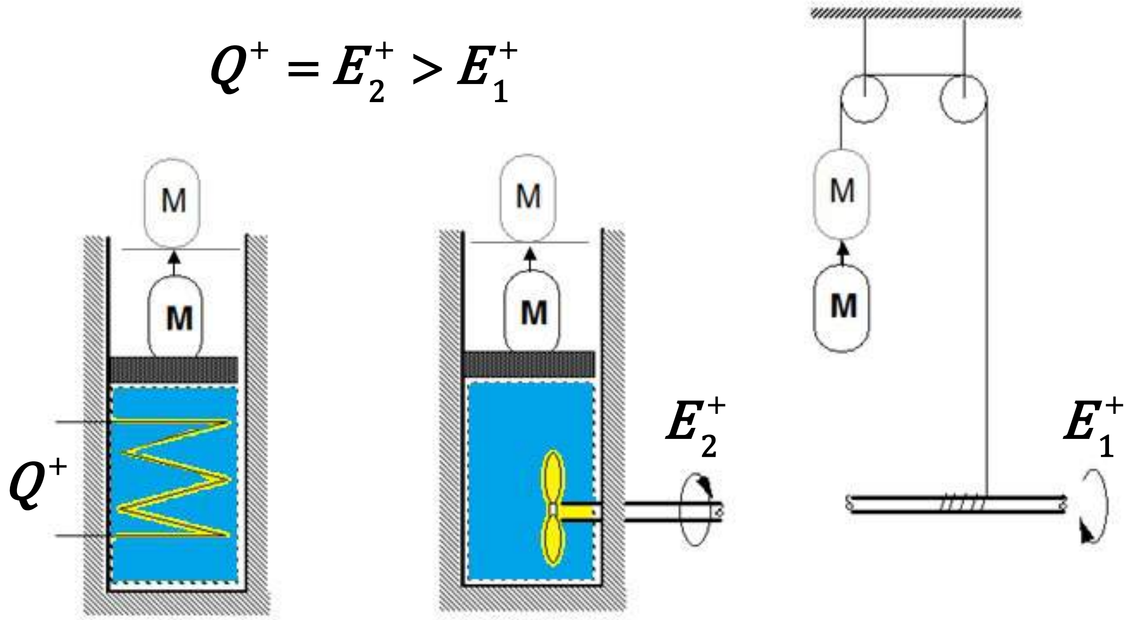
Bin for entropy

300K

Problem: with our emissions of GHG we partially block reradiation to space

Second Law of thermodynamics

$$Q^+ = E_2^+ > E_1^+$$



For the same result (lifting a load), one needs more heat energy (=> part of it cannot be converted to work)

Friction => conversion work → heat => degradation of energy

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Exergy

Heat transfer to a closed system: $dS \geq \frac{\delta Q^{+}}{T}$

$$\oint dS = \oint \frac{\delta Q^{+}_{rev}}{T} = 0$$

Energy = Exergy + Anergy

Exergy: Part corresponding to the maximum work possible

Anergy: Part unable to do work

In fact Clausius defined the entropy as proportional to anergy

$$Q^{+} = Q^{+}\left(1 - \frac{T_a}{T}\right) + T_a \frac{Q^{+}}{T}$$

1st and 2nd Laws for open systems

Stored energy — Work — Heat — Energy of transiting masses

$$\frac{d(U_{cz} + P_a V)}{dt} = \sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ - \dot{Q}_a^- + \sum_j \dot{M}_j^+ h_{cz_j}$$

Stored entropy — Entropy of heat — Entropy of transiting masses — Creation of entropy

$$\frac{dS}{dt} = \sum_i \frac{\dot{Q}_i^+}{T_i} - \frac{\dot{Q}_a^-}{T_a} + \sum_j \dot{M}_j^+ s_j - \dot{S}^i$$

Energy and entropy balance -> exergy balance

$$\frac{d(U_{cz}+P_aV)}{dt}=\sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ - \dot{Q}_a^- + \sum_j \dot{M}_j^+ h_{cz_j} \Rightarrow \sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ - \dot{Q}_a^- + \sum_j \dot{M}_j^+ h_{cz_j} - \frac{d(U_{cz}+P_aV)}{dt} = 0$$

$$T_a\frac{dS}{dt}=T_a\sum_i \frac{\dot{Q}_i^+}{T_i} - \dot{Q}_a^- + T_a\sum_j \dot{M}_j^+ s_j - T_a\dot{S}^i \Rightarrow -\left\{T_a\sum_i \frac{\dot{Q}_i^+}{T_i} - \dot{Q}_a^- + T_a\sum_j \dot{M}_j^+ s_j - T_a\frac{dS}{dt} = -T_a\dot{S}^i\right\}$$

$$\sum_k \dot{E}_k^+ + \sum_i \left(1-\frac{T_a}{T_i}\right)\dot{Q}_i^+ + \sum_j \dot{M}_j^+ (h_{cz_j} - T_a s_j) - \frac{d(U_{cz}+P_aV-T_aS)}{dt} = T_a\dot{S}^i$$

Mechanical or electrical exergy

Heat exergy

Exergy of the masses at borders

Stored exergy

Loss of exergy

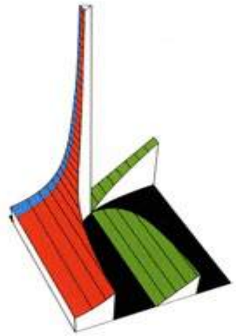
Transformation exergy of networks

$\dot{E}_y^+$

Effectiveness (1st Law) versus Exergy efficiency (1st & 2nd Law)

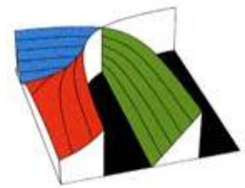
$$\textbf{Effectiveness} = \frac{\text{Energy provided by the system}}{\text{Energy given to the system}} \gtreqless 1$$

(Energy efficiency, COPh,COPf)



Since energy is conserved, often only measures the heat losses to atmosphere

$$\textbf{Exergy efficiency} = \frac{\text{Exergy provided by the system}}{\text{Exergy given to the system}} \leq 1$$



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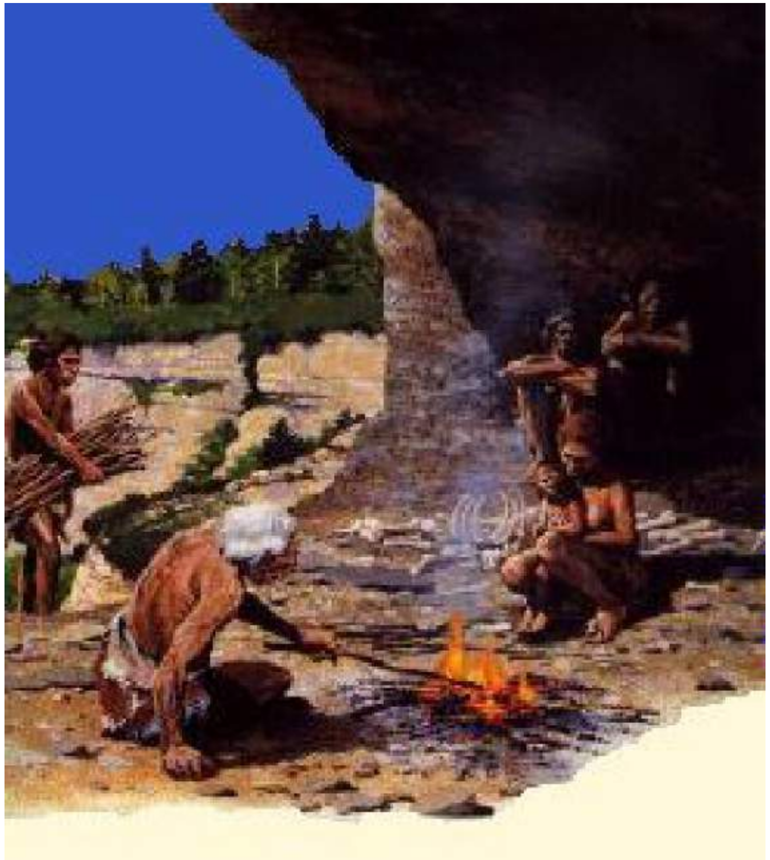
Ex: Combustion and heating

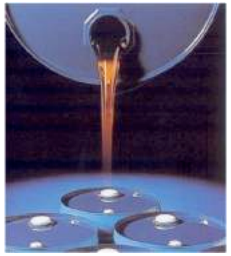
- Simple combustion for heating since around 400'000 years
- Still today the majority of heating systems (oil or gas boilers)
- Boilers = Energy efficiency close to 100% ! (sometimes >100%!!)
- Is it really a 21st century technology ?



Of course not!:
Boiler **exergy** efficiency is only 6%

FAVRAT D., MARECHAL F., EPELLY O. *The challenge of introducing an exergy indicator in a local law on energy.* Energy,33, No2, pp130-136 (2008)

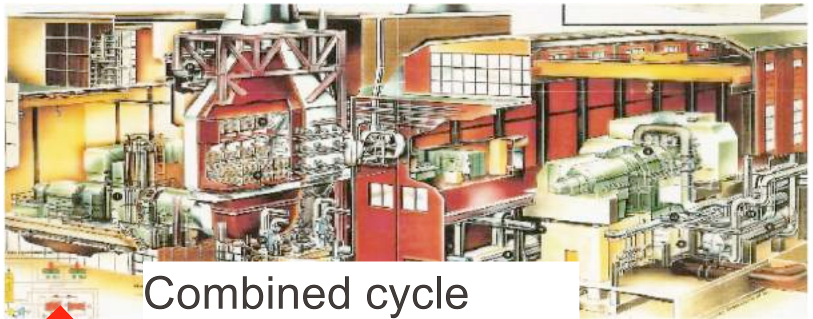
Alternative for heating with the same fuel



Oil or (bio-)gas

1.0

a)



Combined cycle

a) 0.6

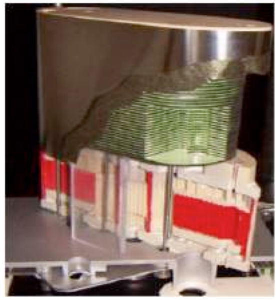
$$0.6 \cdot 4.5 = 2.7$$

$$(0.6 \cdot 4.5) + 0.3 \overset{b)}{=} 3$$

b)

1.0

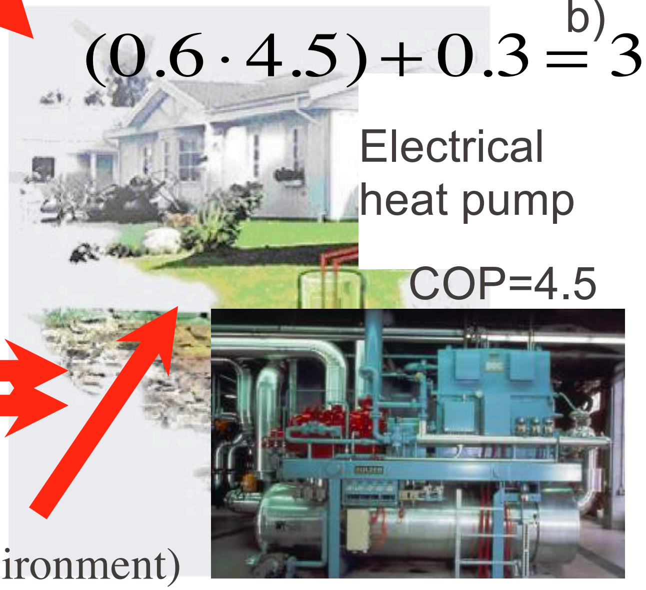
Exergy efficiency >16%



Hybrid Fuel cell SOFC+ GT

0.6 (electricity)

0.3 (heat)



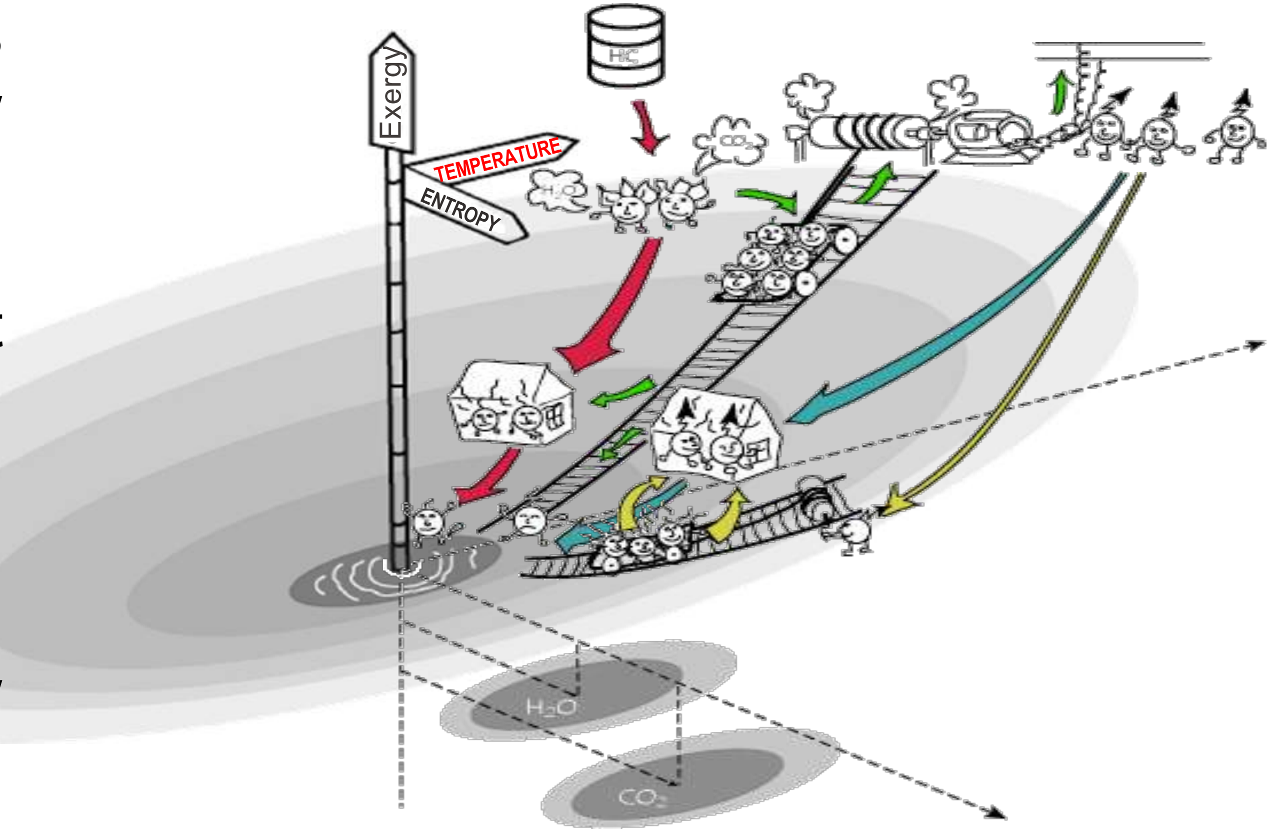
Electrical heat pump

COP=4.5

2.1 (environment)

Exergy efficiency, a better indicator than 1st Law efficiency

- Indicates the true quality of energy conversion technologies (Carnot engine: 100% exergy efficiency)
- Always ≤ 100%
- Coherent ranking of most technologies

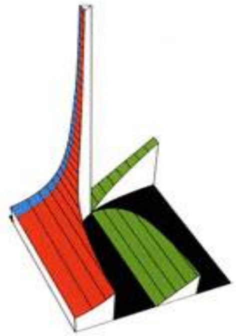


- To be complemented by renewable/non-renewable ratio

BOREL L., FAVRAT D. *Thermodynamics and energy systems analysis.* EPFL Press (2010)

$$\textbf{Effectiveness} = \frac{\text{Energy provided by the system}}{\text{Energy given to the system}} \gtreqless 1$$

(Energy efficiency, COPh,COPf)



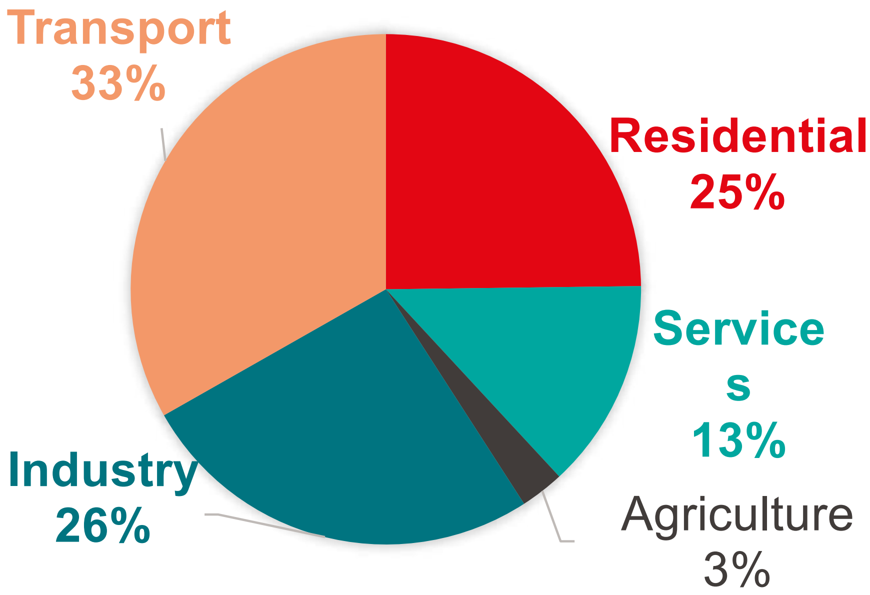
Since energy is conserved, often only measures the heat losses to atmosphere

$$\textbf{Exergy efficiency} = \frac{\text{Exergy provided by the system}}{\text{Exergy given to the system}} \leq 1$$

Exergy efficiency is key: Example of EU

Focus on major sectors:

- 38% for residential and services (mainly for building heating)
- 33% for transport (of which only <1% using electricity)



Major potential of efficiency gains in these 2 major sectors by :

- Heat pumps and cogeneration (with District Heating & Cooling in cities, more compact, see exergo.ch)

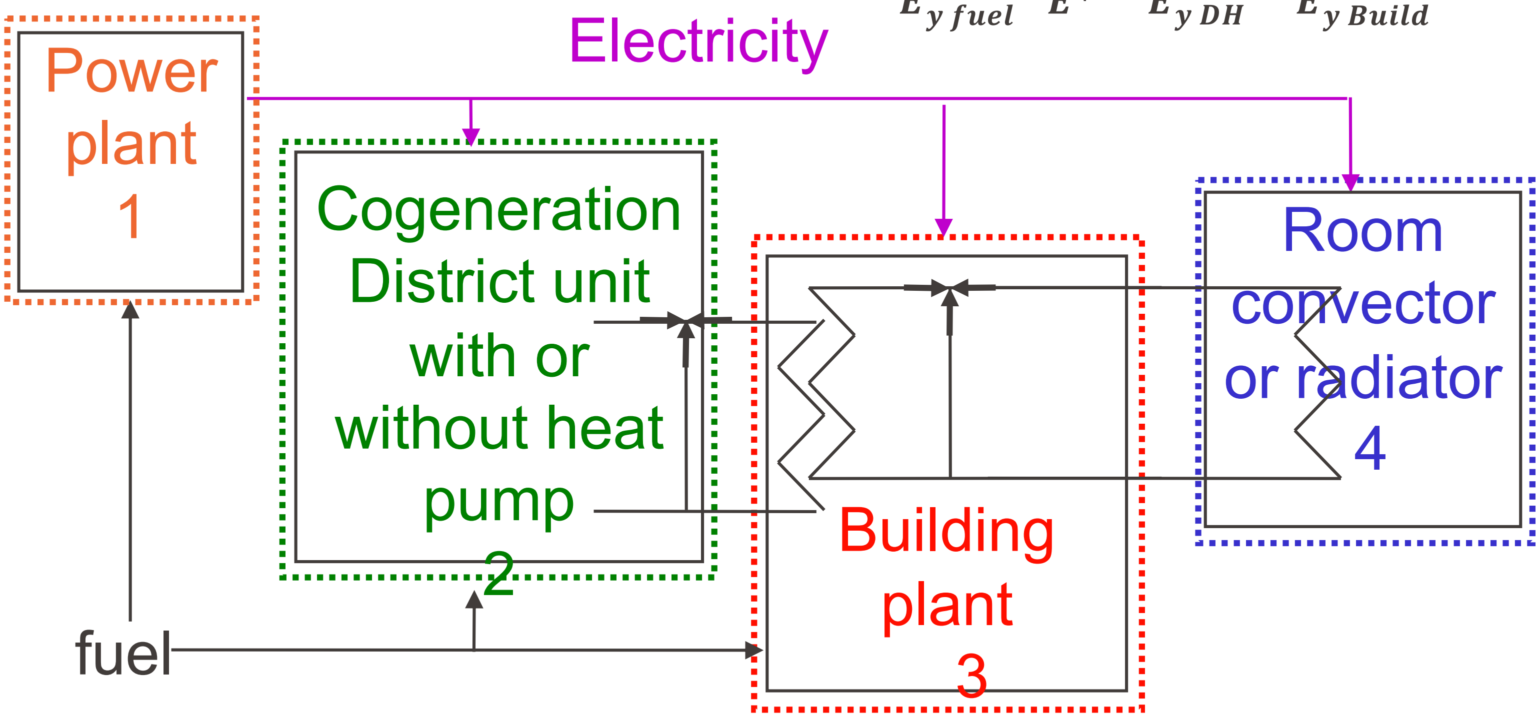
- Electric vehicles (incl. drones and autonomous)

But:

- **Requires efficient and low carbon energy conversion to electricity**
- **+ efficient recycling**

Exergy of heating and cooling: system decomposition

$$\eta = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 = \frac{\dot{E}^-}{\dot{E}^+_{y\,fuel}} \frac{\dot{E}^-_{y\,DH}}{\dot{E}^+} \frac{\dot{E}^-_{y\,Build}}{\dot{E}^+_{y\,DH}} \frac{\dot{E}^-_{y\,radiator}}{\dot{E}^+_{y\,Build}} = \frac{\dot{E}^-_{y\,radiator}}{\dot{E}^+_{y\,fuel}}$$



Key messages from exergy analysis:

- **Heat in the coolest way** **(heating temperature the closest to the need)**
- **Cool in the warmest way** **(cooling temperature the closest to the need)**

FAVRAT D., MARECHAL F., EPELLY O. *The challenge of introducing an exergy indicator in a local law on energy.* Energy,33, No2, pp130-136 (2008)

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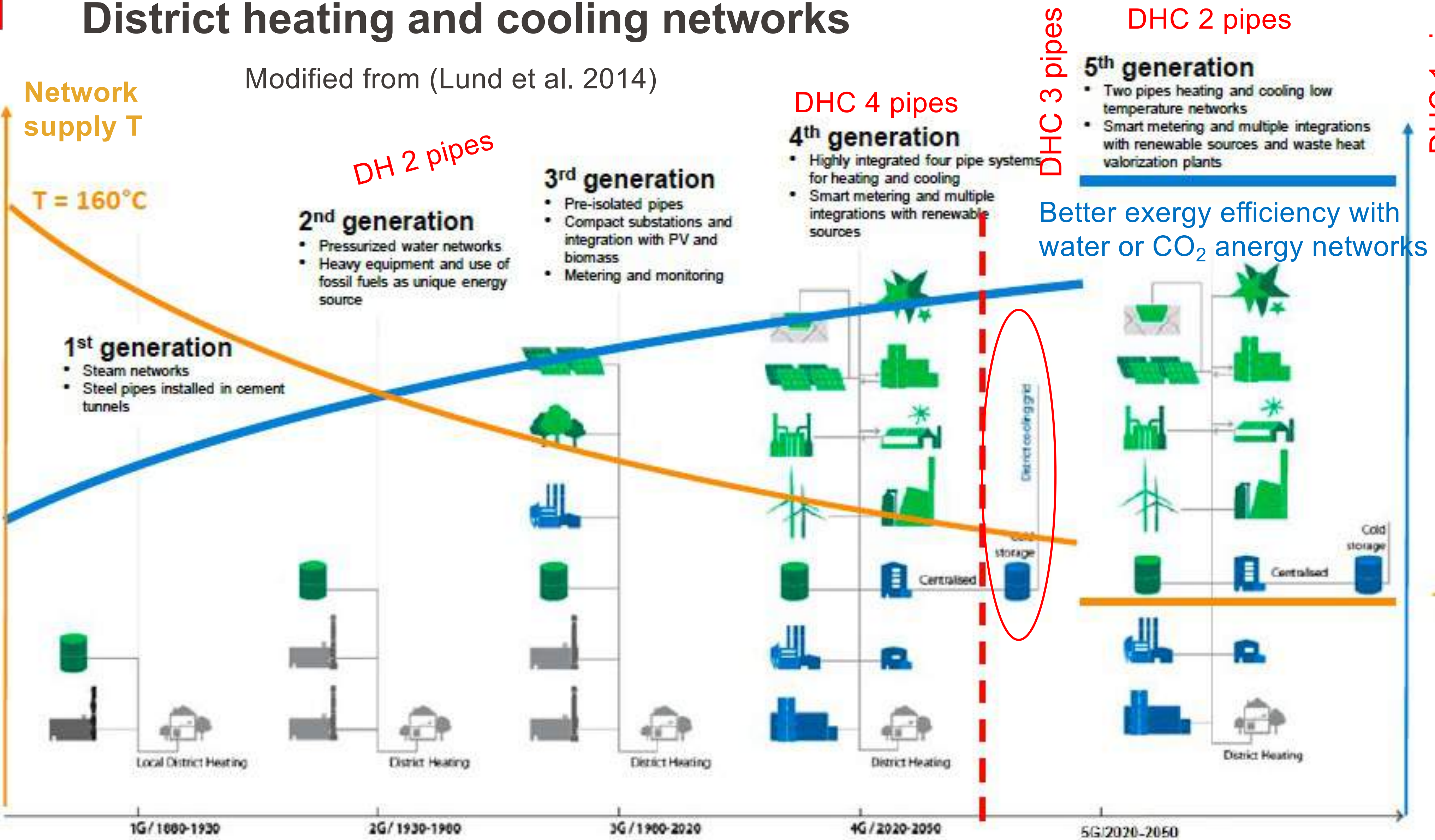
Examples de technologies For heating	Power plant	Dist. plant	Building plant			Room convector			Overall exergy efficiency [%]		
Supply/return temperatures			45°/35°	65°/55°	75°/65°	45°/35°	65°/55°	75°/65°	45°/35°	65°/55°	75°/65°
Direct electric heating (nuclear power)	0.32					0.07	0.07	0.07	2.2	2.2	2.2
Direct electric heating (combined cycle cogeneration)		0.55				0.07	0.07	0.07	3.7	3.7	3.7
Direct electric heating (hydro power)	0.88					0.07	0.07	0.07	6.0	6.0	6.0
District boiler		0.2	0.54	0.76	0.86	0.53	0.38	0.33	5.8	5.8	5.8
Building non-condensing boiler			0.11	0.16	0.18	0.53	0.38	0.33	6.1	6.1	6.1
Building condensing boiler			0.12			0.53			6.6		
District heat pump (nuclear power)	0.32	0.61	0.54	0.76	0.86	0.53	0.38	0.33	5.6	5.6	5.6
Domestic heat pump (nuclear power)	0.32		0.45	0.45	0.45	0.53	0.38	0.33	7.6	5.4	4.8
Domestic cogeneration engine and heat pump			0.22	0.25	0.26	0.53	0.38	0.33	11.8	9.4	8.7
District heat pump (combined cycle power)	0.54	0.61	0.54	0.76	0.86	0.53	0.38	0.33	9.4	9.4	9.4
Domestic heat pump (combined cycle power)	0.54		0.45	0.45	0.45	0.53	0.38	0.33	12.9	9.2	8.1
Domestic heat pump (cogeneration combined cycle power)		0.55	0.45	0.45	0.45	0.53	0.38	0.33	13.2	9.4	8.3
Cogeneration fuel cell and domestic heat pump			0.25	0.27	0.28	0.53	0.38	0.33	13.4	10.4	9.5
District heat pump (hydropower)	0.88	0.61	0.54	0.76	0.86	0.53	0.38	0.33	15.4	15.4	15.4
Domestic heat pump (hydropower)	0.88		0.45	0.45	0.45	0.53	0.38	0.33	21.2	15.1	13.3

Example of cooling technologies

Power plant technologies	Power plant	Dist. plant	Building plant			Room convector			Overall exergy efficiency [%]		
Supply/return temperatures			*10°/15°*	5°/10°	0°/5°	*10°/15°*	5°/10°	0°/5°	*10°/15°*	5°/10°	0°/5°
Nuclear power	0.32		*0.4*	0.4	0.4	*0.56*	0.43	0.34	*7.1*	5.4	4.3
Gas motors	0.36		*0.4*	0.4	0.4	*0.56*	0.43	0.34	*8.1*	6.2	4.9
Combined cycle power plant without cogeneration	0.54		*0.4*	0.4	0.4	*0.07*	0.07	0.07	*12.1*	9.3	7.3
Hydropower	0.88		*0.4*	0.4	0.4	*0.53*	0.38	0.33	*19.8*	15.2	12.0

District heating and cooling networks

Modified from (Lund et al. 2014)



Prof. D. Favrat

Sustainability assessment

- Exergy efficiency is a much better tool to evaluate and rank technology options
- It really allows to assess what is the remaining potential for a more efficient and sustainable society
- Ideally it should include the embedded exergy to implement energy technologies
- An additional important indicator is the ratio between fossil and renewable energy supply of any project

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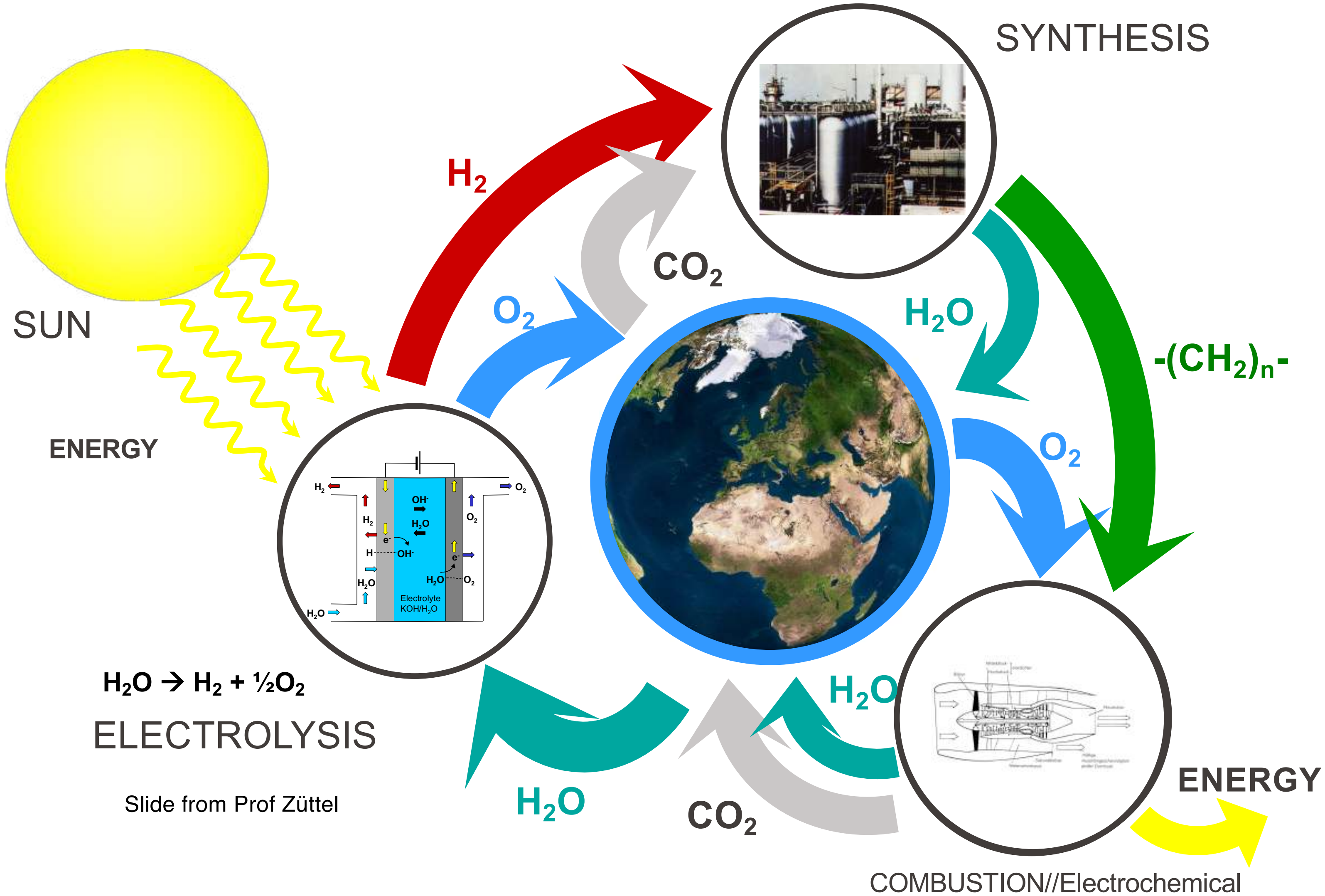
In summary

- **Respect resources**
- **Respect the planet**
- **Think exergy**

Thanks for your attention

Seasonal storage: SYNTHETIC HYDROCARBONS

$n\,CO_2 + (3n+1)\,H_2 \rightarrow CH_3\text{-}(CH_2)_{n-2}\text{-}CH_3 + 2n\,H_2O$



Slide from Prof Züttel