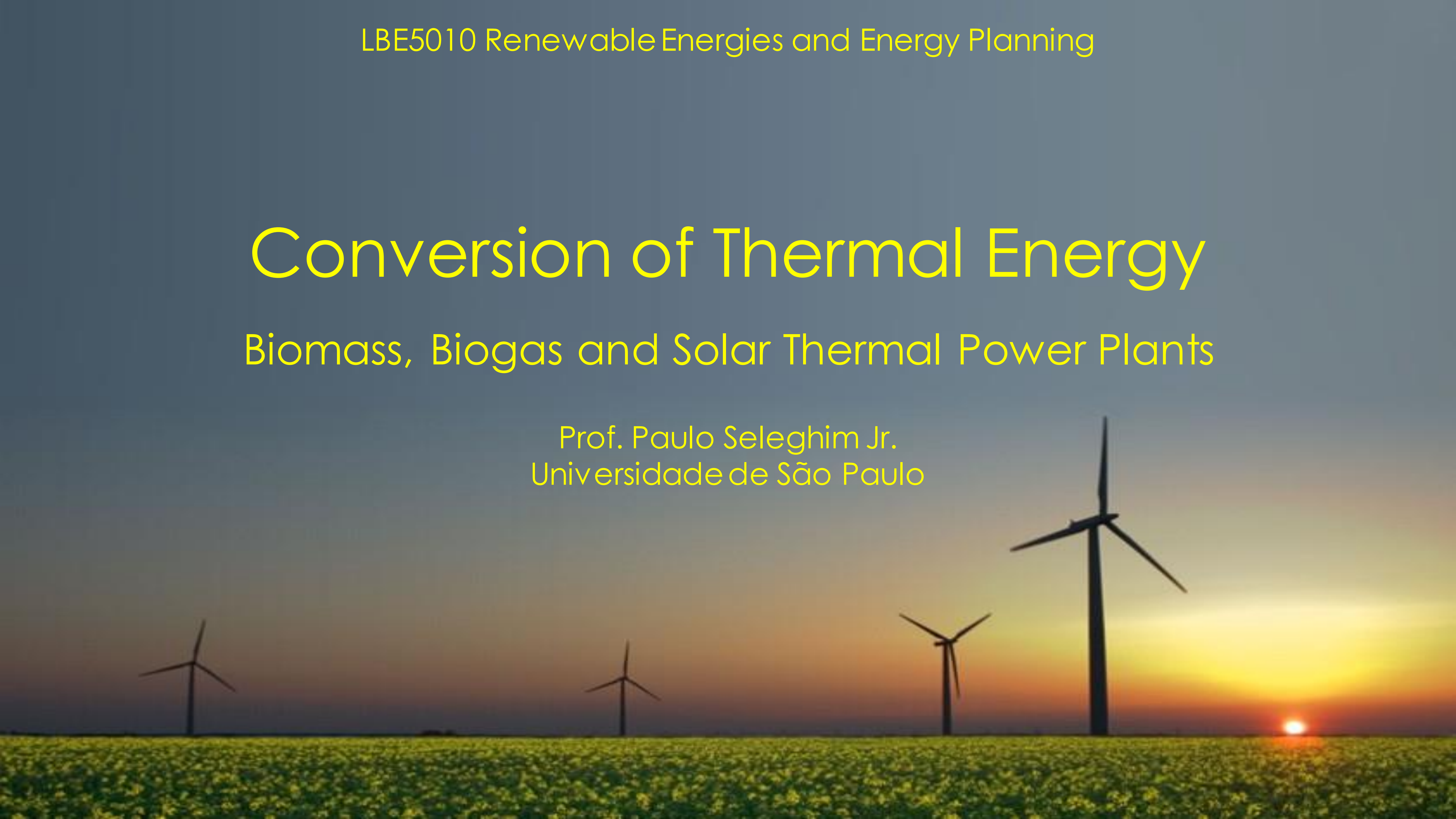
LBE5010 Renewable Energies and Energy Planning

Conversion of Thermal Energy

Biomass, Biogas and Solar Thermal Power Plants

Prof. Paulo Seleghim Jr.
Universidade de São Paulo



LBE5010 Renewable Energies and Energy Planning

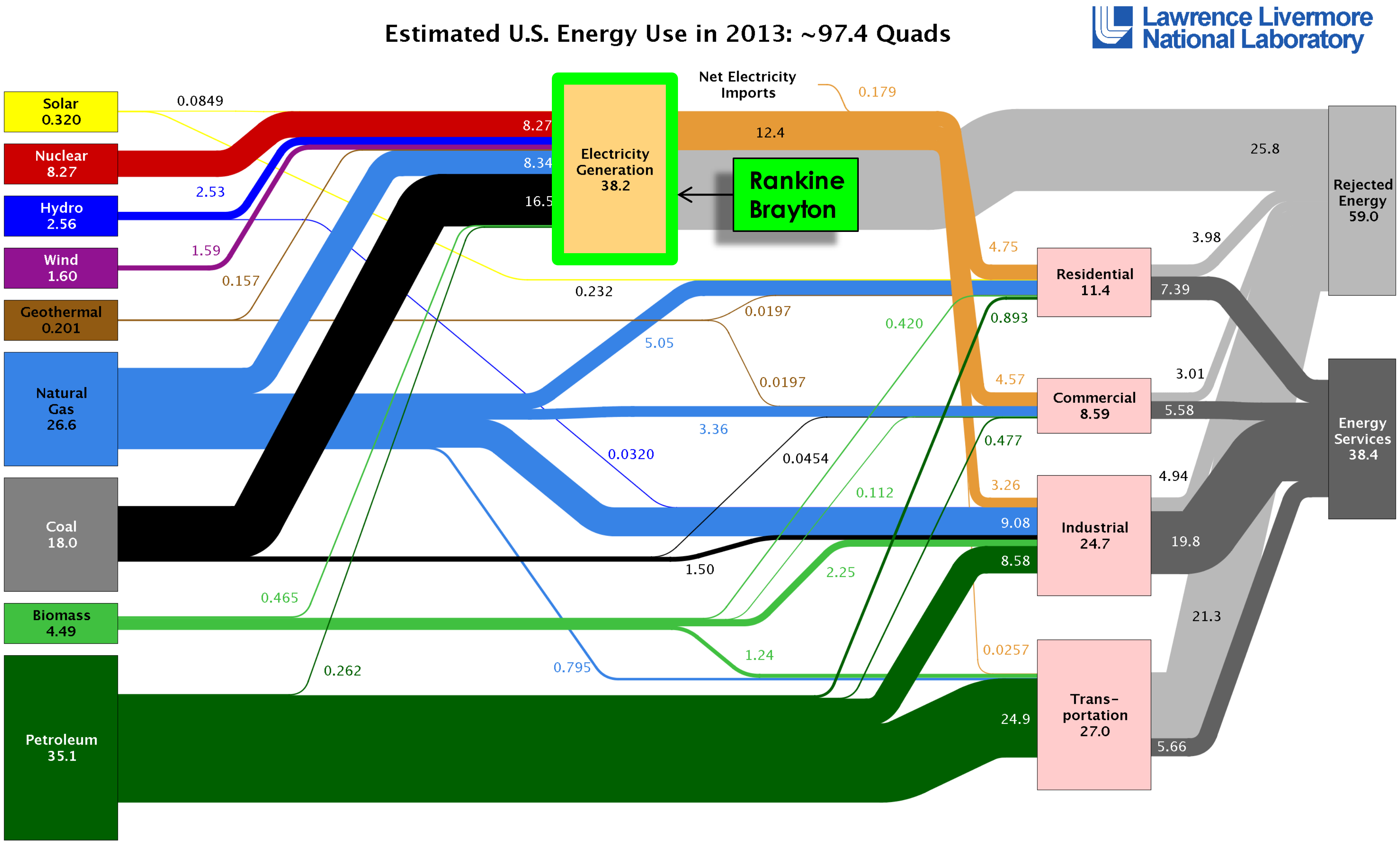
Conversion of Thermal Energy

Context and Theoretical Framework

Prof. Paulo Seleghim Jr.
Universidade de São Paulo

IEA 2015: thermal conversion is responsible for 80% world electrical energy generation

Sankey Diagram



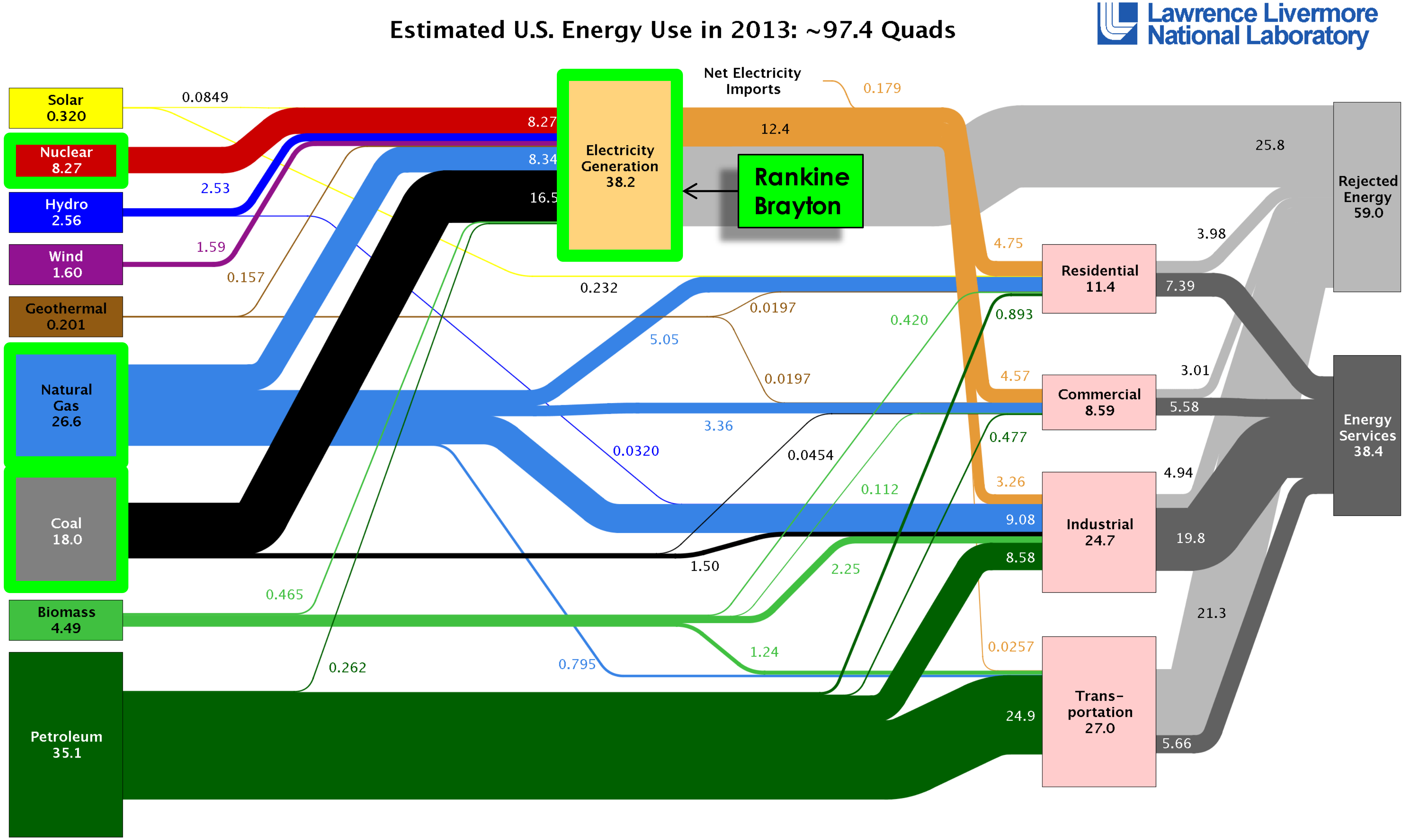
Estimated U.S. Energy Use in 2013: ~97.4 Quads

Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

“Non Renewable”

Non Renewable

Non Renewable



Rankine Brayton

Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Sankey Diagram

Lawrence Livermore National Laboratory

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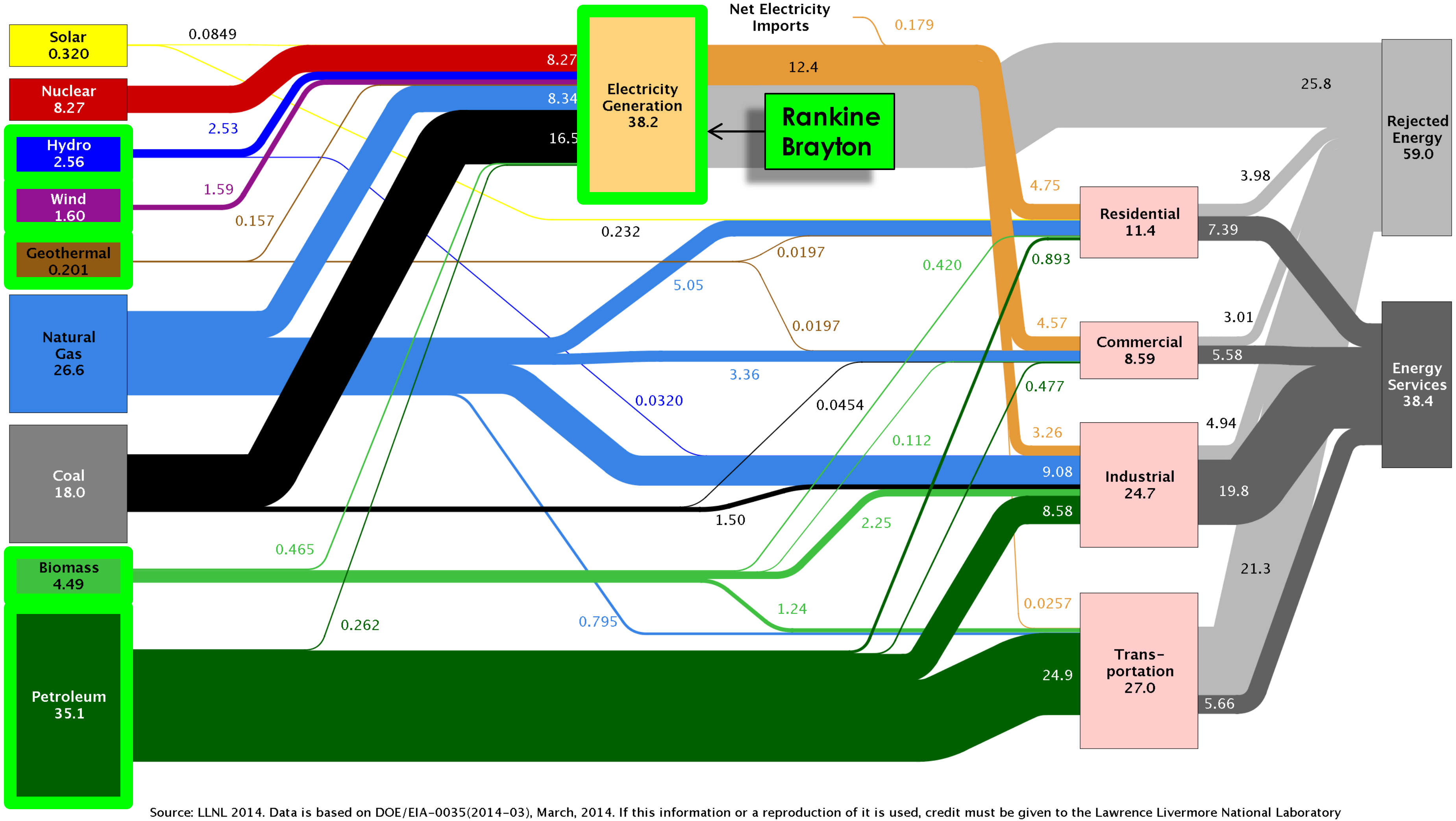

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Renewable ⇦

Renewable ⇦

“Non Renewable” ⇦

Renewable ⇦

Non Renewable ⇦

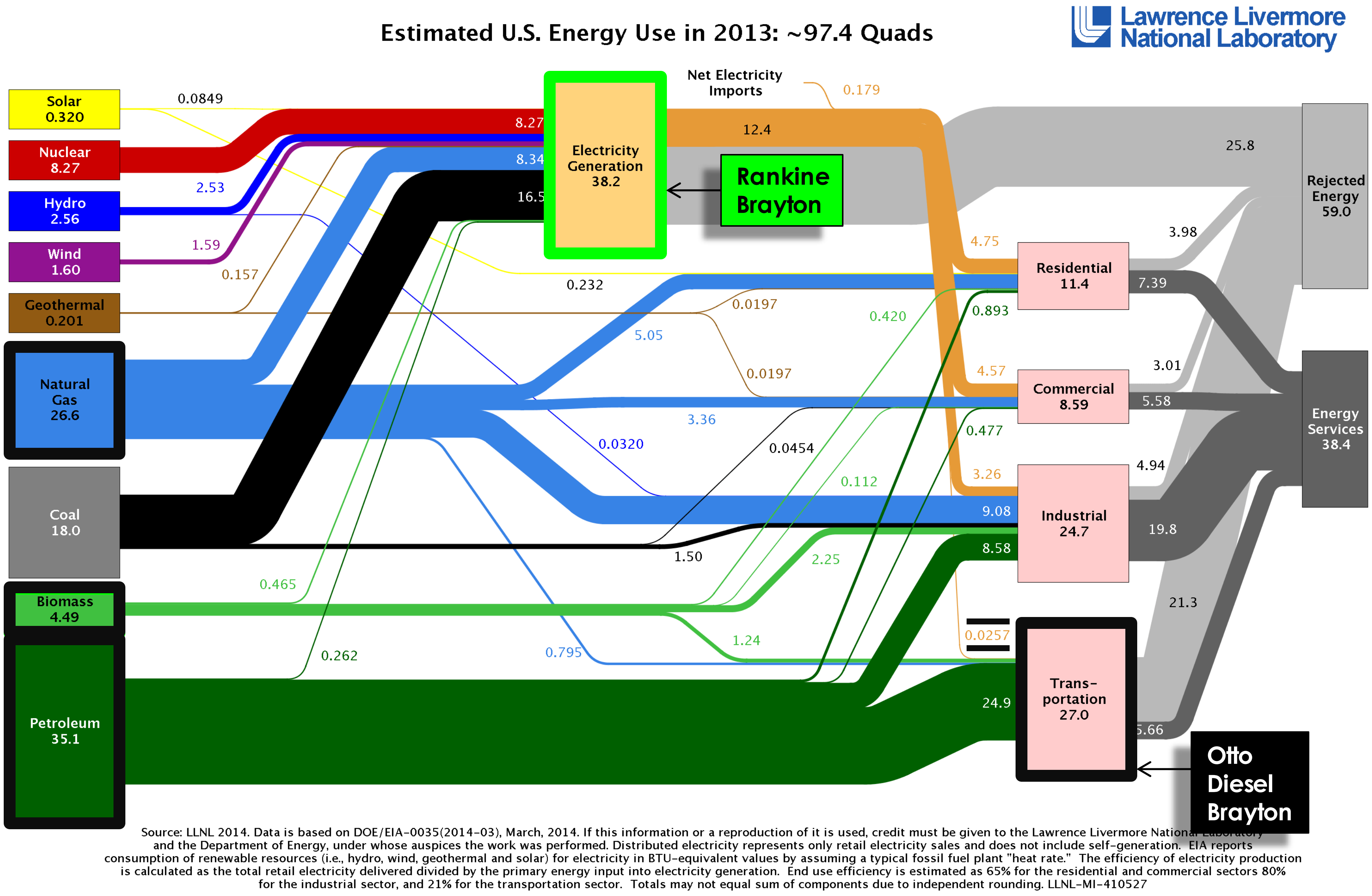
Rankine Brayton →

Sankey Diagram

Non Renewable

Renewable

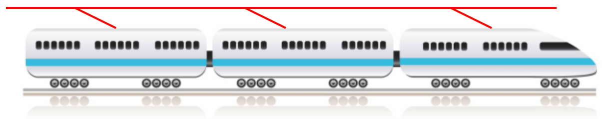
Non Renewable



Source: LLNL 2014. Data is based on DOE/EIA-0035(2014-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

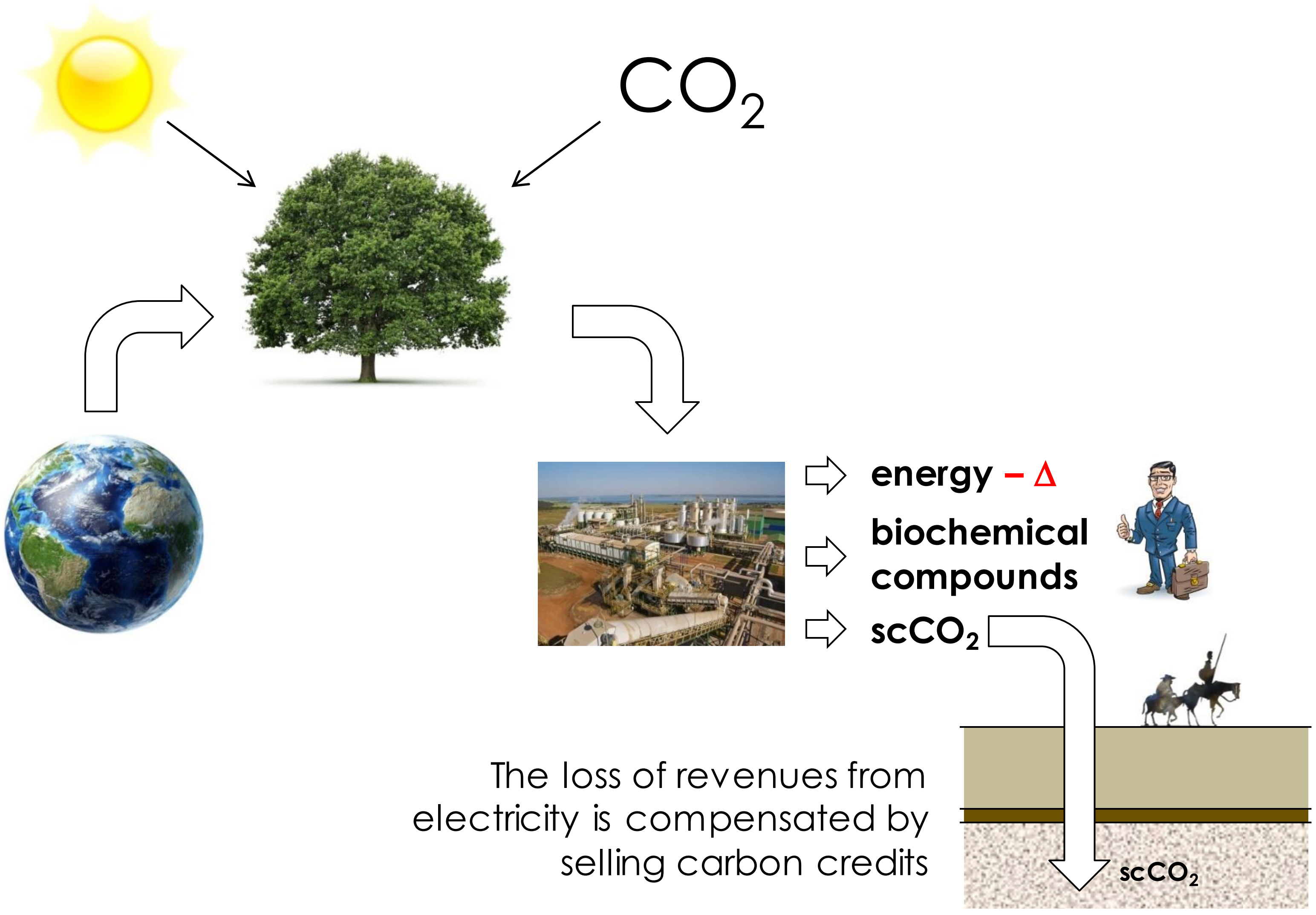
Rankine
Brayton

Otto
Diesel
Brayton



Sankey Diagram

Retrofitting a Biomass Power Plant into a “Sun Driven CCS Machine”…



CO_2

energy – Δ

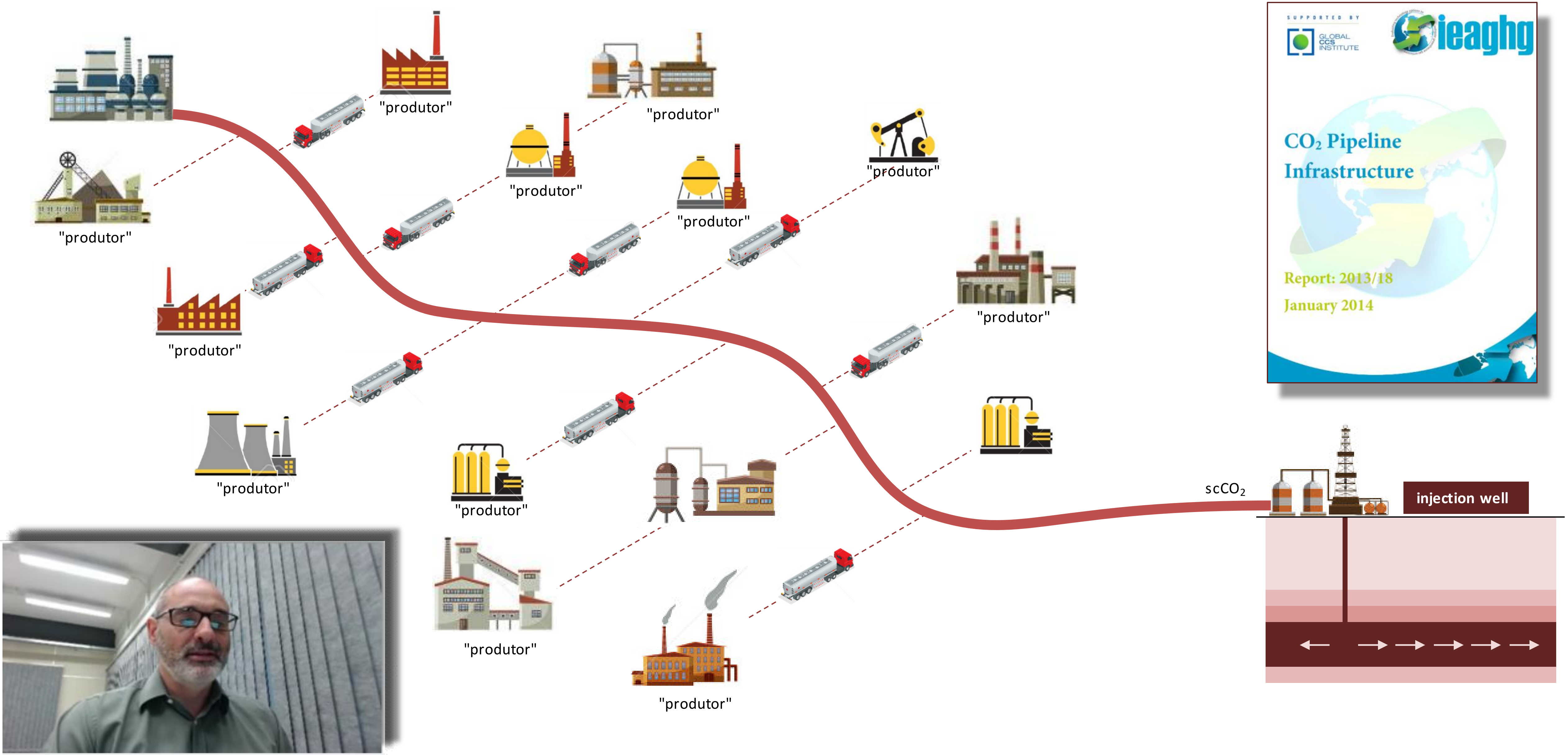
biochemical compounds

$scCO_2$

$scCO_2$

The loss of revenues from electricity is compensated by selling carbon credits

Carbon capture, transportation and geological storage

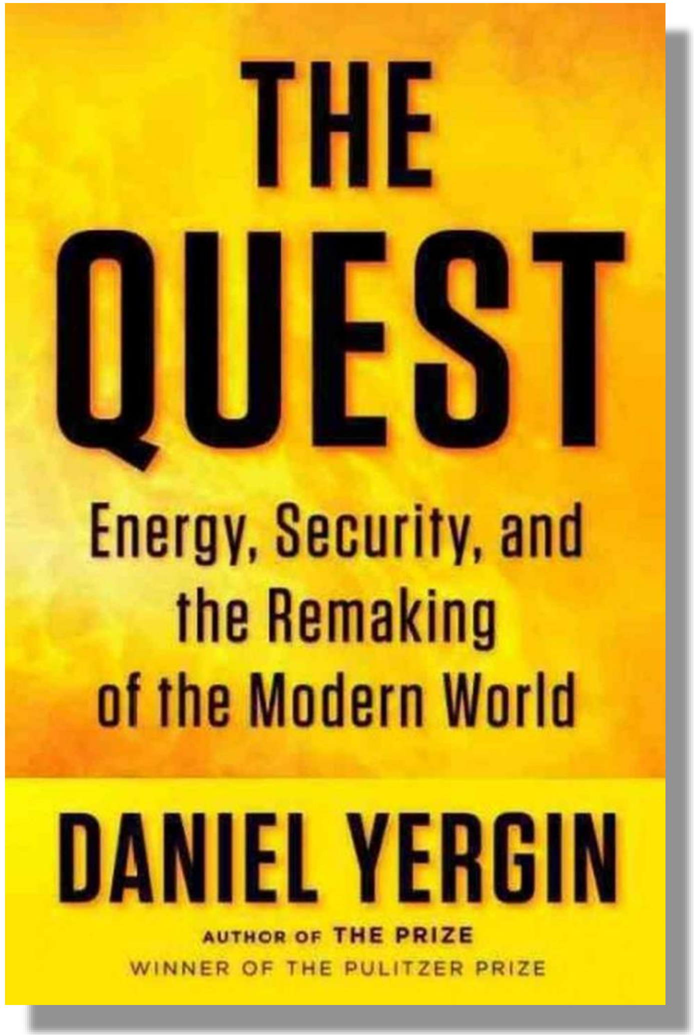


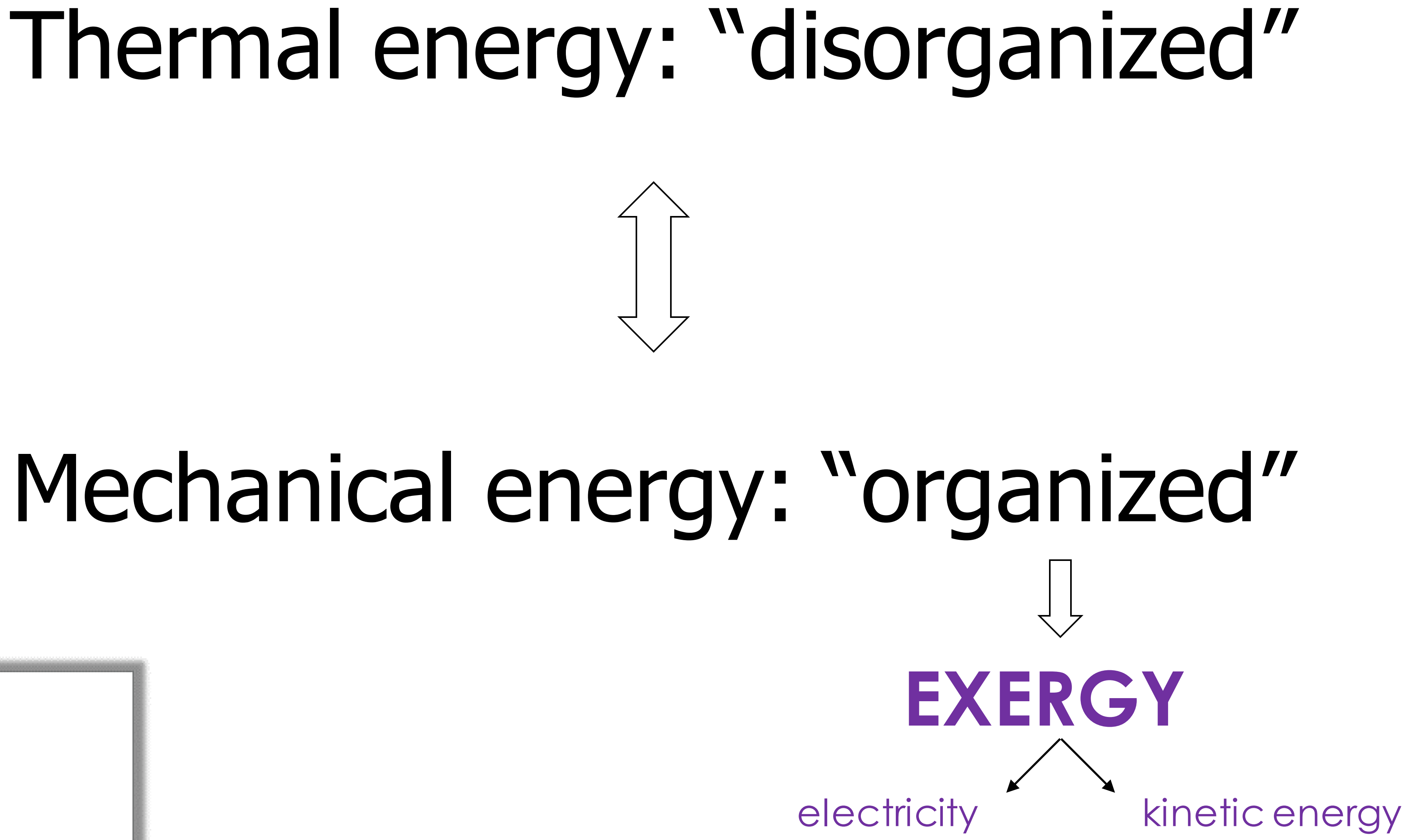
CO$_2$ Pipeline Infrastructure

Report: 2013/18

January 2014

Describes the evolution of energy systems, technologies, regulation and markets





Thermal energy: “disorganized”

Mechanical energy: “organized”

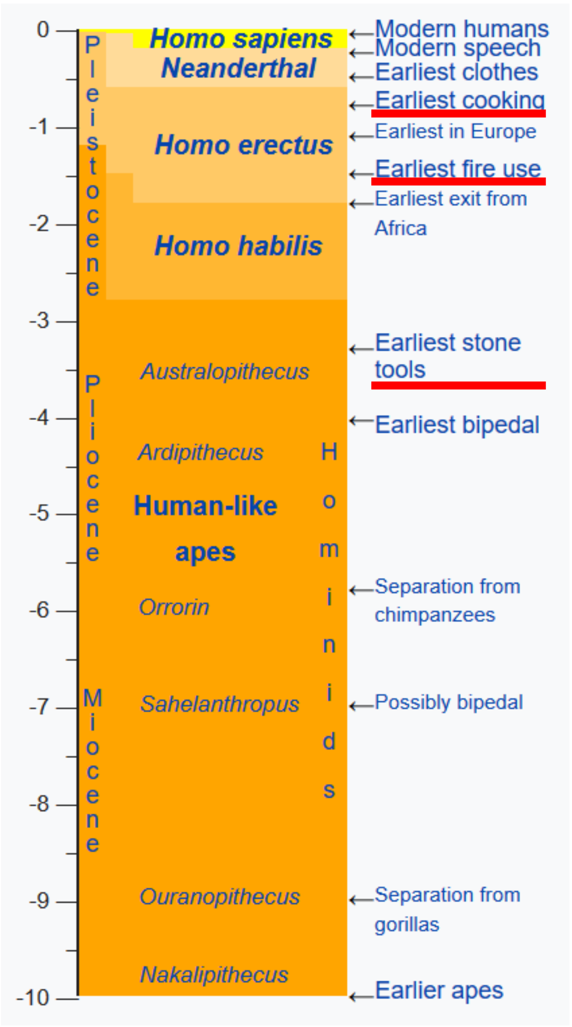
EXERGY

electricity

kinetic energy

Energy and Social Development

Disruptive improvements in the use of energy



Energy and Social Development

Disruptive improvements in the use of energy

✓ Control of fire for food cooking (thermal processing)

~500,000 years ago

- Transportation from burned to unburned areas
- Starting and building hearths or other fire enclosures
- Maintaining over an extended period of time

Incremental technological improvements

Energy and Social Development

Disruptive improvements in the use of energy

- ✓ Control of fire for food cooking
- ✓ Use of wind for water pumping, grain processing, boat propulsion, etc.

Energy and Social Development

Disruptive improvements in the use of energy

- ✓ Control of fire for food cooking
- ✓ Use of wind for water pumping, grain processing, boat propulsion, etc.
- ✓ ……….
- ✓ Conversion of heat to work (force × displacement)
- ✓ Development of general purpose motors
- ✓ Machining machines, mechanical looms, tractors, excavators, etc…

Energy and Social Development

Disruptive improvements in the use of energy

- ✓ Control of fire for food cooking
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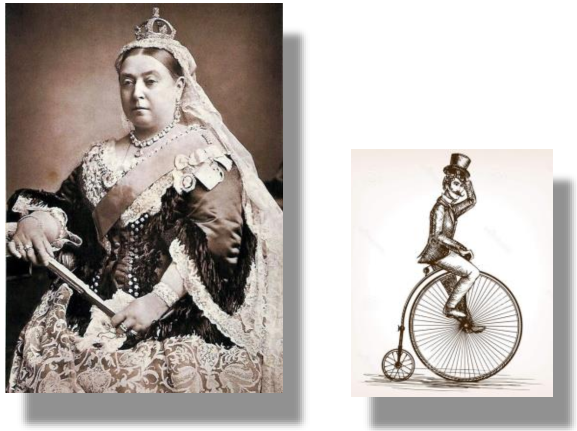
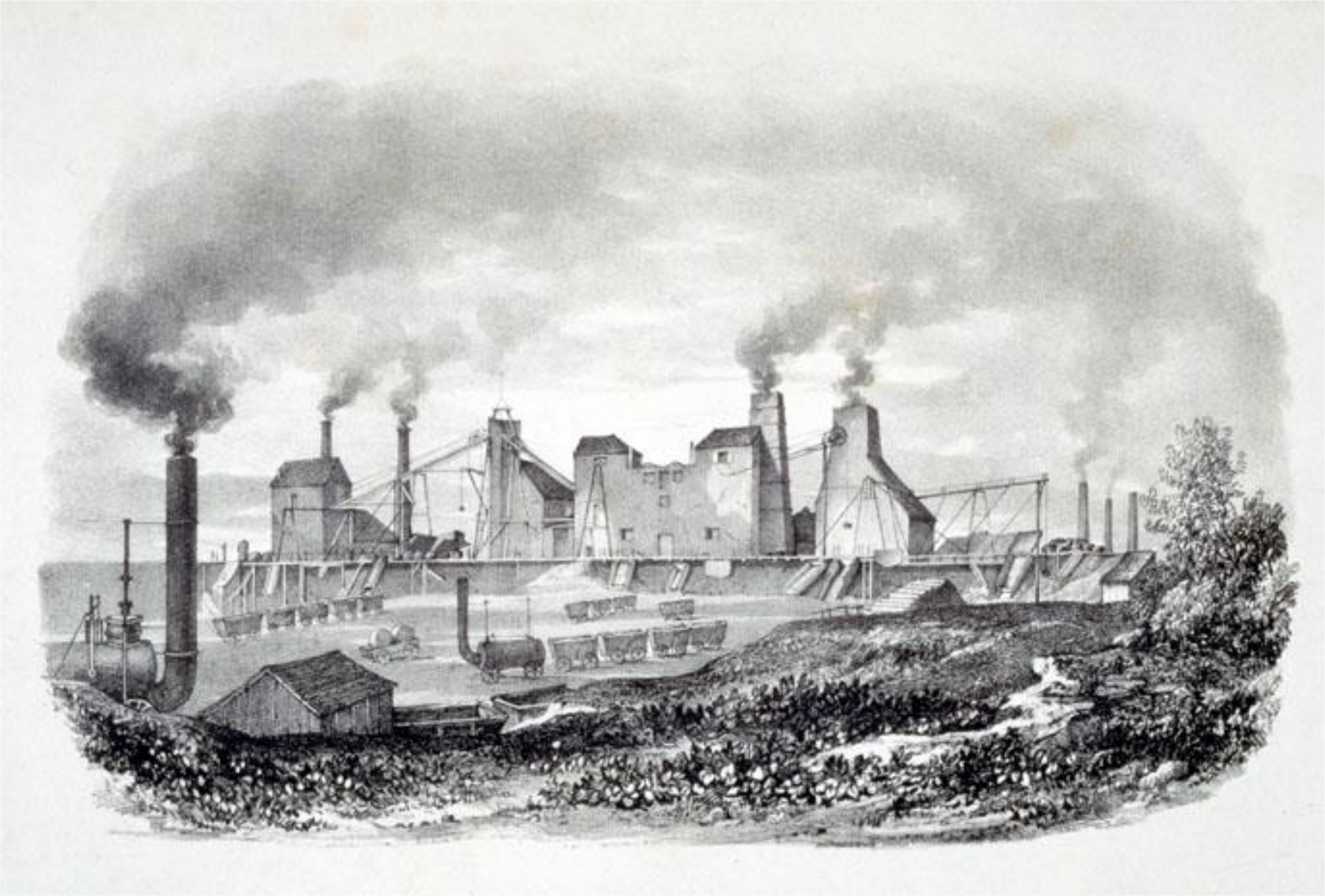
- ✓ ……….



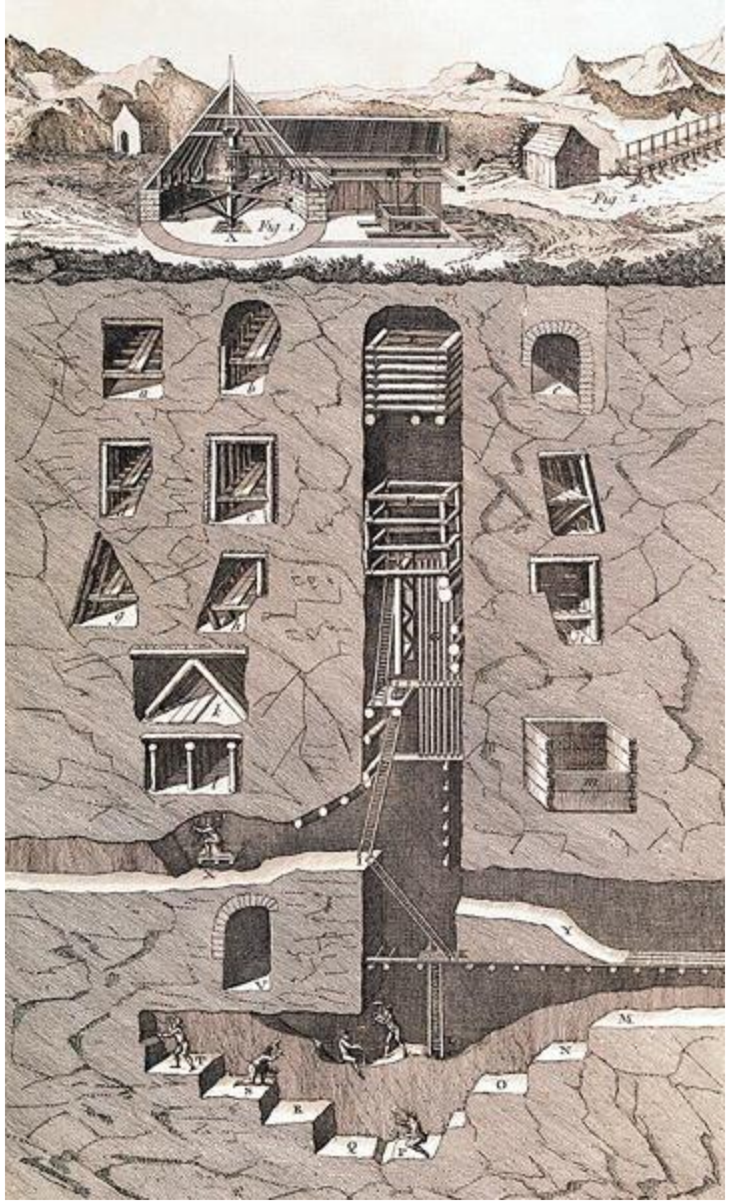
- ✓ Conversion of heat to work (force × displacement)
- ✓ Development of general purpose motors
- ✓ Machining machines, mechanical looms, tractors, excavators, etc…

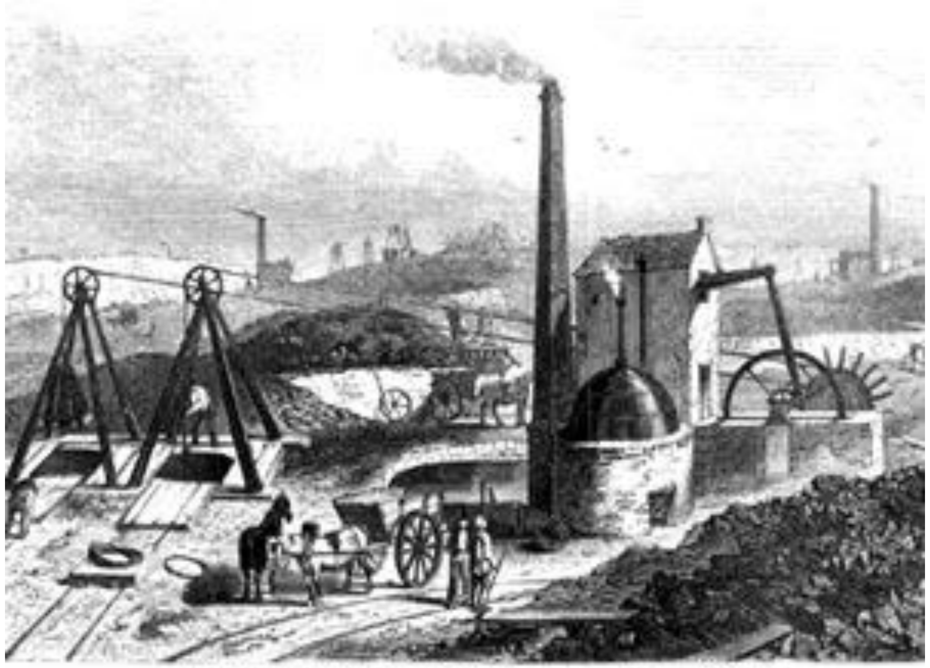
INDUSTRIAL REVOLUTION

Coal mining in the United Kingdom

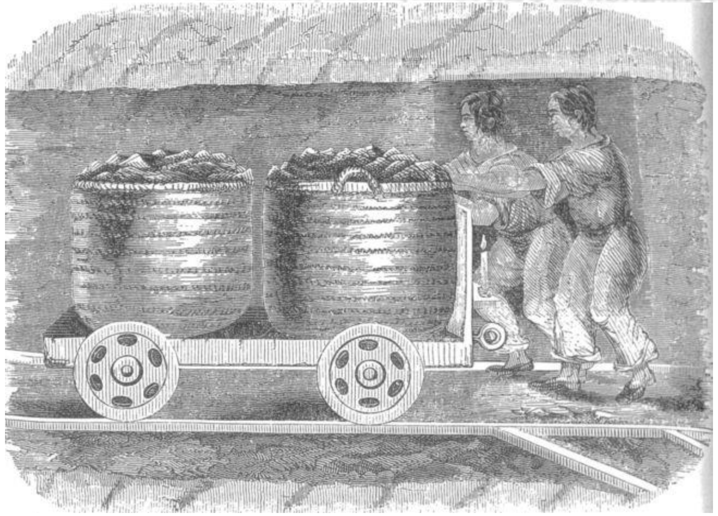


Coal mining in the United Kingdom

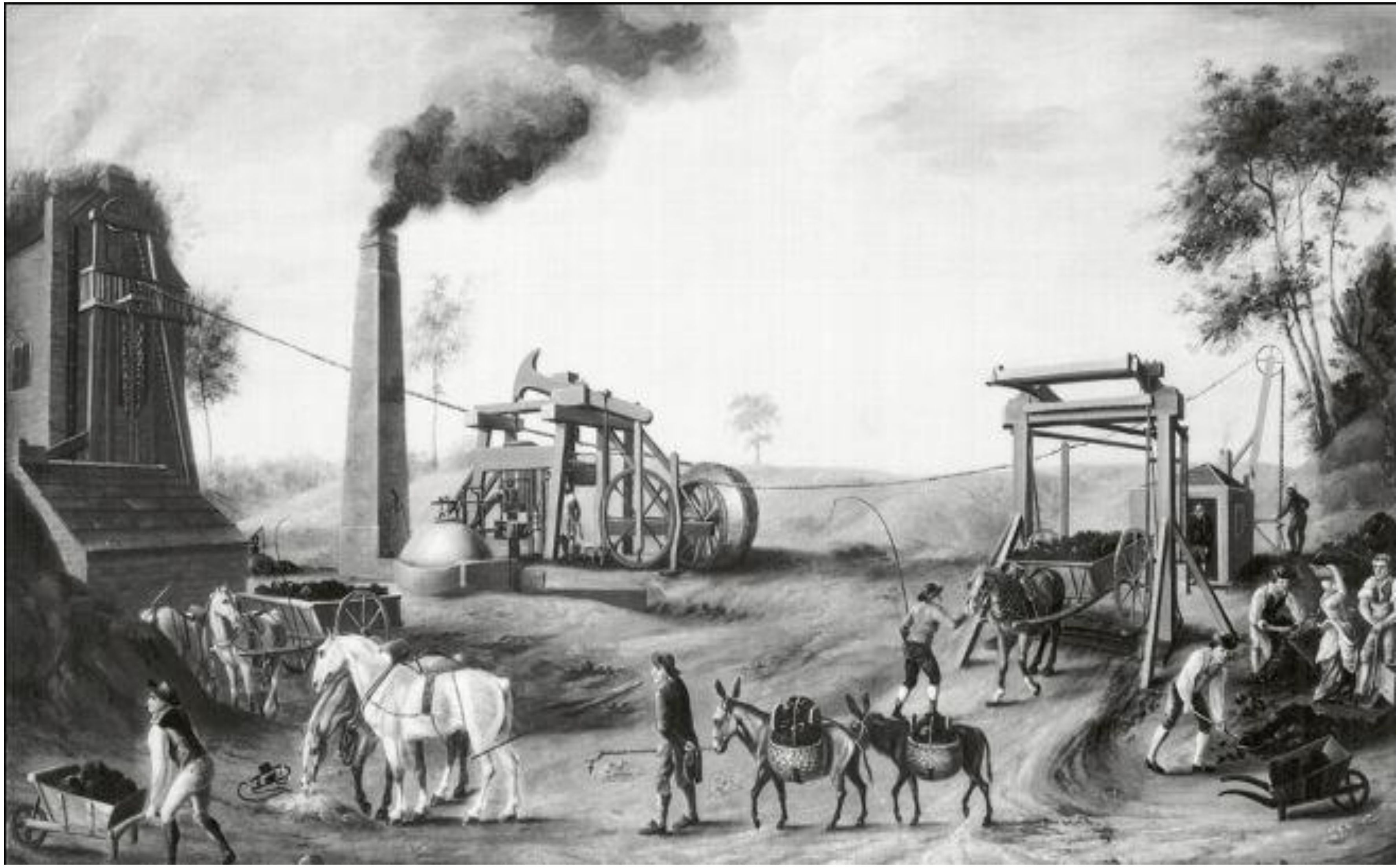




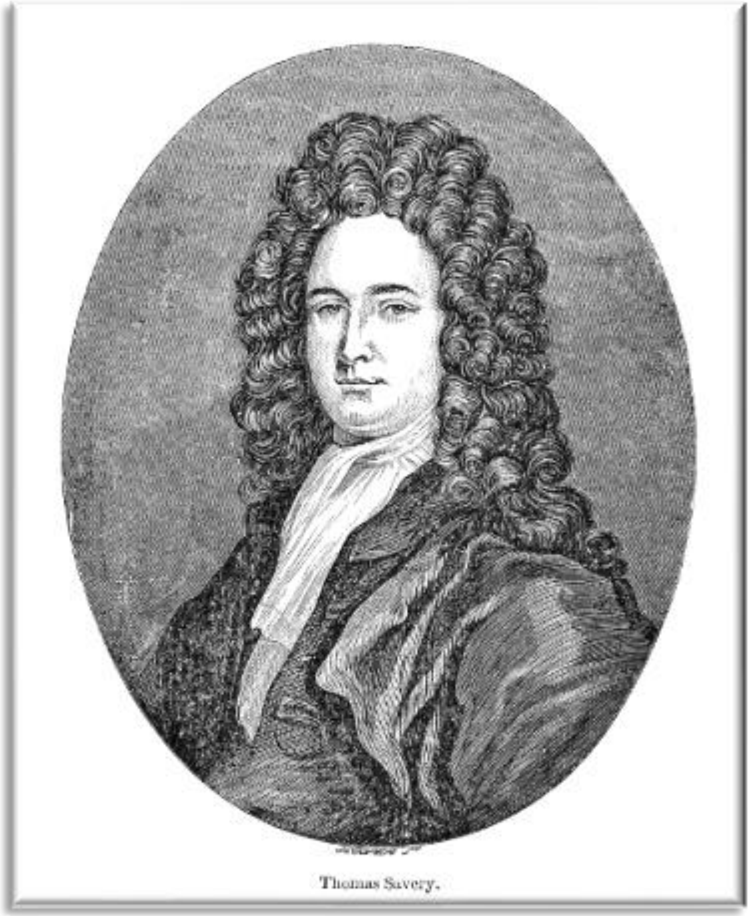
COAL.—WHIMSEY, OR ENGINE, DRAWING COAL IN THE STAFFORDSHIRE COLLIERIES.



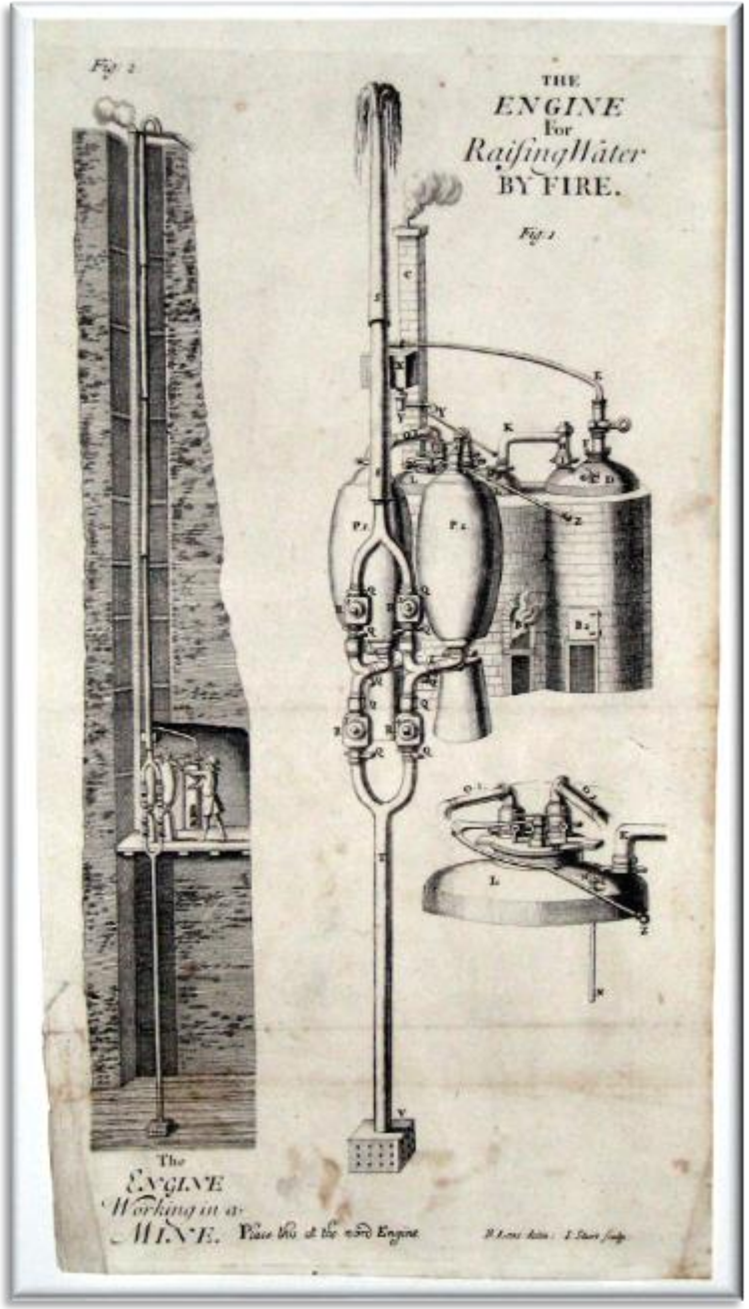
Coal mining in the United Kingdom



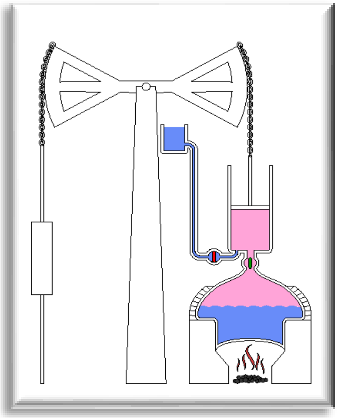
Thomas Savery (1698)

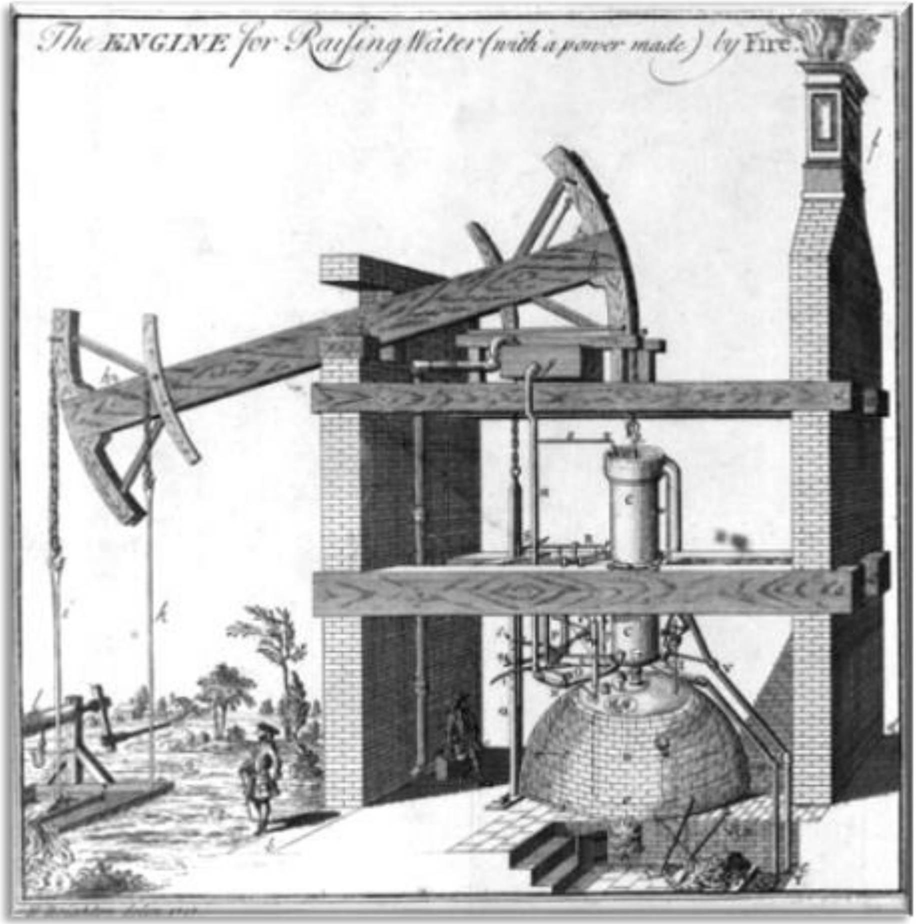


Thomas Savery.



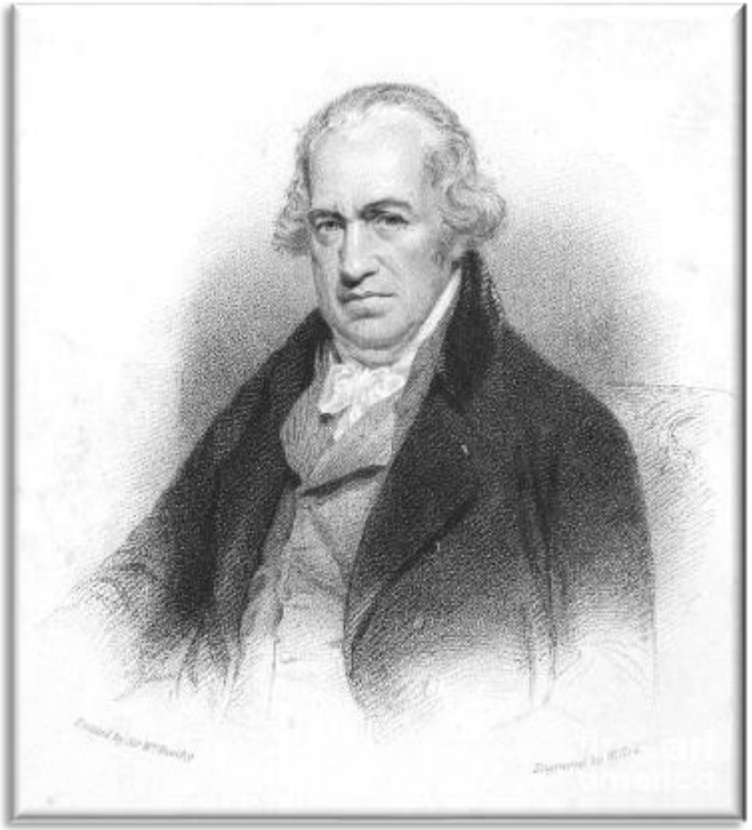
Thomas Newcomen (1712)

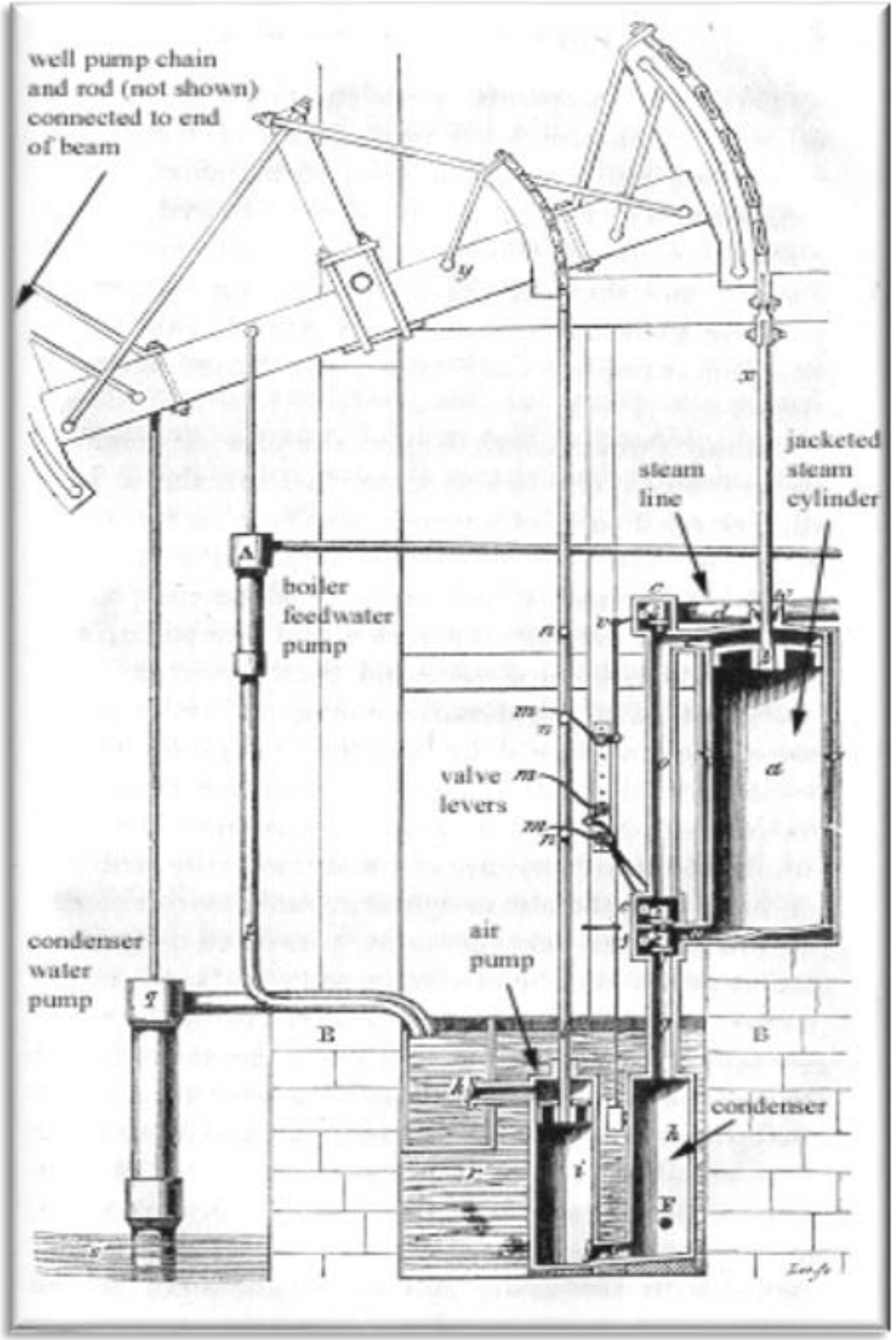




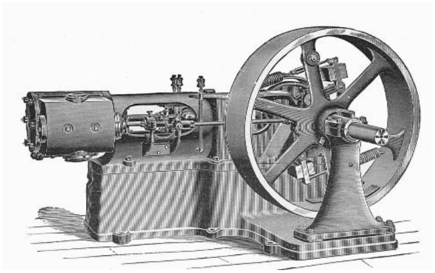

25 ден.
Coca-Cola
PRIGAT

James Watt (1763)

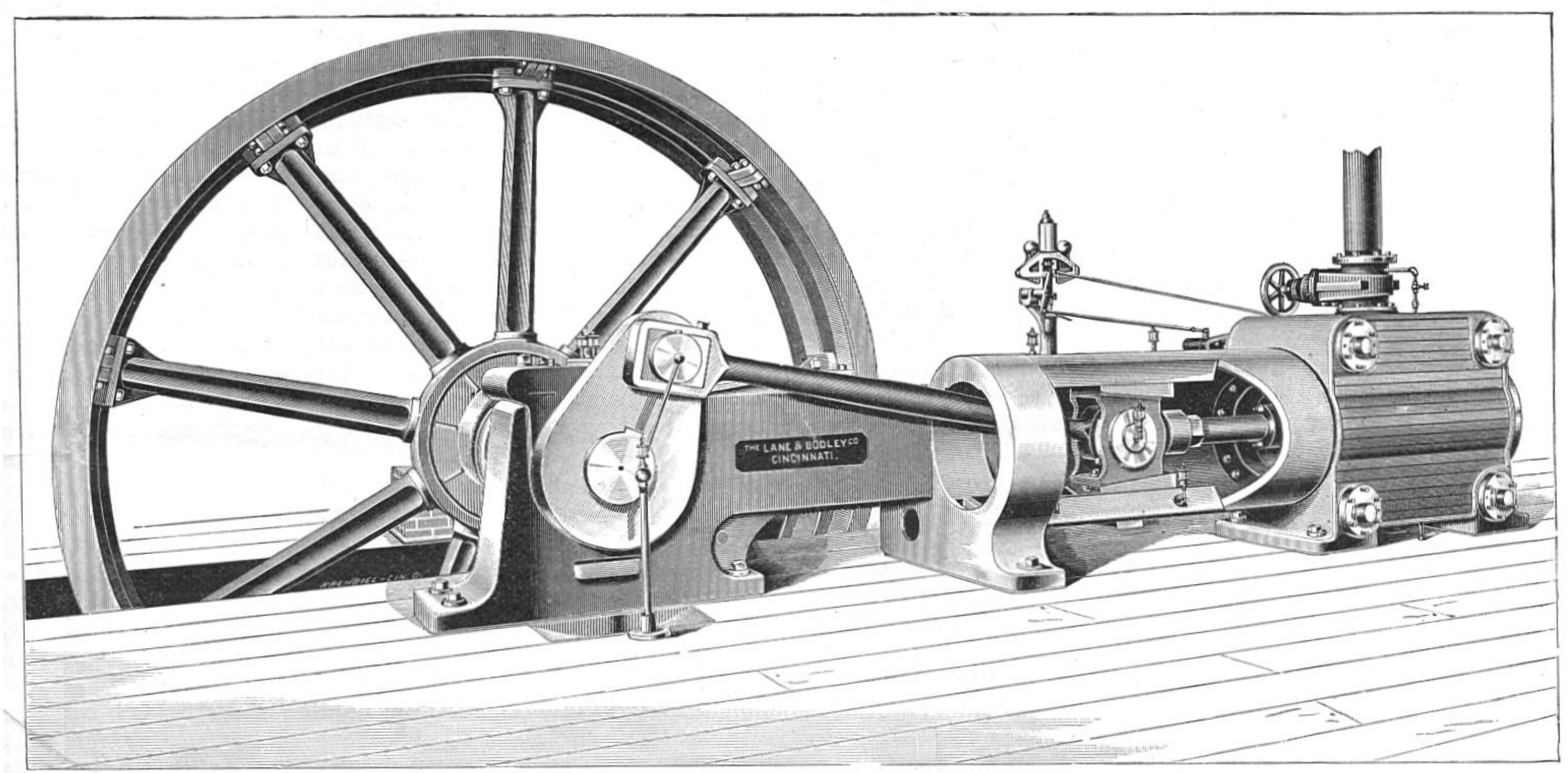




Motors for general purpose applications

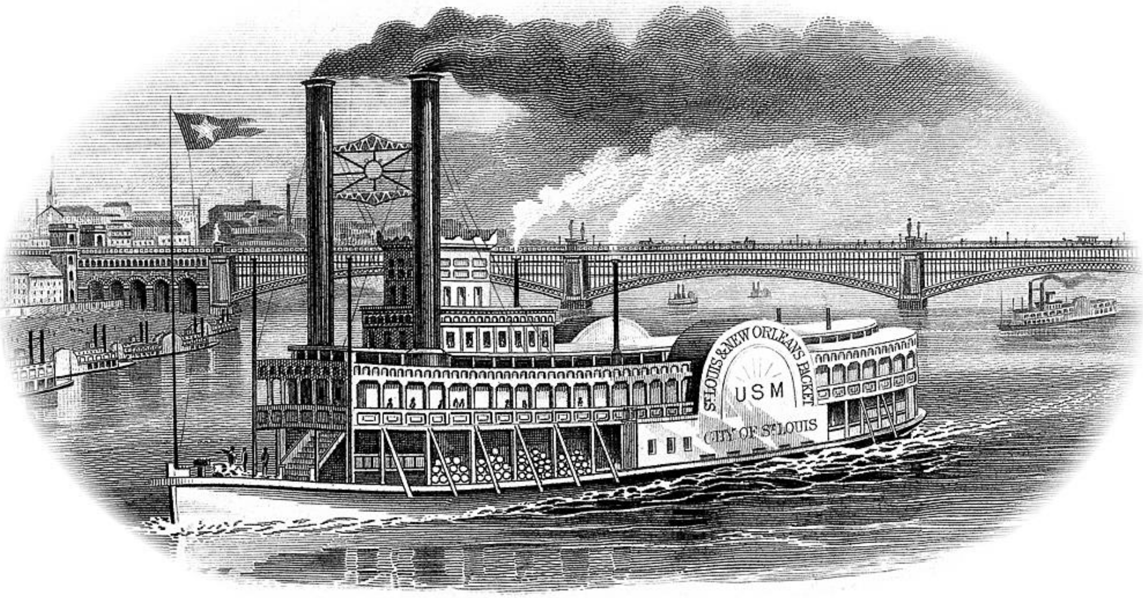


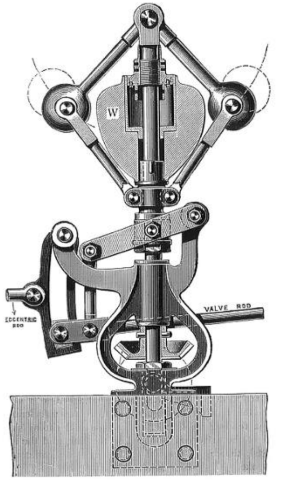
Efficiency and compactness

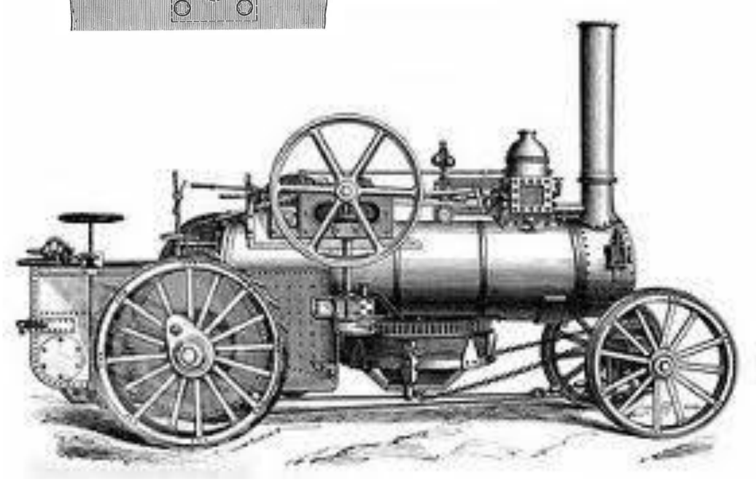


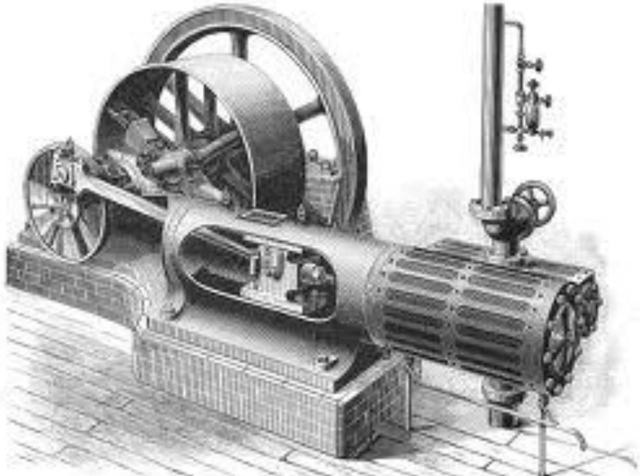
The Lane & Bodley "Columbian" Corliss Engine.

Transportation



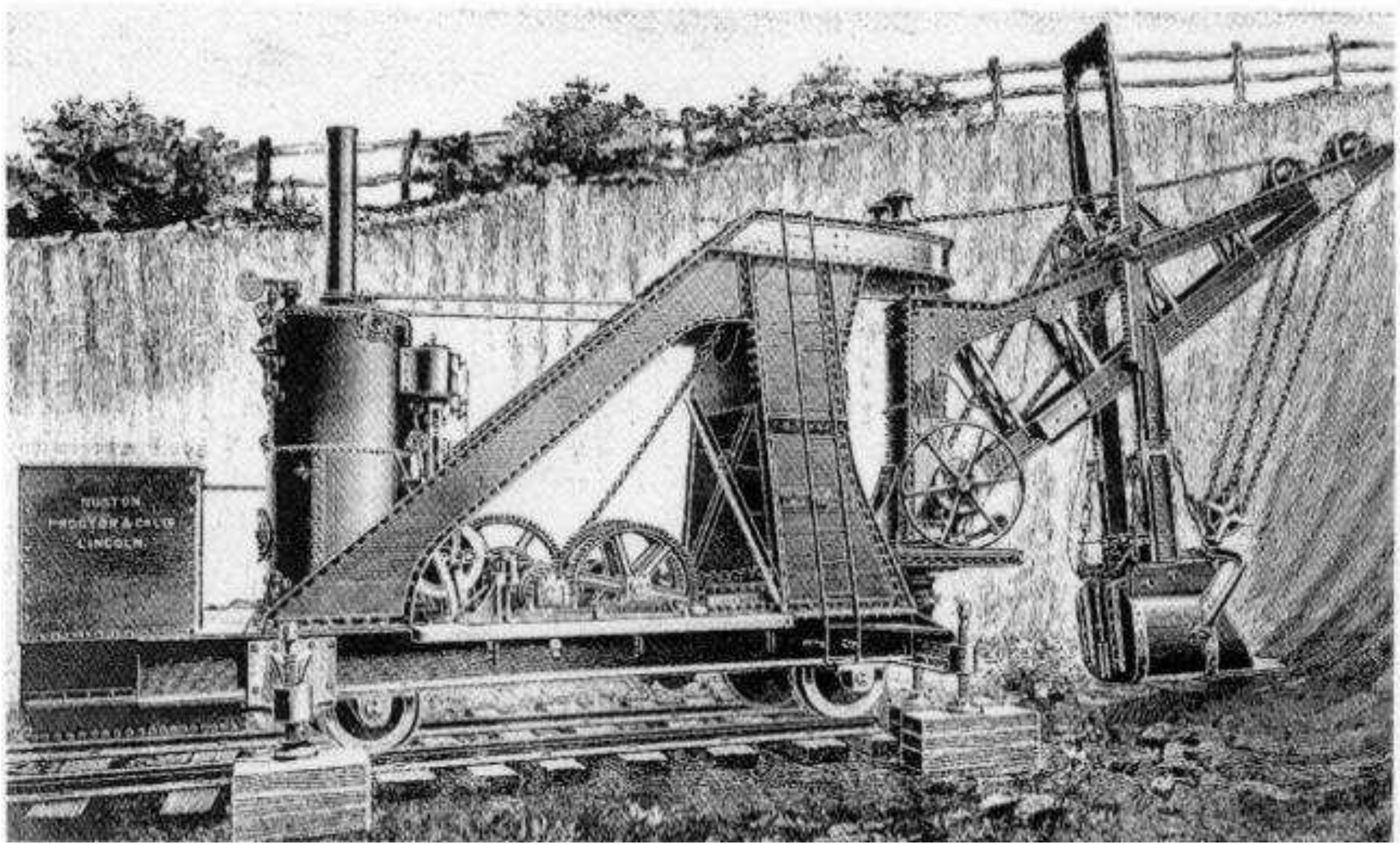




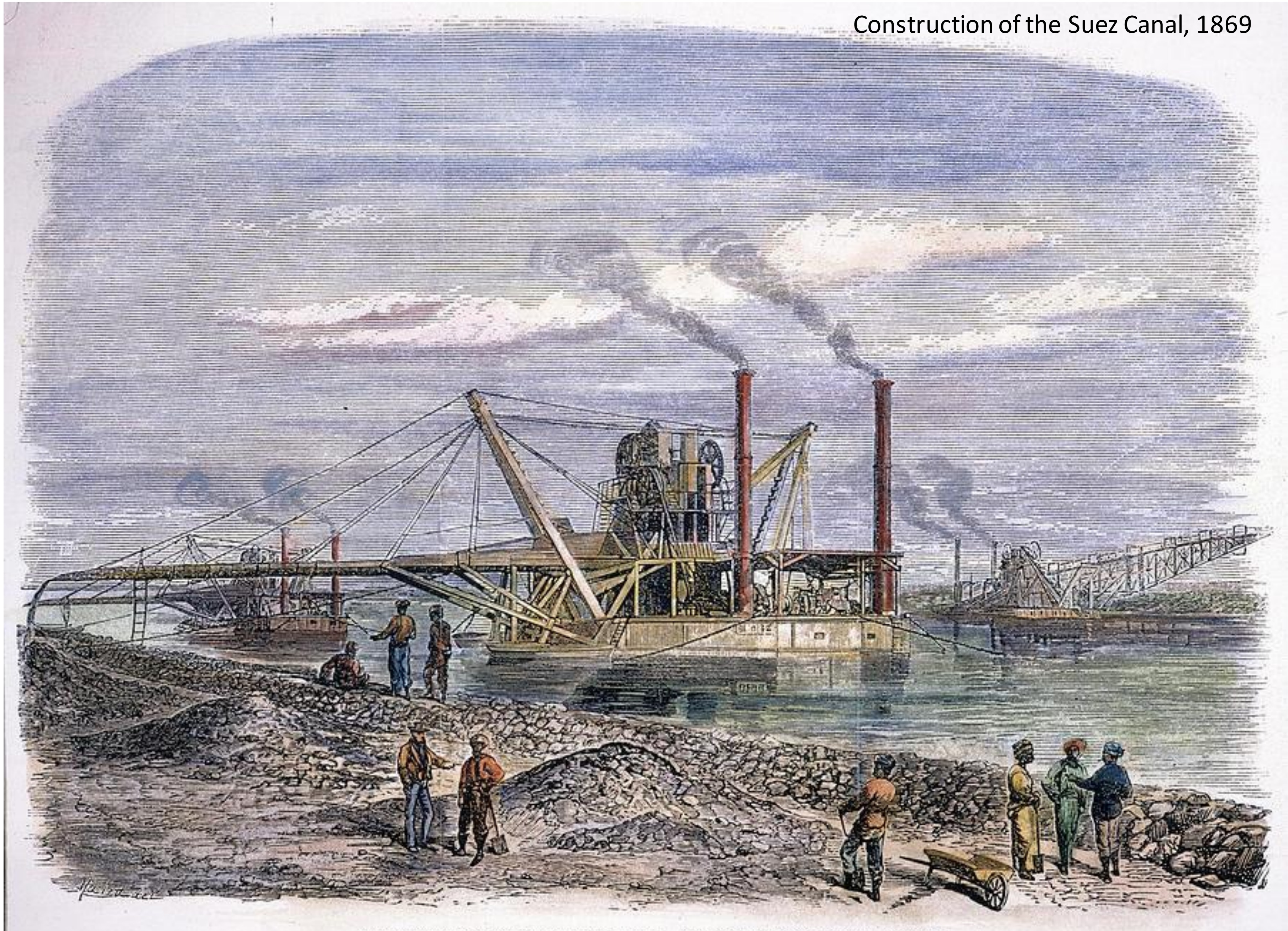


The [illegible] Automatic Cut-off Engine—Vertical and Horizontal Types.

Steam excavators (canals and sewage systems)



Construction of the Suez Canal, 1869


THE ISTHMUS OF SUEZ MARITIME CANAL: DREDGES AND ELEVATORS AT WORK.

HARPER'S WEEKLY

JOURNAL OF CIVILIZATION

Vol. XLVII New York, Saturday, November 21, 1903 No. 2448

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HELD UP THE WRONG MAN

Construction of the Panama Canal, 1881-1914

http://www.vintag.es/2015/08/the-panama-canal-constructio

HARPER'S WEEKLY

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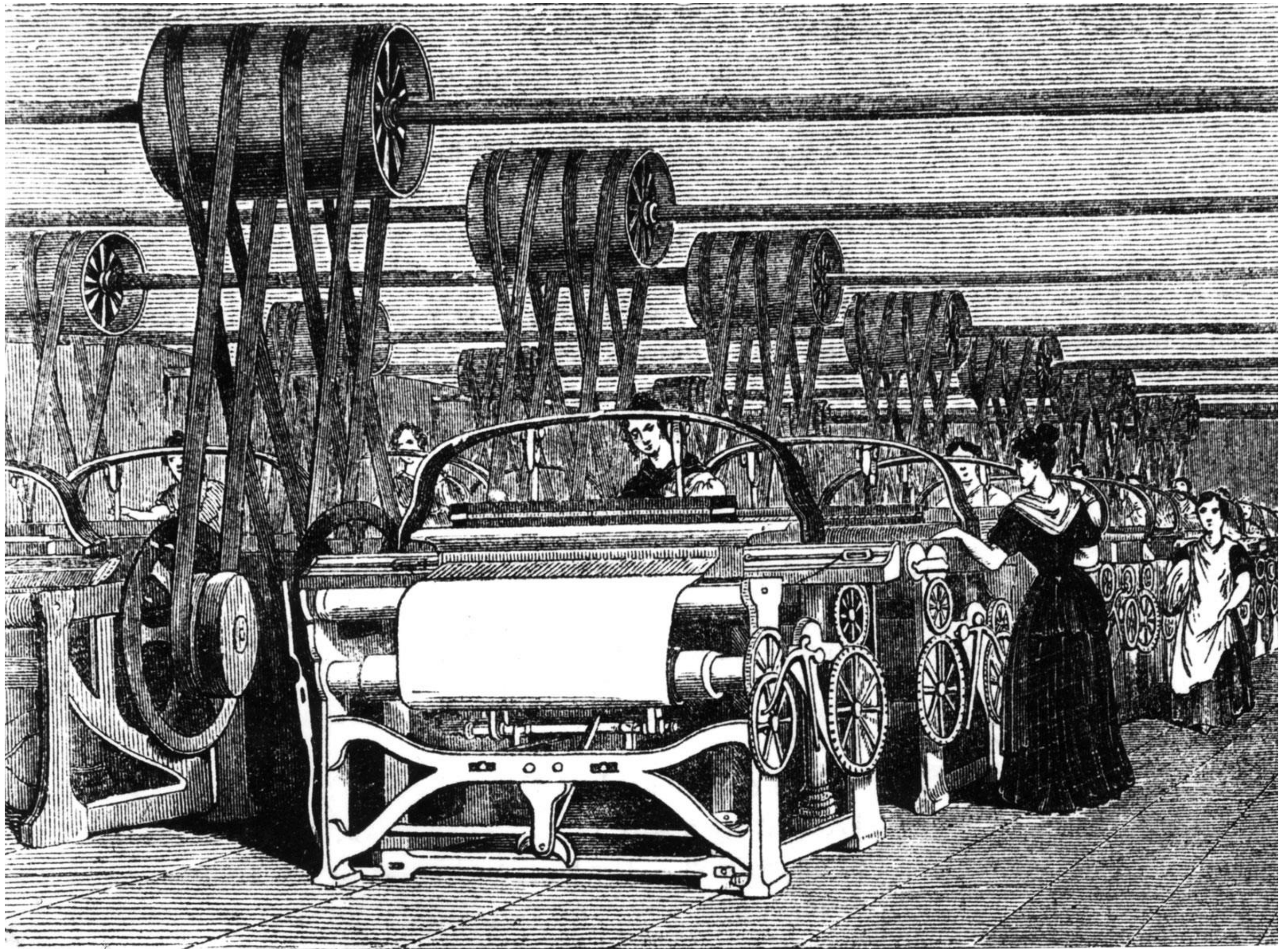
HELD UP THE WRONG MAN

Construction of the Panama Canal, 1881-1914

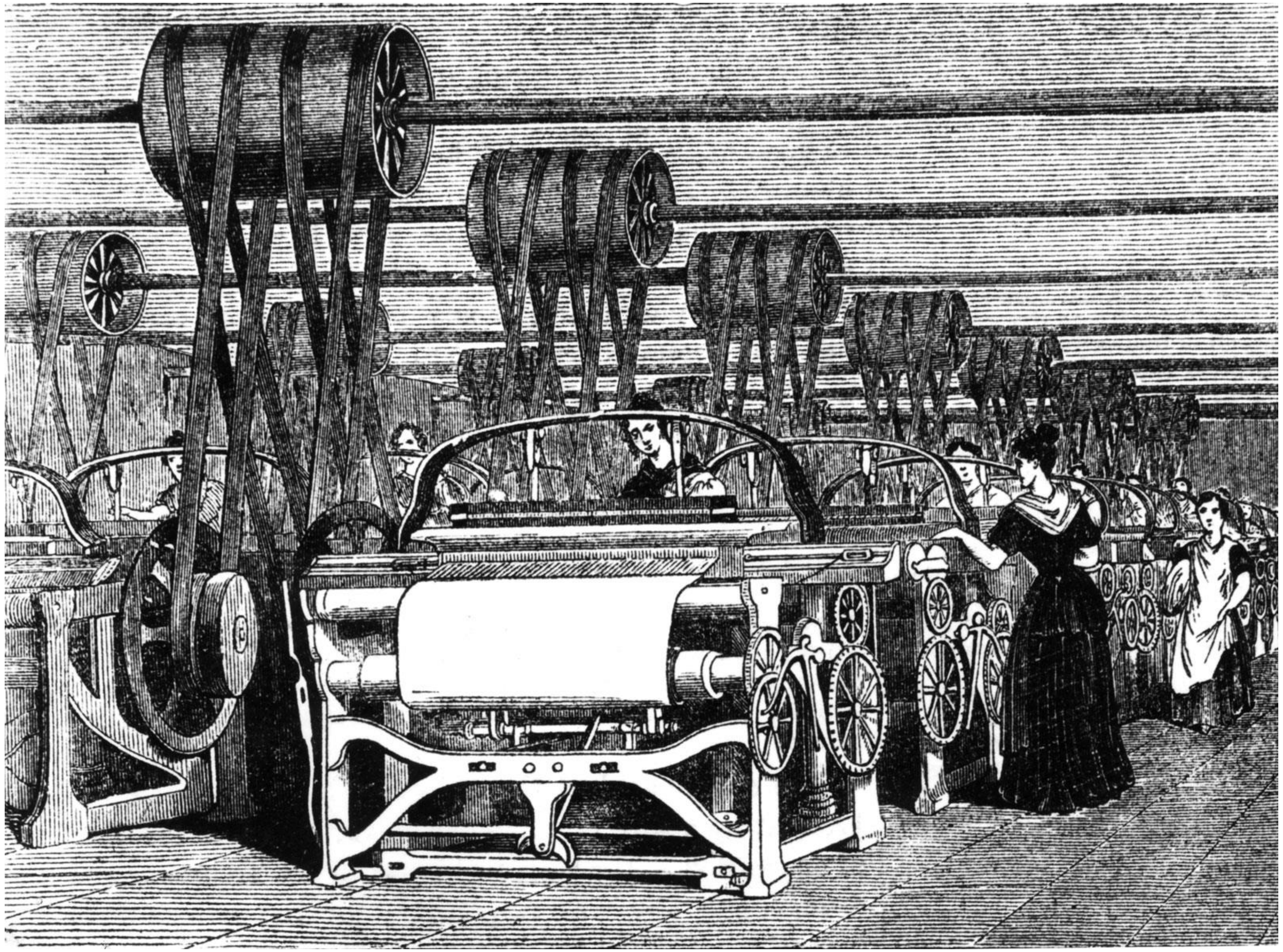
Theodore Roosevelt

http://www.vintag.es/2015/08/the-panama-canal-constructio

Mechanical looms



Mechanical looms



Jacquard

Disruptive improvements in the use of energy

Exergy (mechanical work, electricity) for the large scale production of goods, food, clothing, utensils, etc., and for broadening the access to services such as transportation, illumination, heating, etc.

Energy and social development

Disruptive improvements in the use of energy

Exergy (mechanical work, electricity) for the large scale production of goods, food, clothing, utensils, etc., and for broadening the access to services such as transportation, illumination, heating, etc.

⬇

INDUSTRIAL REVOLUTION

Disruptive improvements in the use of energy

Exergy (mechanical work, electricity) for the large scale production of goods, food, clothing, utensils, etc., and for broadening the access to services such as transportation, illumination, heating, etc.

↓

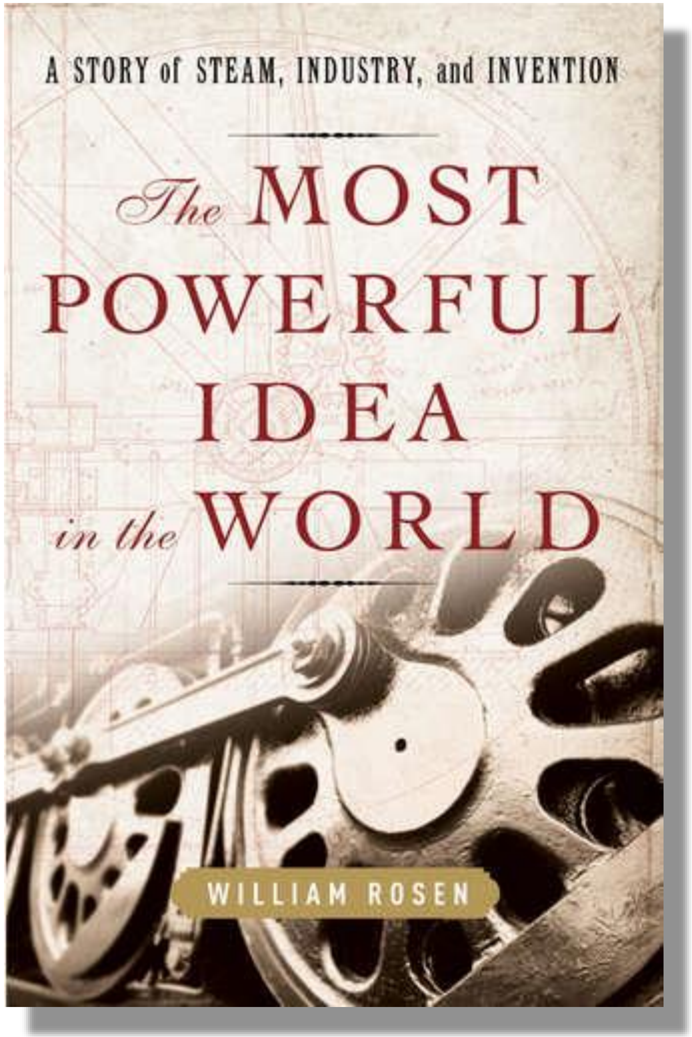
INDUSTRIAL REVOLUTION

↓

BETTER QUALITY OF LIFE

$$\mathrm{HDI} = \frac{1}{3}\left(\mathrm{longevity} + \mathrm{education} + \mathrm{income}\right)$$

Describes the history of the evolution of the steam technology and the corresponding social consequences...



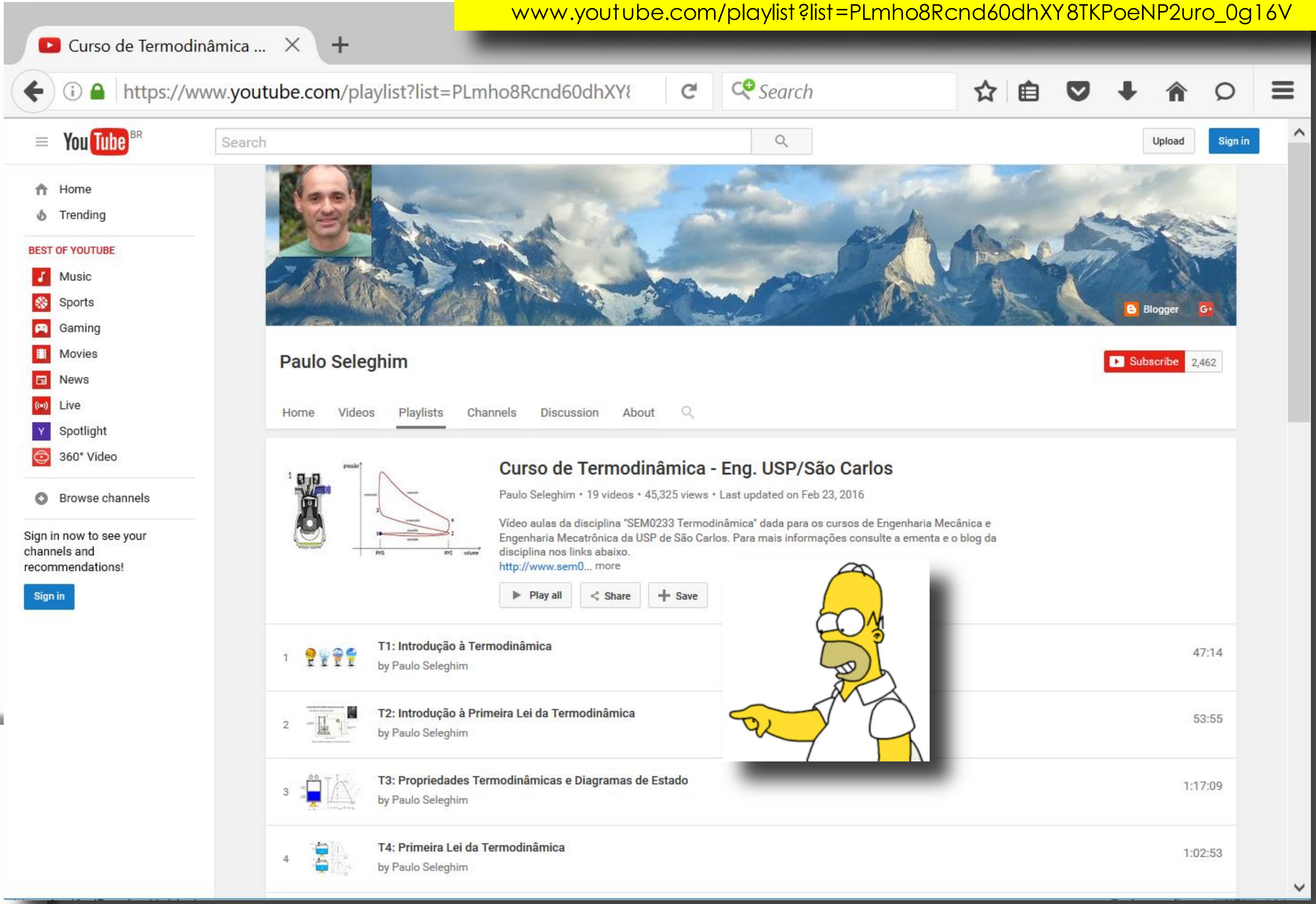
...but what is energy ?

"Is the capacity to do work..."

⇩

"Energy is energy..."

www.youtube.com/playlist?list=PLmho8Rcnd60dhXY8TKPoeNP2uro_0g16V



Curso de Termodinâmica - Eng. USP/São Carlos

Paulo Seleghim • 19 videos • 45,325 views • Last updated on Feb 23, 2016

Vídeo aulas da disciplina "SEM0233 Termodinâmica" dada para os cursos de Engenharia Mecânica e Engenharia Mecatrônica da USP de São Carlos. Para mais informações consulte a ementa e o blog da disciplina nos links abaixo.
http://www.sem0... more

1	**T1: Introdução à Termodinâmica** by Paulo Seleghim	47:14
2	**T2: Introdução à Primeira Lei da Termodinâmica** by Paulo Seleghim	53:55
3	**T3: Propriedades Termodinâmicas e Diagramas de Estado** by Paulo Seleghim	1:17:09
4	**T4: Primeira Lei da Termodinâmica** by Paulo Seleghim	1:02:53

Different types of energy:

- ✓ What is heat? (A self-repellent fluid called caloric...)
- ✓ What is mechanical work ? (force × displacement)
- ✓ Is it possible to convert different types of energy ?
- ✓ Are there efficiency limits to these conversions ?
- ✓ Different types of energy can perform equivalent amounts of work ?
- ✓ ...

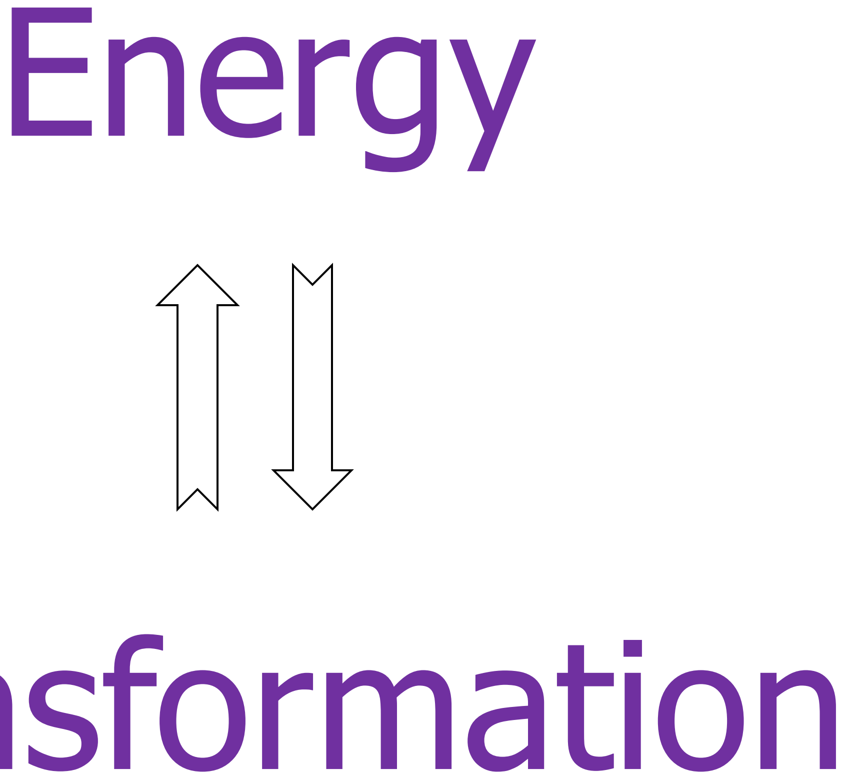
A working definition of energy…

Energy is an abstract quantity with which we can express quantitative laws governing natural physical phenomena…

A working definition of energy…

Energy is an abstract quantity with which we can express quantitative laws governing natural physical phenomena…

Energy is like the number 1 !



Energy

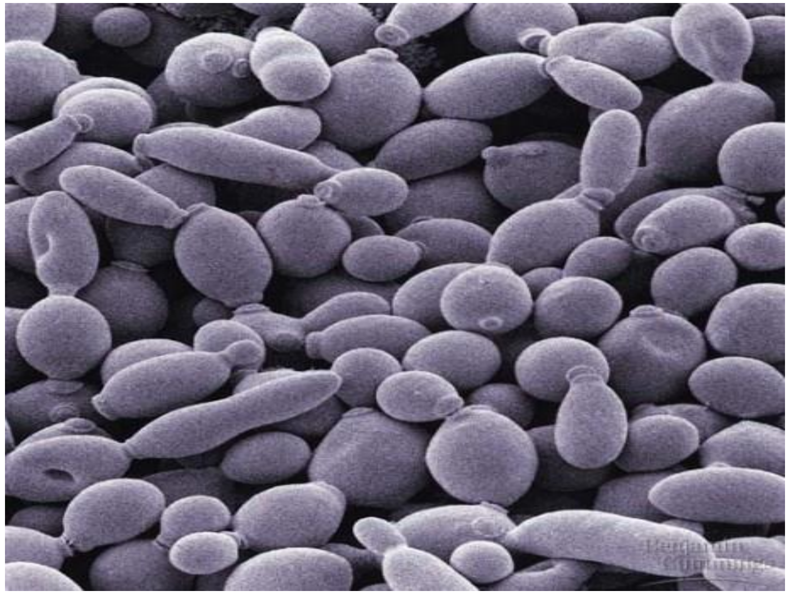
Transformation

light energy (sun)

Chemical energy (biomass)

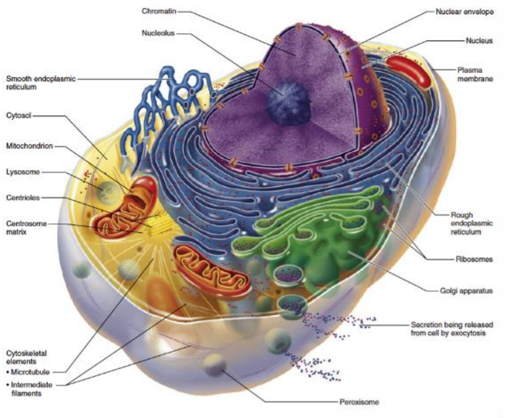
$$6\ CO_2 + 6\ H_2O + \textbf{light} \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Chemical energy (glucose) →



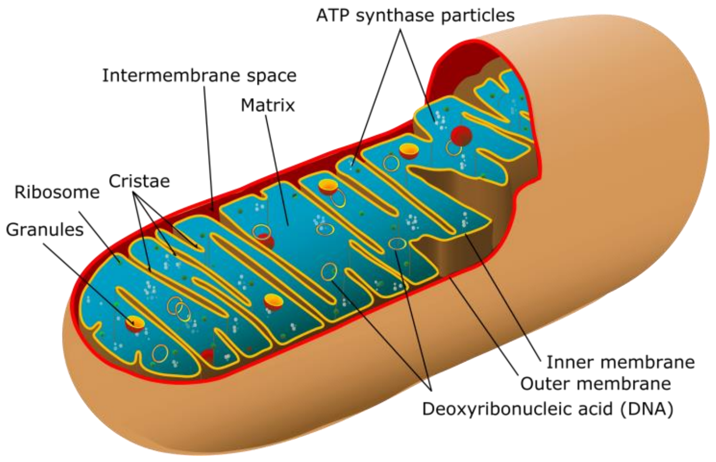
→ **Chemical energy (ethanol)**

$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2 +$ **heat**



$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \textbf{heat}$$

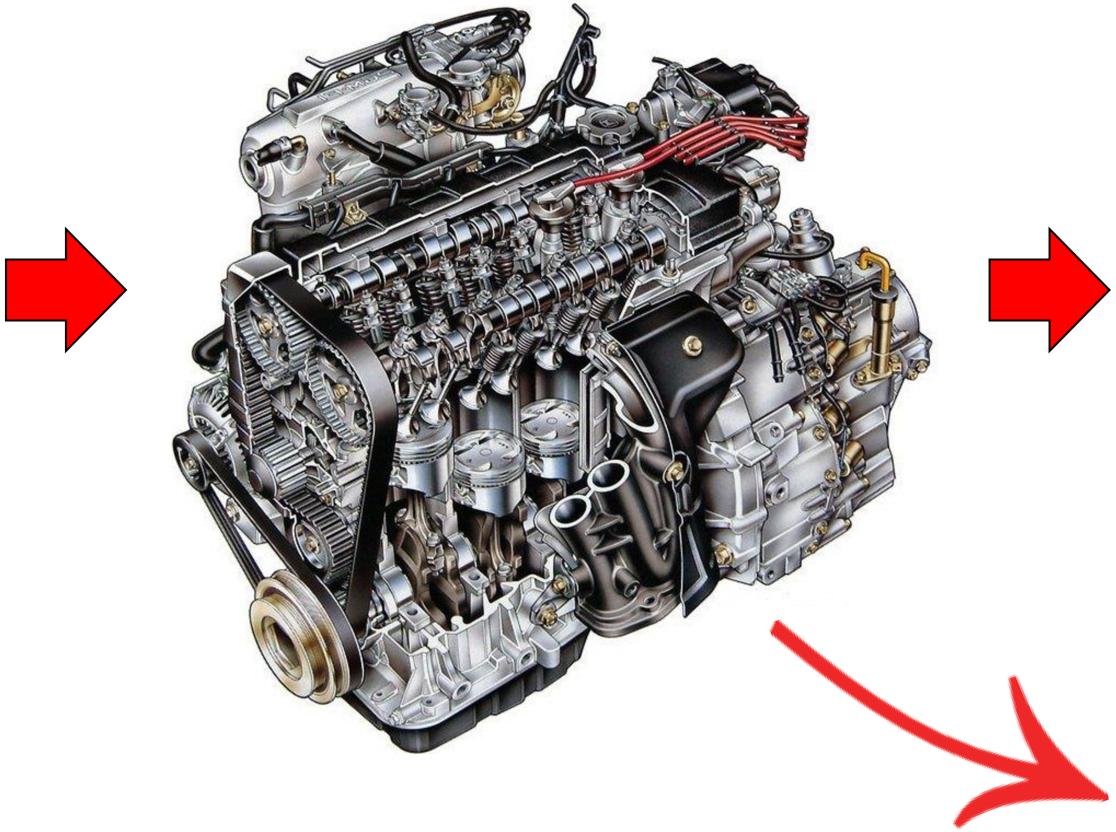
Chemical energy



Chemical energy (ATP)

Lost thermal energy

$C_2H_5OH + 3 O_2 \rightarrow 2 CO_2 + 3 H_2O +$ **heat**

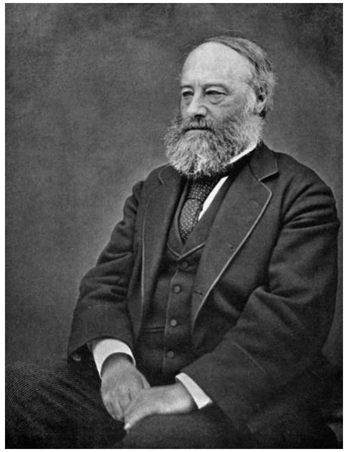


Chemical energy

Mechanical energy

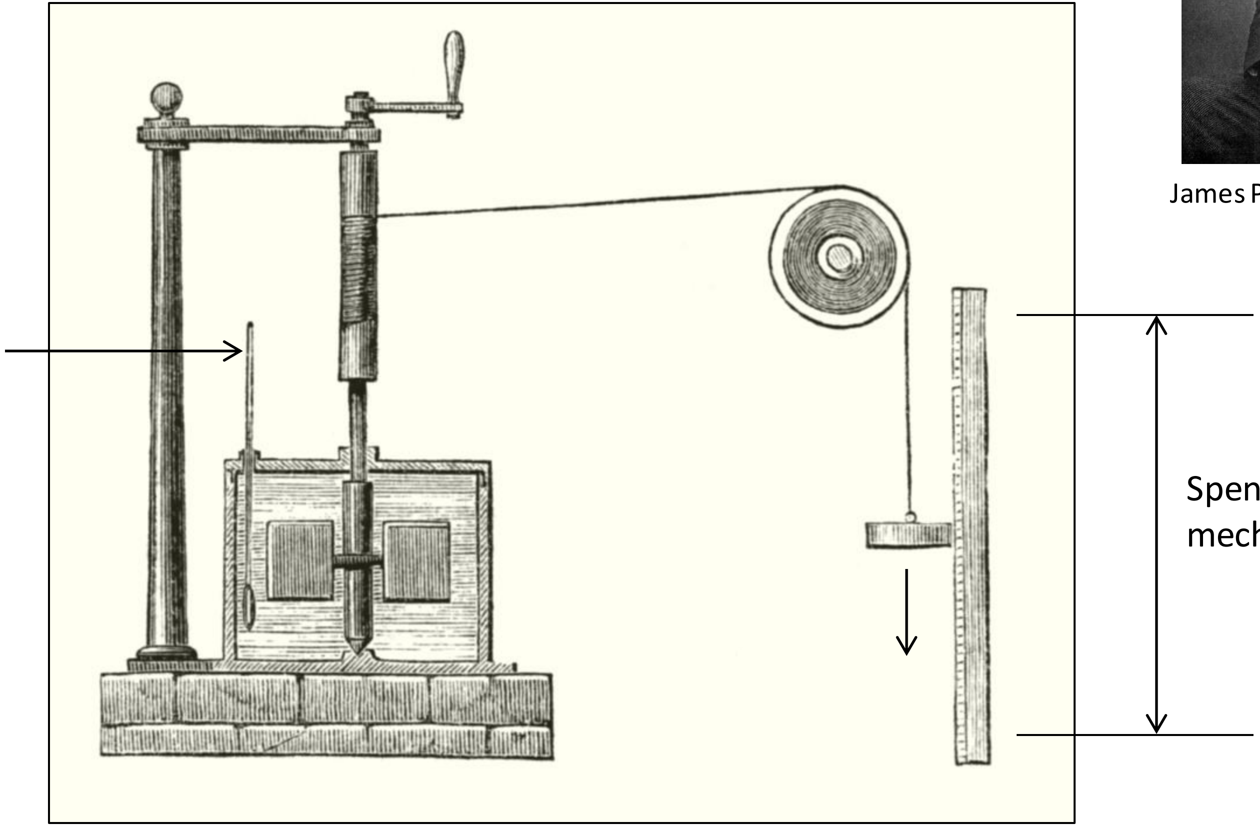
Lost thermal energy

Conversion of mechanical work to heat



James Prescott Joule, 1840

Mechanical equivalent of heat (thermal energy)



Increase in thermal energy

Spent mechanical energy

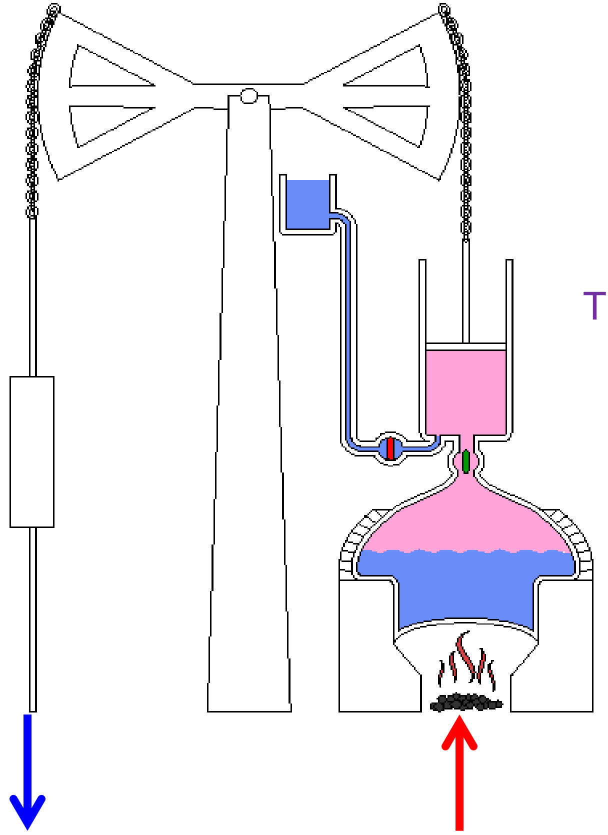
1 calorie = 4.184 Joule

Work is totally converted to heat (thermal energy) !

Conversion of mechanical work to heat

Newcomen's machine

1. Injection of steam at high temperature and pressure into the piston
2. Steam condensation by means of cool water injection creating a partial vacuum in the piston
3. Through action of atmospheric pressure the piston is contracted which pulls the rod down
4. The cycle is restarted

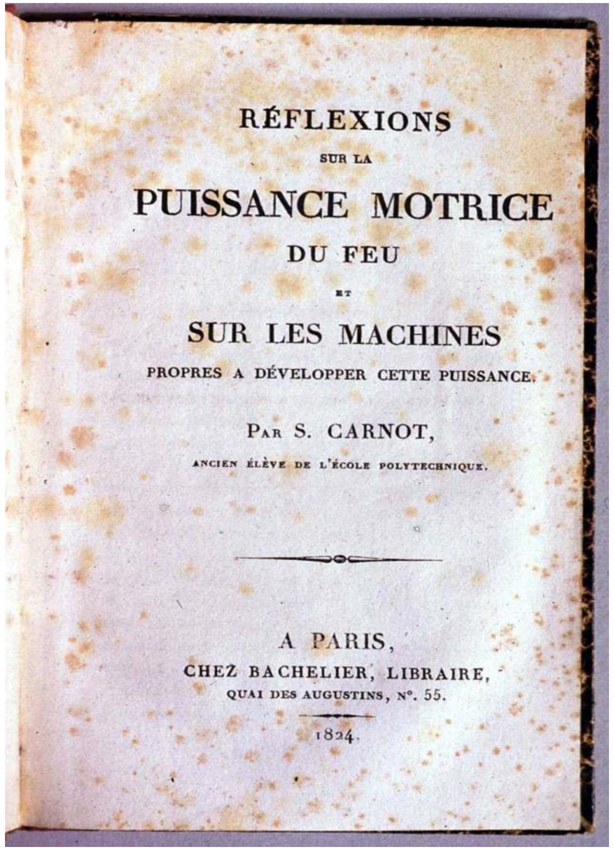


Thomas Newcomen (1712)

Why only a fraction of the heat is converted to work ? Is it possible to develop a perpetual motion machine ?

Some answers to these questions:

- ✓ Heat is a form of "organized" energy
- ✓ Work is a form of "disorganized" energy
- ✓ Work can be totally converted to heat
- ✓ Heat can be partially converted to work (!?)

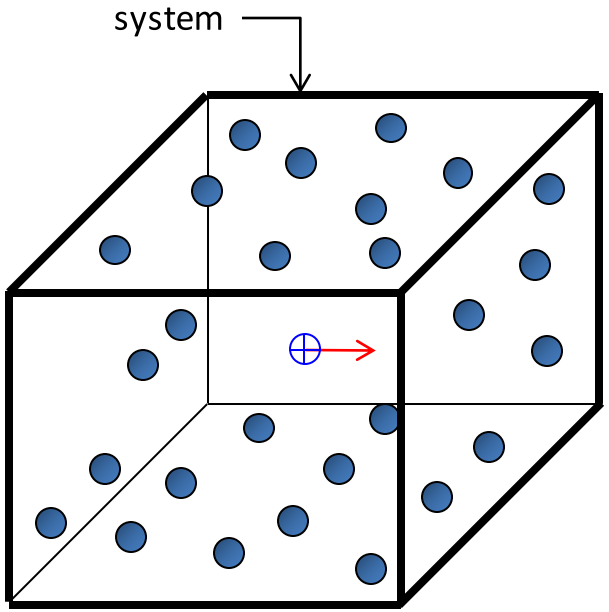


RÉFLEXIONS
SUR LA
PUISSANCE MOTRICE
DU FEU
ET
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.
PAR S. CARNOT,
ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

A PARIS,
CHEZ BACHELIER, LIBRAIRE,
QUAI DES AUGUSTINS, N°. 55.
1824.

Nicolas Léonard Sadi Carnot
in 1824, at 28 years

Different types of energy associated with a system



Macroscopic forms

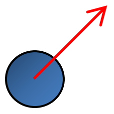
Energy associated to the system's center of mass, relative to na inertial referential

$$EC = m\frac{V^2}{2} \longrightarrow ec = \frac{V^2}{2}$$

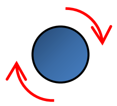
$$EP = mgZ \longrightarrow ep = gZ$$

Microscopic forms

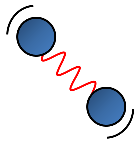
Energy associated to the molecular structure and agitation: internal energy (U)



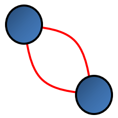
molecular translation



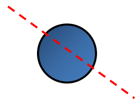
molecular rotation



molecular vibration

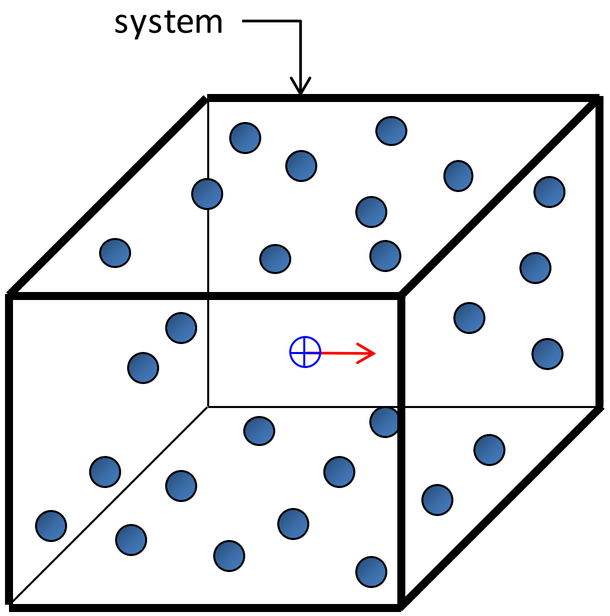


chemical energy



nuclear energy

Different types of energy associated with a system



Macroscopic forms

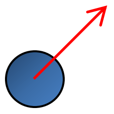
Energy associated to the system's center of mass, relative to na inertial referential

$$EC = m\frac{V^2}{2} \longrightarrow$$ **wind**

$$EP = mgZ \longrightarrow$$ **hydroelectric**

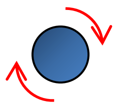
Microscopic forms

Energy associated to the molecular structure and agitation: internal energy (U)

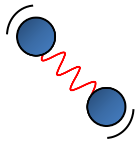


molecular translation

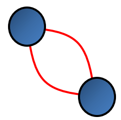
geothermal
solar thermal



molecular rotation

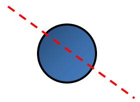


molecular vibration



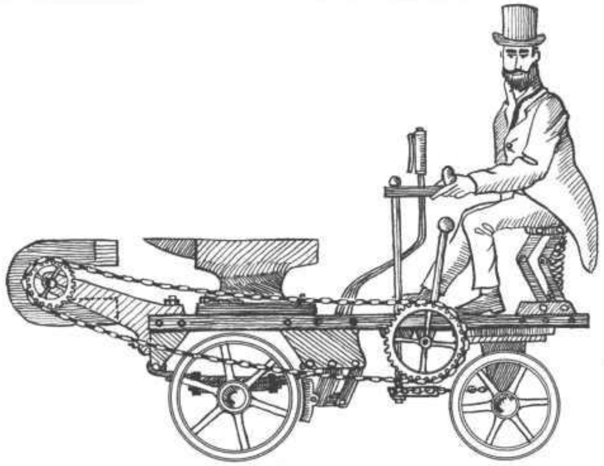
chemical energy

termelétrica



nuclear energy

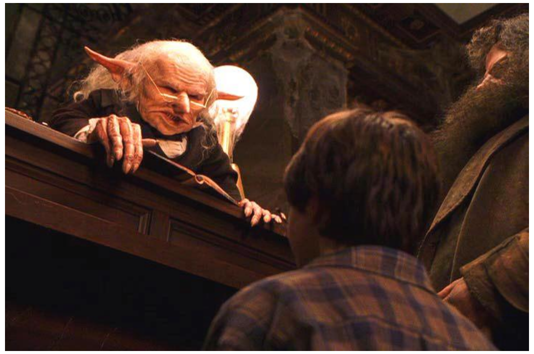
nuclear



First law of thermodynamics...

...energy conservation principle !!!

Account transactions balance...



salary

financial investment

supermarket

rent

electricity

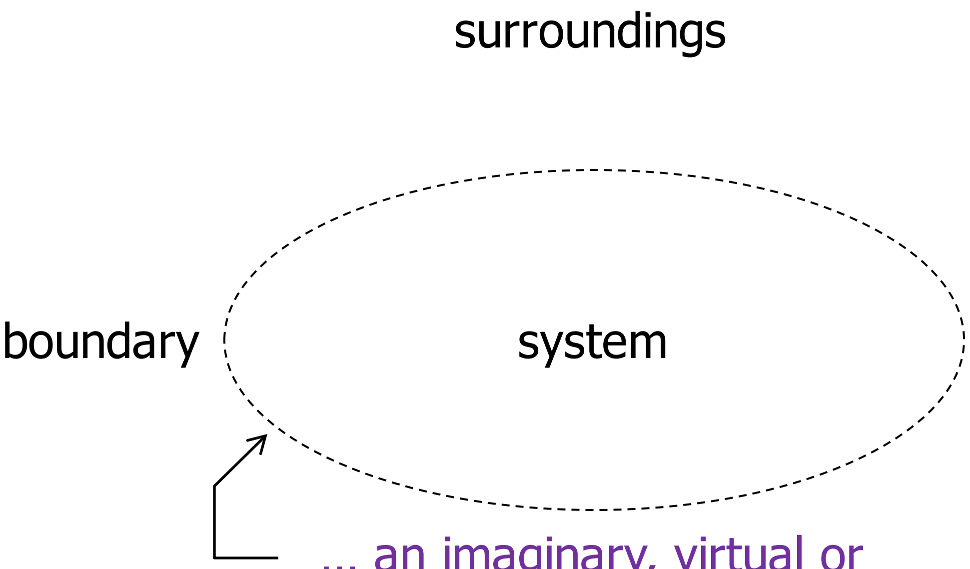
theater

etc.

(variation of the account balance) = (net income) − (net expenses)

FIRST LAW OF THERMODYNAMICS:

open systems



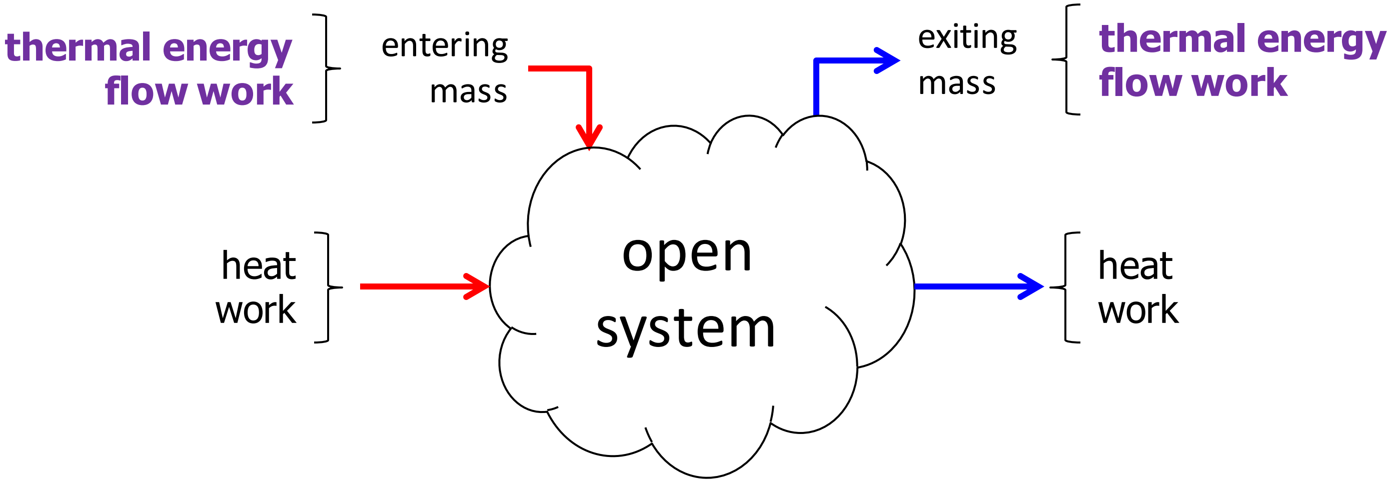
surroundings

boundary

system

… an imaginary, virtual or “mathematical” surface enclosing an amount of mass and separating it from the surroundings

Energy conservation principle: open systems



thermal energy
flow work
entering
mass

exiting
mass
thermal energy
flow work

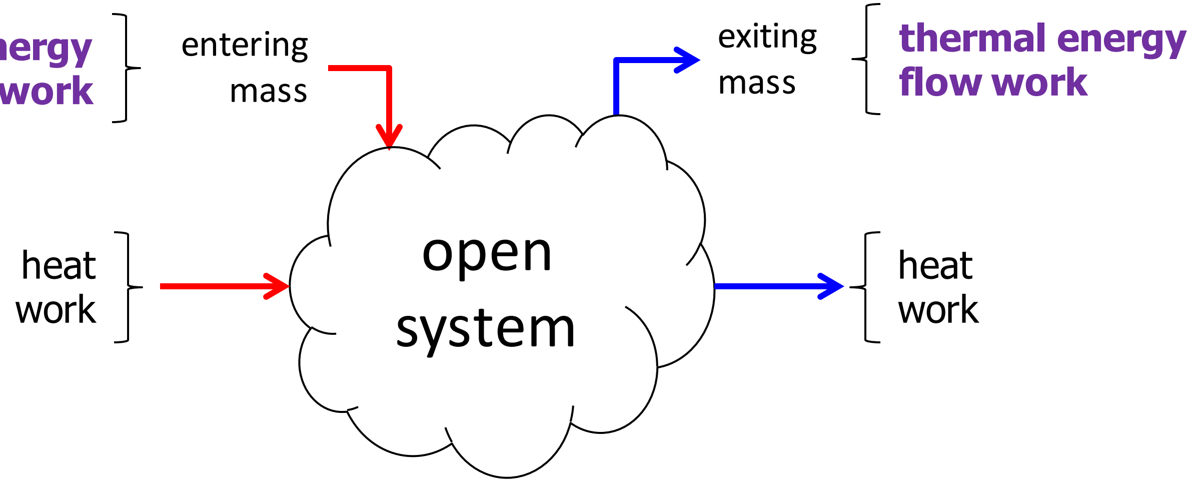
heat
work

open
system

heat
work

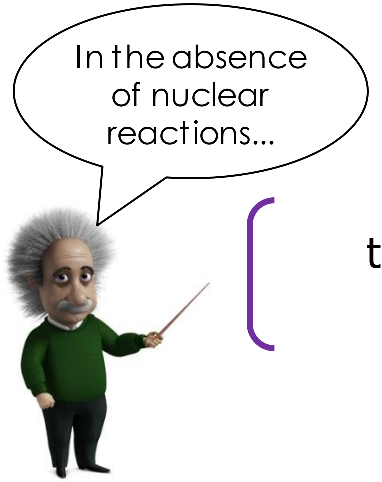
thermal energy transport	⇨	Thermal energy, or "internal energy" (u+ep+ek), associated to the mass flow entering/leaving the cv that must be accounted for..
flow work	⇨	Mechanical work (force × displacement) necessary for an element of mass to be pushed into or pulled out of the system's cv…

Energy inventory in the cv... (steady state)



thermal energy
flow work

thermal energy
flow work



(total (net) energy entering the cv) = (rate of change of the net internal energy confined in the cv)

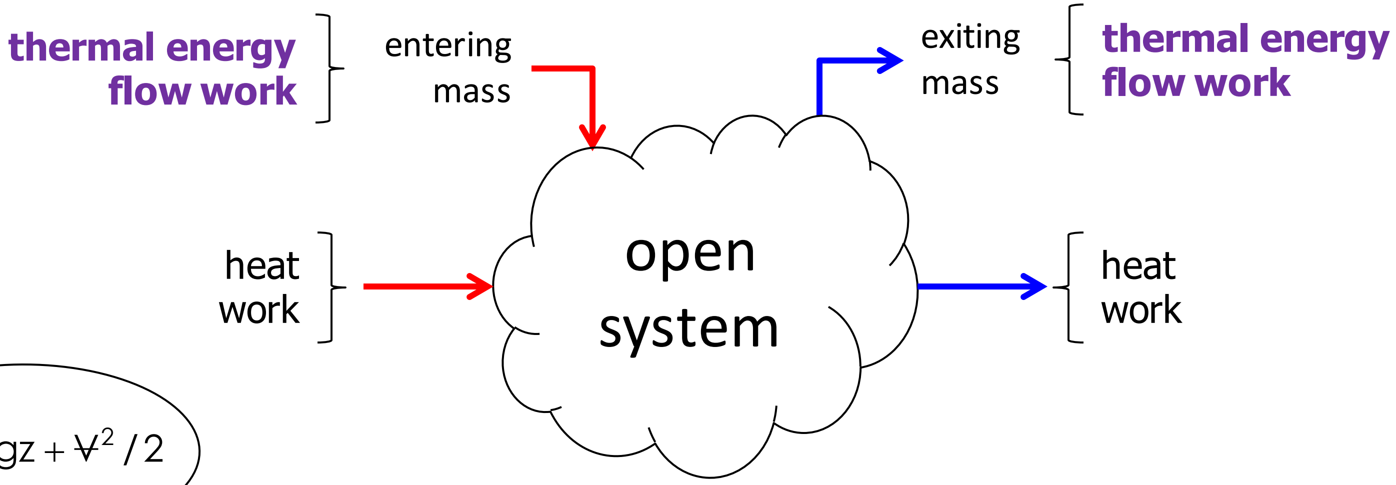
⇩

steady state

⇩

(total (net) energy entering the cv) = (0)

Energy inventory in the cv... (steady state)



thermal energy
flow work

entering
mass

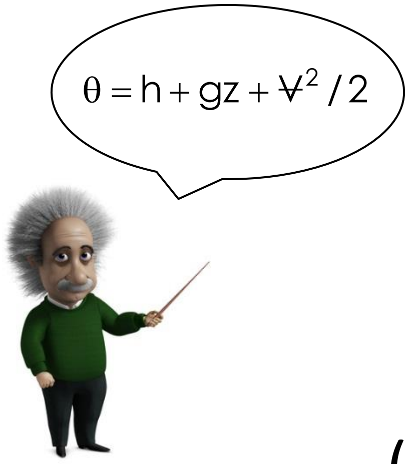
exiting
mass

thermal energy
flow work

heat
work

open
system

heat
work



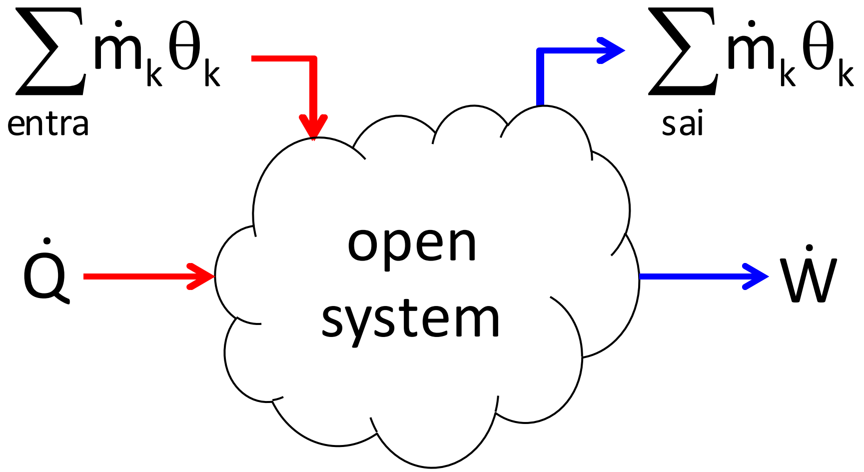
$$\theta = h + gz + \mathbb{V}^2/2$$

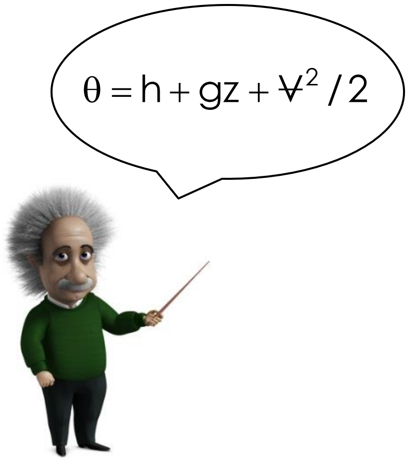
$$\dot{Q}_e + \dot{W}_e + \sum_{\text{entra}} \dot{m}_k \theta_k = \dot{Q}_s + \dot{W}_s + \sum_{\text{sai}} \dot{m}_k \theta_k$$

$$(\dot{Q}_e - \dot{Q}_s) - (\dot{W}_s - \dot{W}_e) = \sum_{\text{sai}} \dot{m}_k \theta_k - \sum_{\text{entra}} \dot{m}_k \theta_k$$

$$\dot{Q} - \dot{W} = \sum_{\text{sai}} \dot{m}_k \theta_k - \sum_{\text{entra}} \dot{m}_k \theta_k$$

Energy inventory in the cv... (steady state)





$$\dot{Q} - \dot{W} = \sum_{\text{sai}} \dot{m}_k \theta_k - \sum_{\text{entra}} \dot{m}_k \theta_k$$

$$\dot{Q} - \dot{W} = \sum_{\text{sai}} \dot{m}_k \cdot \left(h_k + gz_k + \forall_k^2 / 2\right) - \sum_{\text{entra}} \dot{m}_k \cdot \left(h_k + gz_k + \forall_k^2 / 2\right)$$

Application: thermal machines evolution

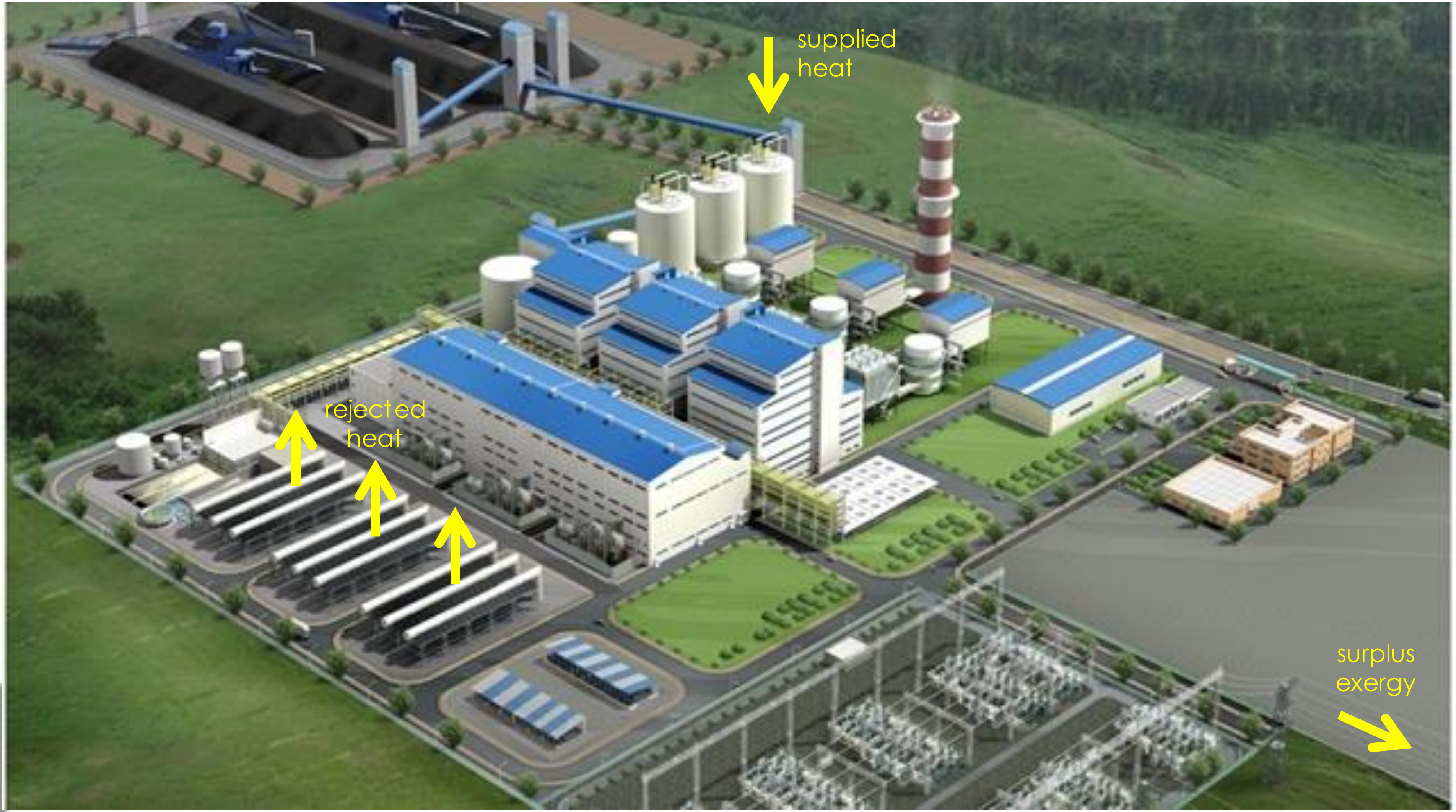
1712

2015: 80% of all electrical energy generated in the world

Typical Thermal Power Generation Plant ...

Tufanbeyli (Turkey) 450 MW
http://www.skec.com

Typical Thermal Power Generation Plant ...



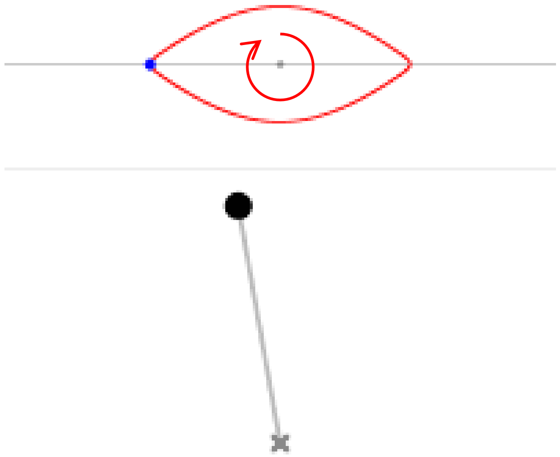
Tufanbeyli (Turkey) 450 MW
http://www.skec.com

Is there a physical limit to the efficiency of the conversion of heat to mechanical work ?

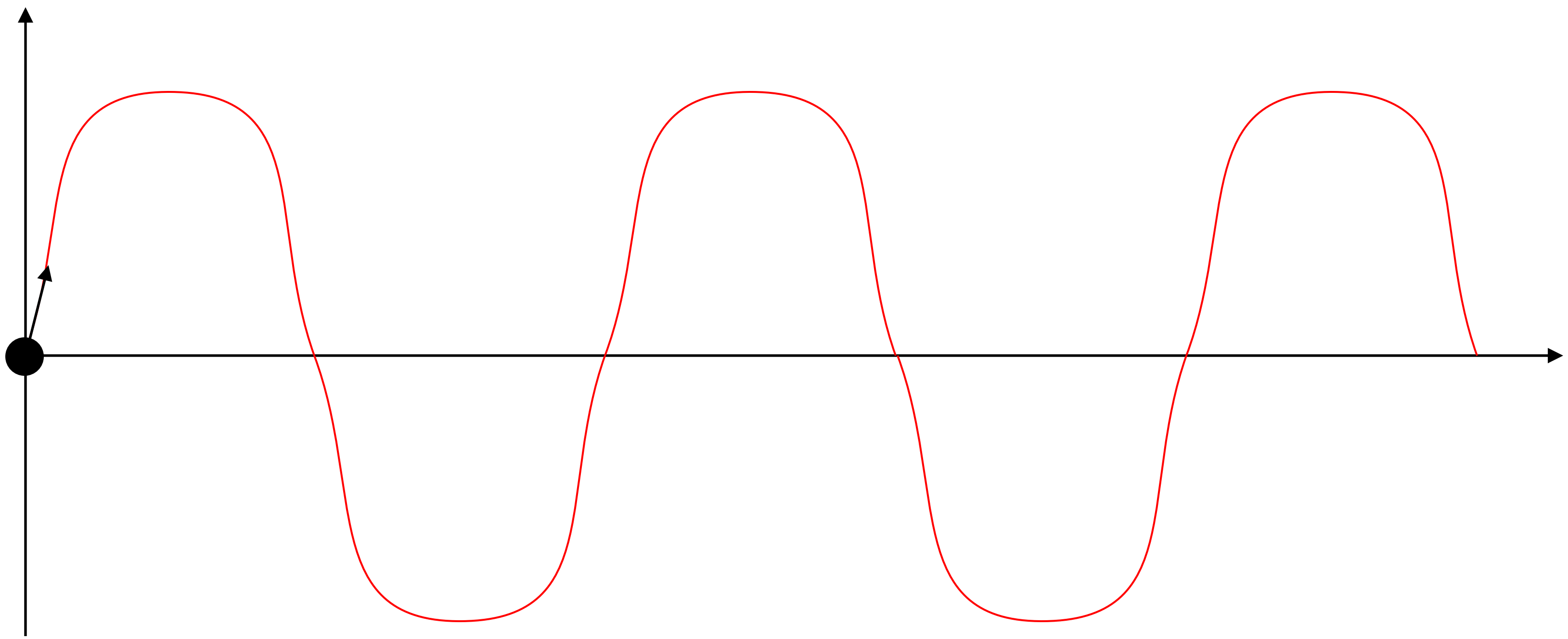
disorganized

organized

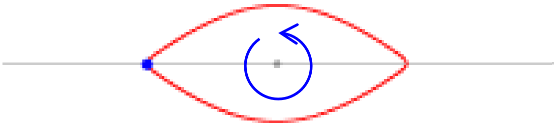
Physical laws are symmetrical with respect to the arrow of time…

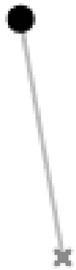


$$M\cdot\frac{d^2\theta}{dt^2}+D\cdot\frac{d\theta}{dt}+k\cdot\sin\theta=0$$

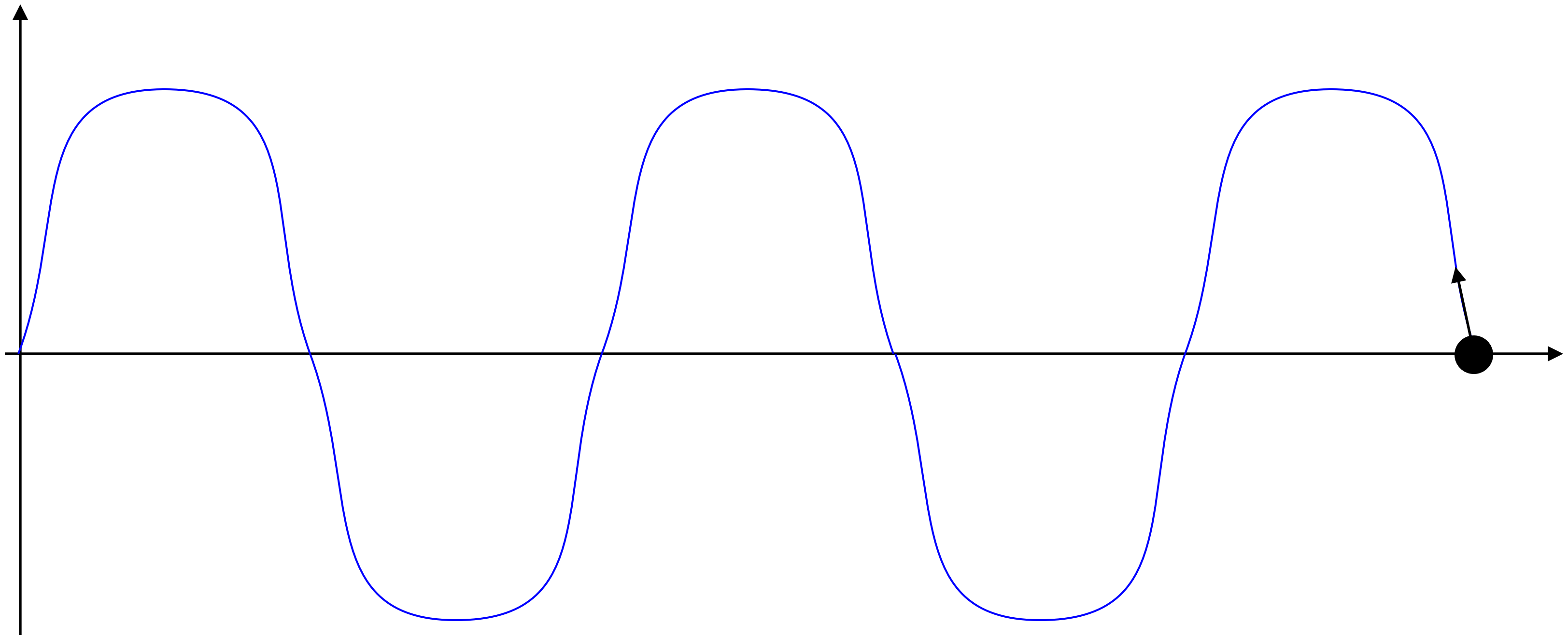


Physical laws are symmetrical with respect to the arrow of time…

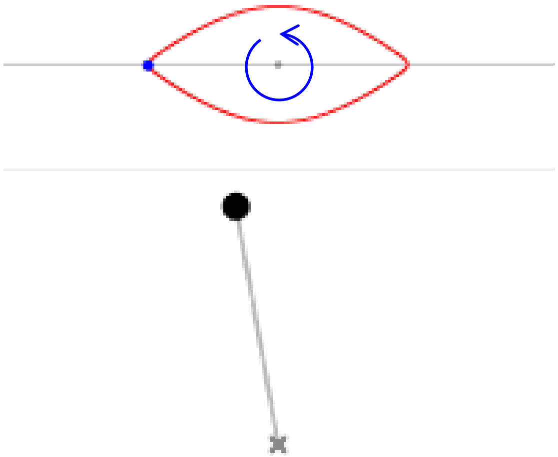




$$M \cdot \frac{d^2\theta}{dt^2} + D \cdot \frac{d\theta}{dt} + k \cdot \sin\theta = 0$$

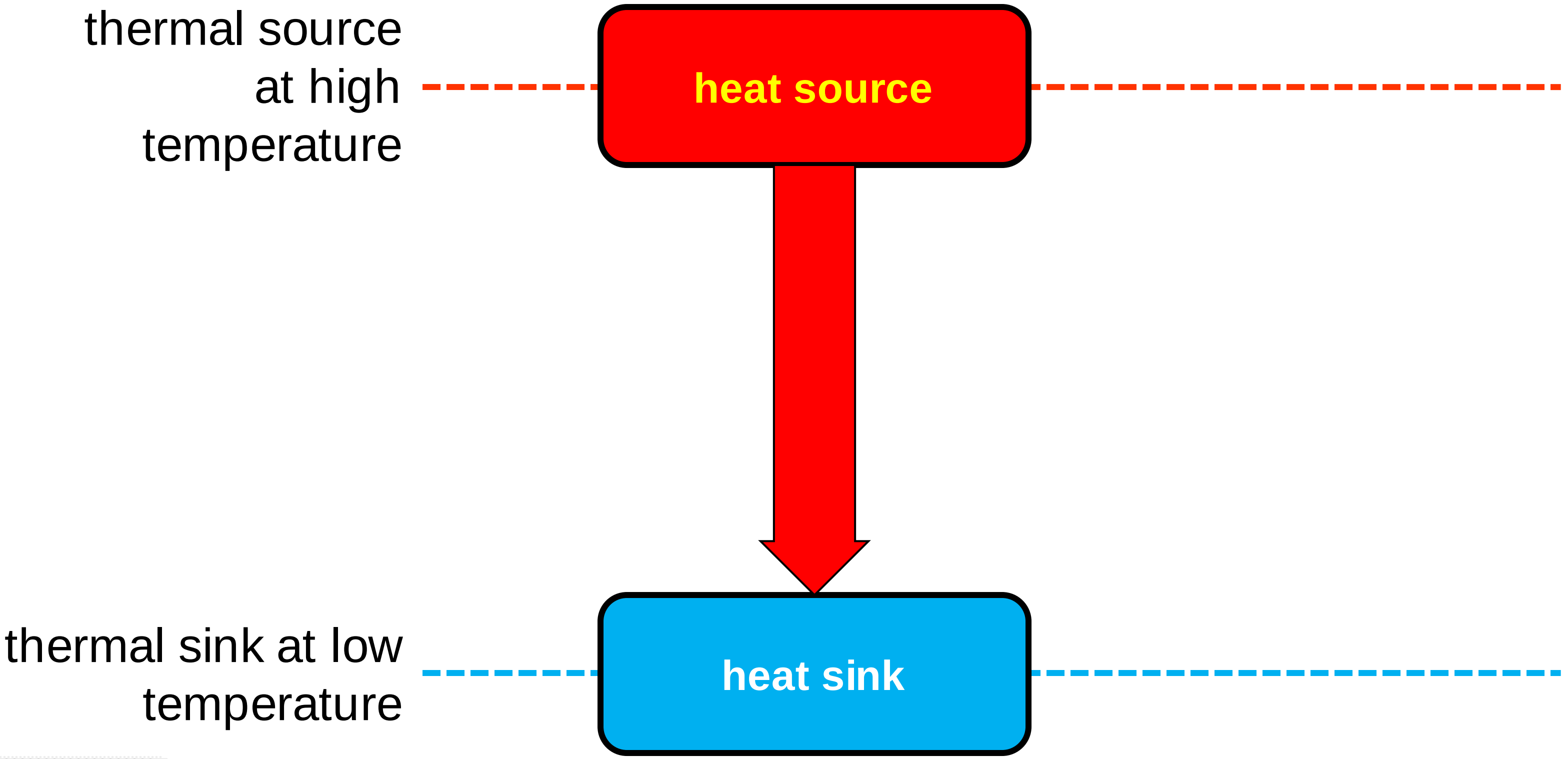


Physical laws are symmetrical with respect to the arrow of time…



…except the second law of thermodynamics !

Spontaneous flow of energy…



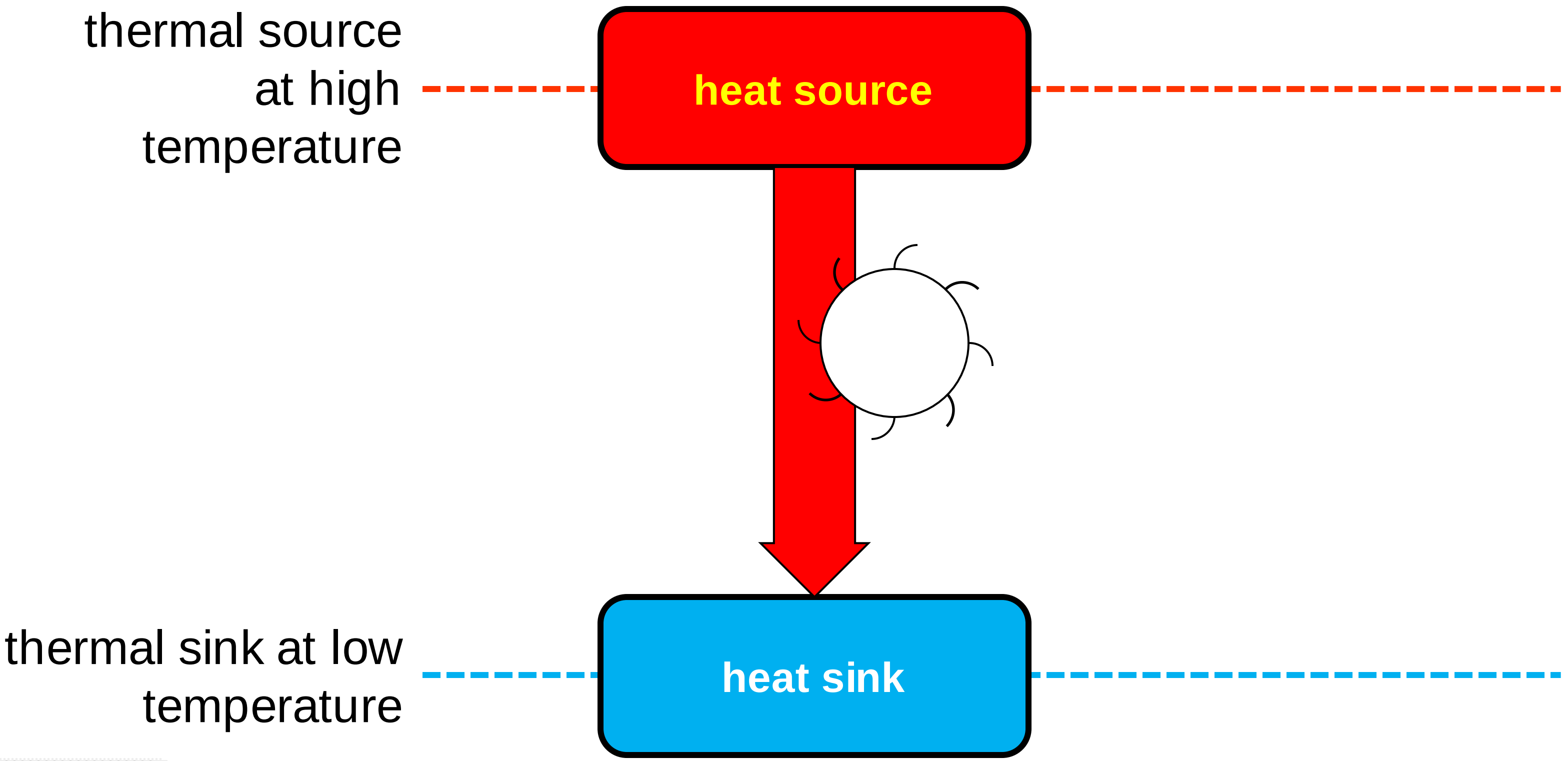
thermal source at high temperature

heat source

thermal sink at low temperature

heat sink

Spontaneous flow of energy…



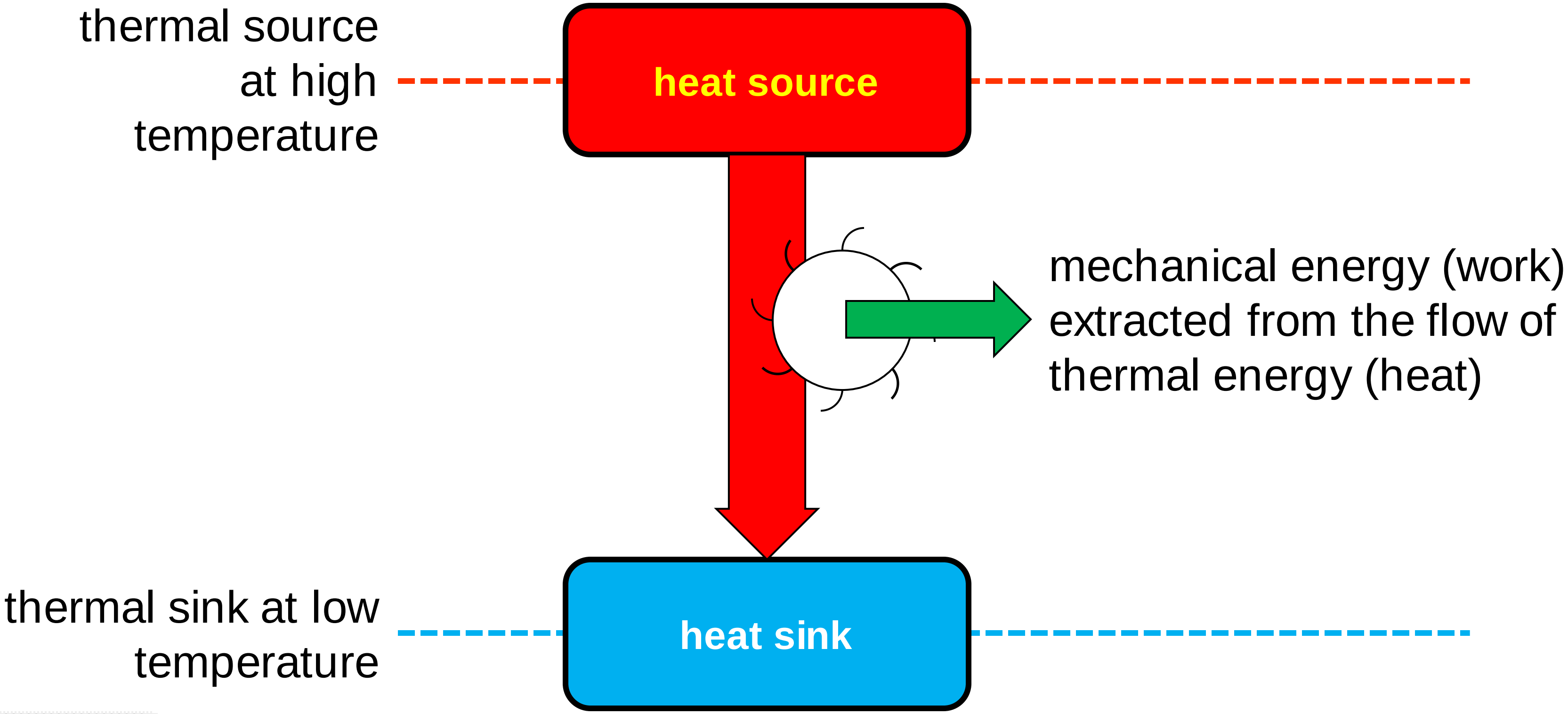
thermal source at high temperature

heat source

heat sink

thermal sink at low temperature

Spontaneous flow of energy…



thermal source
at high
temperature

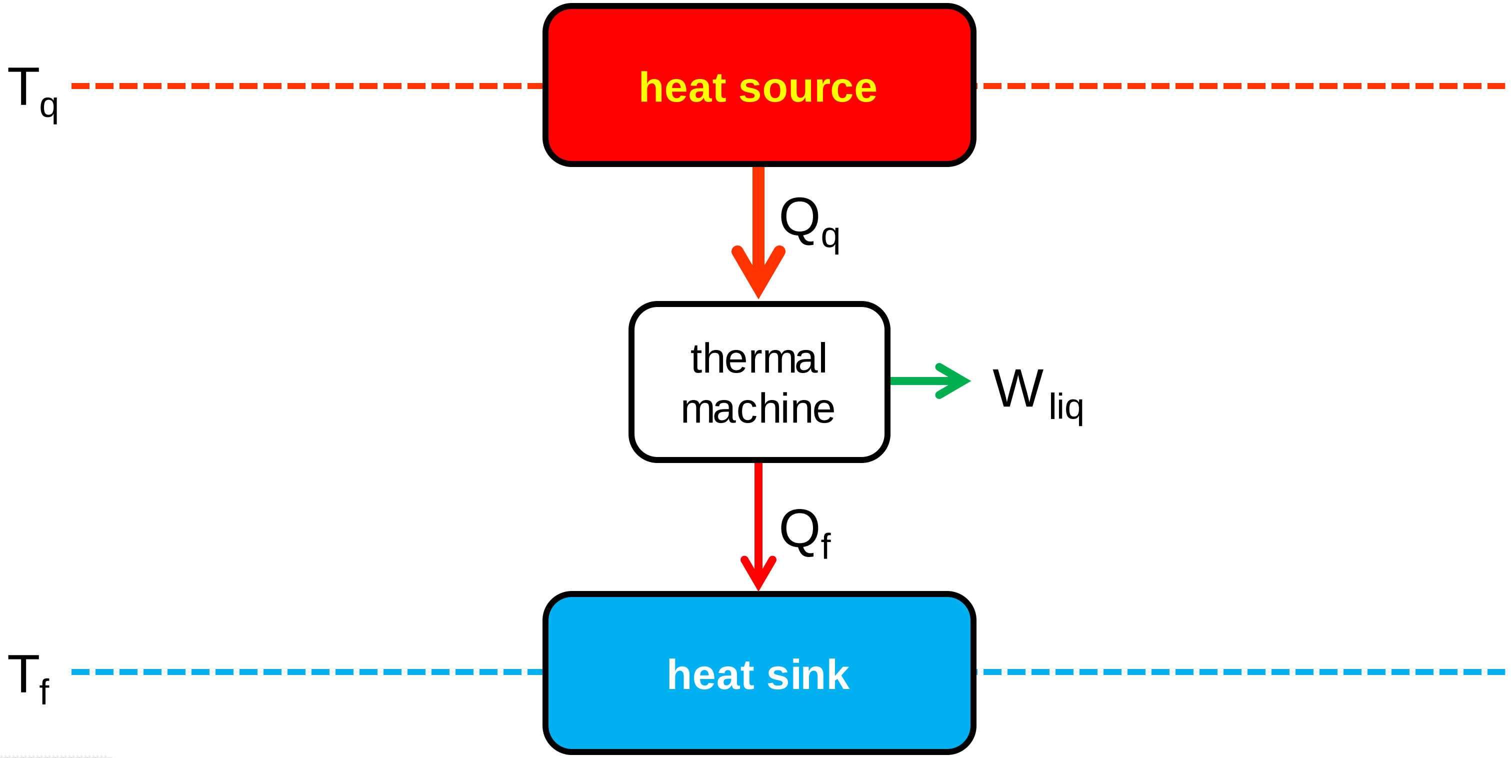
heat source

mechanical energy (work)
extracted from the flow of
thermal energy (heat)

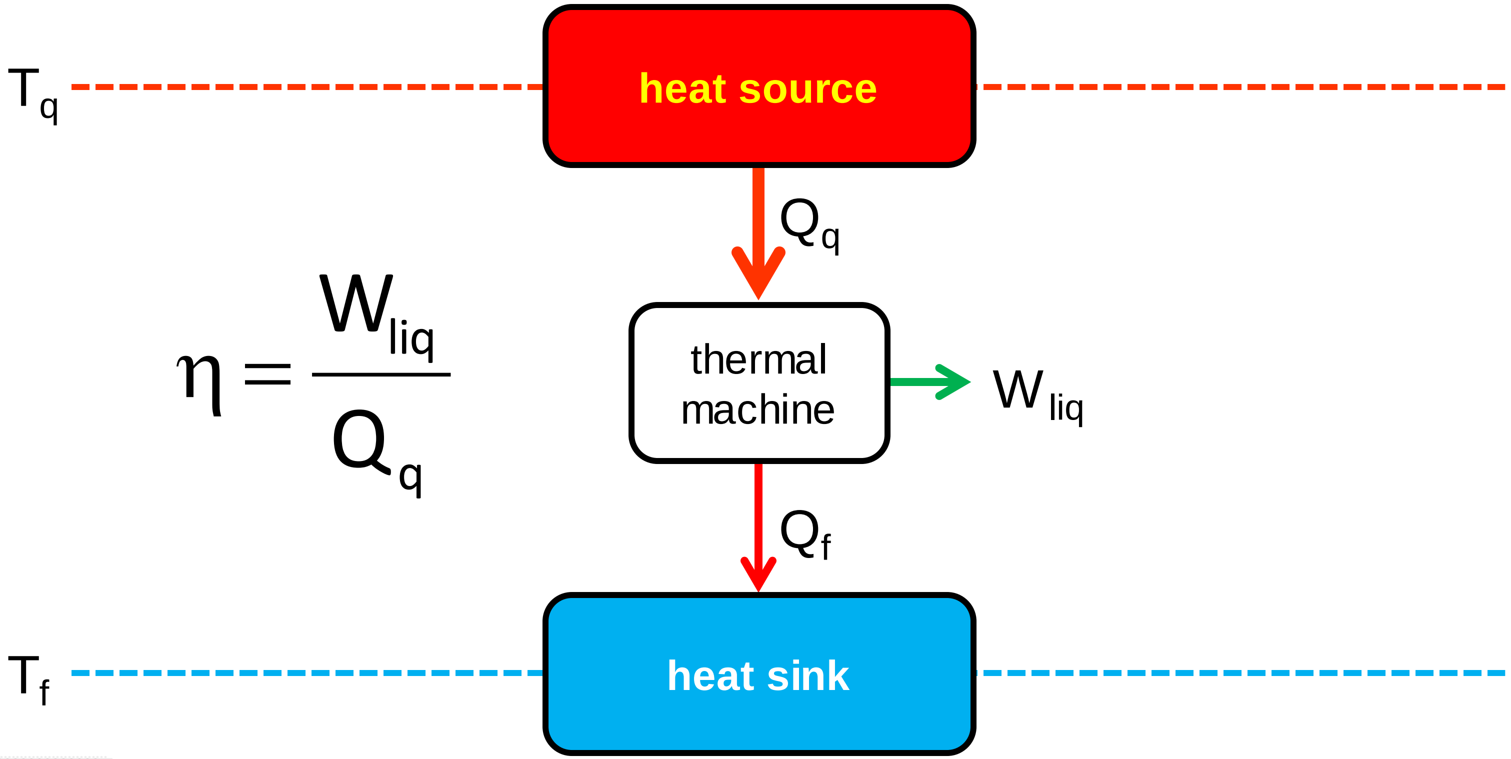
thermal sink at low
temperature

heat sink

Conversion of thermal energy to mechanical energy…



Conversion of thermal energy to mechanical energy...



$$\eta = \frac{W_{liq}}{Q_q}$$

Efficiency of the conversion cycle...

Conversion of thermal energy to mechanical energy…

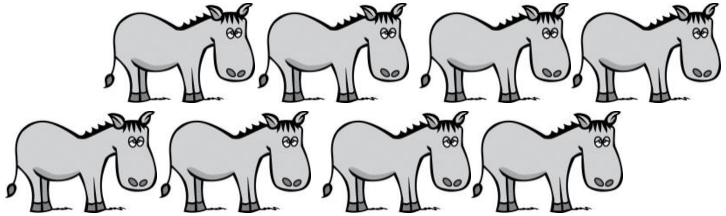
$$\eta = \frac{W_{liq}}{Q_q}$$

equivalent to the work performed by xxx horses (animals)…

power unit → HP

cost; proportional to a certain amount of coal (heat source, fuel)

Conversion of thermal energy to mechanical energy…



equivalent to the work performed
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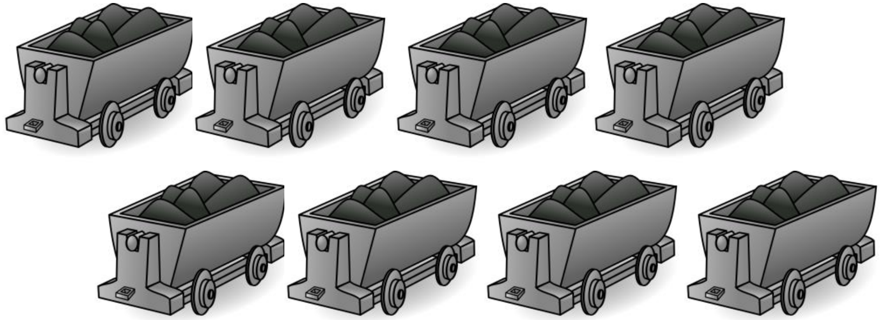
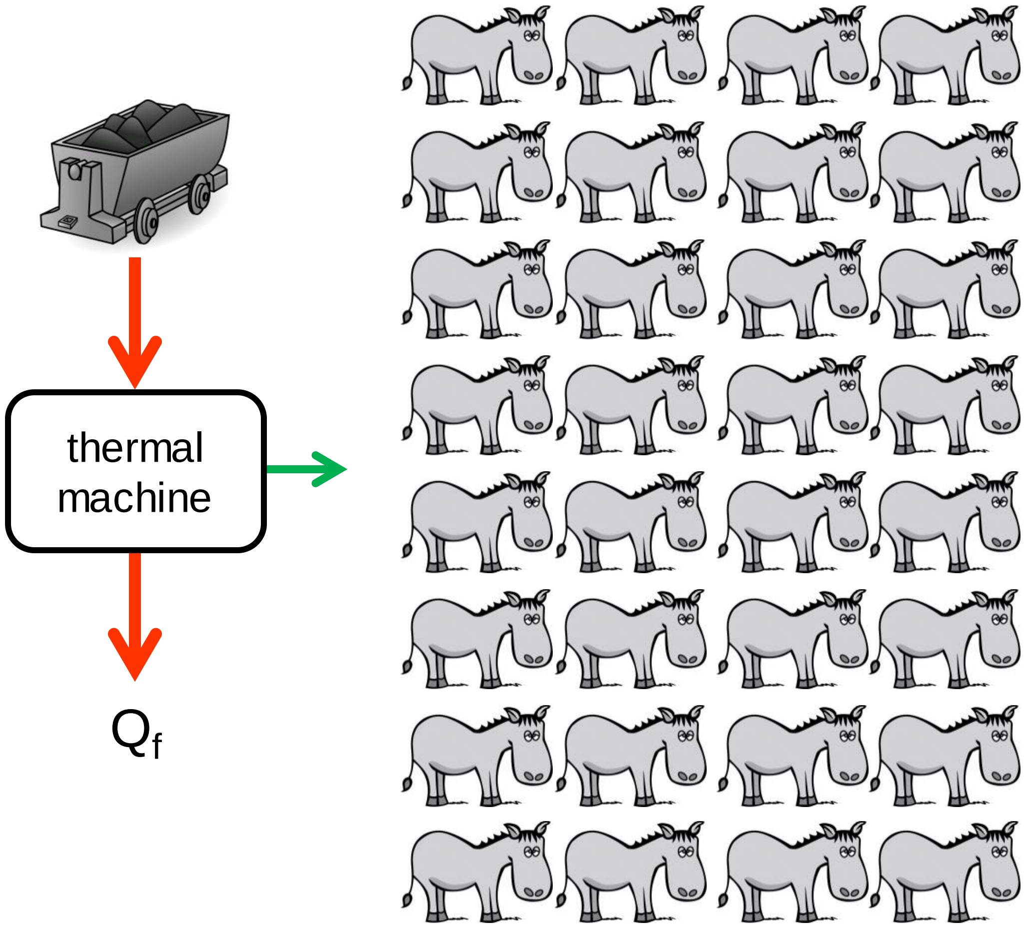


J. Watt developed the
concept of "horse power" to
facilitate his sales !
(He became very rich !)

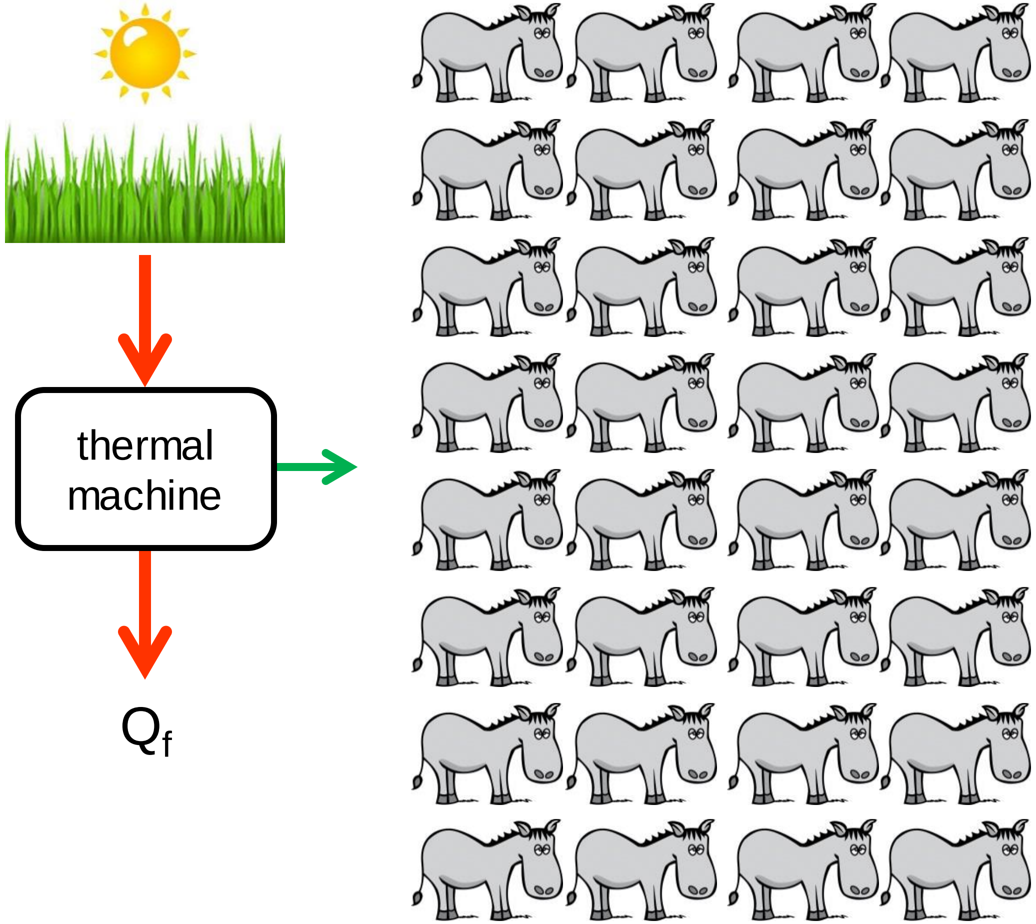
The quest for maximum conversion efficiency...



thermal machine

Q_f

The quest for maximum conversion efficiency...

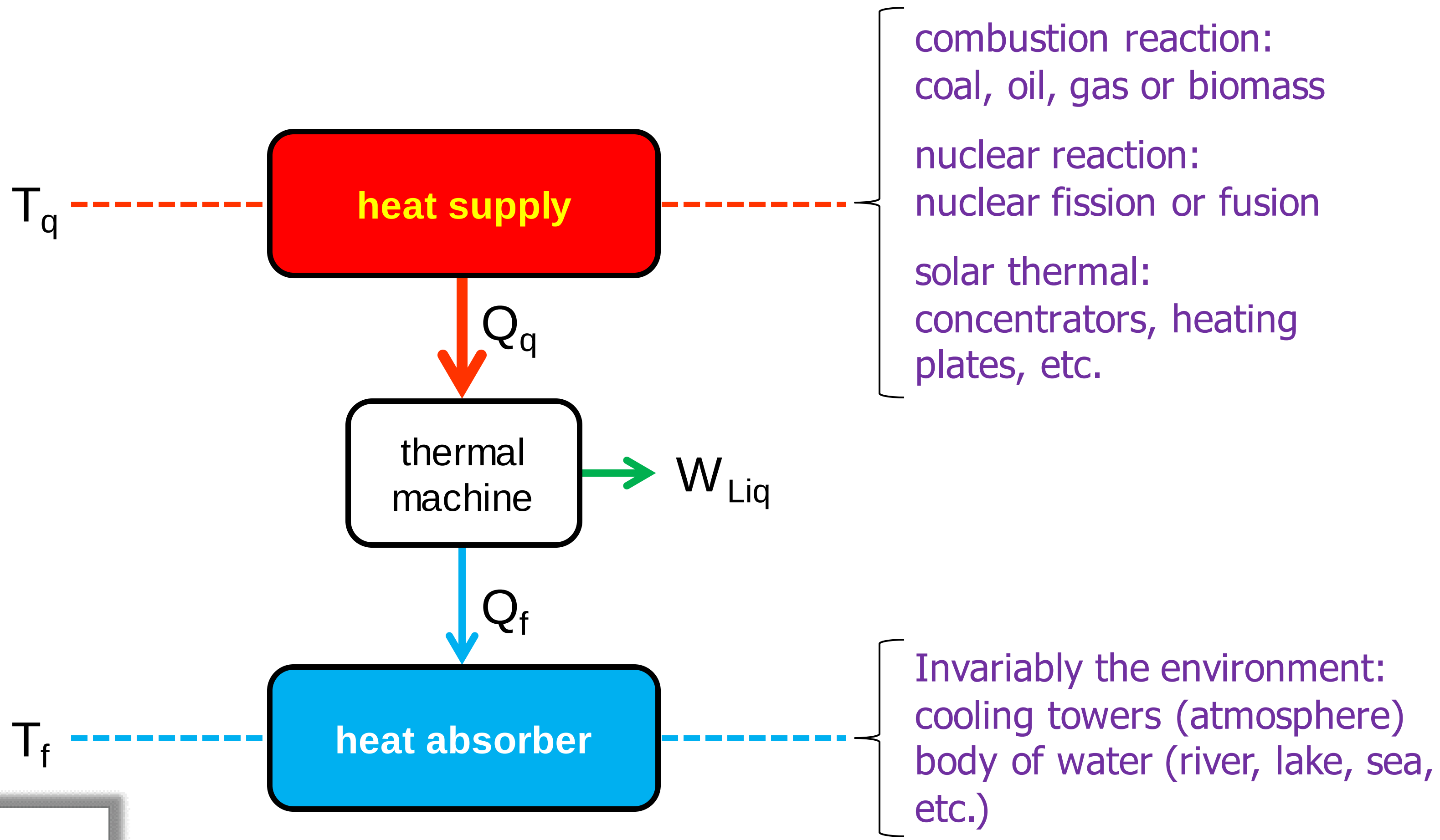


thermal machine

Q_f

… but after all how does a thermal machine exactly works ?

Thermal sources…



T_q

heat supply

Q_q

thermal machine

W_{Liq}

Q_f

T_f

heat absorber

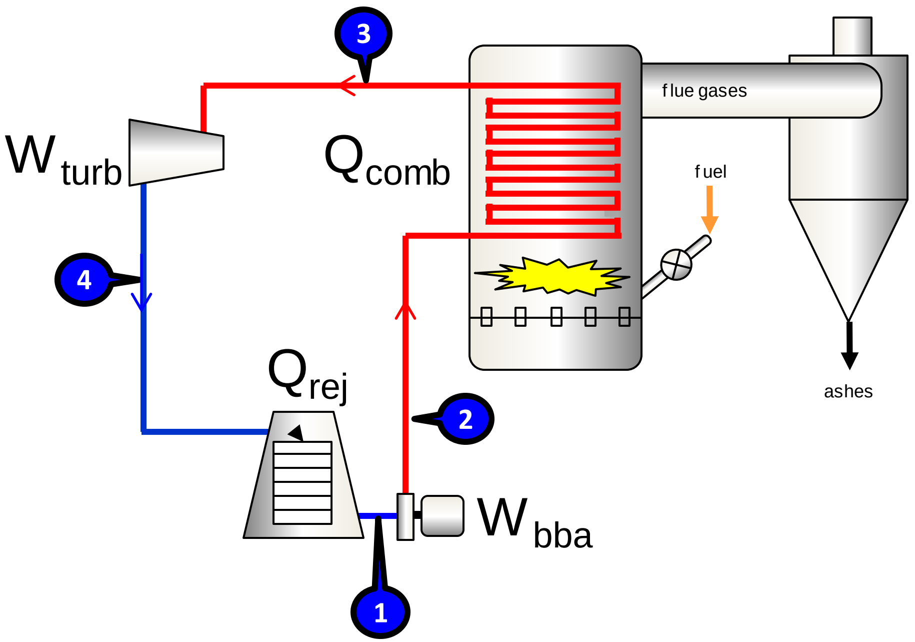
combustion reaction:
coal, oil, gas or biomass

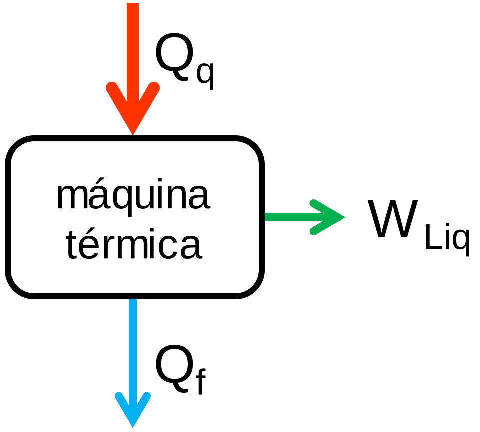
nuclear reaction:
nuclear fission or fusion

solar thermal:
concentrators, heating plates, etc.

Invariably the environment:
cooling towers (atmosphere)
body of water (river, lake, sea, etc.)

Thermal machine...





combustion reaction,
nuclear or solar thermal

Q_q

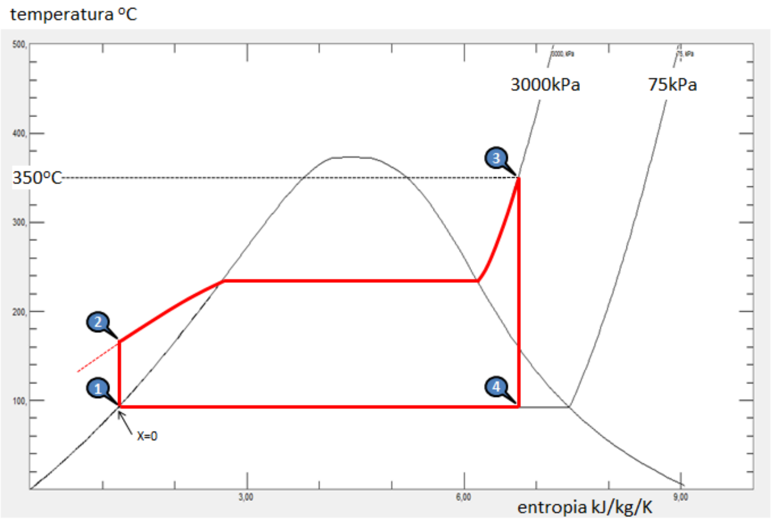
working fluid
executing a
thermodynamic cycle

máquina
térmica

W_{Liq}

Q_f

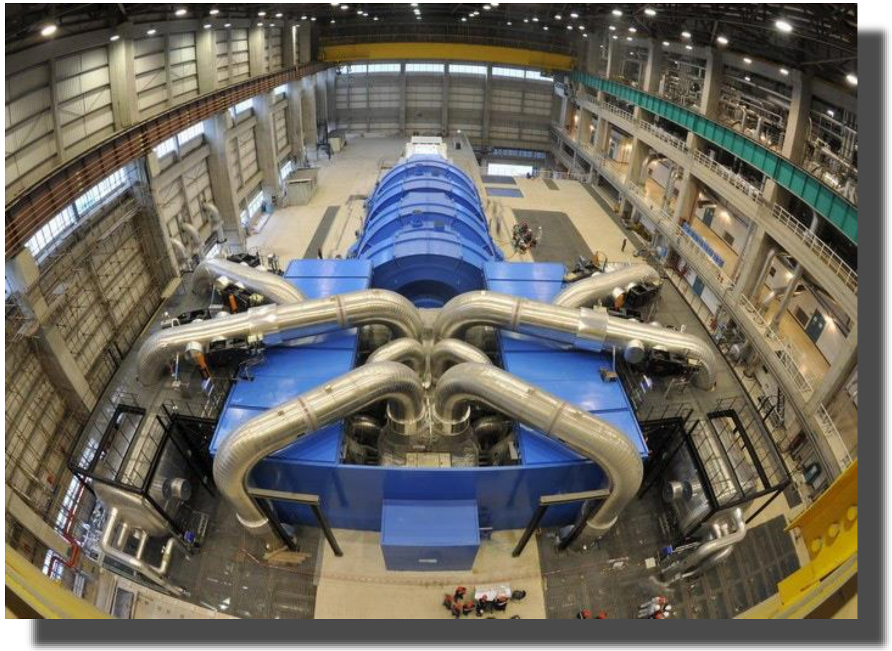
environment

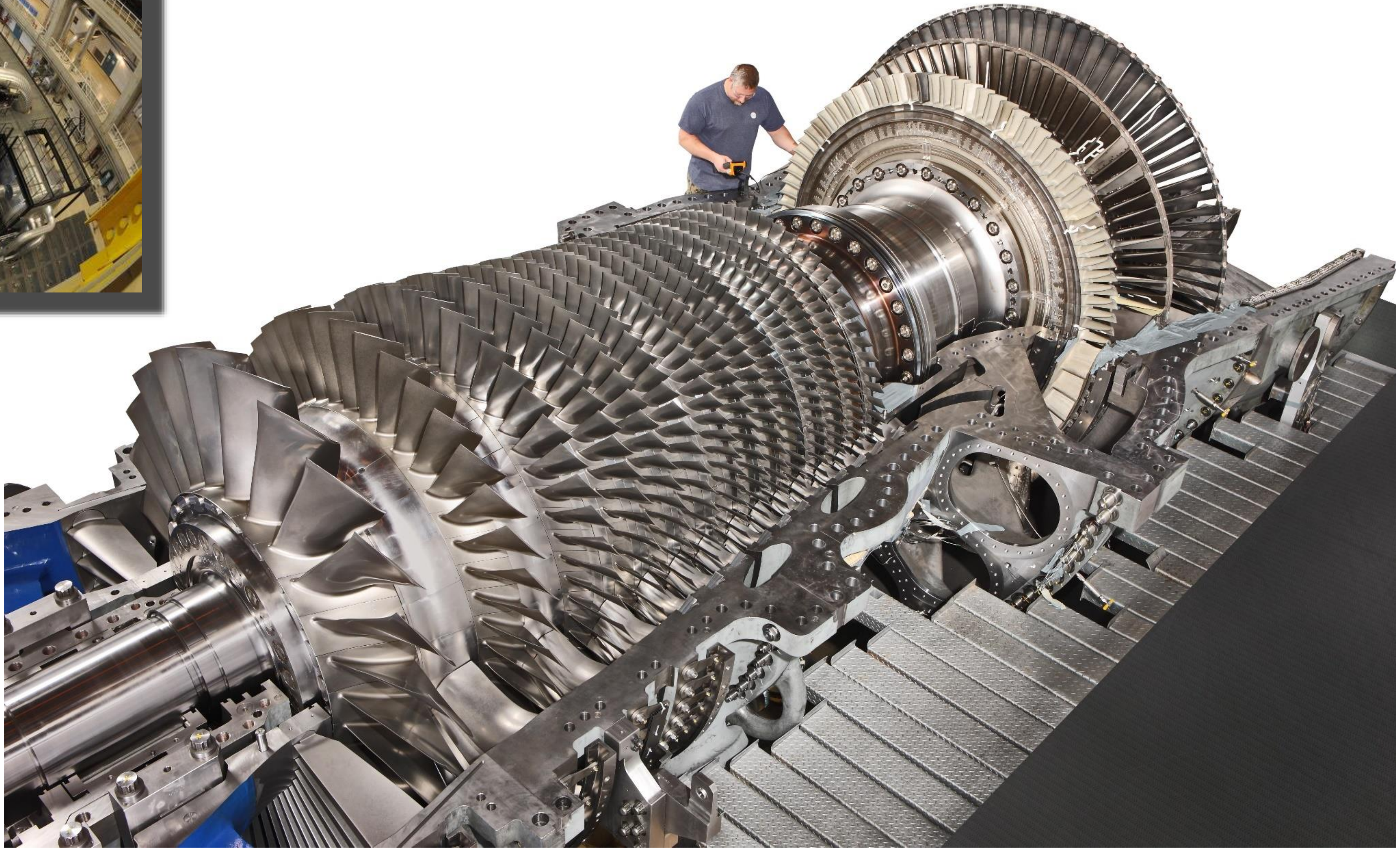


Sugarcane bagasse boiler…

Combustivel
- Bagaço de cana
Capacidade
- 200.000 kg/h
Pressão
- 67 kgf/cm²
Temperatura
- 510 °C

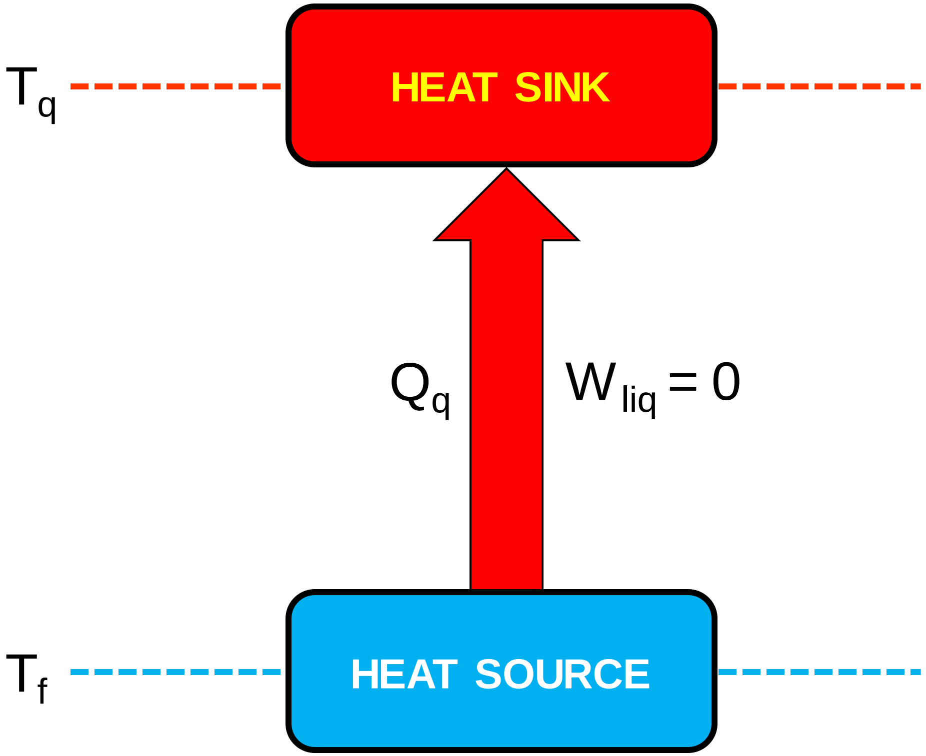
Steam turbine…





Cooling towers…

Second law of thermodynamics: Clausius statement



T_q

HEAT SINK

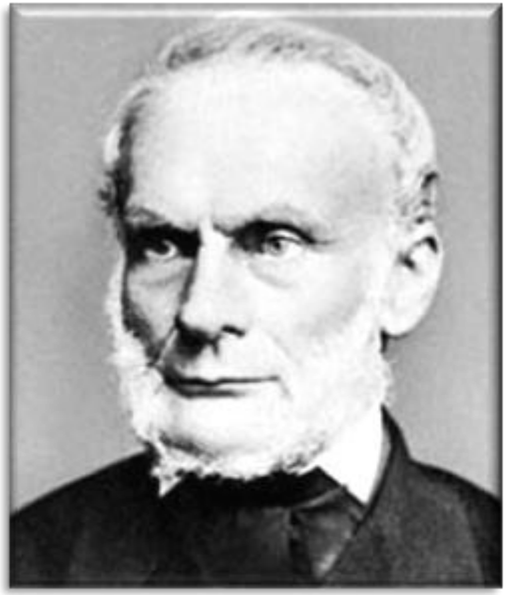
Q_q

$W_{liq} = 0$

T_f

HEAT SOURCE

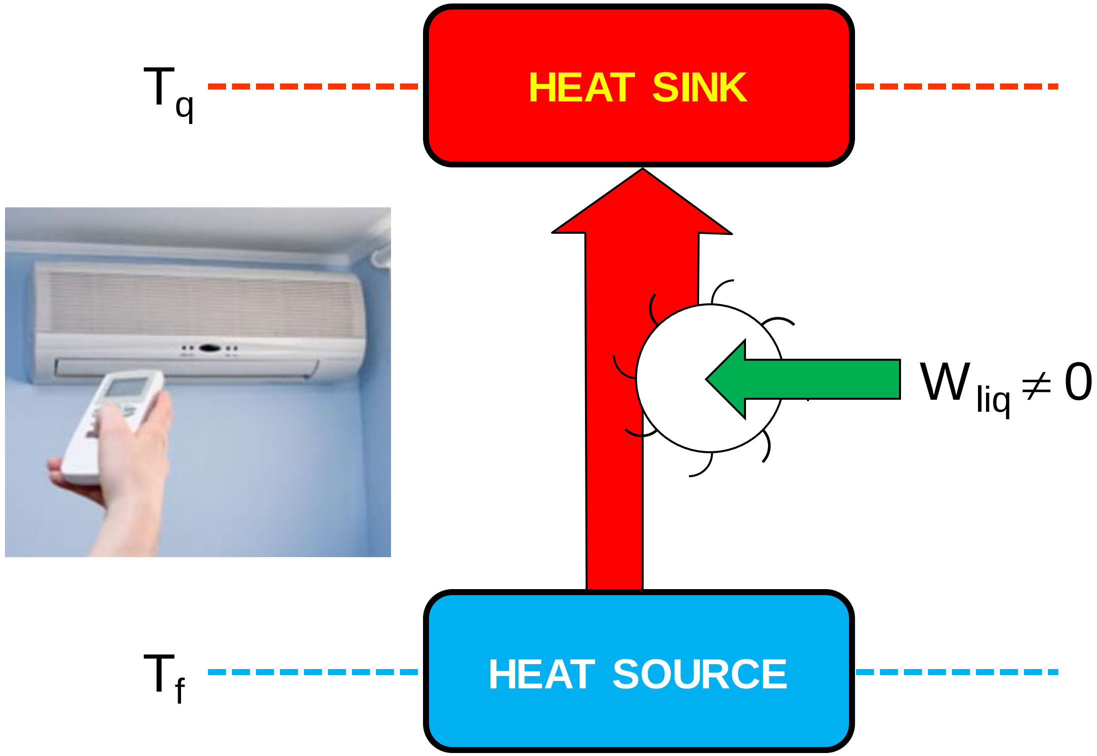
IMPOSSIBLE



Rudolf Julius Emanuel Clausius (1822 – 1888)

R. Clausius.

Second law of thermodynamics: Clausius statement



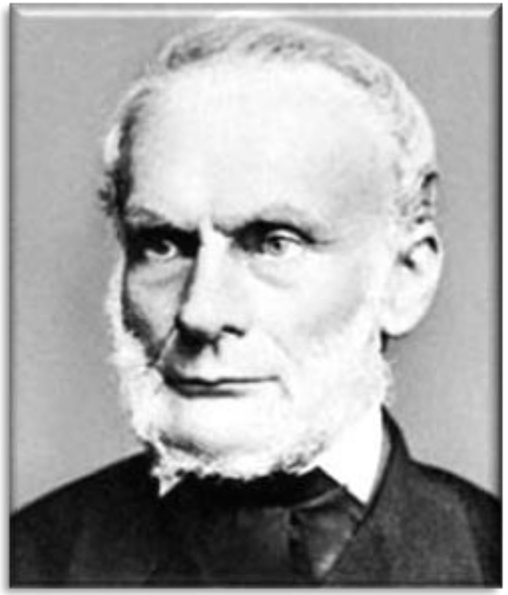
T_q

HEAT SINK

$W_{liq} \neq 0$

T_f

HEAT SOURCE

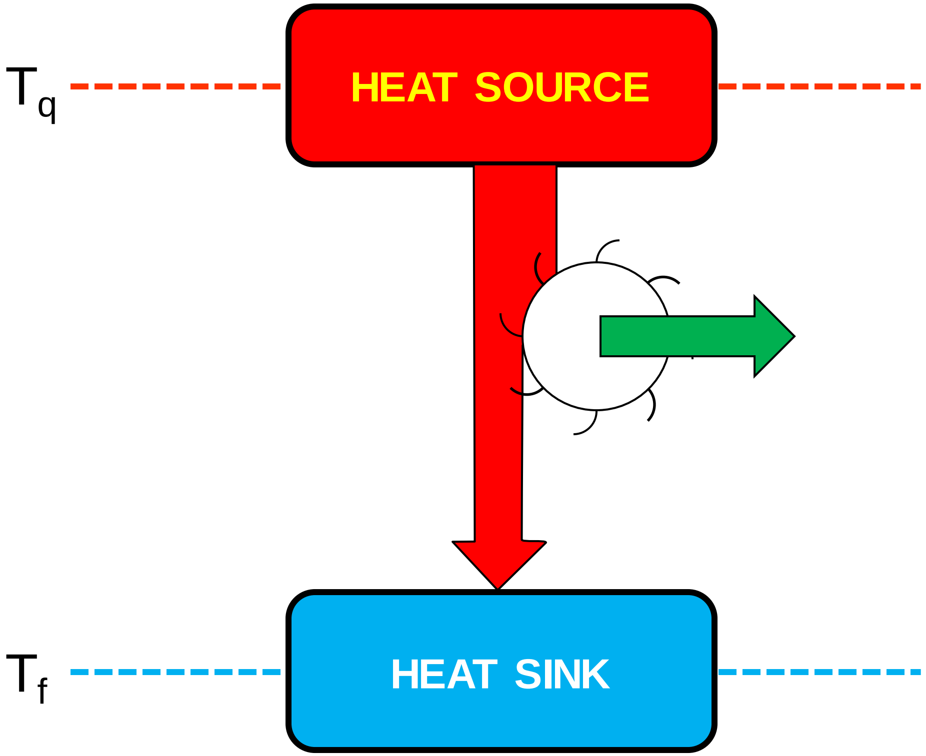


Rudolf Julius Emanuel Clausius
(1822 –1888)

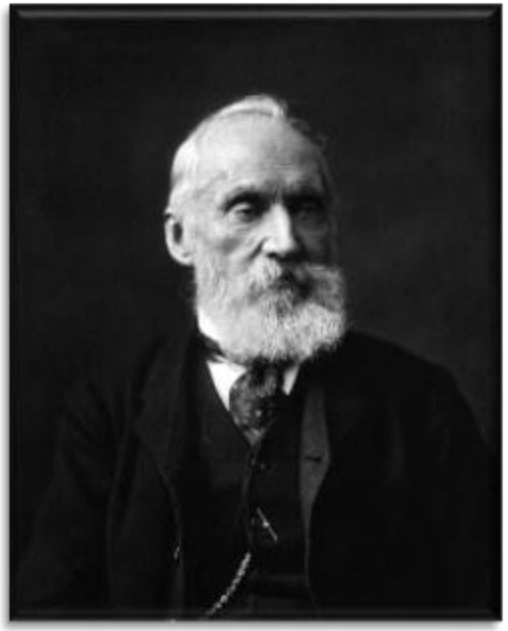
R. Clausius.

POSSIBLE

Second law of thermodynamics: Kelvin-Planck



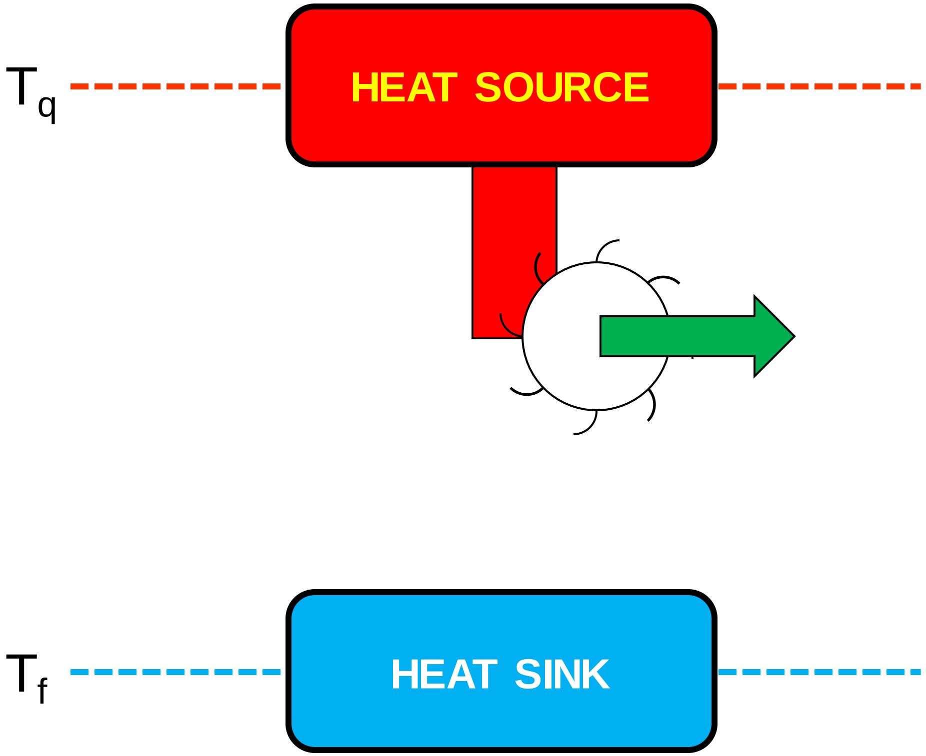
POSSIBLE



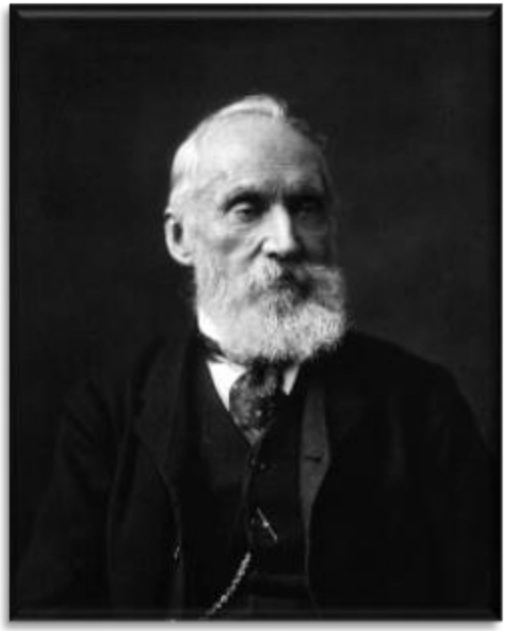
William Thomson, 1st Baron Kelvin
(1824 – 1907)

Kelvin P.N.P

Second law of thermodynamics: Kelvin-Planck



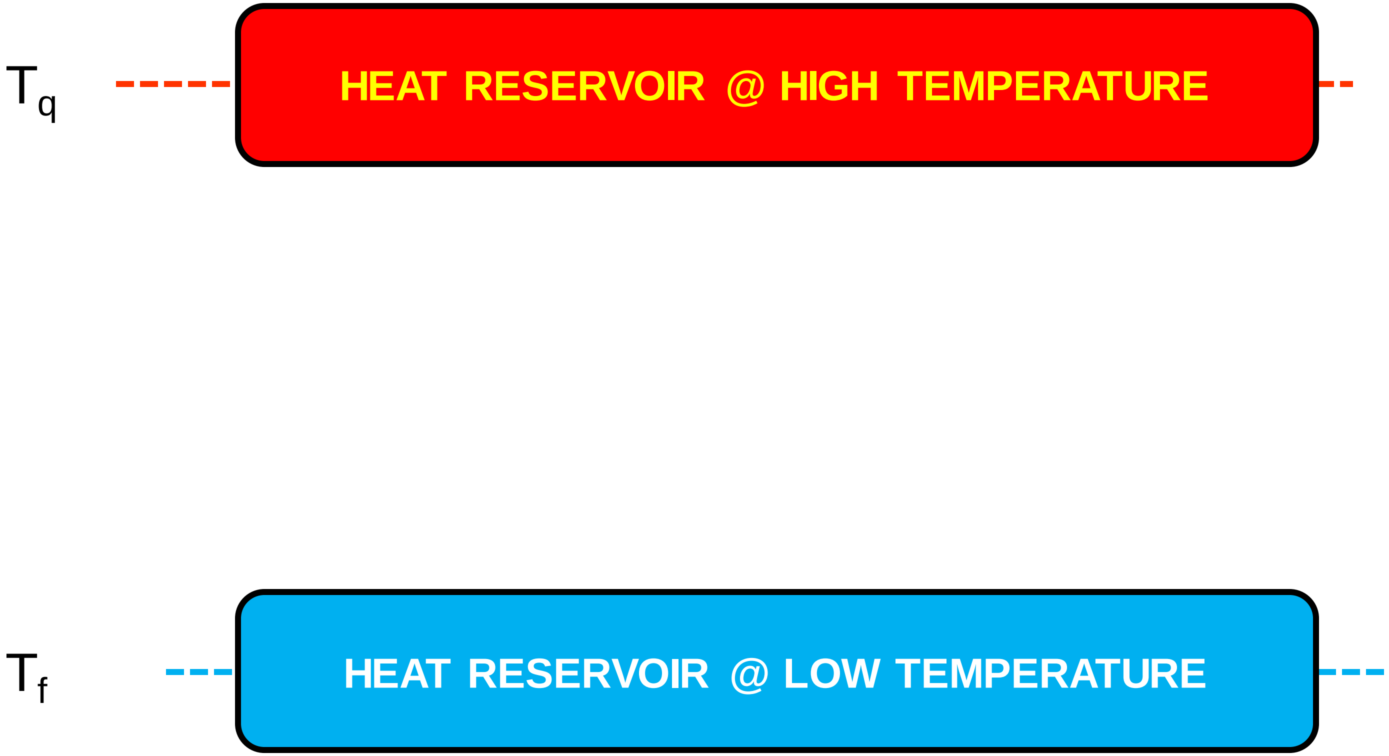
IMPOSSIBLE



William Thomson, 1st Baron Kelvin
(1824 – 1907)

Kelvin P.N.P

Equivalence of both statements of the second law



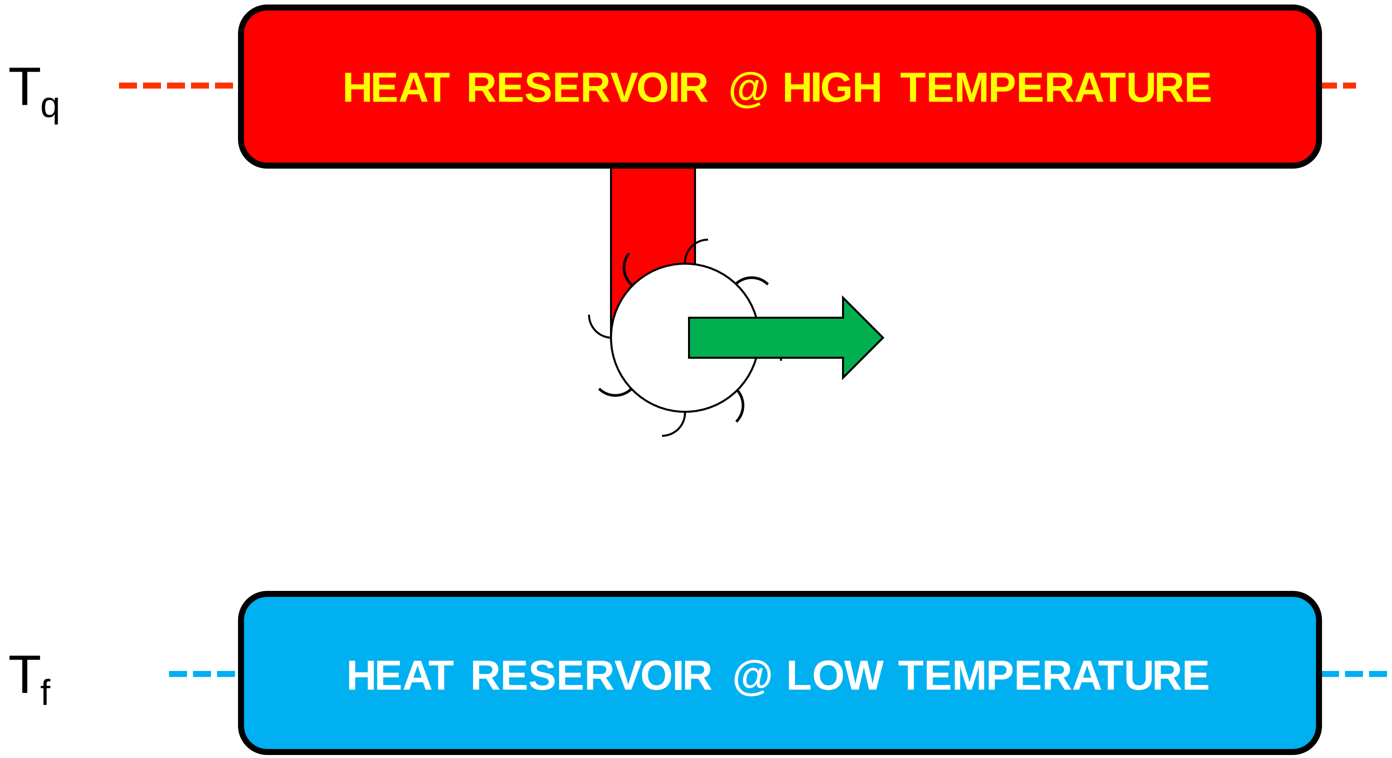
T_q

HEAT RESERVOIR @ HIGH TEMPERATURE

T_f

HEAT RESERVOIR @ LOW TEMPERATURE

Equivalence of both statements of the second law



T_q

HEAT RESERVOIR @ HIGH TEMPERATURE

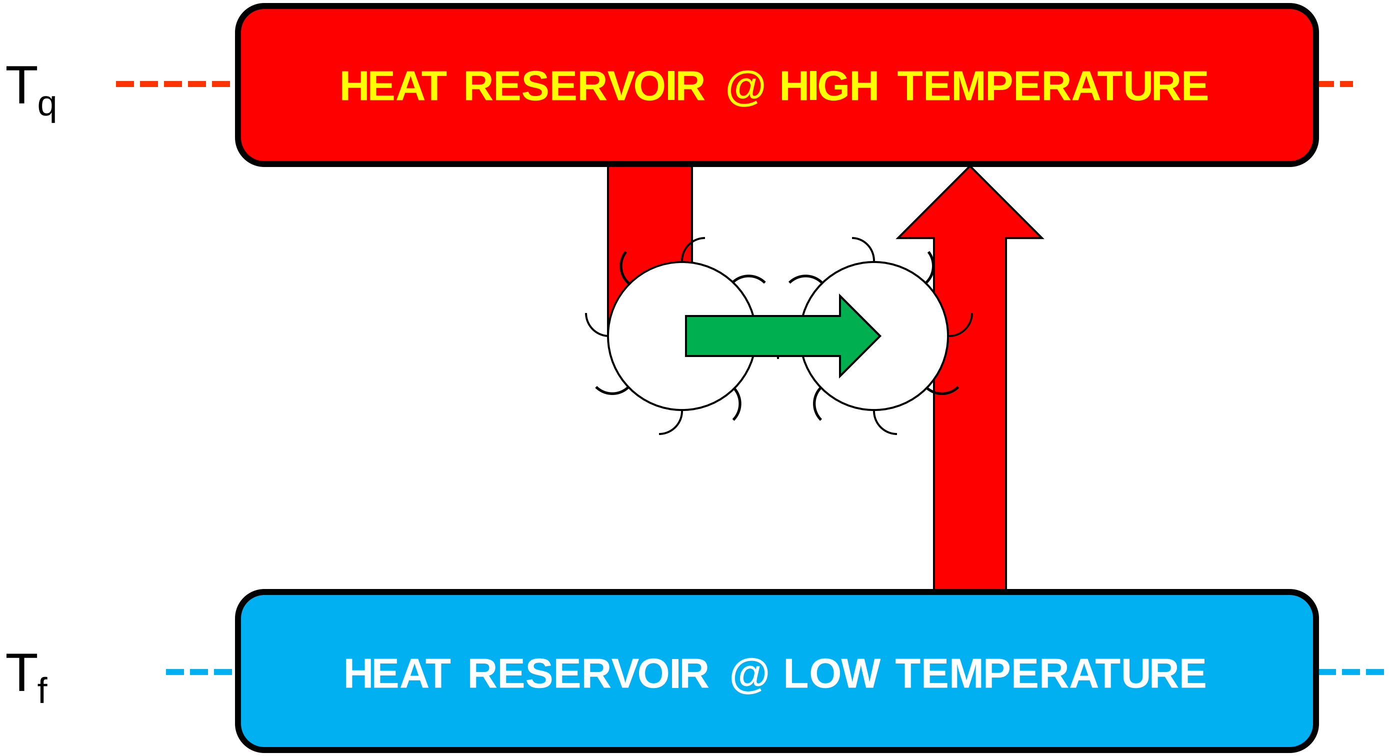
T_f

HEAT RESERVOIR @ LOW TEMPERATURE

Hypothesis:

POSSIBLE

Equivalence of both statements of the second law



T_q

HEAT RESERVOIR @ HIGH TEMPERATURE

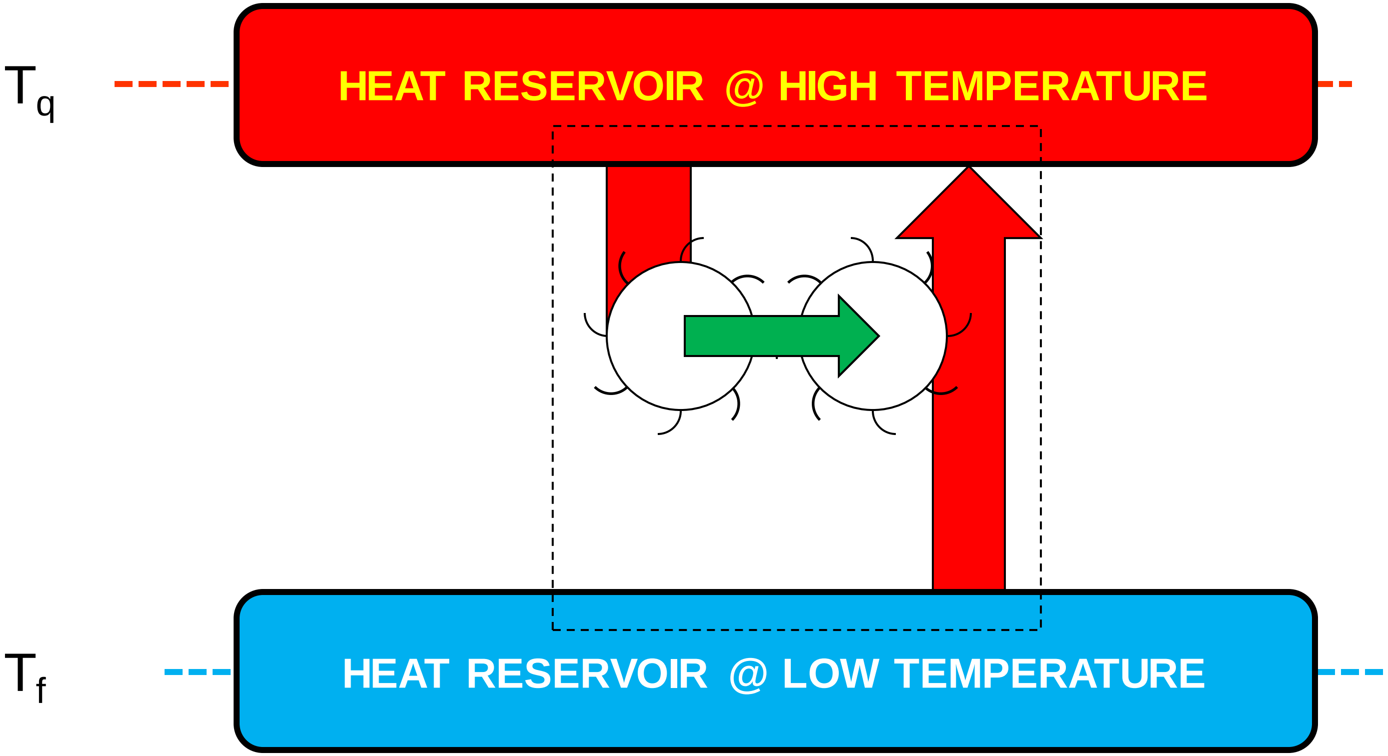
T_f

HEAT RESERVOIR @ LOW TEMPERATURE

Hypothesis:

POSSIBLE

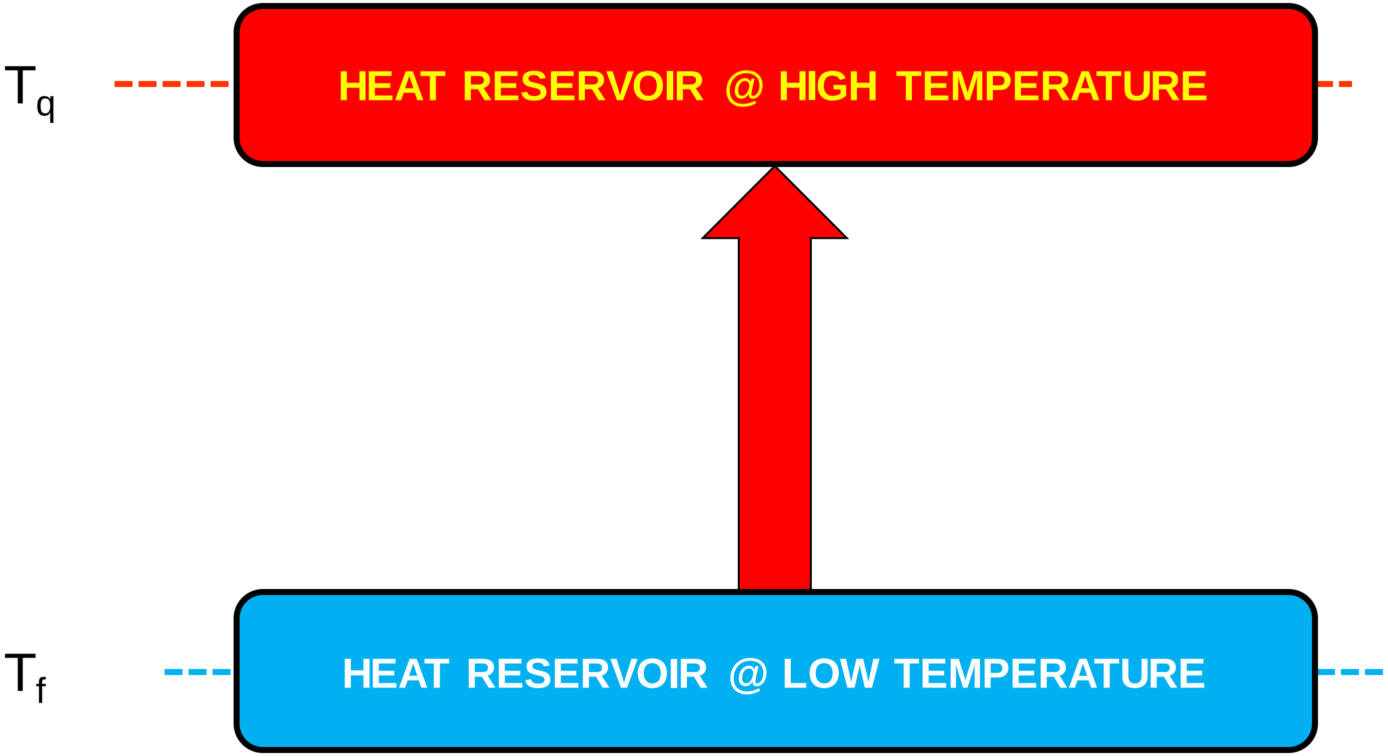
Equivalence of both statements of the second law



Hypothesis:

POSSIBLE

Equivalence of both statements of the second law



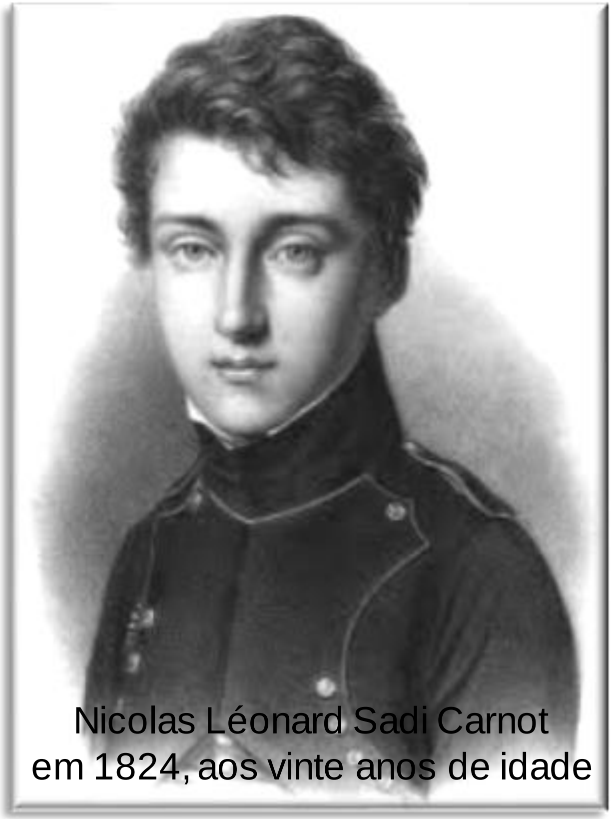
Hypothesis: POSSIBLE ⇨ **ABSURDITY**

reductio ad absurdum

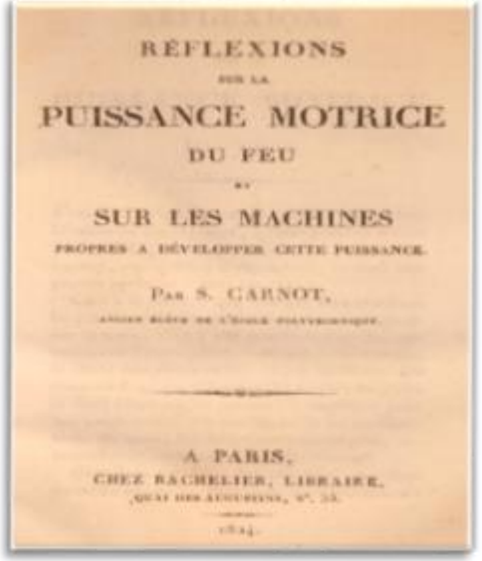
The quest for maximum conversion efficiency…

Battle of Waterloo fought in 06/18/1815
Duke of Wellington × Napoleon
by William Sadler

The quest for maximum conversion efficiency…



Nicolas Léonard Sadi Carnot
em 1824, aos vinte anos de idade



RÉFLEXIONS

PUISSANCE MOTRICE
DU FEU

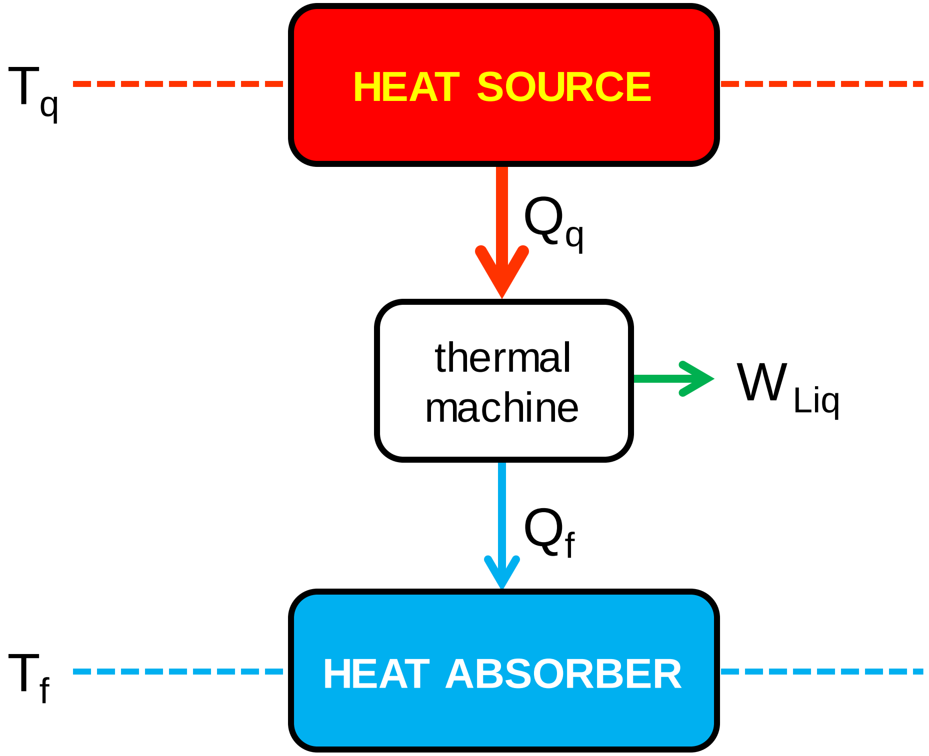
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.

Par S. CARNOT,

A PARIS,
CHEZ BACHELIER, LIBRAIRE,

"Leurs industrie est
plus avancé ! "

The quest for maximum conversion efficiency…



T_q

HEAT SOURCE

Q_q

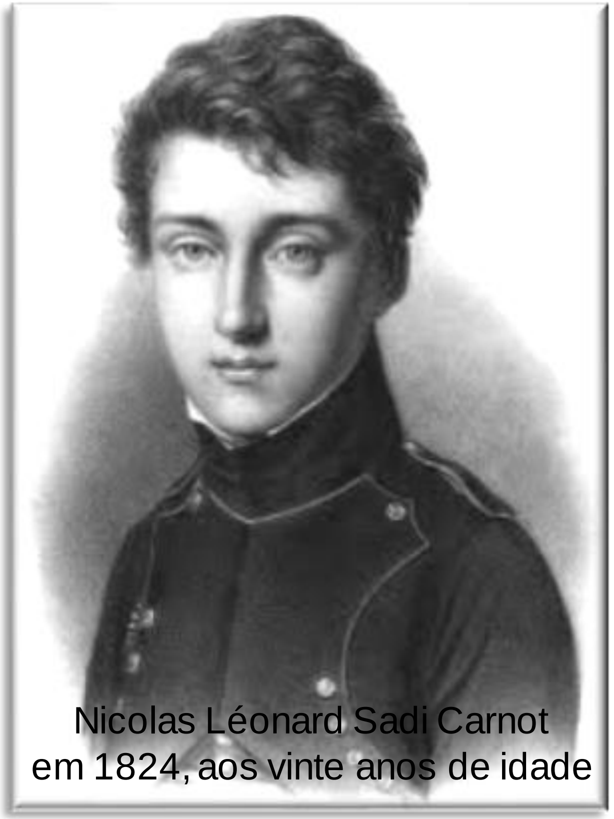
thermal machine

W_{Liq}

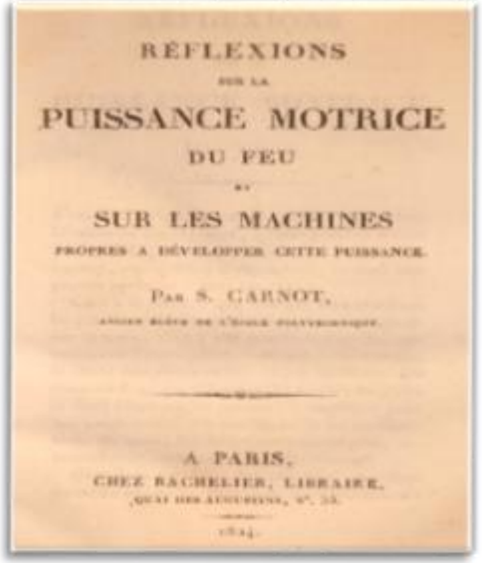
Q_f

HEAT ABSORBER

T_f



Nicolas Léonard Sadi Carnot
em 1824, aos vinte anos de idade



RÉFLEXIONS

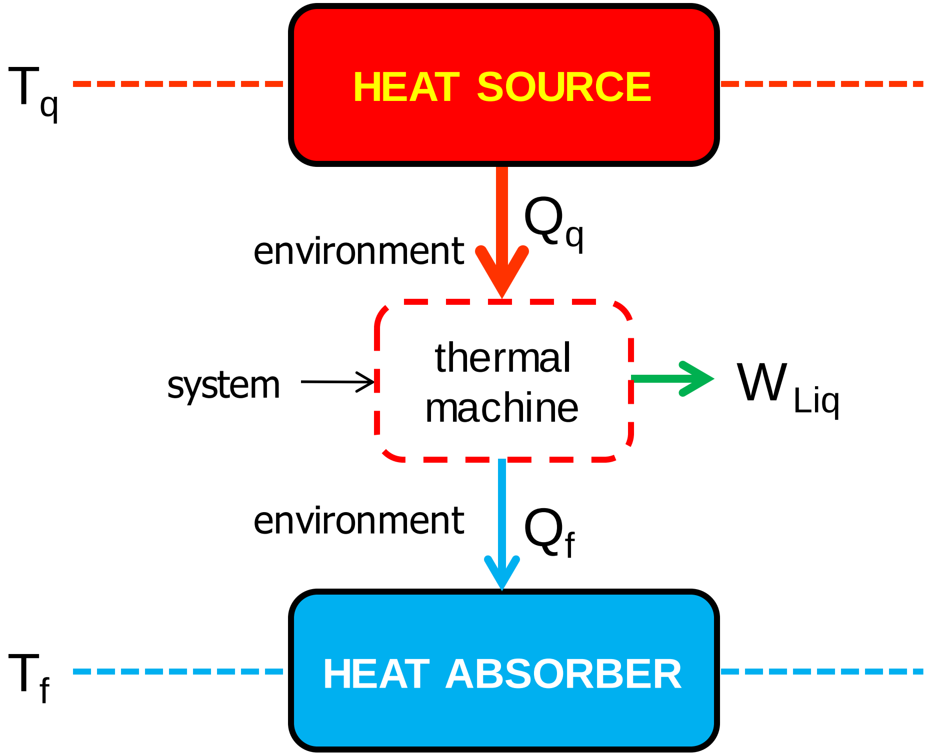
PUISSANCE MOTRICE
DU FEU

SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.

Par S. CARNOT,

A PARIS,
CHEZ BACHELIER, LIBRAIRE,

The quest for maximum conversion efficiency…



T_q

HEAT SOURCE

Q_q

environment

system

thermal machine

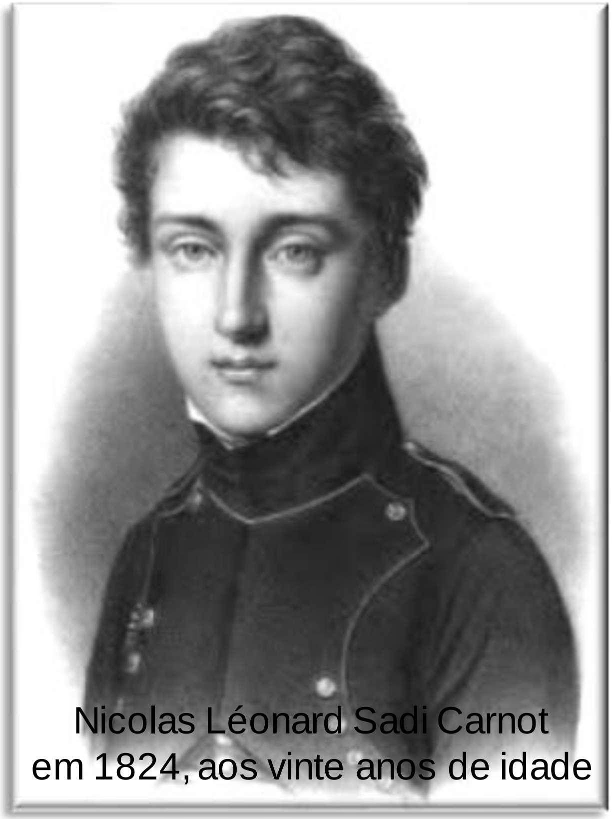
W_{Liq}

environment

Q_f

T_f

HEAT ABSORBER



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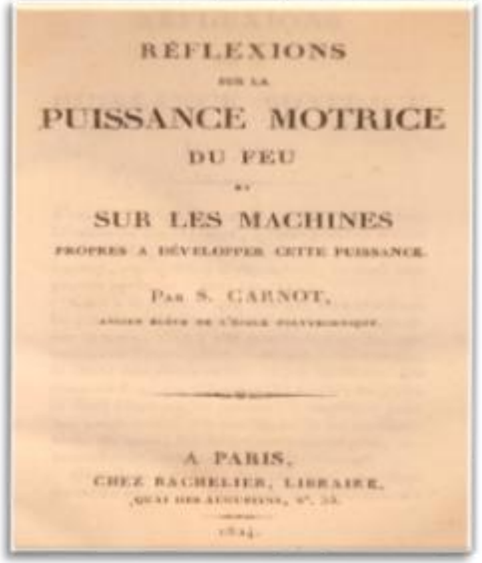

RÉFLEXIONS

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SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.

Par S. CARNOT,

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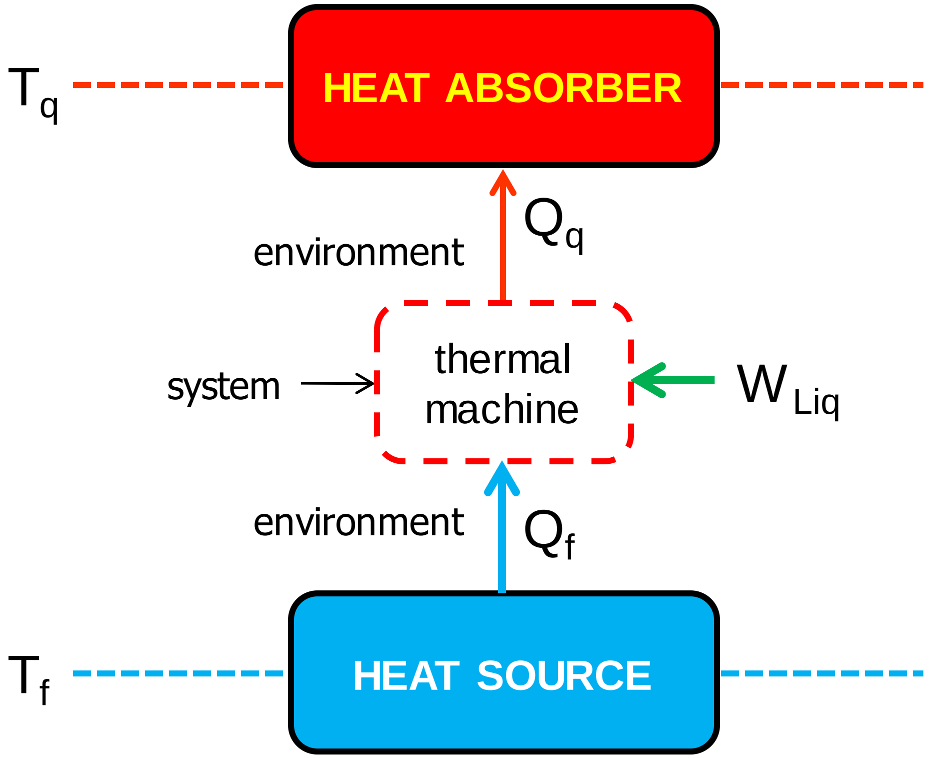
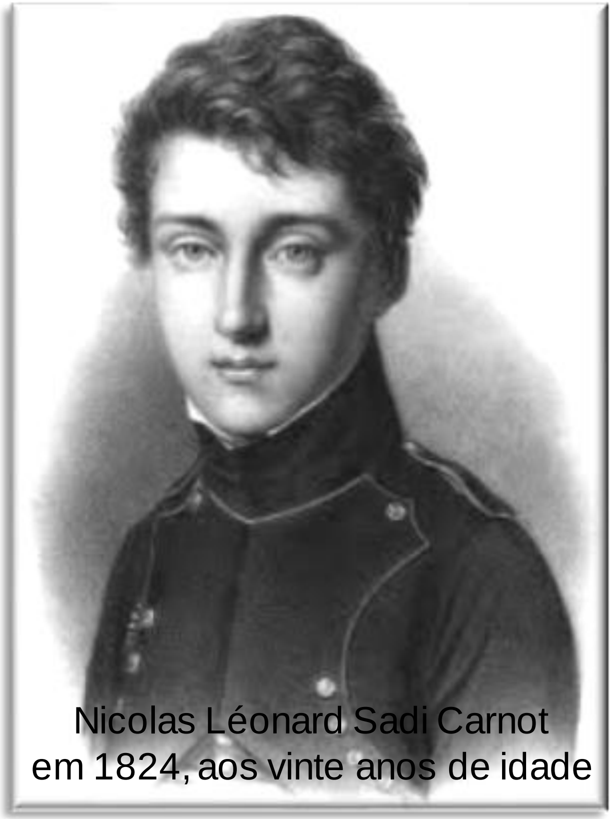
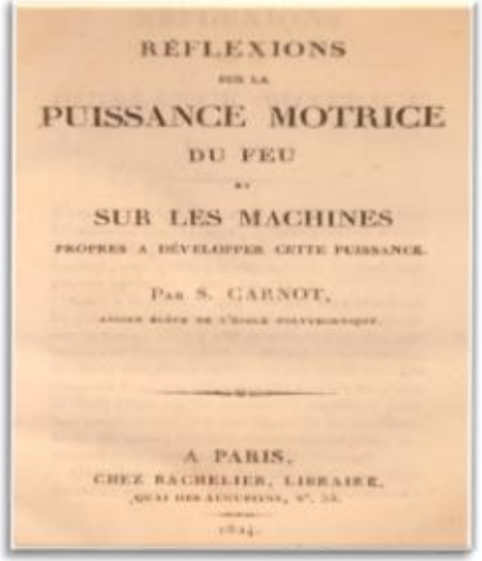
The quest for maximum conversion efficiency…




Nicolas Léonard Sadi Carnot
em 1824, aos vinte anos de idade


RÉFLEXIONS

PUISSANCE MOTRICE

DU FEU

SUR LES MACHINES

PROPRES A DÉVELOPPER CETTE PUISSANCE.

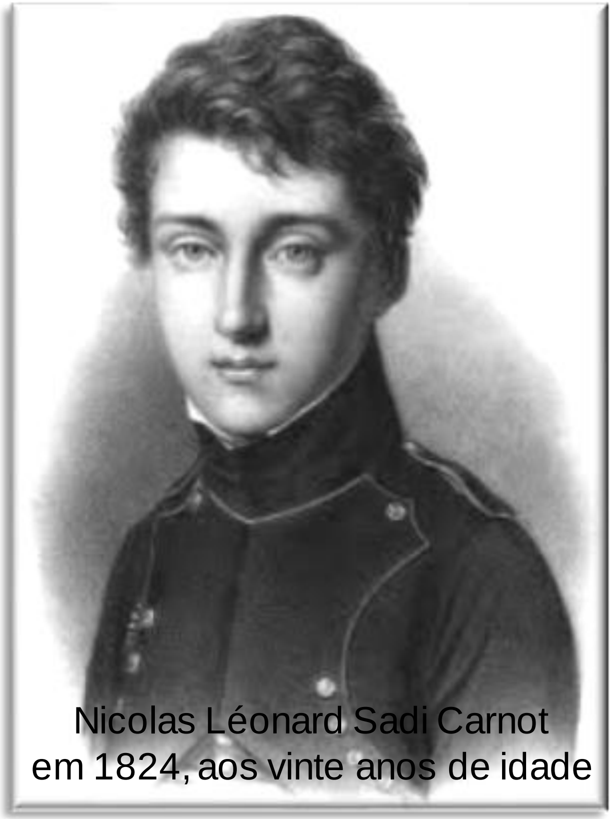
PAR S. CARNOT,

A PARIS,

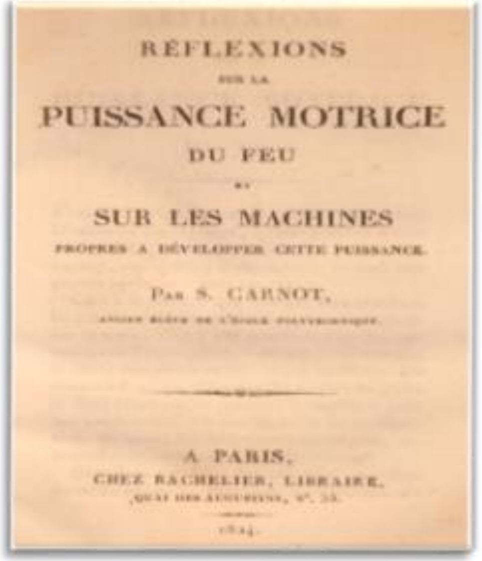
CHEZ BACHELIER, LIBRAIRE,

The quest for maximum conversion efficiency…

"Le moteur peut être actionné en sens inverse et le résultat net serait alors que la consommation d'un travail égal à celui produit par le fonctionnement en sens direct et le transfert de la même quantité de chaleur, mais, dans ce cas, du corps froid au corps chaud..."



Nicolas Léonard Sadi Carnot
em 1824, aos vinte anos de idade

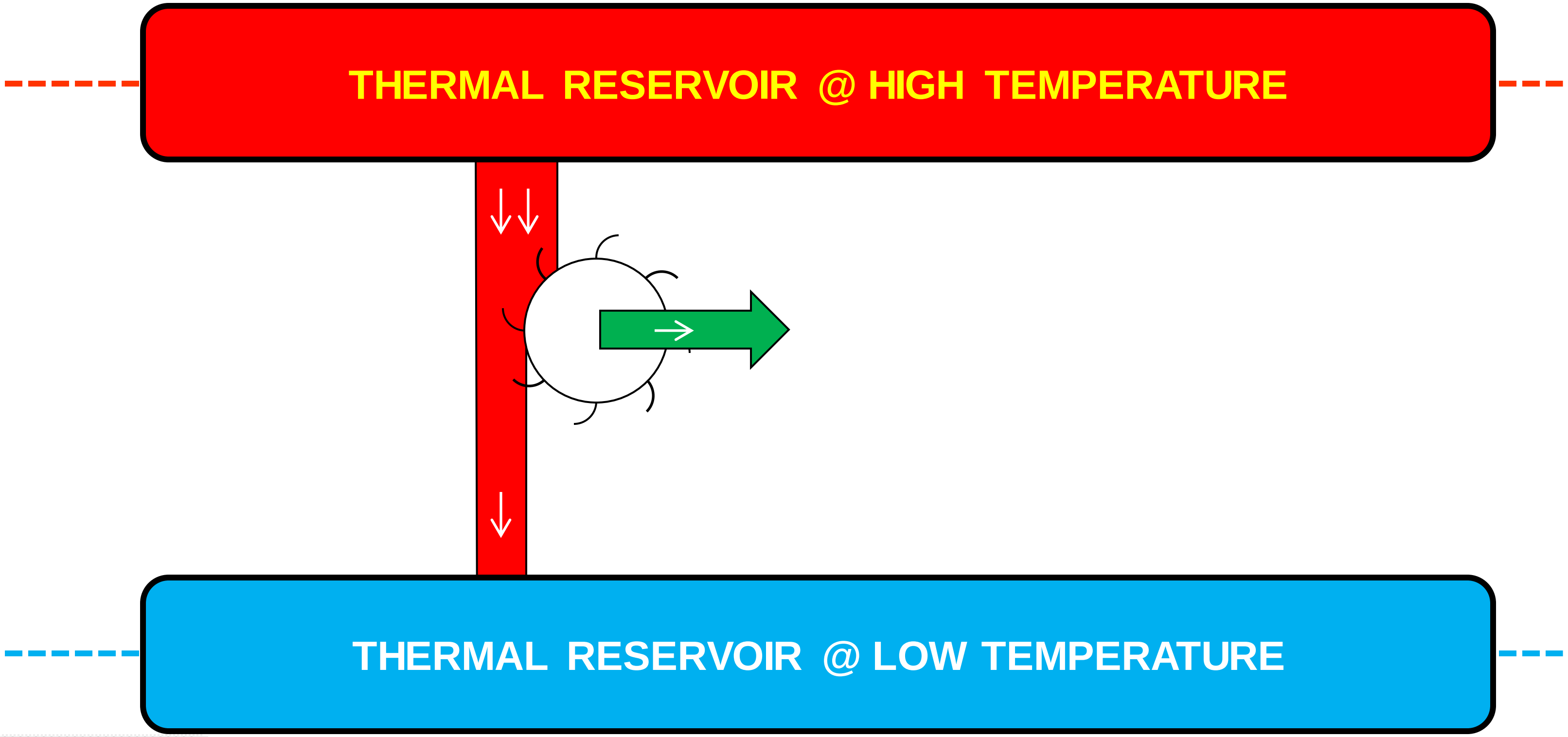


RÉFLEXIONS
PUISSANCE MOTRICE
DU FEU
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.
Par S. CARNOT,

A PARIS,
CHEZ BACHELIER, LIBRAIRE,

Maximum efficiency occurs when the thermal machine is reversible !!!

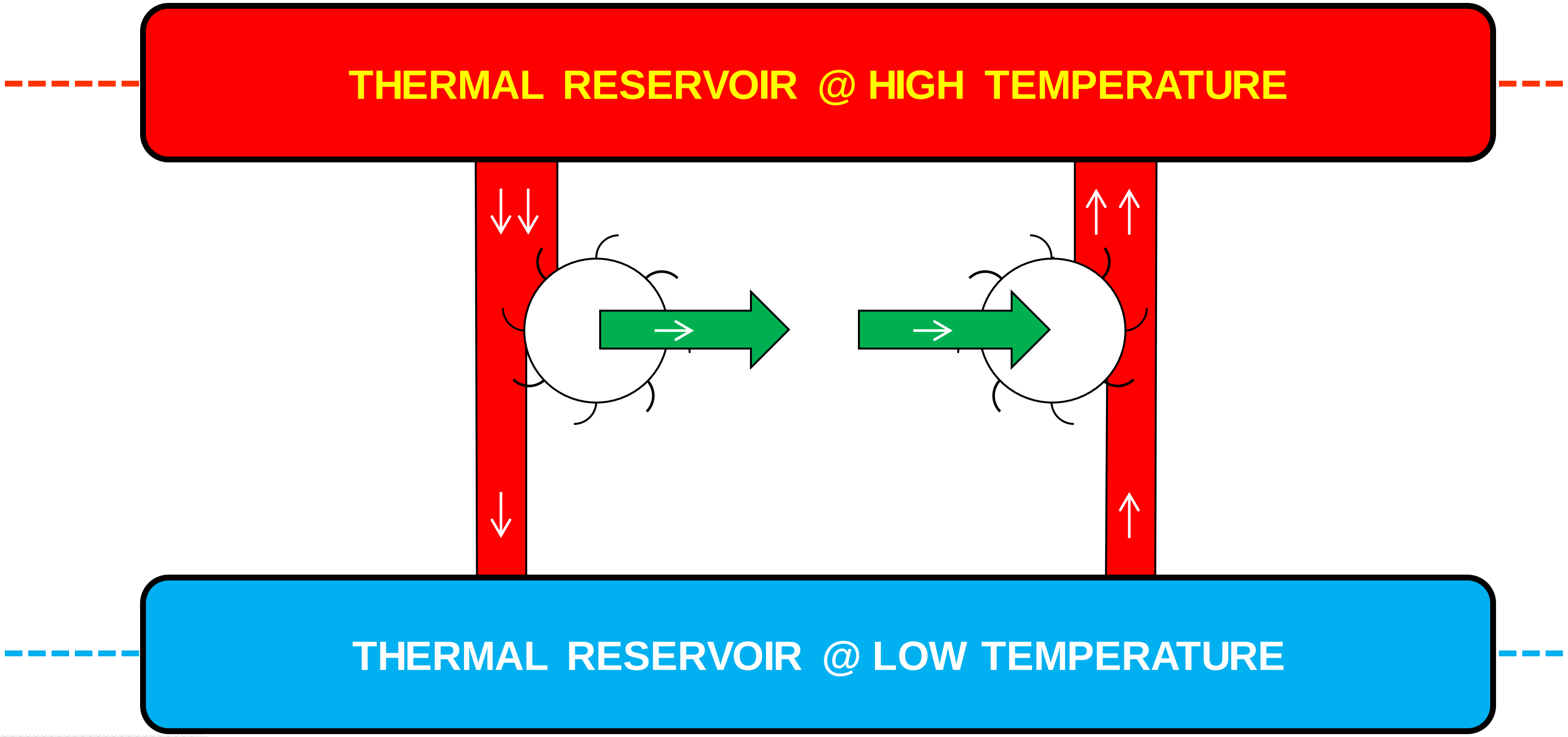
Strict reversibility…



THERMAL RESERVOIR @ HIGH TEMPERATURE

THERMAL RESERVOIR @ LOW TEMPERATURE

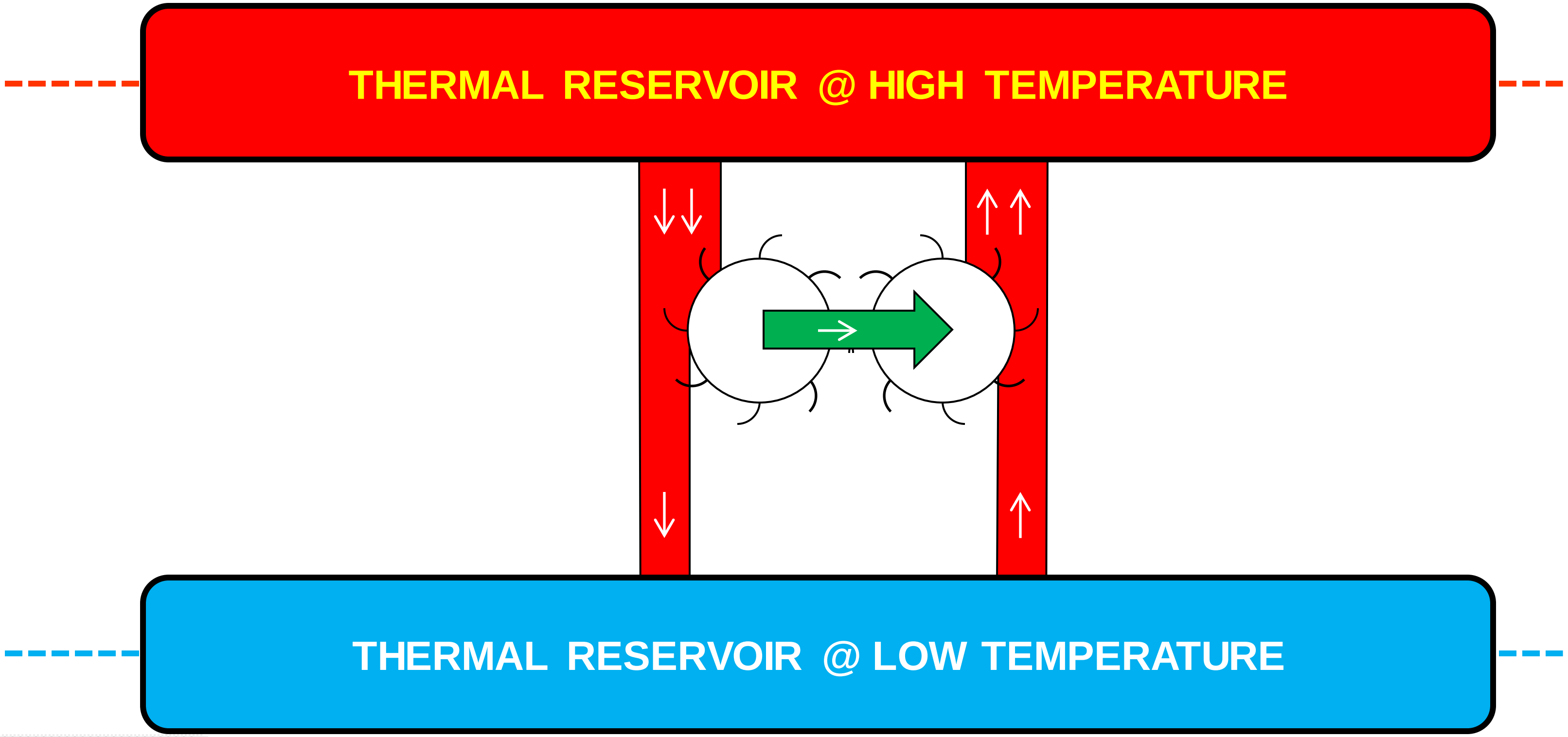
Strict reversibility…



THERMAL RESERVOIR @ HIGH TEMPERATURE

THERMAL RESERVOIR @ LOW TEMPERATURE

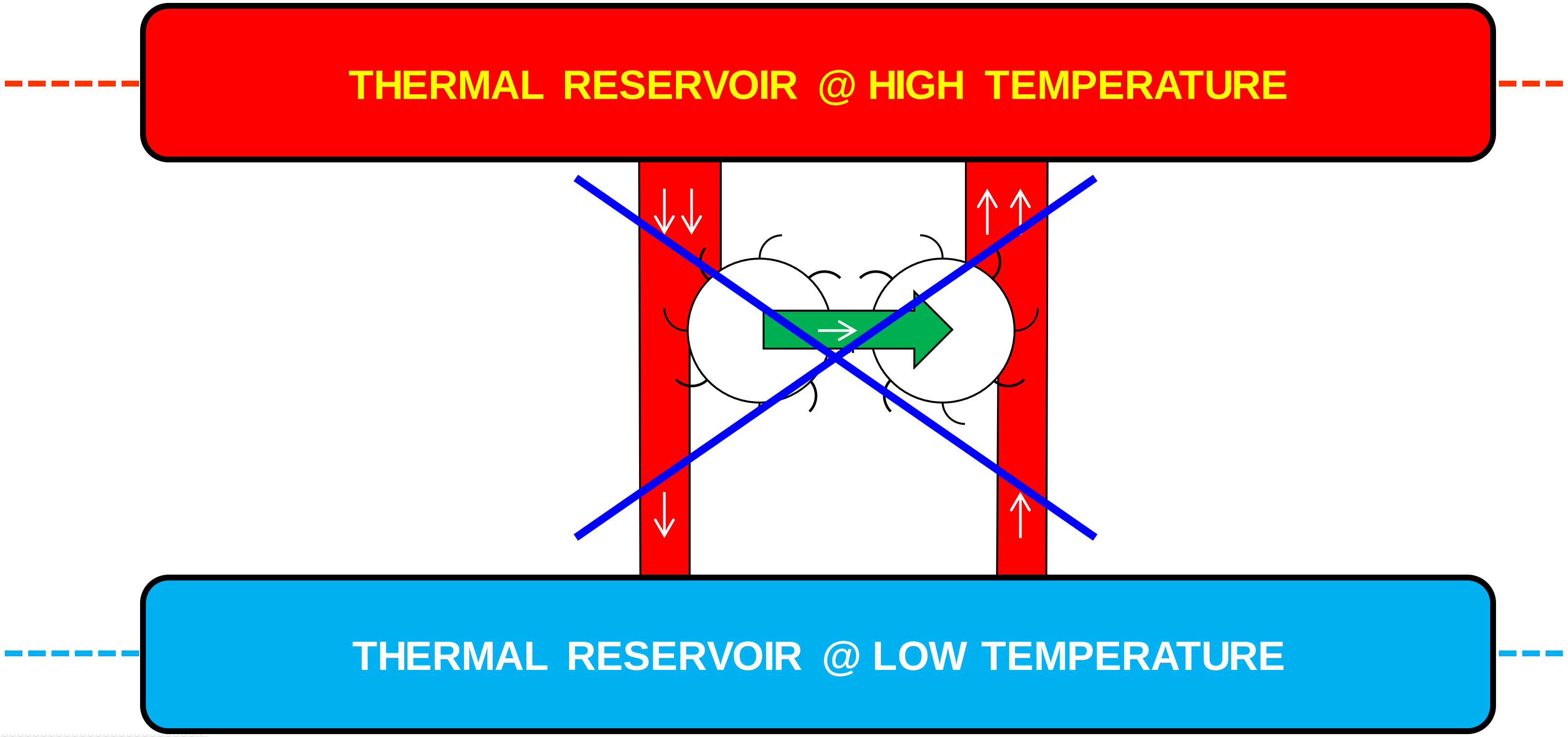
Strict reversibility…



THERMAL RESERVOIR @ HIGH TEMPERATURE

THERMAL RESERVOIR @ LOW TEMPERATURE

Strict reversibility…



THERMAL RESERVOIR @ HIGH TEMPERATURE

THERMAL RESERVOIR @ LOW TEMPERATURE

Strict reversibility...

THERMAL RESERVOIR @ HIGH TEMPERATURE

THERMAL RESERVOIR @ LOW TEMPERATURE

Maximum conversion efficiency:

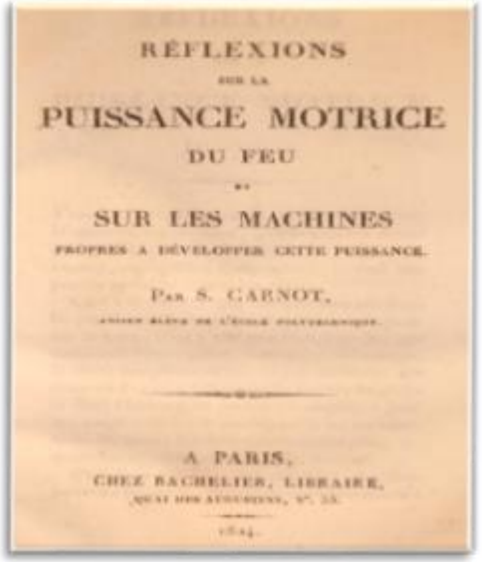
Robert Stirling

- $\eta < 1$ for $\Delta T < \infty$
- $\eta_{rev} > \eta_{irrev}$
- ← $\eta_{rev,m} = \eta_{rev,n} \; \forall \; m,n$
- ← $\eta_{rev} = 1 - T_f / T_q$

$T_f = T_{amb}$

$T_q = T_f + \Delta T$

Nicolas Léonard Sadi Carnot
em 1824, aos 28 anos de idade...



RÉFLEXIONS

PUISSANCE MOTRICE
DU FEU

SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.

PAR S. CARNOT,

A PARIS,
CHEZ BACHELIER, LIBRAIRE,

Maximum conversion efficiency:

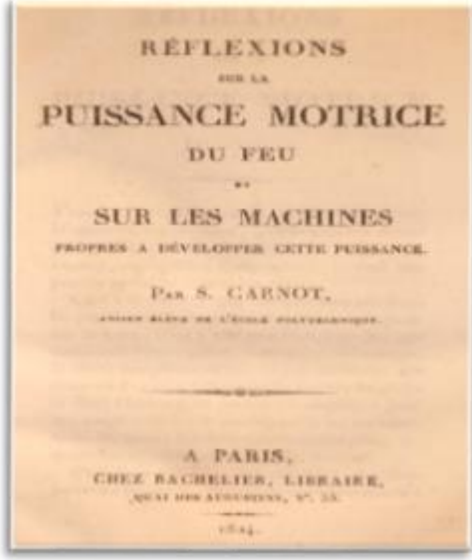
Robert Stirling

- $\eta < 1$ for $\Delta T < \infty$
- $\eta_{rev} > \eta_{irrev}$
- ← $\eta_{rev,m} = \eta_{rev,n} \; \forall \; m,n$
- ← $\eta_{rev} = 1 - T_f / T_q$

It is the temperature difference between the thermal reservoirs that influences the efficiency, and not the pressure as it was commonly accepted…

$$\longrightarrow \quad \eta_{rev} = 1 - \frac{1}{1 + \Delta T / T_{amb}}$$

Nicolas Léonard Sadi Carnot
em 1824, aos 28 anos de idade...



RÉFLEXIONS

PUISSANCE MOTRICE
DU FEU

SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.

Par S. CARNOT,

A PARIS,
CHEZ BACHELIER, LIBRAIRE,

Definition of the Carnot cycle:

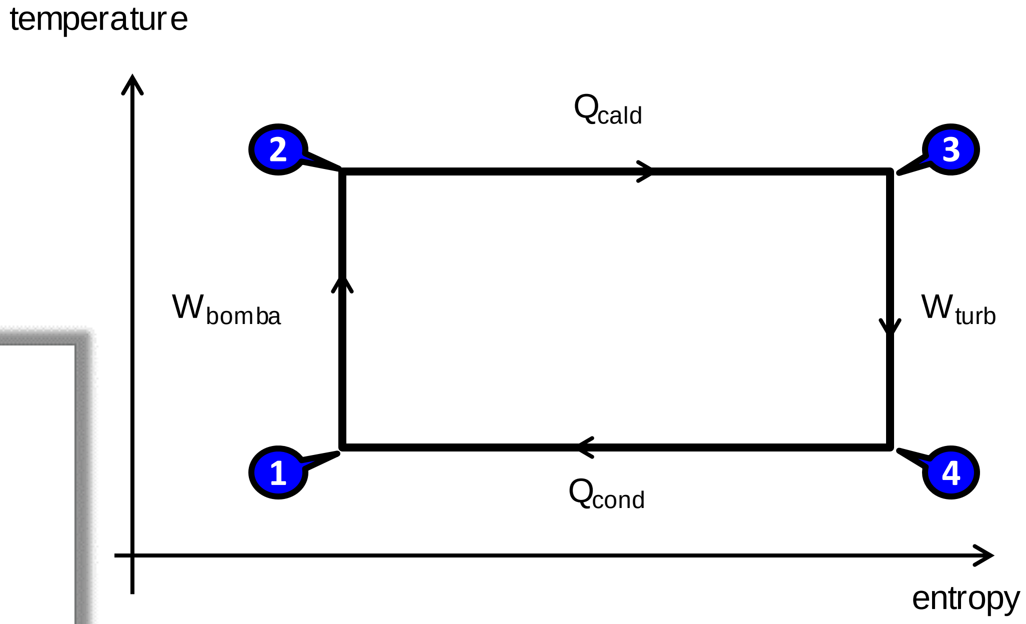
1-2) Isentropic compression (pump)

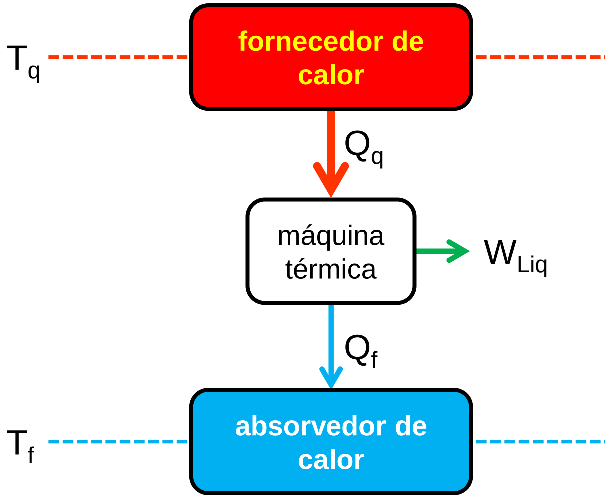
2-3) Isothermal heating (boiler)

3-4) Isentropic expansion (turbine)

4-1) Isothermal cooling (condenser)

Nicolas Léonard Sadi Carnot
em 1824, aos 28 anos de idade...





T_q

fornecedor de calor

Q_q

máquina térmica

W_{Liq}

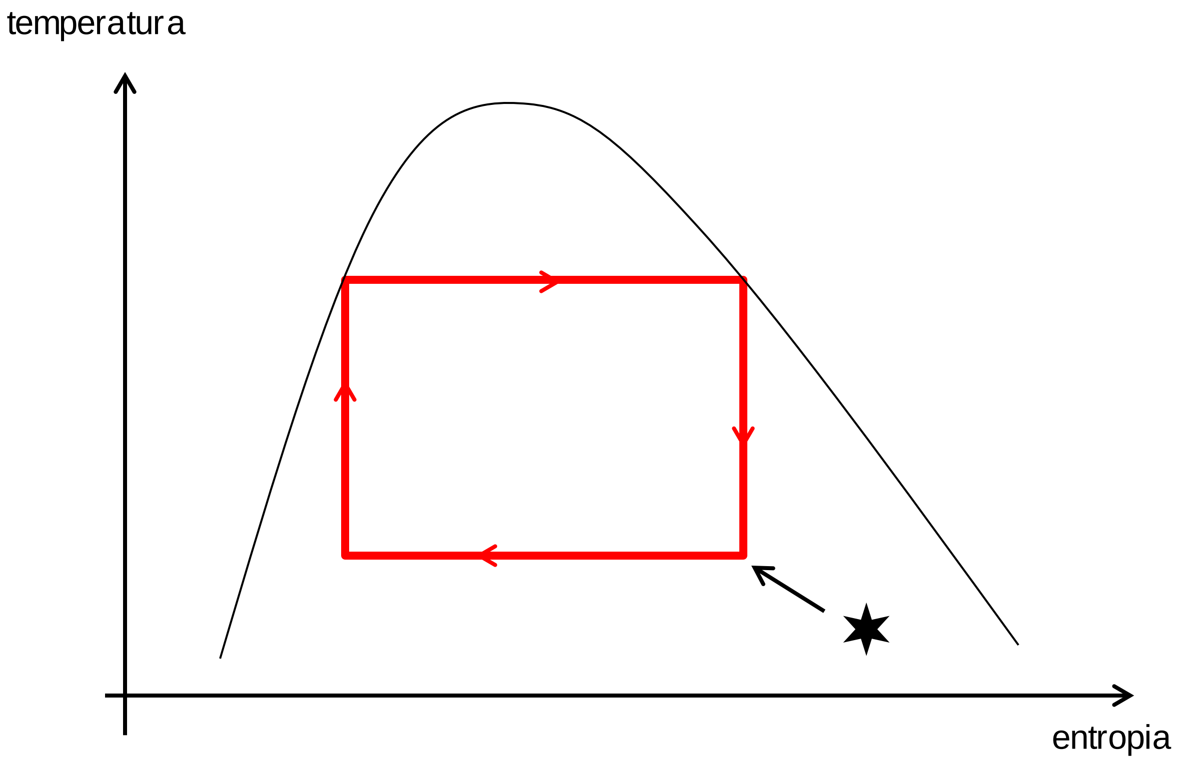
Q_f

T_f

absorvedor de calor

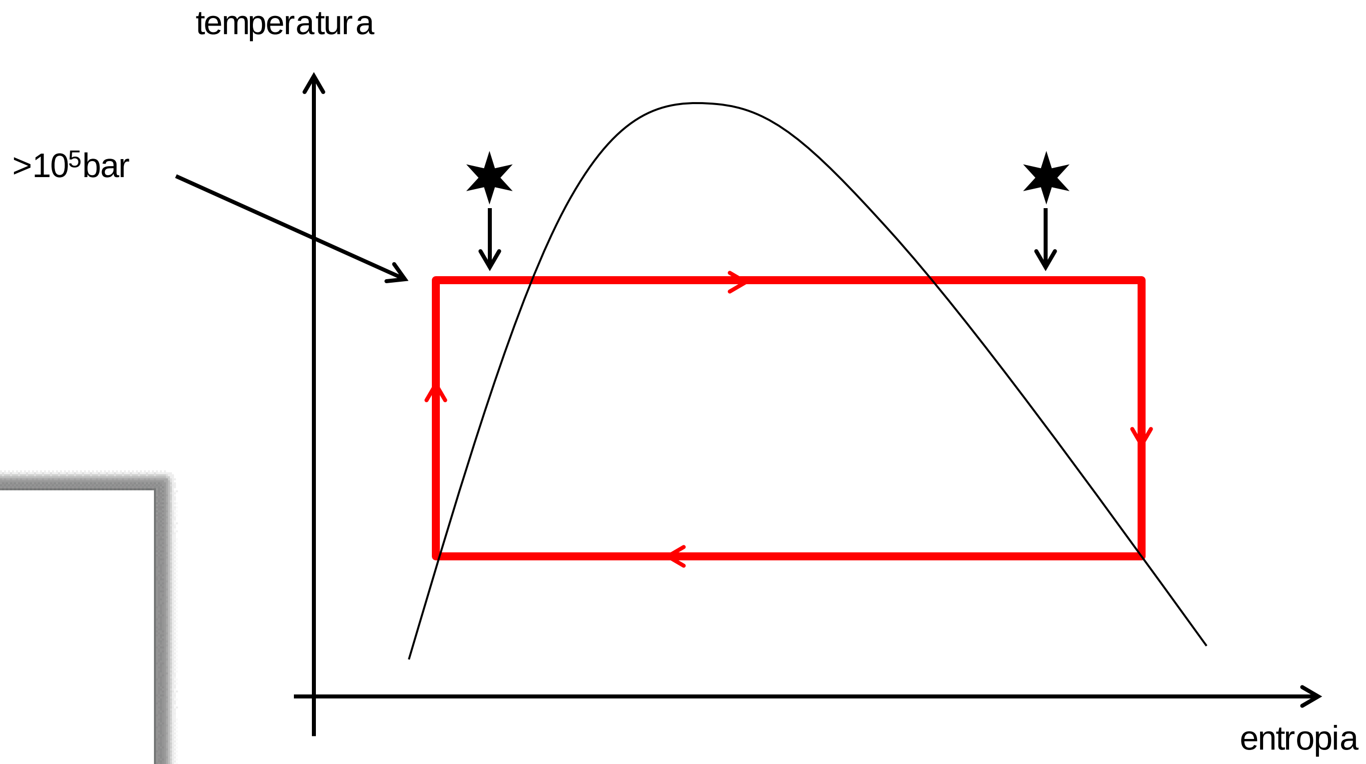
The Carnot cycle: practical realization problems …

- T=cte → impractical for gases
- T=cte → performed in the phase change region
- Turbine blades erosion due to droplets (✶)
- Low pumping hydromechanical efficiency (two-phase flow)



The Carnot cycle: practical realization problems …

- Okay → pump, turbine (x=1) and T=cte @ condenser
- Compressed liquid pressure impossibly high, > 10^5 bar (✶)
- Complicated control of boiler's temperature (✶)



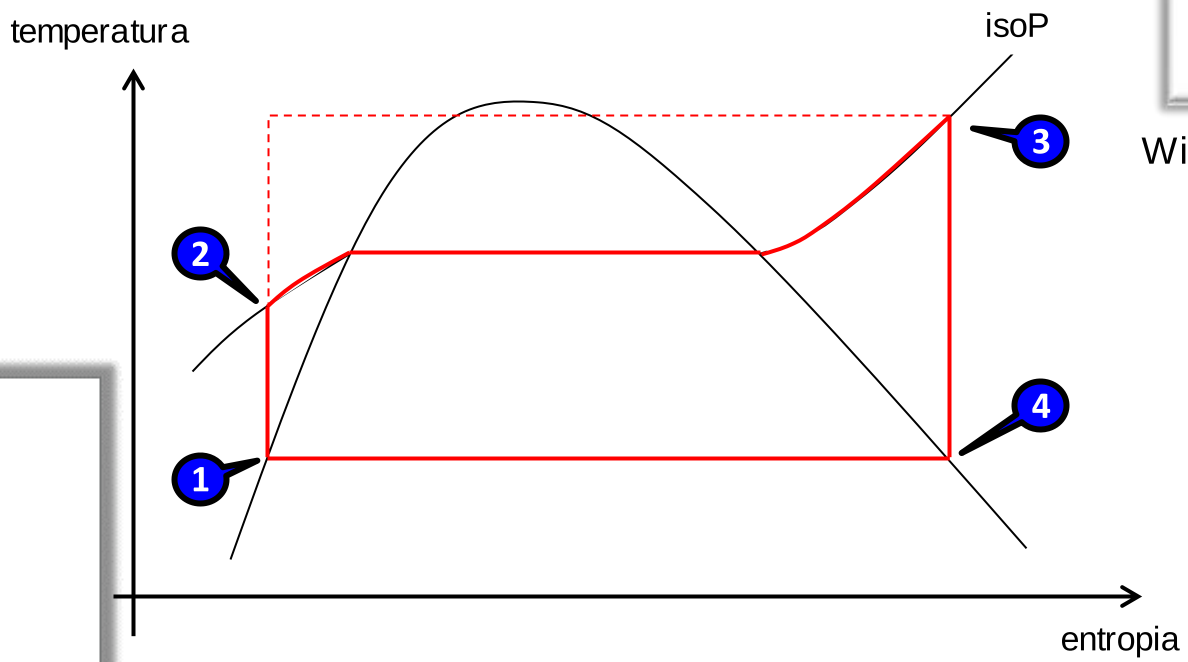
Definition of the Rankine cycle:

1-2) Isentropic compression (pump)

2-3) Isobaric heating (boiler)

3-4) Isentropic expansion (turbine)

4-1) Isothermal cooling (condenser)



William John Macquorn Rankine

University of Glasgow

VIA VERITAS VITA

Application:

Thermodynamic analysis of combined gas-steam cycles

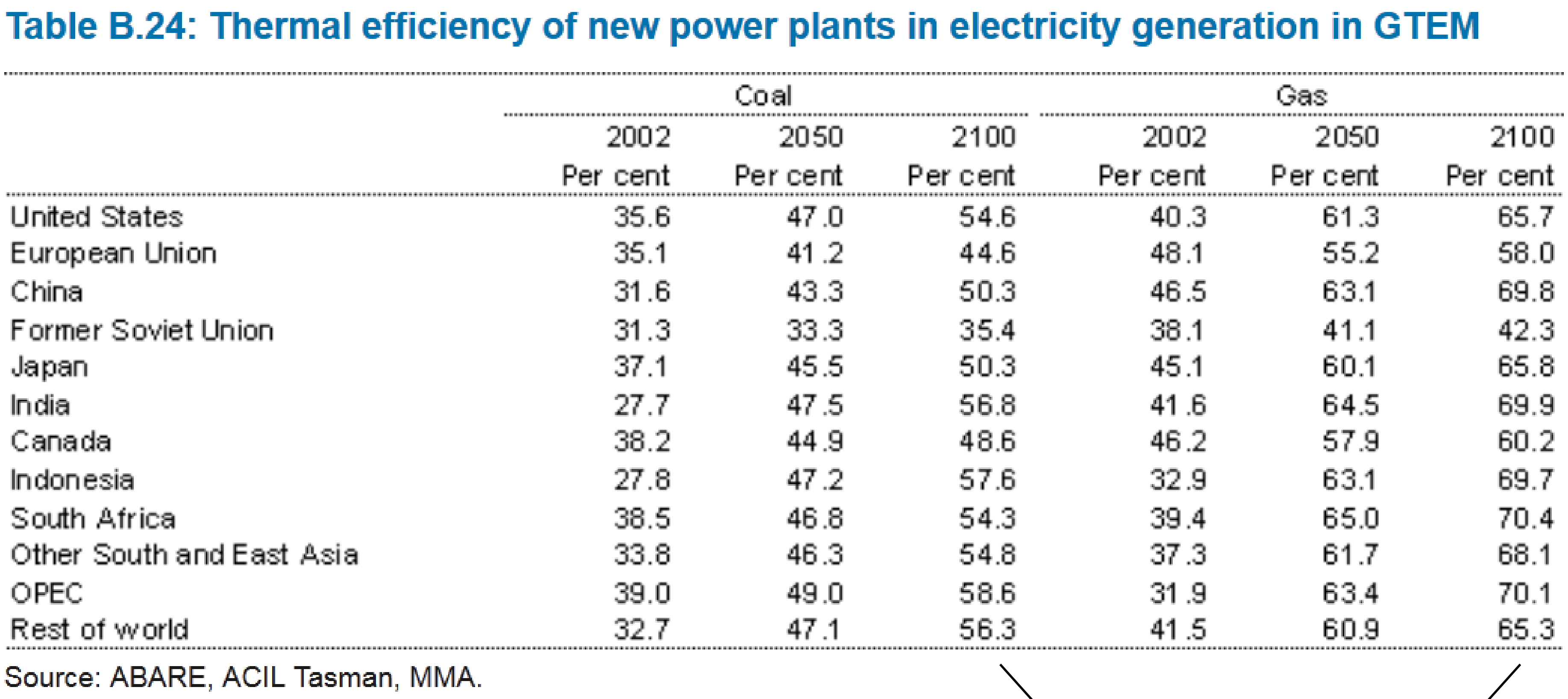


Table B.24: Thermal efficiency of new power plants in electricity generation in GTEM

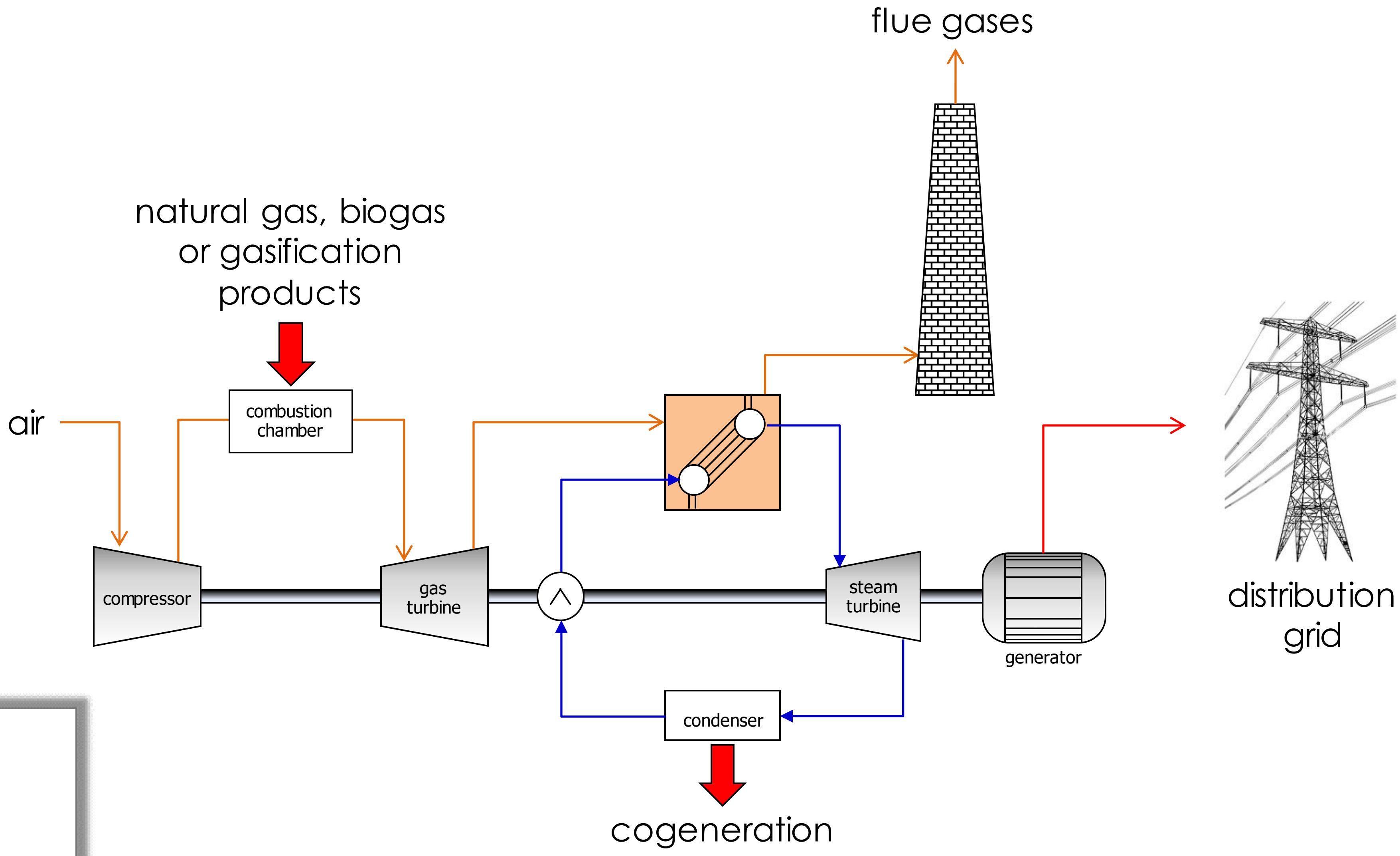
	Coal			Gas		
	2002	2050	2100	2002	2050	2100
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
United States	35.6	47.0	54.6	40.3	61.3	65.7
European Union	35.1	41.2	44.6	48.1	55.2	58.0
China	31.6	43.3	50.3	46.5	63.1	69.8
Former Soviet Union	31.3	33.3	35.4	38.1	41.1	42.3
Japan	37.1	45.5	50.3	45.1	60.1	65.8
India	27.7	47.5	56.8	41.6	64.5	69.9
Canada	38.2	44.9	48.6	46.2	57.9	60.2
Indonesia	27.8	47.2	57.6	32.9	63.1	69.7
South Africa	38.5	46.8	54.3	39.4	65.0	70.4
Other South and East Asia	33.8	46.3	54.8	37.3	61.7	68.1
OPEC	39.0	49.0	58.6	31.9	63.4	70.1
Rest of world	32.7	47.1	56.3	41.5	60.9	65.3

Source: ABARE, ACIL Tasman, MMA.

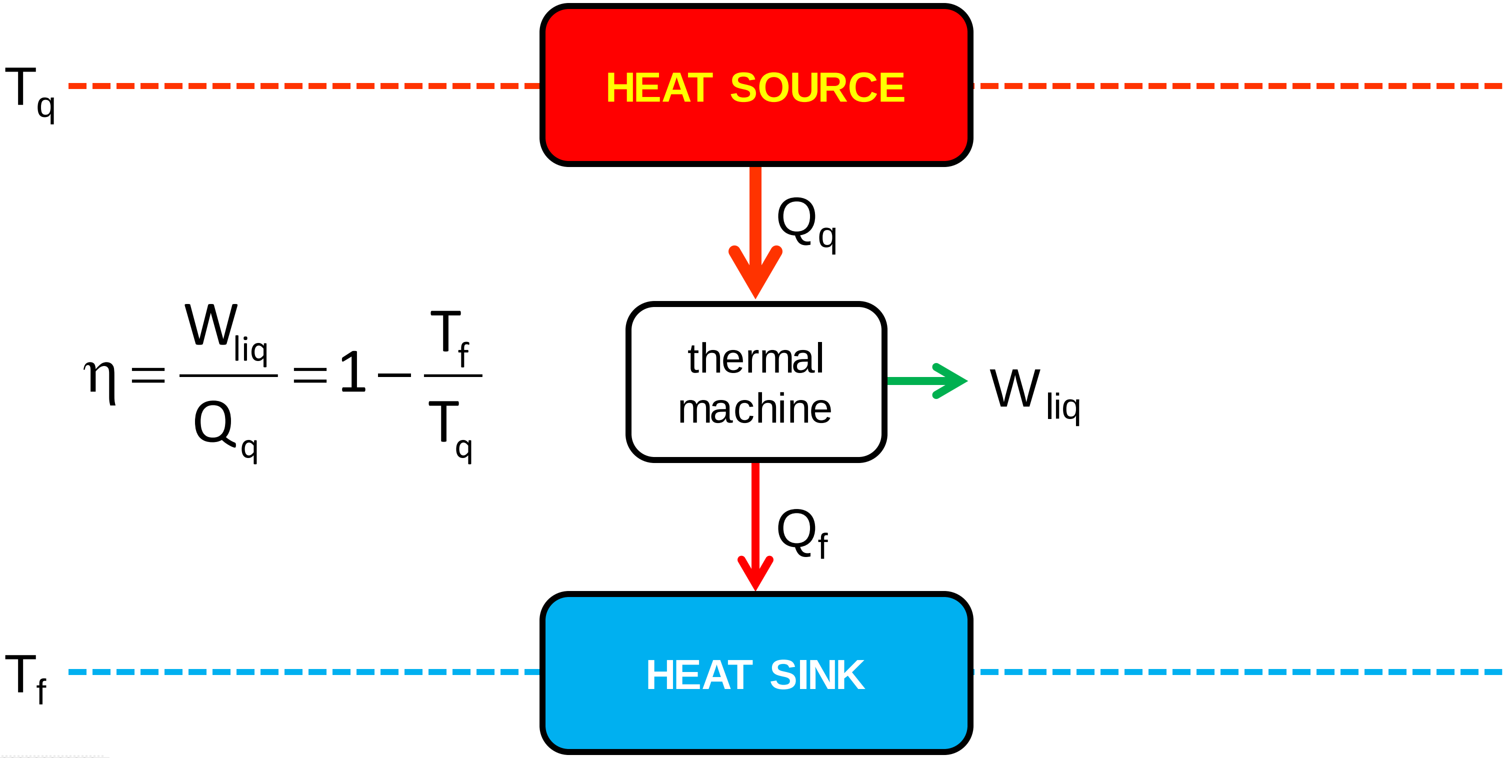
combined gas-steam

Combined cycle: gas-steam (η~60%)

Combined cycle: gas-steam (η~60%)



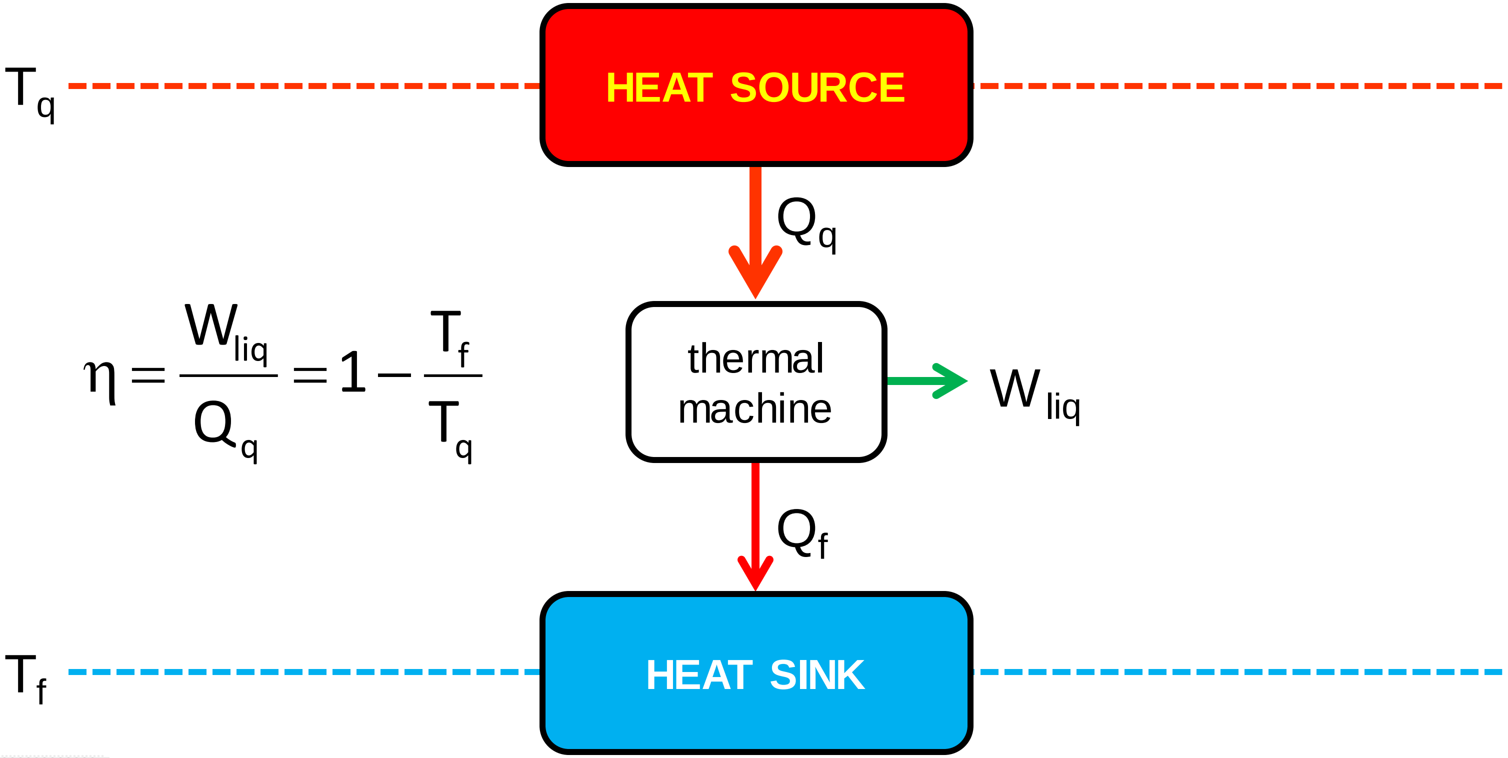
Alternatives to the exploitation of a thermal energy…



$$\eta = \frac{W_{liq}}{Q_q} = 1 - \frac{T_f}{T_q}$$

$$\eta\uparrow \Rightarrow T_f \downarrow \text{ e/ou } T_q \uparrow$$

Alternatives to the exploitation of a thermal energy...



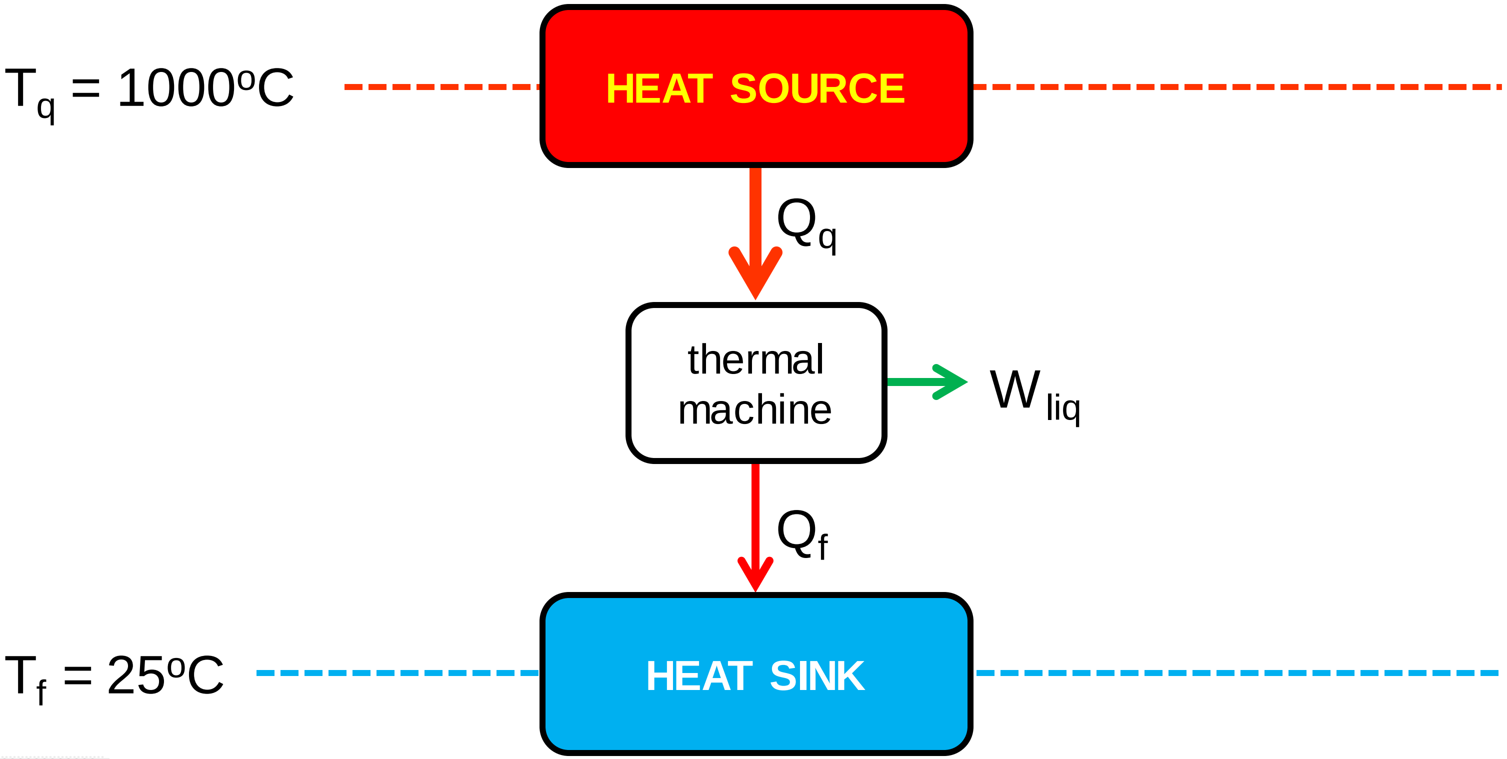
$$\eta = \frac{W_{liq}}{Q_q} = 1 - \frac{T_f}{T_q}$$

$$\eta\uparrow \Rightarrow \cancel{T_f\downarrow} \text{ e/ou } \boxed{T_q\uparrow}$$

ambiente

limites do material

Alternatives to the exploitation of a thermal energy…



T_q = 1000ºC

HEAT SOURCE

Q_q

thermal machine

W_{liq}

Q_f

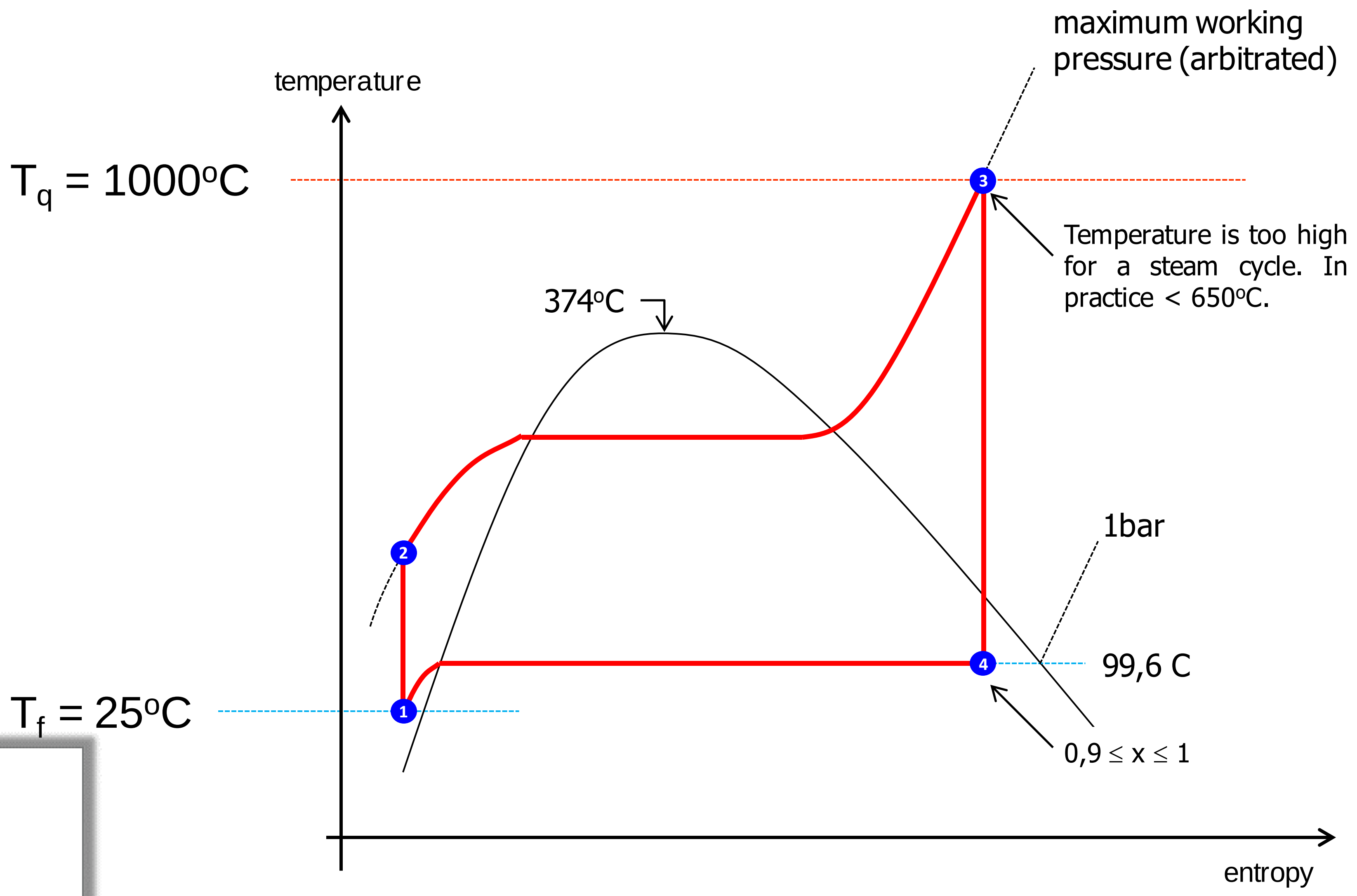
HEAT SINK

T_f = 25ºC

$$\eta_{Carnot} = 1 - \frac{25+273}{1000+273} = 0,766 \longrightarrow$$

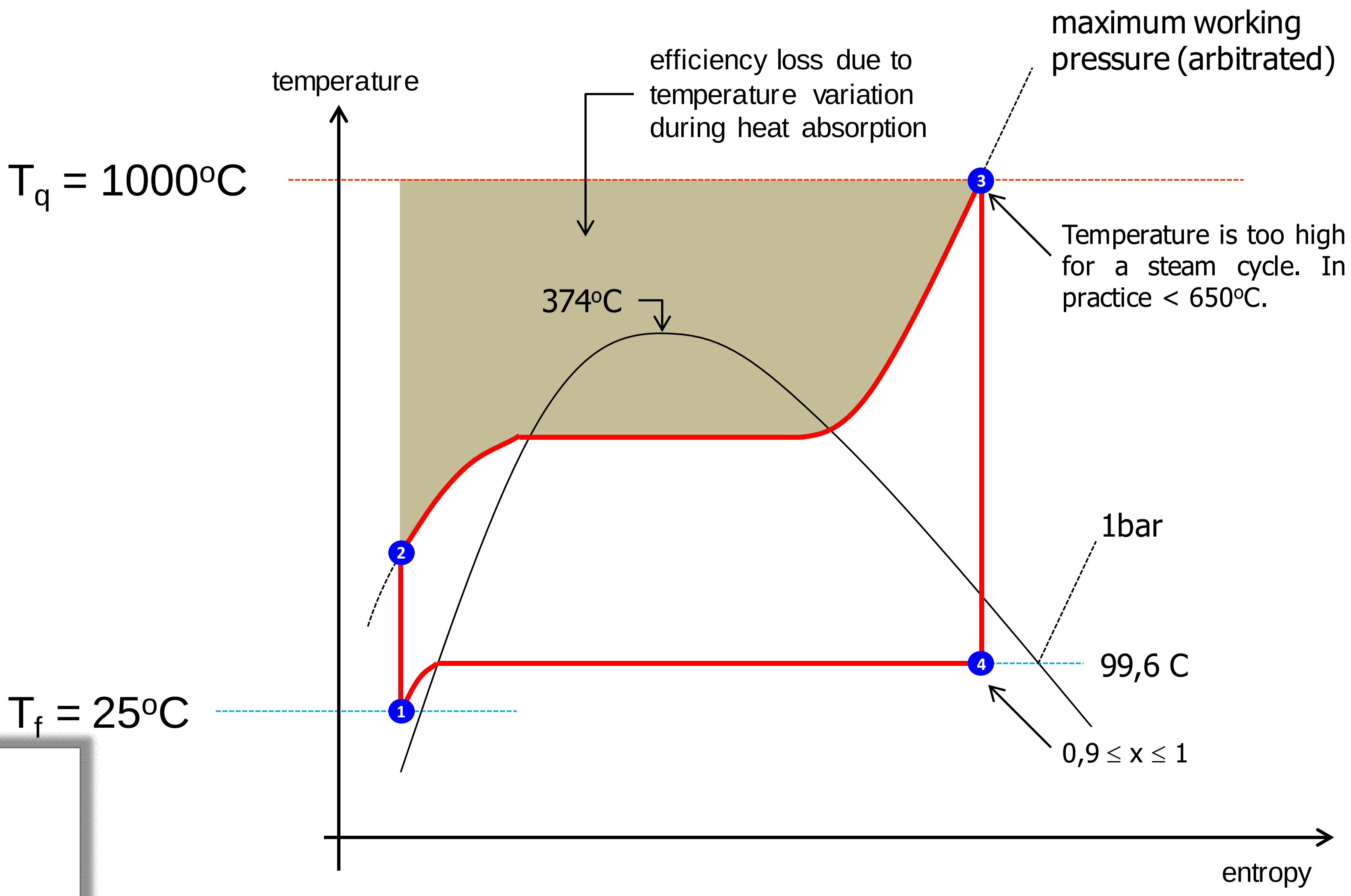
maximum (possible) thermodynamic efficiency

Alternatives to the exploitation of a thermal energy: Rankine (water)



Temperature is too high for a steam cycle. In practice < 650^oC.

Alternatives to the exploitation of a thermal energy: Rankine (water)

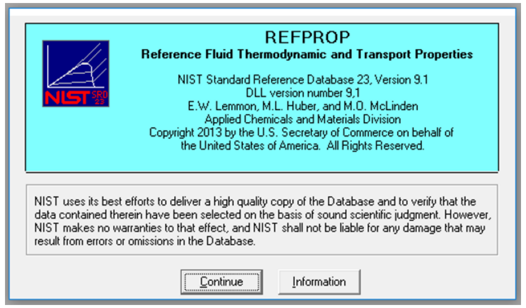


maximum working pressure (arbitrated)

efficiency loss due to temperature variation during heat absorption

Temperature is too high for a steam cycle. In practice < 650ºC.

$0{,}9 \le x \le 1$



REFPROP

Reference Fluid Thermodynamic and Transport Properties

NIST Standard Reference Database 23, Version 9.1
DLL version number 9,1
E.W. Lemmon, M.L. Huber, and M.O. McLinden
Applied Chemicals and Materials Division
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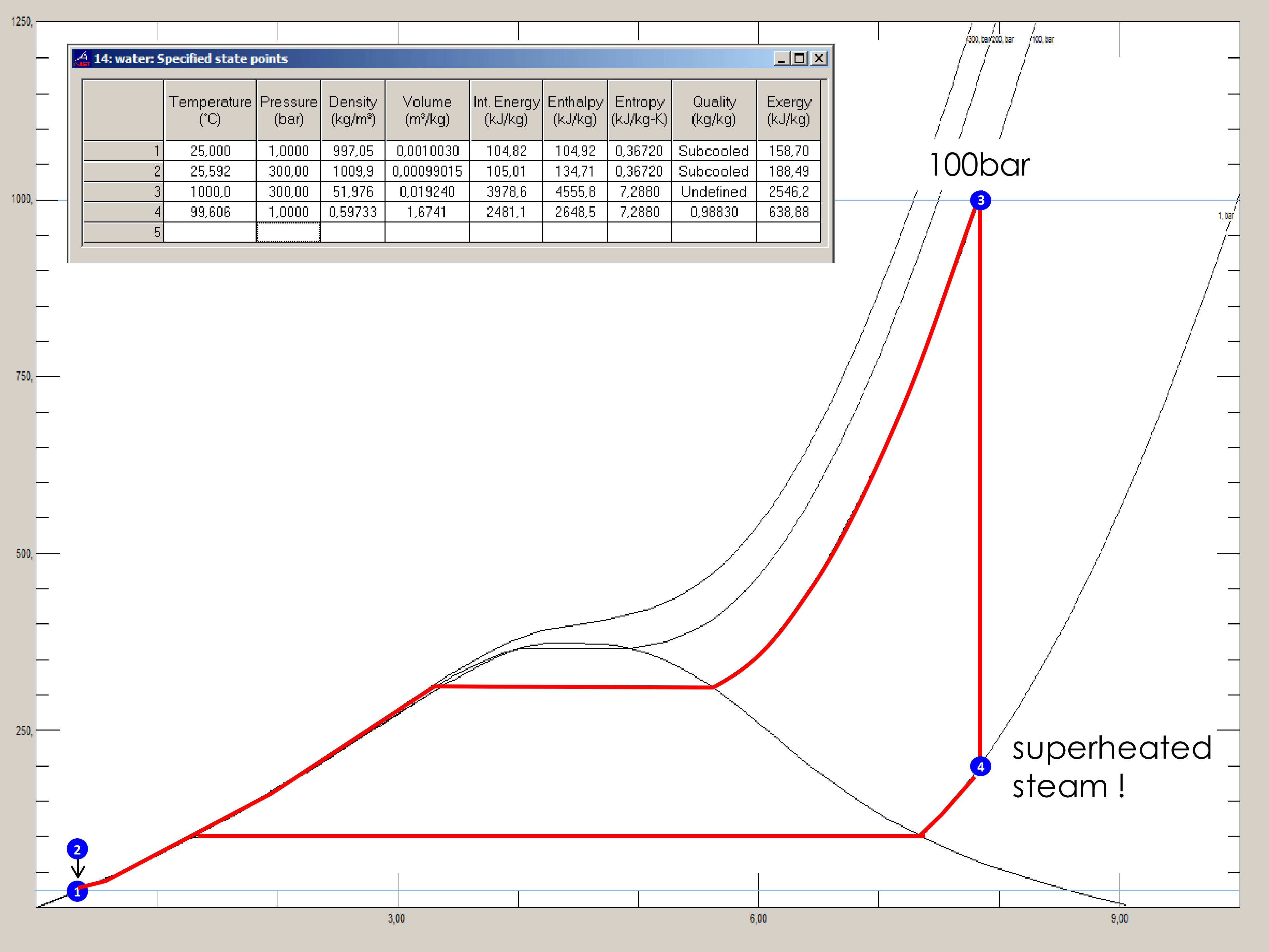
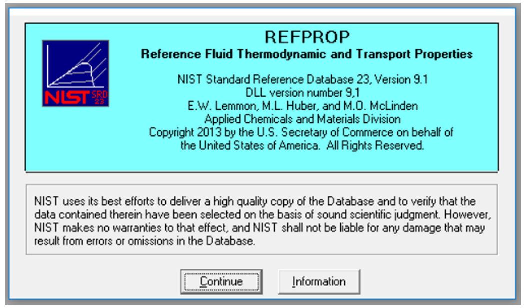


14: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Volume (m³/kg)	Int. Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality (kg/kg)	Exergy (kJ/kg)
1	25,000	1,0000	997,05	0,0010030	104,82	104,92	0,36720	Subcooled	158,70
2	25,592	300,00	1009,9	0,00099015	105,01	134,71	0,36720	Subcooled	188,49
3	1000,0	300,00	51,976	0,019240	3978,6	4555,8	7,2880	Undefined	2546,2
4	99,606	1,0000	0,59733	1,6741	2481,1	2648,5	7,2880	0,98830	638,88
5									

100bar

superheated steam !



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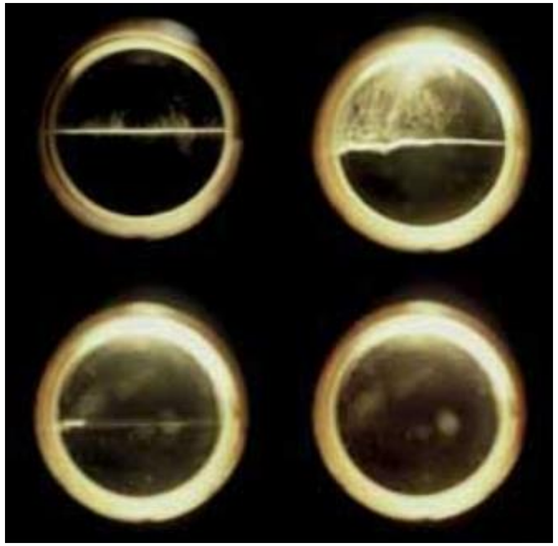
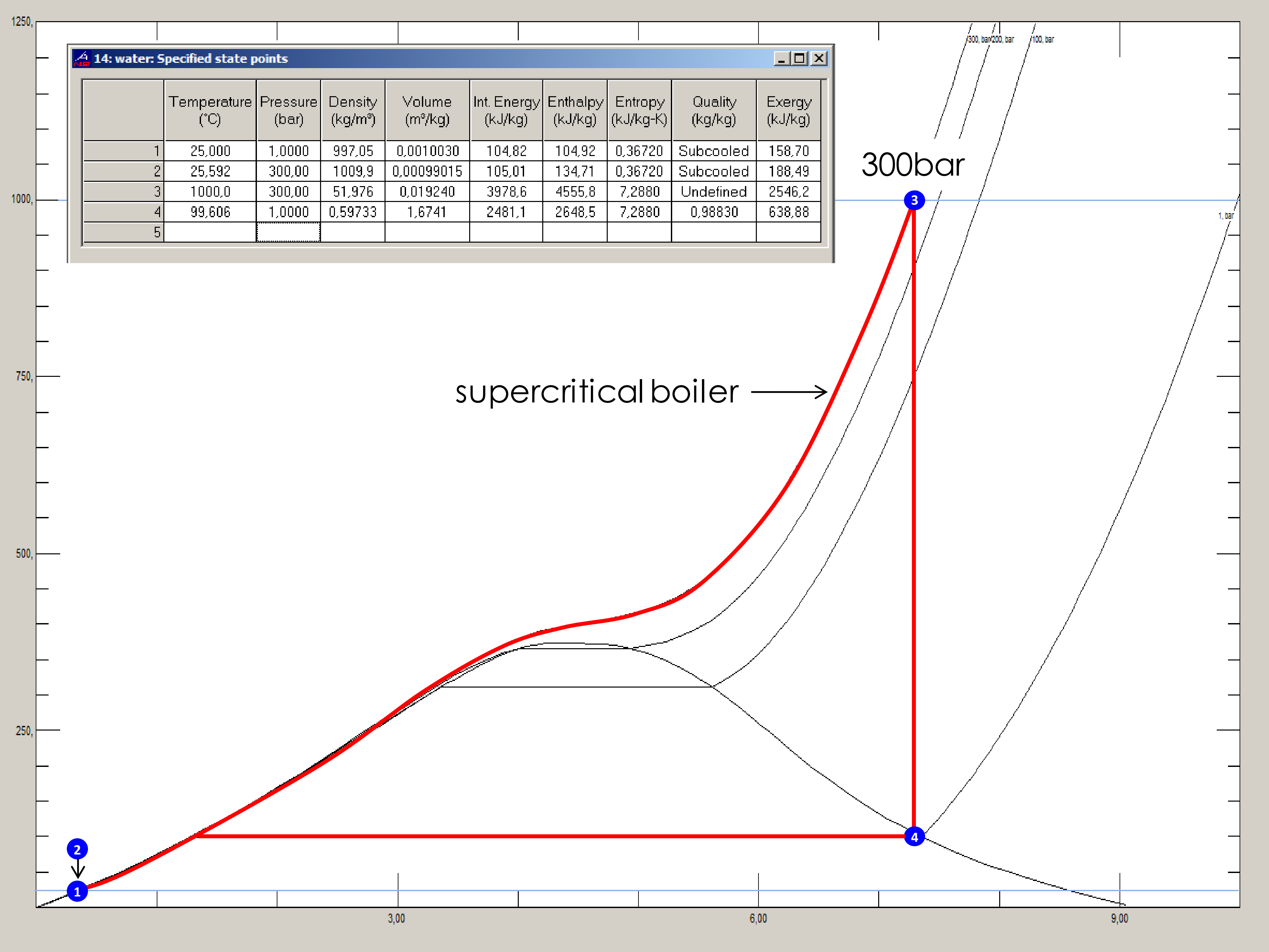


$$\rho_{liq} \equiv \rho_{gas}$$



14: water: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Volume (m³/kg)	Int. Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality (kg/kg)	Exergy (kJ/kg)
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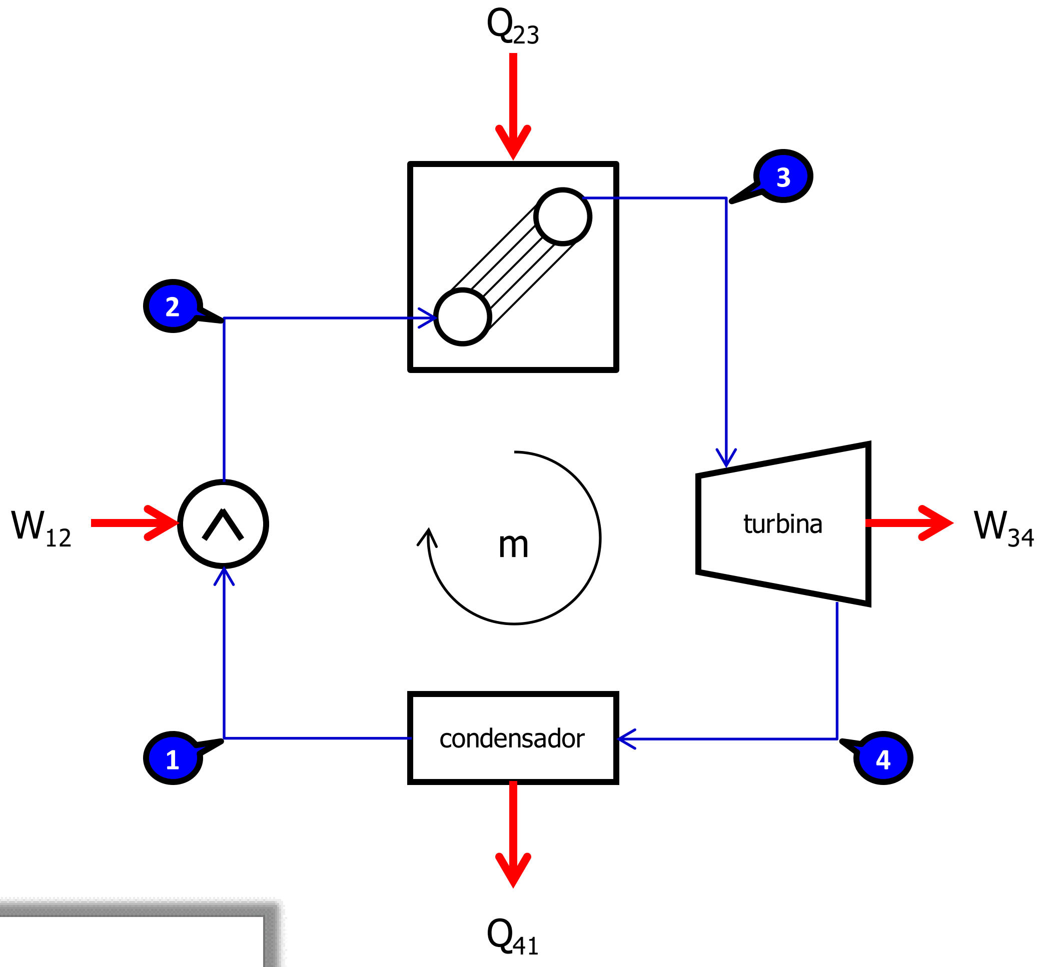
2	25,592	300,00	1009,9	0,00099015	105,01	134,71	0,36720	Subcooled	188,49
3	1000,0	300,00	51,976	0,019240	3978,6	4555,8	7,2880	Undefined	2546,2
4	99,606	1,0000	0,59733	1,6741	2481,1	2648,5	7,2880	0,98830	638,88
5									

300bar

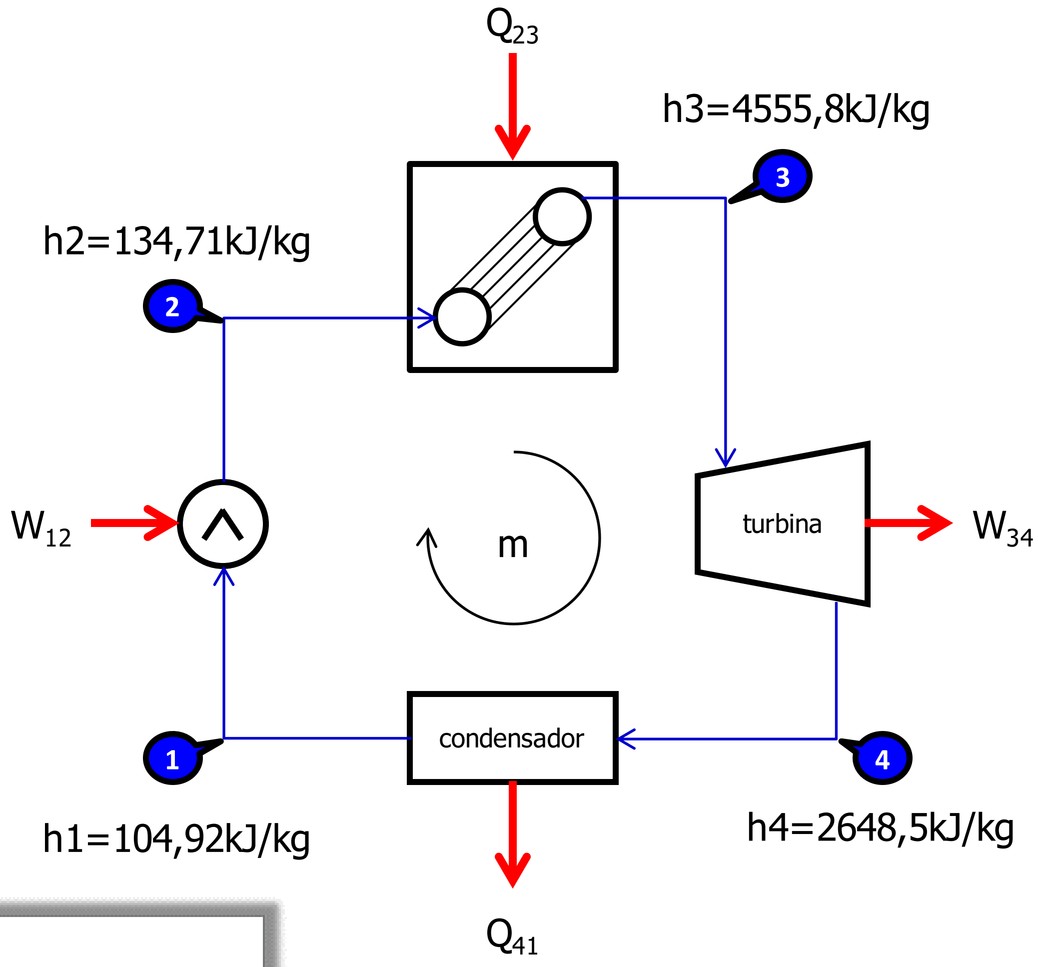
supercritical boiler →

Alternatives to the exploitation of a thermal energy: Rankine (water)



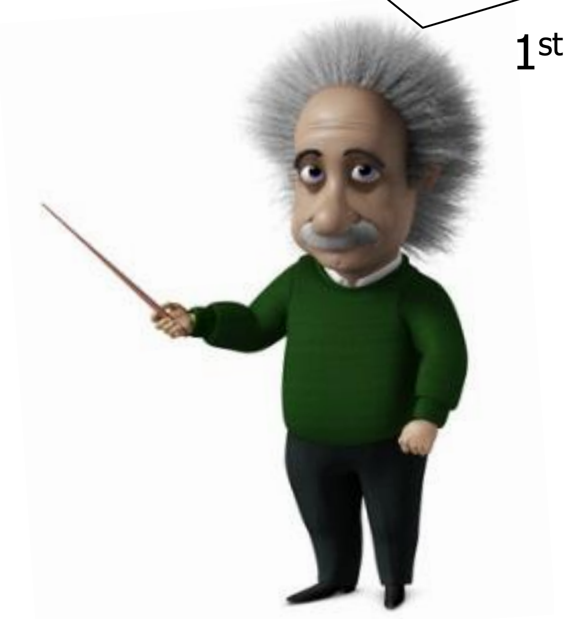
$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Rankine (water)



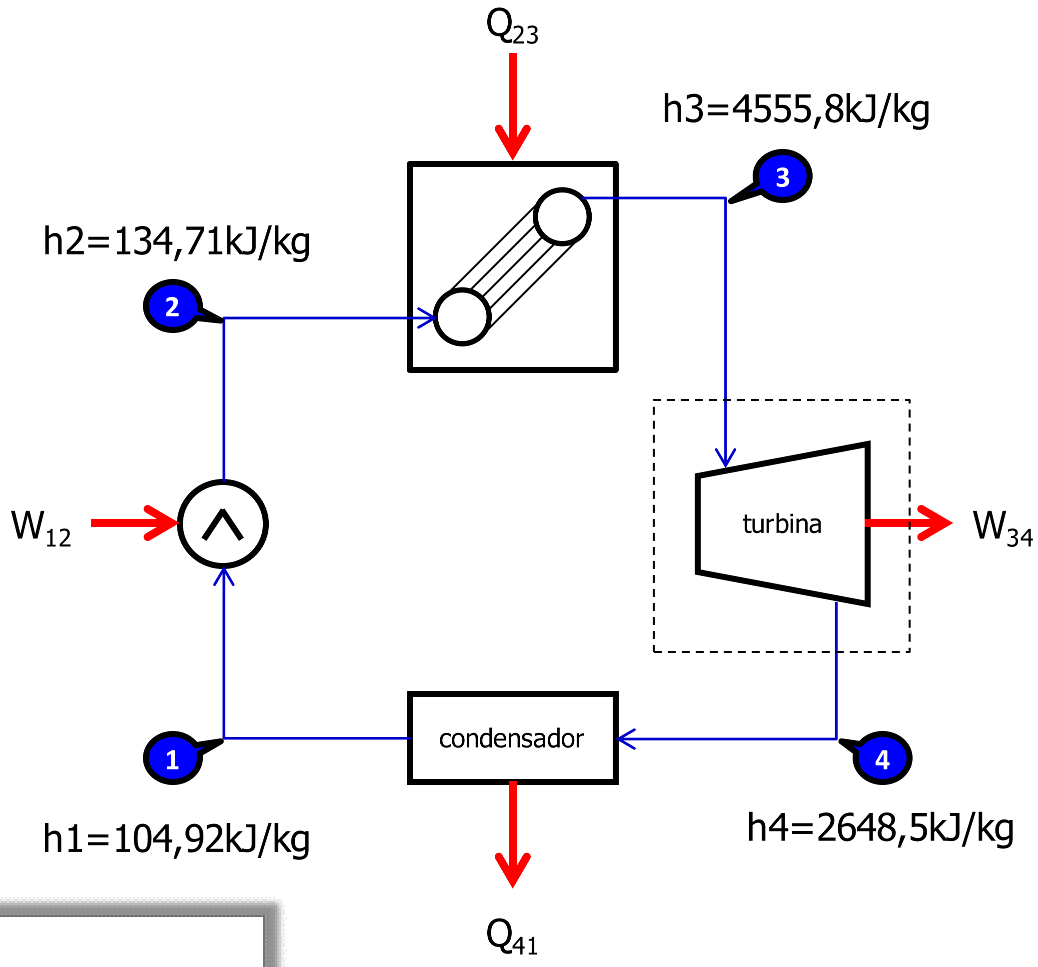
$$\dot{Q}-\dot{W}=\sum_{\text{sai}}\dot{m}_k\theta_k-\sum_{\text{entra}}\dot{m}_k\theta_k$$

1st law



$$\eta=\frac{W_{liq}}{Q_q}=\frac{W_{34}-W_{12}}{Q_{23}}=\frac{w_{34}-w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Rankine (water)

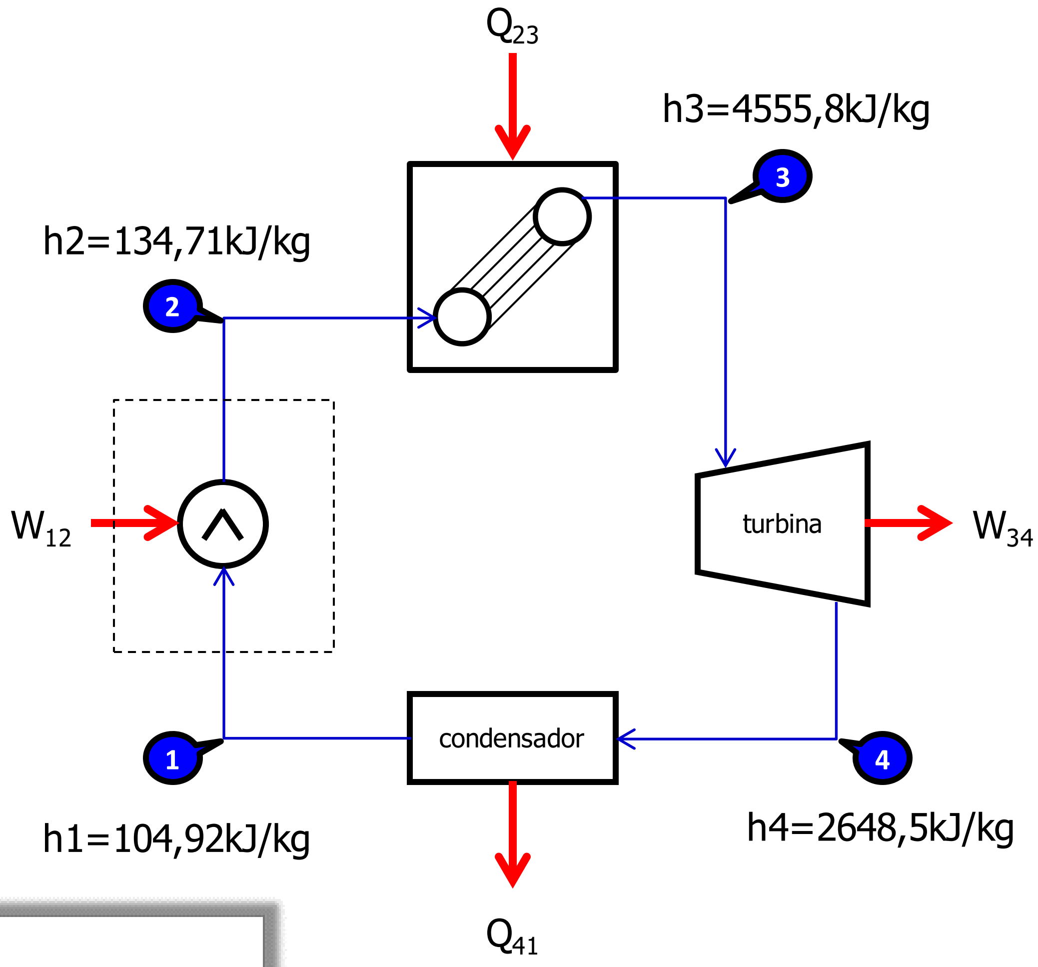


$$Q - W_{34} = m \cdot (h_4 - h_3)$$

$$W_{34} / m = w_{34} = h_3 - h_4$$

$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Rankine (water)



$$Q - W_{34} = m \cdot (h_4 - h_3)$$

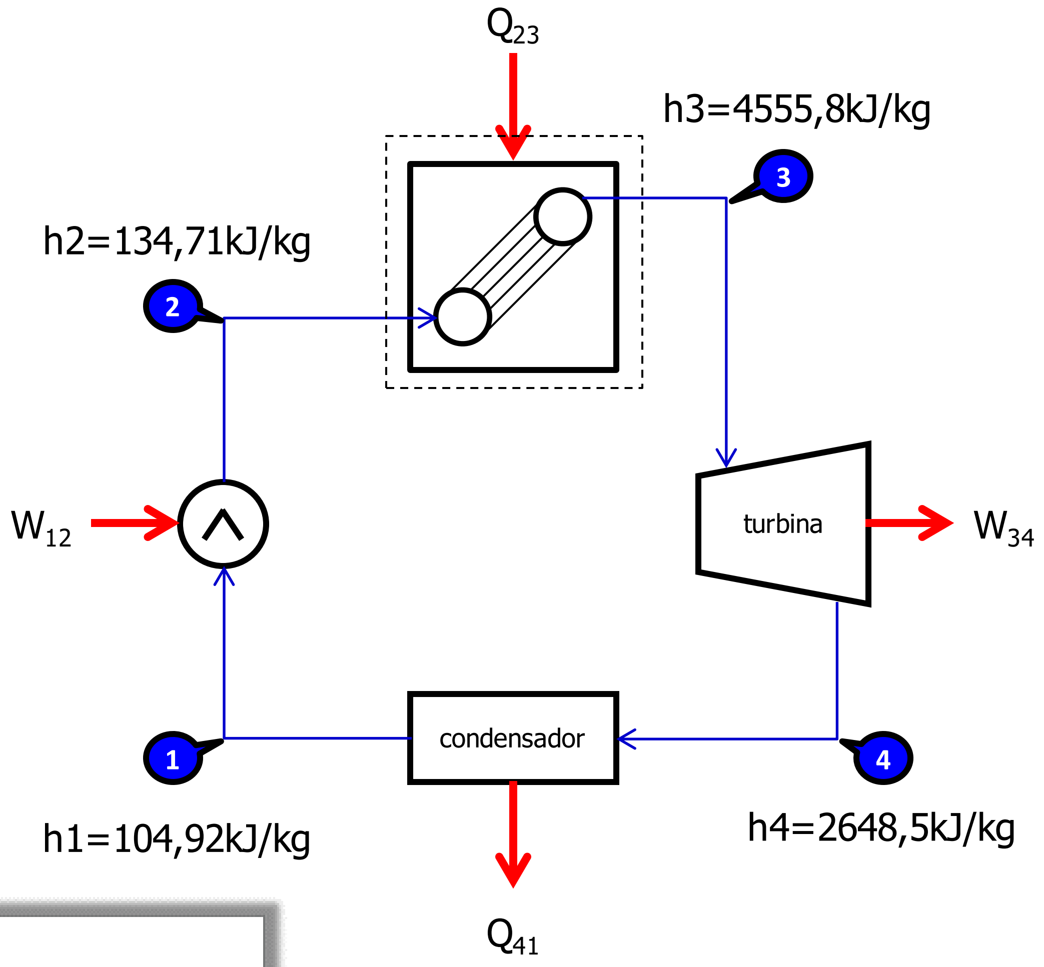
$$W_{34} / m = w_{34} = h_3 - h_4$$

$$Q - W_{12} = m \cdot (h_2 - h_1)$$

$$W_{12} / m = w_{12} = h_1 - h_2$$

$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Rankine (water)



$$Q - W_{34} = m \cdot (h_4 - h_3)$$

$$W_{34} / m = w_{34} = h_3 - h_4$$

$$Q - W_{12} = m \cdot (h_2 - h_1)$$

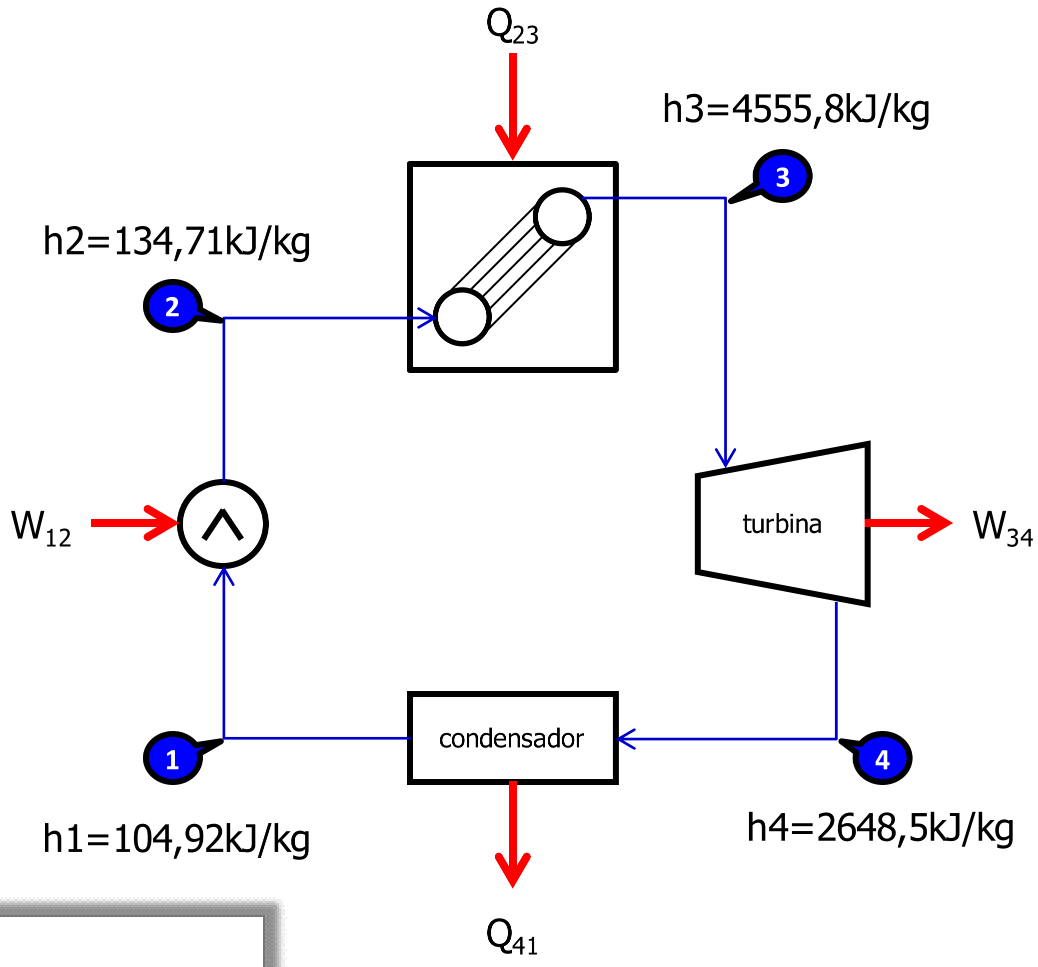
$$W_{12} / m = w_{12} = h_1 - h_2$$

$$Q_{23} - W = m \cdot (h_3 - h_2)$$

$$Q_{23} / m = q_{23} = h_3 - h_2$$

$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Rankine (water)



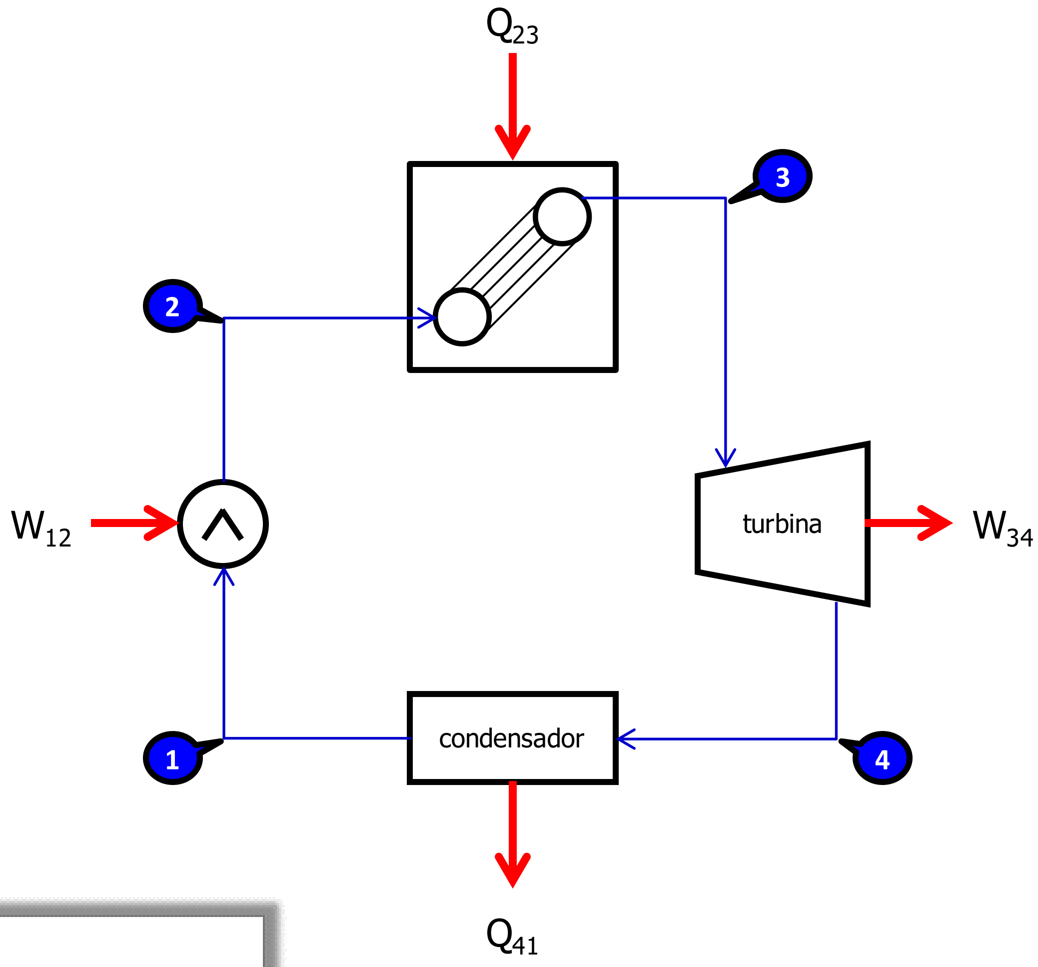
$$w_{34} = +1907{,}3\text{kJ/kg}$$

$$w_{12} = -29{,}79\text{kJ/kg}$$

$$q_{23} = +4421{,}1\text{kJ/kg}$$

$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Rankine (water)



$$w_{34} = +1907{,}3\,kJ/kg$$

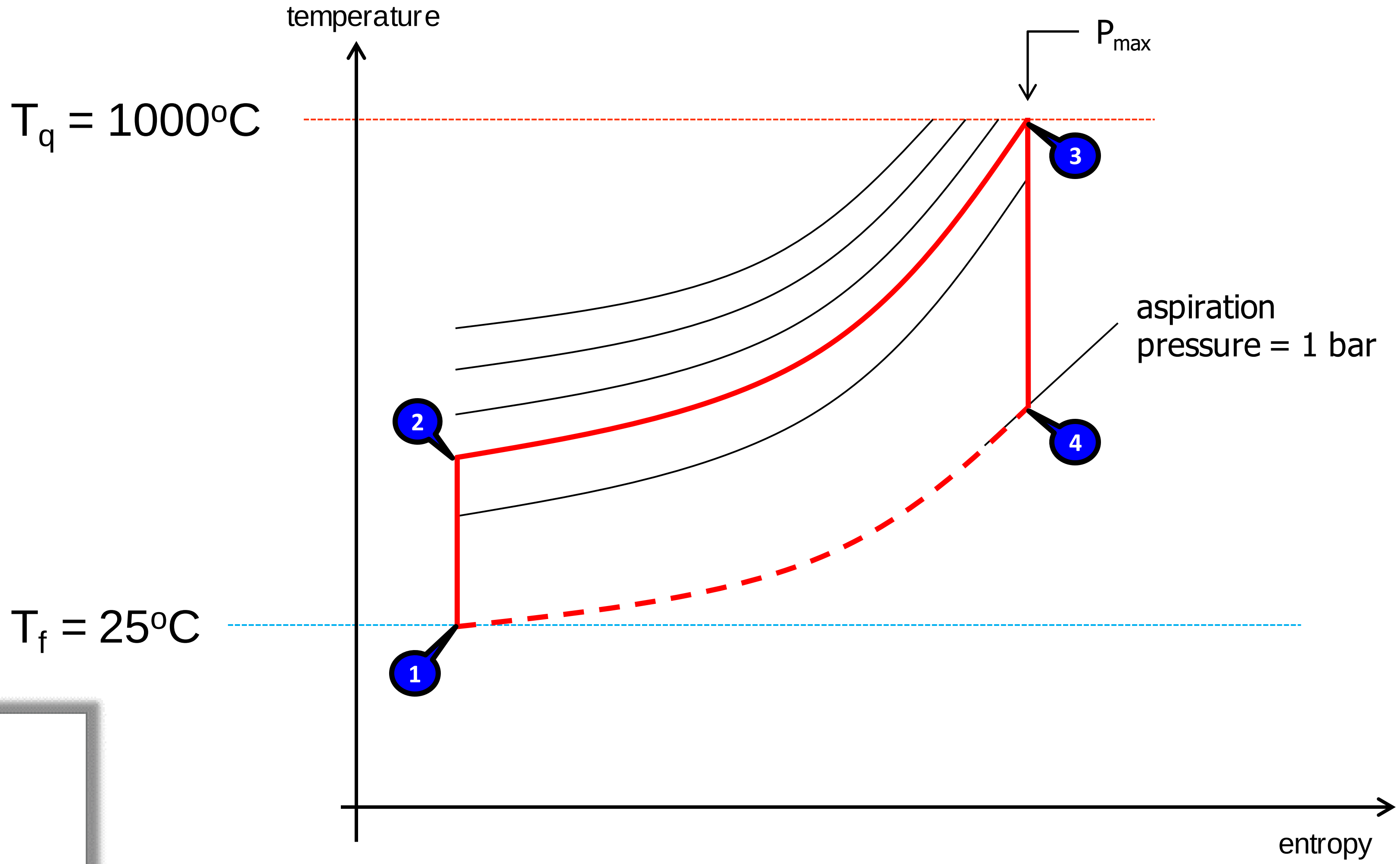
$$w_{12} = -29{,}79\,kJ/kg$$

$$q_{23} = +4421{,}1\,kJ/kg$$

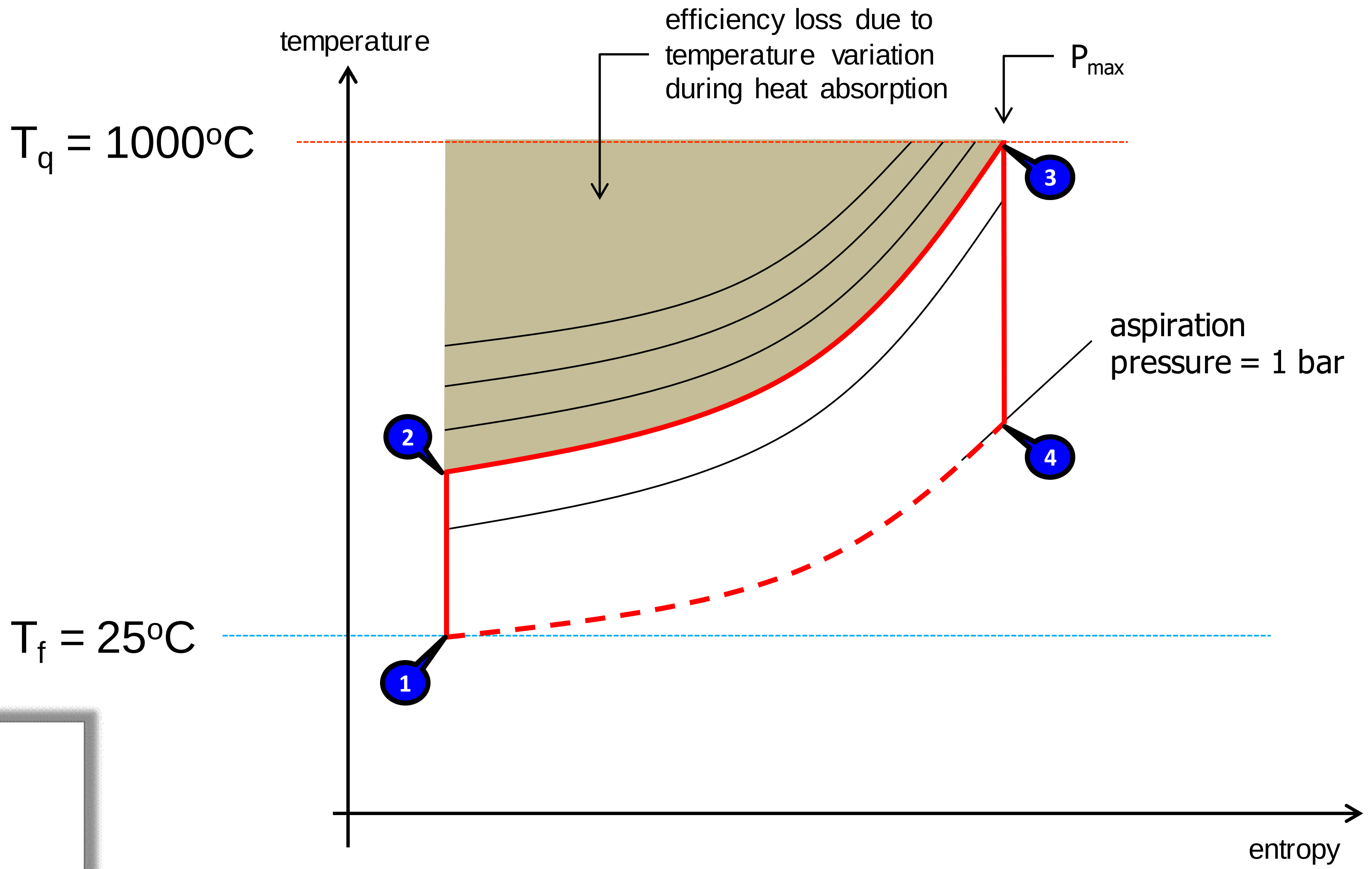
$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}} = \frac{+1907{,}3 - 29{,}79}{+4421{,}1} = 0{,}425$$

$$0{,}766 = \eta_C$$

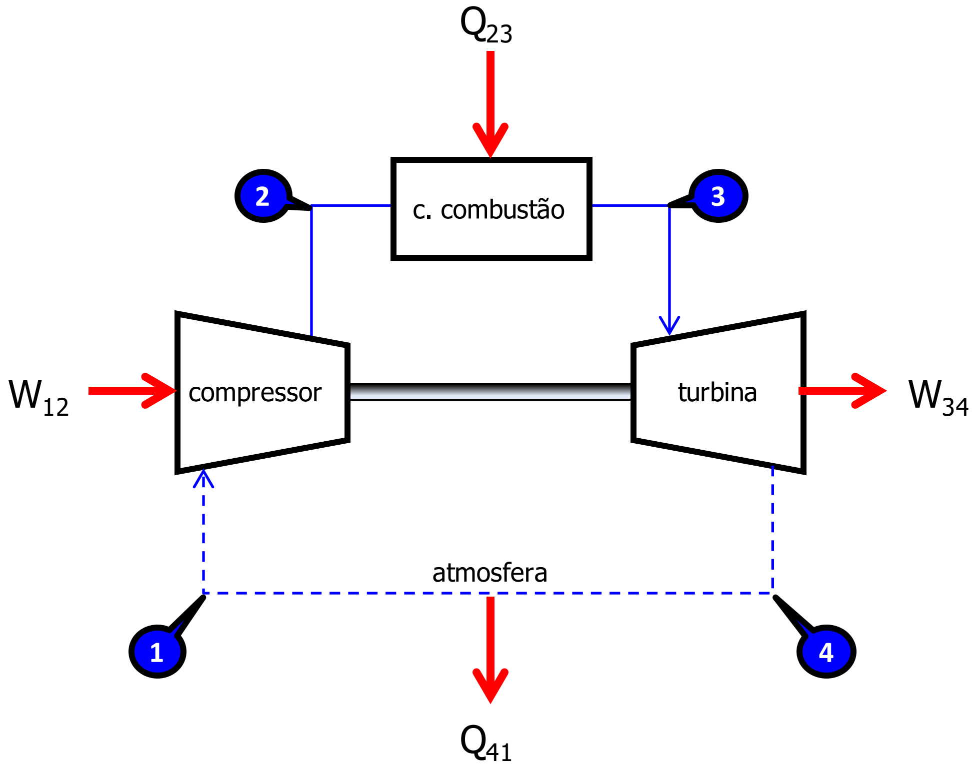
Alternatives to the exploitation of a thermal energy: Brayton (air)



Alternatives to the exploitation of a thermal energy: Brayton (air)

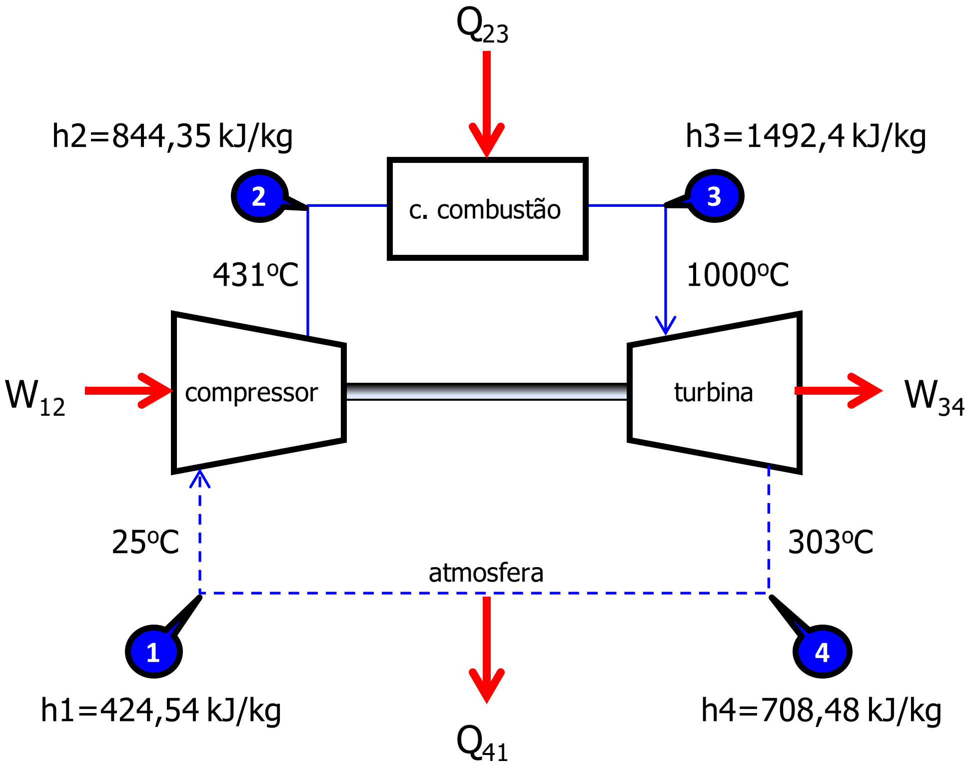


Alternatives to the exploitation of a thermal energy: Brayton (air)



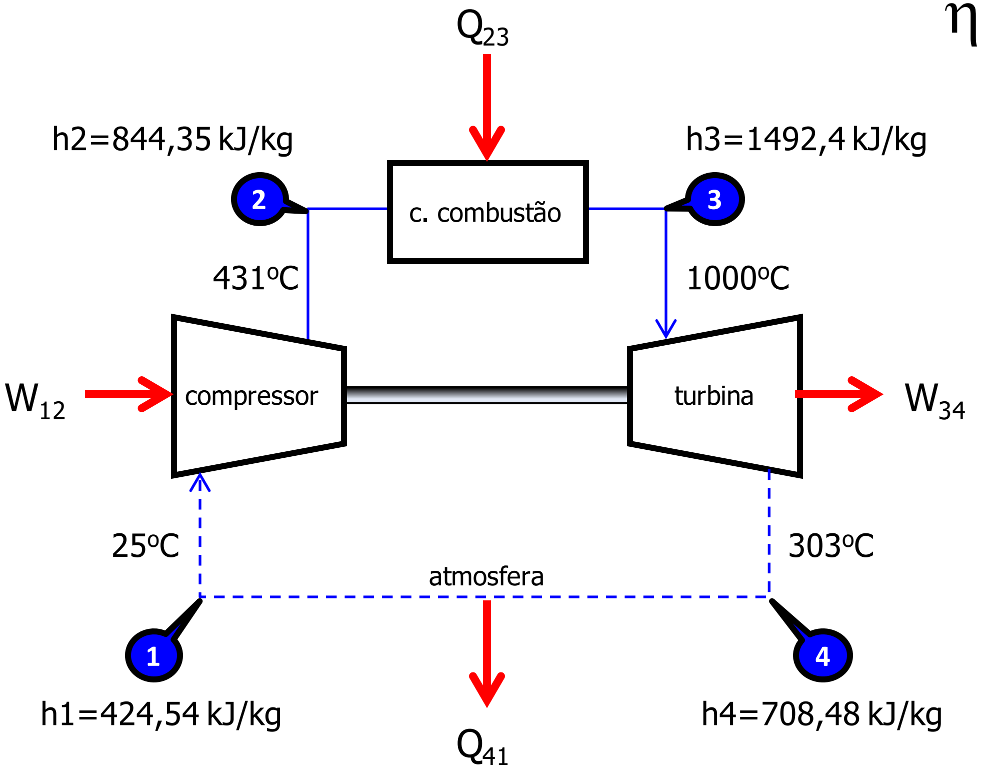
$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Brayton (air)



$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

Alternatives to the exploitation of a thermal energy: Brayton (air)



$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}}$$

$$w_{34} = h_3 - h_4 = +783{,}92\text{kJ/kg}$$

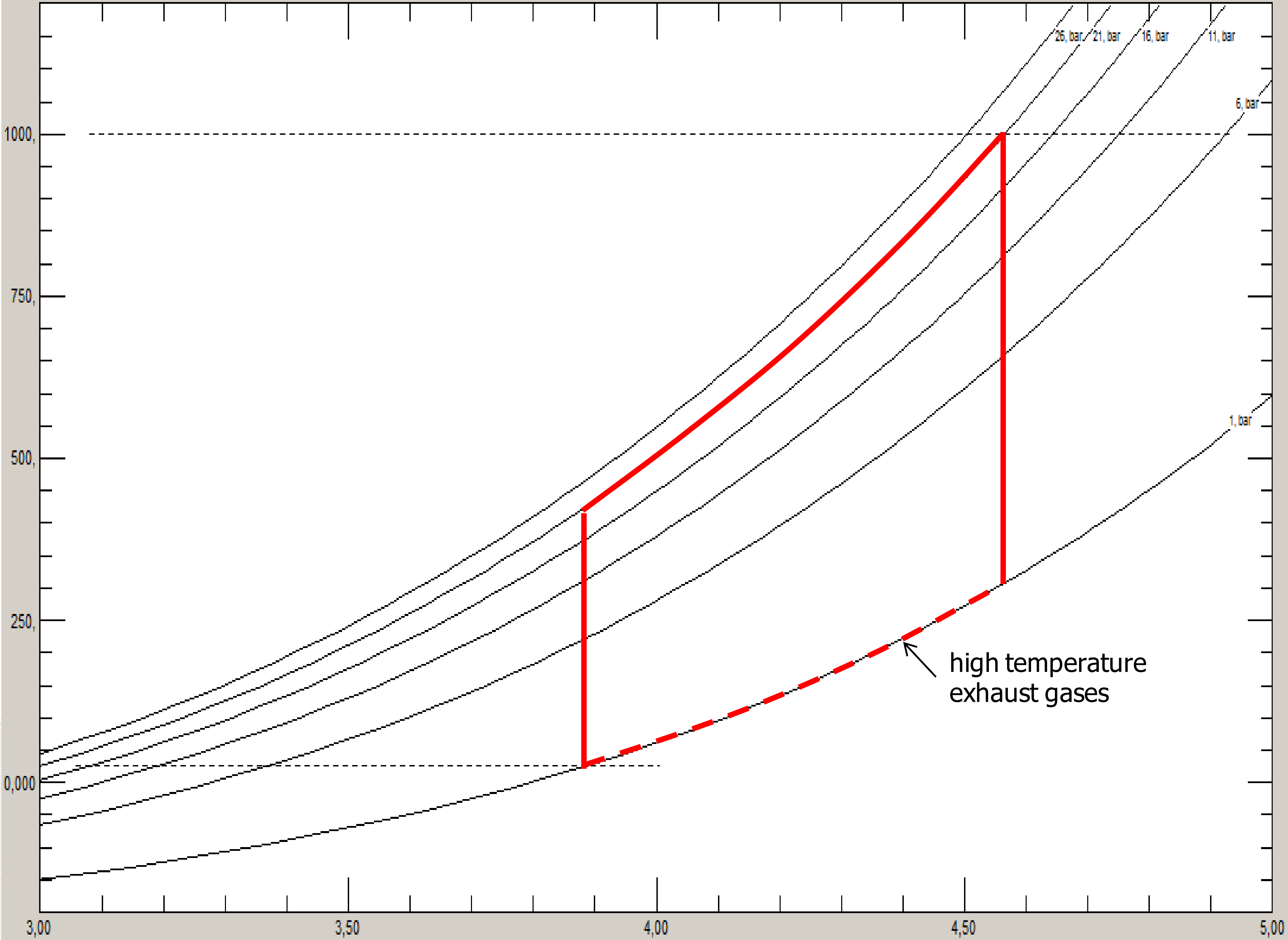
$$w_{12} = h_1 - h_2 = \text{-}419{,}81\text{kJ/kg}$$

$$q_{23} = h_3 - h_2 = +648{,}05\text{kJ/kg}$$

$$\eta = \frac{W_{liq}}{Q_q} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{w_{34} - w_{12}}{q_{23}} = \frac{+783{,}92 - 419{,}81}{+648{,}05} = 0{,}5618$$

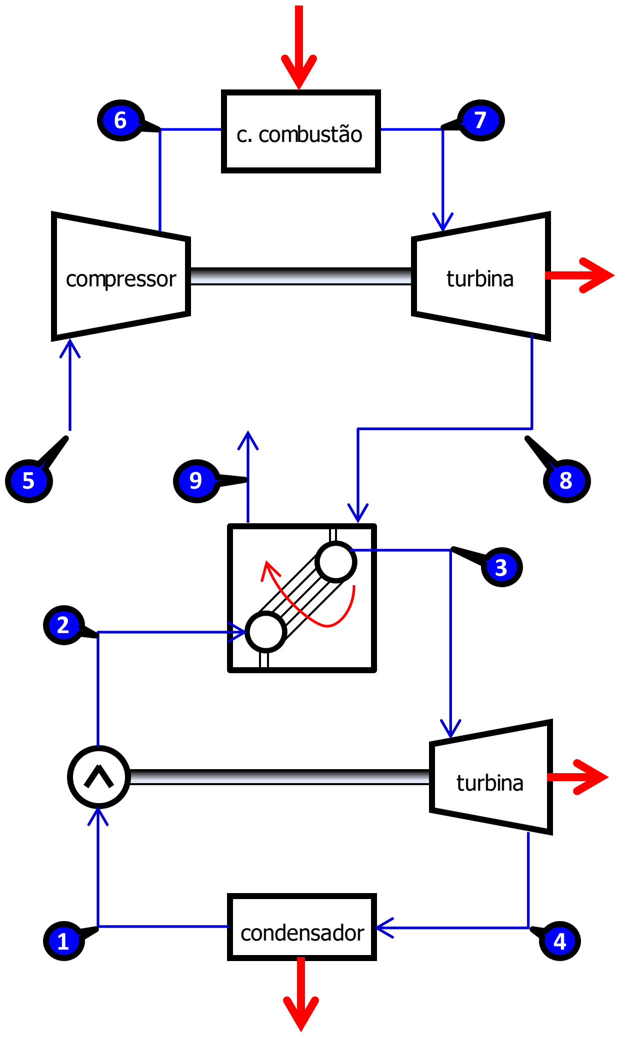
$$\eta_C = 0{,}766$$

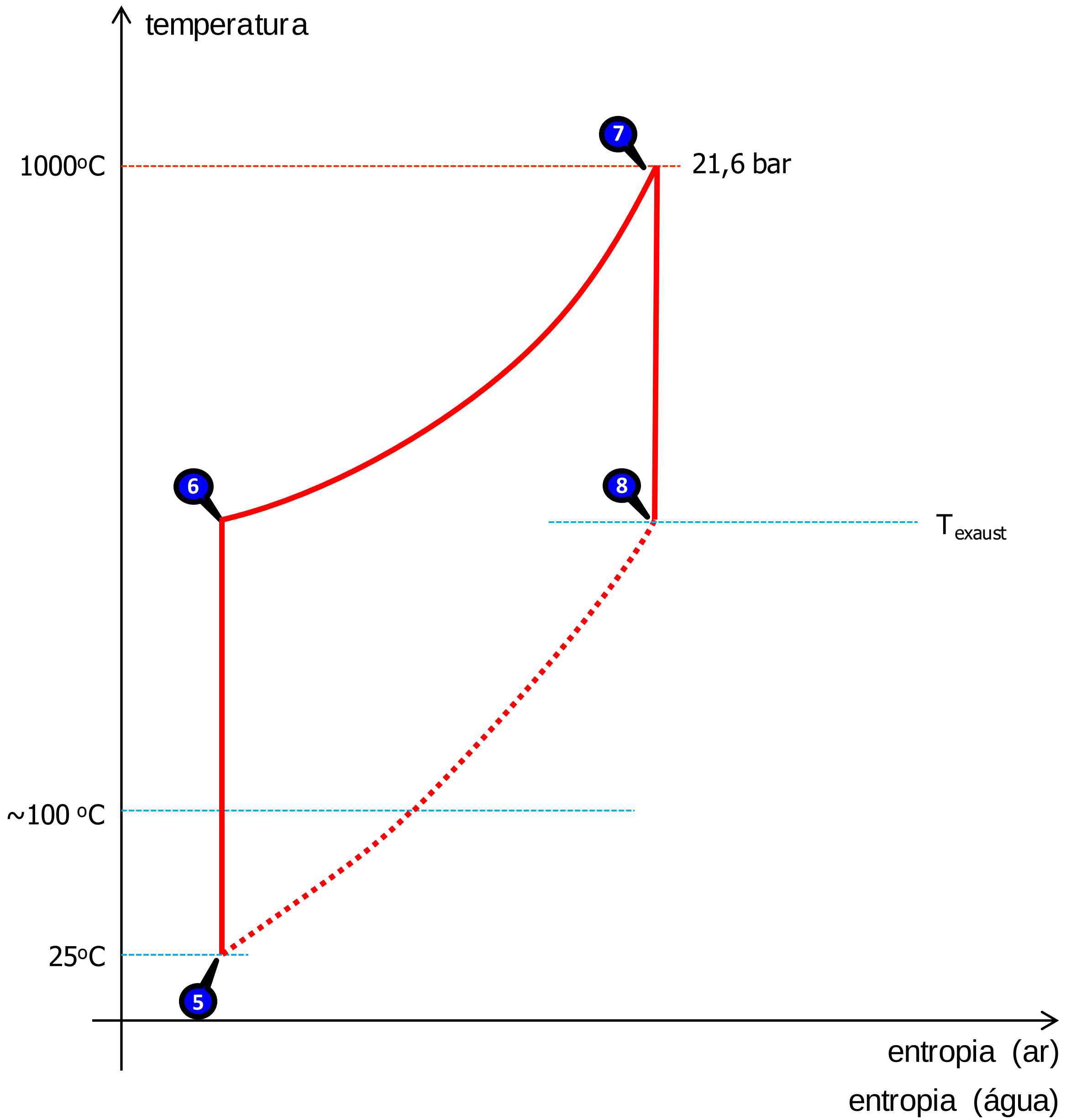
$$\eta_R = 0{,}425$$



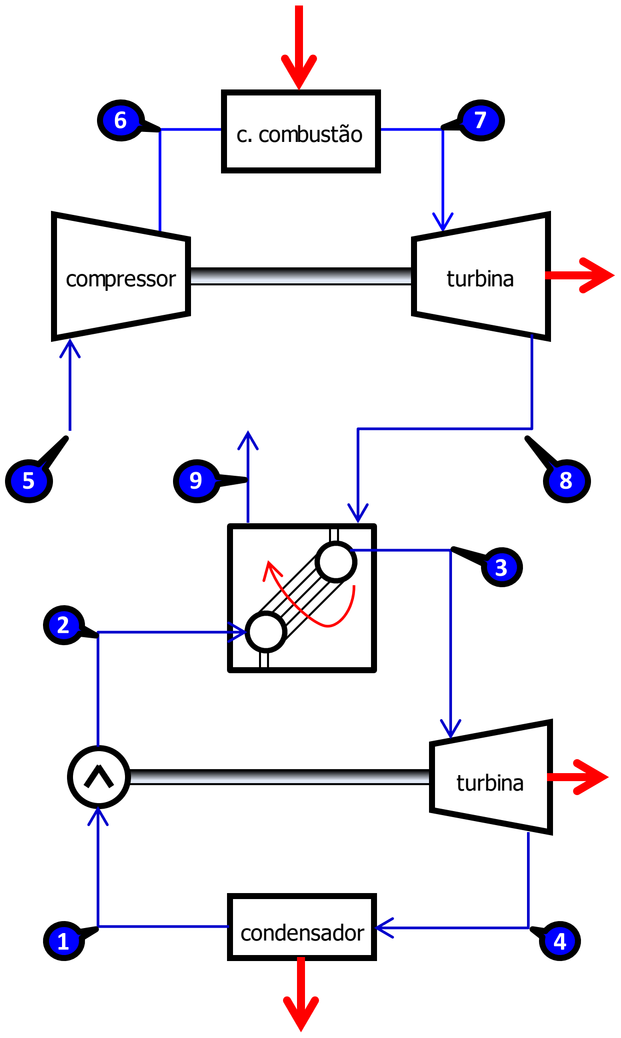
high temperature exhaust gases

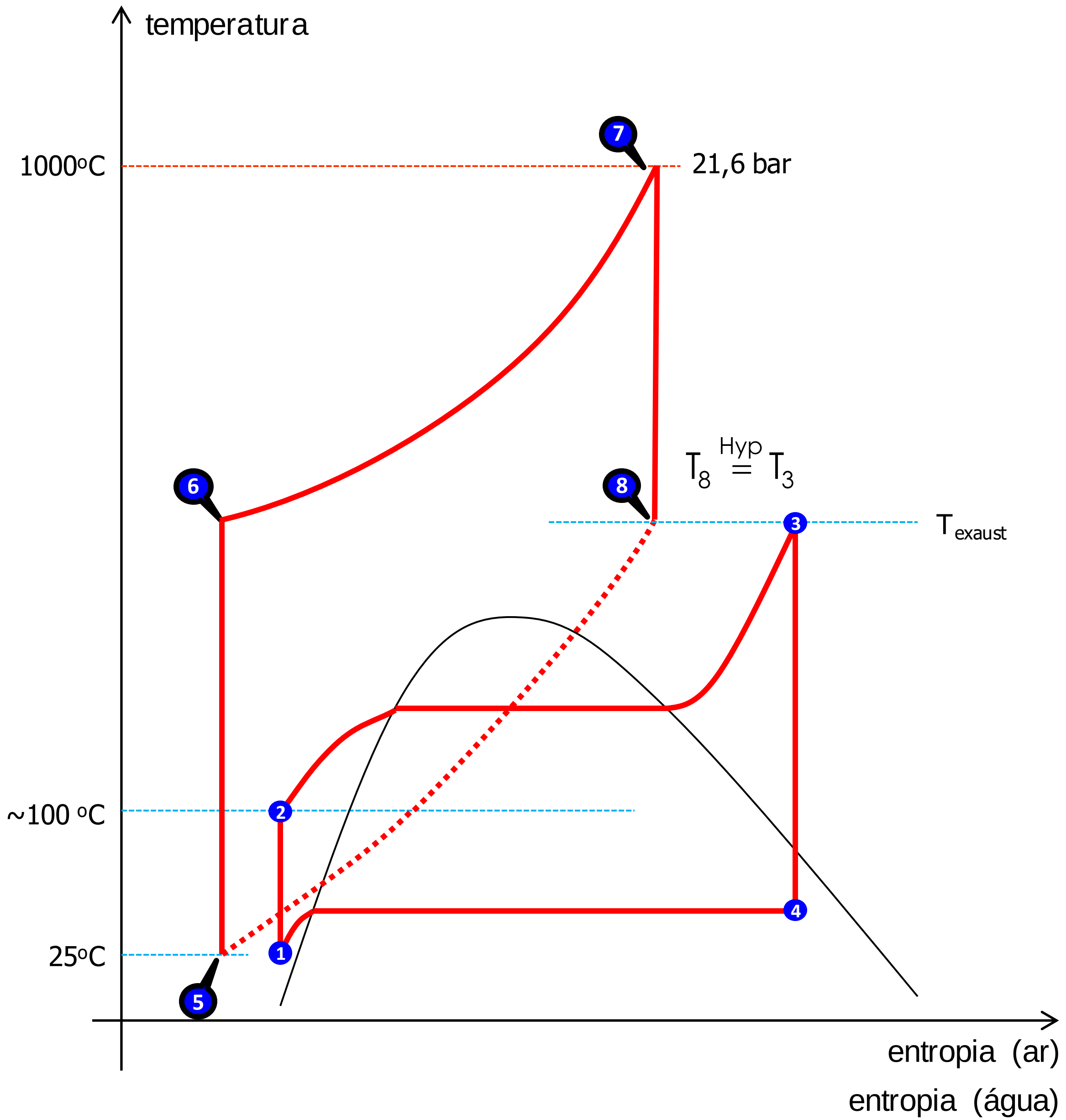
Alternatives to the exploitation of a thermal energy: Brayton+ Rankine



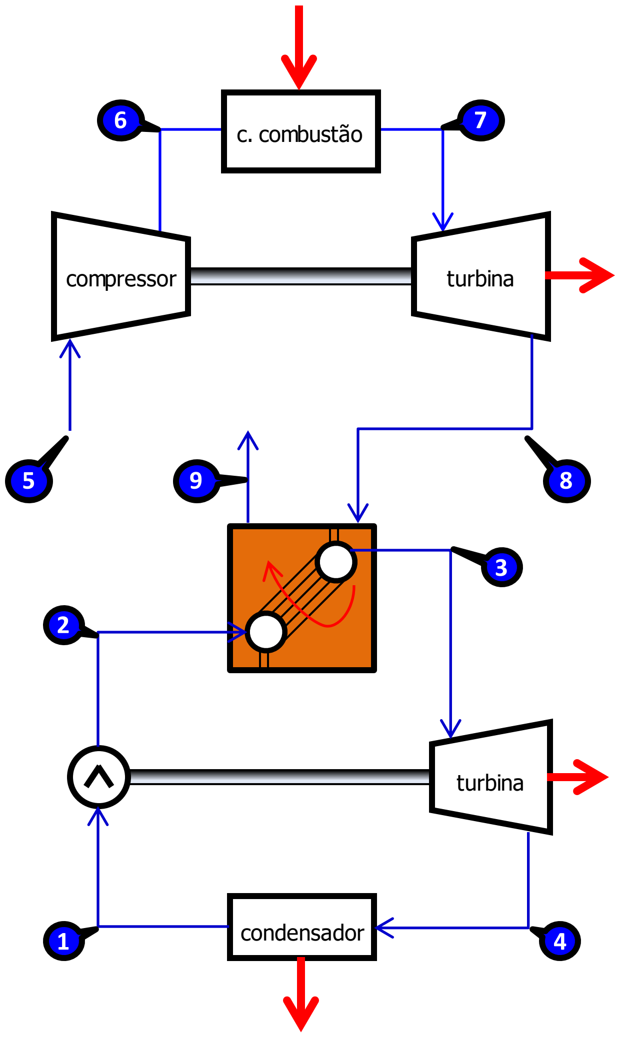


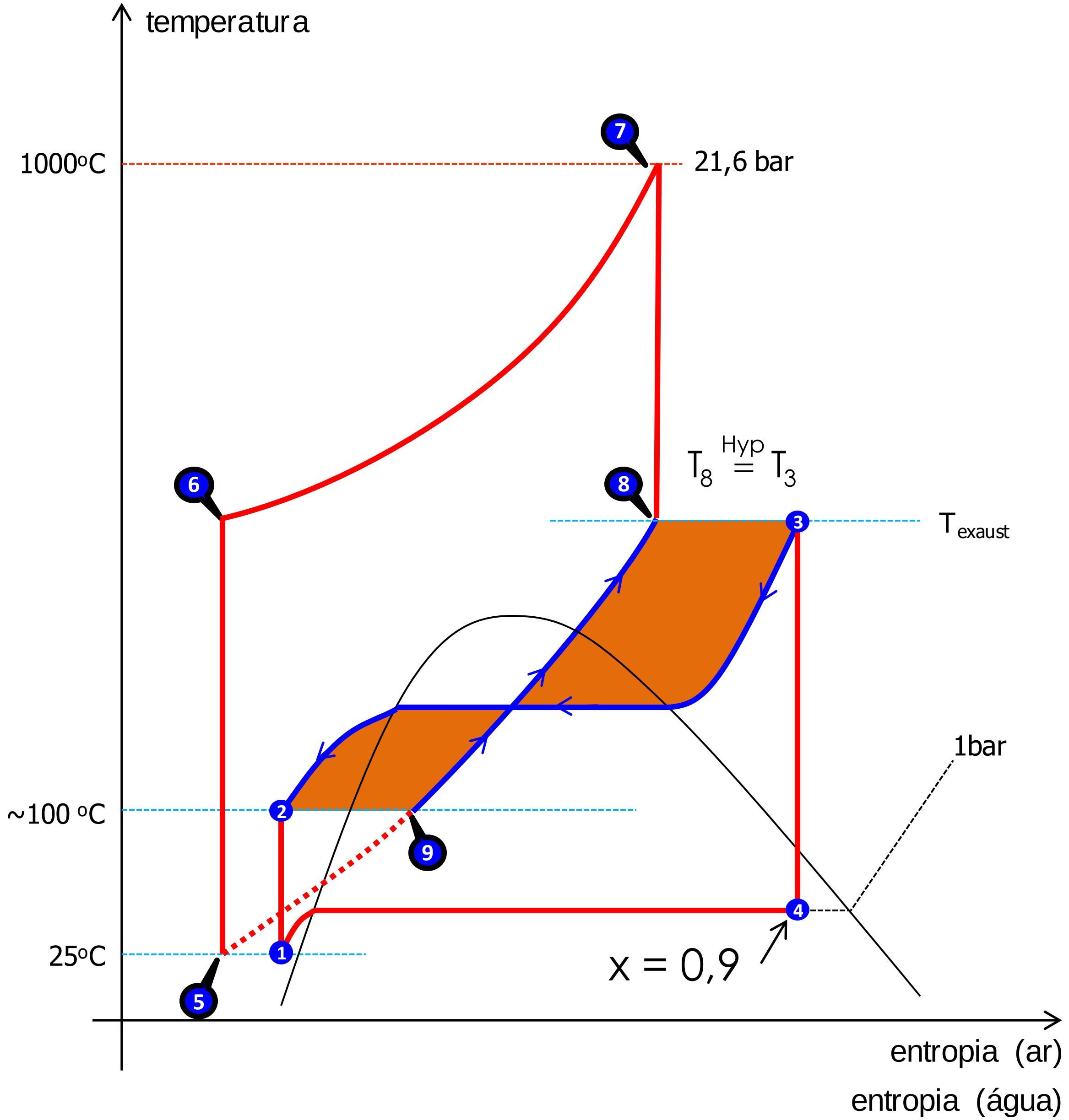
Alternatives to the exploitation of a thermal energy: Brayton+ Rankine





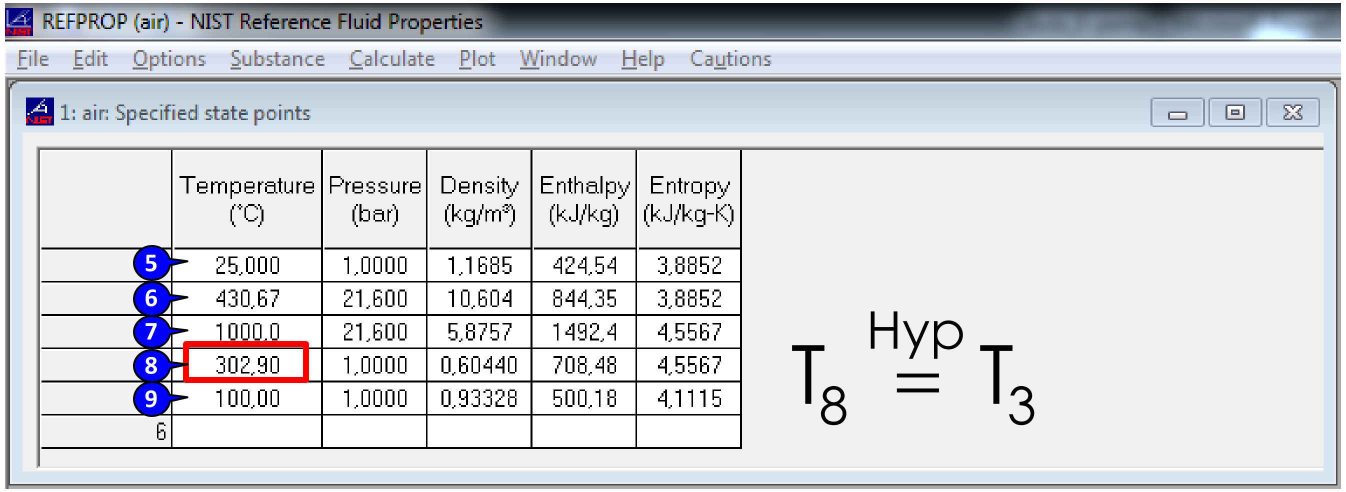
Alternatives to the exploitation of a thermal energy: Brayton+ Rankine





Alternatives to the exploitation of a thermal energy: Brayton+ Rankine

Determination of the thermodynamic states

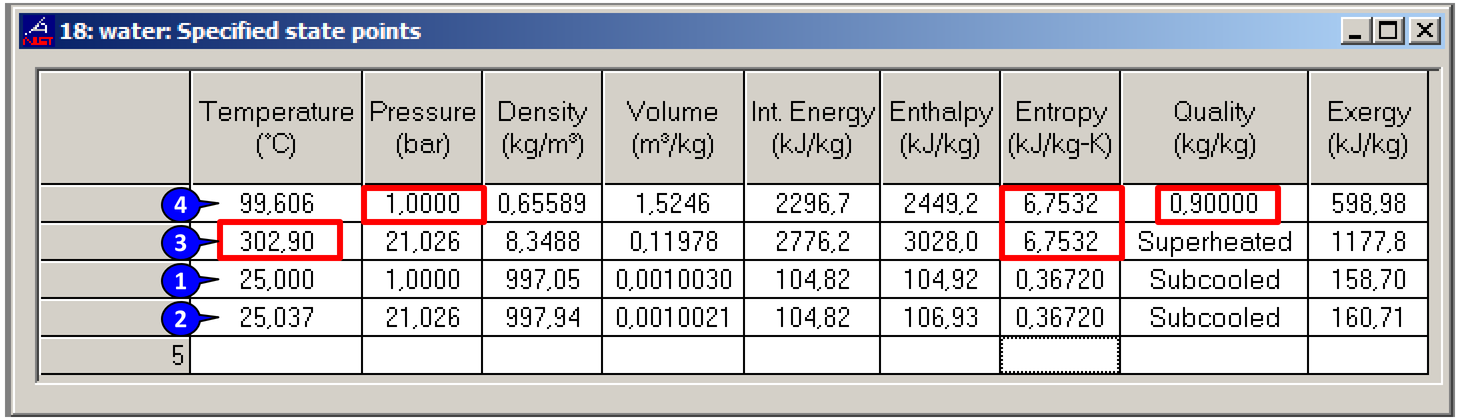


REFPROP (air) - NIST Reference Fluid Properties

1: air: Specified state points

	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)
⑤	25,000	1,0000	1,1685	424,54	3,8852
⑥	430,67	21,600	10,604	844,35	3,8852
⑦	1000,0	21,600	5,8757	1492,4	4,5567
⑧	302,90	1,0000	0,60440	708,48	4,5567
⑨	100,00	1,0000	0,93328	500,18	4,1115
6					

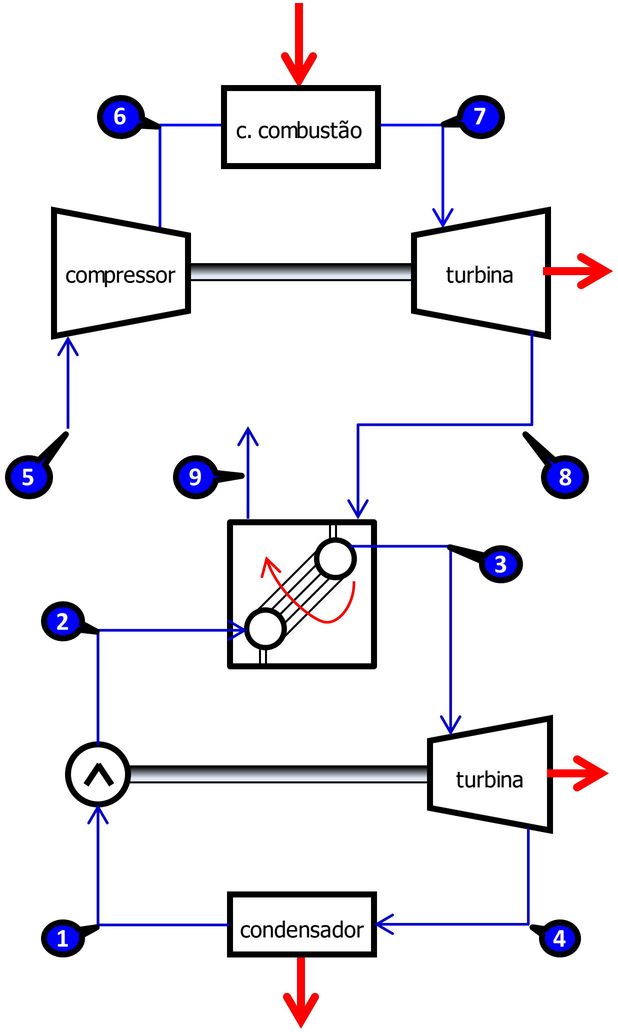
$$T_8 \overset{Hyp}{=} T_3$$



18: water: Specified state points

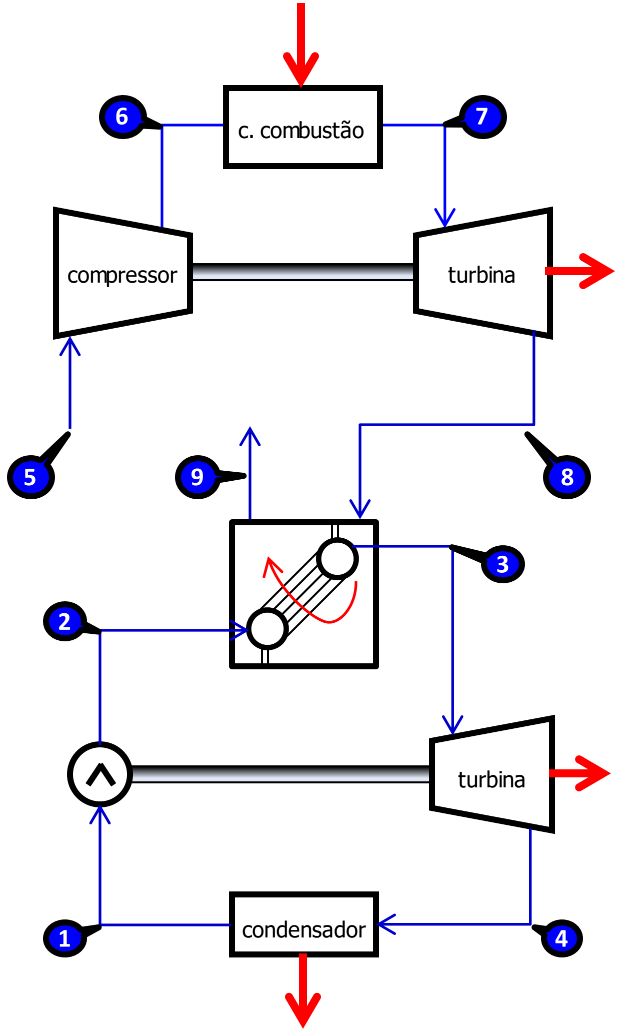
	Temperature (°C)	Pressure (bar)	Density (kg/m³)	Volume (m³/kg)	Int. Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Quality (kg/kg)	Exergy (kJ/kg)
④	99,606	1,0000	0,65589	1,5246	2296,7	2449,2	6,7532	0,90000	598,98
③	302,90	21,026	8,3488	0,11978	2776,2	3028,0	6,7532	Superheated	1177,8
①	25,000	1,0000	997,05	0,0010030	104,82	104,92	0,36720	Subcooled	158,70
②	25,037	21,026	997,94	0,0010021	104,82	106,93	0,36720	Subcooled	160,71
5									

Calculation of the steam/air ratio and thermodynamic efficiency



$$Q = m_g(h_8 - h_9) = m_v(h_3 - h_2)$$

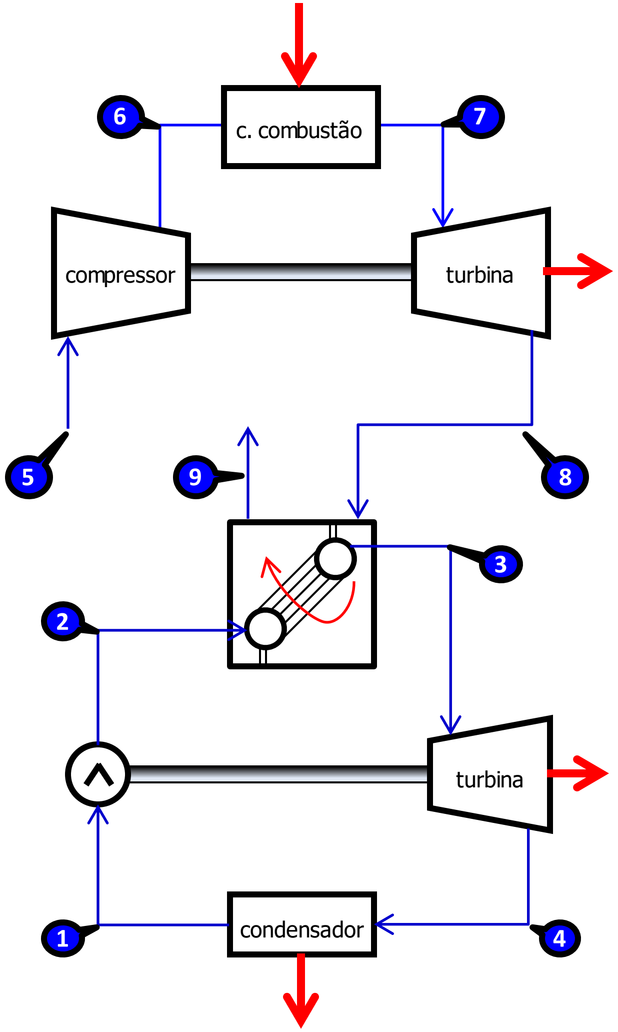
Calculation of the steam/air ratio and thermodynamic efficiency



$$Q = m_g(h_8 - h_9) = m_v(h_3 - h_2)$$

$$\frac{m_v}{m_g} = \frac{(h_8 - h_9)}{(h_3 - h_2)}$$

Calculation of the steam/air ratio and thermodynamic efficiency

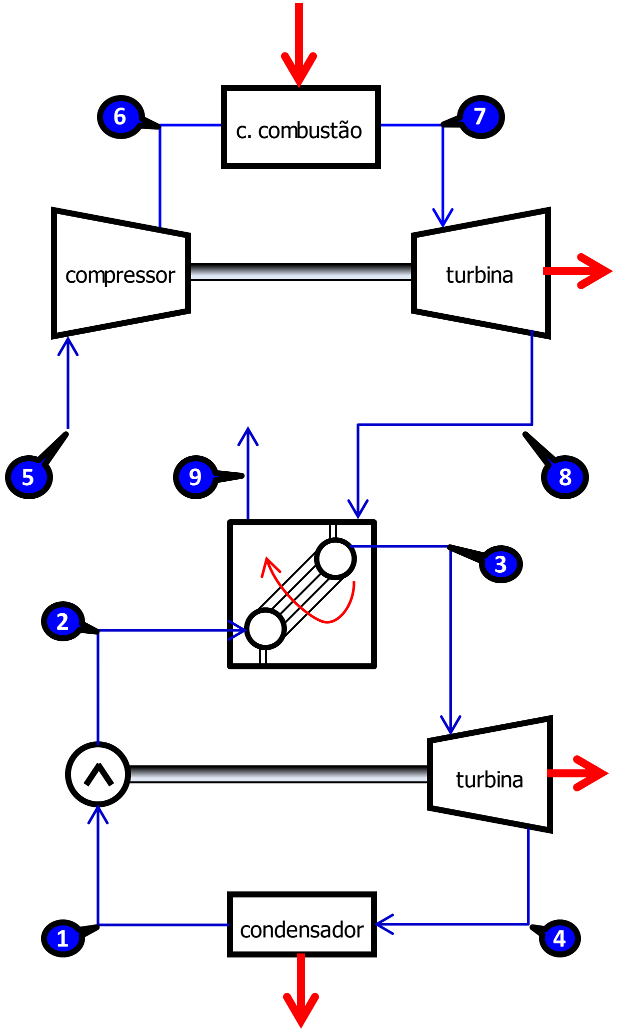


$$Q = m_g(h_8 - h_9) = m_v(h_3 - h_2)$$

$$\frac{m_v}{m_g} = \frac{(h_8 - h_9)}{(h_3 - h_2)}$$

$$\eta = \frac{m_g(w_{78} - w_{56}) + m_v(w_{34} - w_{12})}{m_g q_{67}}$$

Calculation of the steam/air ratio and thermodynamic efficiency



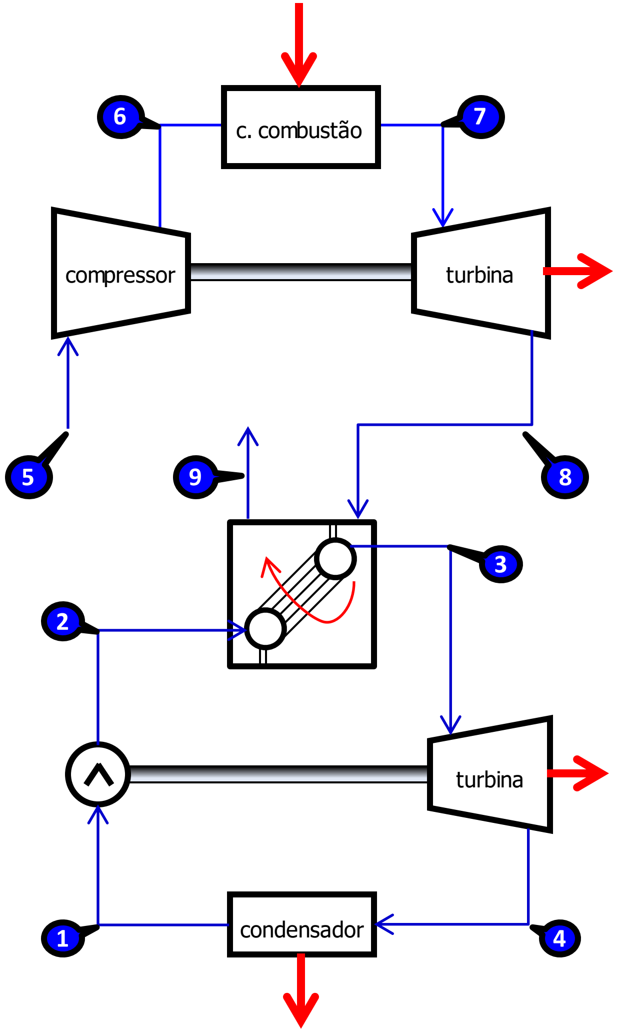
$$Q = m_g(h_8 - h_9) = m_v(h_3 - h_2)$$

$$\frac{m_v}{m_g} = \frac{(h_8 - h_9)}{(h_3 - h_2)}$$

$$\eta = \frac{m_g(w_{78} - w_{56}) + m_v(w_{34} - w_{12})}{m_g q_{67}}$$

$$\eta = \frac{(w_{78} - w_{56}) + m_v / m_g(w_{34} - w_{12})}{q_{67}}$$

Calculation of the steam/air ratio and thermodynamic efficiency



$$Q = m_g(h_8 - h_9) = m_v(h_3 - h_2)$$

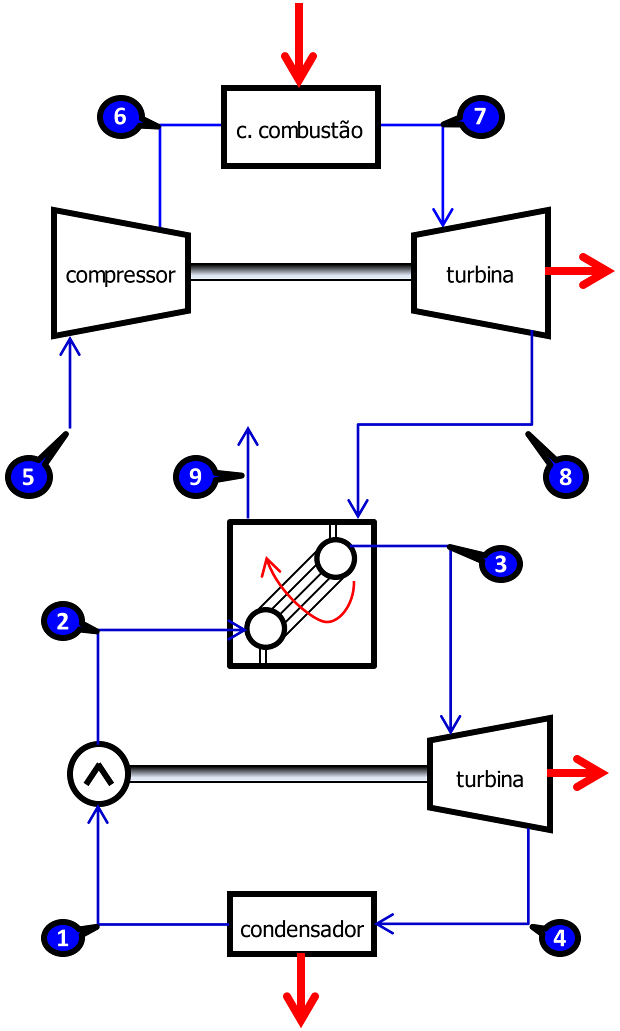
$$\frac{m_v}{m_g} = \frac{(h_8 - h_9)}{(h_3 - h_2)}$$

$$\eta = \frac{m_g(w_{78} - w_{56}) + m_v(w_{34} - w_{12})}{m_g q_{67}}$$

$$\eta = \frac{(w_{78} - w_{56}) + m_v/m_g(w_{34} - w_{12})}{q_{67}}$$

$$\eta = \frac{h_7 - h_8 - h_6 + h_5 + (h_3 - h_4 - h_2 + h_1)\cdot m_v/m_g}{h_7 - h_6}$$

Calculation of the steam/air ratio and thermodynamic efficiency



$$Q = m_g(h_8 - h_9) = m_v(h_3 - h_2)$$

$$\frac{m_v}{m_g} = \frac{(h_8 - h_9)}{(h_3 - h_2)}$$

$$\eta = \frac{m_g(w_{78} - w_{56}) + m_v(w_{34} - w_{12})}{m_g q_{67}}$$

$$\eta = \frac{(w_{78} - w_{56}) + m_v/m_g(w_{34} - w_{12})}{q_{67}}$$

$$\eta = \frac{h_7 - h_8 - h_6 + h_5 + (h_3 - h_4 - h_2 + h_1) \cdot m_v/m_g}{h_7 - h_6}$$

$$\eta = \frac{h_7 - h_8 - h_6 + h_5 + (h_3 - h_4 - h_2 + h_1) \cdot (h_8 - h_9)/(h_3 - h_2)}{h_7 - h_6}$$

Calculation of the steam/air ratio and thermodynamic efficiency

$$\frac{m_v}{m_g} = \frac{(h_8 - h_9)}{(h_3 - h_2)} = 0{,}071$$ kg steam/ kg air

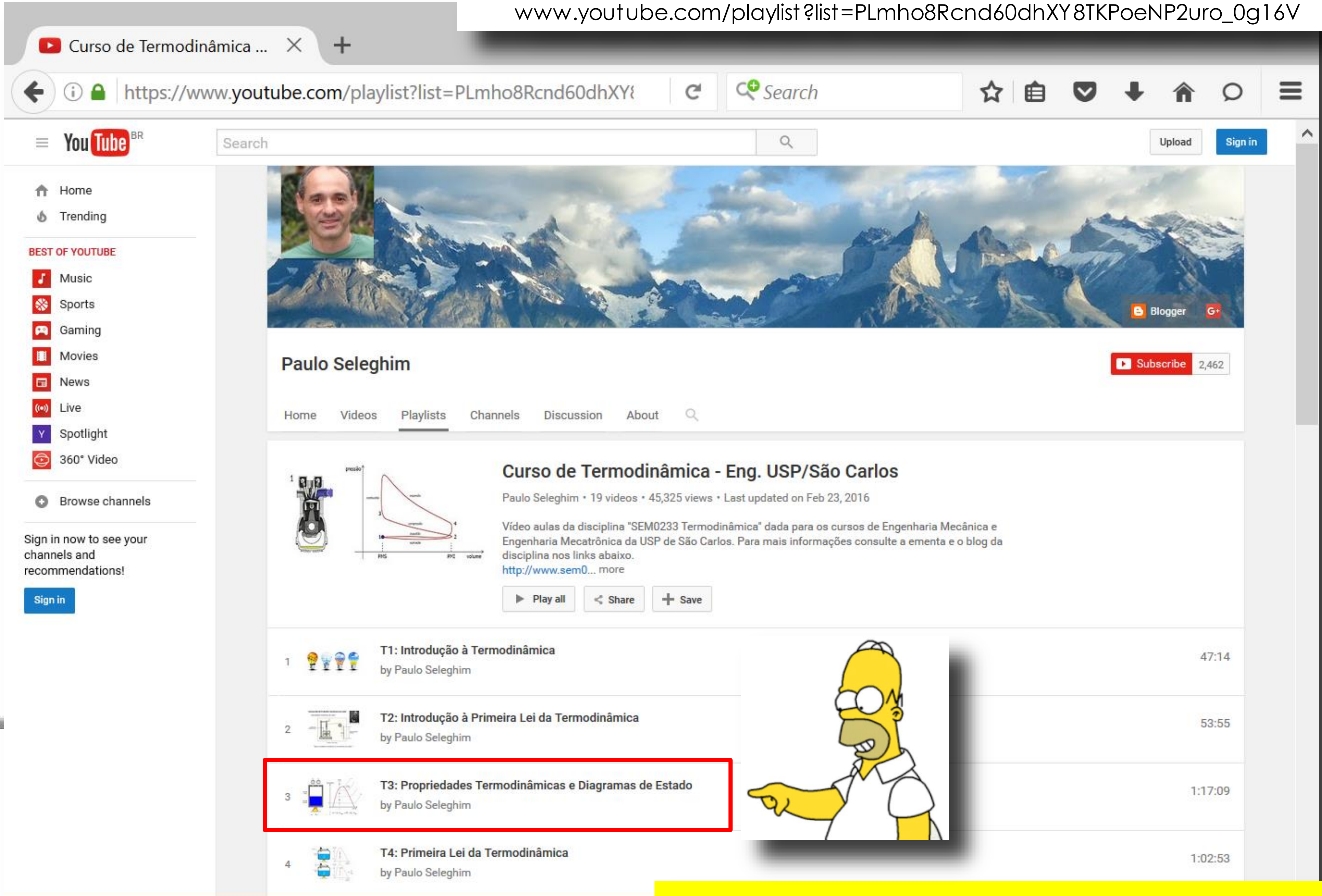
$$\eta = \frac{h_7 - h_8 - h_6 + h_5 + (h_3 - h_4 - h_2 + h_1) \cdot (h_8 - h_9)/(h_3 - h_2)}{h_7 - h_6} = 0{,}625$$

$$\left.\begin{array}{ll} \text{gás-vapor:} & \eta_{GV} = 0{,}625 \\ \text{Rankine:} & \eta_R = 0{,}425 \end{array}\right\} \text{cogeneration}$$

Brayton: $\eta_B = 0{,}5618$

Carnot: $\eta_C = 0{,}766$

www.youtube.com/playlist?list=PLmho8Rcnd60dhXY8TKPoeNP2uro_0g16V



Paulo Seleghim

Curso de Termodinâmica - Eng. USP/São Carlos

Paulo Seleghim • 19 videos • 45,325 views • Last updated on Feb 23, 2016

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http://www.sem0... more

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2	T2: Introdução à Primeira Lei da Termodinâmica by Paulo Seleghim	53:55
3	T3: Propriedades Termodinâmicas e Diagramas de Estado by Paulo Seleghim	1:17:09
4	T4: Primeira Lei da Termodinâmica by Paulo Seleghim	1:02:53