Lecture 6
Thermal energy

PHY 555 – Energy & Environment

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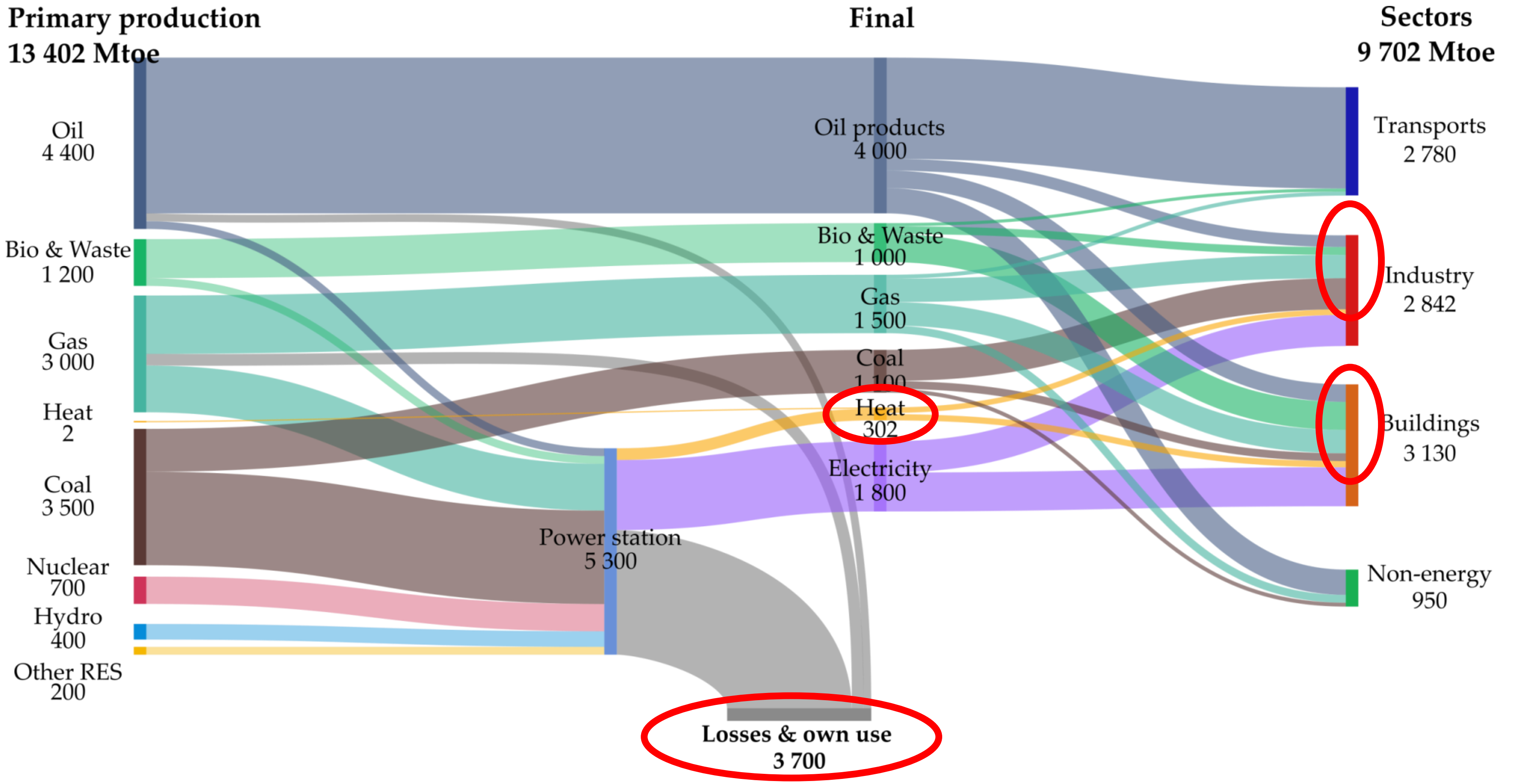
Today’s menu



Heat = 50% TFC
(+ losses in conversion)

Is it possible to reach the same temperatures with less heat ?

Is it possible to provide heat from different sources ?

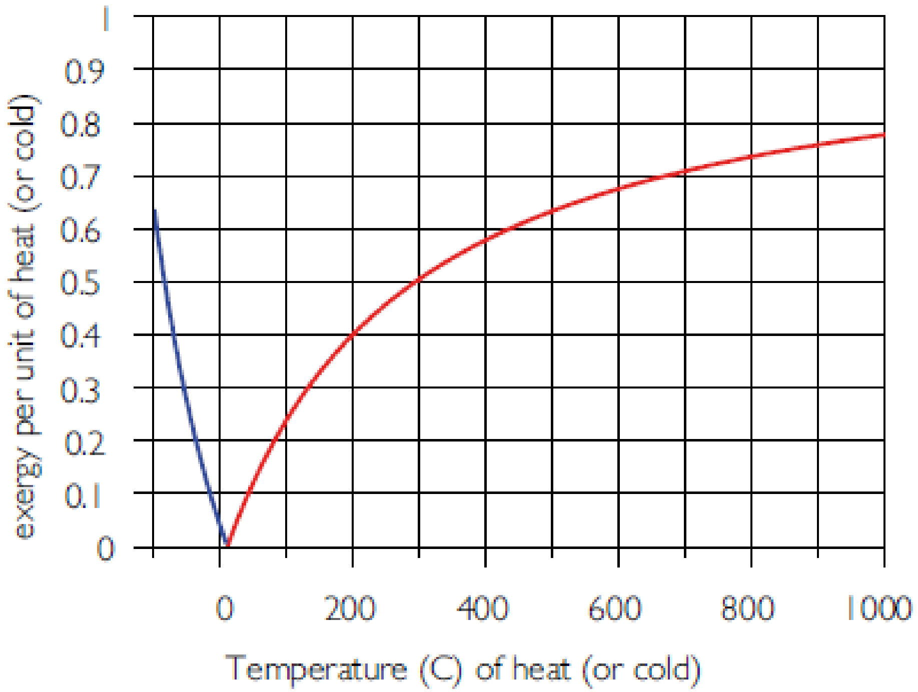
Is it possible to recover the energy lost as heat?

Hot reminders

All heats are not equal!

Exergy : in a given environment, how much work can be recovered from the provided heat?

$$W_{\max} = Q \times \left(1 - \frac{T_{\text{envir.}}}{T_{\text{source}}}\right)$$



Heat [J] is not temperature [K]

(even though heat is often used to increase temperature)

Heat is not stored. Thermal energy is.

Lecture 8 – thermal energy

I. Overview of heat consumption (what, why, how much ?)

II. Heat conduction

- Heat transfer & heat equation
- Insulation 101
- Thermal energy management

III. Heat generation

- Geothermal energy
- Heat pump
- Combined heat and power generation

The roof, the roof, the roof is on fire

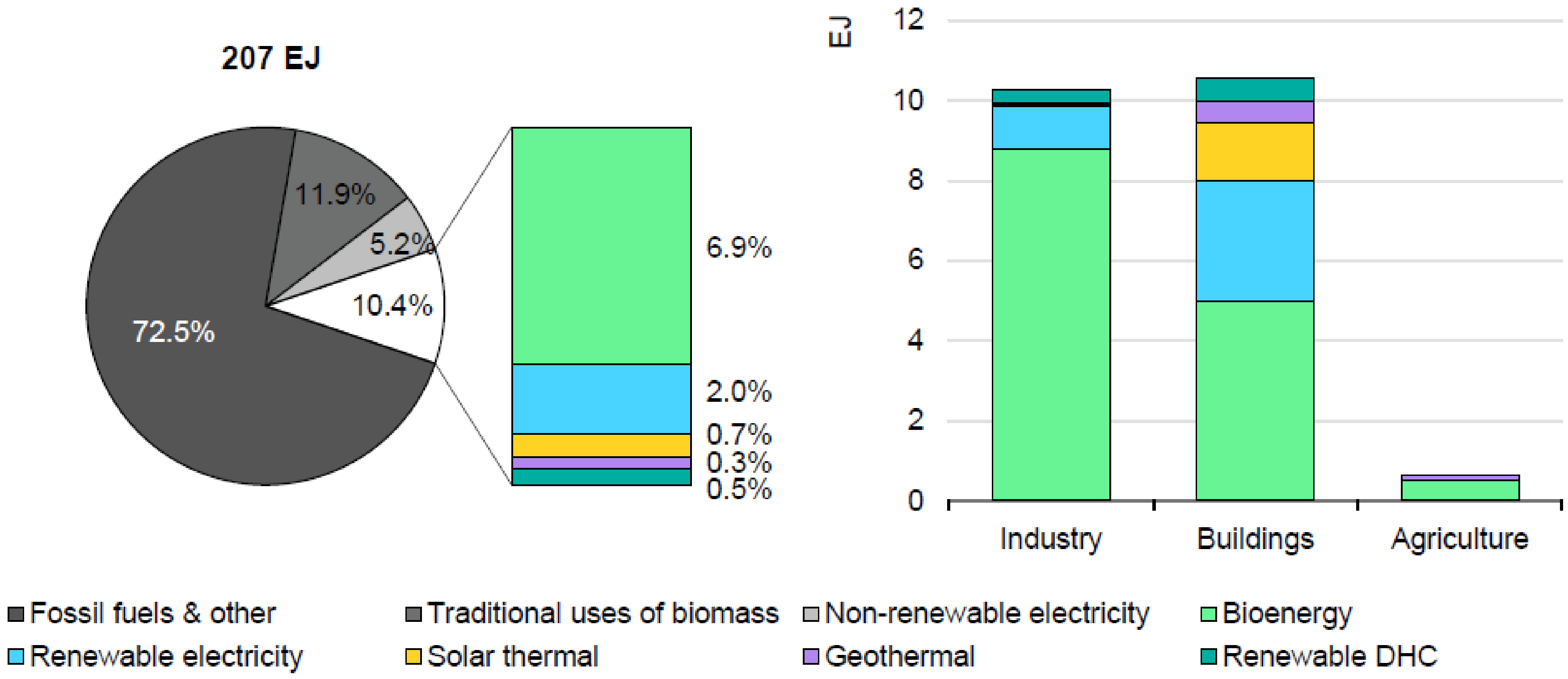


Figure 7.1 Global renewable heat consumption by fuel and technology, 2019

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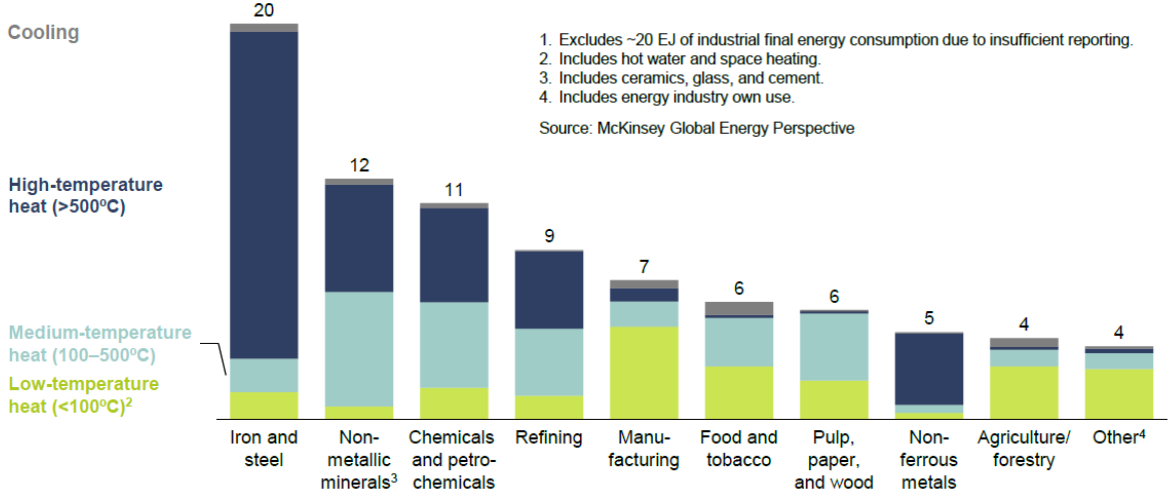
Industrial heat

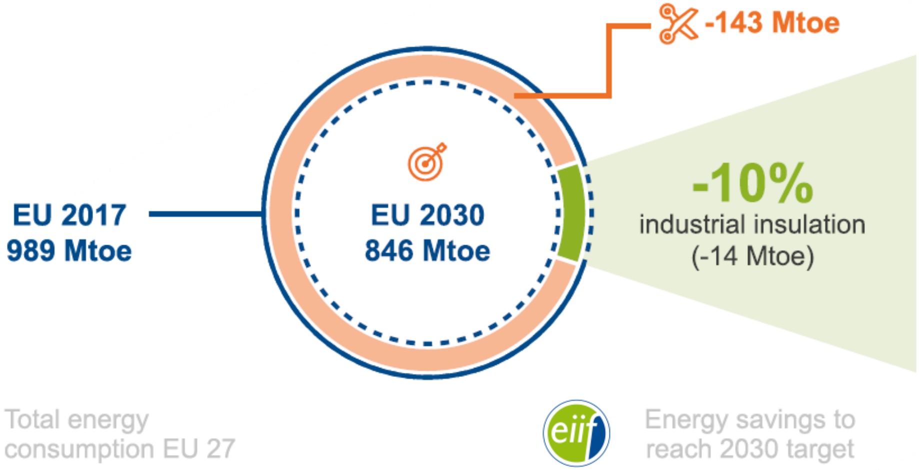
Industrial energy consumption is concentrated in high-temperature applications

Global industrial final energy consumption by sector[1]
Exajoules, 2019

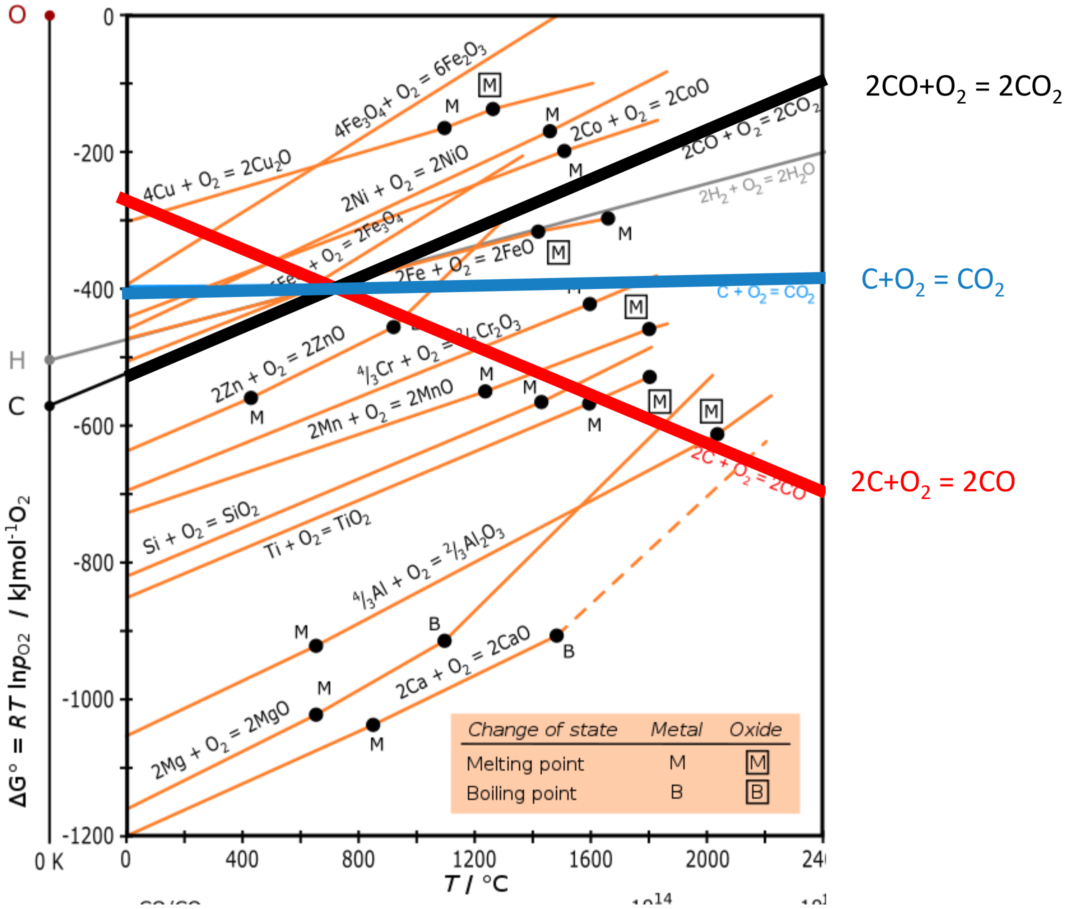


1. Excludes ~20 EJ of industrial final energy consumption due to insufficient reporting.
2. Includes hot water and space heating.
3. Includes ceramics, glass, and cement.
4. Includes energy industry own use.

Source: McKinsey Global Energy Perspective



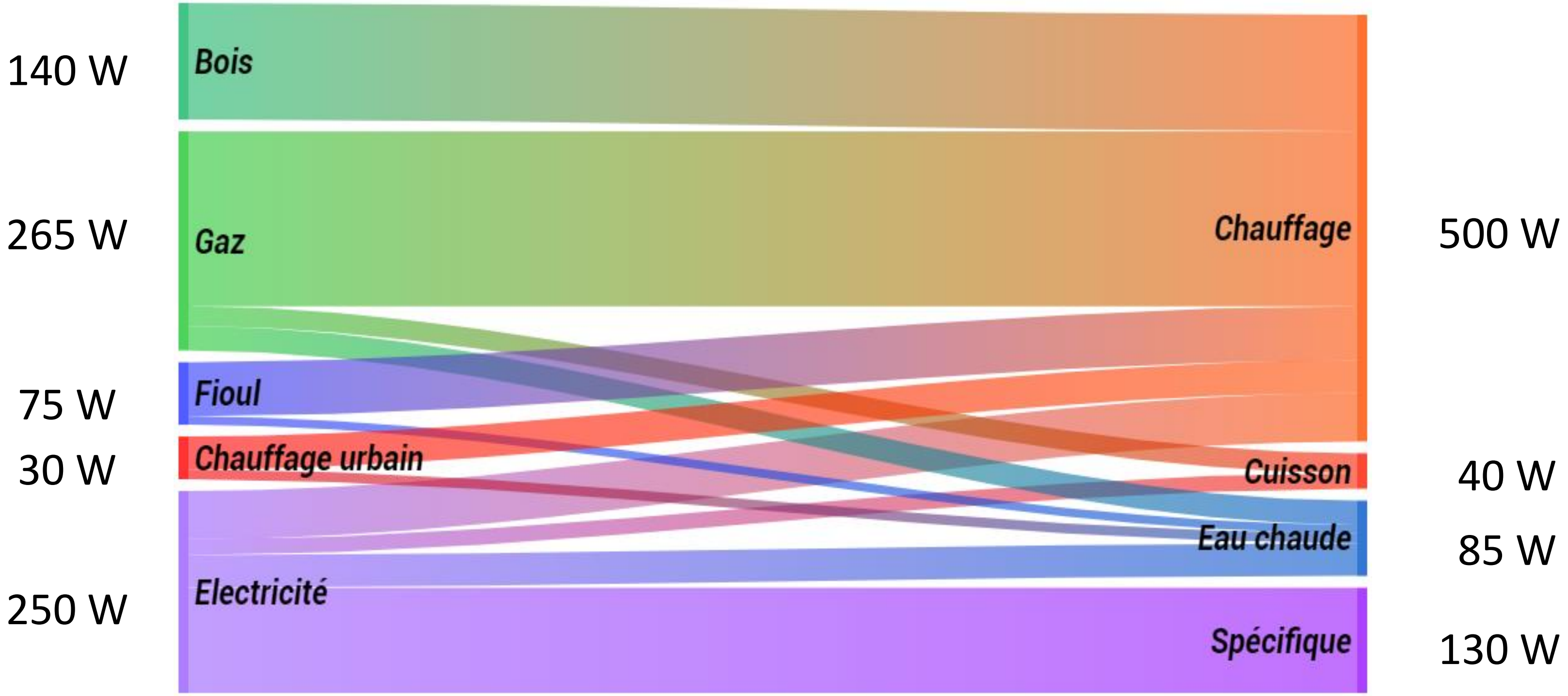
High temperatures are required to reduce oxides

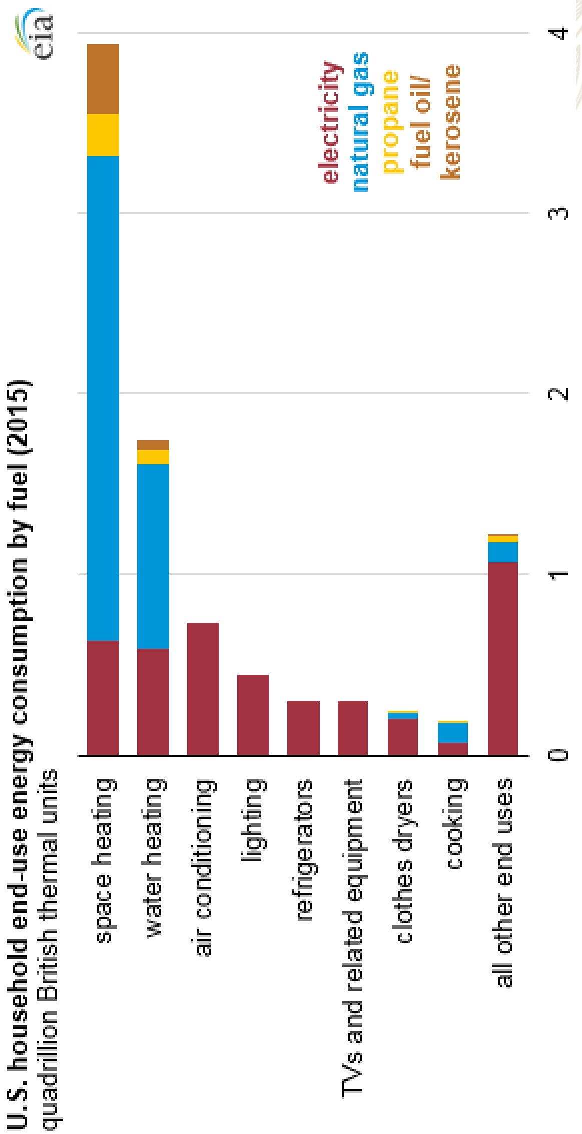


Ellington diagram : ΔG versus T

Domestic heat

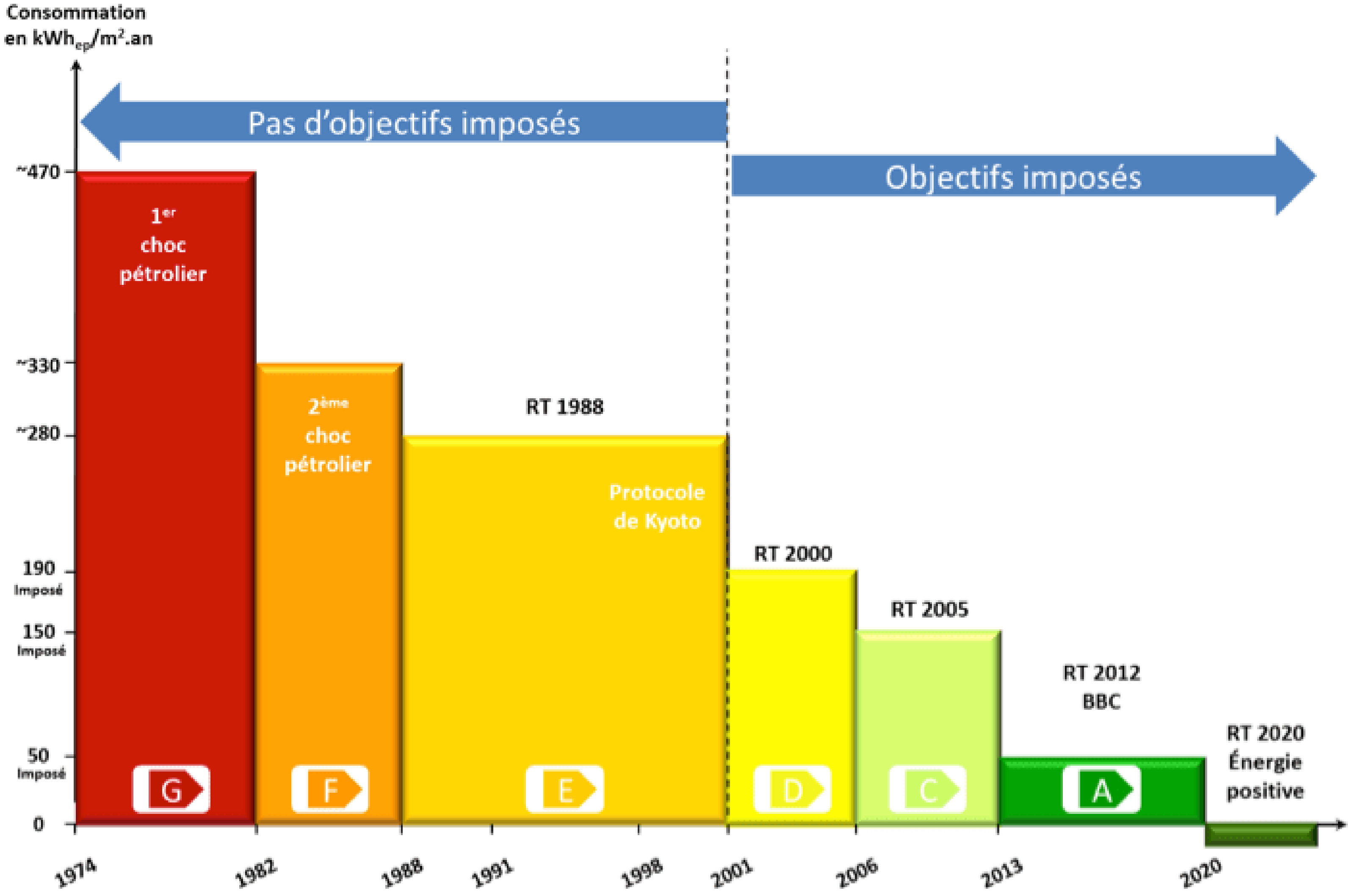
Average residential consumption per capita in France (data : CEREN (2019))




U.S. household end-use energy consumption by fuel (2015)

quadrillion British thermal units

French heat regulation



RT 2012

Values in *primary energy*

1 kWh final

= 2.58 kWh for electricity

= 1 kWh for other vectors

RT 2020

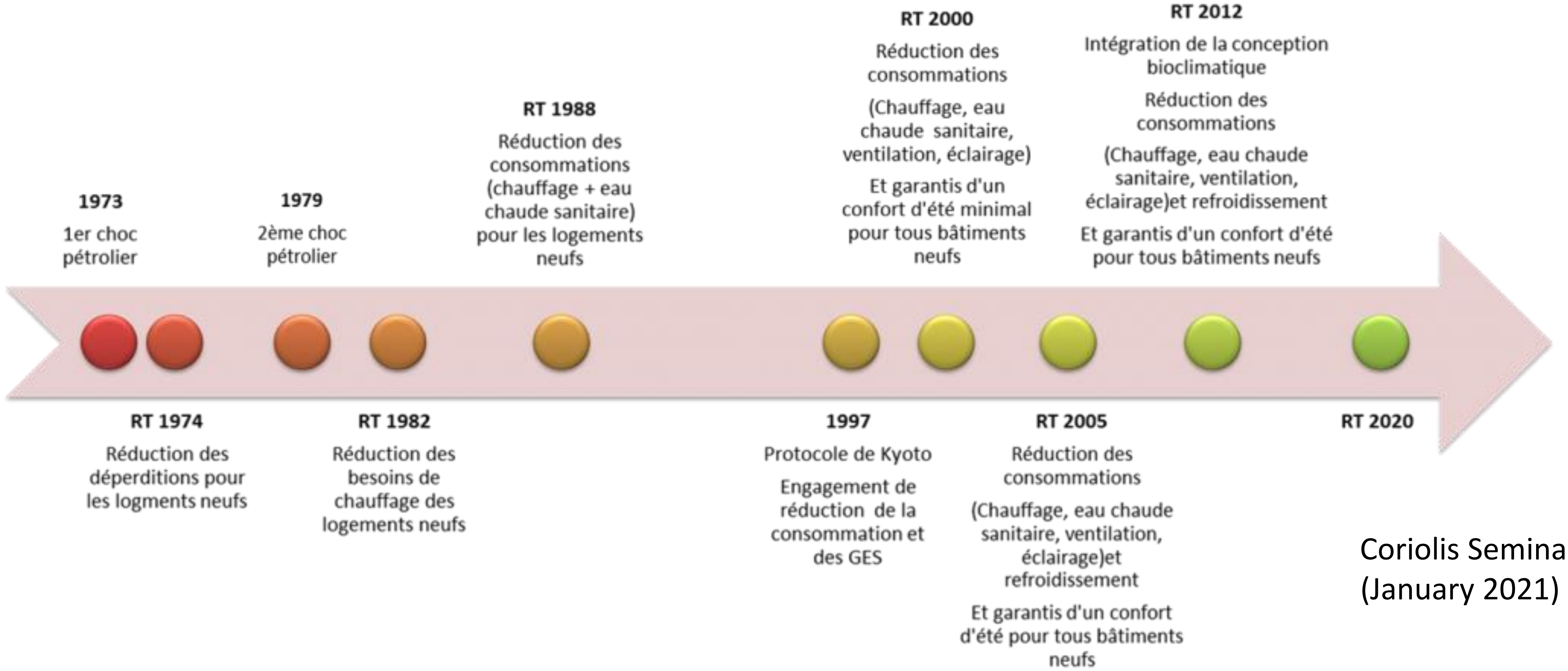
Values in *primary energy*

1 kWh final

= 2.3 kWh for electricity

= 1 kWh for other vectors

French heat regulation (cont’d)



1973

1er choc pétrolier

RT 1974

Réduction des déperditions pour les logments neufs

1979

2ème choc pétrolier

RT 1982

Réduction des besoins de chauffage des logements neufs

RT 1988

Réduction des consommations (chauffage + eau chaude sanitaire) pour les logements neufs

1997

Protocole de Kyoto

Engagement de réduction de la consommation et des GES

RT 2000

Réduction des consommations

(Chauffage, eau chaude sanitaire, ventilation, éclairage)

Et garantis d'un confort d'été minimal pour tous bâtiments neufs

RT 2005

Réduction des consommations

(Chauffage, eau chaude sanitaire, ventilation, éclairage)et refroidissement

Et garantis d'un confort d'été pour tous bâtiments neufs

RT 2012

Intégration de la conception bioclimatique

Réduction des consommations

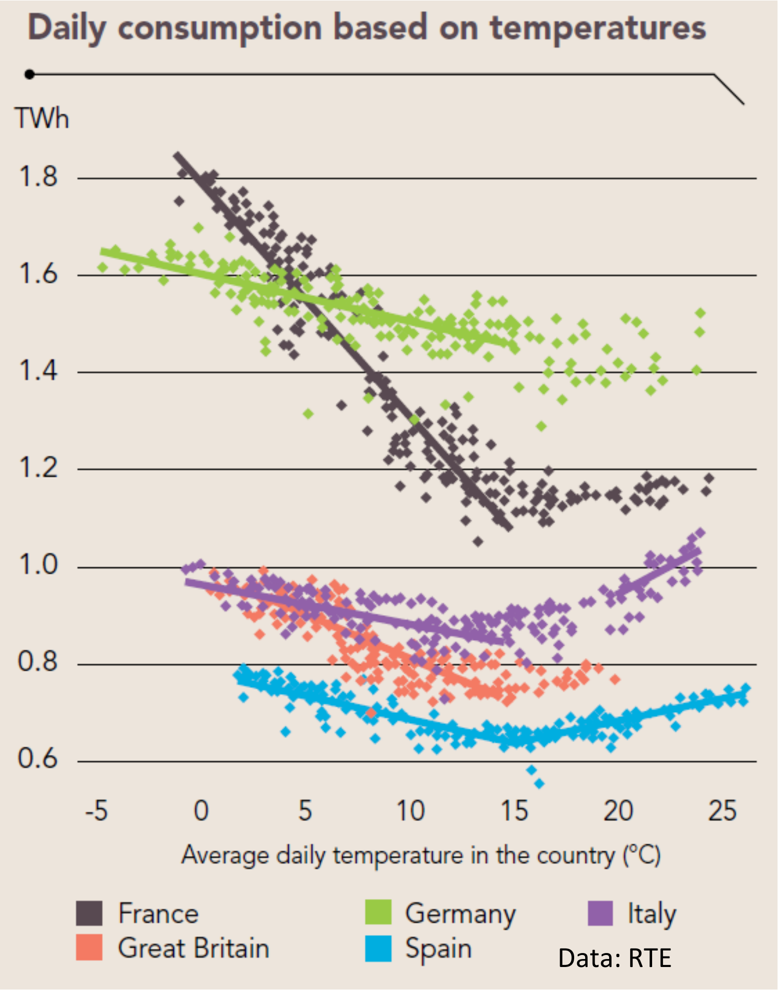
(Chauffage, eau chaude sanitaire, ventilation, éclairage)et refroidissement

Et garantis d'un confort d'été pour tous bâtiments neufs

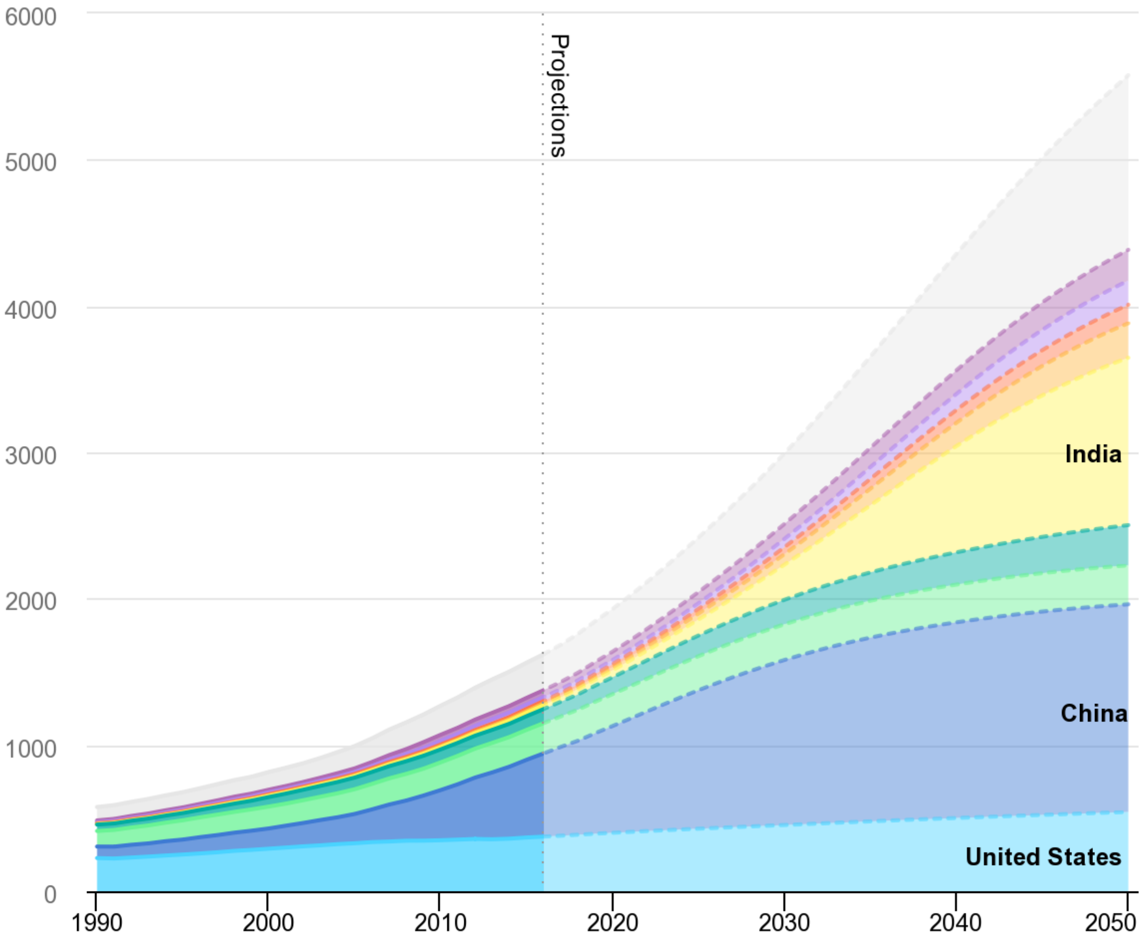
RT 2020

Coriolis Seminar
(January 2021) !

Heating and cooling



Global air conditioner stock [Million units]



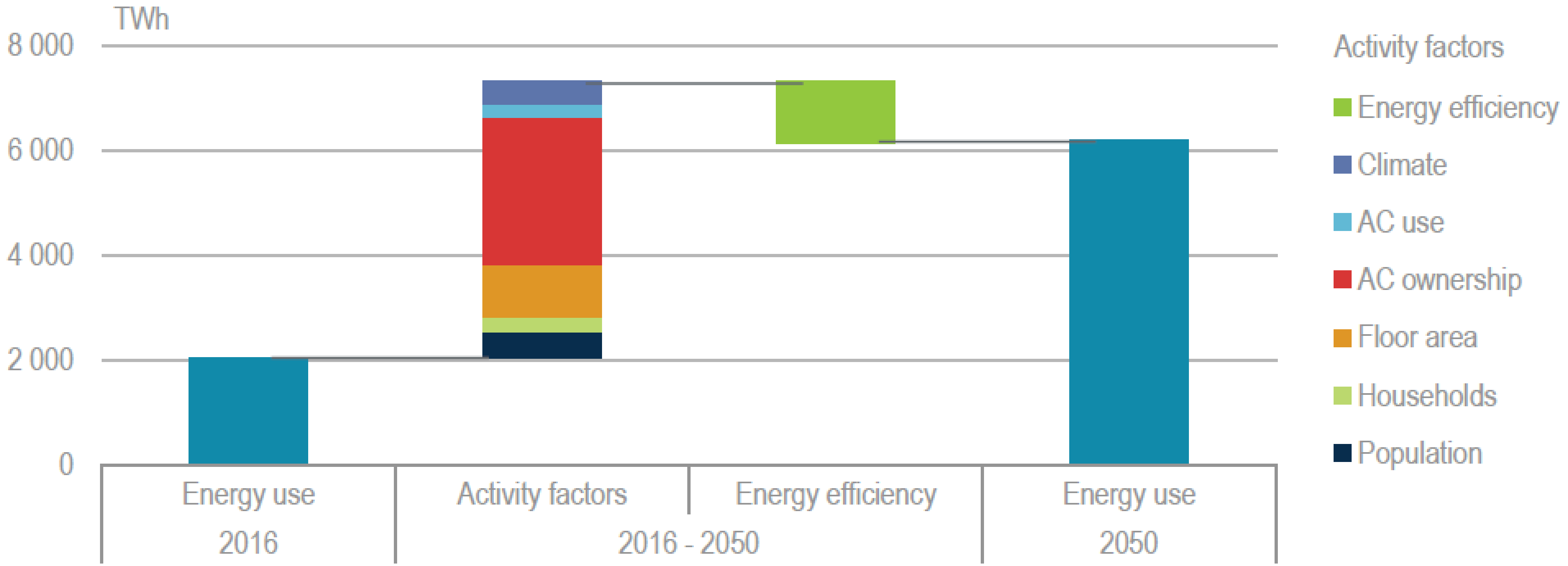
Today :
Air conditioners
and electric fans
= 20% buildings electricity

2050:
The share of space cooling in total electricity use in buildings grows to 30%. Cooling becomes the strongest driver of growth in buildings electricity demand, responsible for 40% of the total growth

Cooling

The Future of Cooling
Opportunities for energy-efficient air conditioning

Figure 3.7 • The role of drivers of energy demand for space cooling in the Baseline Scenario



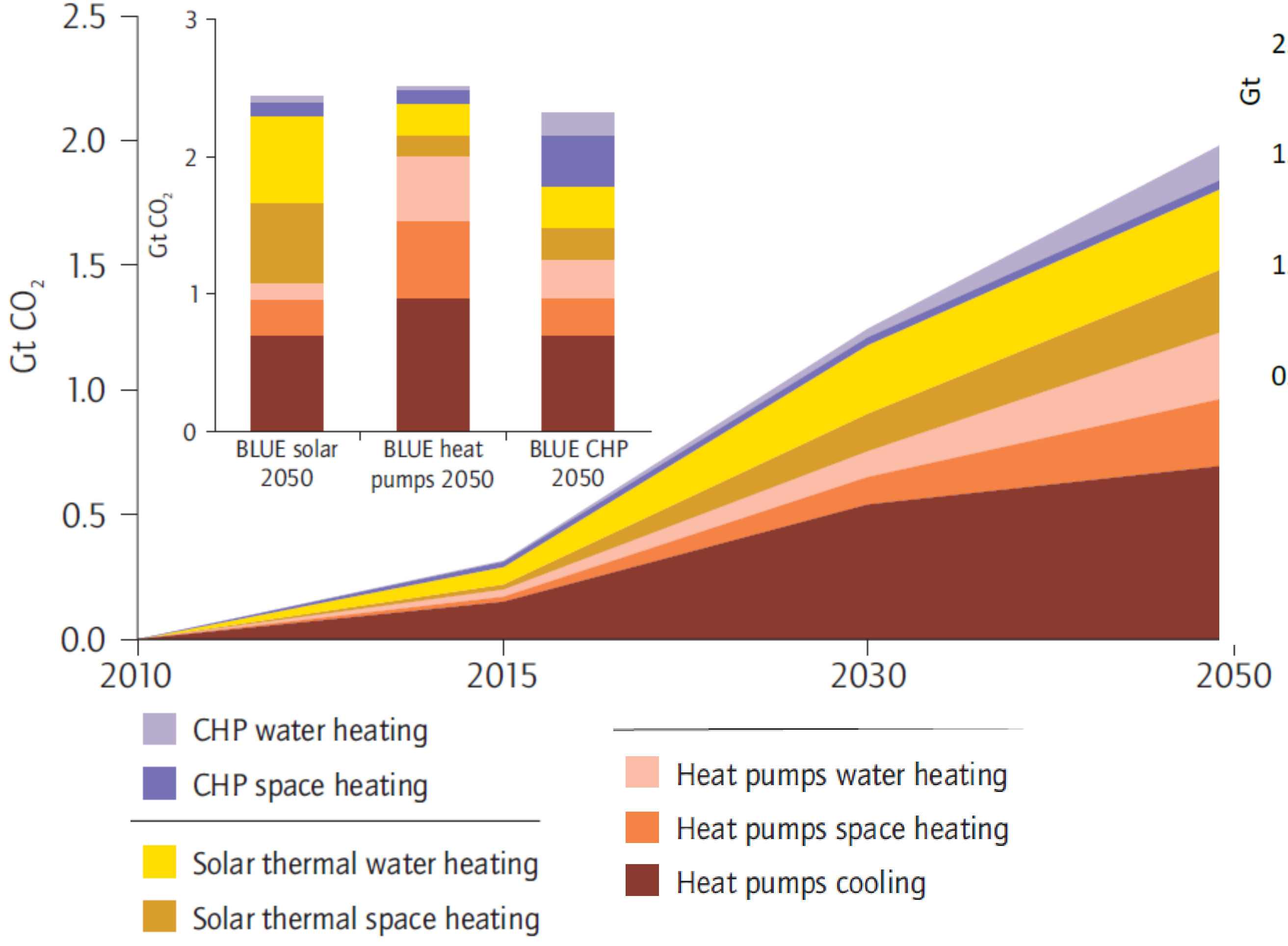
Key message • Booming sales of ACs more than outweigh the impact of continuing gains in energy efficiency.

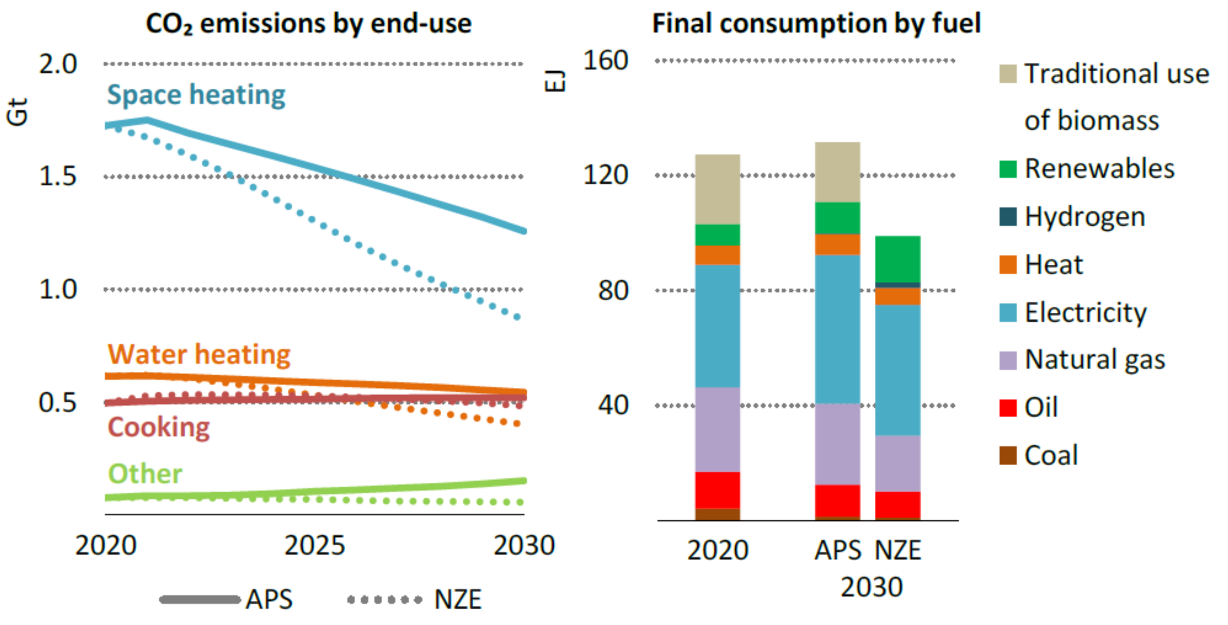
Jevon’s paradox again !

Perspective for domestic heating and cooling

Heating and cooling technologies’ contribution to CO2 emissions reduction

World energy outlook, 2021





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Lecture 8 – thermal energy

I. Overview of heat consumption (what, why, how much ?)

II. **Heat conduction**

- **Heat transfer & heat equation**
- Insulation 101
- Thermal energy management

III. Heat generation

- Geothermal energy
- Heat pump
- Combined heat and power generation

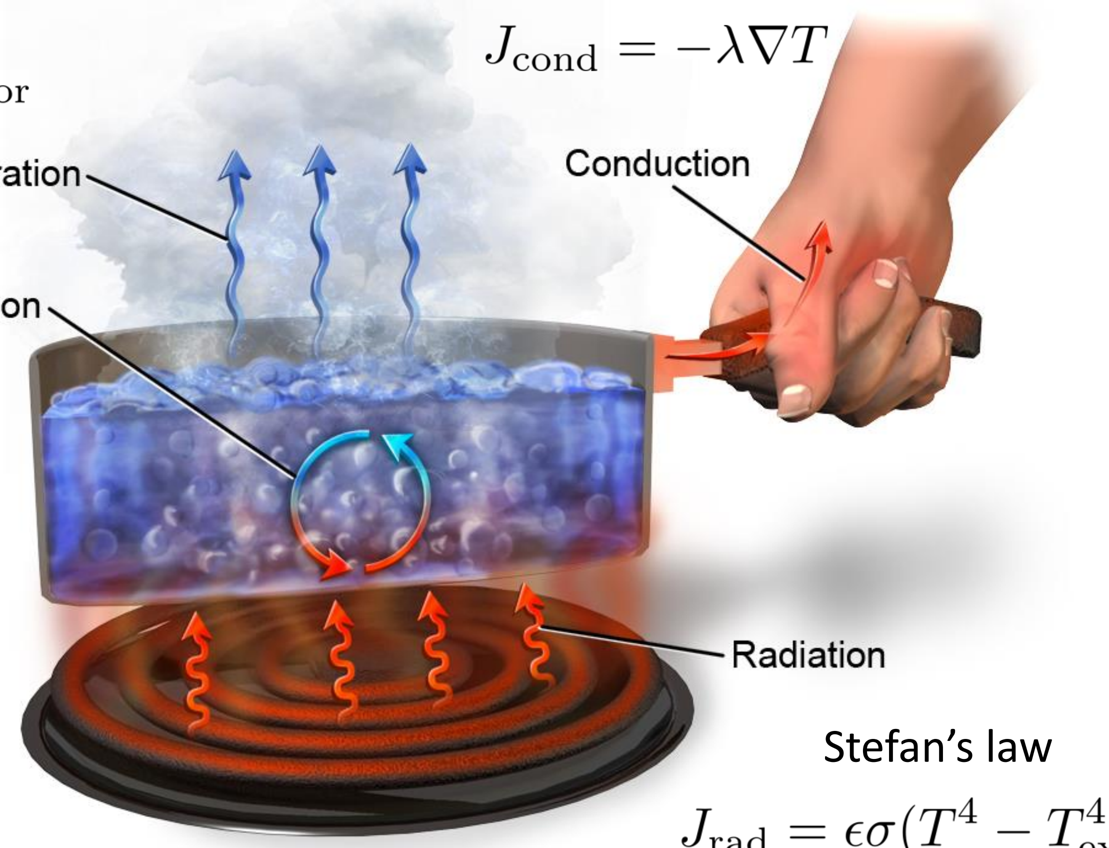
Heat loss mechanisms

Evaporative cooling

$$J_{\mathrm{latent}} = L_{\mathrm{evap}} \dot{n}_{\mathrm{vapor}}$$

Fourier's law

$$J_{\mathrm{cond}} = -\lambda \nabla T$$



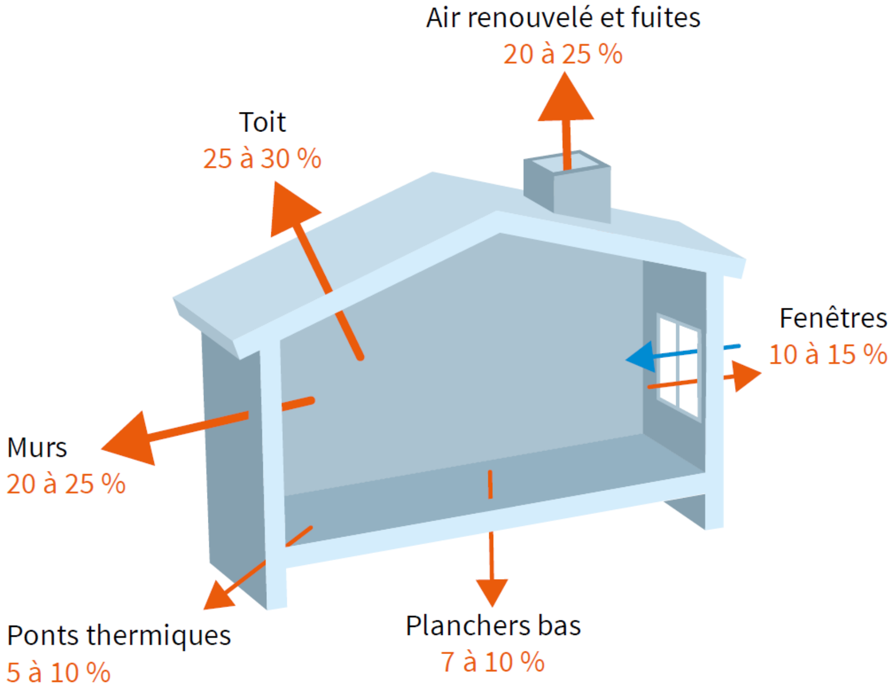
Newton's cooling law

$$J_{\mathrm{conv}} = h(T - T_{\mathrm{ext}})$$

Stefan's law

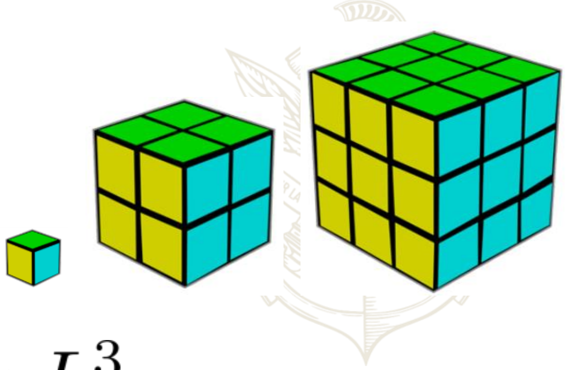
$$J_{\mathrm{rad}} = \epsilon\sigma(T^4 - T_{\mathrm{ext}}^4)$$

Source: thermtest



See PC 8

Heat loss scaling laws



- Heat is produced in the volume of the system

  More volume means more production

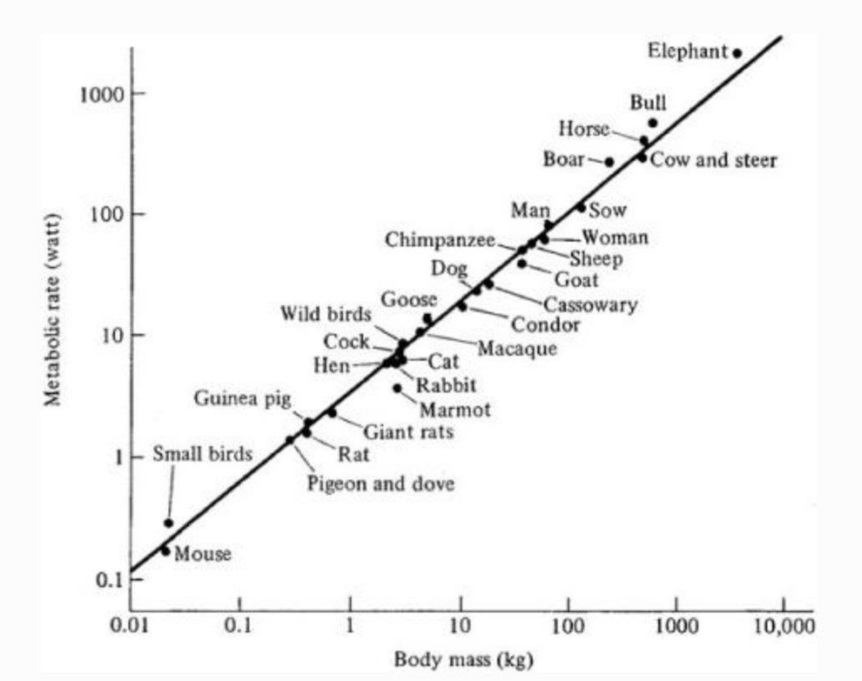
$$Q_{\text{generated}} \propto V \propto L^3$$

- Heat is exchanged through the interface with the environment

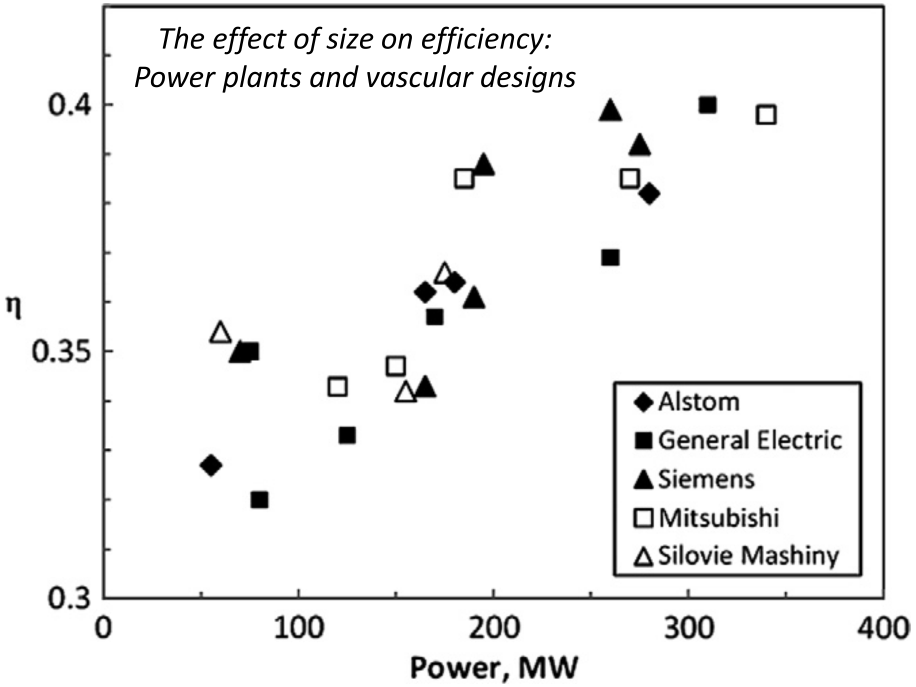
$$\frac{Q_{\text{lost}}}{Q_{\text{generated}}} \propto \frac{1}{L}$$

  More surface means more losses

$$Q_{\text{lost}} \propto S \propto L^2$$



Actual exponent is still debated



The effect of size on efficiency: Power plants and vascular designs

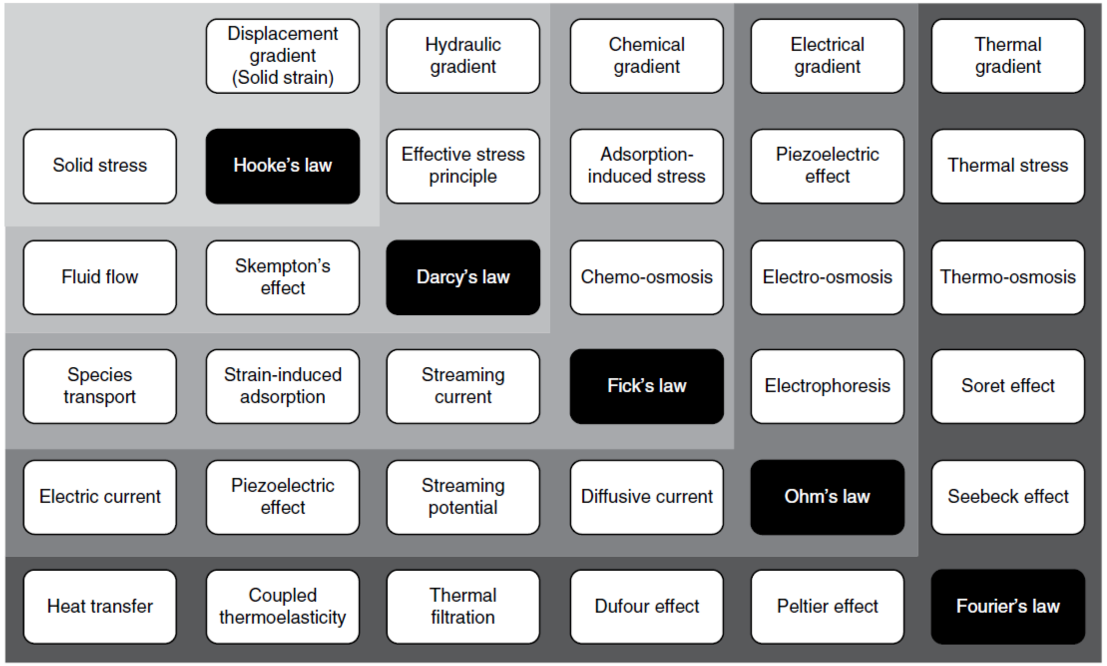
Heat conduction – Fourier's law

Gradient in potential(s) → flow of conjugated quantity(ies)

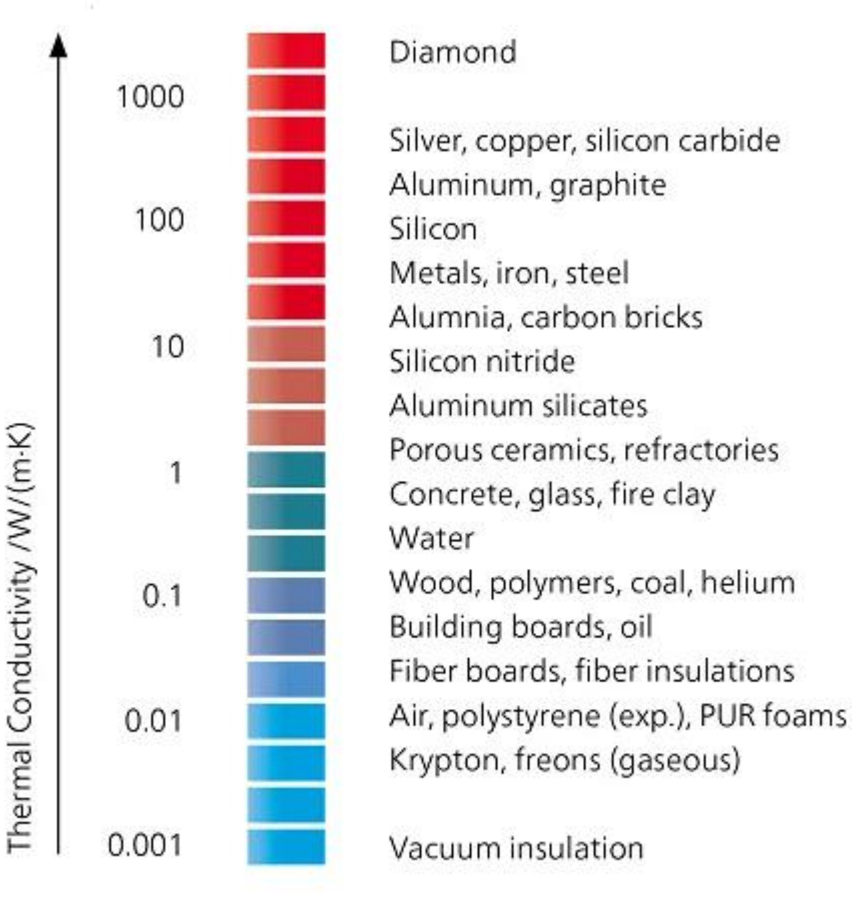
Gradient in temperature → flow of heat

$$\mathbf{J} = -\lambda \boldsymbol{\nabla} T$$

λ Thermal conductivity [W/K/m^2]



	Displacement gradient (Solid strain)	Hydraulic gradient	Chemical gradient	Electrical gradient	Thermal gradient
Solid stress	**Hooke's law**	Effective stress principle	Adsorption-induced stress	Piezoelectric effect	Thermal stress
Fluid flow	Skempton's effect	**Darcy's law**	Chemo-osmosis	Electro-osmosis	Thermo-osmosis
Species transport	Strain-induced adsorption	Streaming current	**Fick's law**	Electrophoresis	Soret effect
Electric current	Piezoelectric effect	Streaming potential	Diffusive current	**Ohm's law**	Seebeck effect
Heat transfer	Coupled thermoelasticity	Thermal filtration	Dufour effect	Peltier effect	**Fourier's law**



(Thermal Conductivity at RT)

Heat equation

Fourier's law $\mathbf{J} = -\lambda \boldsymbol{\nabla} T$

Energy conservation $\frac{du}{dt} + \mathrm{div}\mathbf{J} = 0$

Heat capacity $du = C dT$

Heat equation

$$\frac{\partial T}{\partial t} = D \, \Delta T$$

with

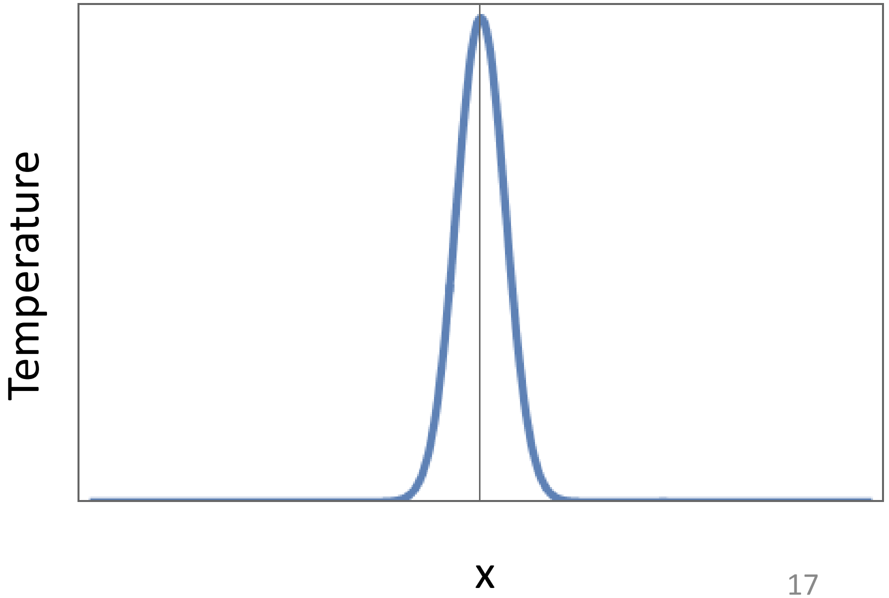
Diffusion coefficient

$$D = \frac{\lambda}{\rho c} [\mathrm{m}^2.\mathrm{s}^{-1}]$$

Typical diffusion behavior

$$\Delta T(x,t) = \frac{\Delta T_0}{\sqrt{2\pi D t}} \exp\left(-\frac{x^2}{2Dt}\right)$$

Scaling $x \sim \sqrt{Dt}$



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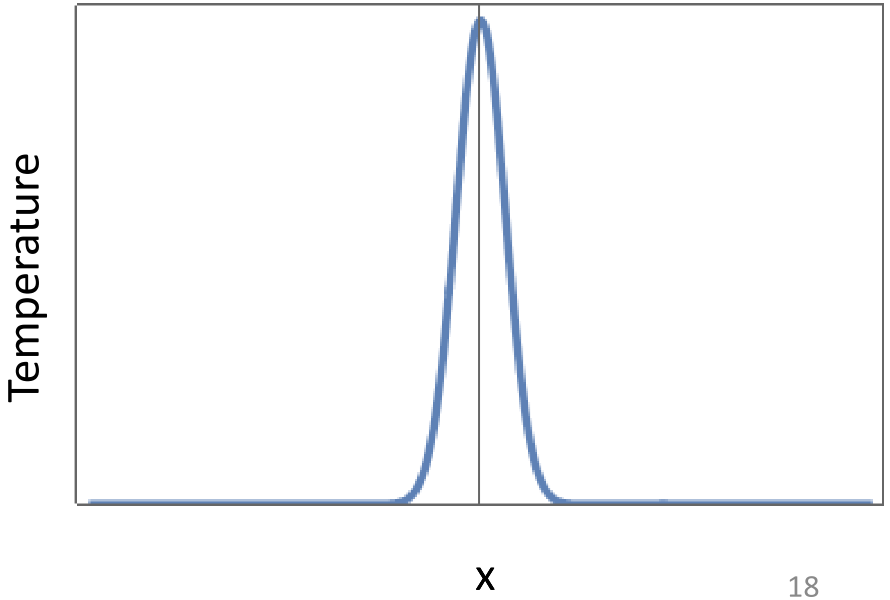


Lecture 8 – thermal energy

I. Overview of heat consumption (what, why, how much ?)

II. **Heat conduction**

- Heat transfer & heat equation
- **Insulation 101**
- Thermal energy management

Three direct consequences :

- **Thermal resistance**
- **Thermal inertia**
- **Thermal comfort**

Two indirect consequences :

- Thermal energy transmission
- Thermal energy storage

III. Heat generation

- Geothermal energy
- Heat pump
- Combined heat and power generation

Stationnary state - Thermal resistance

$$\mathbf{J} = -\lambda \boldsymbol{\nabla} T$$

$$\frac{\partial T}{\partial t} = D\,\Delta T$$

We want to maintain a different temperature inside as compared to outside.
What is the heat flow that must be sustained?

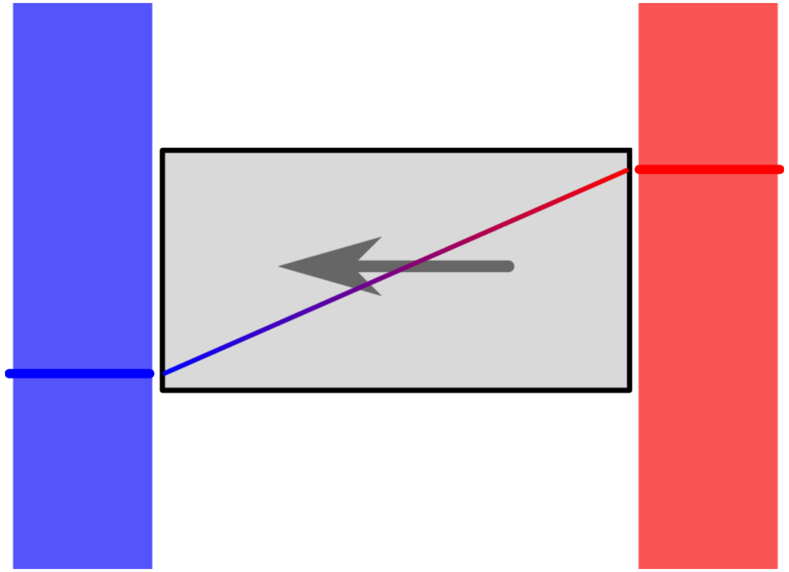
Steady state $\frac{\partial T}{\partial t} = 0 \Rightarrow \Delta T = 0$ ❗ $\mathbf{J} = -\lambda \boldsymbol{\nabla} T \neq 0$

Linear temperature profile $T(x) = T_{\text{in}} + \frac{T_{\text{out}} - T_{\text{in}}}{w} x$

Heat density of flux $J = -\lambda \frac{T_{\text{out}} - T_{\text{in}}}{w}$

Heat flow $\phi = J \times S = \frac{T_{\text{in}} - T_{\text{out}}}{R}$

Heat resistivity $R = \frac{w}{S\lambda}$



See PC 6

Series resistance

We want to maintain a different temperature inside as compared to outside.
What is the heat flow that must be sustained?

Heat flow

$$\phi_1 = \frac{T_{\text{in}} - T_{\text{middle}}}{R_1} \qquad \phi_2 = \frac{T_{\text{middle}} - T_{\text{out}}}{R_2}$$

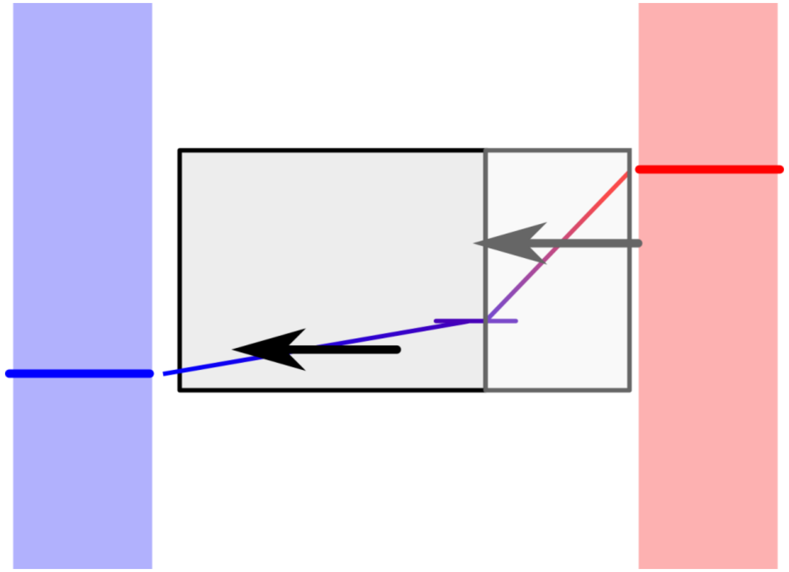
Flow continuity

$$\phi_1 = \phi_2 = \phi$$

$$\Rightarrow \quad \phi = \frac{T_{\text{in}} - T_{\text{out}}}{R_1 + R_2}$$

Equivalent resistance

$$R_{\text{tot}} = R_1 + R_2$$



See PC 6

Insulation

$$R_{\text{tot}} = R_1 + R_2$$

Adding more layers will decrease the heat flow

$$R = \frac{w}{S\lambda}$$

Thick layers with low conductivity

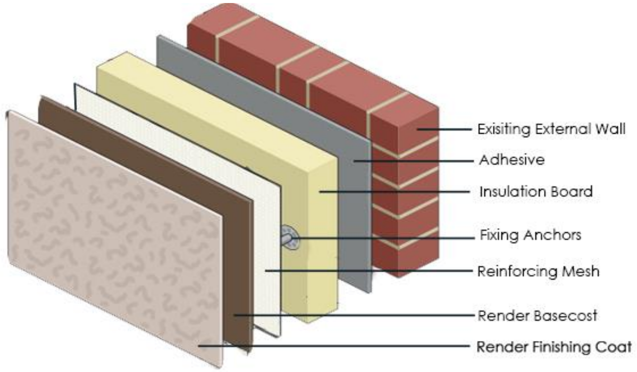
$$\phi = J \times S = \frac{T_{\text{in}} - T_{\text{out}}}{R}$$

Complementary approach: thermal transmittance [W/m²/K]

$$U = \frac{1}{SR} = \frac{\lambda}{w}$$

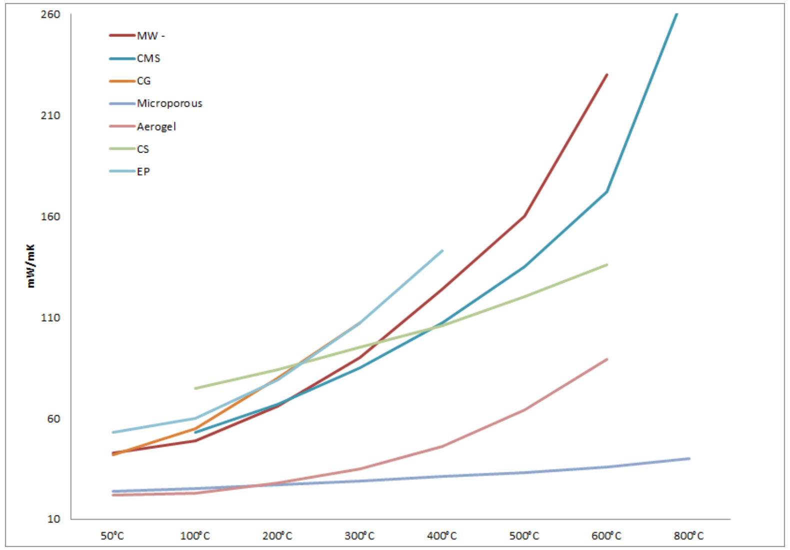
$$J = U \times (T_{\text{in}} - T_{\text{out}})$$

Wall insulation
Aim U ~ 0.2 W/m²/K



Pipe insulation
Current regulation : T < 60°C

λ is actually
temperature dependent !

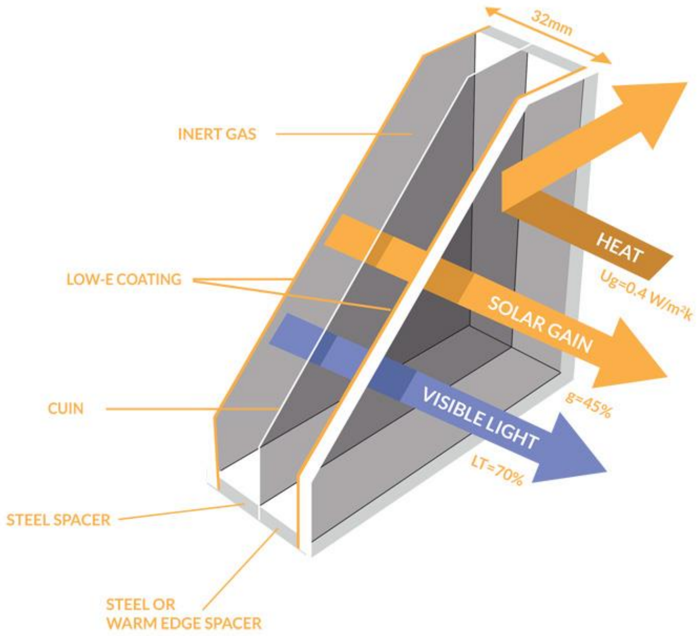


Insulation – trade off

$$R_{\mathrm{tot}} = R_1 + R_2 \qquad R = \frac{w}{S\lambda} \qquad U = \frac{1}{SR} = \frac{\lambda}{w}$$

Window: not just insulation !

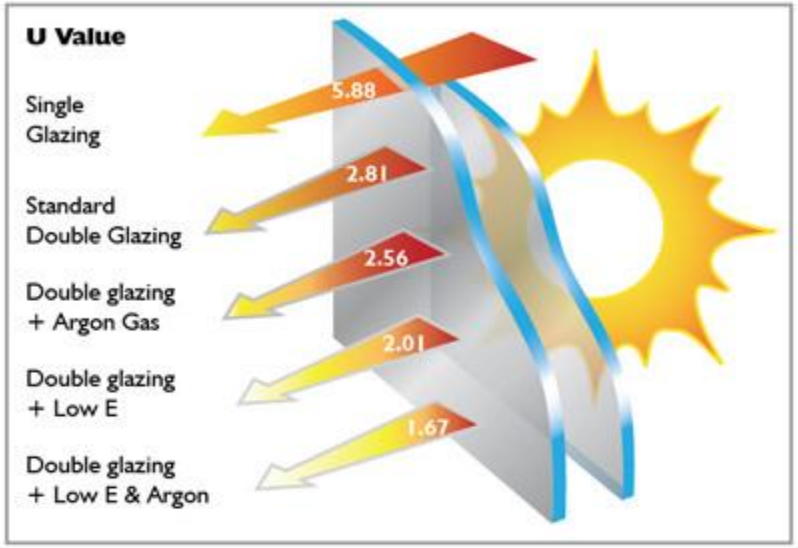
+ Transparent to visible light
+ Transparent to solar heat



U: thermal transmittance

Ug = glazing only

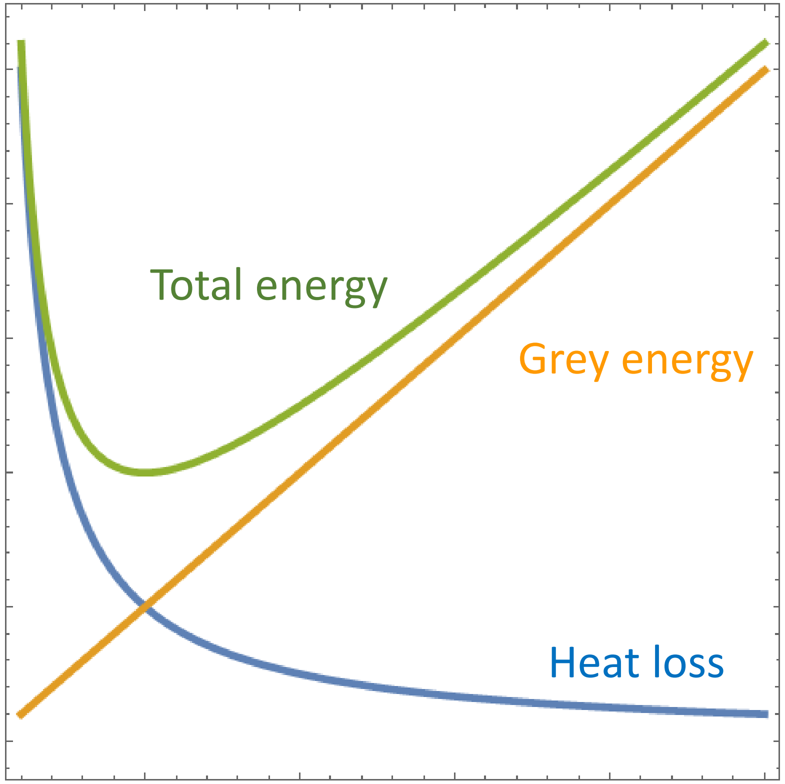
Uw = full window



S, g, F: Solar IR transmission

LT : Optical transmission

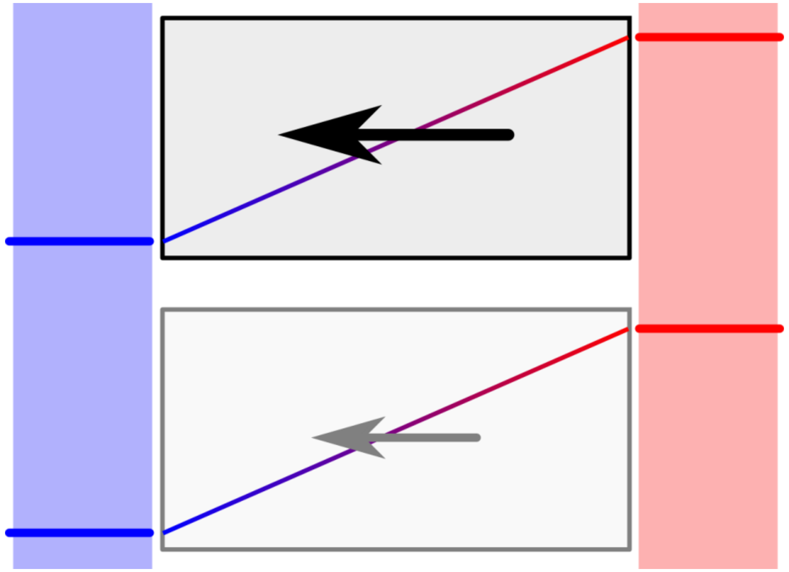
Return on investment



Increasing insulation thickness

Parallel resistance

We want to maintain a different temperature inside as compared to outside.
What is the heata flow that must be sustained?



Heat flows $\phi_1 = \frac{T_{\text{in}} - T_{\text{out}}}{R_1}$ $\phi_2 = \frac{T_{\text{in}} - T_{\text{out}}}{R_2}$

Flow additivity $\phi_1 + \phi_2 = \phi$

$$\Rightarrow \phi = (T_{\text{in}} - T_{\text{out}}) \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

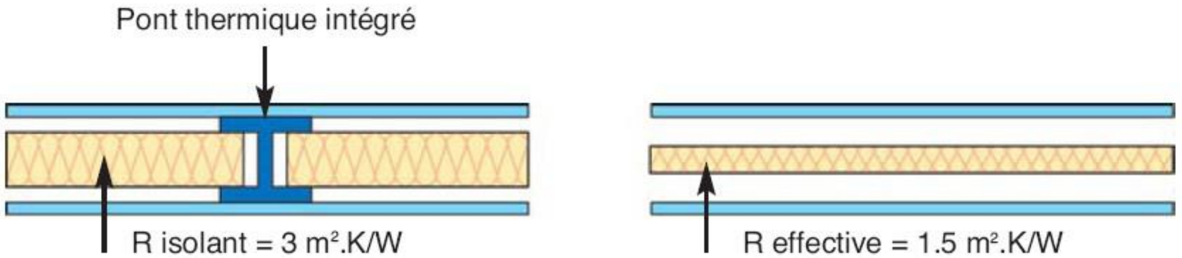
Equivalent resistance

$$R_{\text{tot}}^{-1} = R_1^{-1} + R_2^{-1}$$

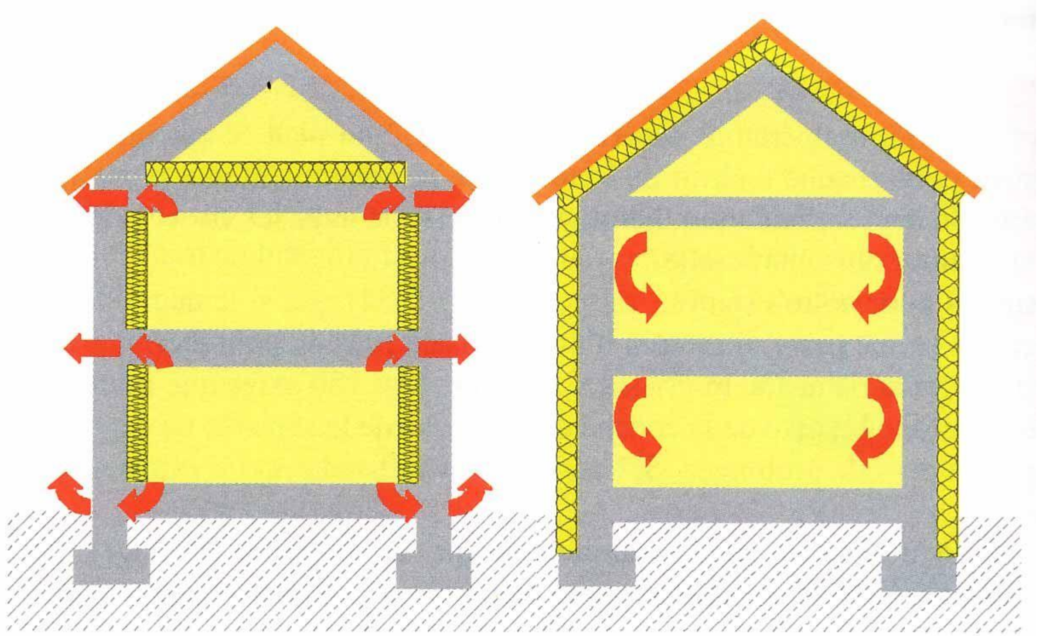
See PC 6

Thermal bridge

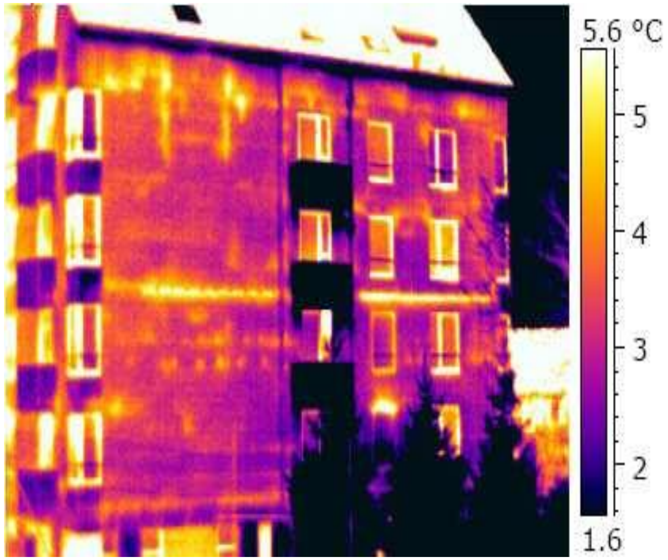
Small resistance // large resistance = small resistance



Why is insulation difficult



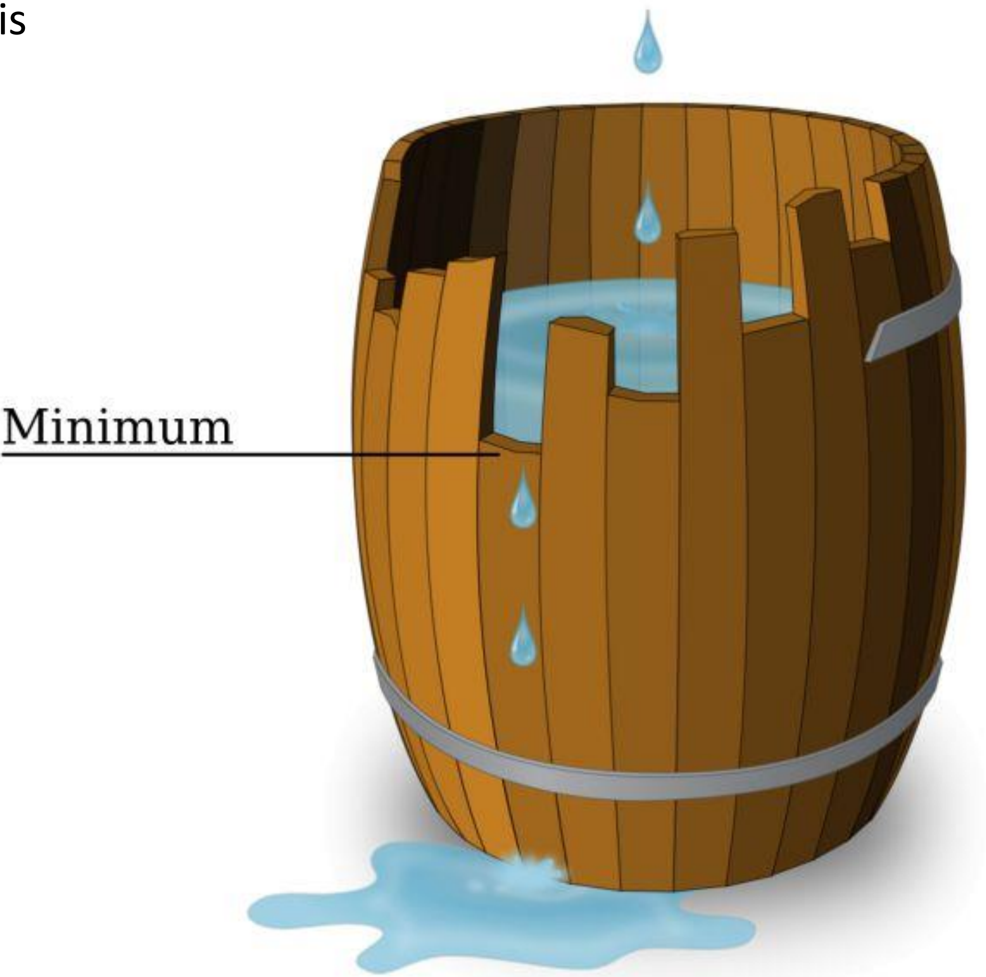
Practical application: where is the thermal bridge?



Law of the minimum

"You are dealing, you see, with the law of the minimum […] Growth is limited by that necessity which is present in the least amount. And, naturally, the least favorable condition controls the growth rate. "

Liet Kynes, imperial planetologist



$$\phi = (T_{\text{in}} - T_{\text{out}}) \left(\frac{1}{R_{\text{wall}}} + \frac{1}{R_{\text{window}}} \right)$$

If the window is already more insulated than the wall, there is no point adding a triple glazing…

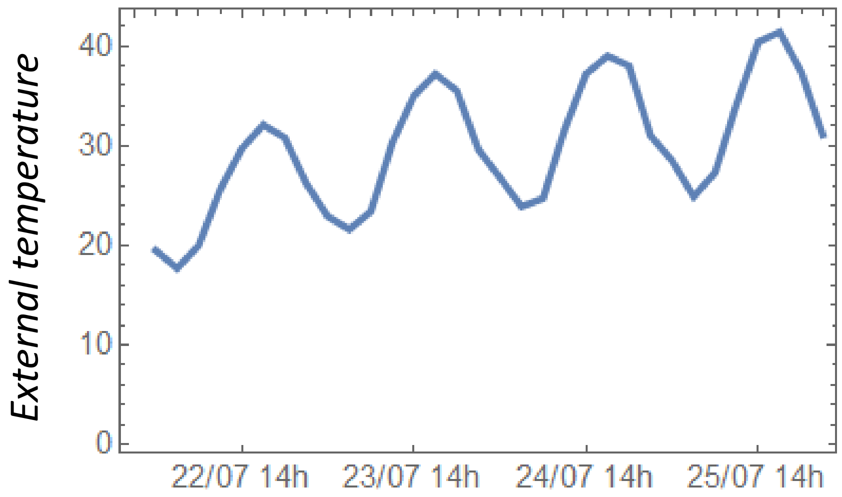
Periodic forcing

$$\mathbf{J} = -\lambda \boldsymbol{\nabla} T$$

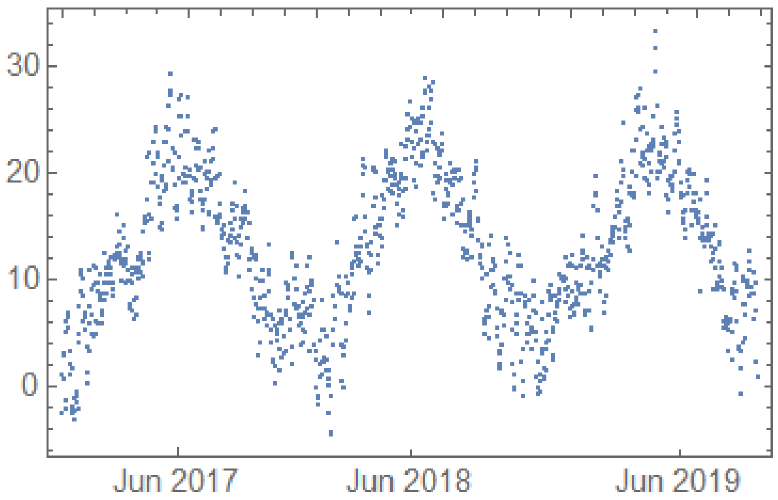
$$\frac{\partial T}{\partial t} = D\,\Delta T$$

Impact of external variations ?

Day / night cycle



Summer / winter cycle



$$T_{\mathrm{out}}(t) = \bar{T}_{\mathrm{out}} + \delta T_{\mathrm{out}} \cos \omega t$$

➡

$$T(x,t) = \bar{T}(x) + \delta T_{\mathrm{out}} e^{-x/\delta} \cos\left(\omega t - \frac{x}{\delta}\right)$$

Skin depth

$$\delta = \sqrt{\frac{2\lambda}{\omega \rho c}}$$

Increases with conductivity

Decreases with frequency

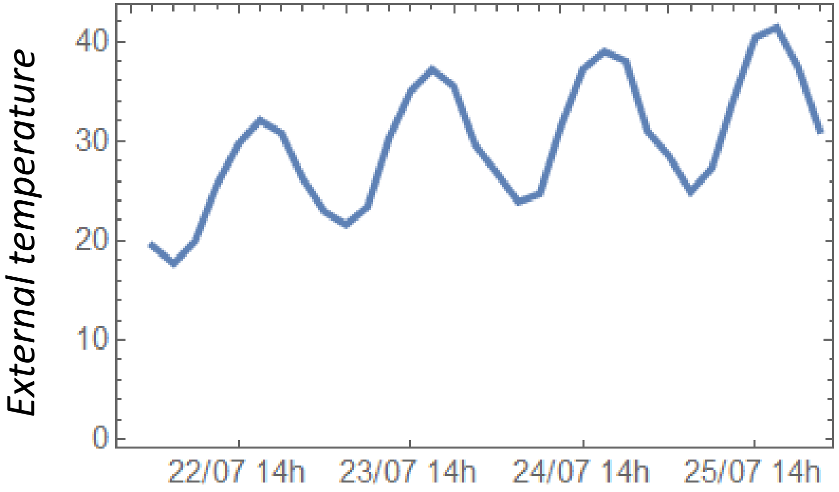
Periodic forcing – skin depth

$$\mathbf{J} = -\lambda \boldsymbol{\nabla} T$$

$$\frac{\partial T}{\partial t} = D\,\Delta T$$

Impact of external variations ?

Day / night cycle



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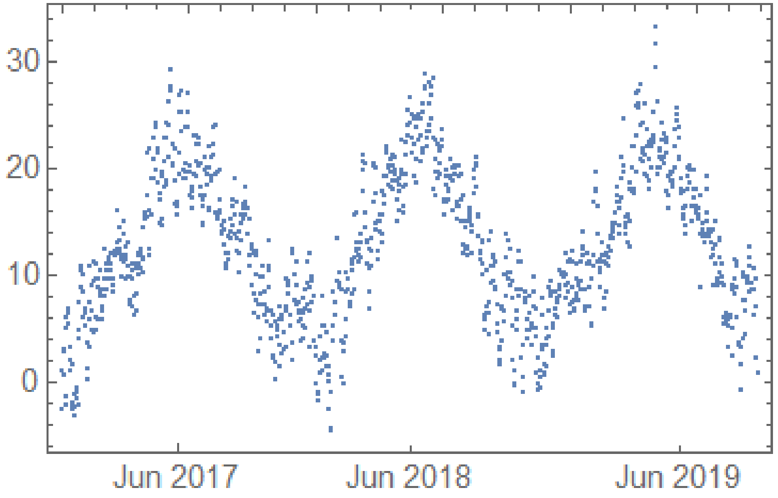
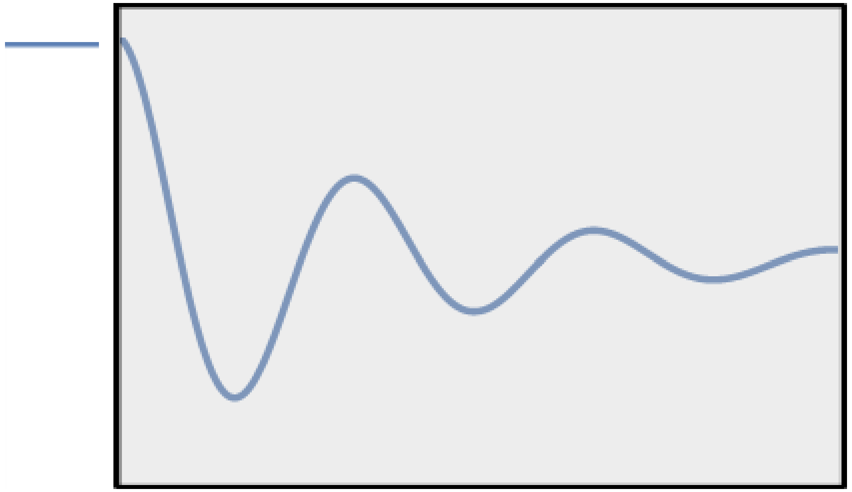




$$T_{\text{out}}(t) = \bar{T_{\text{out}}} + \delta T_{\text{out}} \cos \omega t$$

➡ $$T(x,t) = \bar{T}(x) + \delta T_{\text{out}} e^{-x/\delta} \cos\left(\omega t - \frac{x}{\delta}\right)$$

Damping

Dephasing

Skin depth

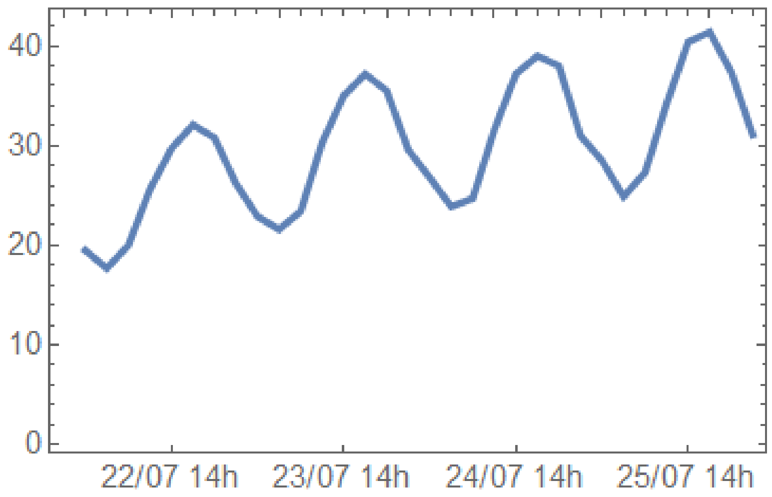
$$\delta = \sqrt{\frac{2\lambda}{\omega \rho c}}$$

Increases with conductivity

Decreases with frequency

Thermal inertia

$$\delta = \sqrt{\frac{2\lambda}{\omega \rho c}}$$



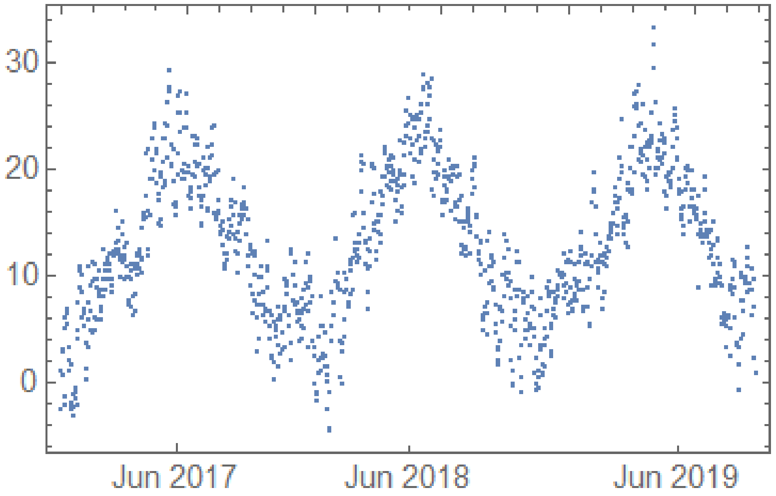
Earth walls

ρ = 1600 kg/m^3

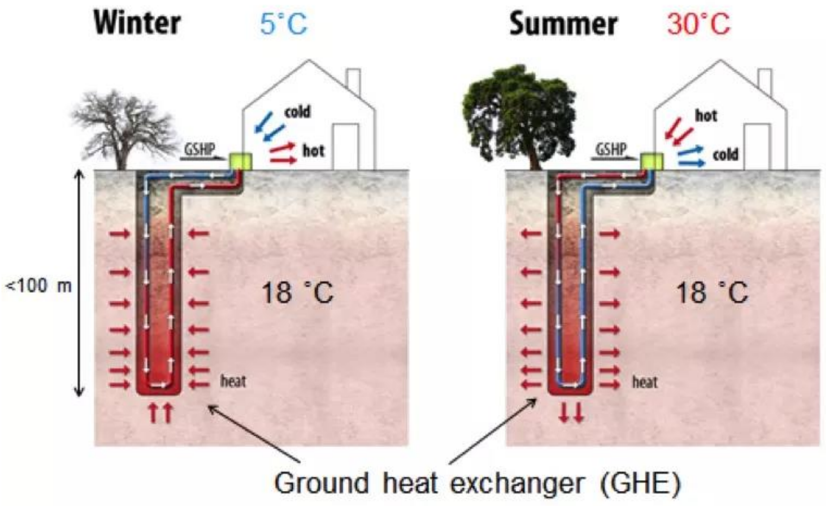
C = 1 kJ/kg/K

λ = 0,65 W/m/K

Day-night cycles
→ δ = 10 cm

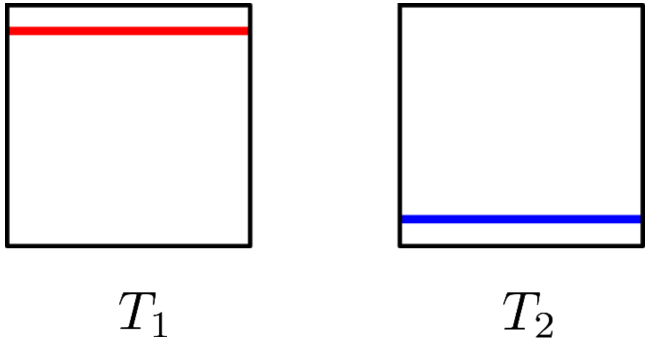


Seasonal cycles
→ δ ~1 m

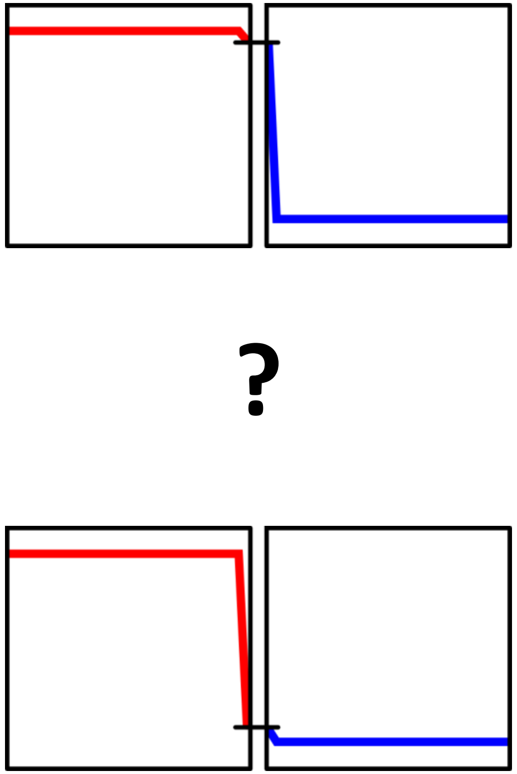


Temperature quench - effusivity

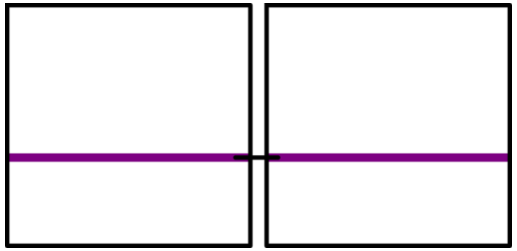
What happens when 2 systems at 2 different temperatures are put in contact?



Before contact



Right after contact

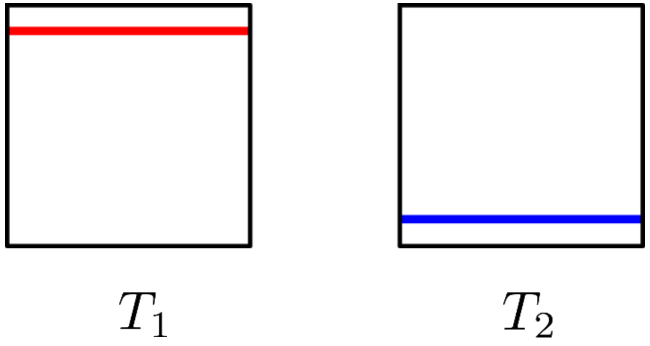


$$T_{\text{final}} = \frac{C_1 T_1 + C_2 T_2}{C_1 + C_2}$$

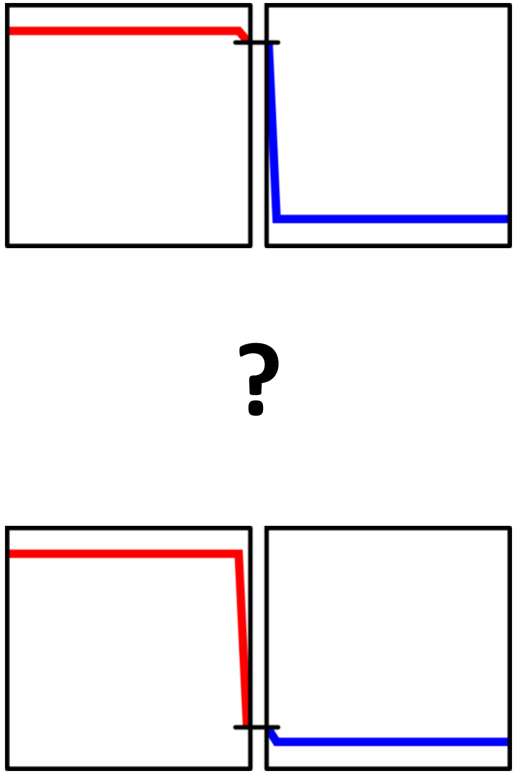
After a long time

Temperature quench - effusivity

What happens when 2 systems at 2 different temperatures are put in contact?



Before contact



Right after contact

$$J(0^+) = J(0^-) \qquad J \sim -\lambda \frac{\Delta T}{\delta}$$

$$T_{\text{contact}} = \frac{e_1 T_1 + e_2 T_2}{e_1 + e_2}$$

Effusivity

$$e = \sqrt{\rho c \lambda}$$

The material with the largest effusivity imposes its temperature

Thermal comfort

	ρ	c_p	k	ρc_p	a	e
	kg/m^3	J/kgK	W/mK	J/m^{3}K*10^6	mm^2/s	w/cm^2/k/s$^{0.5}$
air	1.3	1004	0.03	0.001	19.2	0.0006
wool	100	1500	0.04	0.15	0.23	0.007
balsa wood	130	2301	0.05	0.30	0.17	0.012
polyvinyl chloride	1500	1674	0.17	2.51	0.07	0.06
skin	1000	2500	0.40	2.50	0.16	0.10
quartz	2200	745	1.40	1.64	0.85	0.15
silicon oxide	2200	745	1.40	1.64	0.85	0.15
water	1000	4184	0.60	4.18	0.14	0.16
ice	917	4217	2.10	3.87	0.54	0.28
aluminum oxide	2200	778	18	1.71	10.5	0.56
stainless steel (CrNi)	8000	502	15	4.02	3.73	0.78
tin	7310	226	61	1.65	36.9	1.00
silicon	2330	703	126	1.64	76.9	1.44
iron	7870	448	72	3.52	20.4	1.59
aluminum alloy (7079)	2740	795	121	2.18	55.5	1.62
aluminum	2698	921	226	2.48	91	2.37
gold	19300	128	320	2.47	129	2.81
copper	8940	385	396	3.44	115	3.69

Thermal comfort

	ρ	c_p	k	ρc_p	a	e
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Holding space shuttle tiles at 2200 degrees

Sum up

Heat conductivity	Diffusion coefficient	Thermal resistance	Skin depth	Effusivity
λ	$D = \frac{\lambda}{\rho c}$	$R = \frac{w}{S\lambda}$	$\delta = \sqrt{\frac{2\lambda}{\omega \rho c}}$	$e = \sqrt{\rho c \lambda}$
$\mathbf{J} = -\lambda \boldsymbol{\nabla} T$	$\frac{\partial T}{\partial t} = D \, \Delta T$	$\phi = \frac{T_{\mathrm{in}} - T_{\mathrm{out}}}{R}$	$\exp\left(-\frac{x}{\delta}\right) \cos\left(\omega t - \frac{x}{\delta}\right)$	$T_{\mathrm{c}} = \frac{e_1 T_1 + e_2 T_2}{e_1 + e_2}$

Lecture 8 – thermal energy

I. Overview of heat consumption (what, why, how much ?)

II. **Heat conduction**

- Heat transfer & heat equation
- Insulation 101
- **Thermal energy management**

III. Heat generation

- Geothermal energy
- Heat pump
- Combined heat and power generation

Three direct consequences :

- Thermal resistance
- Thermal inertia
- Thermal comfort

Two indirect consequences :

- **Thermal energy transmission**
- **Thermal energy storage**

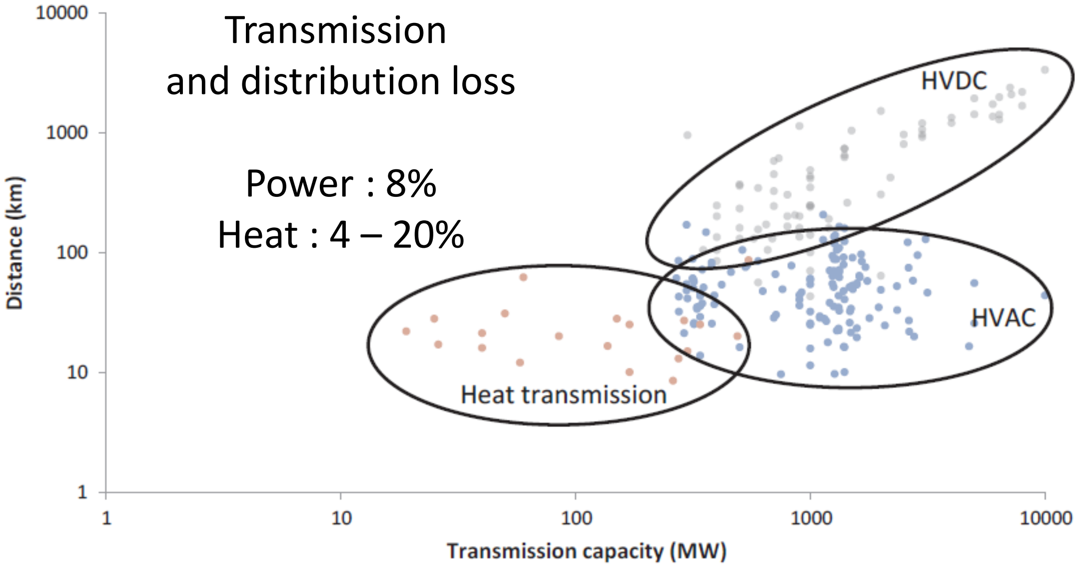
Heat distribution

Small difference bewteen conducting and insulating material

Conductors	10^6 x D [m²/s]	Insulator	10^6 x D [m²/s]
Steel	12	Concrete	0,42
Silver	171	Wood	0,45
Copper	114	Granit	1,10
Brass	33	Glass	0,58

By constrat,
Electrical conductivity [S/m]
Silver ~ 10^7
Quartz ~ 10^{-18}

Heat transport through convection,
not diffusion



Transmission
and distribution loss

Power : 8%
Heat : 4 – 20%

Exploiting waste heat potential by long distance heat transmission

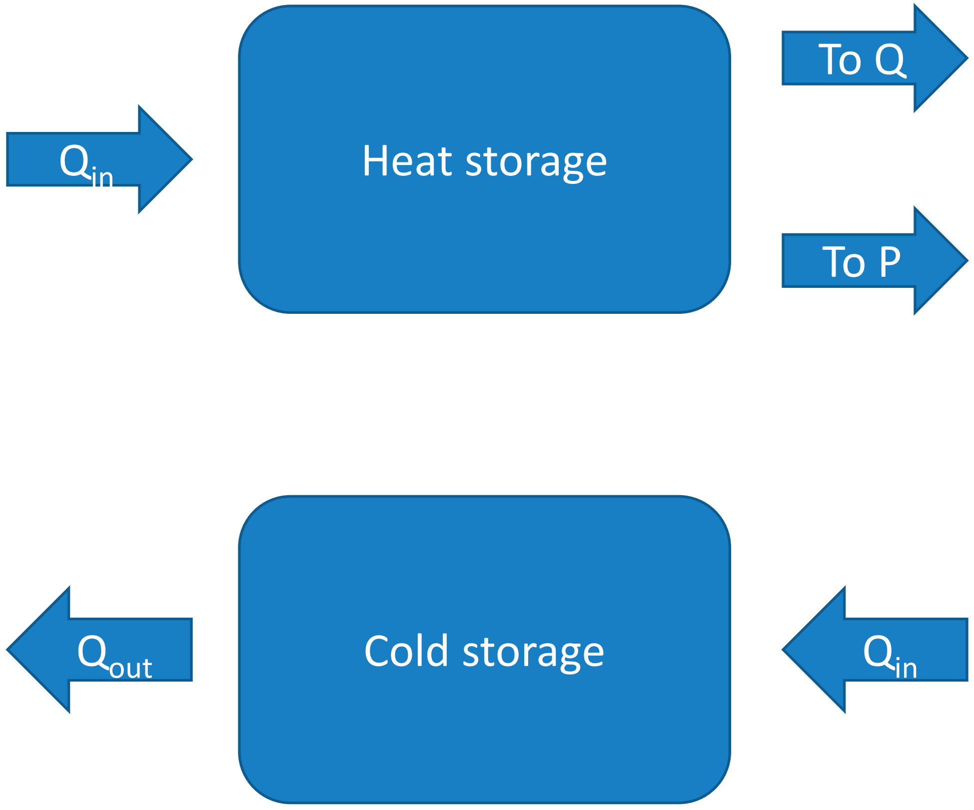
Steam : 120 – 250°C
3-5 km

Water : 90 – 175°C
30 km

Heat (and cold) storage


IRENA

INNOVATION OUTLOOK
THERMAL ENERGY STORAGE


Q_{in}

Heat storage

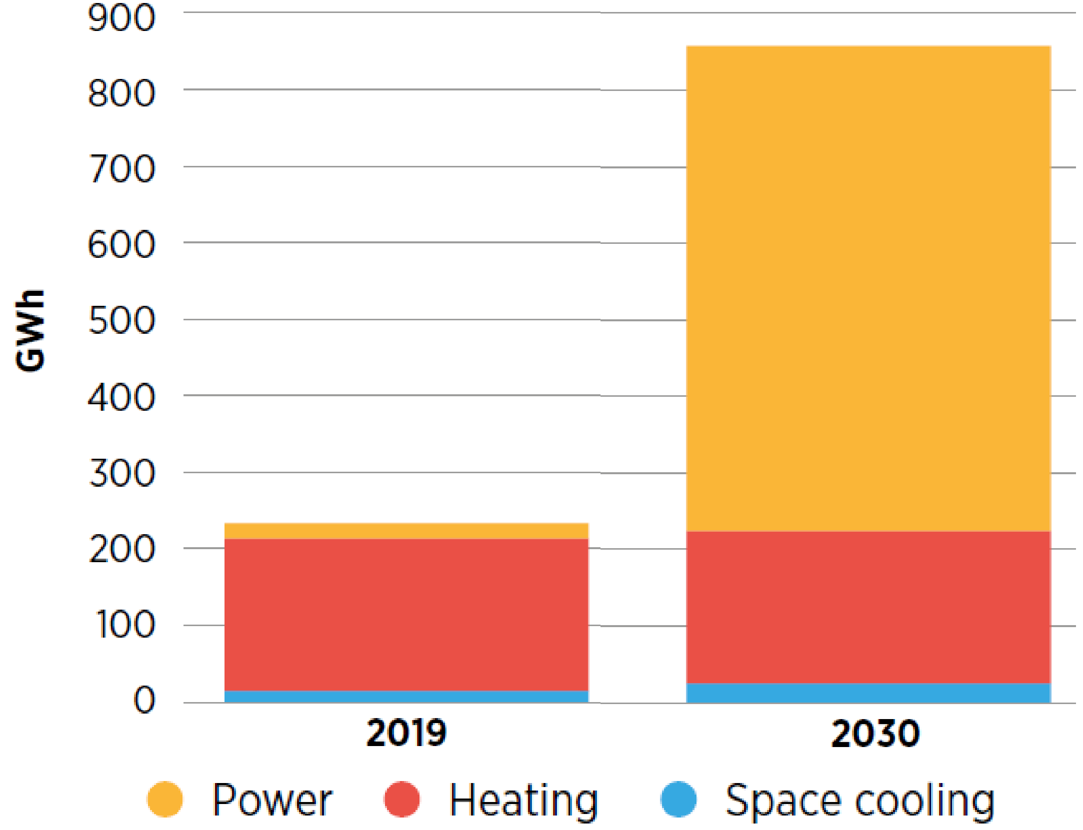
To Q

To P

Q_{out}

Cold storage

Q_{in}

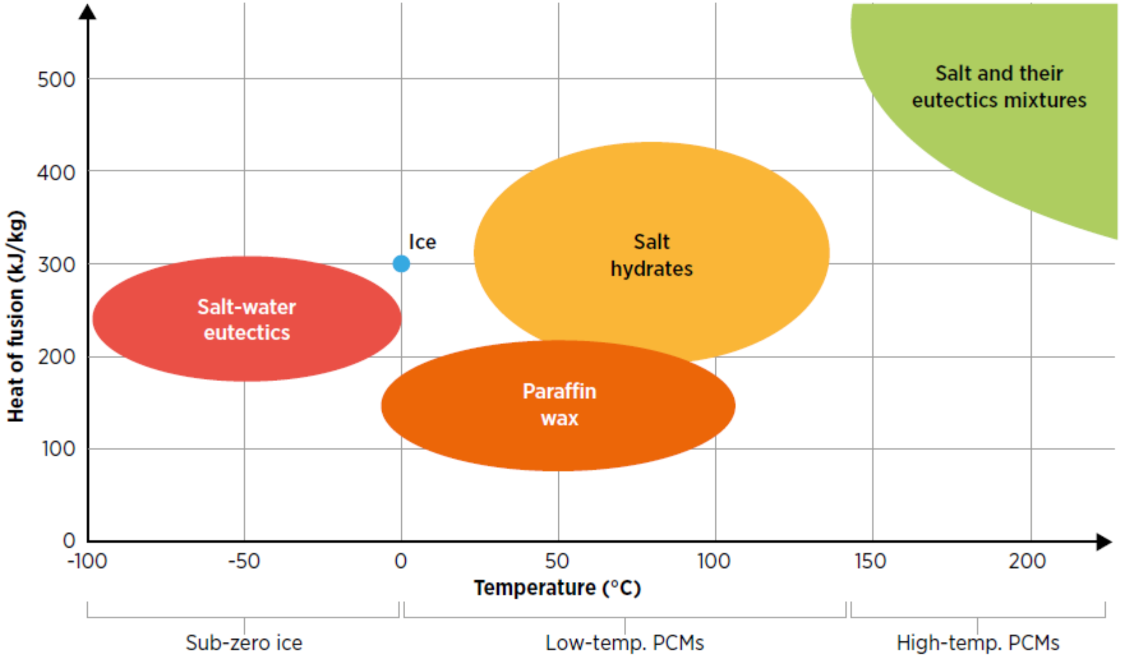


Thermal Energy Storage (TES)

IRENA

INNOVATION OUTLOOK
THERMAL ENERGY STORAGE

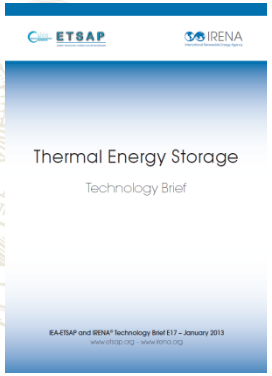
Sensible heat *(change T)*	Water tank Molten salts Solid state (bricks…) Underground (Borehole, aquifer…)
Latent heat *(change phase)*	Phase change at constant temperature Much larger density *Melt 1kg of ice == 1kg of water 0°C → 80°C*
Thermo chemical *(reaction)*	Chemical looping ($CaCO_3 \leftrightarrow CaO + CO_2$) Sorption based (salt hydratation)
Mechanical TES *(reaction)*	Compressed / liquified air



Heat storage technologies

Technology Roadmap

Energy-efficient Buildings: Heating and Cooling Equipment



ETSAP

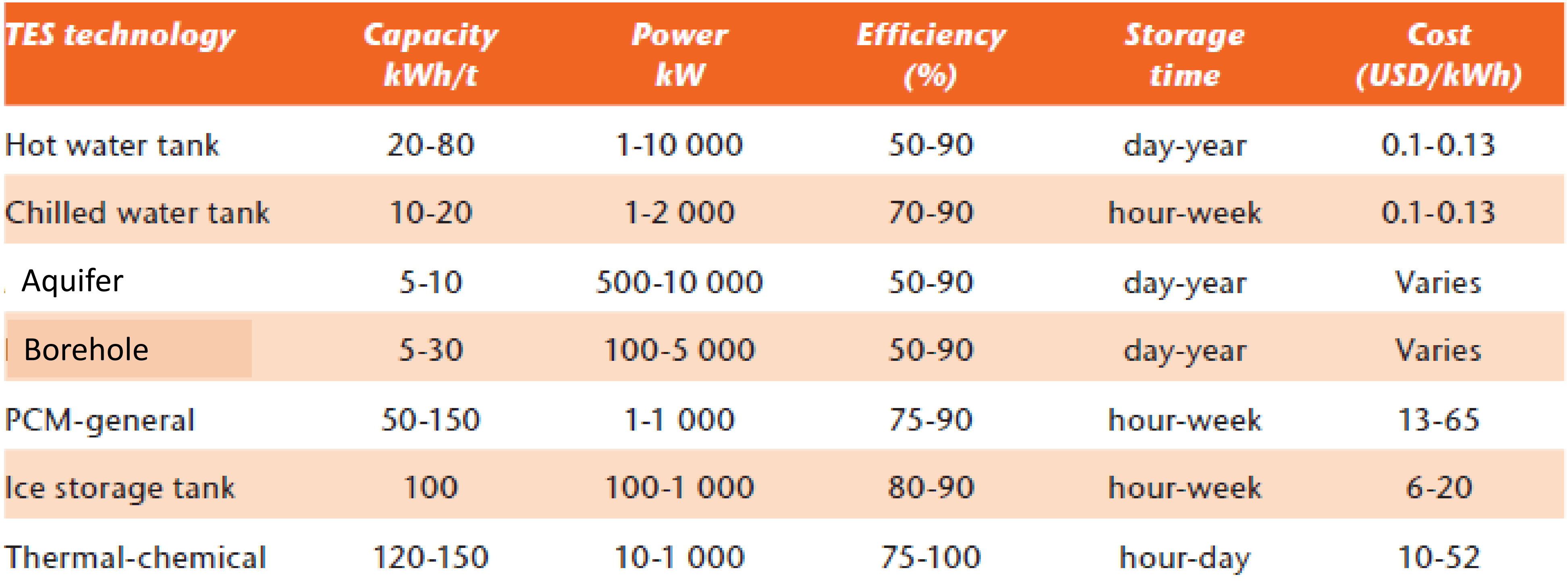
IRENA

Thermal Energy Storage

Technology Brief

IEA-ETSAP and IRENA® Technology Brief E17 – January 2013

Table 6: Energy capacities, power, efficiency and storage time of thermal energy storage technologies

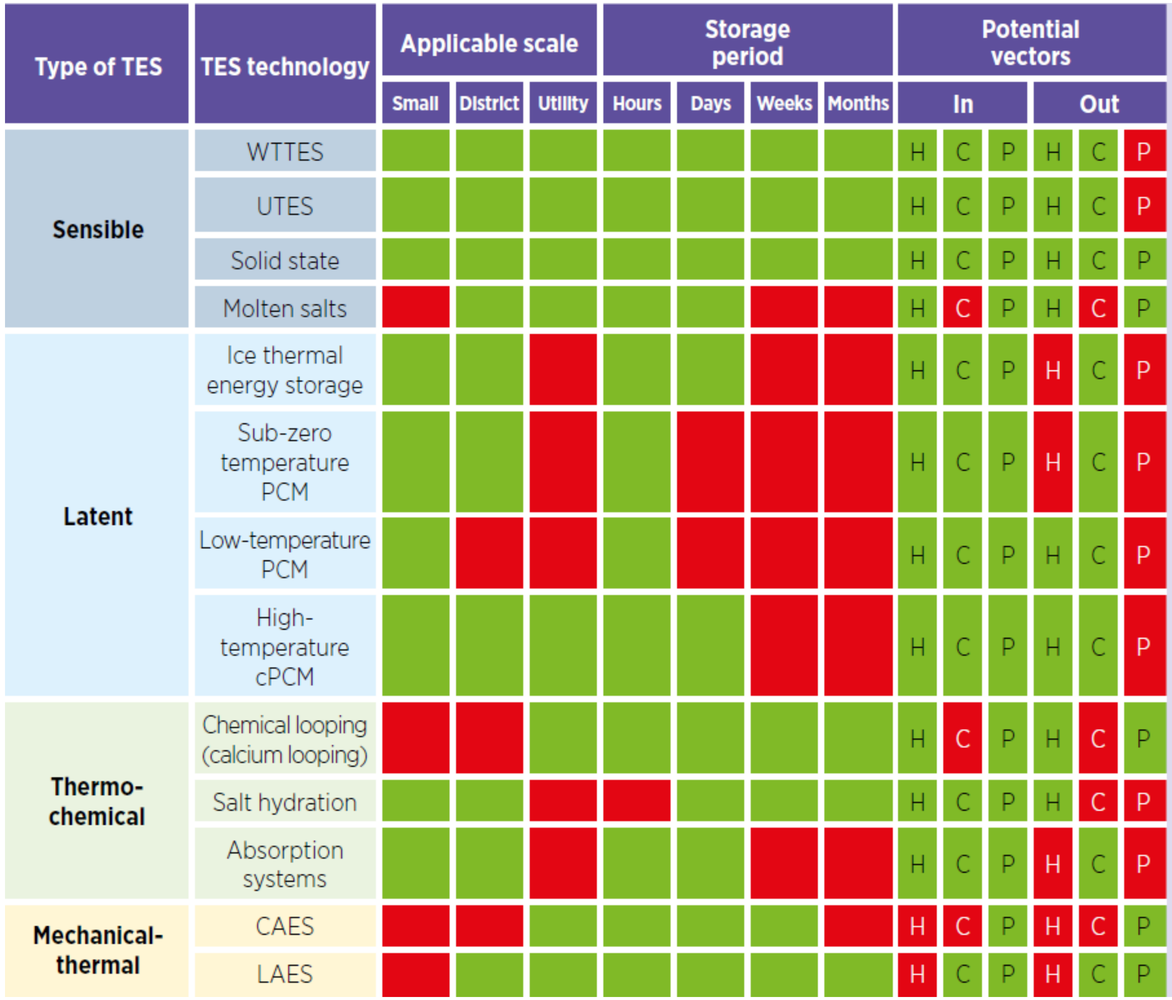


TES technology	Capacity kWh/t	Power kW	Efficiency (%)	Storage time	Cost (USD/kWh)
Hot water tank	20-80	1-10 000	50-90	day-year	0.1-0.13
Chilled water tank	10-20	1-2 000	70-90	hour-week	0.1-0.13
Aquifer	5-10	500-10 000	50-90	day-year	Varies
Borehole	5-30	100-5 000	50-90	day-year	Varies
PCM-general	50-150	1-1 000	75-90	hour-week	13-65
Ice storage tank	100	100-1 000	80-90	hour-week	6-20
Thermal-chemical	120-150	10-1 000	75-100	hour-day	10-52

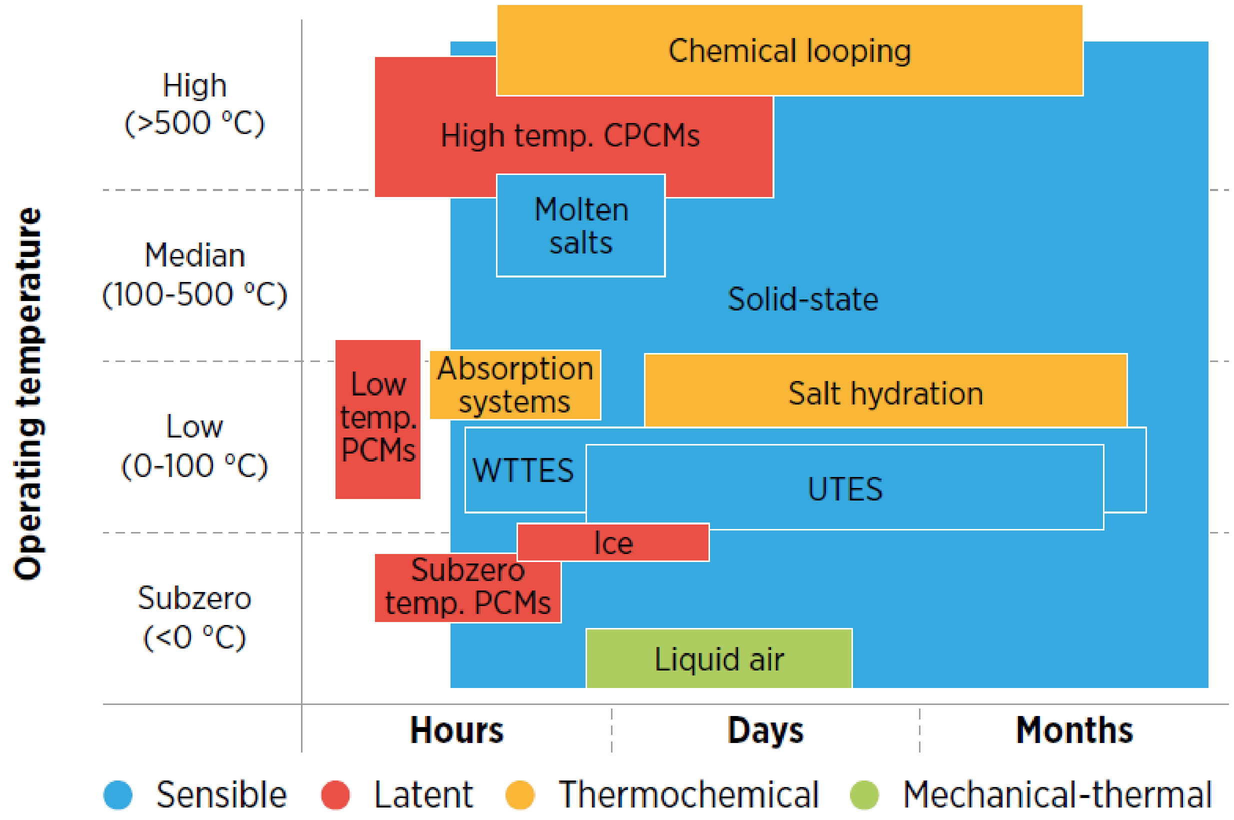
Compairing TES technologies

IRENA

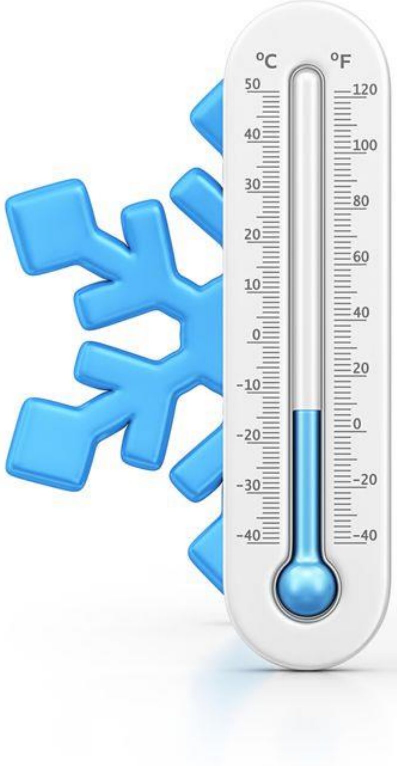
INNOVATION OUTLOOK
THERMAL ENERGY STORAGE



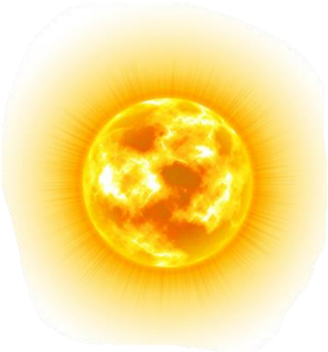
Type of TES	TES technology	Applicable scale			Storage period				Potential vectors					
		Small	District	Utility	Hours	Days	Weeks	Months	In			Out		
Sensible	WTTES	🟩	🟩	🟩	🟩	🟩	🟩	🟩	H	C	P	H	C	🟥 P
	UTES	🟩	🟩	🟩	🟩	🟩	🟩	🟩	H	C	P	H	C	🟥 P
	Solid state	🟩	🟩	🟩	🟩	🟩	🟩	🟩	H	C	P	H	C	P
	Molten salts	🟥	🟩	🟩	🟩	🟩	🟥	🟥	H	🟥 C	P	H	🟥 C	P
Latent	Ice thermal energy storage	🟩	🟩	🟥	🟩	🟩	🟥	🟥	H	C	P	🟥 H	C	🟥 P
	Sub-zero temperature PCM	🟩	🟩	🟥	🟩	🟥	🟥	🟥	H	C	P	🟥 H	C	🟥 P
	Low-temperature PCM	🟩	🟥	🟥	🟩	🟥	🟥	🟥	H	C	P	H	C	🟥 P
	High-temperature cPCM	🟩	🟩	🟩	🟩	🟩	🟥	🟥	H	C	P	H	C	🟥 P
Thermo-chemical	Chemical looping (calcium looping)	🟥	🟥	🟩	🟩	🟩	🟩	🟩	H	🟥 C	P	H	🟥 C	P
	Salt hydration	🟩	🟩	🟥	🟥	🟩	🟩	🟩	H	C	P	H	🟥 C	🟥 P
	Absorption systems	🟩	🟩	🟥	🟩	🟩	🟥	🟥	H	C	P	🟥 H	C	🟥 P
Mechanical-thermal	CAES	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥 H	🟥 C	P	🟥 H	🟥 C	P
	LAES	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟥 H	C	P	🟥 H	C	P

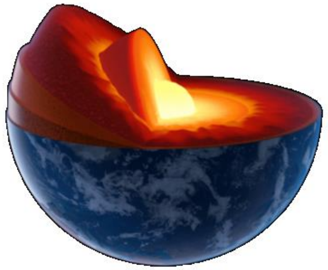


Heat generation - alternatives

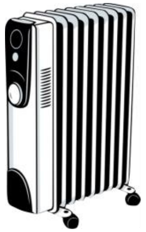


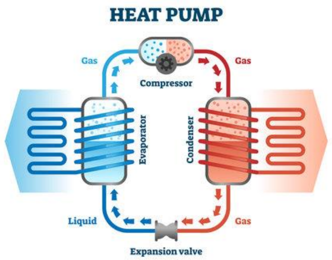
Standard fuels
Mostly gas





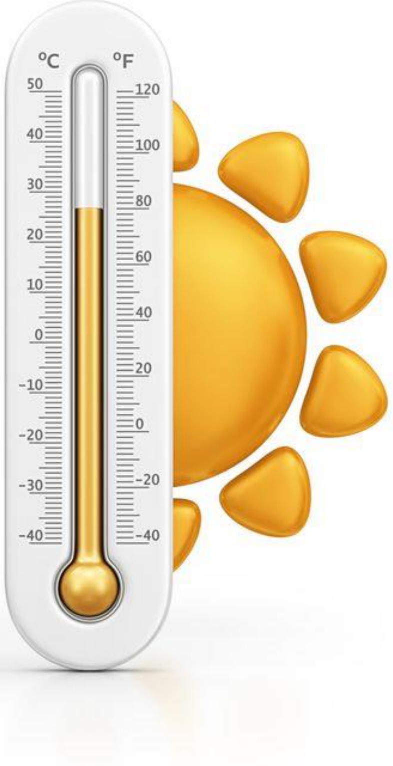
Renewable heat source
Solar (Lecture 6)
Geothermal





Power to heat
Toaster (not addressed)
Heat pump

Recover heat wastes
Combined heat and power (CHP)



Lecture 8 – thermal energy

I. Overview of heat consumption (what, why, how much ?)

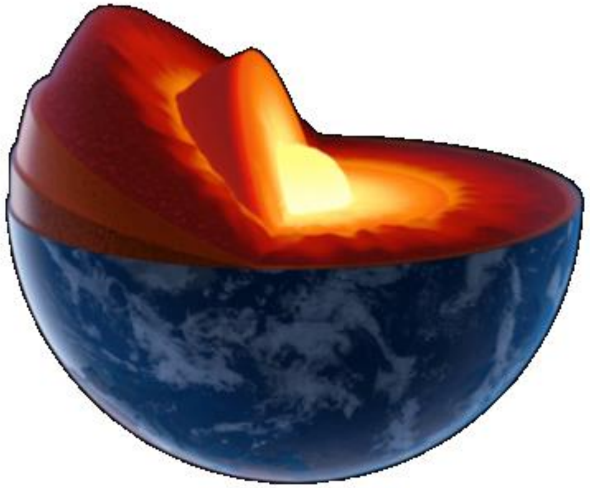
II. Heat conduction

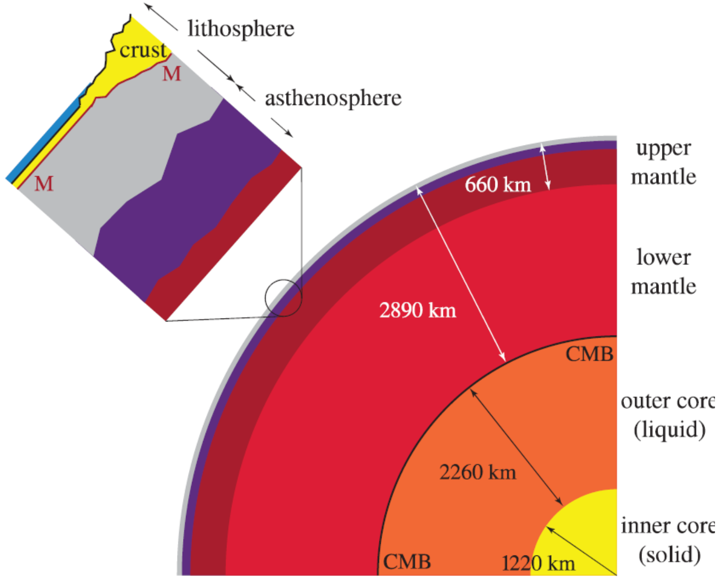
- Heat transfer & heat equation
- Insulation 101
- Thermal energy management

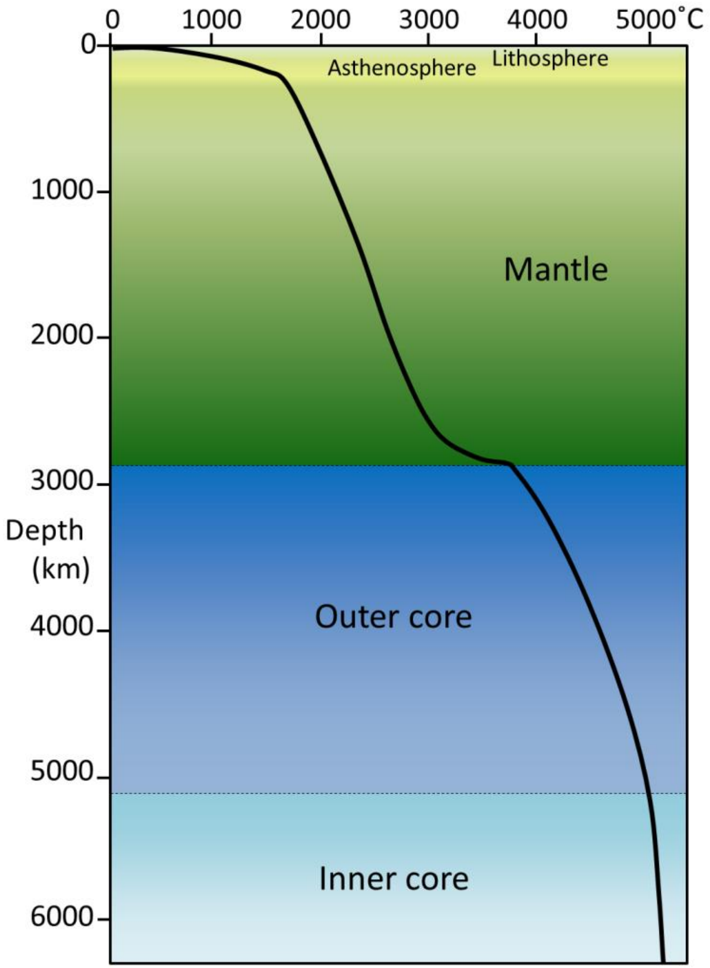
III. Heat generation

- **Geothermal energy**
- Heat pump
- Combined heat and power generation

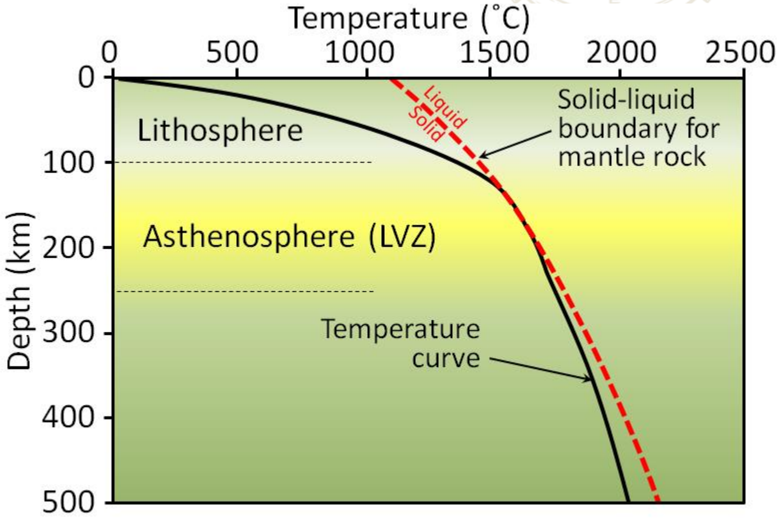
Geothermal ressource







Steven Earle, **Physical Geology**



Gradient close to the surface :

30 K / km

Heat flux

$$J_r(R_T) = 87\,\mathrm{mW/m^2}$$

Total power: $\phi_{\mathrm{tot}} = 44\,\mathrm{TW}$

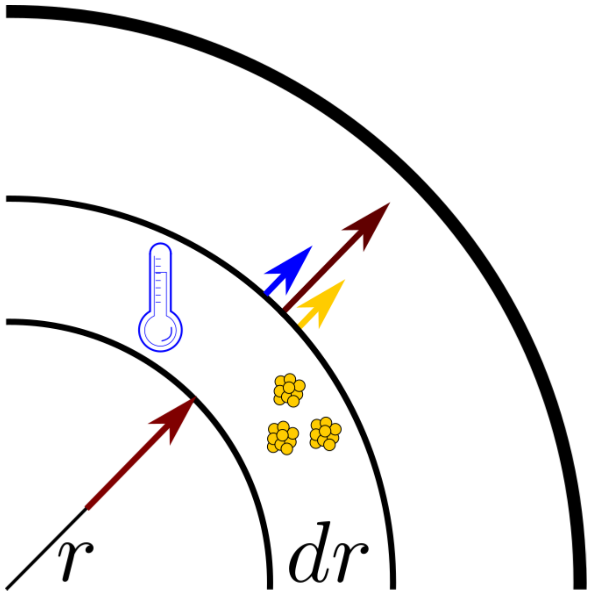
Geothermal ressource: origin

Heat produced by Radioactive decay

Now with a source term $$\frac{\partial u}{\partial t} + \mathrm{div}\mathbf{J} = \mathcal{P}$$

Temperature profile: two contributions $$\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r}\right) T = \frac{1}{D}\left(\frac{\mathcal{P}}{\rho c} - \frac{\partial T}{\partial t}\right)$$

Heat flow at the surface $$\mathbf{J} = -\lambda \boldsymbol{\nabla} T$$

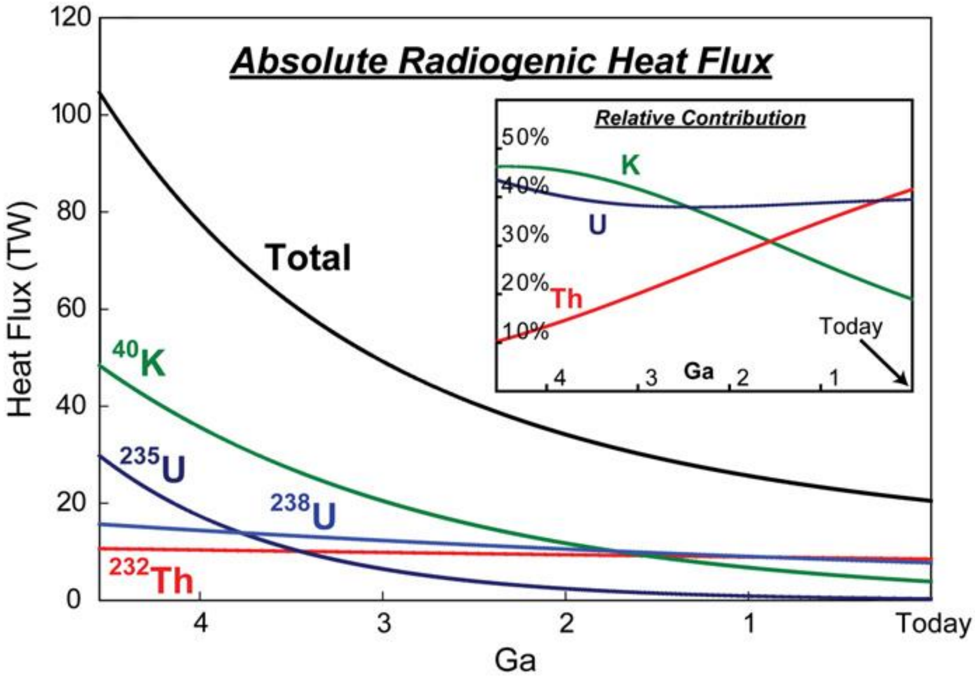


$$\phi_{\mathrm{tot}} = 44\,\mathrm{TW}$$

$$\phi_{\mathrm{radioactivity}} \simeq 30\,\mathrm{TW}$$

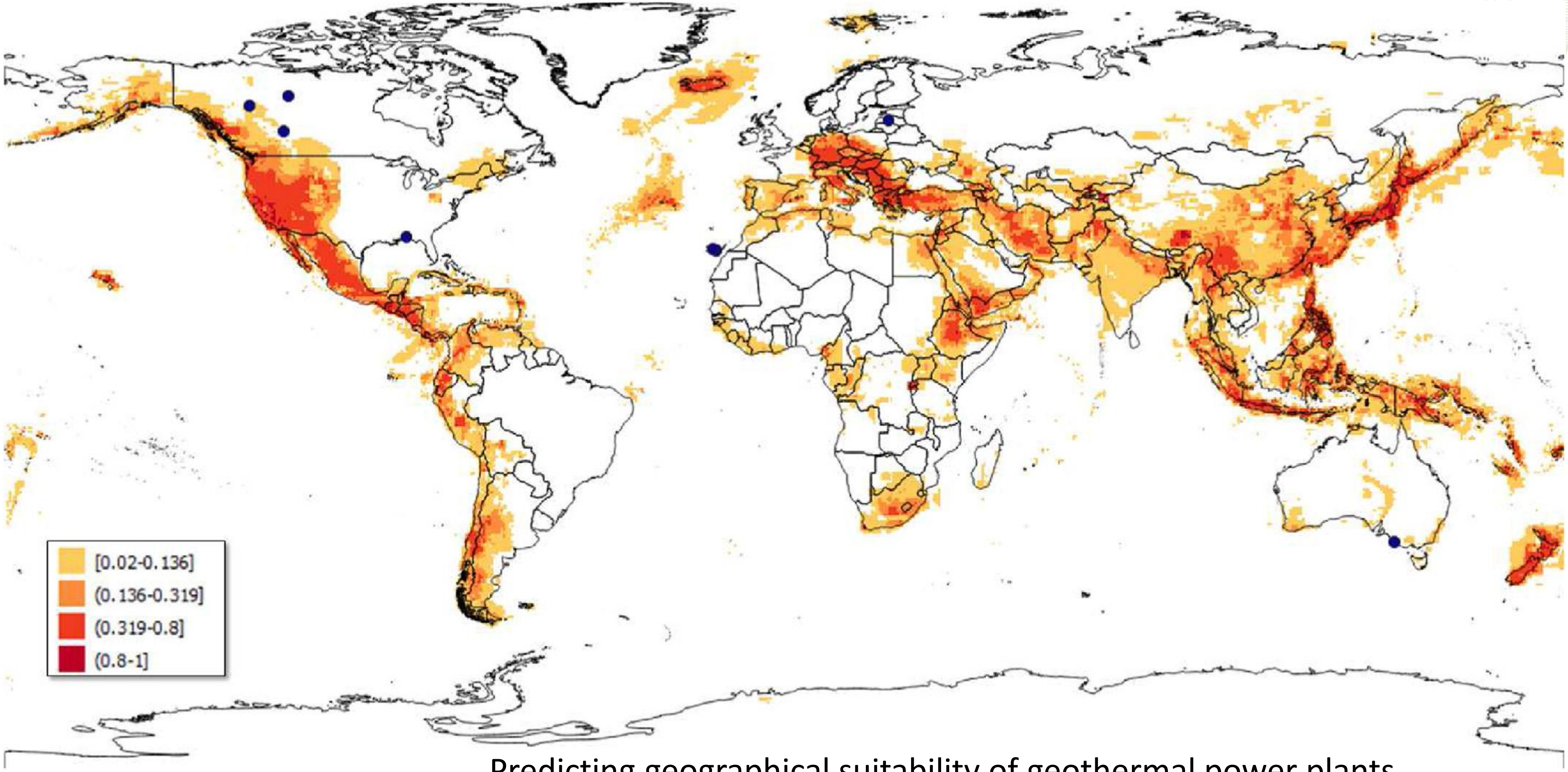
$$\phi_{\mathrm{cooling}} \simeq 14\,\mathrm{TW}$$

Earth cooling : -5 to 10 K / Myr



into mantle composition, structure and thermal evolution

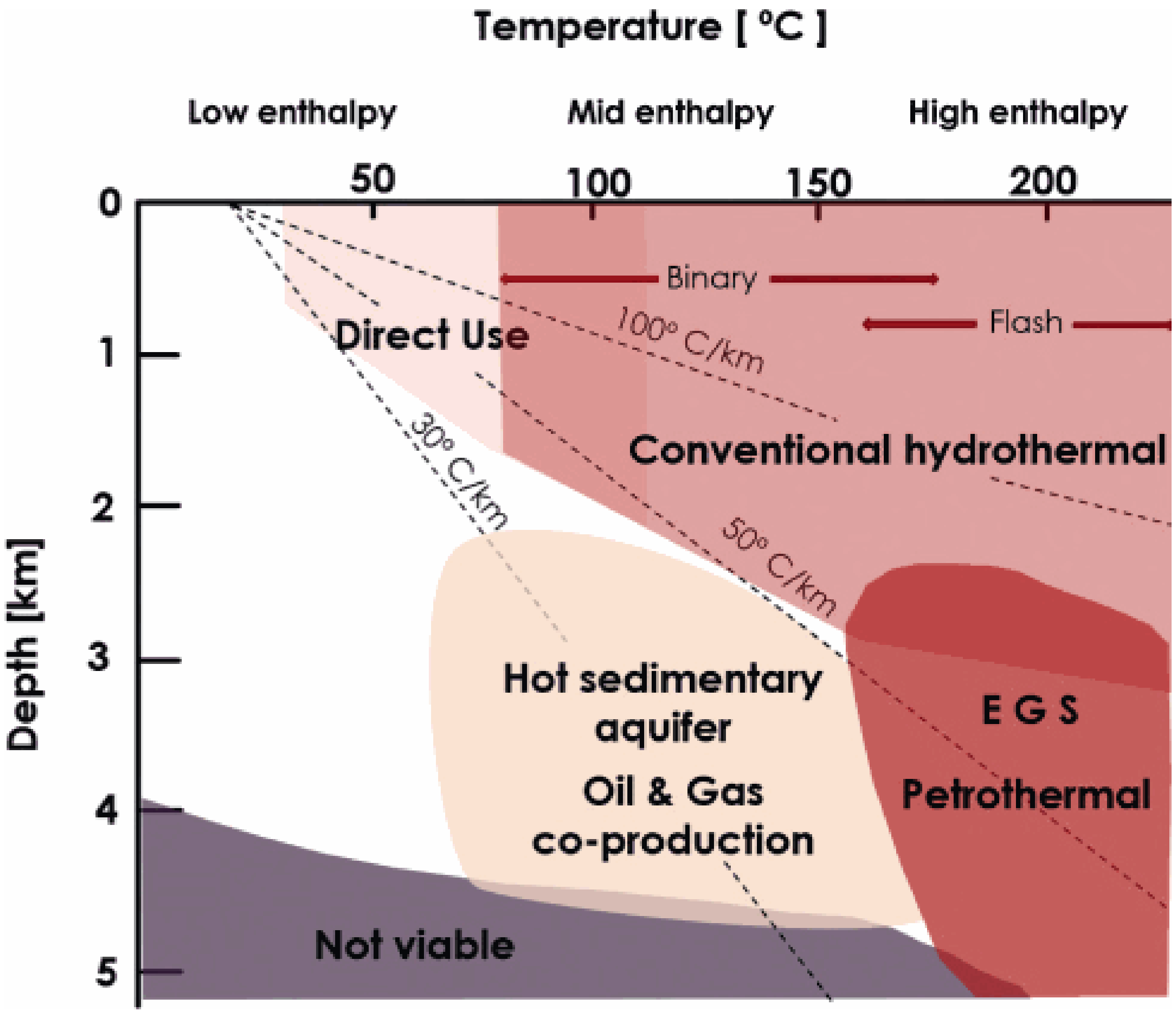
Geothermal ressource distribution

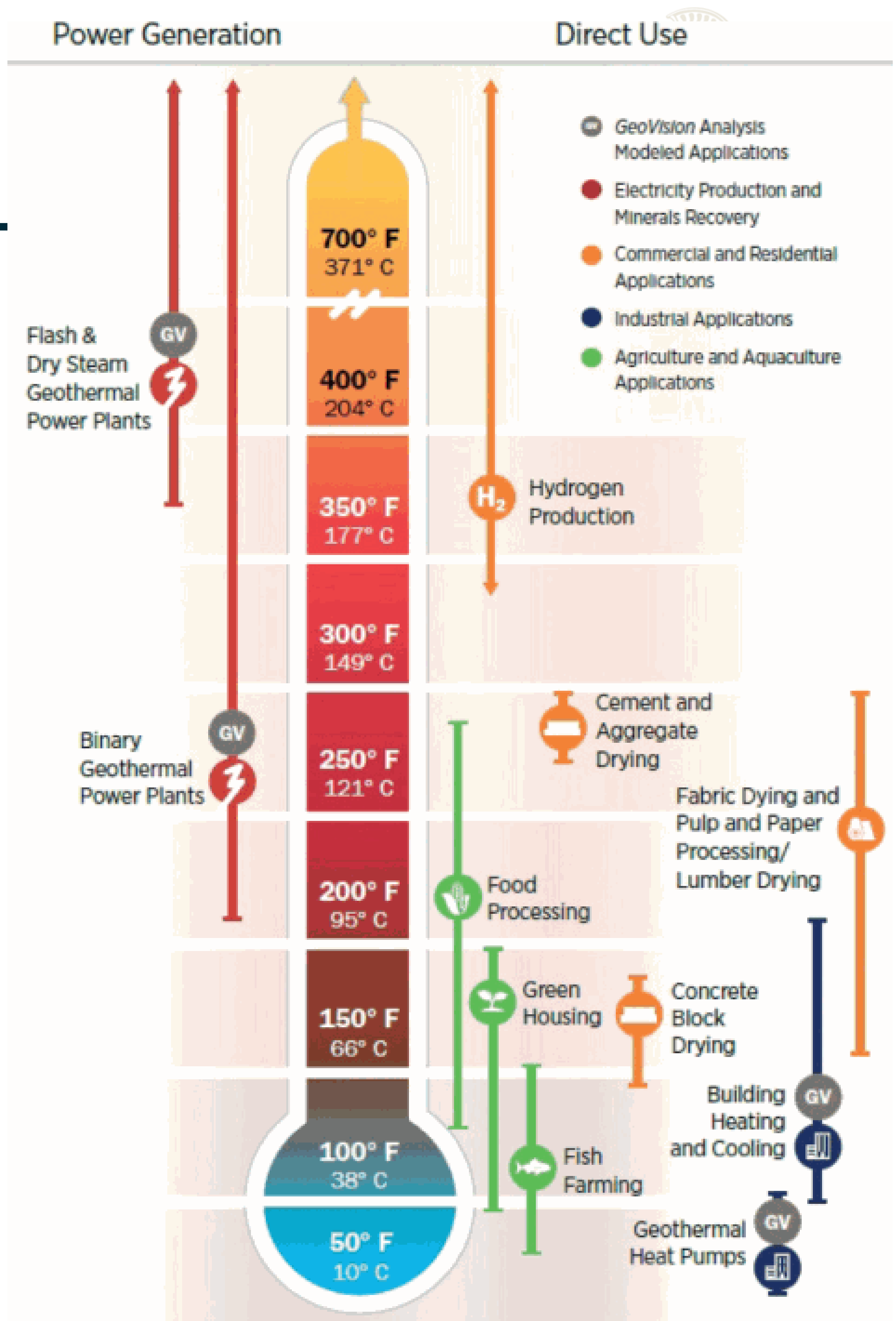


Predicting geographical suitability of geothermal power plants

Low and high temperatures

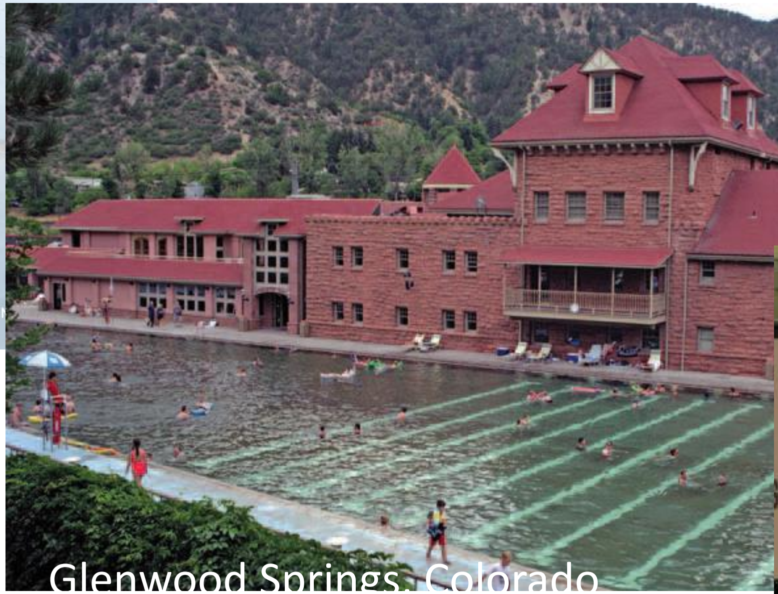
The current status of deep geothermal energy



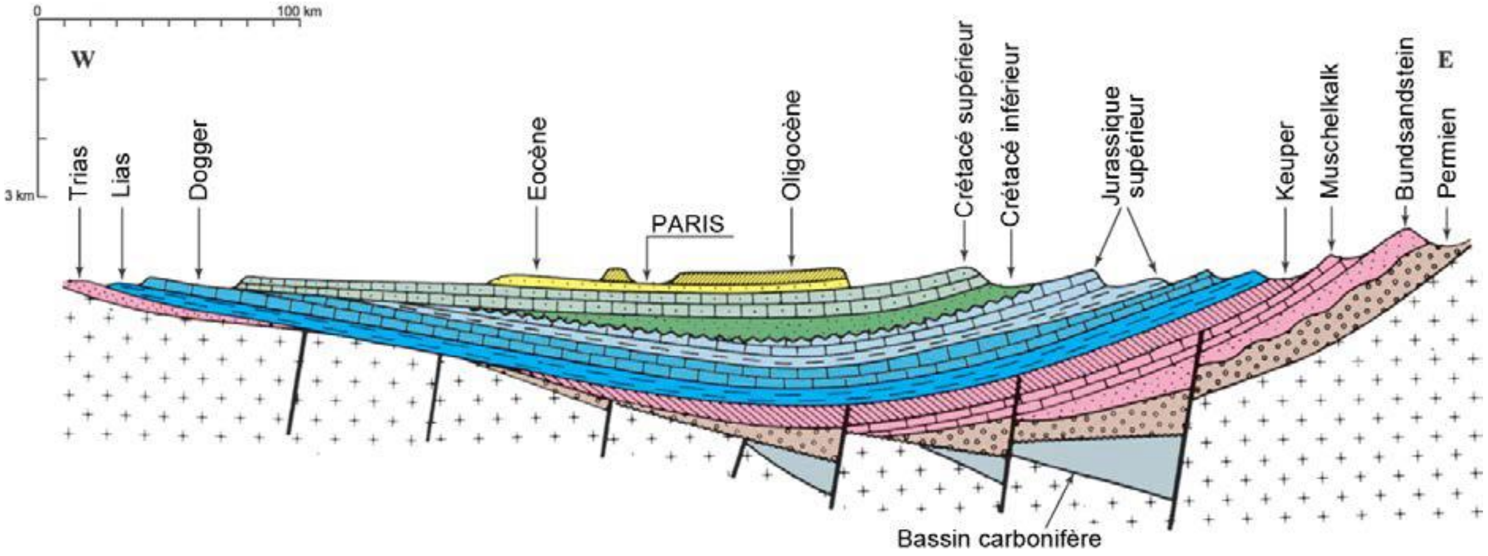


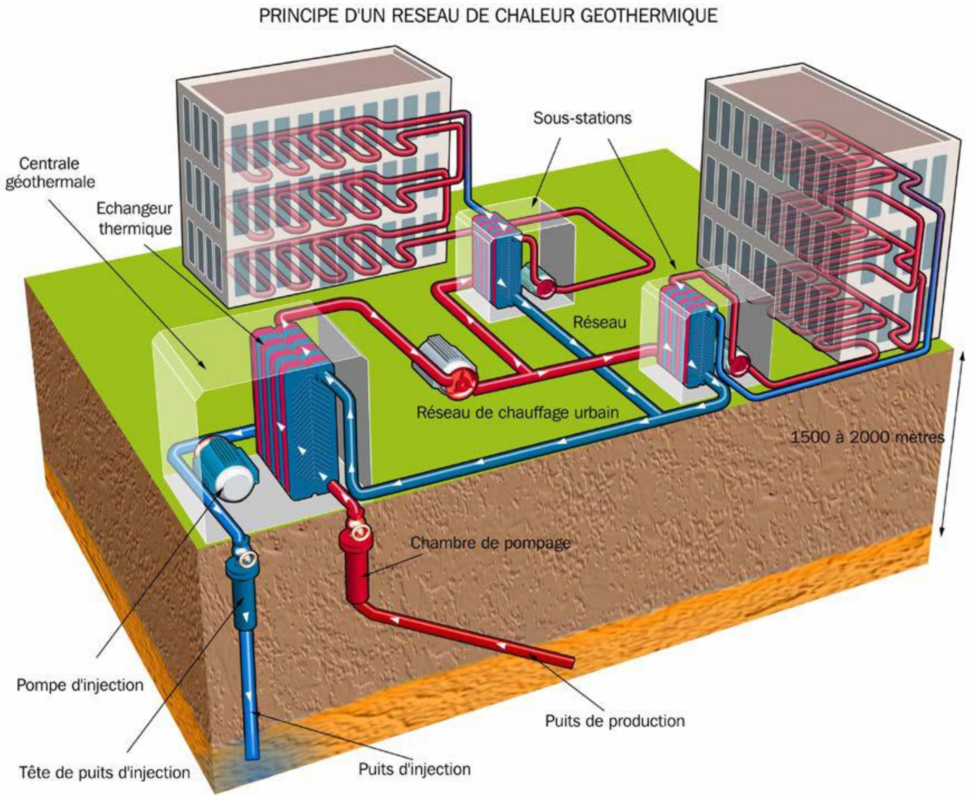
Low temperature geothermy

Natural applications


Glenwood Springs, Colorado

Low temperature geothermy





Dogger aquifer :

15 000 km² large, 1700m deep
Temperature : 55°C – 85°C

Ile de France region:

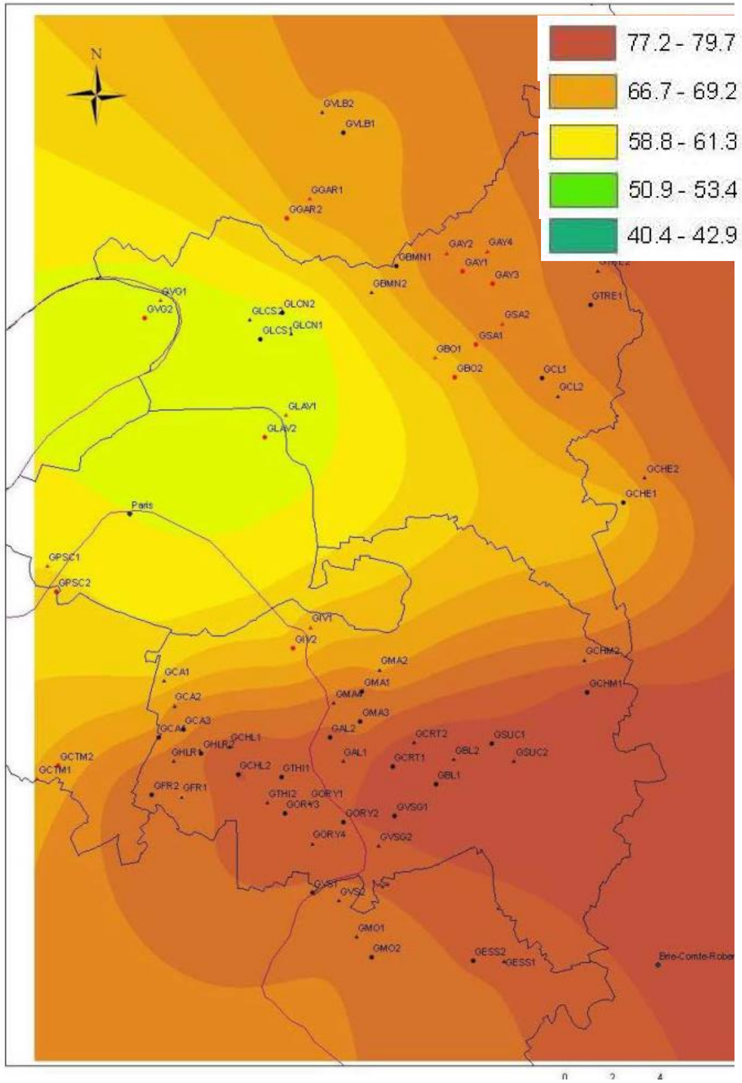
36 installations, 200 000 housings, 500 000 persons
1,5 TWh/yr

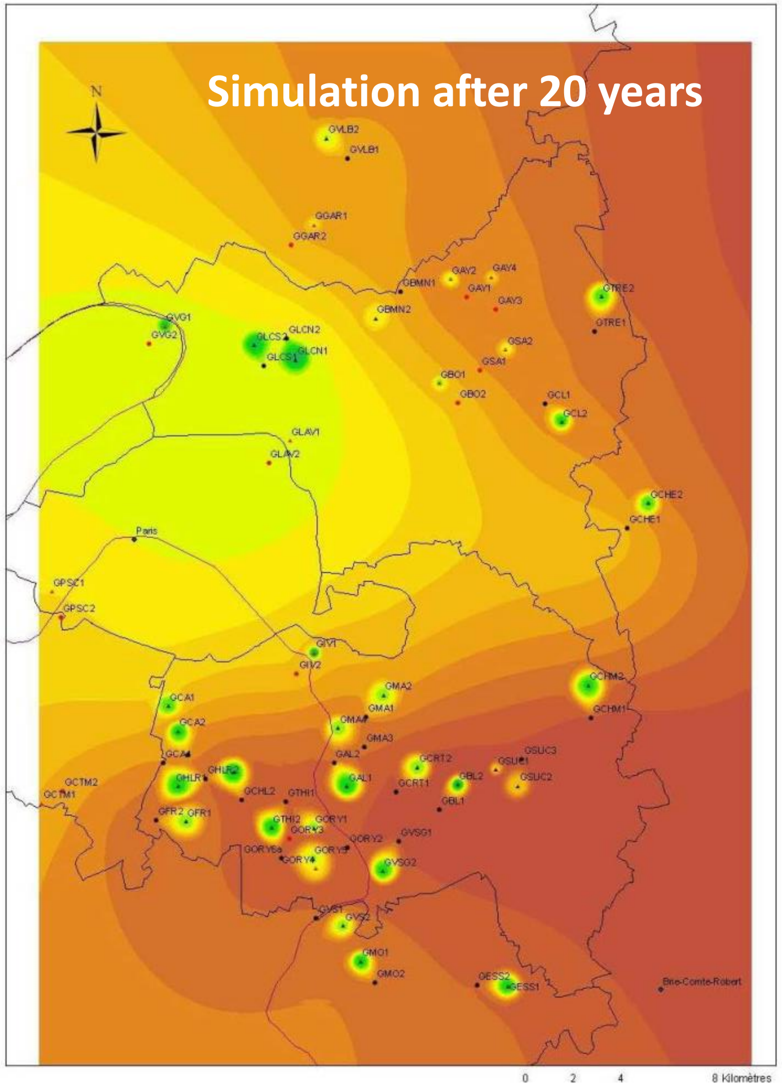
Low temperature geothermy

Uneven distributions

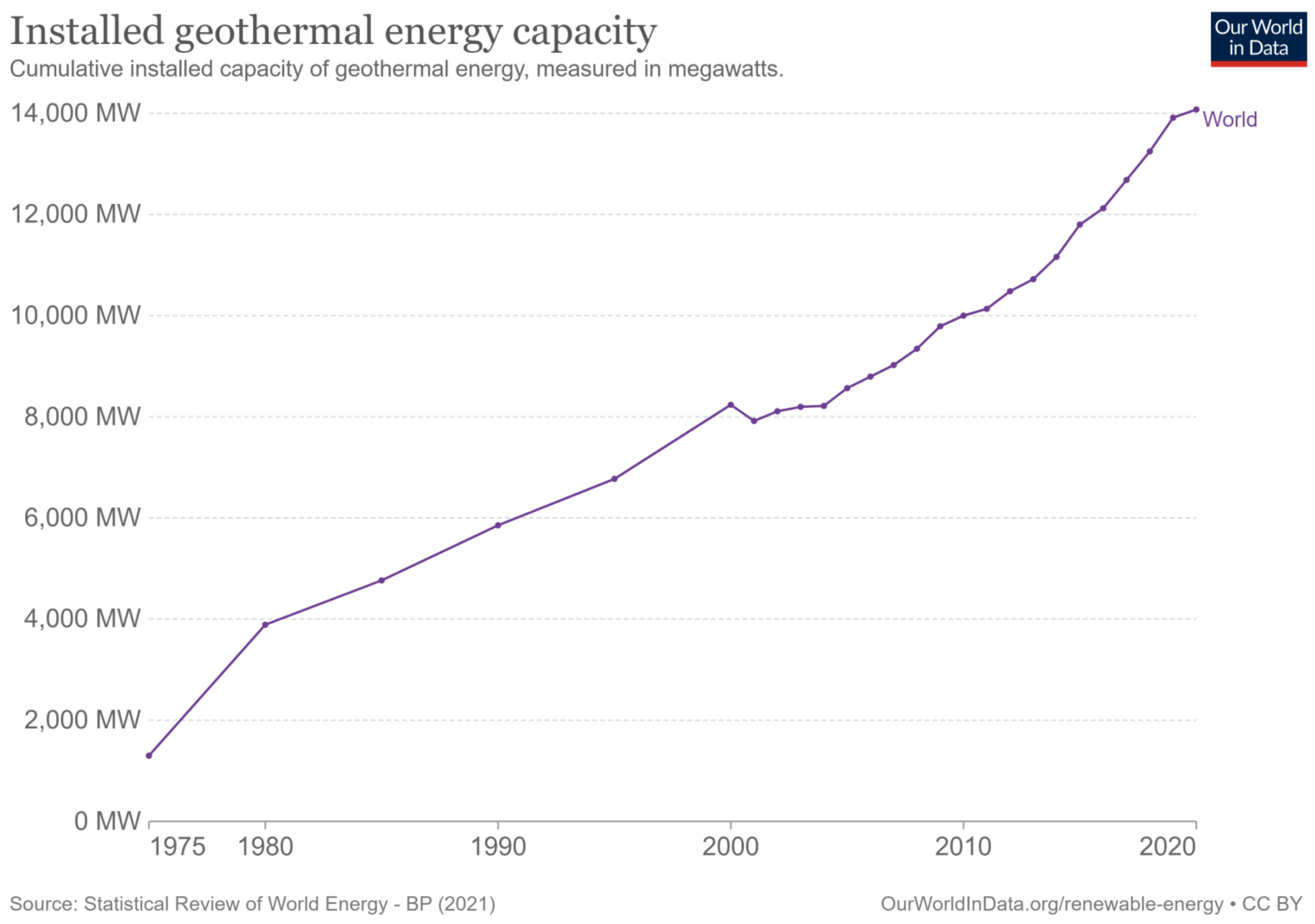
Cold bubbles ? (not as bad as expected)

Heat distribution




Simulation after 20 years

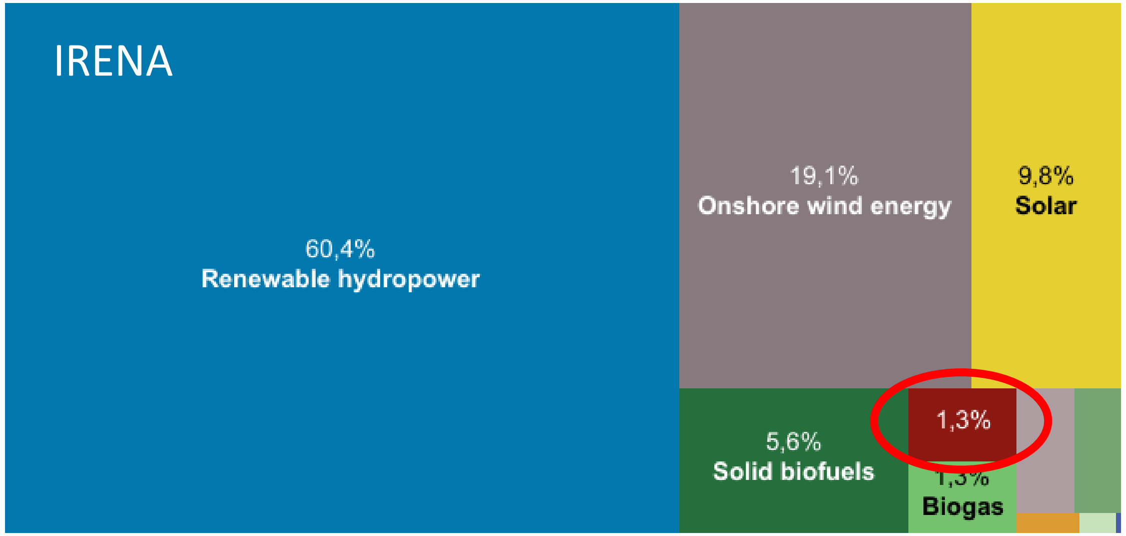
Geothermal installed capacity

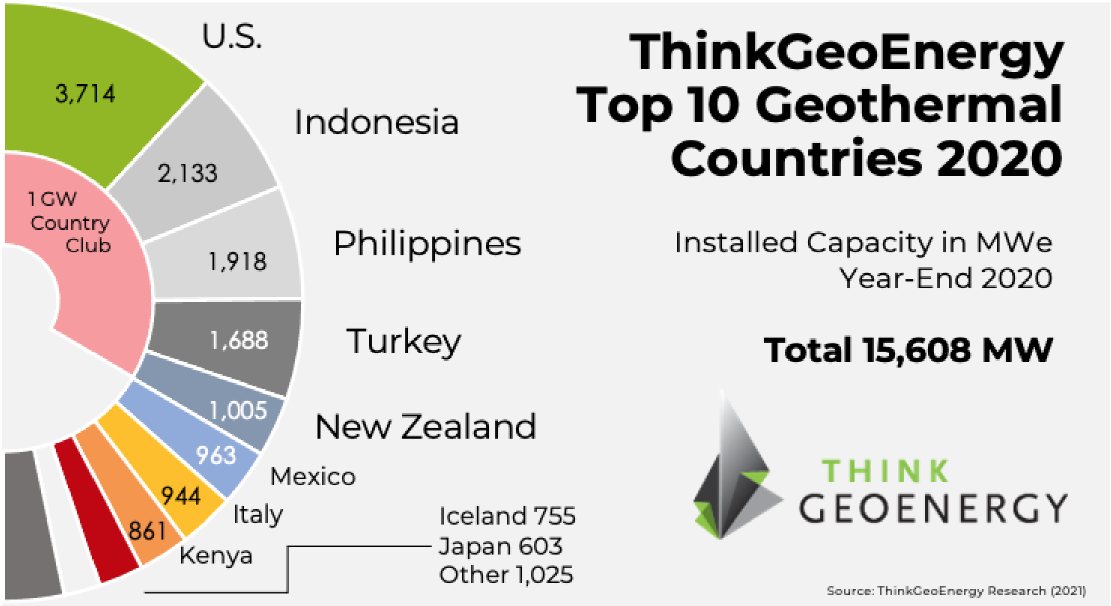

Installed geothermal energy capacity

Cumulative installed capacity of geothermal energy, measured in megawatts.

Source: Statistical Review of World Energy - BP (2021)

OurWorldInData.org/renewable-energy • CC BY




ThinkGeoEnergy Top 10 Geothermal Countries 2020

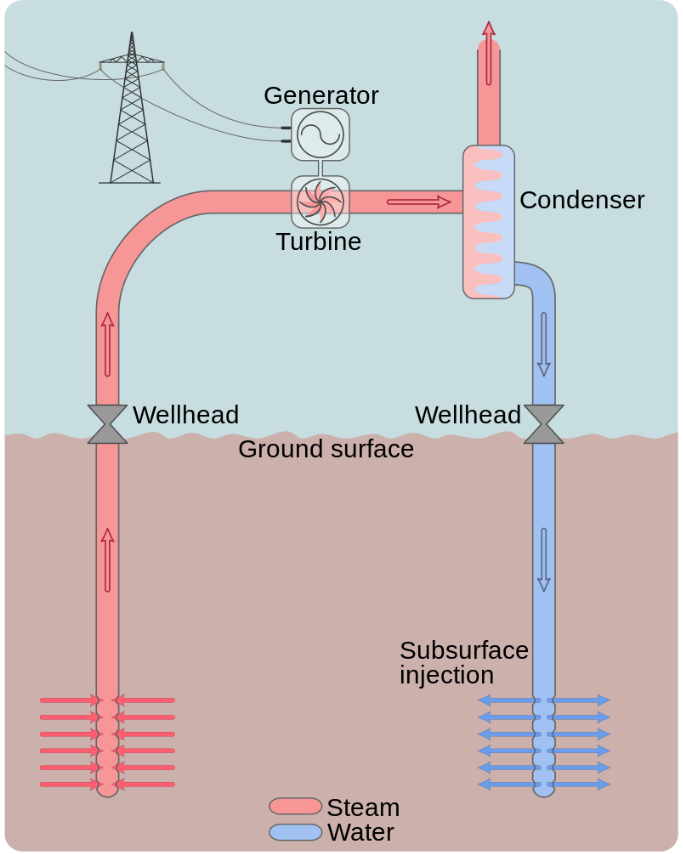
Installed Capacity in MWe
Year-End 2020

Total 15,608 MW

Source: ThinkGeoEnergy Research (2021)

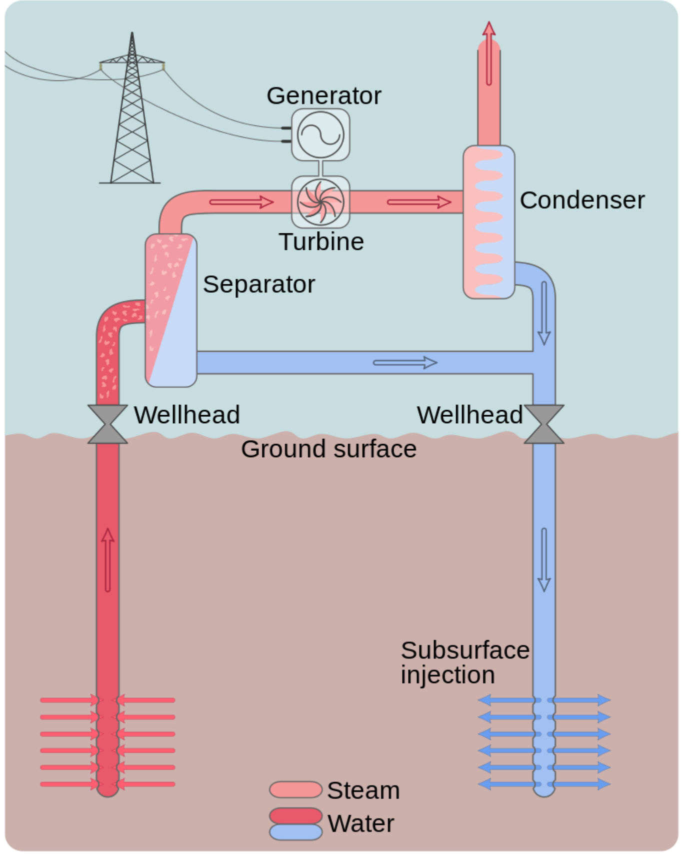
High temperature geothermy

Dry steam



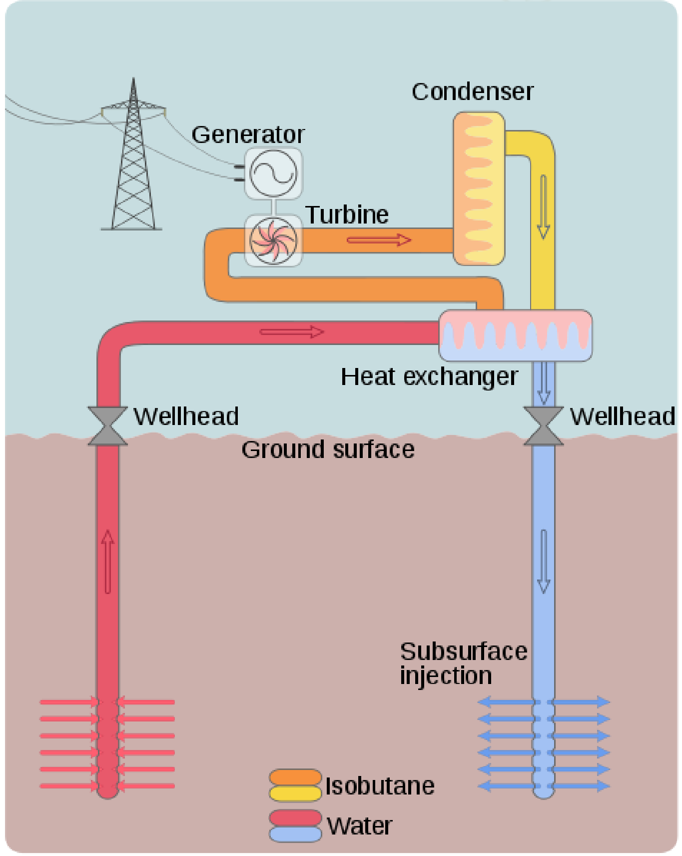
First geothermal plant
(1904, Lardarello, Italy)

Flash



Most of currently operating plants

Binary



Most of currently planned plants

Wikimedia Commons

Example of geothermal power plant

Nesjavellir Geothermal Power Station

Commissioned 1990 as thermal plant
upgraded to power plant in 1998
further improved capacity

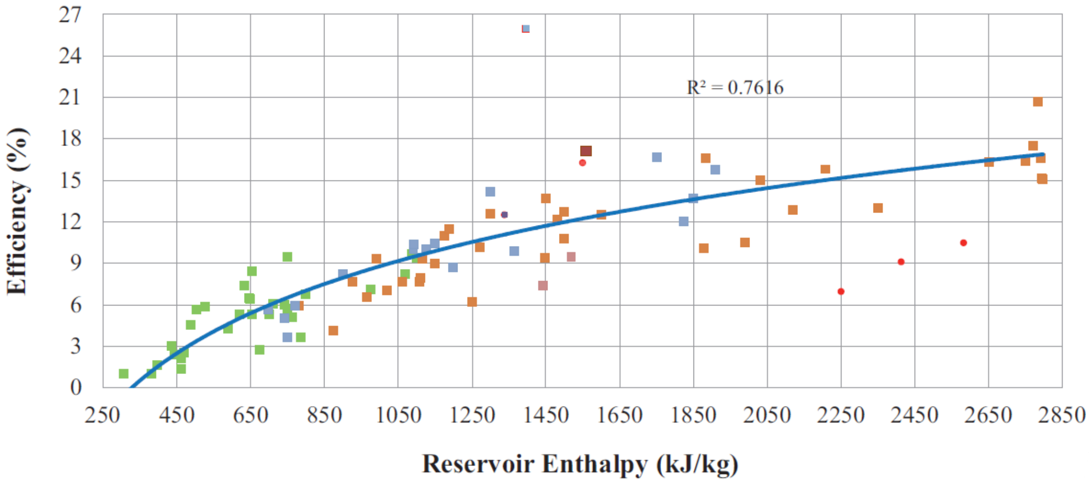
25 wells, down to 2km
Water and steam 190°C
~1 000 L / s

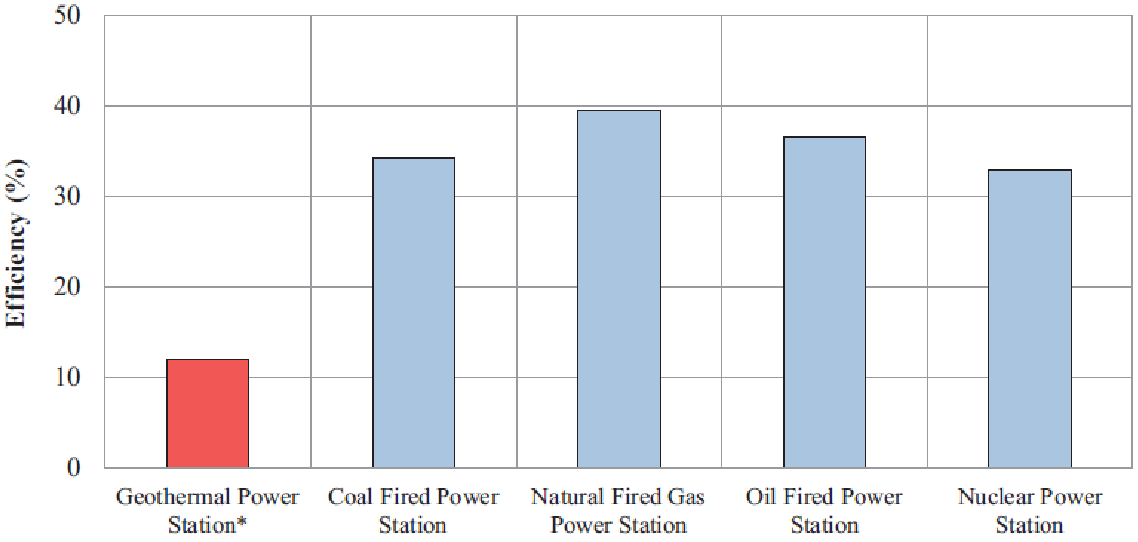
Flash
120 MWe
+ 1000 L hot water @85°C / second

THE GEOTHERMAL POWER PLANT AT NESJAVELLIR, ICELAND, Ballzus et al., Proceedings World Geothermal Congress 2000

Geothermal efficiency

$$\eta_{\text{act}}(\%) = \frac{W}{\dot{m} \times h}$$





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Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Review

Efficiency of geothermal power plants: A worldwide review

Sadiq J. Zarrouk[a,*], Hyungsul Moon[b]

[a] Department of Engineering Science, The University of Auckland, Private Bag 92019, Auckland, New Zealand
[b] Mighty River Power, 283 Vaughan Rd, PO Box 245, Rotorua 3040, New Zealand

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Letter to the Editor

Comments on "Efficiency of geothermal power plants: A worldwide review" by Sadiq J. Zarrouk and Hyungsul Moon

"At best [this definition of efficiency] is merely unconventional; at worst it is unjustifiable. In my view, it is both."

$$\eta_U = \frac{\dot{W}_N}{\dot{m} e_R} \qquad e_R = h_R - h_0 - T_0(s_R - s_0),$$

Lecture 8 – thermal energy

I. Overview of heat consumption (what, why, how much ?)

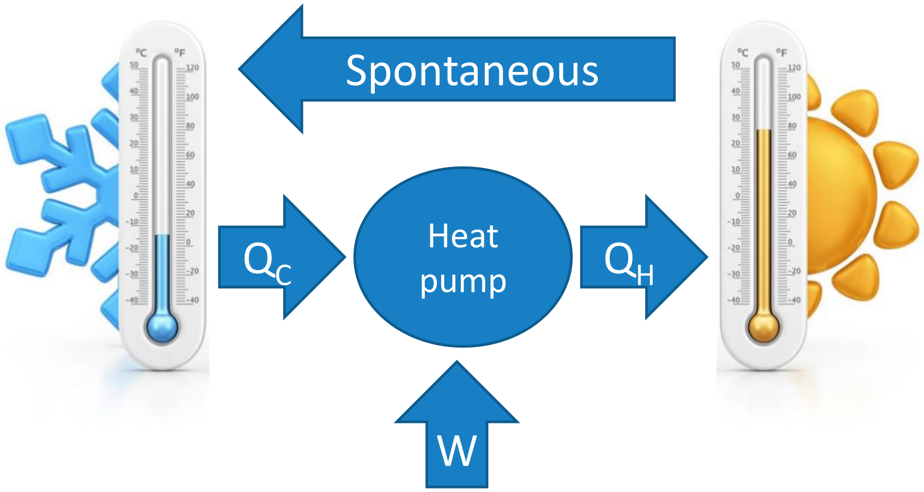
II. Heat conduction

- Heat transfer & heat equation
- Insulation 101
- Thermal energy management

III. Heat generation

- Geothermal energy
- **Heat pump**
- Combined heat and power generation

Heat pumps



Heat from the cold source Q_C

Entropy coming along $S_{\text{in}} = Q_C/T_C$

Heat given to the hot source Q_H

Such that $S_{\text{out}} = Q_H/T_H = S_{\text{in}}$

Leading to $Q_H > Q_C$

Energy conservation $W = Q_H - Q_C$

Refrigerator "efficiency"

$$\mathrm{COP}_{\text{cool}} = \frac{Q_C}{W} = \frac{1}{\frac{T_H}{T_C} - 1}$$

Heat pump "efficiency"

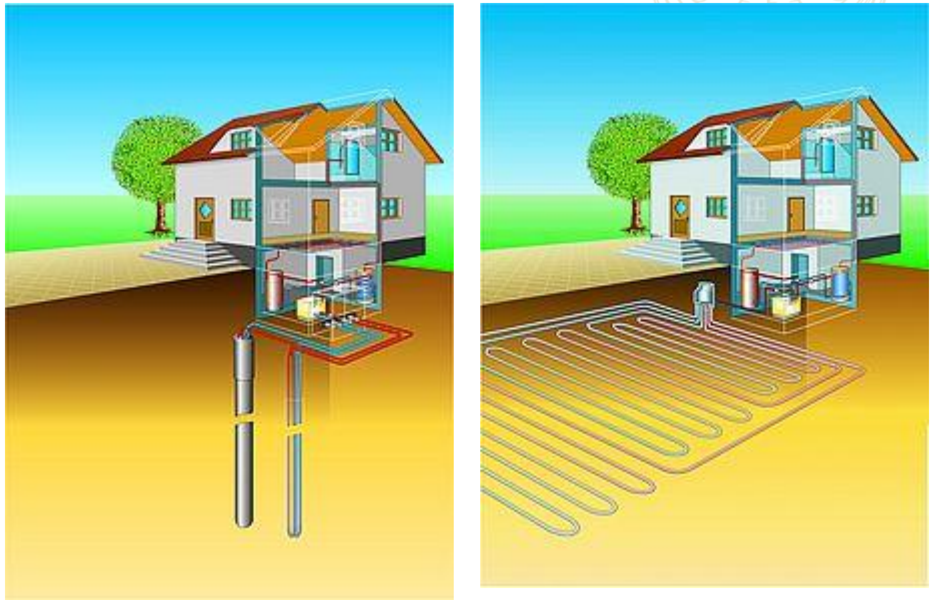
$$\mathrm{COP}_{\text{heat}} = \frac{Q_H}{W} = \frac{1}{1 - \frac{T_C}{T_H}} = \mathrm{COP}_{\text{cool}} + 1$$

Heat pumps – generic idea

(From)
External reservoir:

Air source heat pump

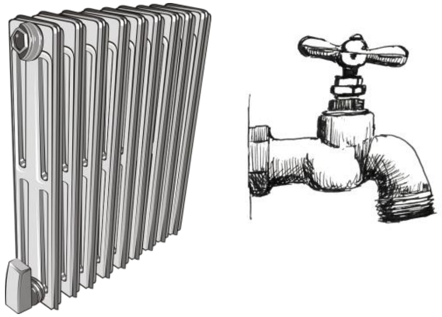
Water source heat pumps



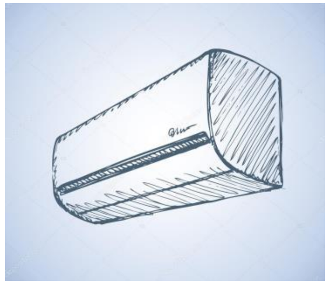
Ground source heat pumps

(To)
Internal reservoir:

Water

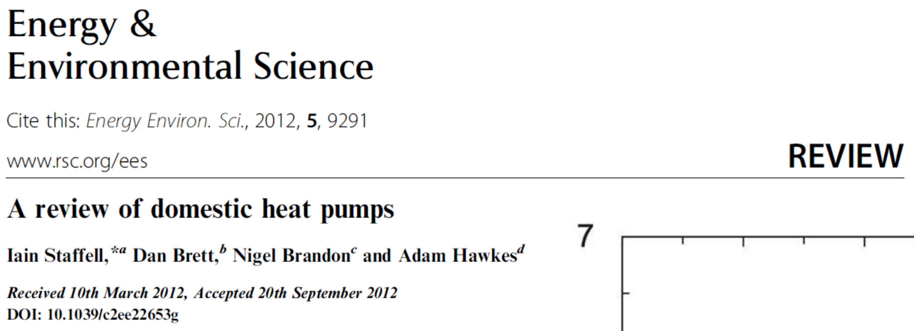


Air



https://www.ehpa.org/technology/types-of-heat-pumps/

Heat pump in real conditions



Energy &
Environmental Science

Cite this: *Energy Environ. Sci.*, 2012, **5**, 9291

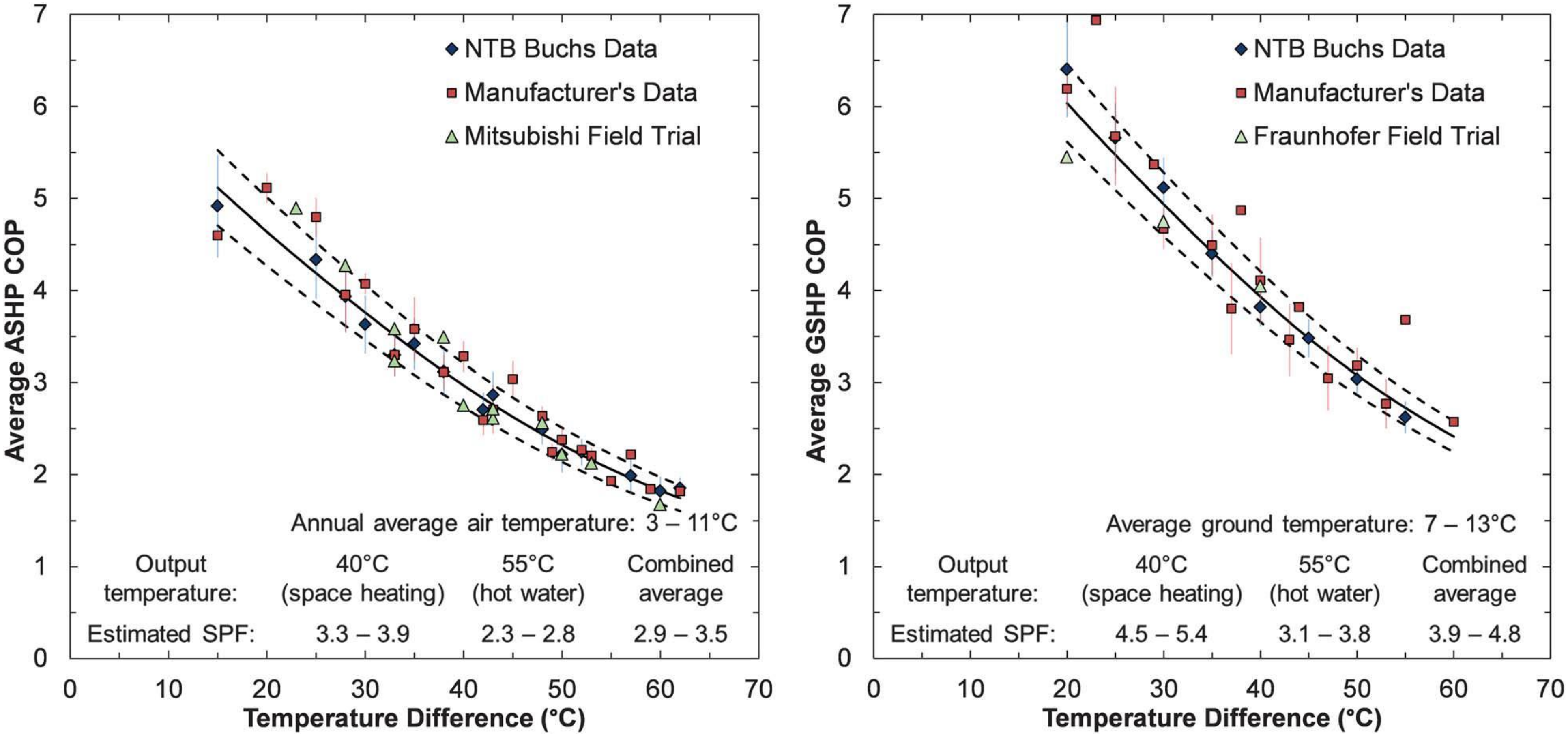
www.rsc.org/ees

REVIEW

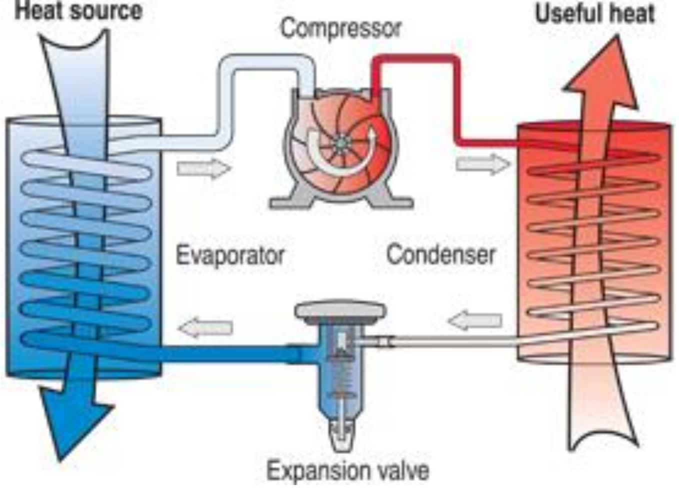
A review of domestic heat pumps

Iain Staffell,*[a] Dan Brett,[b] Nigel Brandon[c] and Adam Hawkes[d]

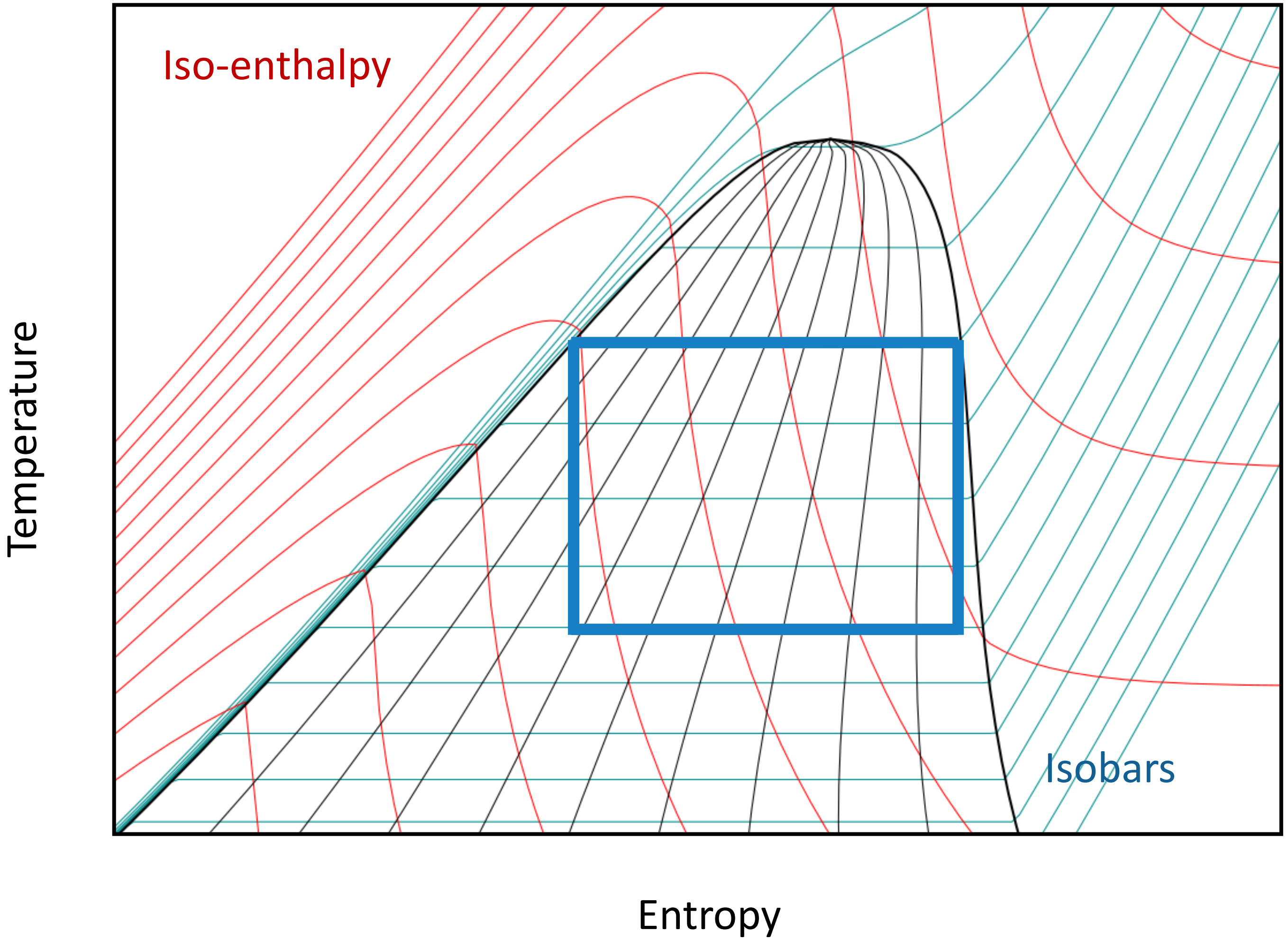
Received 10th March 2012, Accepted 20th September 2012
DOI: 10.1039/c2ee22653g



Heat pump in practice



https://heatpumpingtechnologies.org



Ideal cycle :

Heat release by condensation

$$T_{\mathrm{high}} \geq T_{\mathrm{in}}$$

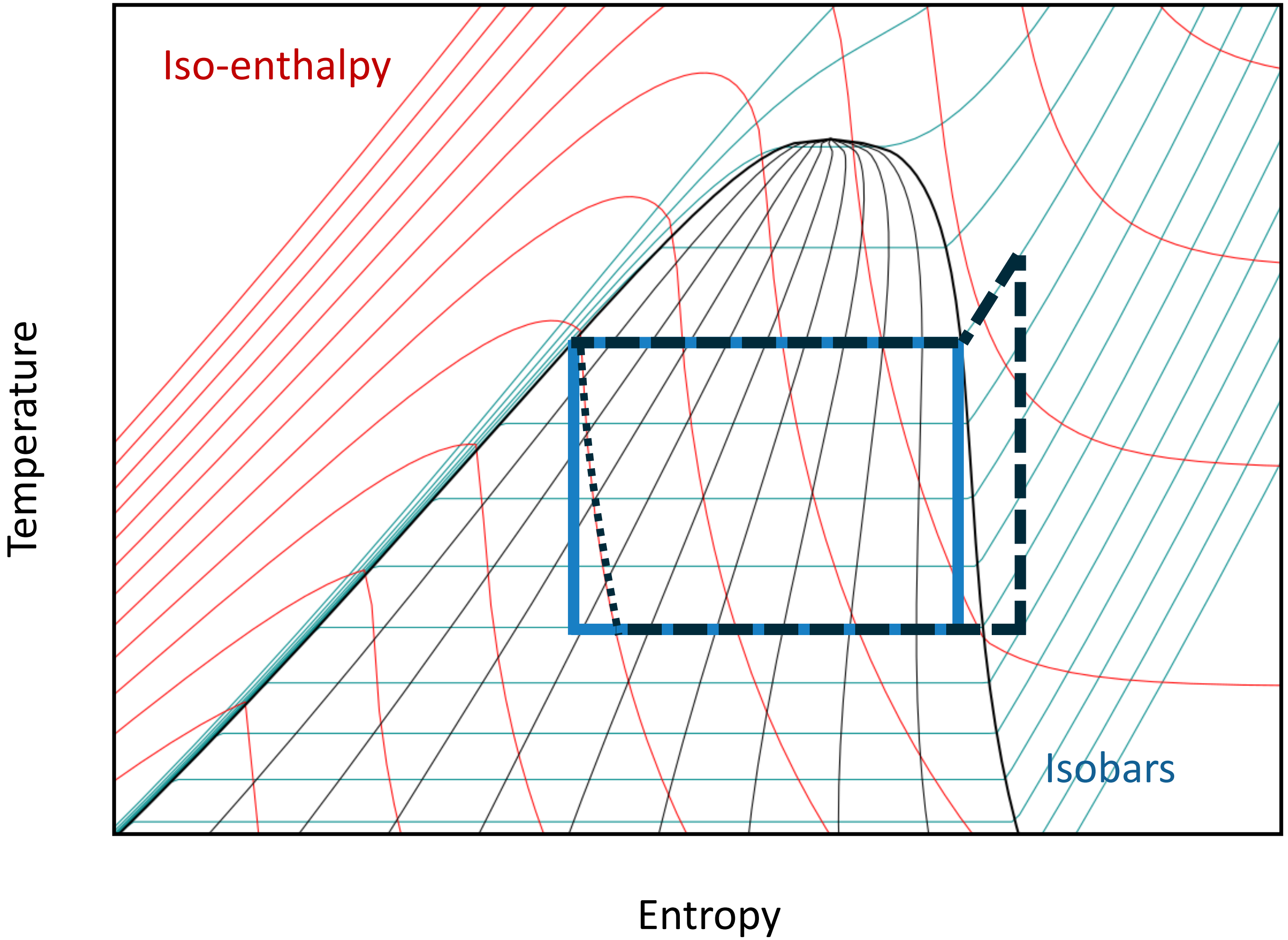
Adiabatic decompression

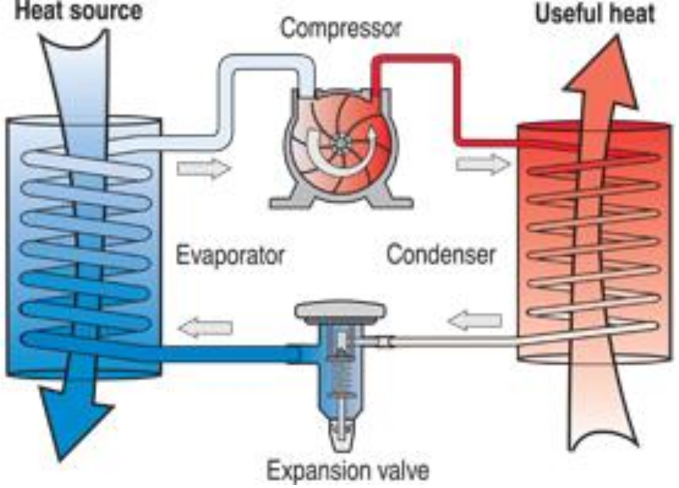
Heat intake by evaporation

$$T_{\mathrm{low}} \leq T_{\mathrm{out}}$$

Adiabatic compression

Heat pump in practice





https://heatpumpingtechnologies.org

Real cycle :

Heat release by condensation

Throttling

Joule-Thomson (isenthalpic) process

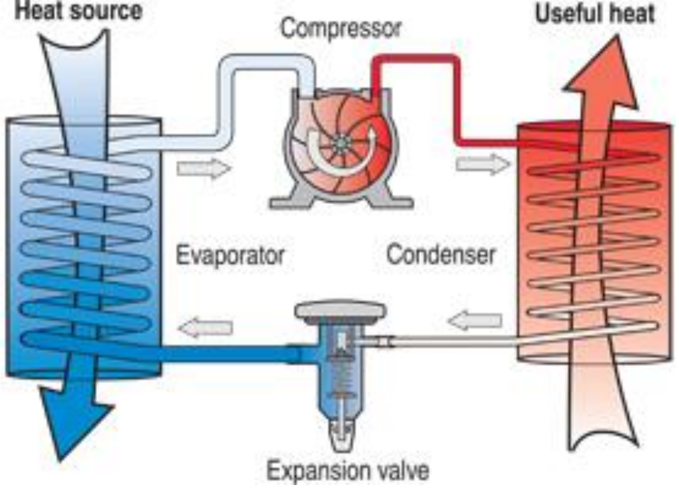
Heat intake by evaporation

With overheating

Adiabatic compression

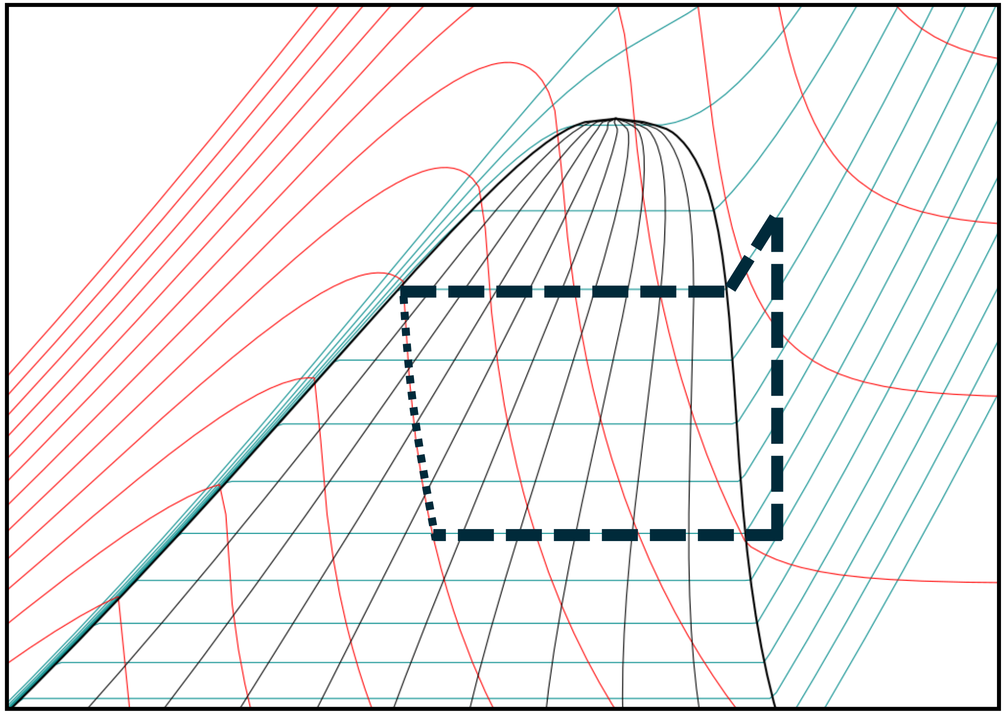
Now without liquid droplets

Refrigerant wish list



Thermodynamic properties

Low boiling T, low freezing T, high critical T	[*working T*]
Reachable saturation pressure	[*working p*]
High density, large latent heat	[*low mass flow*]
Pressures slightly above 1bar	[*avoid air inputs*]



Chemical properties

No reaction with oil / lubricants
Leakage detection?
Toxicity

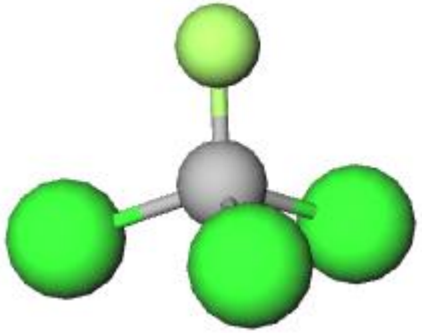
Physical properties

Low viscosity
High thermal conductivity
Warming & Ozozon depletion potentials

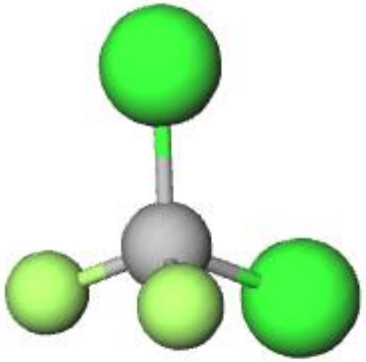
Refrigerant – ''Freon''

CFC
chlorofluorocarbon

R11

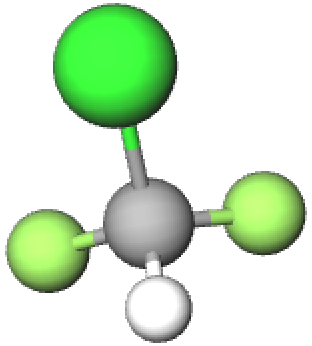


R12

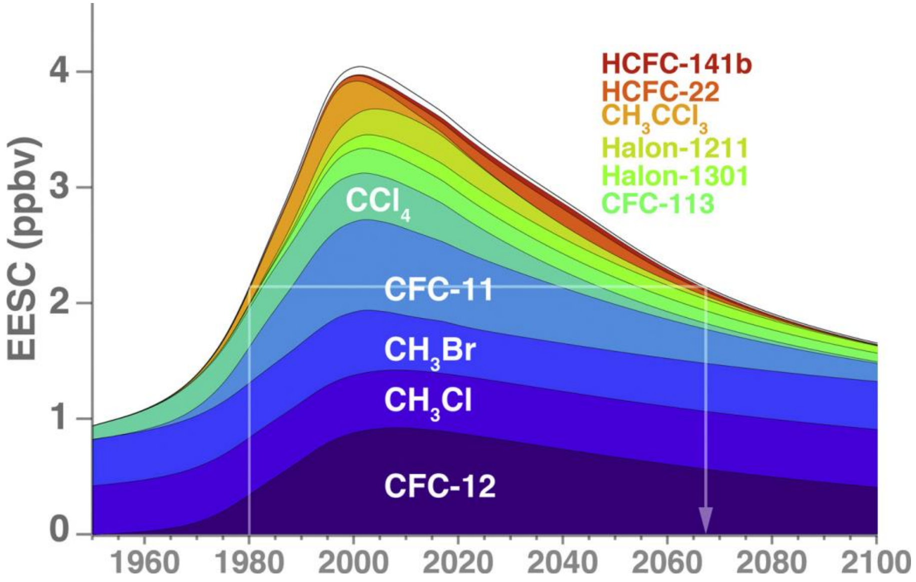


HCFC
hydrochlorofluorocarbon

R22

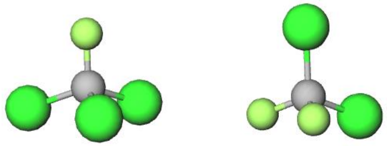


Issue : ozone depletion !

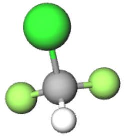


Refrigerant – ‘‘Freon’’

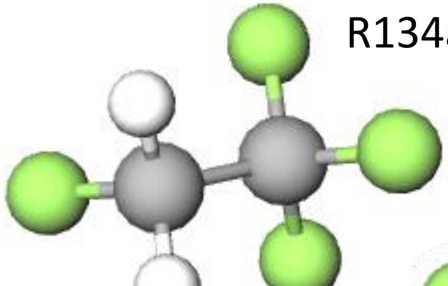
CFC
chlorofluorocarbon



HCFC
hydrochlorofluorocarbon

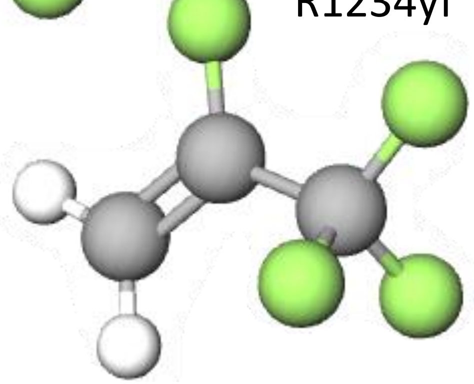


HFC
hydrofluorocarbon



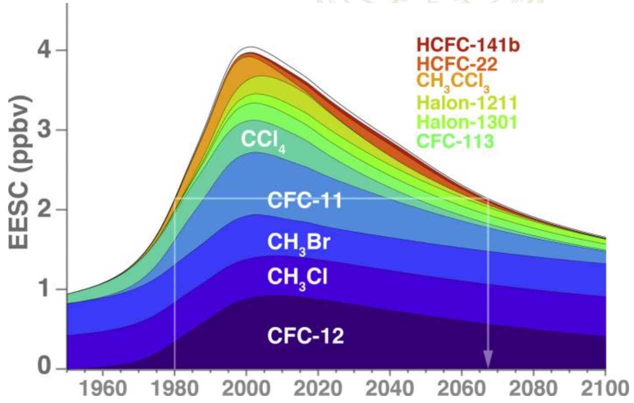
R134a

HFO
Hydrofluo - olefins



R1234yf

HC
Hydrocarbon



Ozone Depleting Potential
0

Global warming potential
1430

Ozone Depleting Potential
0

Global warming potential
< 4

Lecture 8 – thermal energy

I. Overview of heat consumption (what, why, how much ?)

II. Heat conduction

- Heat transfer & heat equation
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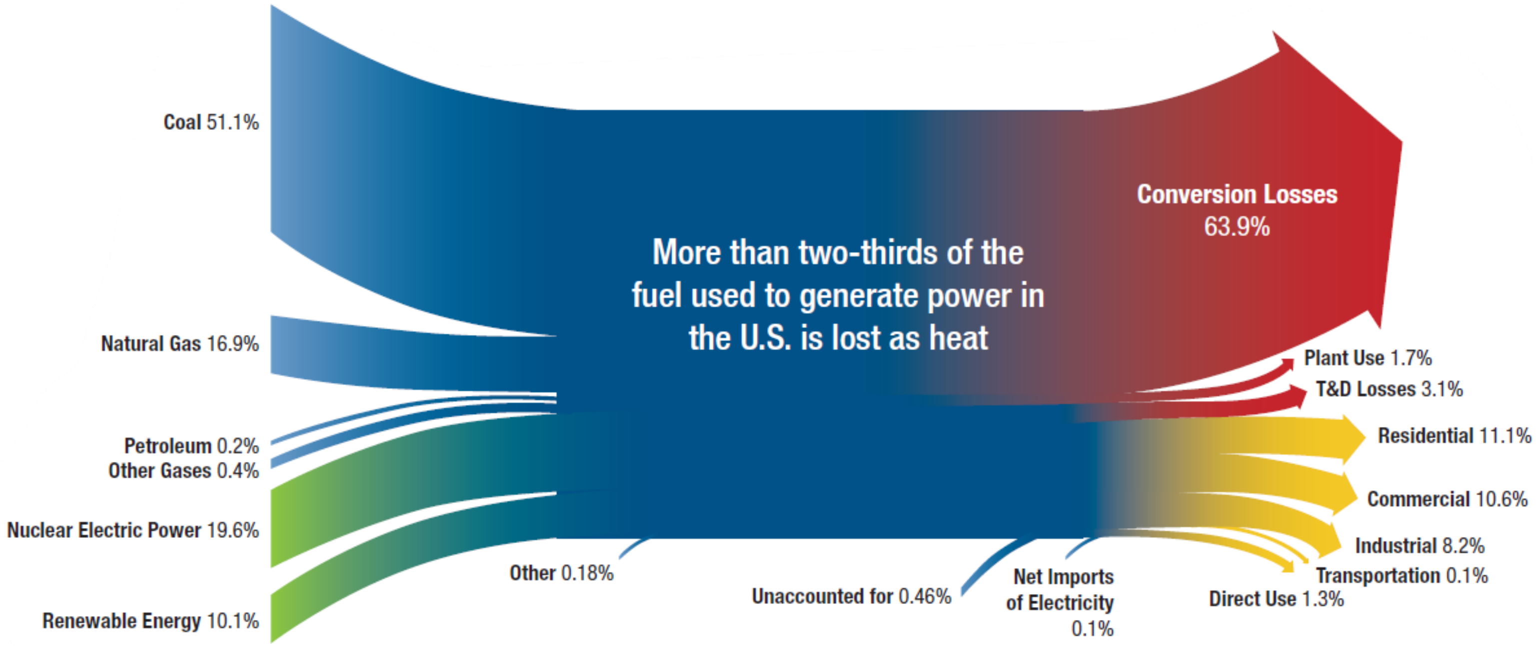
III. Heat generation

- Geothermal energy
- Heat pump
- **Combined heat and power generation**

CHP - principle

Main idea

Try not to waste so much heat !



Source: DOE Energy Information Administration Annual Energy Review 2007

Two options

Topping cycle system

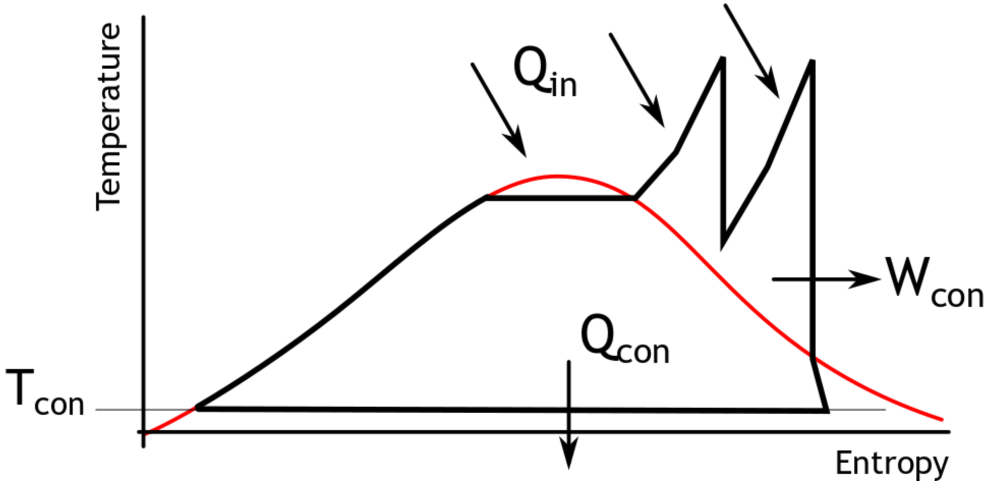
Collect heat normally wasted over electricity production

Bottoming cycle system

Turn wasted heat from industrial processes into electricity

CHP – equivalent cycle

Conventional power plant



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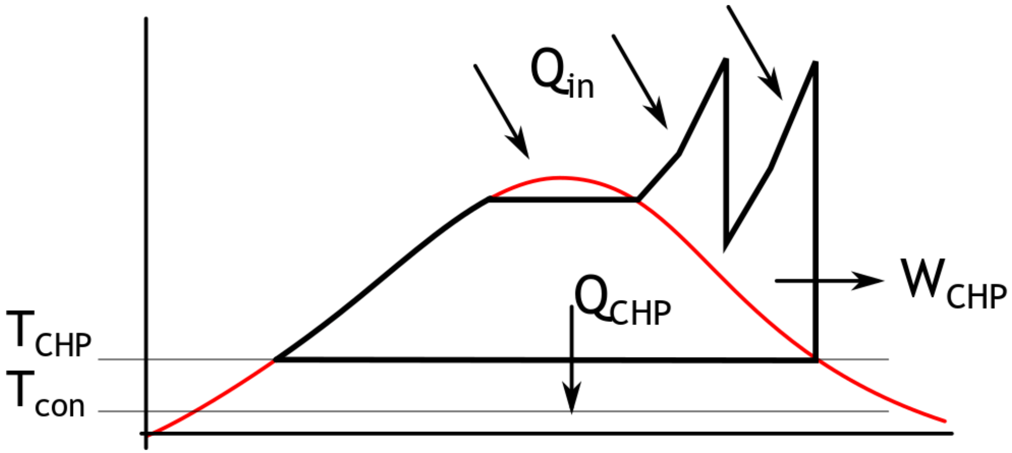
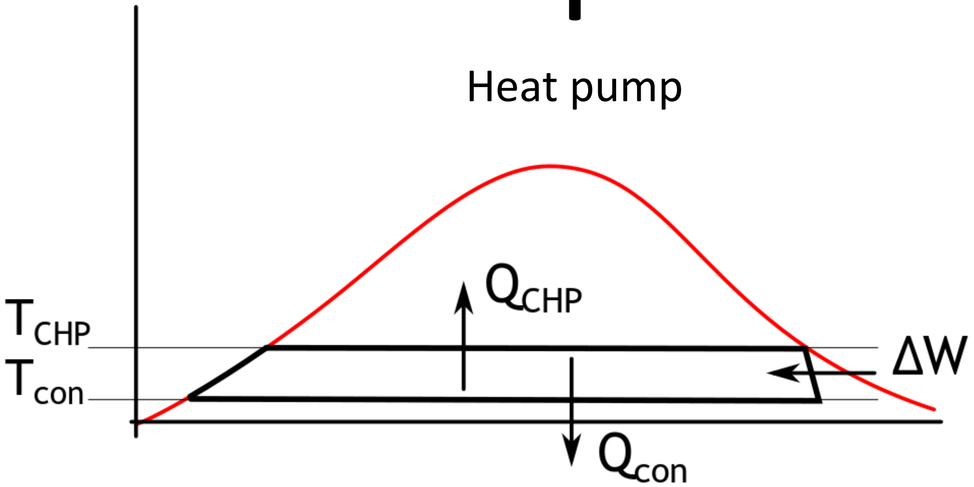
Combined heat and power



+

Heat pump

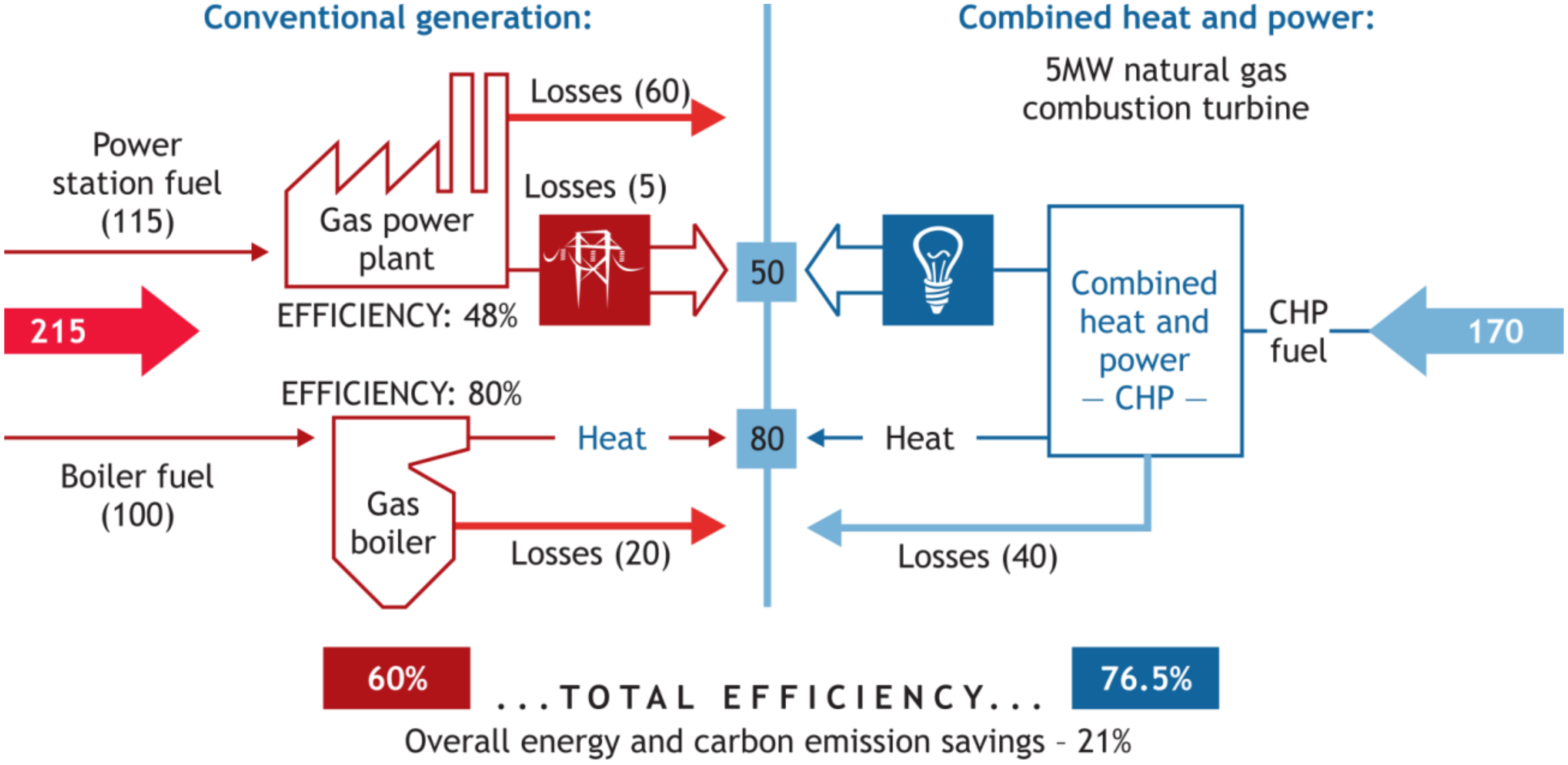


Providing heat at a higher temperature than normal output reduces the work produced by the power plant

As if part of this work was used to power a heat pump !

Lowe, “Combined heat and power considered as a virtual steam cycle heat pump”
Energy Policy 39 (2011) 5528–5534

CHP – efficiency (?)



Conventional generation:

Power station fuel (115)

215

Gas power plant

Losses (60)

Losses (5)

EFFICIENCY: 48%

EFFICIENCY: 80%

Boiler fuel (100)

Gas boiler

Heat

Losses (20)

50

80

Combined heat and power:

5MW natural gas combustion turbine

Combined heat and power – CHP –

CHP fuel

170

Heat

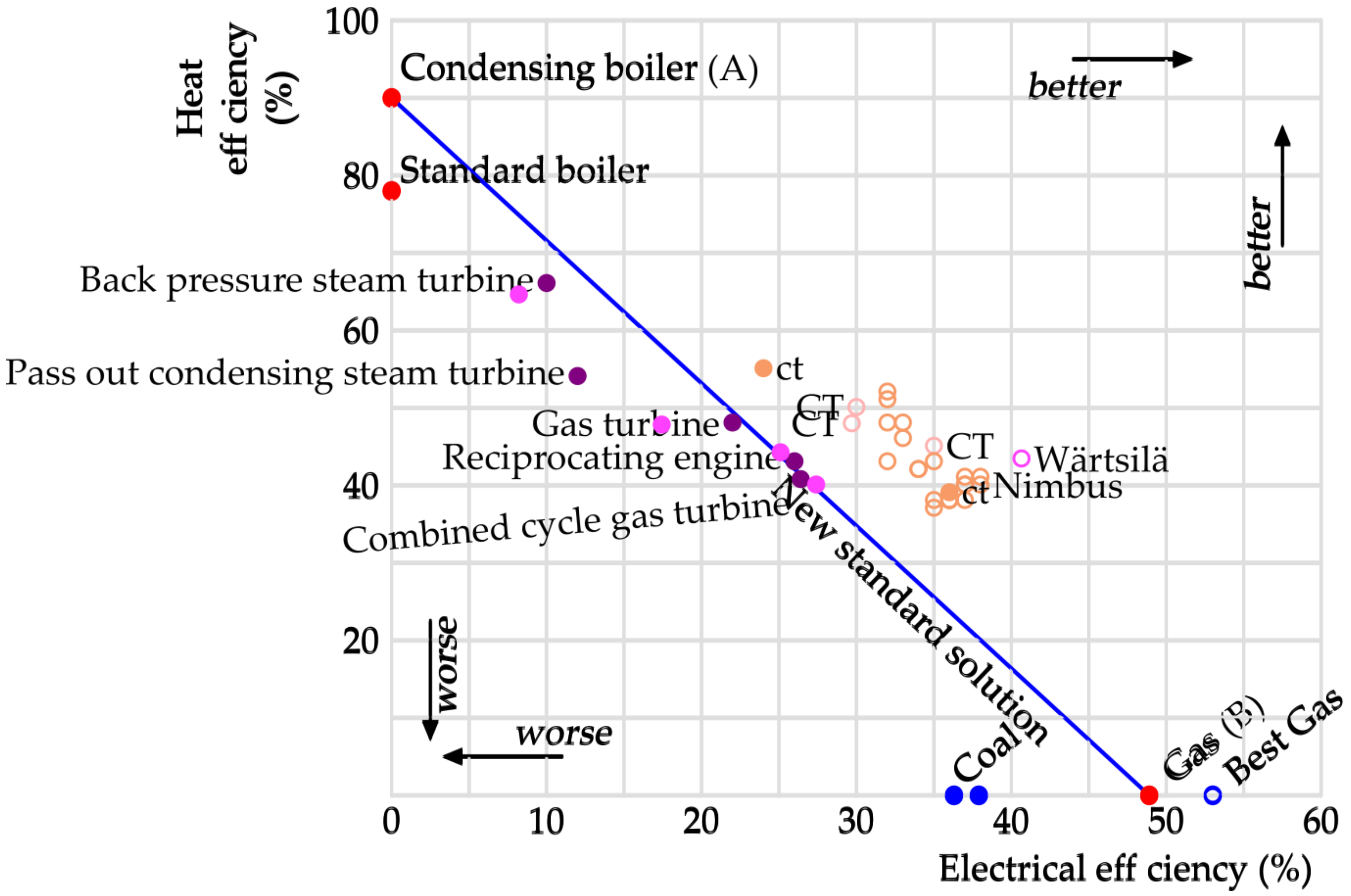
Losses (40)

60% ...TOTAL EFFICIENCY... 76.5%

Overall energy and carbon emission savings - 21%

Source: IEA analysis, USEPA, 2008.

CHP - efficiency



David MacKay

+ simultaneous use of

heat and power

CHP - implementation

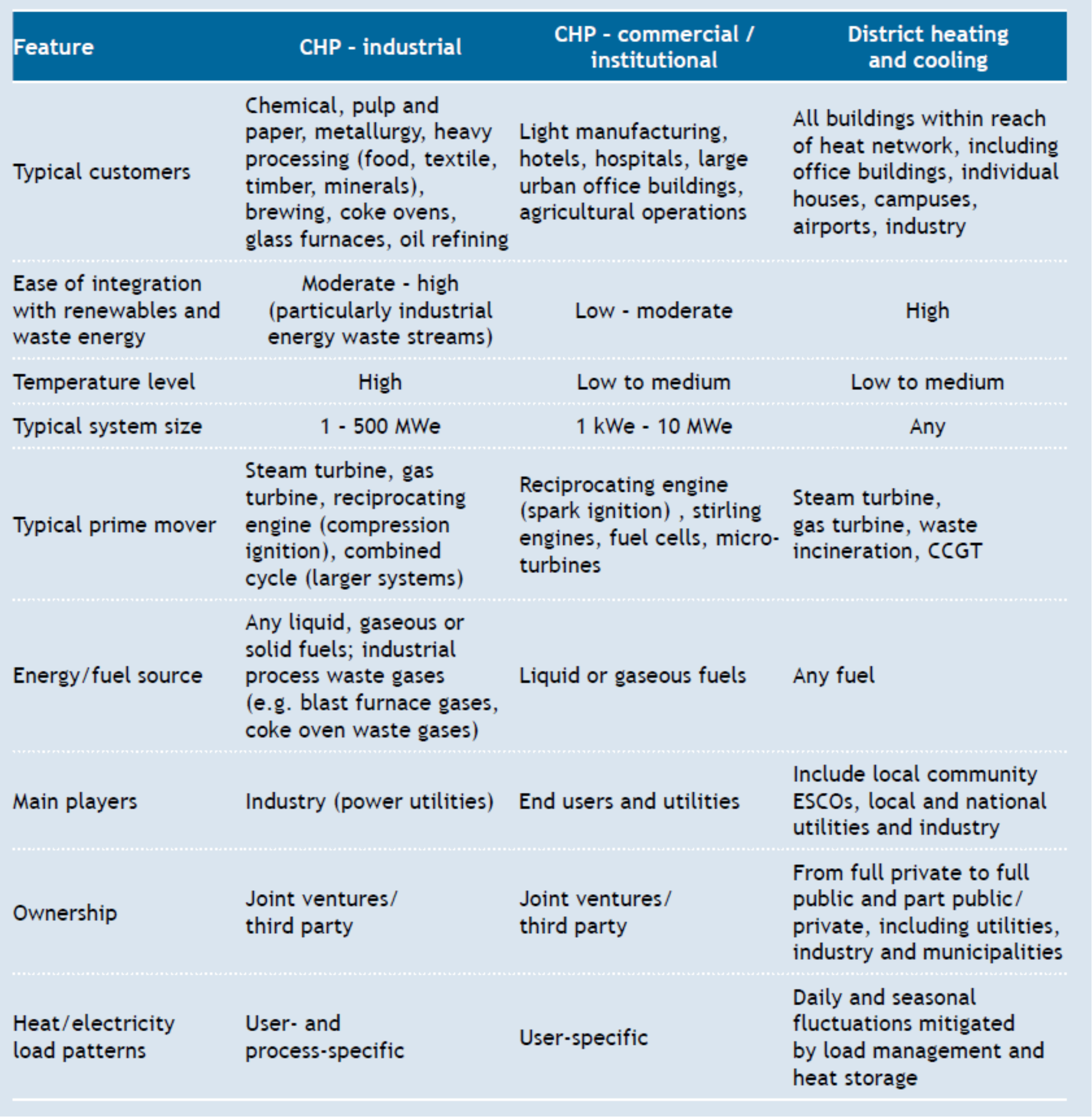
INTERNATIONAL ENERGY AGENCY

Combined Heat and Power

Evaluating the benefits of greater global investment

CHP requirement

- A ratio of electricity to fuel costs of at least 2.5:1;
- Relatively high requirements for heating and / or cooling (e.g. annual demand for at least 5 000 hours);
- The ability to connect to the grid (if present) at a reasonable price with the availability of back-up and top-up power at reasonable and predictable prices;
- Availability of space for the equipment and (for non-DHC related systems) short distances for heat transport.



Feature	CHP - industrial	CHP - commercial / institutional	District heating and cooling
Typical customers	Chemical, pulp and paper, metallurgy, heavy processing (food, textile, timber, minerals), brewing, coke ovens, glass furnaces, oil refining	Light manufacturing, hotels, hospitals, large urban office buildings, agricultural operations	All buildings within reach of heat network, including office buildings, individual houses, campuses, airports, industry
Ease of integration with renewables and waste energy	Moderate - high (particularly industrial energy waste streams)	Low - moderate	High
Temperature level	High	Low to medium	Low to medium
Typical system size	1 - 500 MWe	1 kWe - 10 MWe	Any
Typical prime mover	Steam turbine, gas turbine, reciprocating engine (compression ignition), combined cycle (larger systems)	Reciprocating engine (spark ignition) , stirling engines, fuel cells, micro-turbines	Steam turbine, gas turbine, waste incineration, CCGT
Energy/fuel source	Any liquid, gaseous or solid fuels; industrial process waste gases (e.g. blast furnace gases, coke oven waste gases)	Liquid or gaseous fuels	Any fuel
Main players	Industry (power utilities)	End users and utilities	Include local community ESCOs, local and national utilities and industry
Ownership	Joint ventures/ third party	Joint ventures/ third party	From full private to full public and part public/ private, including utilities, industry and municipalities
Heat/electricity load patterns	User- and process-specific	User-specific	Daily and seasonal fluctuations mitigated by load management and heat storage

IEA Research

Example of CHP

Yuengling®

AMERICA'S OLDEST BREWERY.

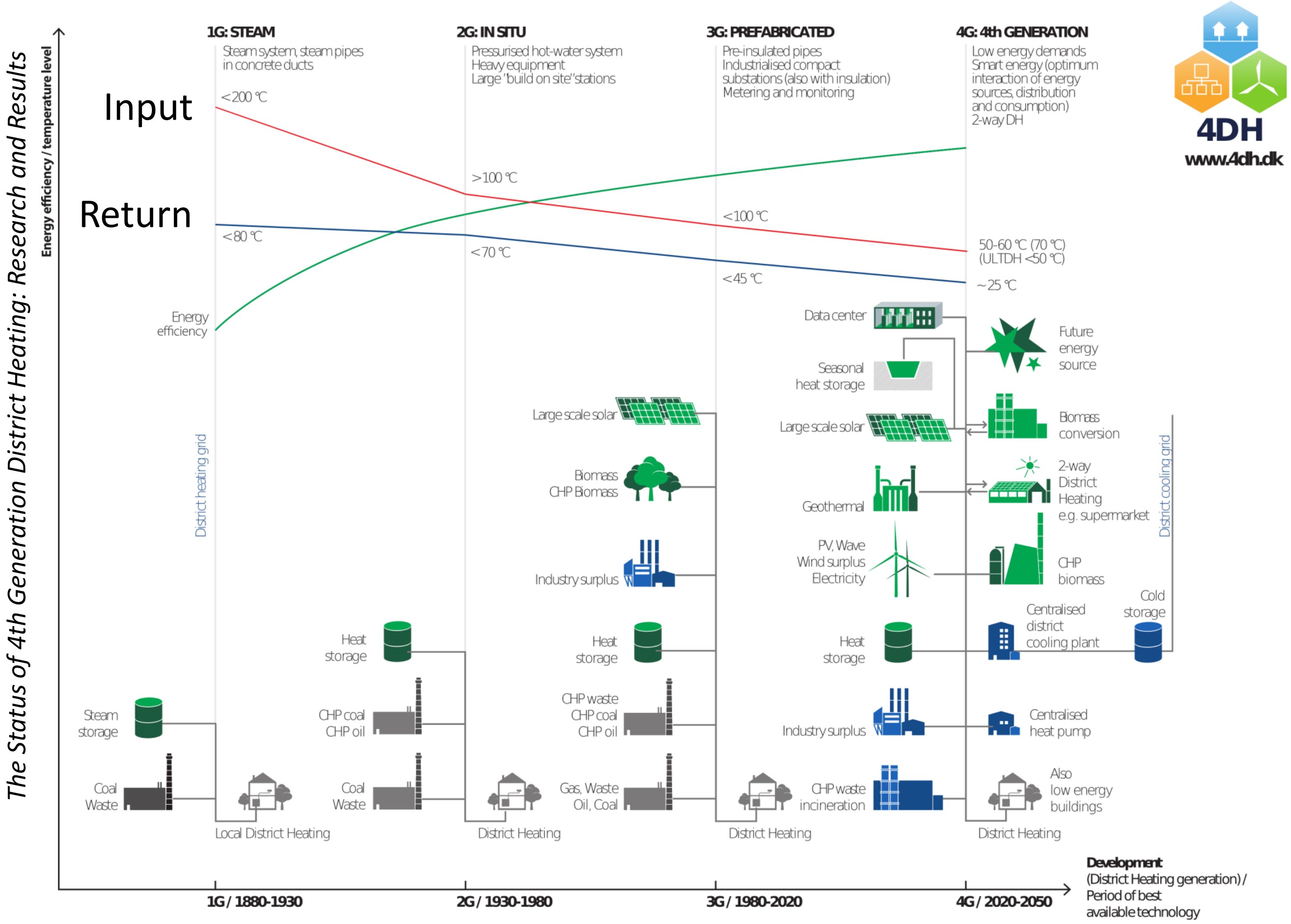
Biogas from brewery wastewater treatment
+ natural gas

Electricity : 400 kW (=20% brewery consumption)
Heat : 545 kW

Heat used for
- wastewater preheating
- brewery's pasteurization process

“2G Energy inc. was selected to supply and install a fully containerized agenitor 212 thermodynamically optimized MAN-based engine with 400 ekW/h or 3,320 MW p.a. electrical power and 474 kWh/th thermal power output.”

District heating


The Status of 4th Generation District Heating: Research and Results

Typical input

- waste heat from thermal power stations
- heat obtained from waste incineration
- useful waste heat from industrial processes
- natural geothermal heat sources
- fuels difficult to manage

(wood waste, peat, straw, or olive stones.)

First modern DH: Lockport, New York in 1877

Example of District heating

Nuclear Power Plant in Beznau (Switzerland)

2 x 365 MW PWR reactors

Commissioned in 1969

REFUNA District heating network

Operating since 1984

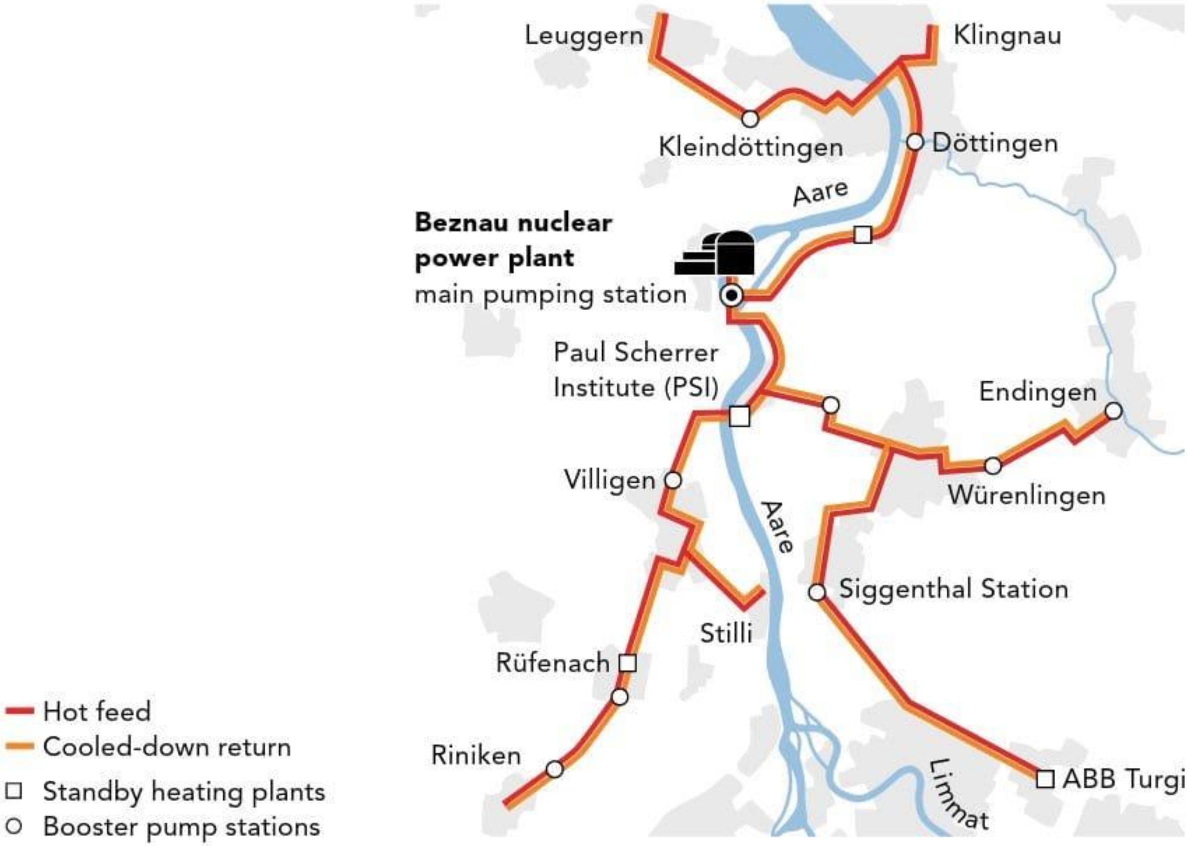
31 km transmission lines

100 km distribution lines

2400 consumers

Capacity : 76 MW_{th}

Annual prod : 142 GWh_{th}



Take home messages

Thermal physics 101

$$\lambda,\ D,\ R,\ \delta,\ e$$

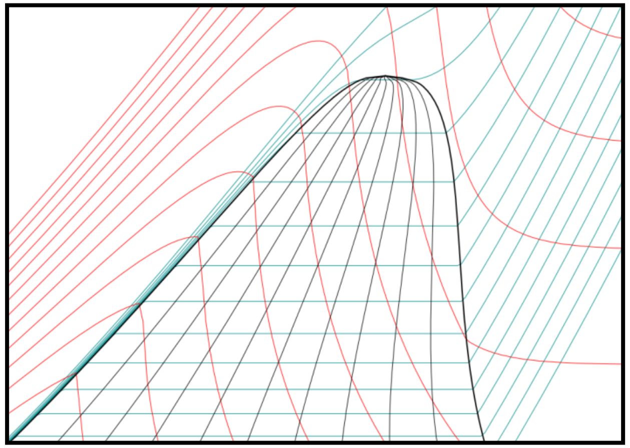
$$\mathbf{J} = -\lambda \boldsymbol{\nabla} T$$

$$\frac{\partial T}{\partial t} = D\,\Delta T$$

Insulation

$$\phi = (T_{\text{in}} - T_{\text{out}}) \left(\frac{1}{R_1 + R_1'} + \frac{1}{R_2} \right)$$

Thermal cycles & Ts chart



Thermal energy management

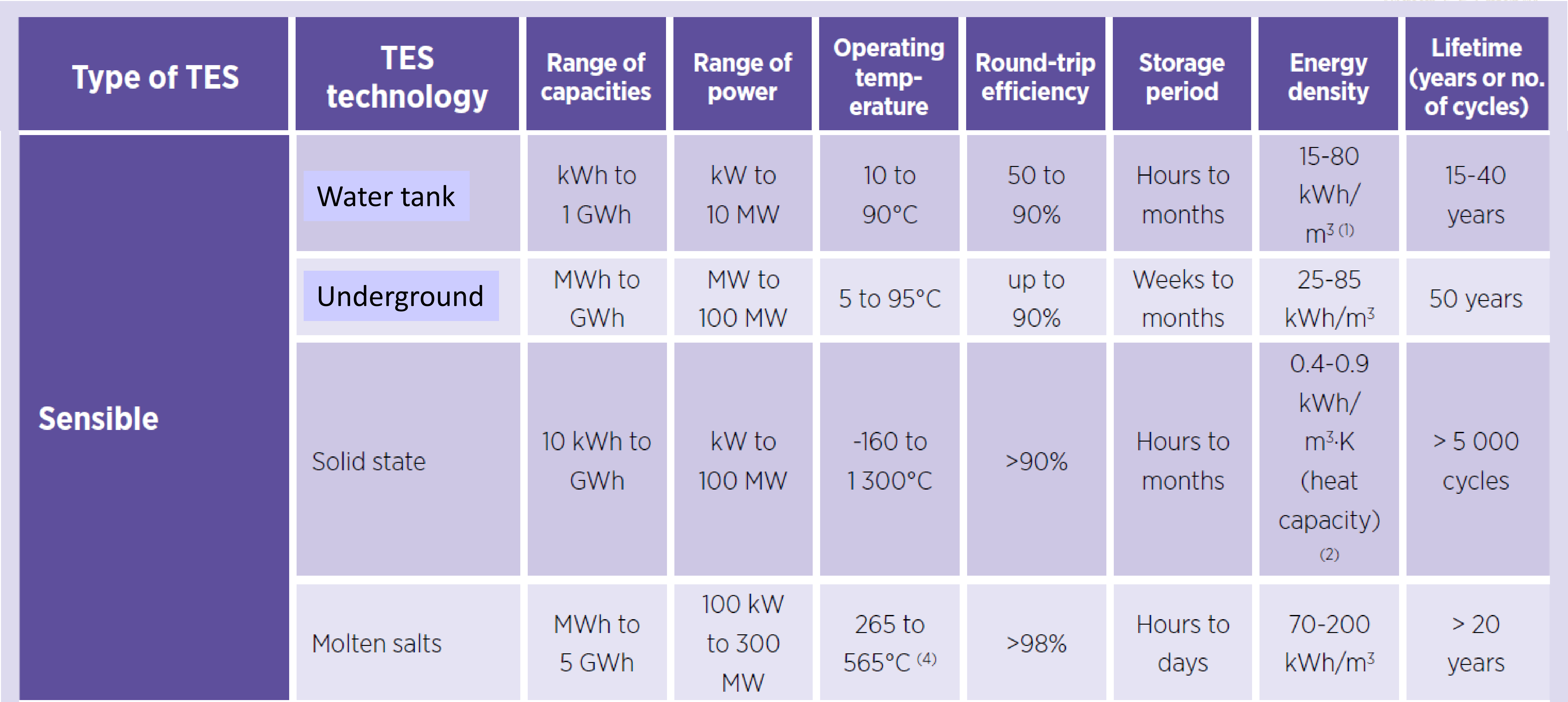
Usage

Transport

Storage

Thermal energy perspectives


POUR LA PATRIE LES SCIENCES ET LA GLOIRE



Type of TES	TES technology	Range of capacities	Range of power	Operating temp-erature	Round-trip efficiency	Storage period	Energy density	Lifetime (years or no. of cycles)
Sensible	Water tank	kWh to 1 GWh	kW to 10 MW	10 to 90°C	50 to 90%	Hours to months	15-80 kWh/m^3 (1)	15-40 years
	Underground	MWh to GWh	MW to 100 MW	5 to 95°C	up to 90%	Weeks to months	25-85 kWh/m^3	50 years
	Solid state	10 kWh to GWh	kW to 100 MW	-160 to 1 300°C	>90%	Hours to months	0.4-0.9 kWh/m^3·K (heat capacity) (2)	> 5 000 cycles
	Molten salts	MWh to 5 GWh	100 kW to 300 MW	265 to 565°C (4)	>98%	Hours to days	70-200 kWh/m^3	> 20 years

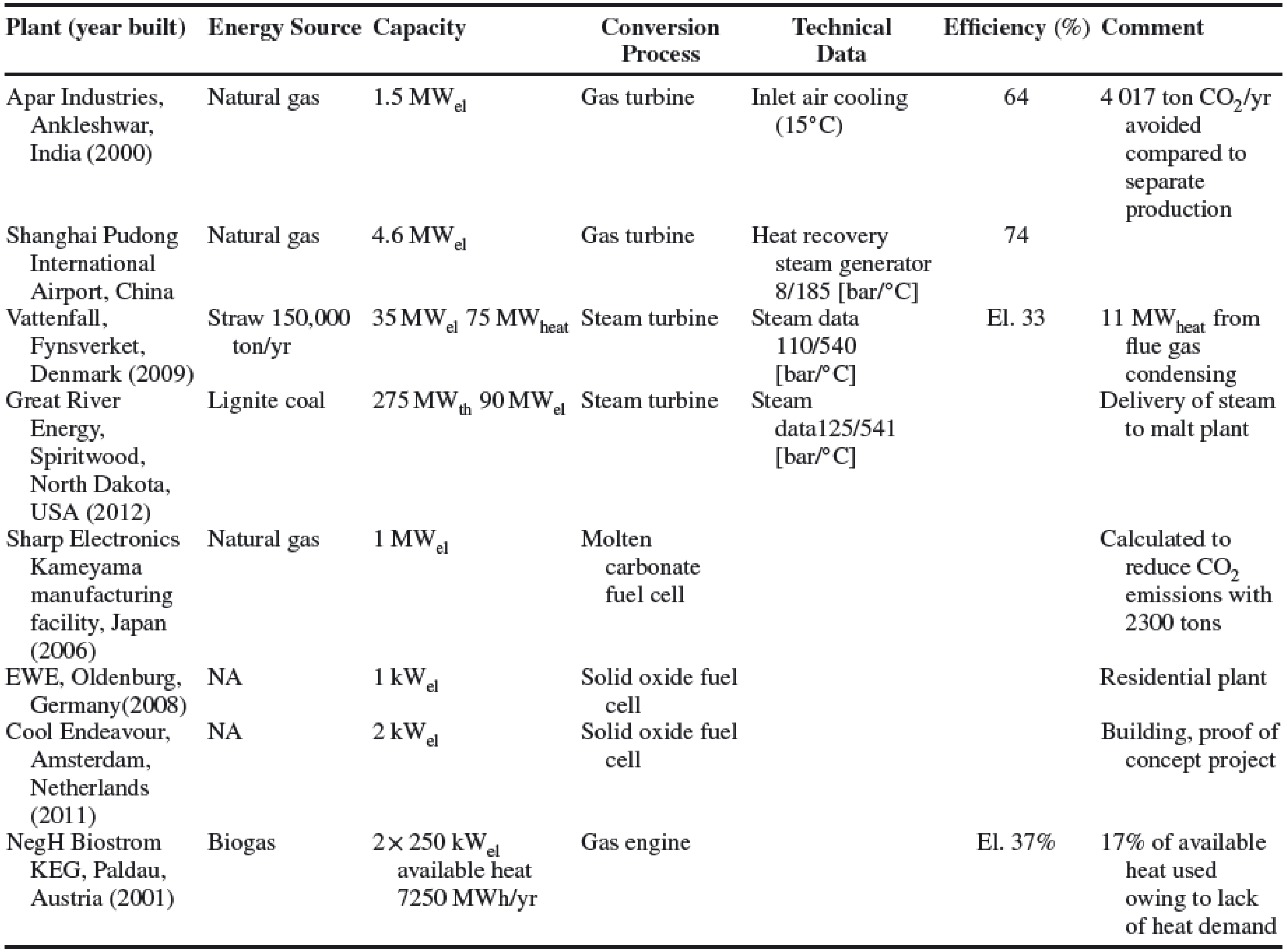
Type of TES	TES technology	Range of capacities	Range of power	Operating temp-erature	Round-trip efficiency	Storage period	Energy density	Lifetime (years or no. of cycles)
Latent	Ice thermal energy storage	kWh to 100 MWh	kW to 10 MW	-3 to 3°C	>95%	Hours to days	92 kWh/ m^3	> 20 years
	Sub-zero temperature PCM	kWh to 100 kWh	kW to 10 kW	down to -114°C	>90%	Hours	30-85 kWh/m^3	> 20 years
	Low-temperature PCM	kWh to 100 kWh	kW to 10 kW	up to 120°C	>90%	Hours	56-60 kWh/m^3	300-3 000 cycles
	High-temperature cPCM	10 kWh to GWh	10 kW to 100 MW	up to 1 000°C	>90%	Hours to days	30-85 kWh/m^3	> 5 000 cycles

Type of TES	TES technology	Range of capacities	Range of power	Operating temp-erature	Round-trip efficiency	Storage period	Energy density	Lifetime (years or no. of cycles)
Thermo-chemical	Chemical looping (calcium looping) (5)	MWh to 100 MWh	10 kW to 1 MW	500 to 900°C	45-63%	Months	800-1200 kWh/m^3	>30 years
	Salt hydration	10 kWh to 100 kWh	N/A	30 to 200°C	50% (open systems) 60% (closed systems)	Months	200-350 kWh/m^3	20 years
	Absorption Systems	10 kWh to 100 kWh	10 kW to 1 MW	5 to 165°C	COP: 0.7-1.7	Hours to days	180-310 kWh/m^3	50 years

IRENA
INNOVATION OUTLOOK
THERMAL ENERGY STORAGE

Type of TES	TES technology	Range of capacities	Range of power	Operating temp-erature	Round-trip efficiency	Storage period	Energy density	Lifetime (years or no. of cycles)
Mechanical-thermal systems	CAES	10 to 1 000 MWh	10 to 1000 MW	up to 600°C	> 90% (thermal efficiency)	Hours to weeks	N/A	20-40 years
	LAES	MWh to GWh	10 to 300 MW	> 300°C (heat) -150°C (cold) -196°C (liquid air)	> 90% (thermal efficiency)	Hours to months	N/A	> 25 years

Example of CHP



Plant (year built)	Energy Source	Capacity	Conversion Process	Technical Data	Efficiency (%)	Comment
Apar Industries, Ankleshwar, India (2000)	Natural gas	1.5 MW_{el}	Gas turbine	Inlet air cooling (15°C)	64	4 017 ton CO_2/yr avoided compared to separate production
Shanghai Pudong International Airport, China	Natural gas	4.6 MW_{el}	Gas turbine	Heat recovery steam generator 8/185 [bar/°C]	74	
Vattenfall, Fynsverket, Denmark (2009)	Straw 150,000 ton/yr	35 MW_{el} 75 MW_{heat}	Steam turbine	Steam data 110/540 [bar/°C]	El. 33	11 MW_{heat} from flue gas condensing
Great River Energy, Spiritwood, North Dakota, USA (2012)	Lignite coal	275 MW_{th} 90 MW_{el}	Steam turbine	Steam data125/541 [bar/°C]		Delivery of steam to malt plant
Sharp Electronics Kameyama manufacturing facility, Japan (2006)	Natural gas	1 MW_{el}	Molten carbonate fuel cell			Calculated to reduce CO_2 emissions with 2300 tons
EWE, Oldenburg, Germany(2008)	NA	1 kW_{el}	Solid oxide fuel cell			Residential plant
Cool Endeavour, Amsterdam, Netherlands (2011)	NA	2 kW_{el}	Solid oxide fuel cell			Building, proof of concept project
NegH Biostrom KEG, Paldau, Austria (2001)	Biogas	2 × 250 kW_{el} available heat 7250 MWh/yr	Gas engine		El. 37%	17% of available heat used owing to lack of heat demand

Combined Heat and Power, Thorin et al., Handbook of Clean Energy Systems (2015)