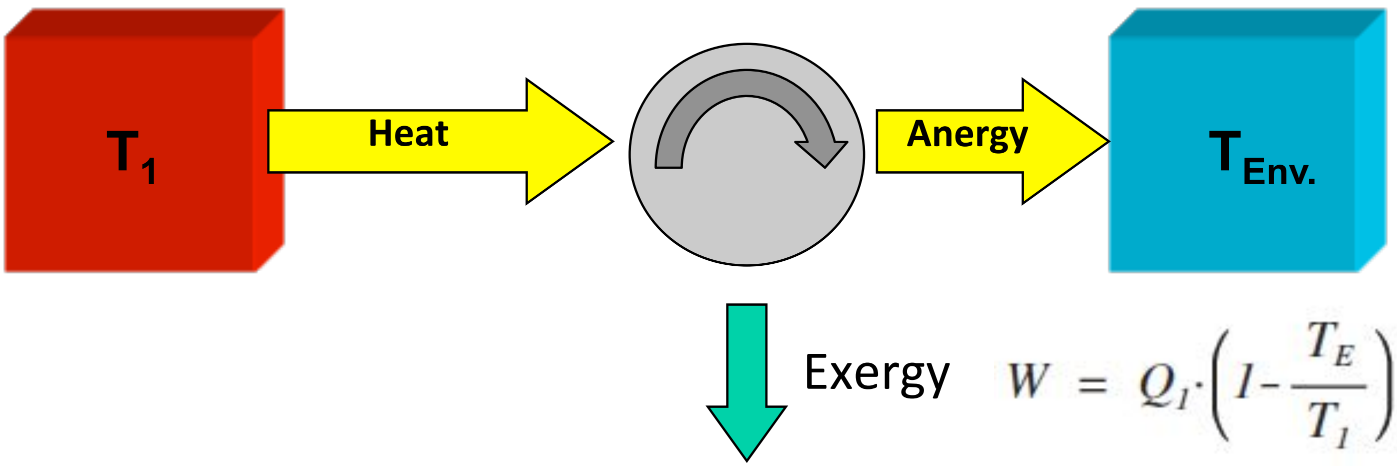
Thermodynamics of Energy Conversion & Storage

1. BASICS

$$\Delta Q_1 = \Delta S_1 \cdot T_1$$

$$\Delta Q_2 = \Delta S_2 \cdot T_E$$



$$W = Q_1 \cdot \left(1 - \frac{T_E}{T_1}\right)$$

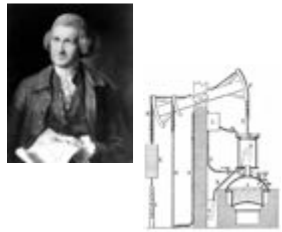
1. BASICS

1.1. ENERGY: Heat and Work 1.1.1. History of Energy

Steam turbine

Hero of ALEXANDRIA
10 - 70

1st Steam engine

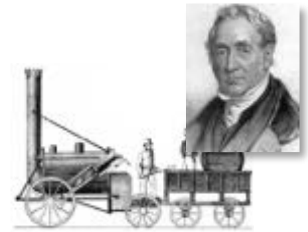


Thomas NEWCOMEN
1712

Steam engine opt.

James WATT
1783

1st Steam locomotive



George STEPHENSON
1828

Standard Oil Company

John D. ROCKEFELLER
1865

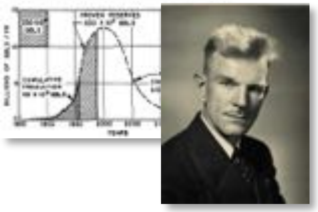
Patent Motorwagen

Carl BENZ
1886

1st motorized flight

Wilbur & Orville WRIGHT
1903

Model for oil mining



M. King HUBBERT
1957

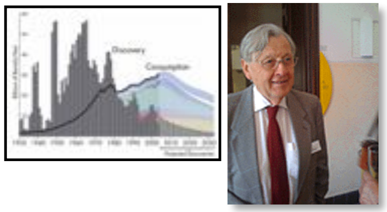
Club of Rome

Jimmy“ CARTER
1978

Solar energy & H_2

Carl-J. WINTER
1989

Fossil resource model



Colin J. CAMPBELL
1998

REWTHA

Sir David J. C. MACKAY
2008

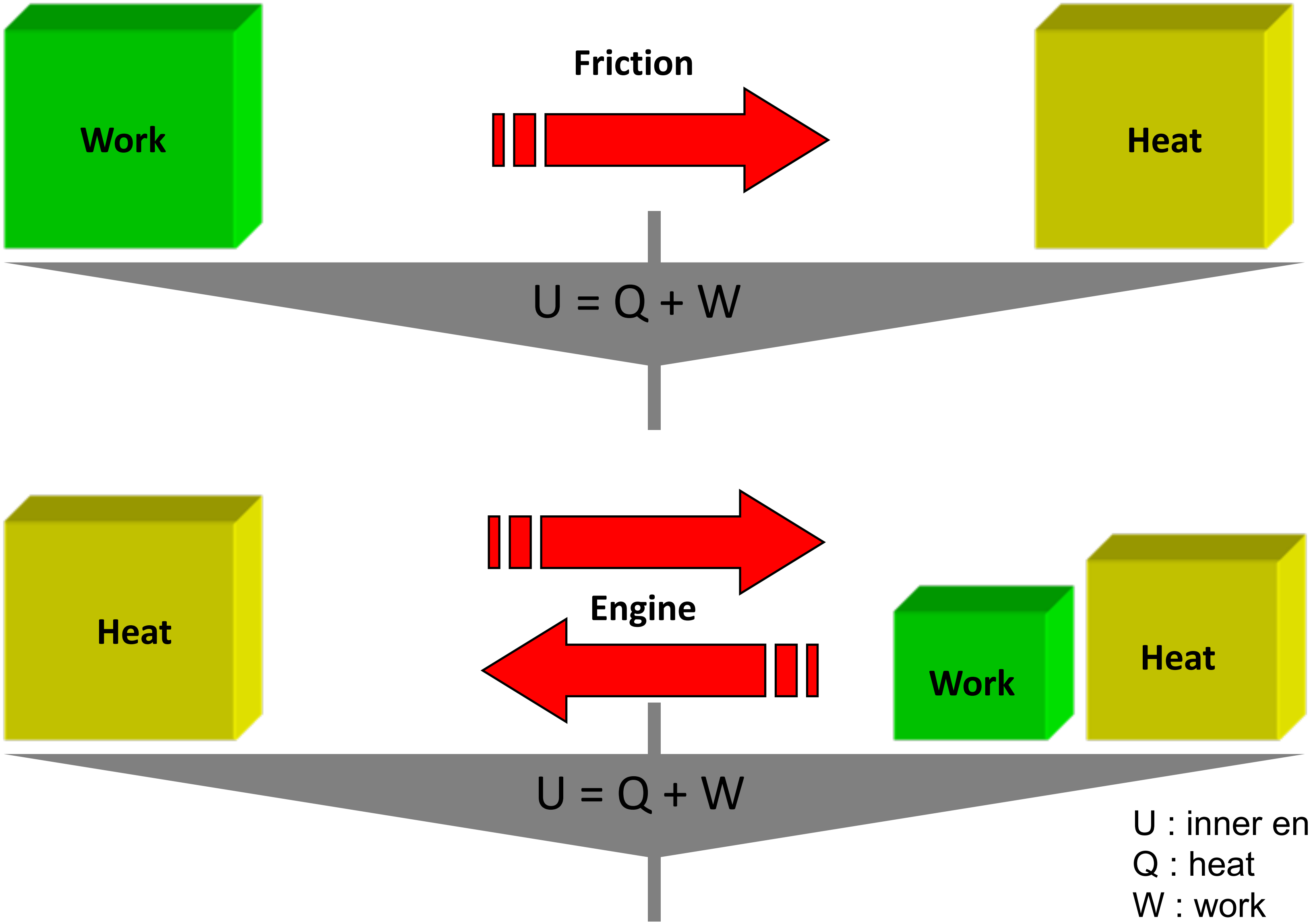
CO_2 Air Capture

Klaus S. LACKNER
2009

Gapminder

Hans ROSLING
2009

1.1.2. Two forms of ENERGY: HEAT and WORK



U : inner energy
Q : heat
W : work

QUESTIONS

Q 1.1.: How does nature convert work into heat?

Q 1.2.: What technology converts work into heat?

Q 1.3.: How does nature convert heat into work?

Q 1.4.: What technology converts heat into work?

SOLUTIONS

Q1.1.: How does nature convert work into heat?
Friction in fluids, gases, between solids, impact, deformation

Q1.2.: What technology converts work into heat?
Breaks, electric heater, Heat pump

Q1.3.: How does nature convert heat into work?
evaporation of water and condensation, wind, streams

Q1.4.: What technology converts heat into work?
piston engines, turbines

1.2. ENERGY STATISTICS

1.2.1. IEA World Energy Outlook

https://www.iea.org/newsroom/news/2016/november/world-energy-outlook-2016.html

1.2.2. Our World in Data

Our World
in Data

Our World in Data:
https://ourworldindata.org

QUESTIONS

Q1.5. How much energy (and power) does a human being consume?

Q1.6. How much can a human body work? How do we measure the work?

SOLUTION

Q1.5. How much energy (and power) does a human being consume?

Food 2060 kcal/day = 8640 kJ/day = 8640 kJ/(24h·3600 sec) = 100 W

Q1.6. How much can a human body work? How do we measure the work?

Clime a mountain 400m/hour, walk horizontal 4 km/h

$P = m \cdot g \cdot h/t = 70\ kg \cdot 9.81\ m/s^2 \cdot 400\ m/h = 76\ J \cdot s\text{-}1 = 76\ W$

$W = m \cdot g \cdot h = 70\ kg \cdot 9.81\ m/s^2 \cdot 400\ m/h \cdot 4h = 1000\ kJ$

1.3. ENERGY UNITS

Name	Symb.	J	kWh	TWa	kg SKE
Joule	J	1.000	$2.778 \cdot 10^{-7}$	$3.171 \cdot 10^{-20}$	$3.41 \cdot 10^{-8}$
Erg	erg	$1.000 \cdot 10^{-7}$	$2.778 \cdot 10^{-14}$	$3.171 \cdot 10^{-27}$	$3.41 \cdot 10^{-15}$
Calorie	cal	4.1855	$1.160 \cdot 10^{-6}$	$1.327 \cdot 10^{-19}$	$1.427 \cdot 10^{-7}$
Electronvolt	eV	$1.600 \cdot 10^{-19}$	$4.500 \cdot 10^{-26}$	$5.073 \cdot 10^{-39}$	$5.456 \cdot 10^{-27}$
Kilowatthour	kWh	$3.600 \cdot 10^{6}$	1.000	$1.141 \cdot 10^{-13}$	$1.228 \cdot 10^{-1}$
Megatonns Oil Eq.	Mtoe	$4.186 \cdot 10^{16}$	$1.163 \cdot 10^{10}$	$1.02 \cdot 10^{-1}$	$1.427 \cdot 10^{9}$
Mega British thermal unit	MBtu	$1.055 \cdot 10^{9}$	293.1	$3.345 \cdot 10^{-11}$	$3.598 \cdot 10^{1}$
Terajoule	TJ	$1.000 \cdot 10^{12}$	$2.778 \cdot 10^{5}$	$3.171 \cdot 10^{-8}$	$3.410 \cdot 10^{4}$
Terawattyear	TWa	$3.160 \cdot 10^{19}$	$8.778 \cdot 10^{12}$	1.000	$1.078 \cdot 10^{12}$
kg SKE	kg SKE	$2.930 \cdot 10^{7}$	8.139	$9.291 \cdot 10^{-13}$	1.000

QUESTIONS

Q1.7. Convert 1 kWh in kJ

Q1.8. Convert 1 kJ in Wh

Q1.9. Convert 1 eV in $J \cdot mol^{-1}$

Q 1.10. Convert 1 kcal in kJ

SOLUTION

Q1.7. Convert 1 kWh in kJ

$1\ kWh = 1\ kJ\cdot s^{-1}\cdot h = 1kJ\cdot s^{-1}\cdot 3600s\cdot h^{-1}\cdot h = 3600\ kJ$

Q1.8. Convert 1 kJ in Wh

$1\ kJ = 1\ kWs = 1000\ Ws\cdot h\cdot (3600s)^{-1} = 0.278\ Wh$

Q1.9. Convert 1 eV in $J\cdot mol^{-1}$

$1\ eV = 1.6\cdot 10^{-19}\ As\cdot V = 96.4\ kJ\cdot mol^{-1}$

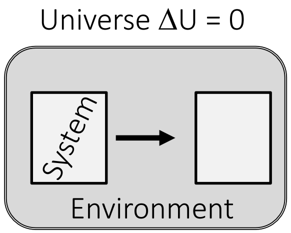
Q 1.10. Convert 1 cal in J

1 kcal = 4.187 kJ (heat 1 kg H_2O by 1°C or lift 4.2 kg by 1 m up)

1.4. 1st and 2nd LAW OF THERMODYNAMICS

1st law: $\Delta U = \Delta Q + \Delta W$

Energy conservation
System, Environment, Universe

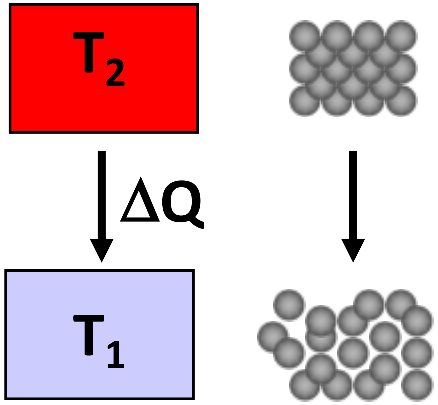


Ludwig Eduard Boltzmann
(* 20. 2 1844 in Wien;
† 5. 9. 1906 in Duino,
Österreich-Ungarn)

2nd law: $\Delta S \geq 0$

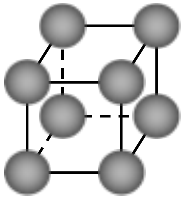
$$\Delta S = \frac{\Delta Q}{T} \quad \text{and} \quad \Delta S = k \cdot ln\left(P_{n,m}\right)$$

Heat spontaneously moves from hot to cold
Disorder spontaneously increases



3rd law: $\Delta S_{minimal}$ at T = 0 K

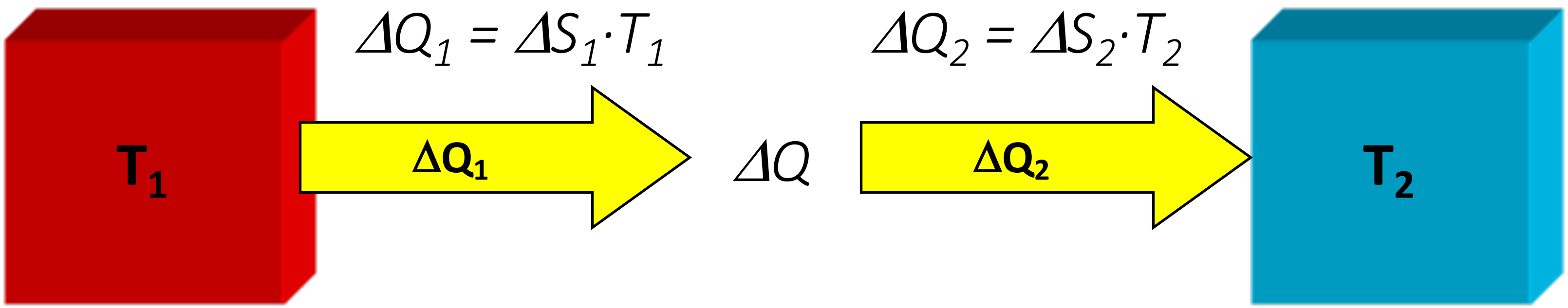
At 0K the entropy in an ideal crystal is minimal.



1.5. ENTROPY (S)

ENTROPY = HEAT/TEMPERATURE

$\Delta Q_1 = \Delta S_1 \cdot T_1$ $\Delta Q_2 = \Delta S_2 \cdot T_2$



Reservoir 1 Reservoir 2

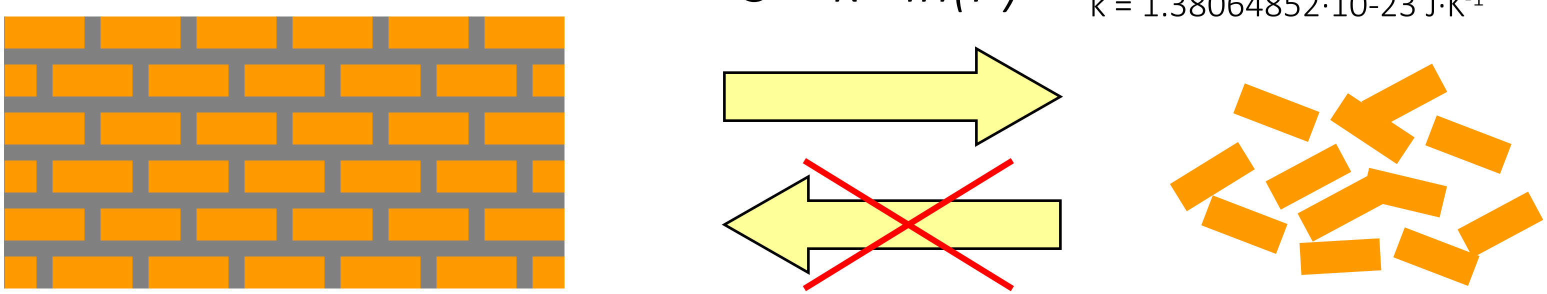
$$\Delta Q = -\Delta Q_1 = \Delta Q_2$$

$$\Delta S = -\Delta Q_1 / T_1 + \Delta Q_2 / T_2$$

ENTROPY = DISORDER (Probability)

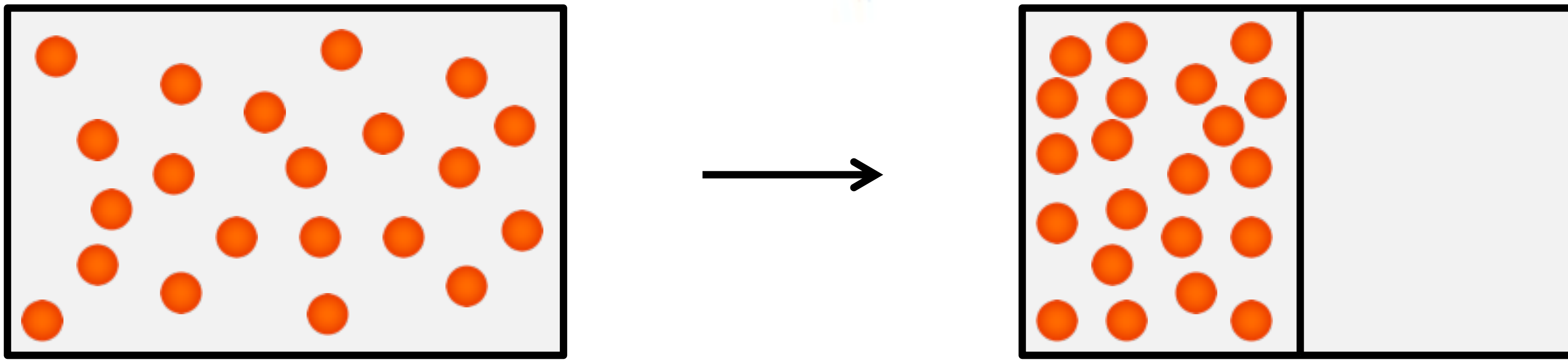
$$S = k \cdot \ln(P)$$

Boltzmann constant $k = R/N_A$
$k = 1.38064852 \cdot 10\text{-}23\ J \cdot K^{-1}$



1.5.1. ENTROPY FROM HEAT

$$\Delta S = \frac{\delta Q}{T}$$



isothermal compression T = const. $\Delta U = \Delta Q + \Delta W = 0$

$$\Delta W = -\int_V^{V/2} p \cdot dV = -n \cdot R \cdot T \int_V^{V/2} \frac{dV}{V} = -n \cdot R \cdot T \cdot ln\left(\frac{V/2}{V}\right)$$

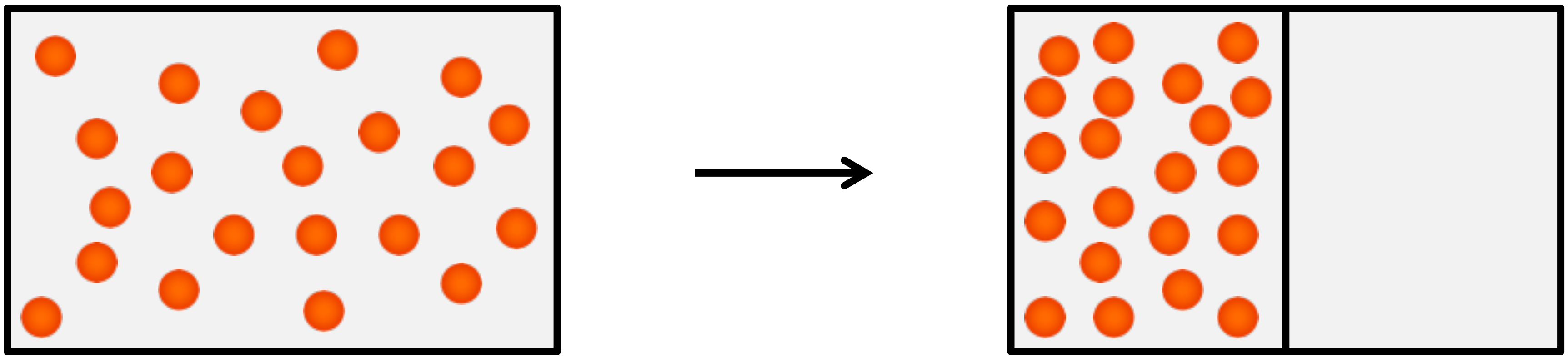
$$= n \cdot R \cdot T \cdot ln(2)$$

$\Delta Q = - \Delta W$

$$\Delta S = \frac{\delta Q}{T} = -n \cdot R \cdot ln(2)$$

1.5.2. ENTROPY FROM PROBABILITY

$$\Delta S = k \cdot ln(P)$$



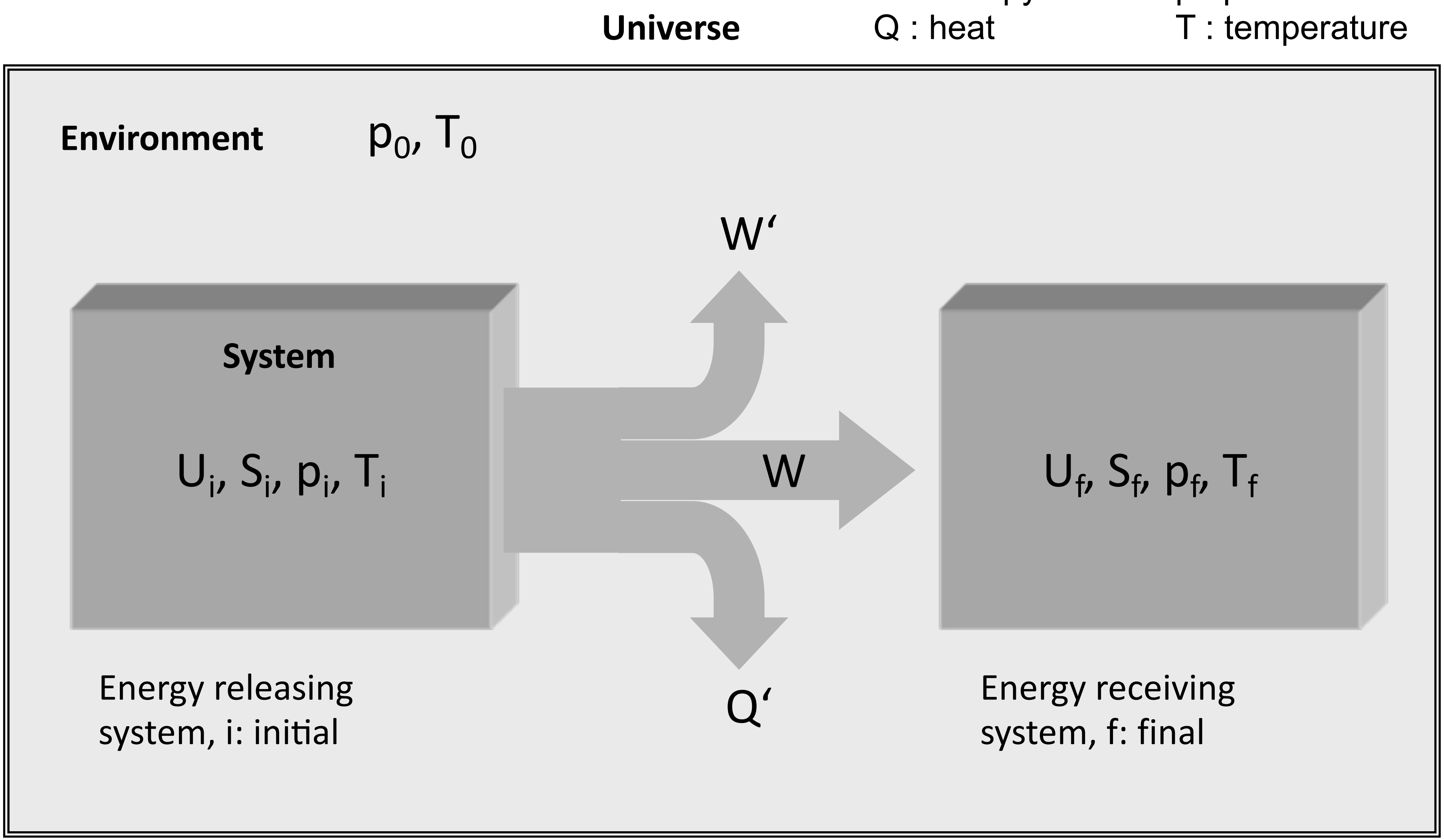
the probability to find all the molecules in half of the volume is

$$\Delta S = k_B \cdot ln\left(\frac{1}{2}\right)^N$$
$$= -N \cdot k_B \cdot ln(2)$$
$$= -n \cdot R \cdot ln(2)$$

1.6. ENERGY CONVERSION

U : inner energy
S : entropy
Q : heat

W : work
p : pressure
T : temperature



1.6.1. ENERGY CONVERSION ΔS_{tot}

$$-\Delta U = W + W' + Q' \quad with \quad \Delta U = U_0 - U$$

$$\Delta S = S_0 - S \quad with \quad \Delta S' = \frac{Q'}{T_0}$$

$$\Delta S_{tot} = \Delta S + \Delta S' = S_0 - S + \frac{Q'}{T_0}$$

$$Q' = T_0 \cdot (\Delta S_{tot} - \Delta S)$$

for the work W = -ΔU' – W' – Q'

$$W + T_0 \cdot \Delta S_{tot} = -\Delta U - W' + T_0 \cdot \Delta S$$
$$= (U - U_0) + p_0 \cdot (V - V_0) - T_0 \cdot (S - S_0)$$

$$for \quad \Delta S_{tot} = 0: \; W = (U - U_0) + p_0 \cdot (V - V_0) - T_0 \cdot (S - S_0) \; Exergy$$
$$and \; T_0 \cdot \Delta S_{tot} = Anergy$$

1.6.2. GIBBS FREE ENERGY ΔG

$$\Delta S_{Universe} = \Delta S_{tot} = \Delta S + \Delta S' = S_0 - S + \frac{Q'}{T_0}$$

$$\Delta S' = -\frac{\Delta H}{T} = -\frac{Q'_{rev}}{T_0} \qquad \Delta p = 0$$

$$-T \cdot \Delta S_{tot} = \Delta H - T \cdot \Delta S$$

$$\Delta G = -T \cdot \Delta S_{tot}$$

$$\Delta G = \Delta H - T \cdot \Delta S$$

$$G = H - T \cdot S \quad or \quad \Delta G = \Delta H - \Delta(T \cdot S)$$

ΔG is a state function (independent of the path)

1.6.3. SPONTANEOUS PROCESS

$\Delta S_{Universe} > 0$ spontaneous process

$\Delta S_{Universe} < 0$ spontaneous process in opposit direction

$\Delta S_{Universe} = 0$ process in equilibrium

$$\Delta G = -T \cdot \Delta S_{Universe} = \Delta H - T \cdot \Delta S$$

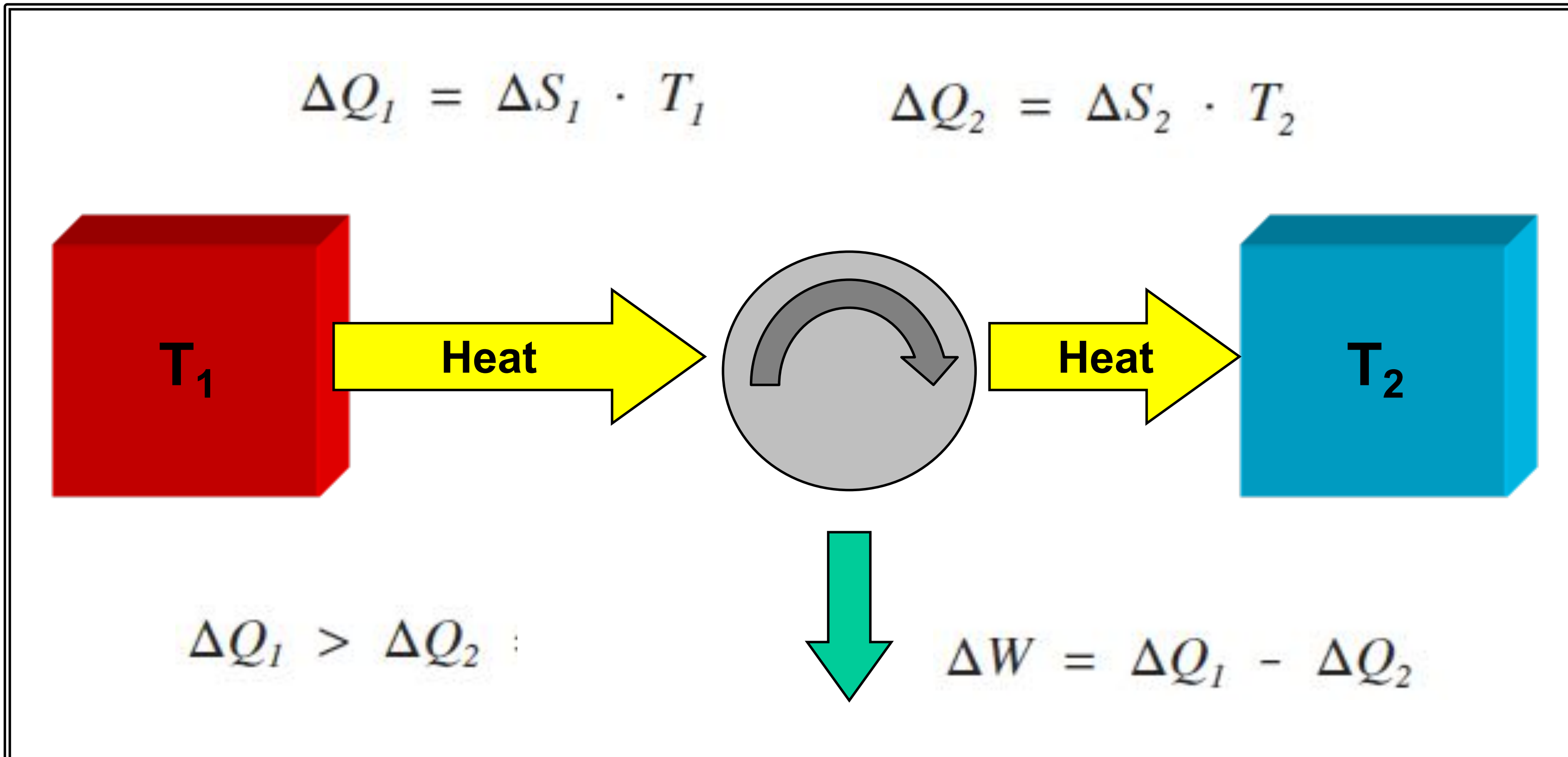
$\Delta G < 0$ spontaneous process $(\Delta H < 0,\ \Delta S > 0)$
$(\Delta H < 0,\ \Delta S < 0$ at low $T)$
$(\Delta H > 0,\ \Delta S > 0$ at high $T)$

$\Delta G > 0$ spontaneous process in opposite direction $(\Delta H > 0,\ \Delta S < 0)$

$\Delta G = 0$ process in equilibrium $(\Delta H = -T \cdot \Delta S)$

1.7. HEAT CONVERSION INTO WORK

Nicolas Léonard Sadi Carnot
(* 1. Juni 1796 in Paris;
† 24. August 1832 Paris)



1.7.1. EFFICIENCY (Conversion of Heat to Work)

$$Energy\ conservation:\ Q_1 = W + Q_2$$

$$Entropy\ change:\ \Delta S = -S_1 + S_2 = -\frac{Q_1}{T_1} + \frac{Q_2}{T_2}$$

$$Reversible:\ \Delta S = 0$$

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2} = S$$

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = \frac{S \cdot T_1 - S \cdot T_2}{S \cdot T_1} = \frac{T_1 - T_2}{T_1} = \frac{\Delta T}{T_1} = 1 - \frac{T_2}{T_1}$$

η : Efficiency

Irreversible: $\Delta S > 0$

$$\left|\frac{Q_1}{T_1}\right| < \left|\frac{Q_2}{T_2}\right|_{Q_1 < 0} \rightarrow \frac{T_2}{T_1} > \frac{Q_2}{Q_1}$$

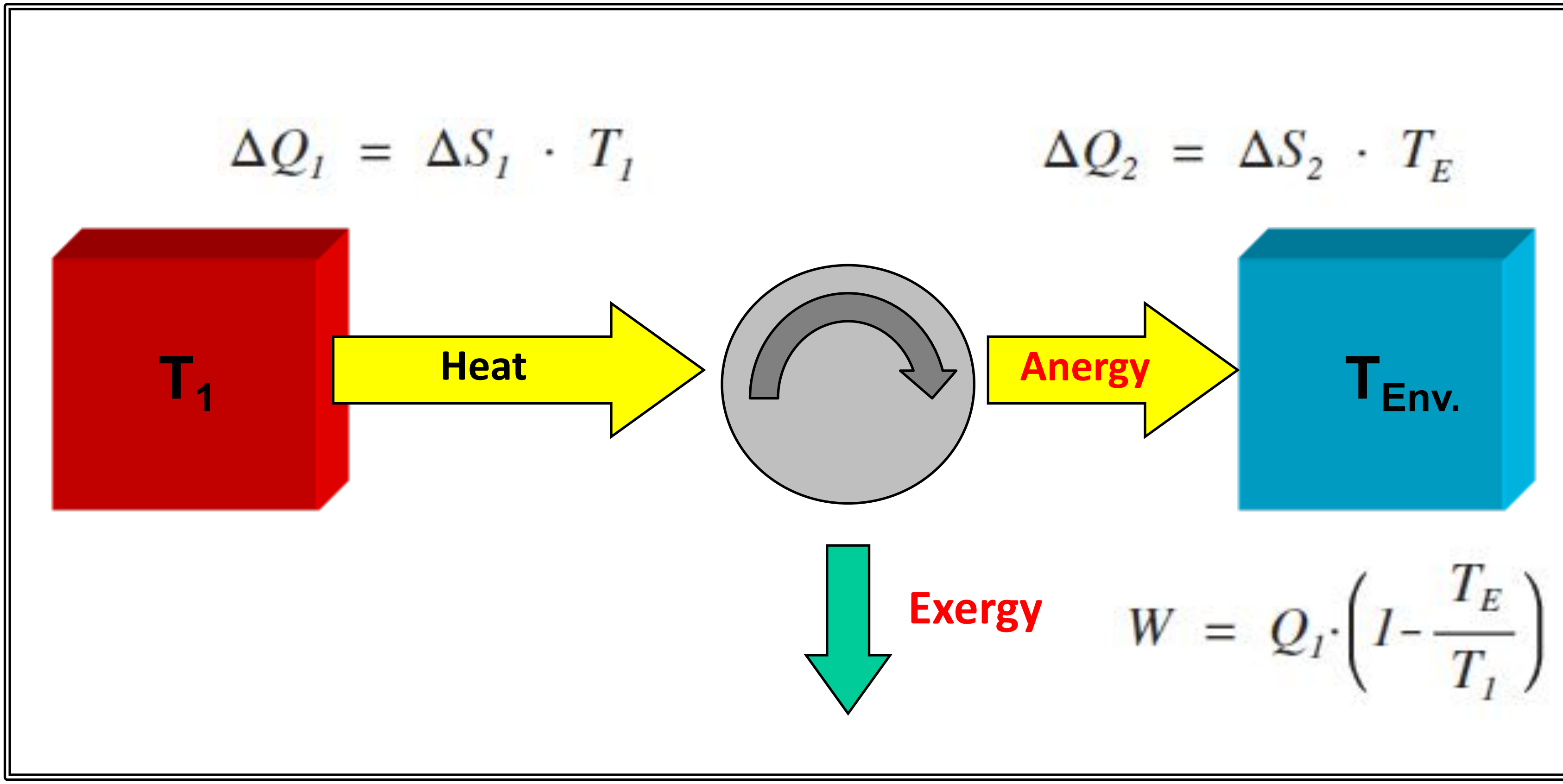
$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} < 1 - \frac{T_2}{T_1}$$

Impossible: $\Delta S < 0$

$$\left|\frac{Q_1}{T_1}\right| > \left|\frac{Q_2}{T_2}\right| \rightarrow \frac{T_2}{T_1} < \frac{Q_2}{Q_1}$$

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} > 1 - \frac{T_2}{T_1}$$

1.8. EXERGY AND ANERGY



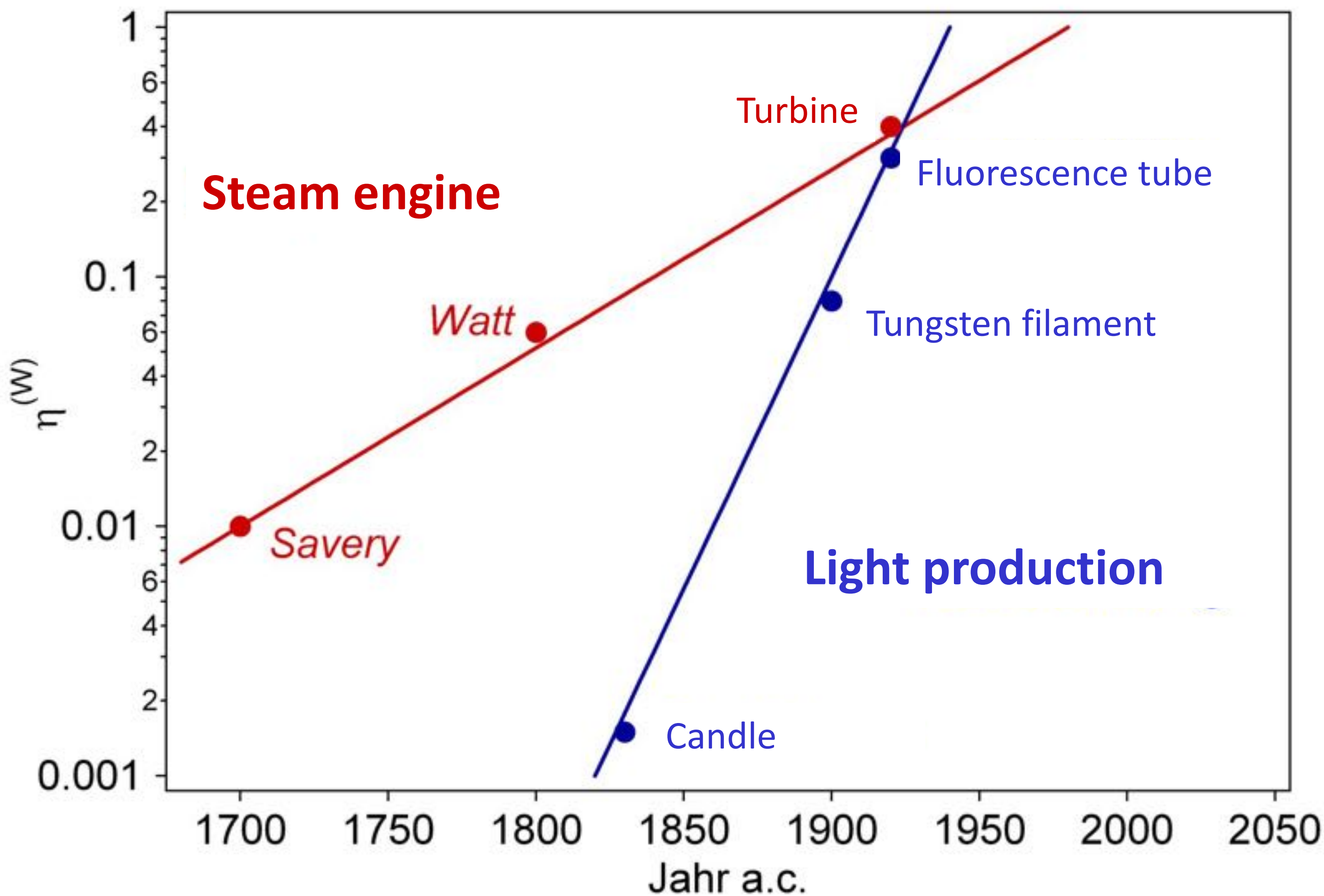
$$Special\ case:\ T_2 = T_E$$

$$W = Q_1 \cdot \left(1 - \frac{T_E}{T_1}\right) \quad Exergy$$

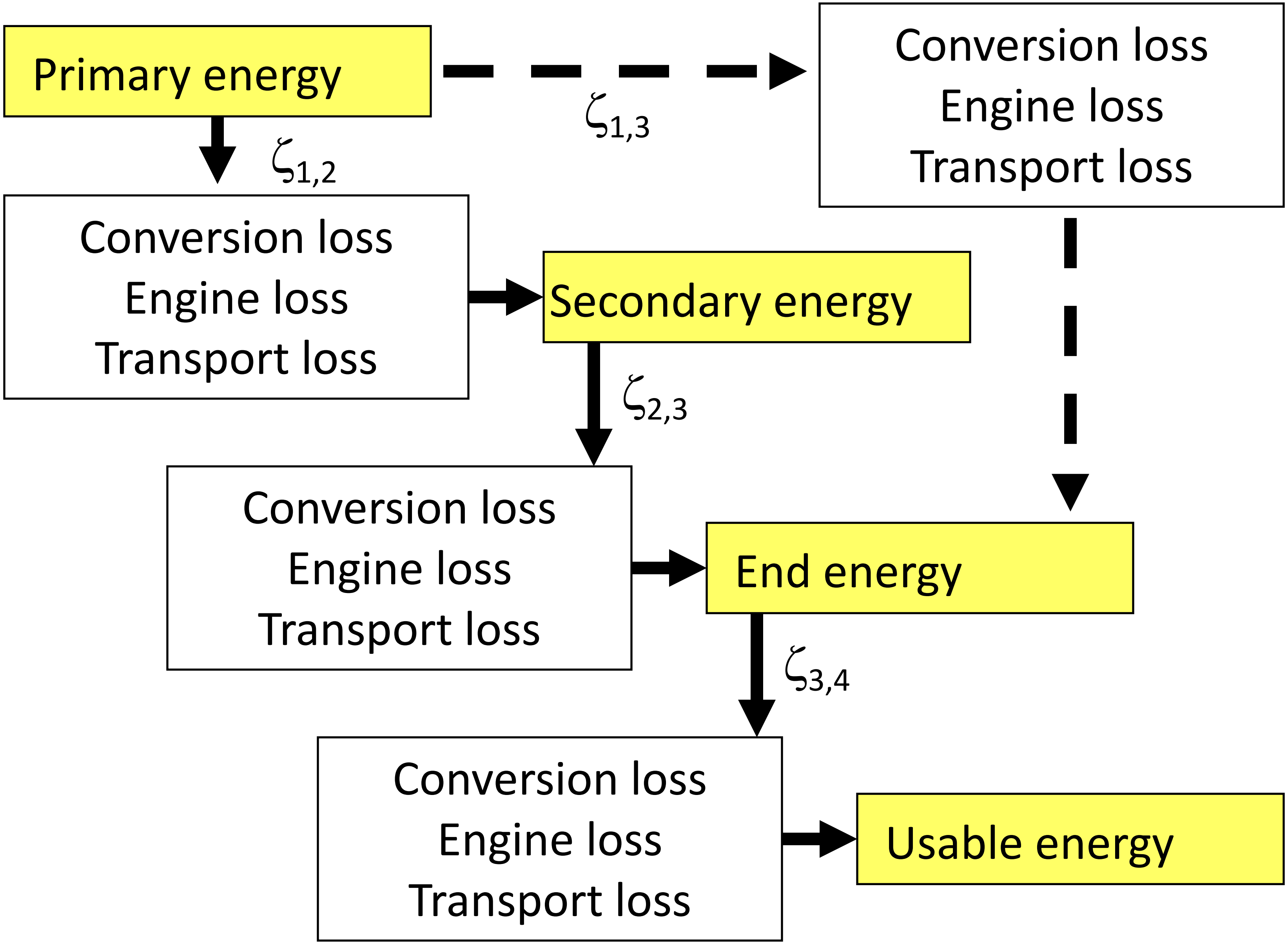
$$Q_2 = Q_1 - W = Q_1 \cdot \left(\frac{T_E}{T_1}\right) \quad Anergy$$

The heat Q_1 = Exergy + Anergy is the sum of Exergy and Anergy.

1.9. DEVELOPMENT OF THE EFFICIENCY

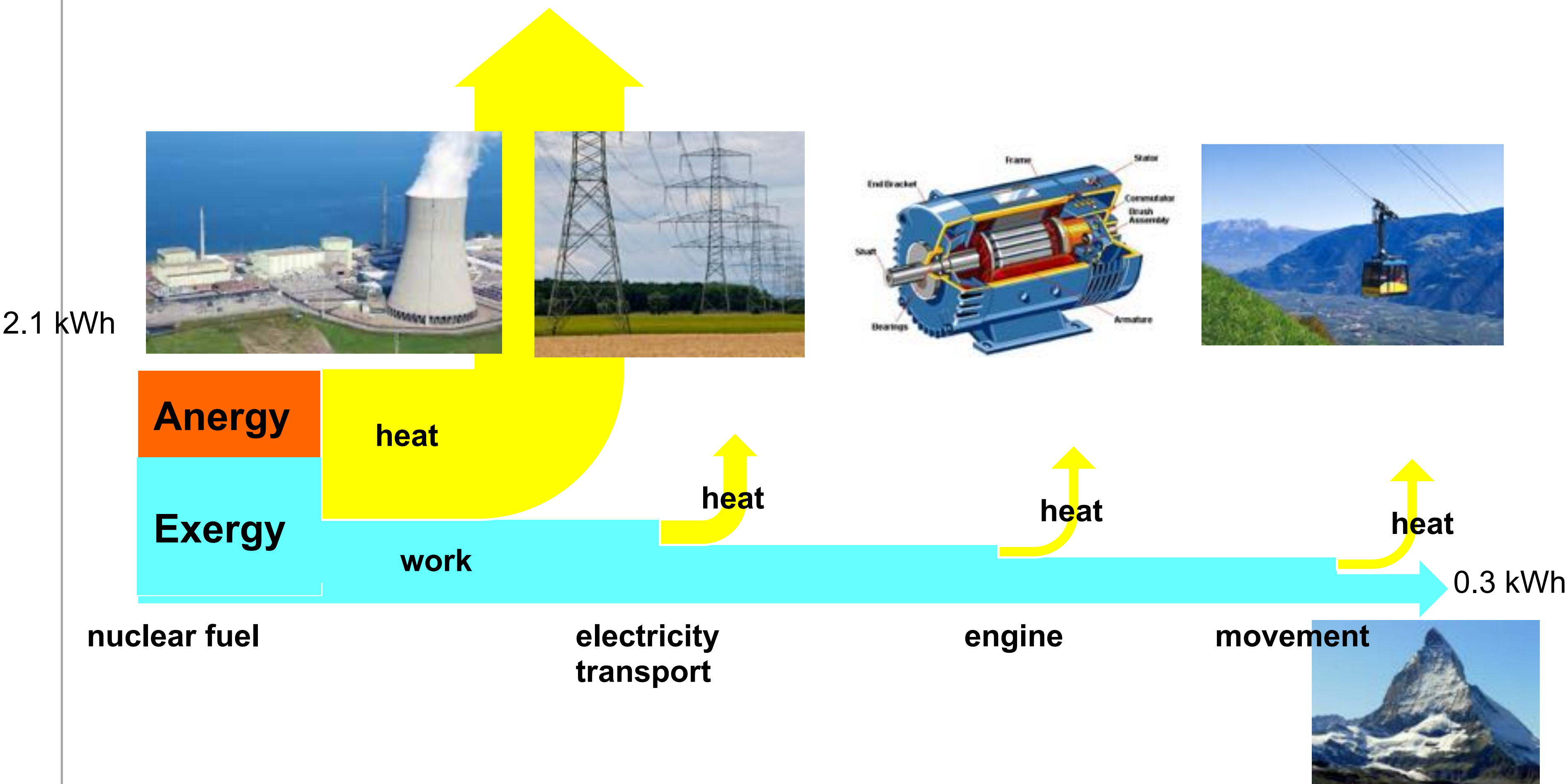


1.10. ENERGY CONVERSION PROCESS

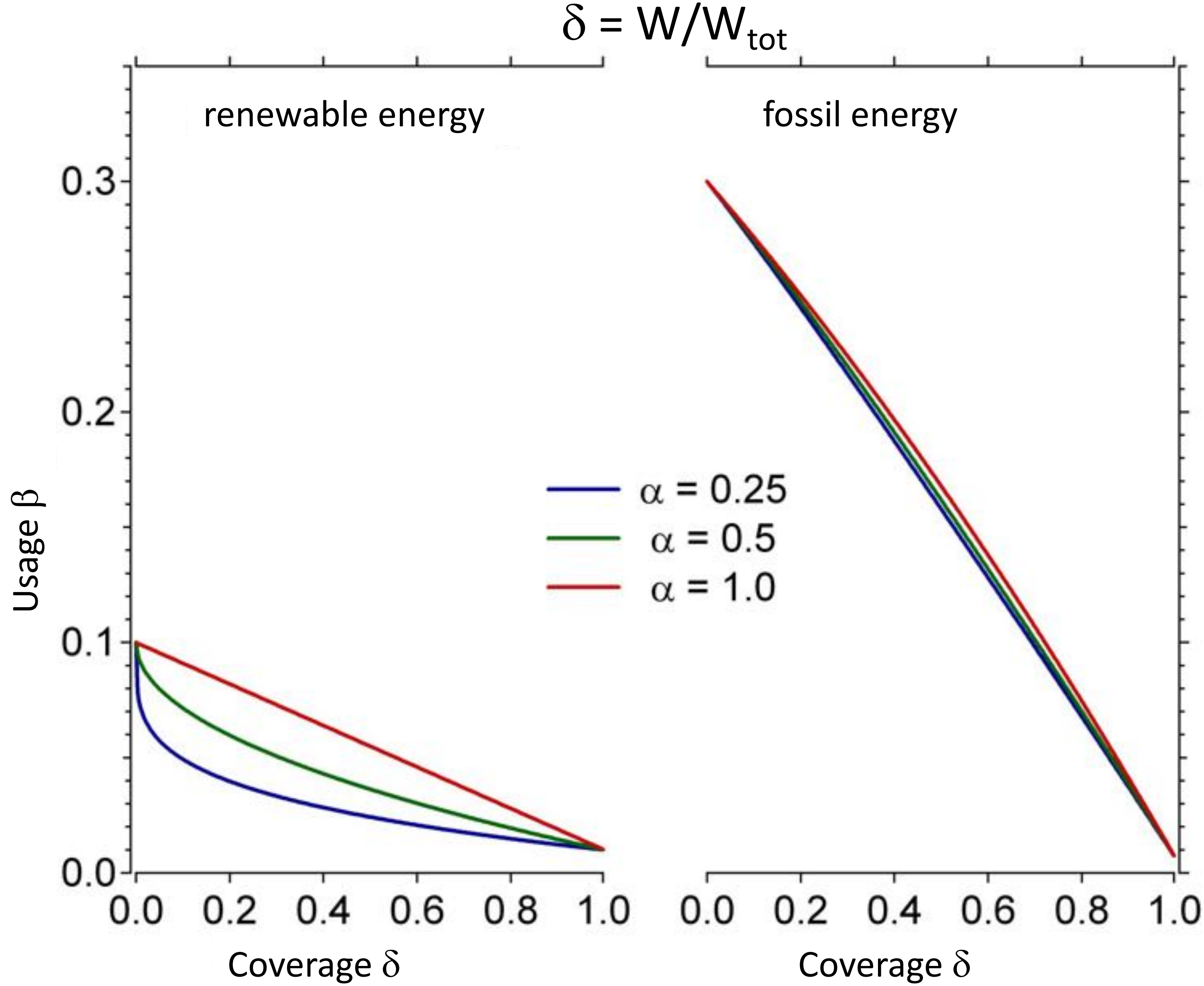


1.10.1. ENERGY CONVERSION PROCESS

Example: Move from the valley to the mountain,
potential energy = 100 kg·9.81 m/s²·1000 m = 1 MJ = 0.3 kWh

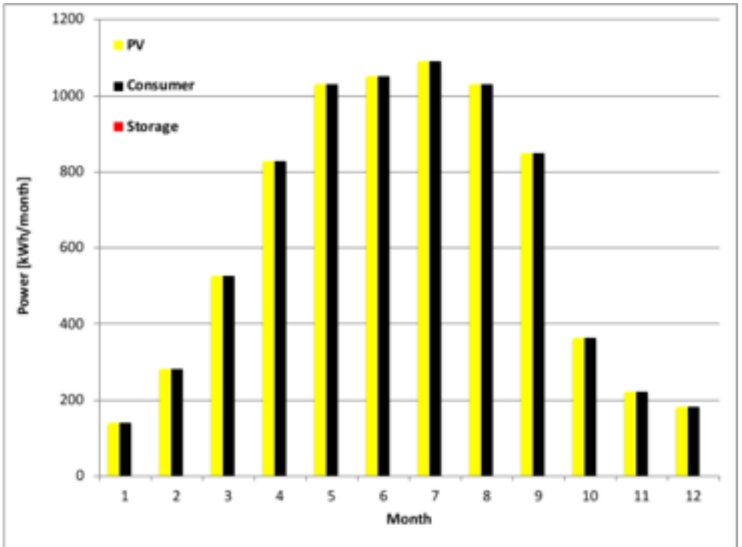


1.11. USAGE versus COVERAGE



1.11.1. EXAMPLE: PHOTOVOLTAICS

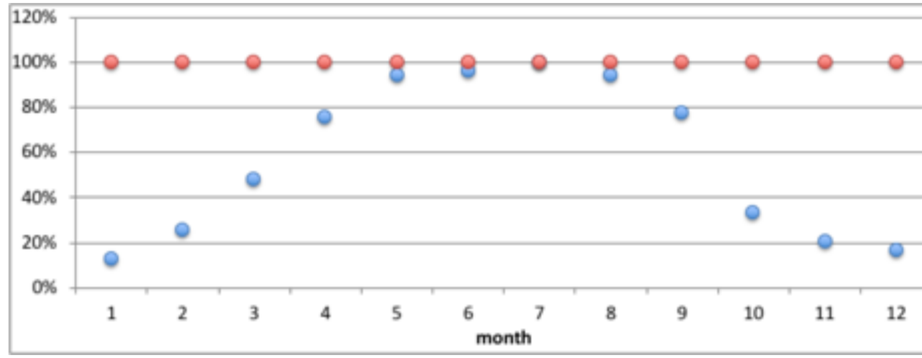
Photovoltaics η = 25%

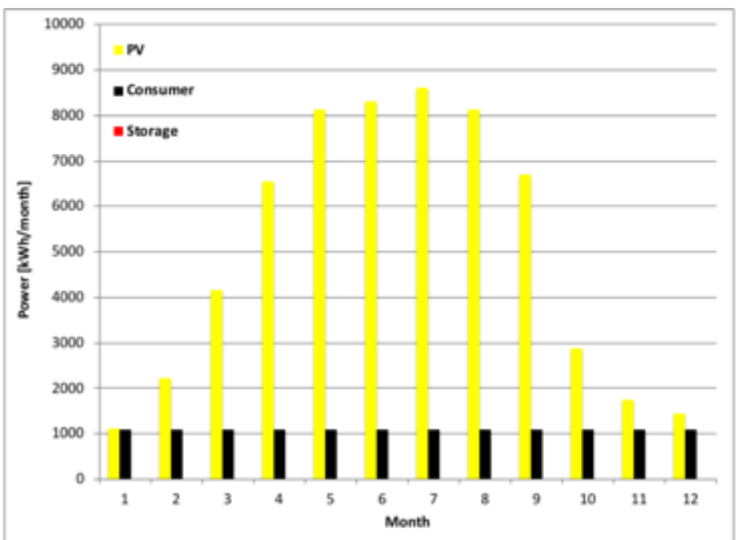


Min. production

Consumption: 13320 kWh
Production: 7600 kWh

coverage = 58%
usage = 25%·100%

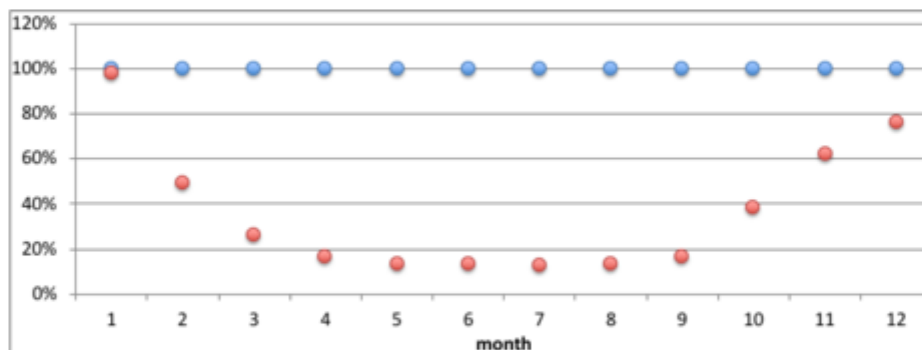


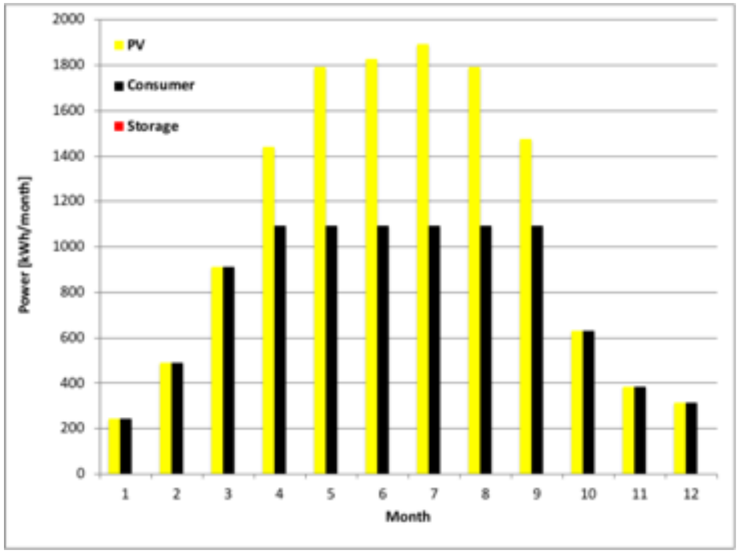


Max. production

Consumption: 13320 kWh
Production: 64000 kWh

coverage = 100%
usage = 25%·21%

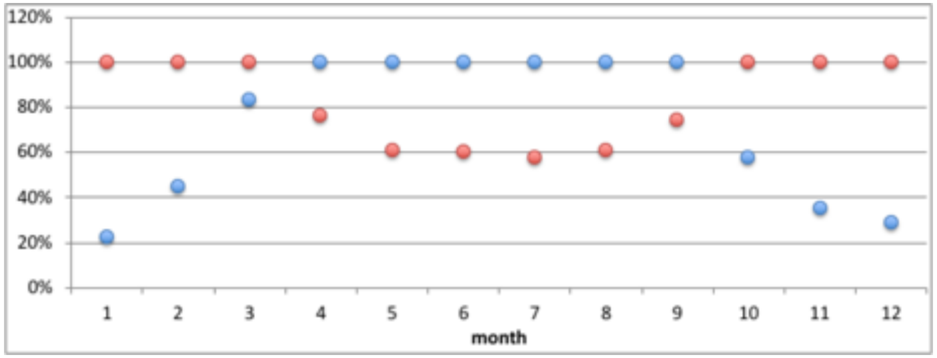


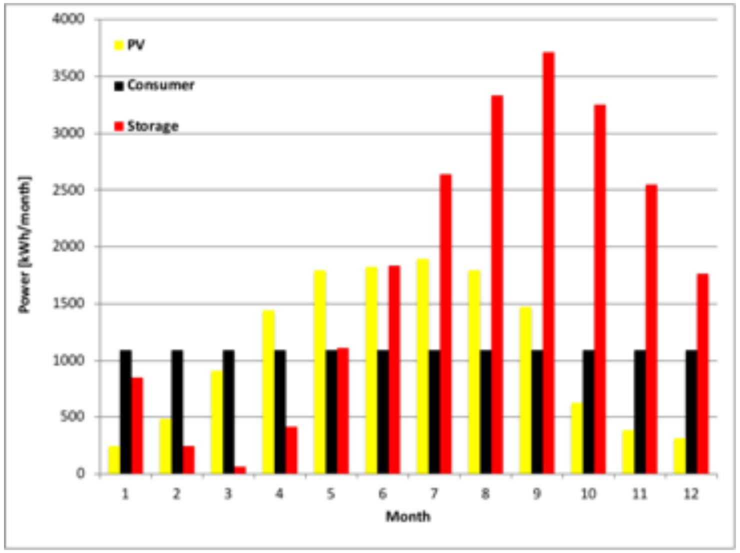


Equal production and consumption

Consumption: 13320 kWh
Production: 13200 kWh

coverage = 20 - 100%
usage = 25%·(60 - 100%)

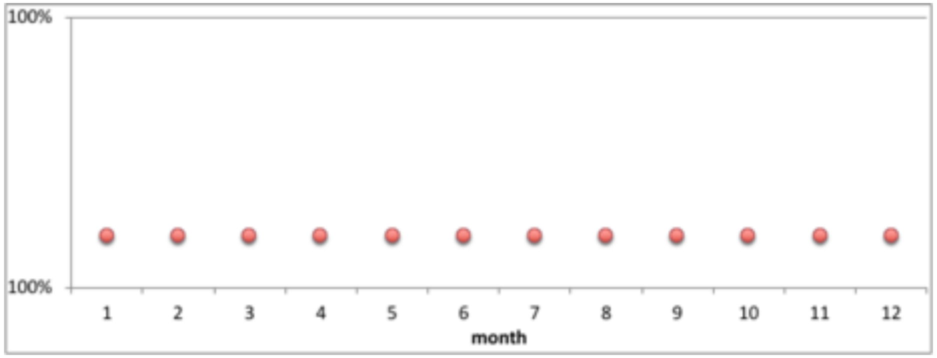




Equal production and consumption and storage

Consumption: 13320 kWh
Production: 13320 kWh
Storage: 5900 kWh

coverage = 100%
usage = 100%



1.12. ENERGY and POWER

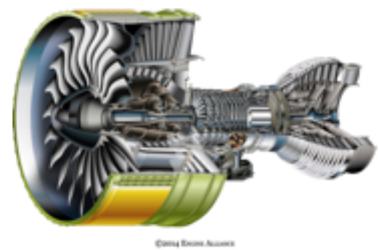
Energy
(E or E/m or E/V)

8000 kJ = 2.4 kWh

1300 MWh

Power
(P = dE/dt)

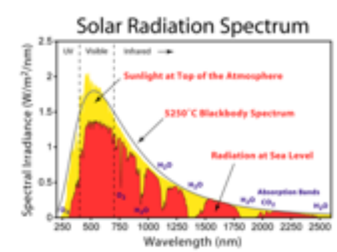
8000 kJ/day = 100 W



160 MW

33’000 TW

Intensity
(I = dP/dA)



1.3 kW/m^2

1.13. ENERGY CARRIER and ENERGY FLUX

$$Energy:\ W + Q$$

$$Power:\ P = \frac{d(W+Q)}{dt}$$

1.13.1. EXAMPLE Space Shuttle

1535 m^3 liq. H_2, 120t

m = 2'000 t, 2 solid state rockets 590 t (500t fuel, energy density 2.78 kWh/kg) each

Reaction: $10Al + 6NH_4ClO_4 \rightarrow 4Al_2O_3 + 2AlCl_3 + 12H_2O + 3N_2$

1.13.1. EXAMPLE Space Shuttle

1535 m^3 liq. H_2, 120t

m = 2'000 t, 2 solid state rockets 590 t (500t fuel, energy density 2.78 kWh/kg) each

Reaction: $10Al + 6NH_4ClO_4 \rightarrow 4Al_2O_3 + 2AlCl_3 + 12H_2O + 3N_2$

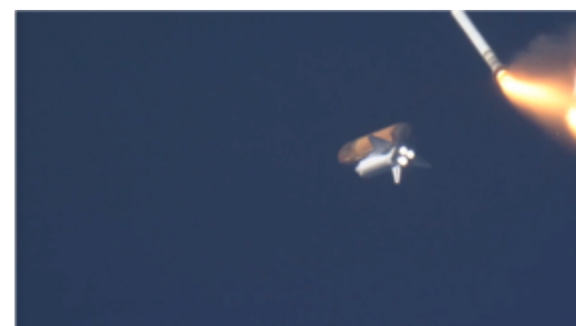
t =-60s

t = -10s

t = 0s ignition

t = 2s take off

t = 42s speed of sound



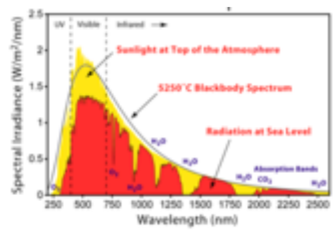
t = 120s release buster rockets

1.14. RENEWABLE ENERGY CONVERSION AND STORAGE

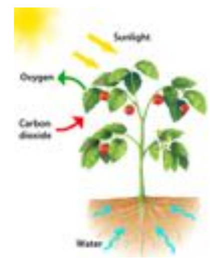
Energy carrier | **Energy flux** | **Conversion** | **Storage**

Sun (H)

Intensity



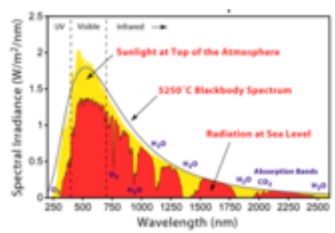
Photosynthesis



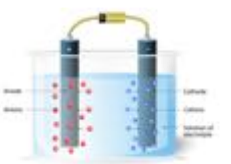
Biomass / Oil

Sun (H)

Intensity



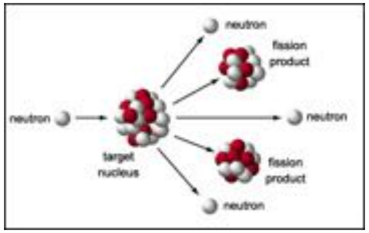
Photovoltaik/Electrolysis



Hydrogen

nuclear fuel (U^{235})

fission (n)



Turbine

Battery

EXERCISES 1

1) Describe the forms of work and heat you know, e.g. potential energy $W = m \cdot g \cdot h$ or heat capacity $Q = m \cdot c \cdot dT$. Make an example to each form with the corresponding quantity.

2) Calculate the energy consumed of an average human (J/day) and convert into power (Watts).

3) Compare in view of energy and entropy the heating of 1kg of water from 10°C to 100°C by using a coal fire (800°C).

4) Calculate the Exergy and Anergy of coal fire (800°C), in the steam entering the turbine (400°C), in boiling hot water (100°C) and in a heated room (22°C) when the temperature of the environment is at 15°C.

5) Calculate the primary energy necessary and the increase of entropy for drinking a cup of tea. Describe the energy chain from primary to usable energy and all the conversion steps.