Lecture 4
Heat engines

PHY 555 – Energy & Environment

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Lecture 4
Heat engines

I. What, why, where ?

II. Thermodynamics framework

III. Standard cycles and their applications

IV. Perspectives

Heat is work and work is heat – or is it ?

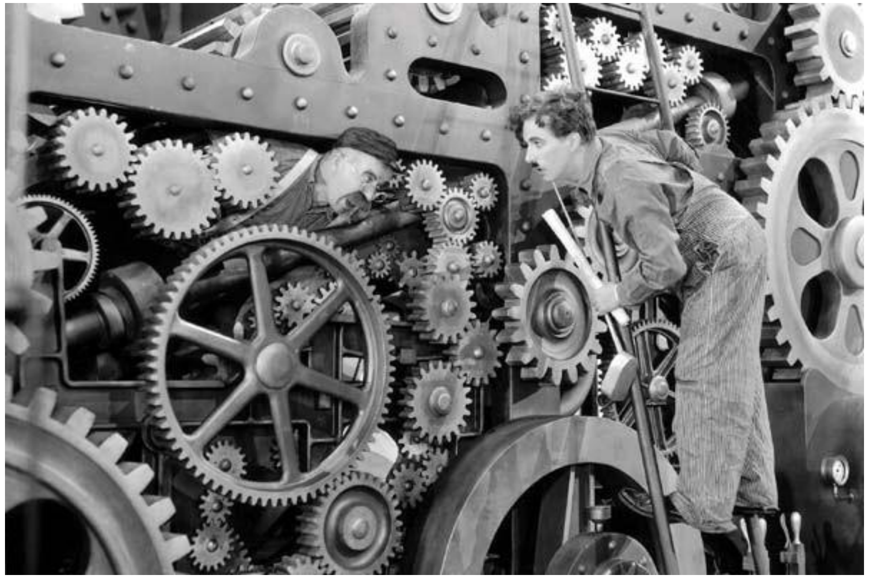
https://www.youtube.com/watch?v=VnbiVw_1FNs

$$dU = \delta W + \delta Q$$

$$\delta W = \mathbf{F}.d\mathbf{r} = -dEp$$

(for conservative forces)

$$\delta Q = T\delta S_{\text{exchange}}$$



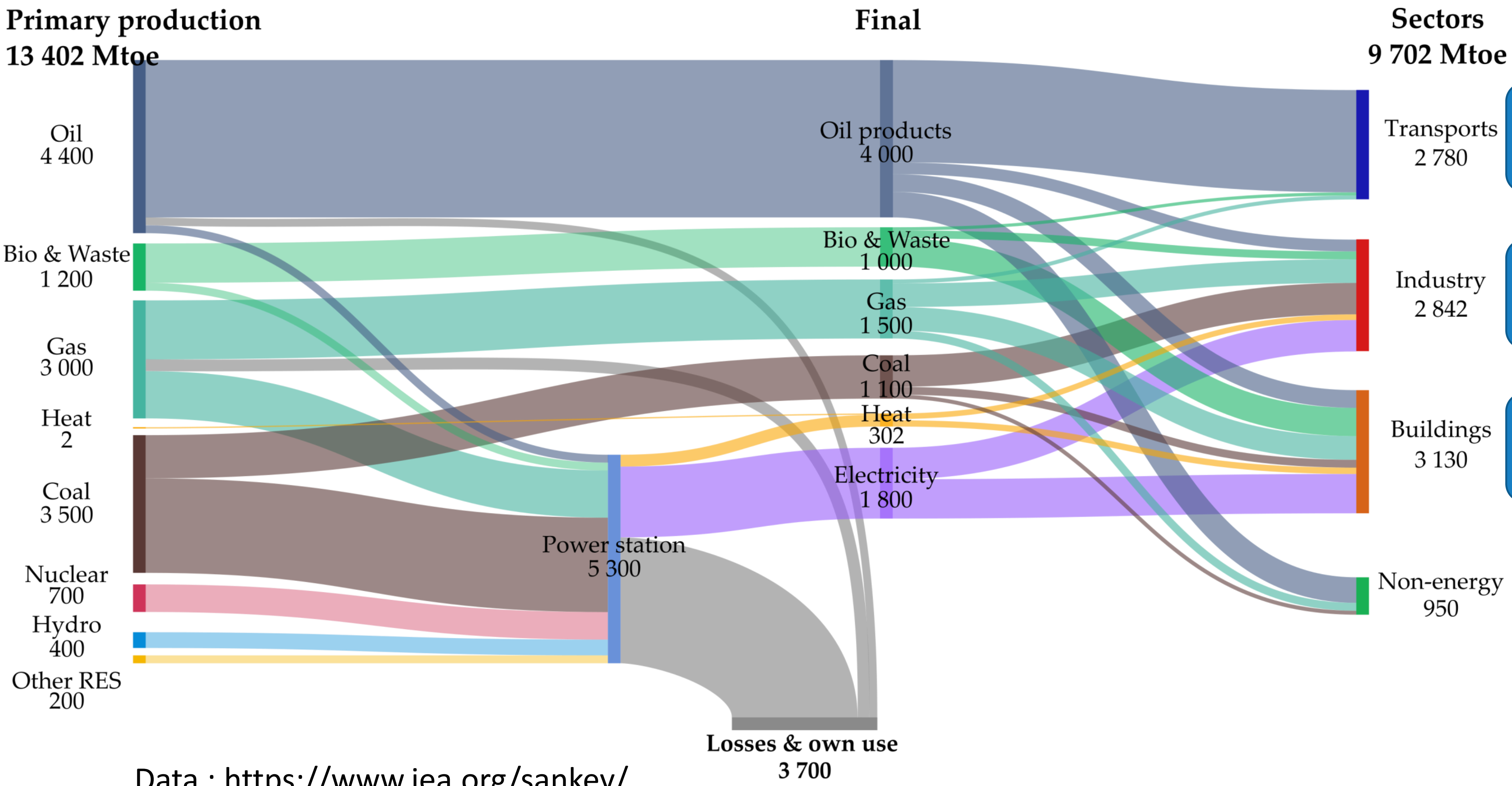
Hard to get

« Easy » to use

Easy to get (combustion)

Hard to use

Work = 50% of energy usage



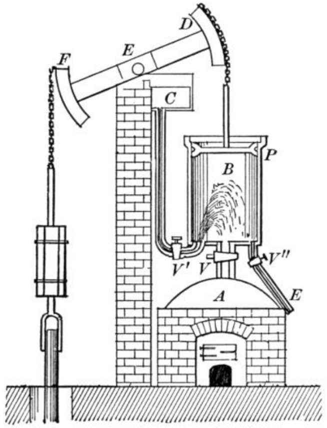
Motion

Machines (pump, press…)

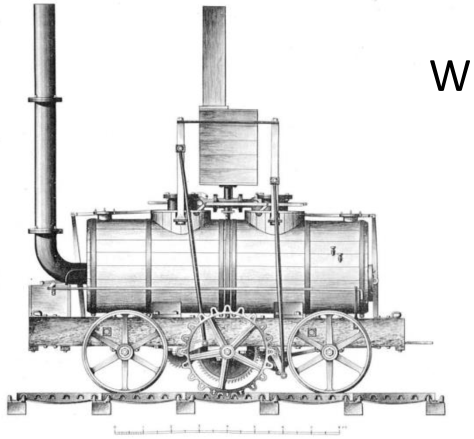
“specific use” of electitricity

Data : https://www.iea.org/sankey/

A HEATED HISTORY

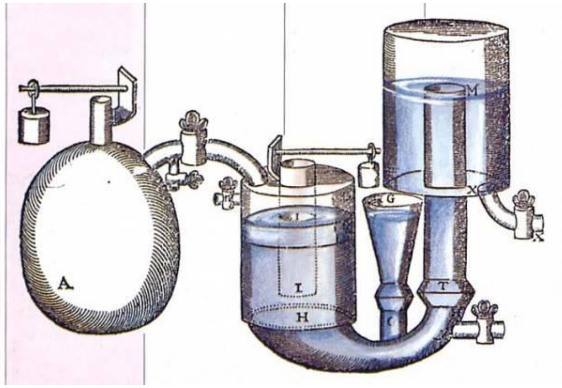


Thomas Newcomen & Savery
Self acting steam engine



William Murdoch & Reynolds
Matthew Murray
Locomotve

90 1700 10 20 30 40 50 60 70 80 90 1800 10 20 30 40 50 60 70 80



Denis Papin
"Nouvelle méthode pour obtenir à bas prix des forces considérables" (1690)

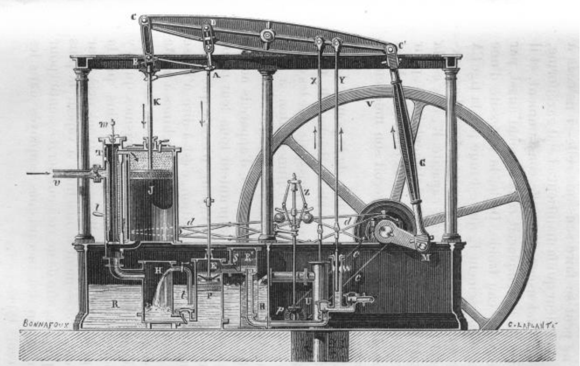
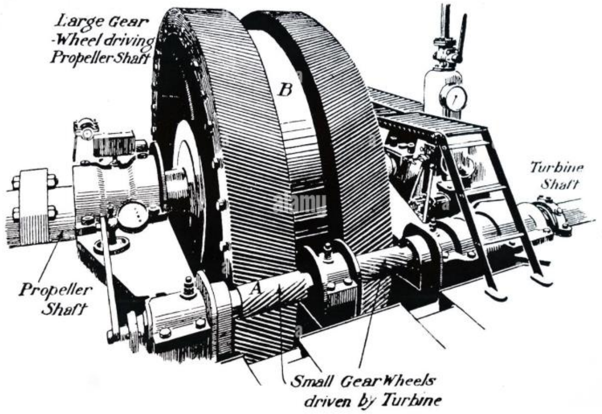


Fig. 59. — Machine à balancier de Watt.

v. Tuyau de prise de vapeur; T, tiroir; J, cylindre; H, condenseur; PE pompe d'épuisement; WY pompe alimentaire de la chaudière UX pompe d'alimentation de la bâche R; *p* Z régulateur; *dd* excentrique; ABCD parallélogramme; GM bielle et manivelle; V volant.

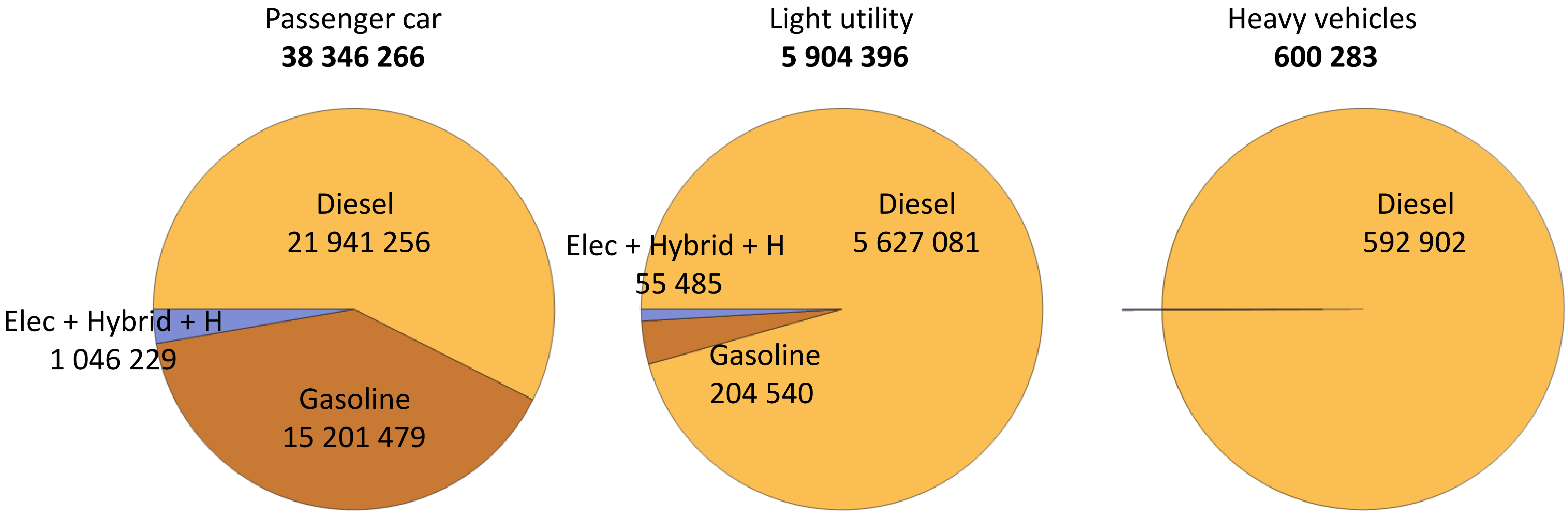
James Watt
Improvements,
Rotating motion



Charles Parson
Turbine

Turning heat into motion

Vehicle fleet in France (2021).
Data : SDES



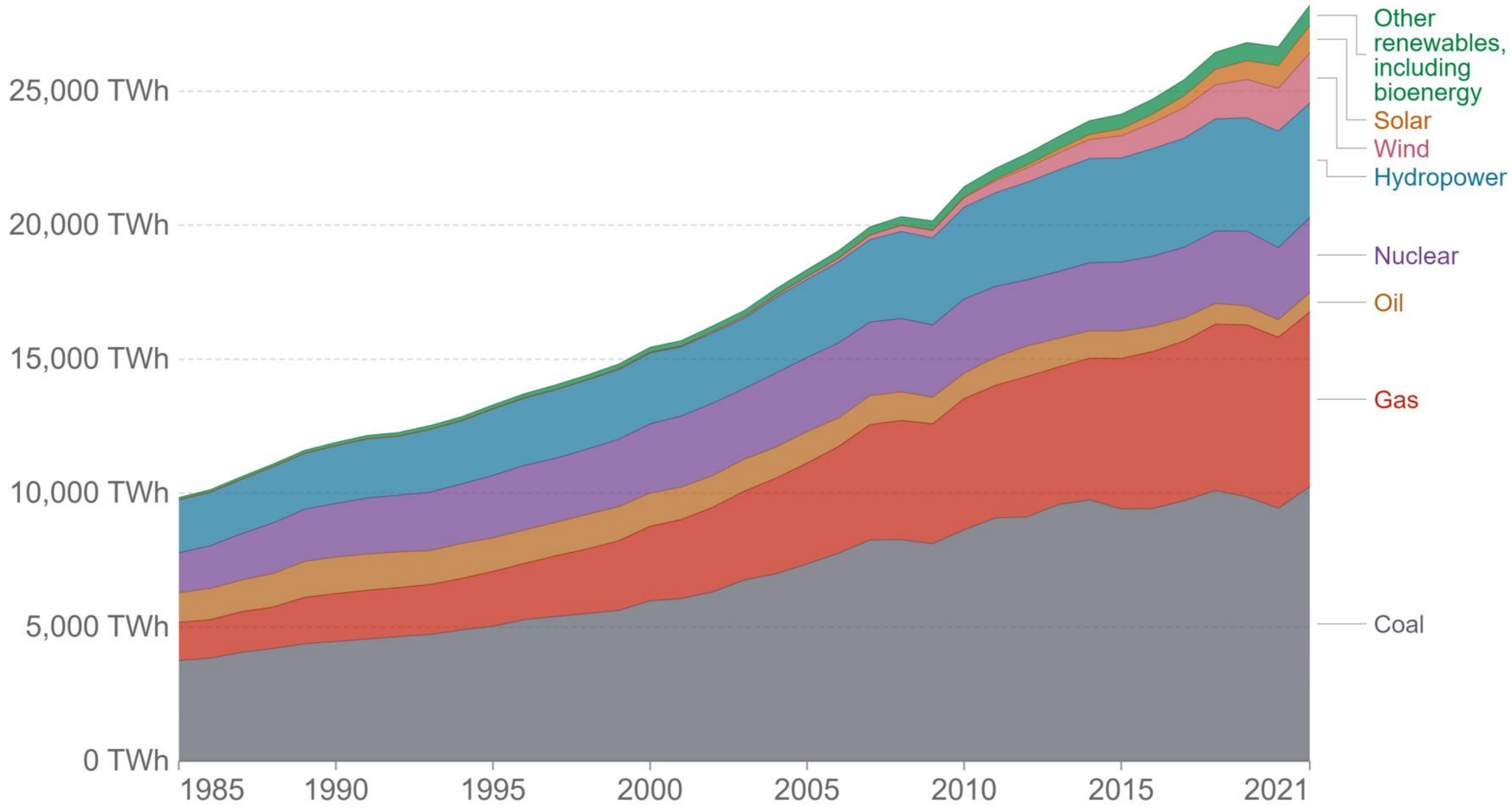
Passenger car
38 346 266

Light utility
5 904 396

Heavy vehicles
600 283

Turning heat into electricity

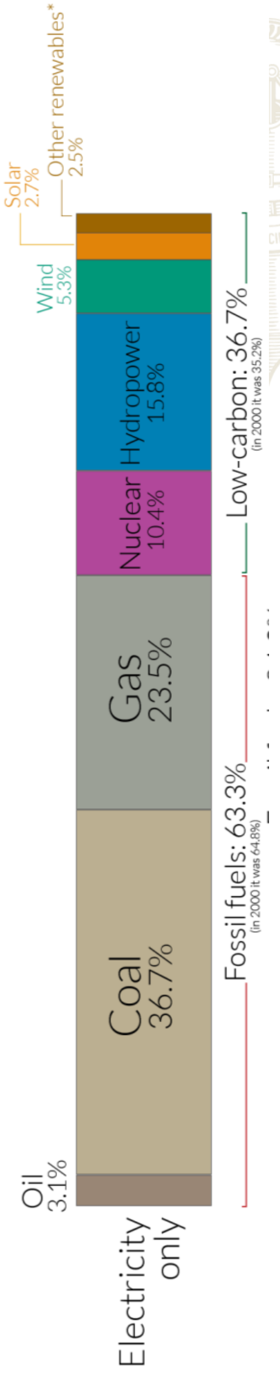
Electricity production by source, World



Source: Our World in Data based on BP Statistical Review of World Energy (2022); Our World in Data based on Ember's Global Electricity Review (2022); Our World in Data based on Ember's European Electricity Review (2022)

Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.

OurWorldInData.org/energy • CC BY

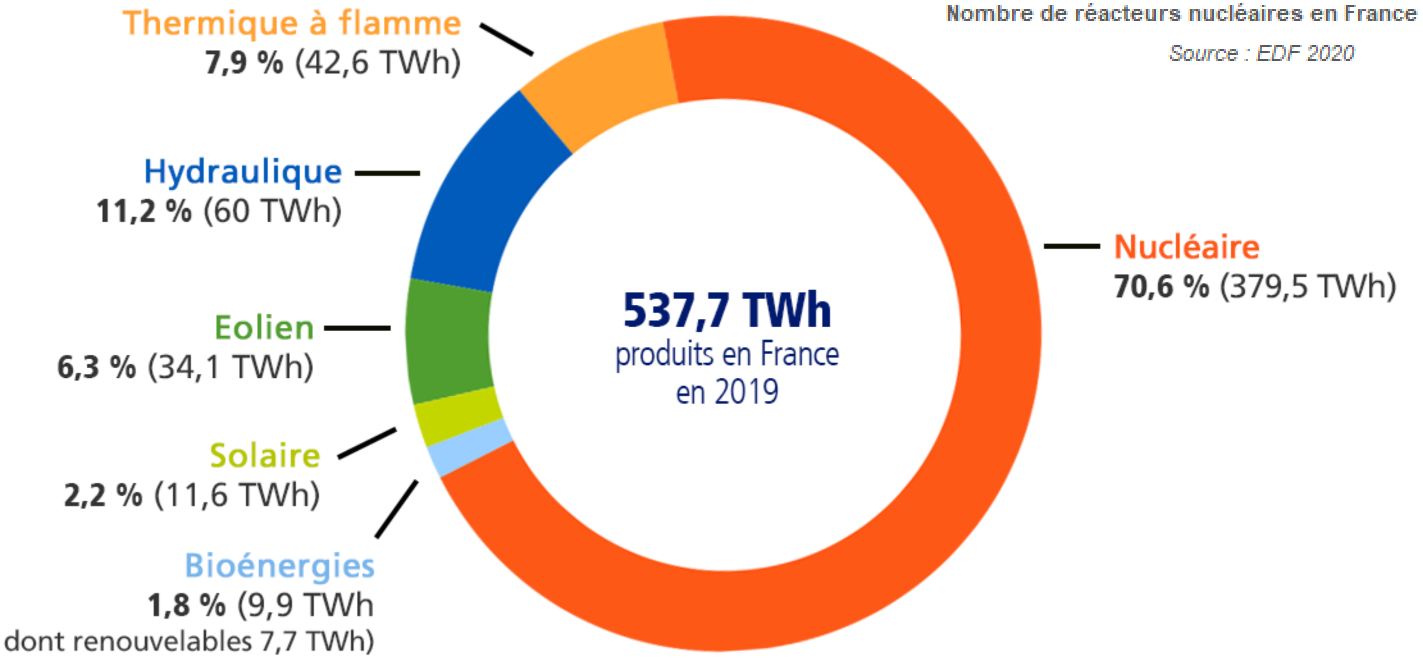


French focus

Puissance	Nombre de réacteurs
1 450 MW	4
1 300 MW	20
900 MW	32

Nombre de réacteurs nucléaires en France par puissance

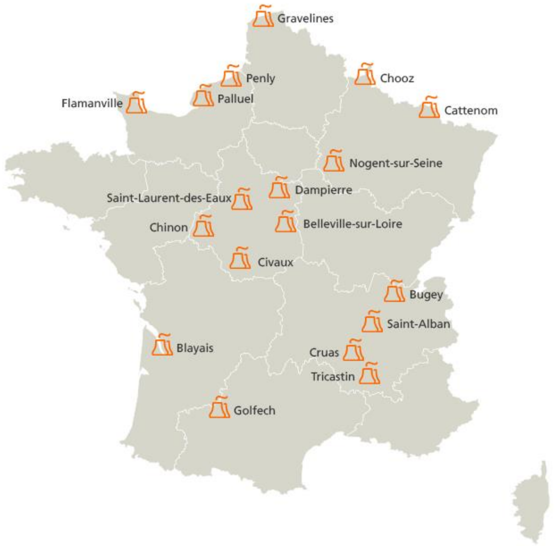
Source : EDF 2020



La production française d’électricité en 2019

Source RTE - bilan électrique 2019

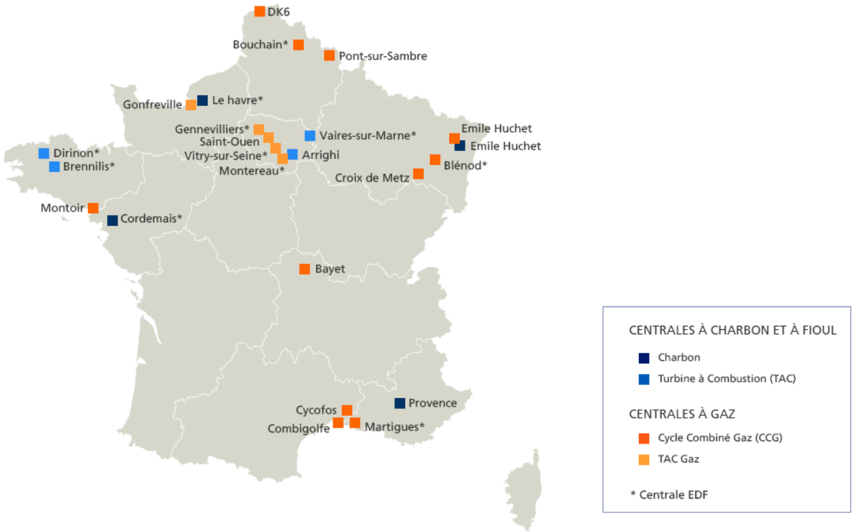
© EDF



Répartition des centrales nucléaires en France en 2021

Source EDF 2021

© EDF

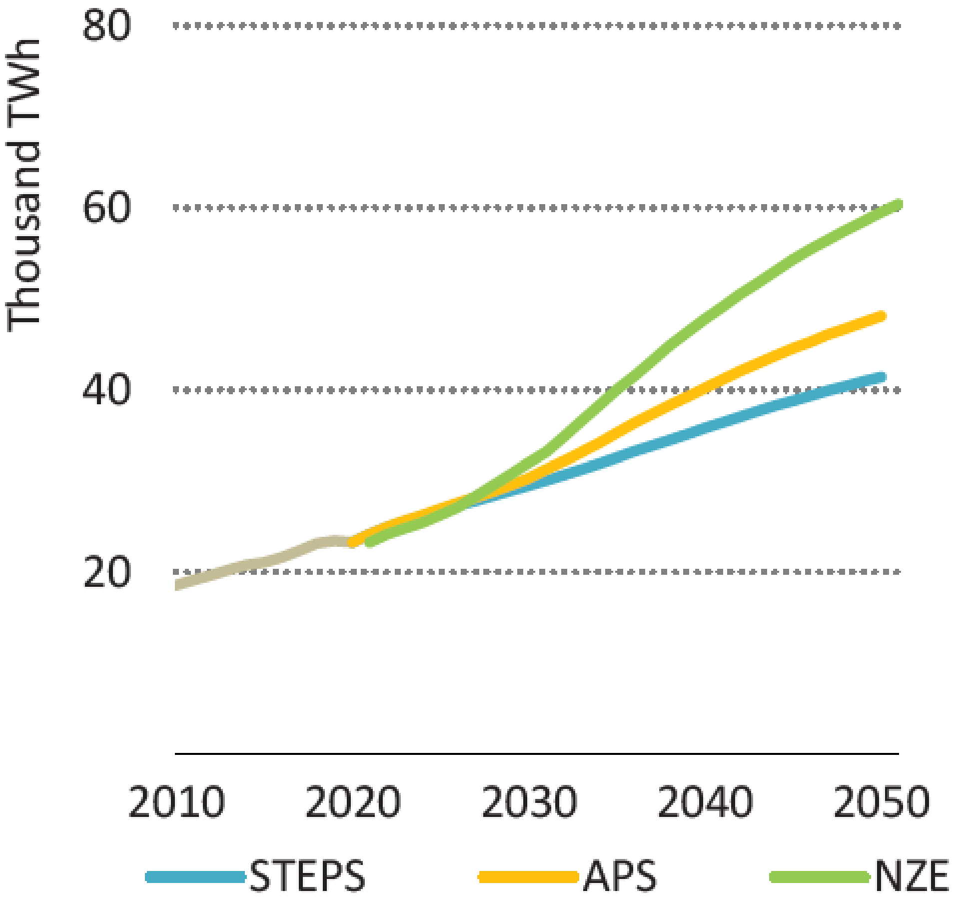


Répartition des centrales thermiques à flamme en France en 2021

Source RTE - Bilan électrique 2019

© EDF

Why electricity matters

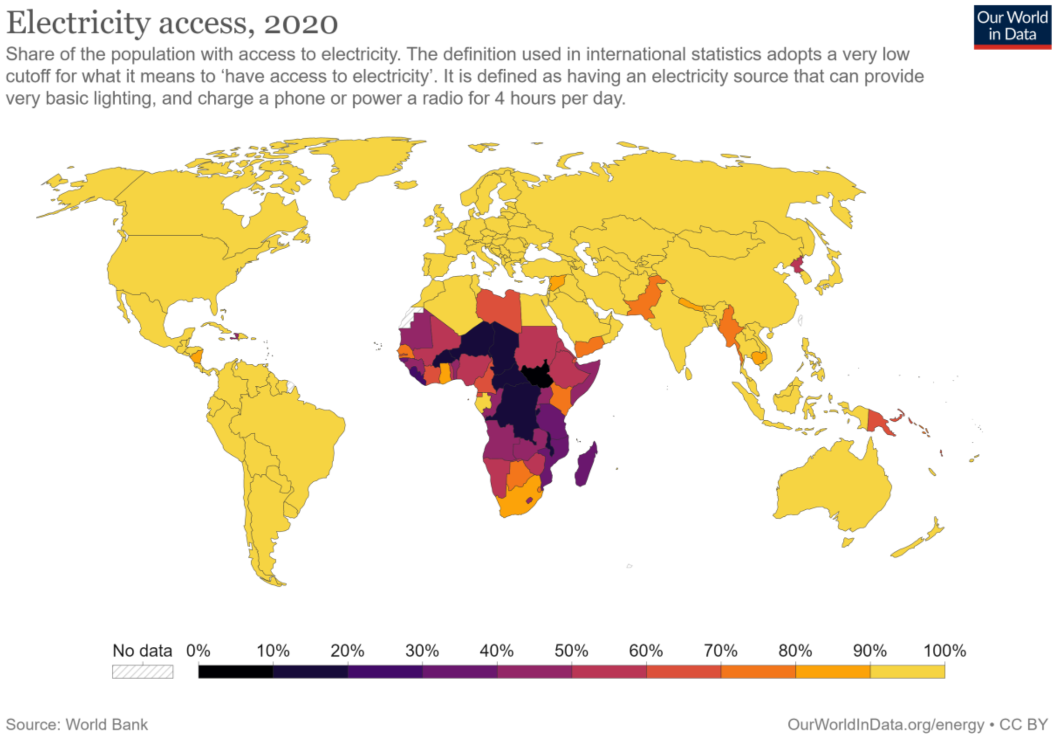


Stated Policies Scenario

Announced Pledges Scenario

Net Zero Emission

10% of humanity doesn't have access to electricity


Electricity access, 2020

Share of the population with access to electricity. The definition used in international statistics adopts a very low cutoff for what it means to 'have access to electricity'. It is defined as having an electricity source that can provide very basic lighting, and charge a phone or power a radio for 4 hours per day.

Source: World Bank

OurWorldInData.org/energy • CC BY

Electrification can be a tool towards decarbonization

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Heat engines

I. What, why, where ?

II. Thermodynamics framework

III. Standard cycles and their applications

IV. Perspectives

Turning heat into **work**

Use a source to provide heat to the converter.

Heat comes with entropy.

Getting rid of entropy requires sacrificing some of the heat.

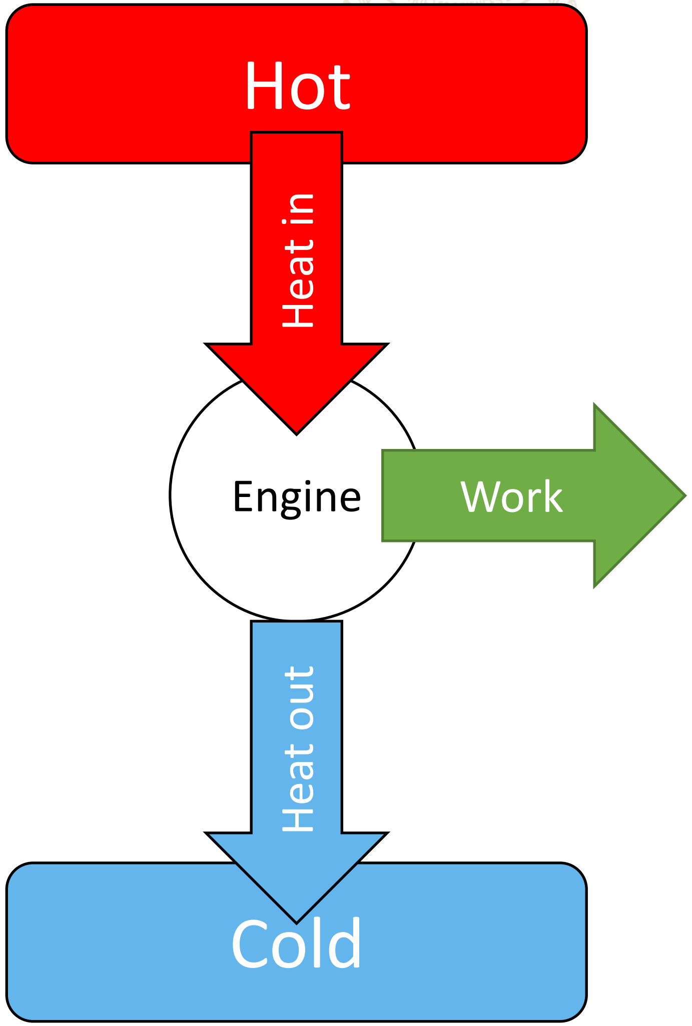
$$\text{work output} \le \text{heat input}\left(1-\frac{T_{\text{cold}}}{T_{\text{hot}}}\right)$$

Carnot efficiency

Ultimate efficiency

Needs no details about operation

0 power !


Hot

Heat in

Engine

Work

Heat out

Cold

Turning heat into **power**

The heat flow depends on the temperature difference

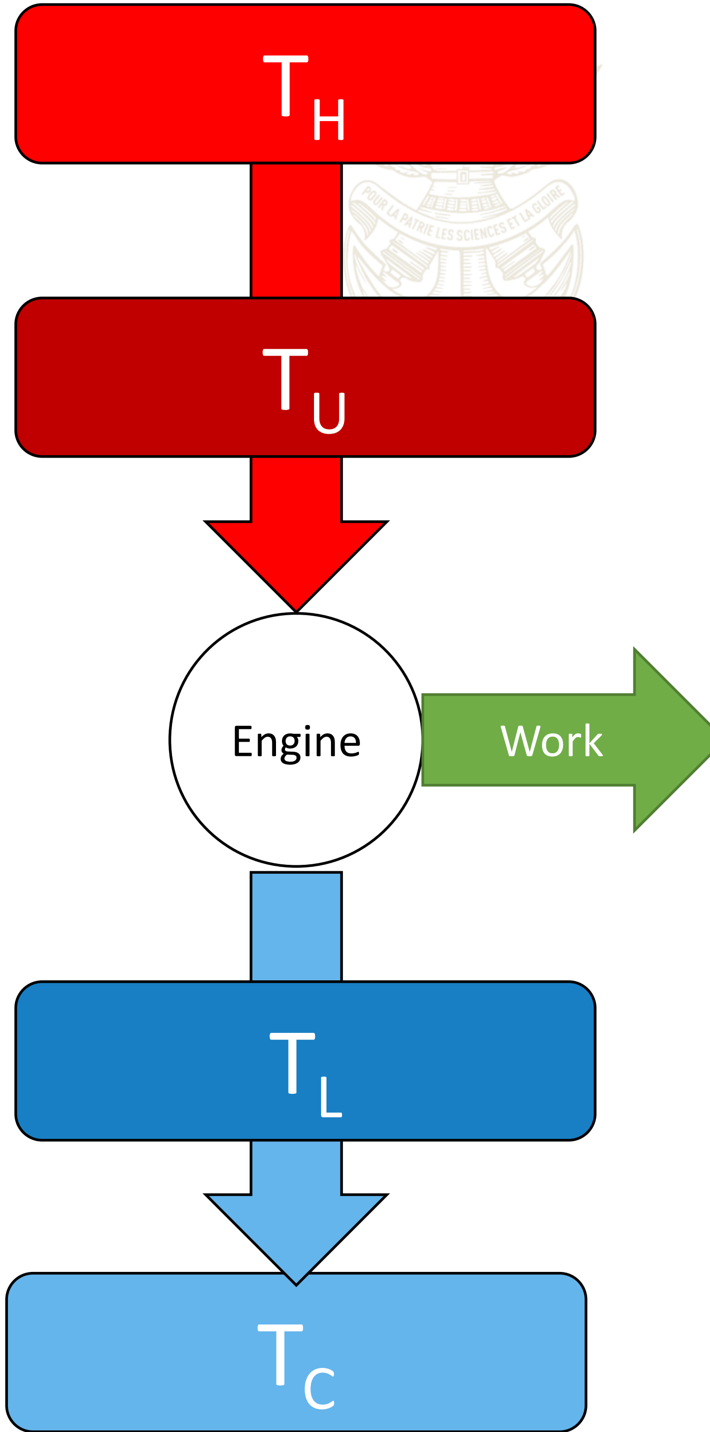
$$\dot{Q}_{\text{in}} \propto (T_H - T_U)$$

$$\dot{Q}_{\text{out}} \propto (T_C - T_L)$$

Larger temperature difference

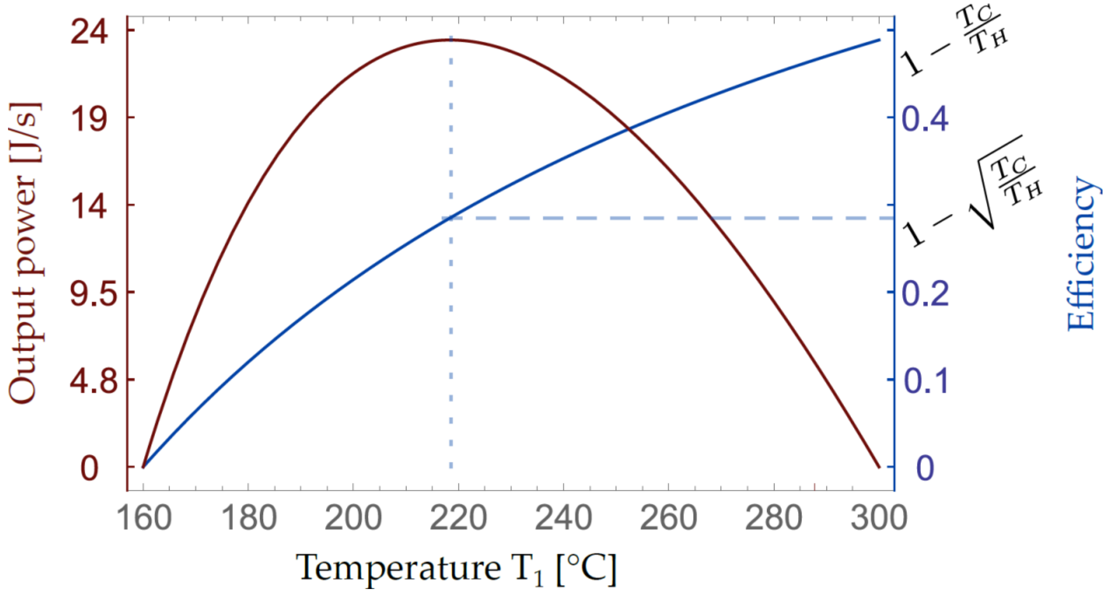
- Larger heat flow 👍
- Larger entropy production 👎

Any entropy input requires heat output



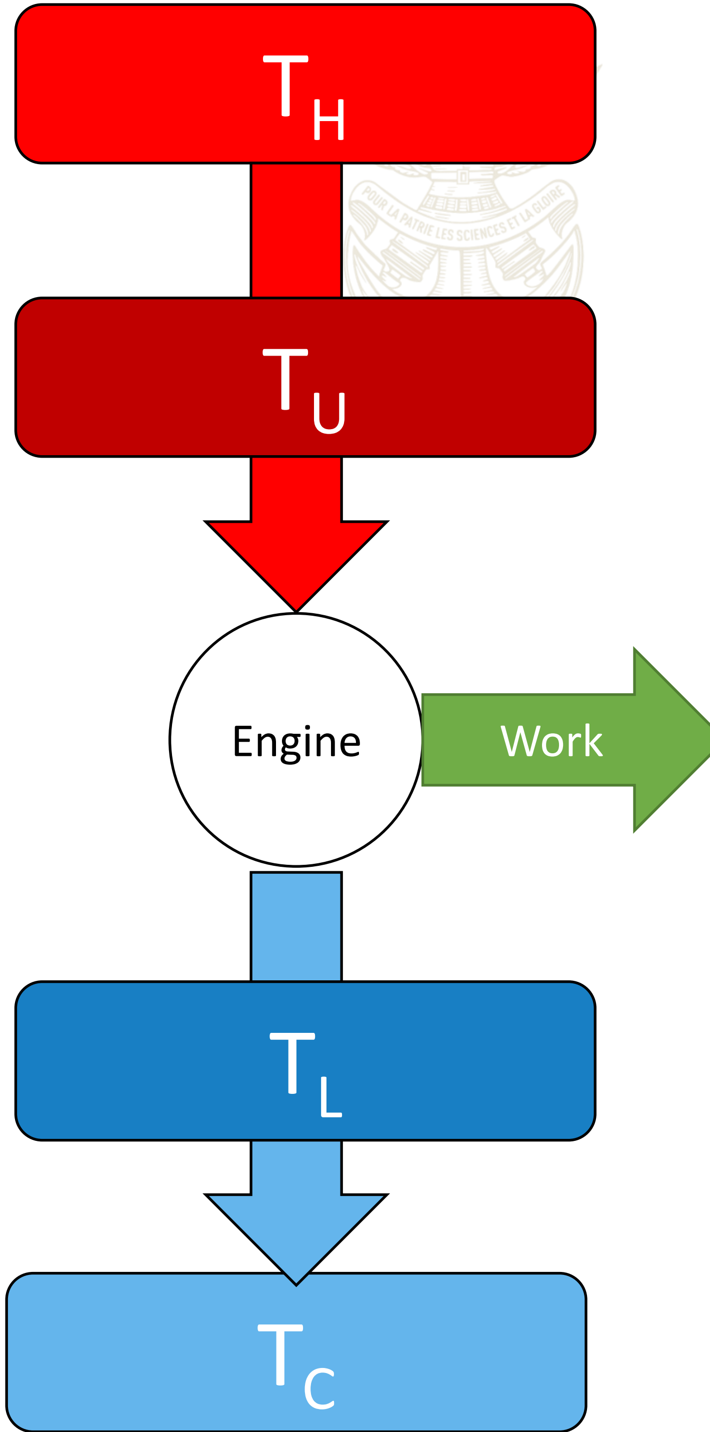
Turning heat into **power**

Hot source @ 300°C, cold source @ 20°C



$$\text{work output} \leq \text{heat input}\left(1-\sqrt{\frac{T_{\text{cold}}}{T_{\text{hot}}}}\right)$$

Curzon-Ahlborn (or Chambadal-Novikov) efficiency



T_H

T_U

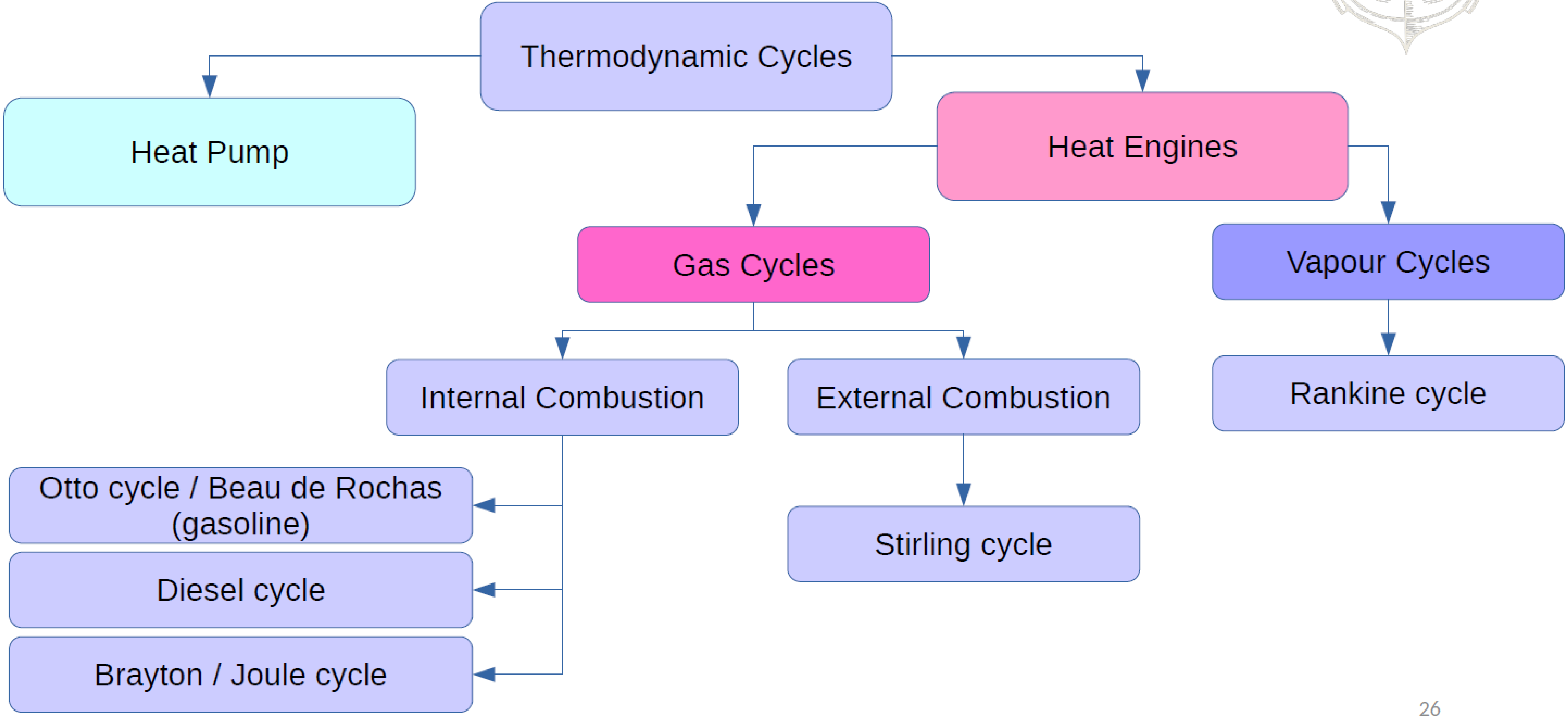
Engine

Work

T_L

T_C

The usual suspects



Thermodynamic Cycles

Heat Pump

Heat Engines

Gas Cycles

Vapour Cycles

Internal Combustion

External Combustion

Rankine cycle

Otto cycle / Beau de Rochas (gasoline)

Diesel cycle

Brayton / Joule cycle

Stirling cycle

Working principle

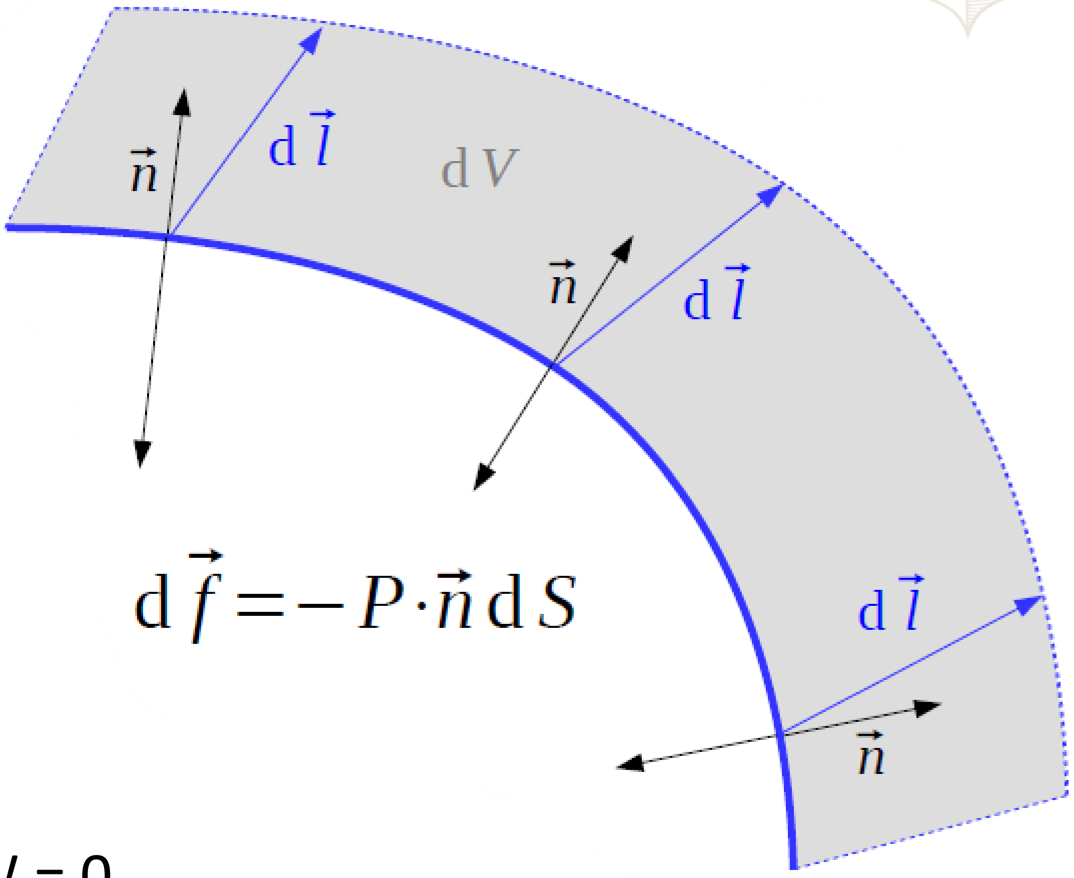
Pressure force : $\mathbf{F} = -p_{\text{ext}}\mathbf{S}$

proportionnal to surface

⊥ to surface

1 bar = 10^5 N/m²

$$\delta W = \mathbf{F}.d\mathbf{r} = -p_{\text{ext}} dV$$



$$d\vec{f} = -P \cdot \vec{n}\, dS$$

Solid & liquid are almost incompressible → W = 0

A word on enthalpy

Transformation under fixed external pressure

1st Law :

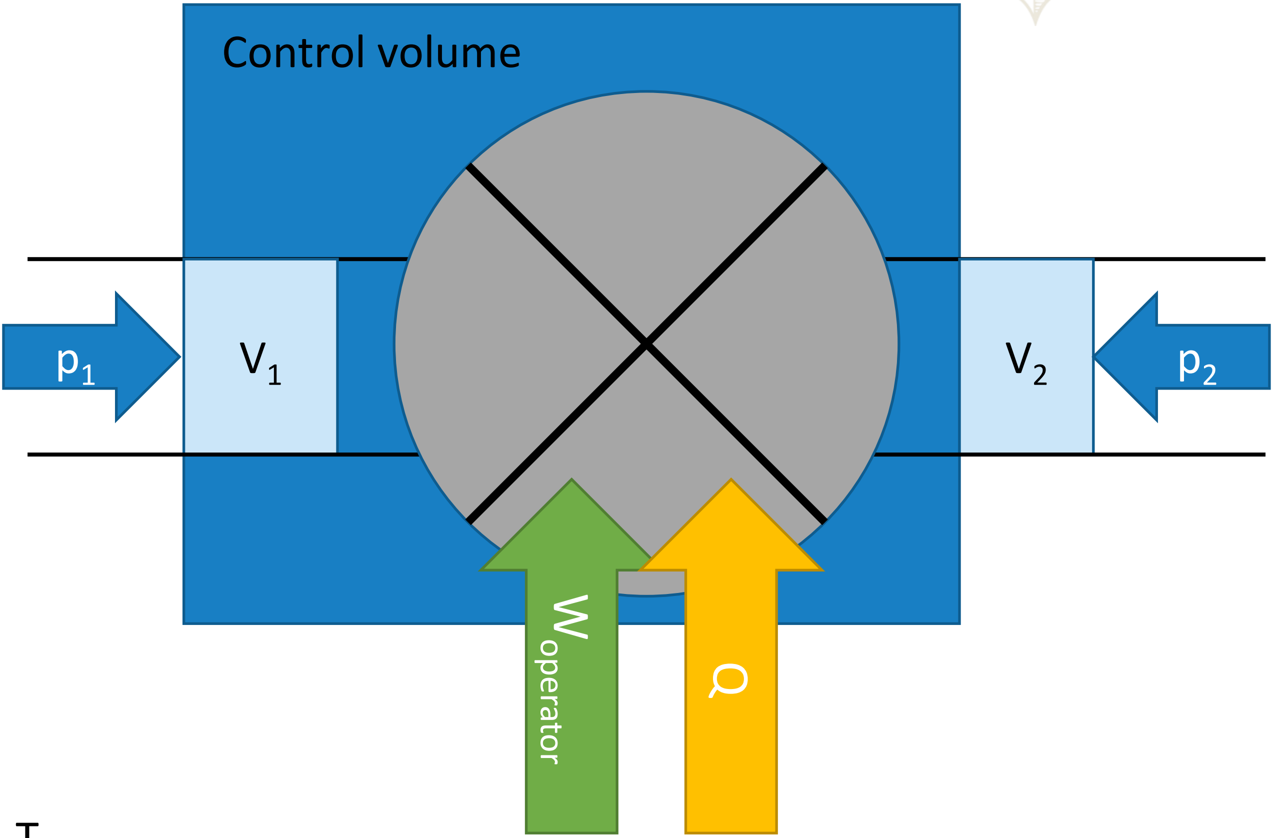
$$dU = \delta W_{\mathrm{p}} + \delta W_{\mathrm{op}} + \delta Q$$

Work of the ambient pressure :

$$\delta W_{\mathrm{p}} = p_1 V_1 - p_2 V_2 = -d(pV)$$

Introducting enthalpy :

$$dH = d(U + pV) = \delta W_{\mathrm{op}} + \delta Q$$



Fixed p_{ext}	Fixed T_{ext}	Fixed p_{ext} & T_{ext}
$H = U + pV$	$F = U - TS$	$G = U + pV - TS$

Everything you need to know about the ideal gas

Equation of state $pV = nRT$ $R = k_B \mathcal{N}_A = 8.314\,\mathrm{J/mol/K}$

Joule’s 1st law : internal energy depends only on temperature $dU = C_V dT$

Reminder : $dU = -pdV + TdS + \mu dN$

Joule’s 2nd law : enthalpy depends only on temperature $dH = C_P dT$

Reminder : $dH = Vdp + TdS + \mu dN$

Mayer’s relation $C_P - C_V = nR$

Definition : Adiabatic index $\frac{C_P}{C_V} = \gamma = 1 + \frac{2}{f}$ $C_V = \frac{nR}{\gamma - 1}$ $C_P = \frac{\gamma nR}{\gamma - 1}$

Everything you need to know about the ideal gas

Equi-parition theorem

$$\frac{U}{N} = f \times \frac{1}{2} k_B T$$

Sackur Terode equation

$$\frac{S}{N} = k_B \left(\frac{5}{2} - \frac{\mu}{k_B T} \right)$$

Chemical potential

$$\mu = k_B T \ln \left(\left(\frac{h}{2\pi m k_B T} \right)^{3/2} \frac{N}{V} \right)$$

Entropy variation in an ideal gas:

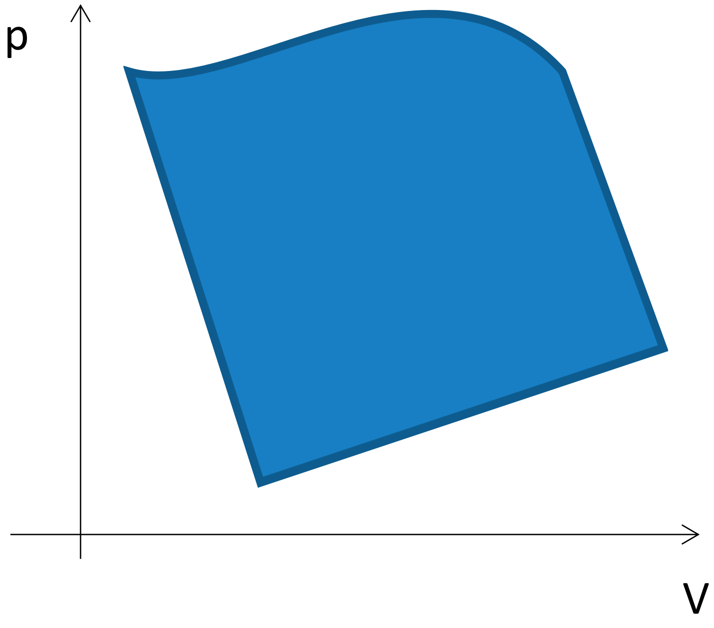
$$\Delta S = nC_V \ln \left(\frac{pV^\gamma}{p_0 V_0^\gamma} \right) = nC_V \ln \left(\frac{TV^{\gamma-1}}{T_0 V_0^{\gamma-1}} \right) = nC_V \ln \left(\frac{T^\gamma p^{1-\gamma}}{T_0^\gamma p_0^{1-\gamma}} \right)$$

Diagrams

pV diagram

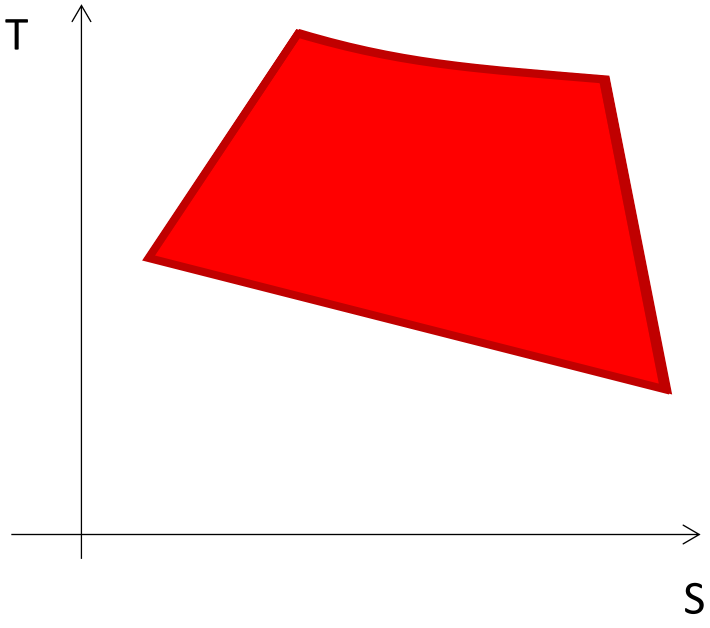
$$W = -\int p dV$$

<0 : engine
>0 : heat pump

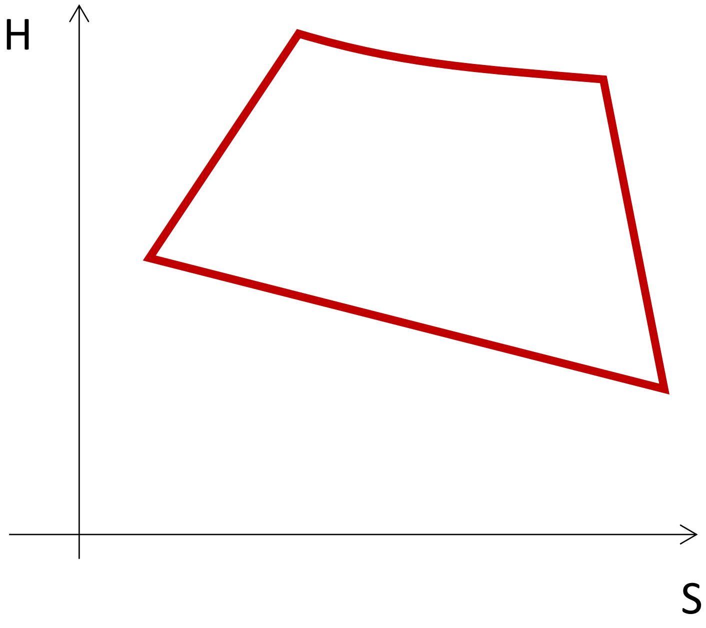


TS diagram

$$Q = \int T dS$$



HS Molier diagram



Usual transformations

Isothermal $T = \text{cst}$ → $pV = nRT = \text{cst}$

Adiabatic + reversible $\delta Q = 0$ → $pV^\gamma = \text{cst}$

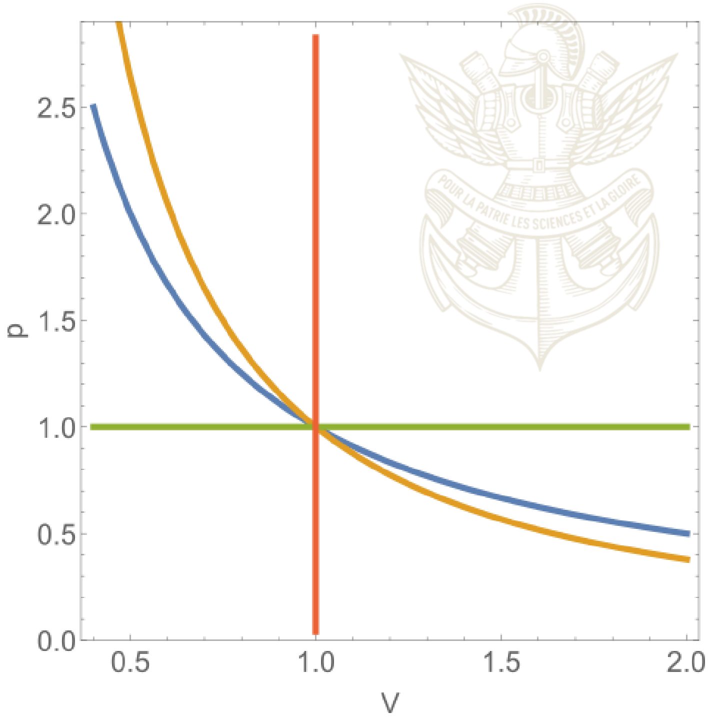
$TV^{\gamma-1} = \text{cst}$

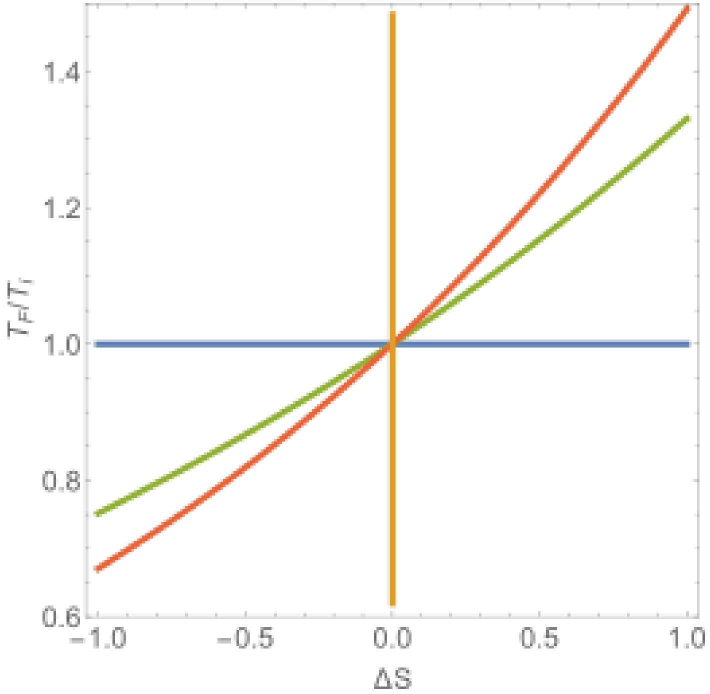
Isobaric $p = \text{cst}$ → $T_f = T_i \exp \Delta S / C_p$

$$\Delta V = \frac{nR}{p} \Delta T$$

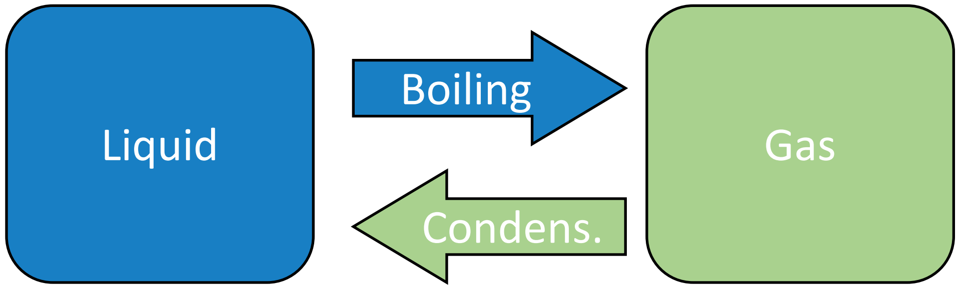
Isochorus $V = \text{cst}$ → $T_f = T_i \exp \Delta S / C_v$

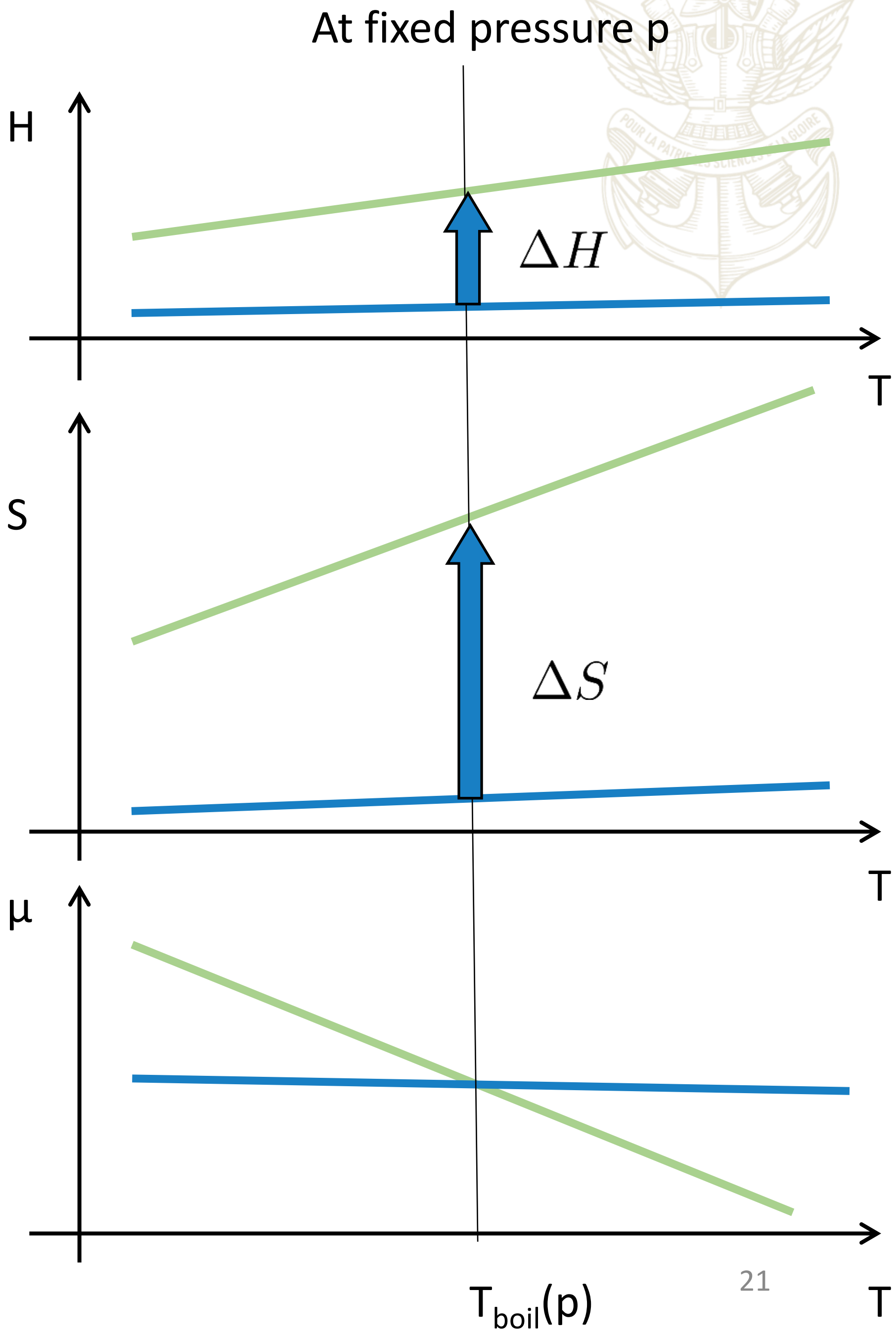
$$\Delta p = \frac{nR}{V} \Delta T$$





Phase change





Phase change happen when… ?

$$\mu_{\varphi_1}(T, p, \ldots) = \mu_{\varphi_2}(T, p, \ldots)$$

Pure body : change at fixed temperature

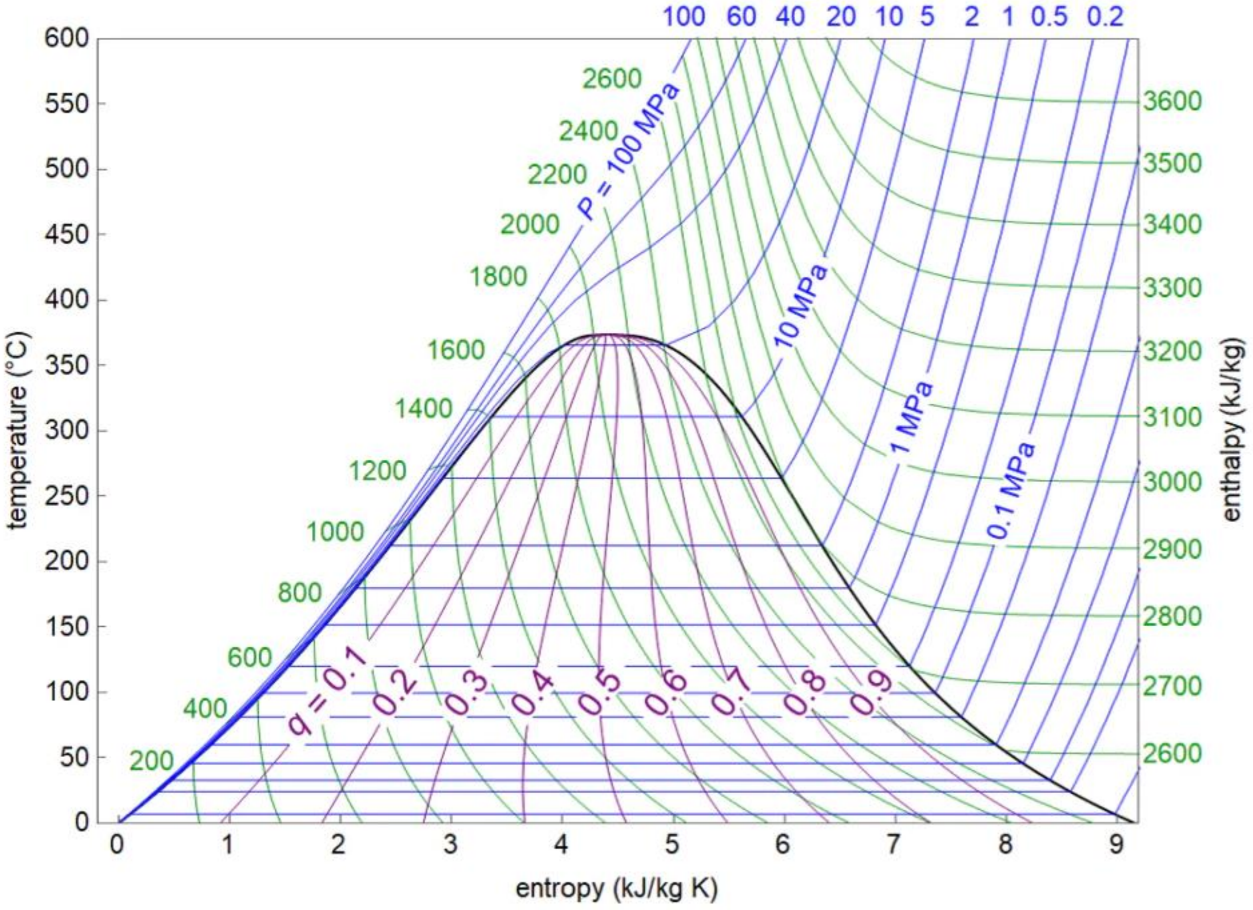
Amount of heat required for full change (*latent heat*) ΔH

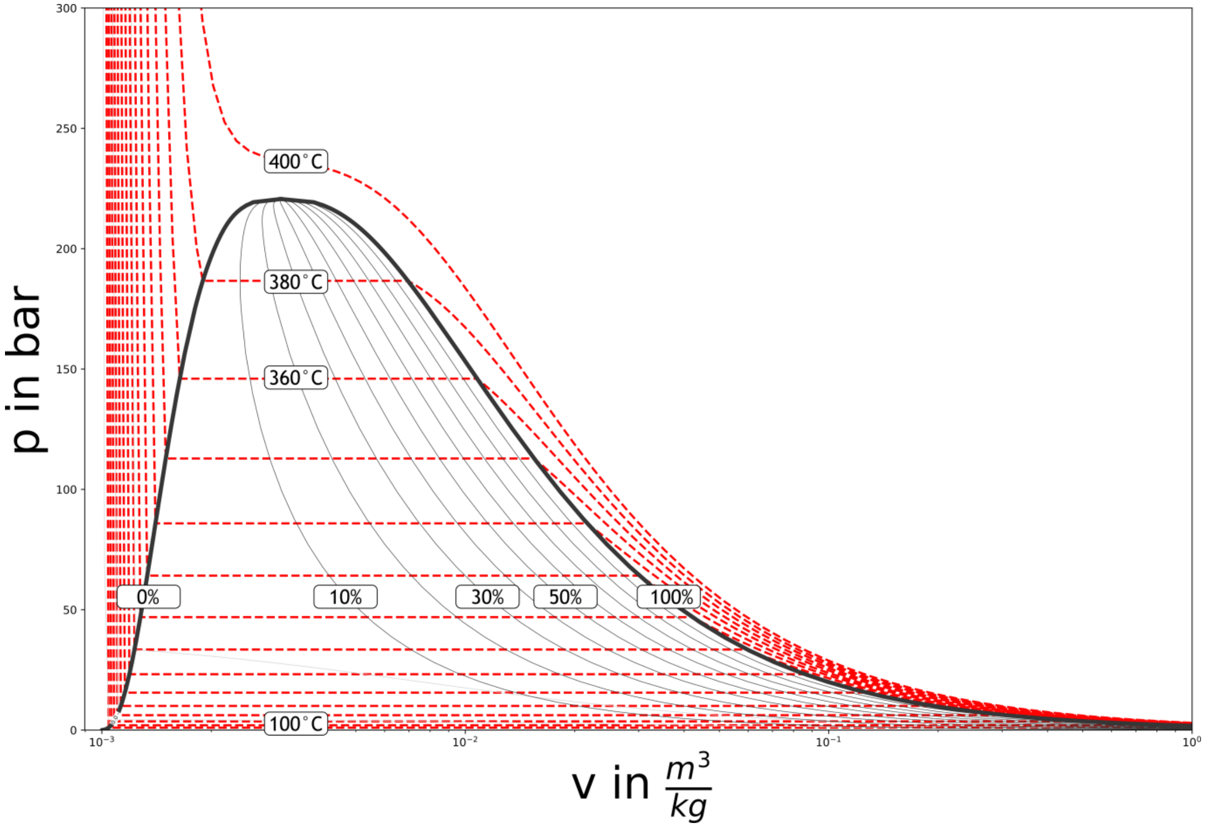
Amount of entropy required for full change ΔS

$$\Delta S = \frac{\Delta H}{T}$$

Reversible transformation

Phase change – diagram view





Lecture 4
Heat engines

I. What, why, where ?

II. Thermodynamics framework

III. Standard cycles and their applications

IV. Perspectives

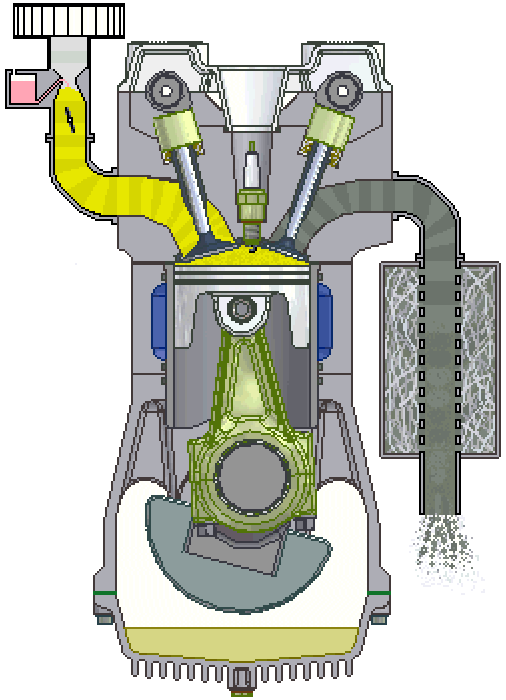
Air-standard assumptions

- Working fluid = pure air = ideal gas.
- Combustion = heat input from an external source
- Cycle = closed, with the same air remaining in the system. Intake and exhaust processes are not considered.
- All processes are reversible

Otto cycle - theory

(aka Beau de Rochas cycle)

Internal combustion engine (ICE)
with spark ignition (SI)



Source : wikimedia

(0-1: intake)

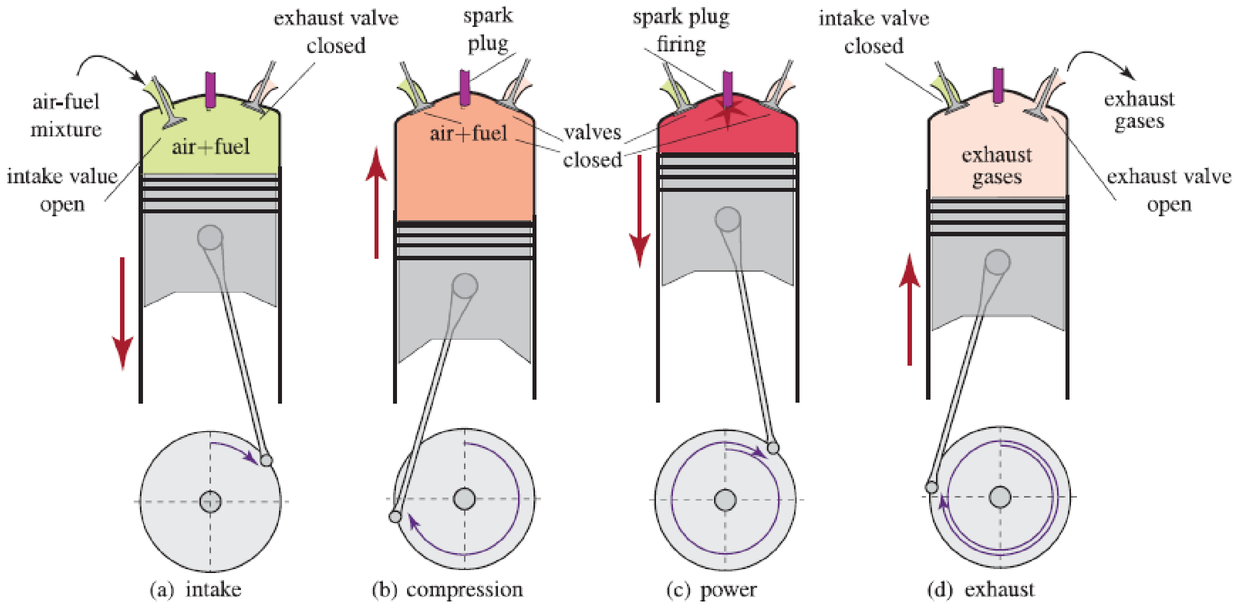
1-2: compression (isentropic)

2-3: ignition (**isochorous**) from a spark plug

3-4: expansion (isentropic)

4-1: ideal heat rejection (isochorous)

(1-0: exhaust)



Otto cycle - theory

(0-1: intake)

1-2: compression (isentropic)

2-3: ignition (**isochorous**) from a spark plug

3-4: expansion (isentropic)

4-1: ideal heat rejection (isochorous)

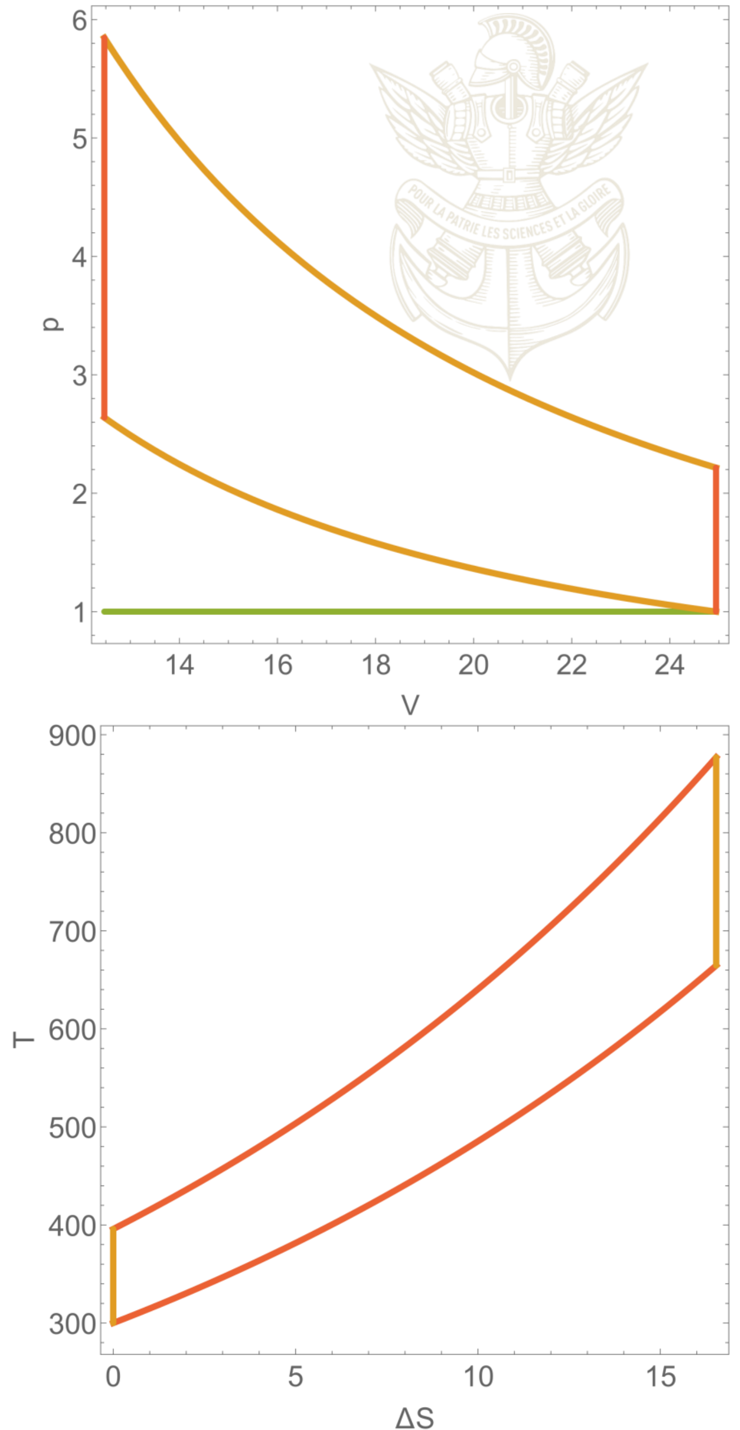
(1-0: exhaust)

(Volumic) compression ratio

$$r = \frac{V_1}{V_2}$$

Efficiency

$$\eta = 1 - \frac{1}{r^{\gamma - 1}}$$



2 stroke versus 4 stroke

Same thermodynamic cycle, different implementation

4 stroke : 1 cycle = 2 full rotations

Stroke = piston move

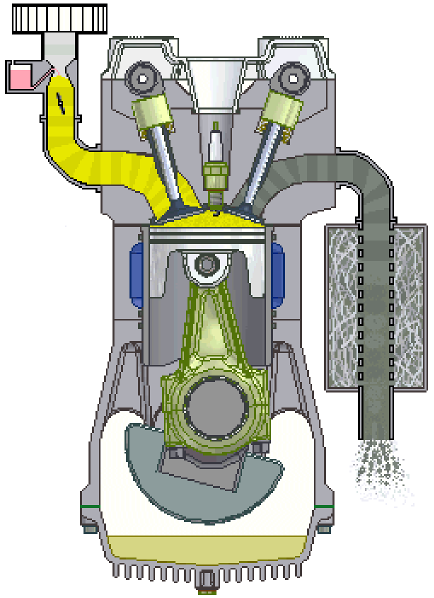
2 stroke : 1 cycle = 1 full rotation

Intake & exhaust at the same time

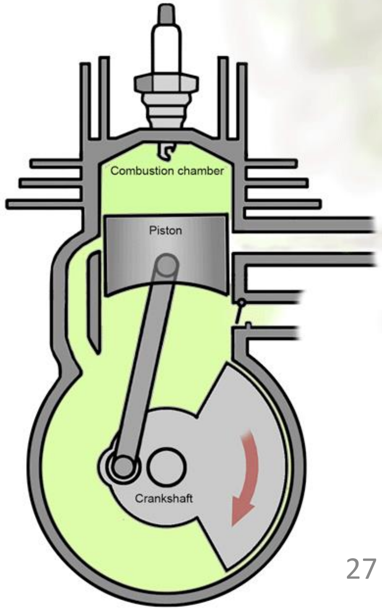
Lighter, less complex

Hand-carried applications (chainsaw…)

Lubrificating oil burnt with fuel (« oil mix »)



Source : wikimedia



Source: UN Environment Program.

Otto cycle - reality

Idealized vs real cycle

- compressions are not fully isentropic
- heat rejection & exhaust at the same time

Mostly used in light vehicles

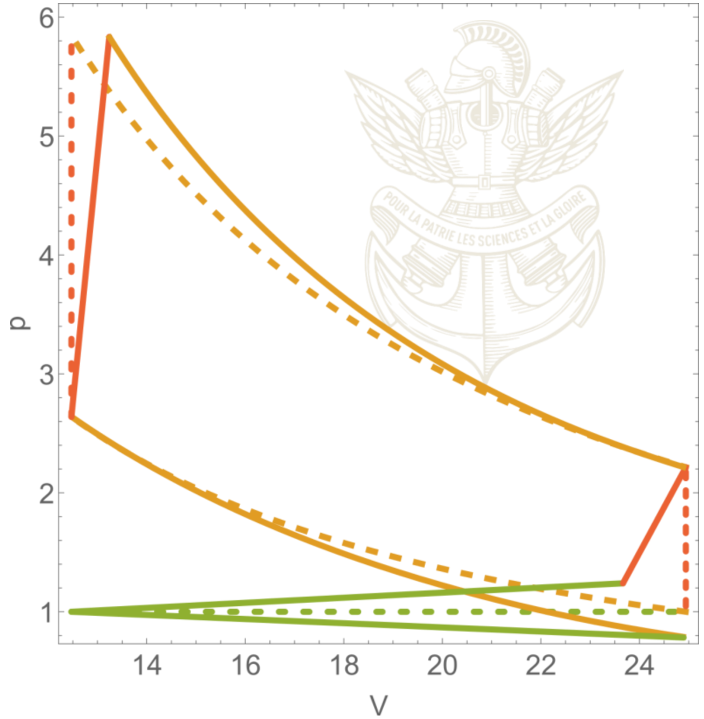
Compression ratio r~10, limited by self-ignition (“knock”)

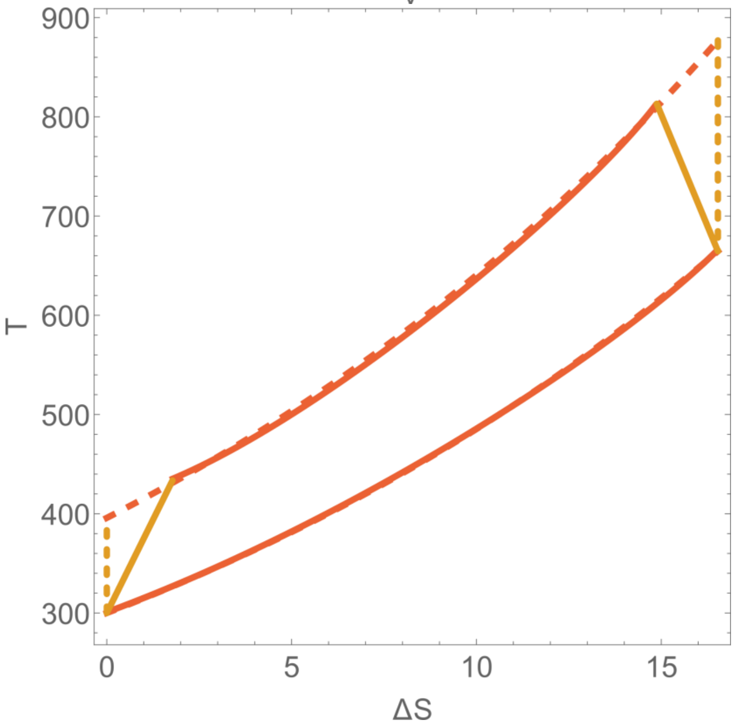
A turbo charger can extract work from the exhaust stream to pressurize intake air

⇒ increased yield

An intercooler can be used to reduce the intake air temperature and thus increase air density

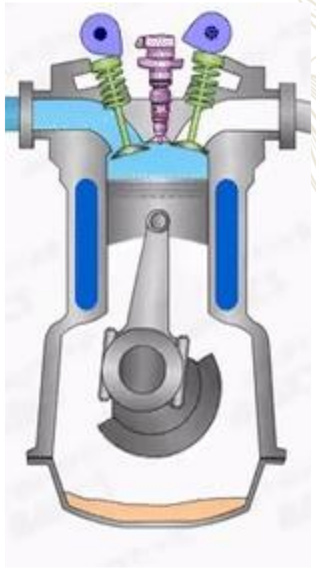
⇒ increased power





Diesel cycle - theory

Internal combustion engine (ICE)
with compression ignition (CI)



Source : extrudesign.com

(0-1: intake)

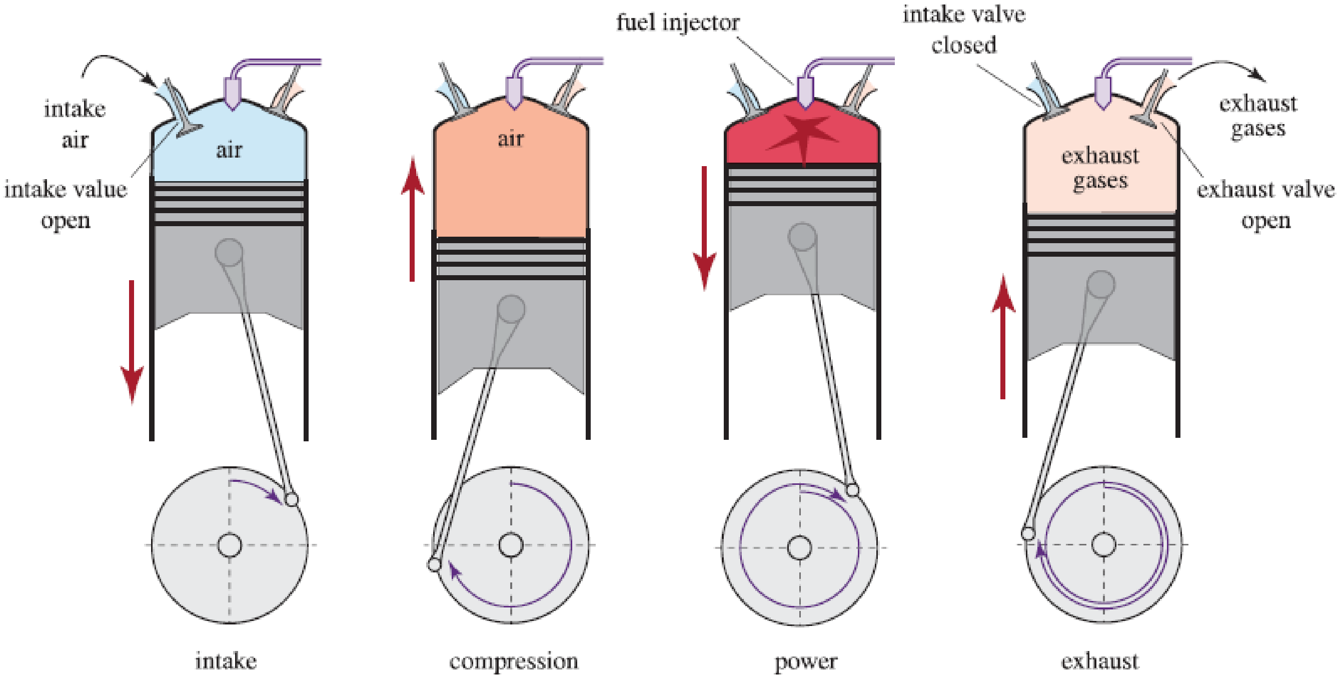
1-2: compression (isentropic)

2-3: ignition (**isobaric**)

3-4: expansion (isentropic) until V_1

4-1: heat rejection (isochorous)

(1-0: exhaust)



Diesel cycle - theory

(0-1: intake)

1-2: compression (isentropic)

2-3: ignition (**isobaric**)

3-4: expansion (isentropic) until V_1

4-1: heat rejection (isochorous)

(1-0: exhaust)

(Volumic) compression ratio

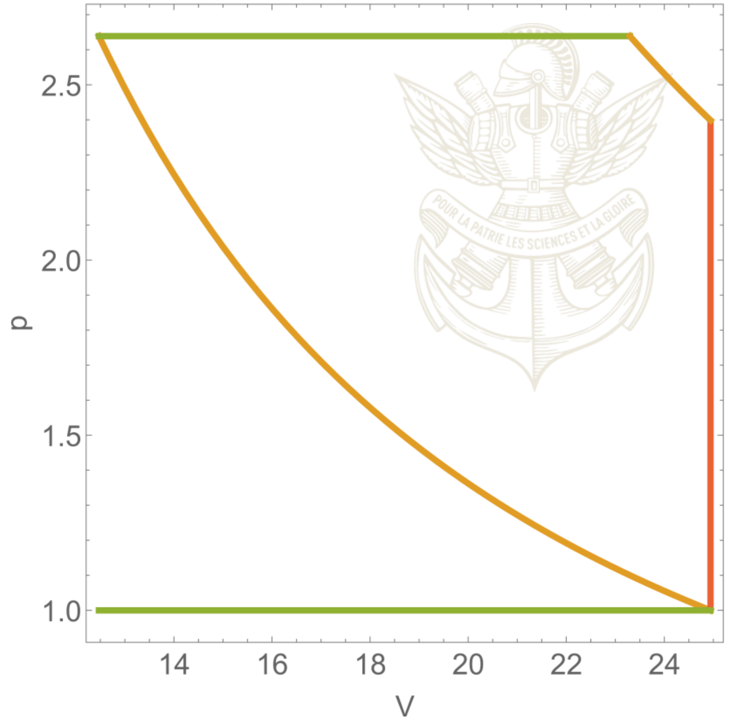
$$r = \frac{V_1}{V_2}$$

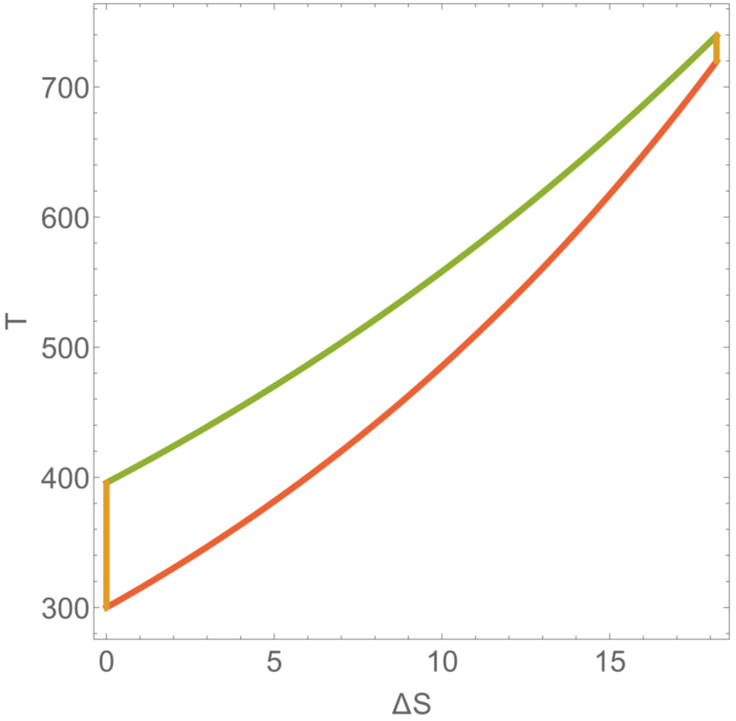
Cut off ratio

$$\beta = \frac{V_3}{V_2}$$

Efficiency

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \frac{\beta^\gamma - 1}{\gamma(\beta - 1)}$$





Diesel cycle - application

Higher compression ratio (between 15 & 23)

→ Higher efficiency

Higher torque

Less sensitive to fuel

Wärtsilä-Sulzer 14RT-flex96C

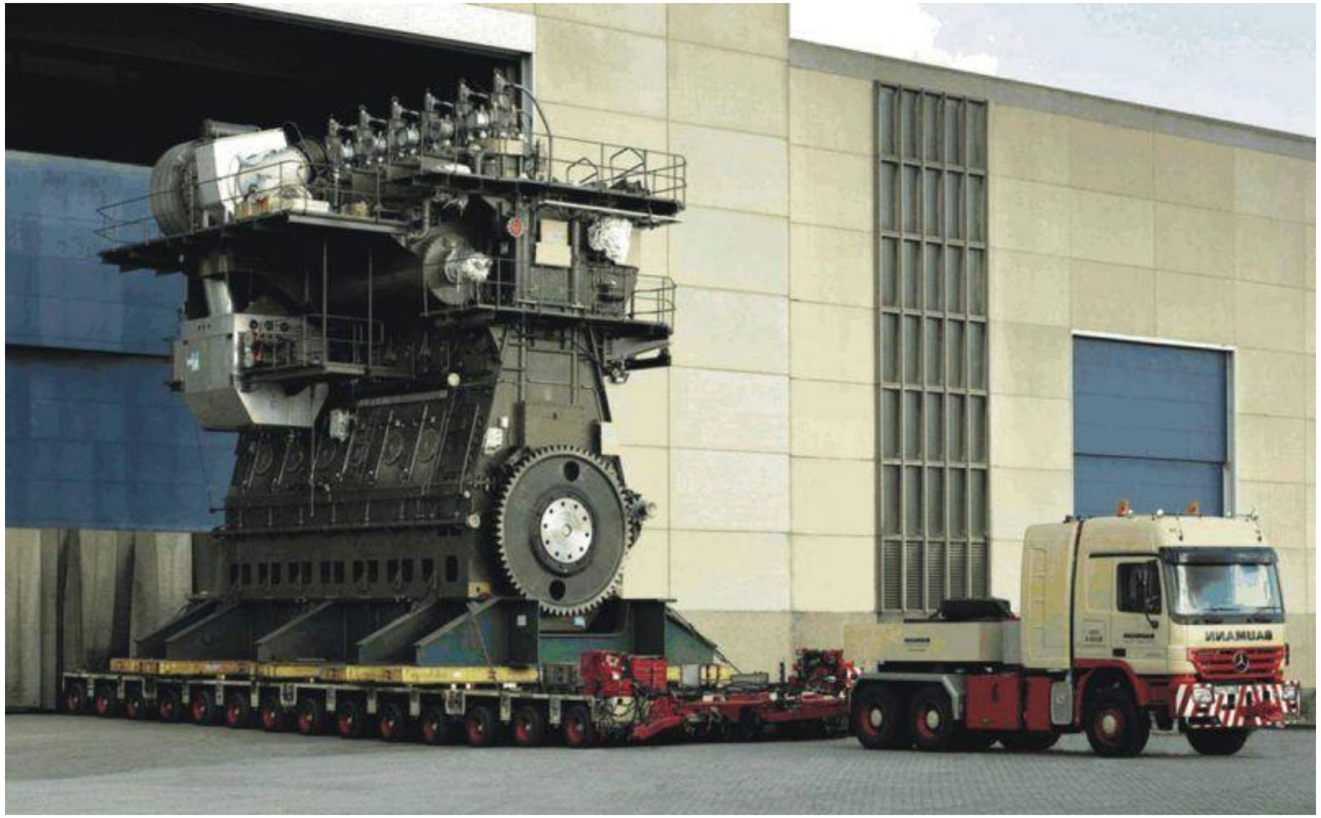
2 stroke, 14 cyclinders

2 300 t, 13.5m high, 27.3m large

80 080 kW @ 102 rpm

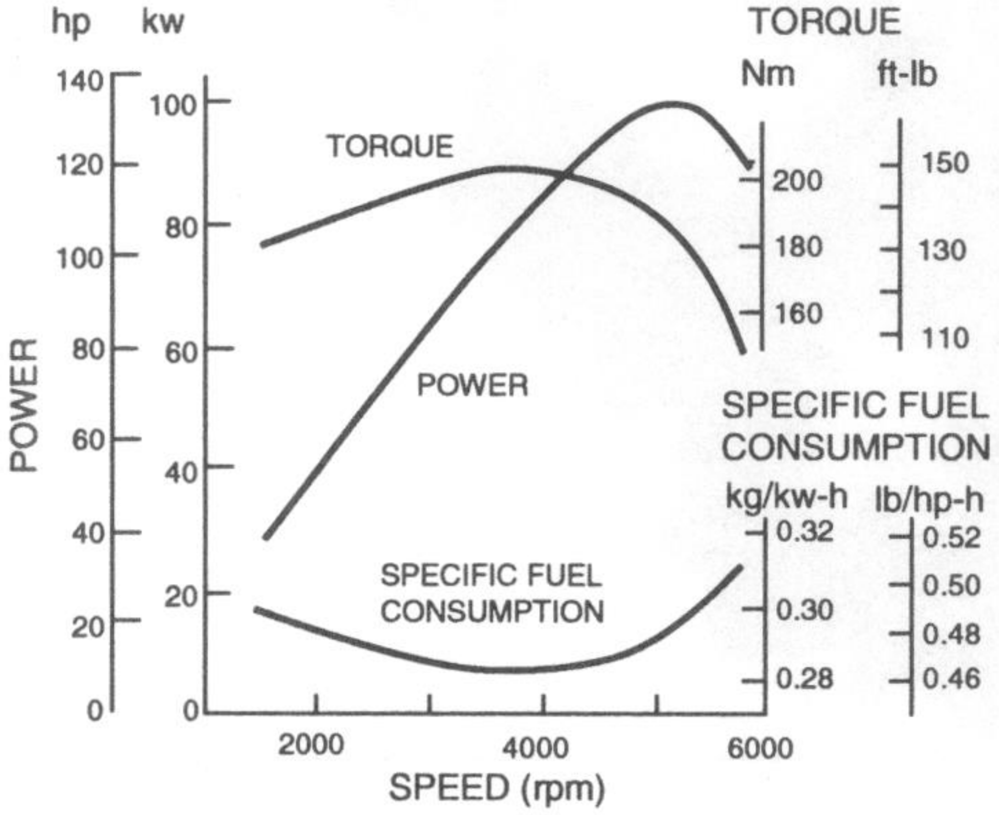
3.8 L/s

~ 50% efficiency

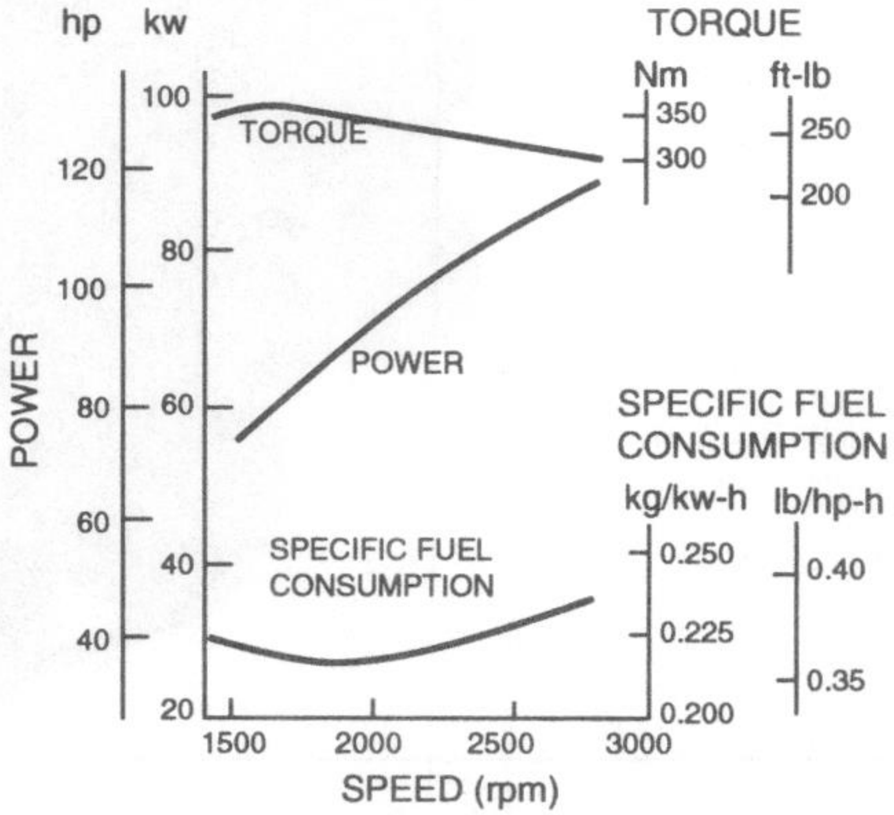


Power & torque

$$P = \eta \times Q_{\text{comb}} \times \frac{1}{T_{\text{cycle}}} = \Gamma \times \omega$$



Gasoline



Diesel

Fundamentals of Vehicle Dynamics, T. D. Gillespie, 1992

Brayton / Joule cycle - theory

(intake)

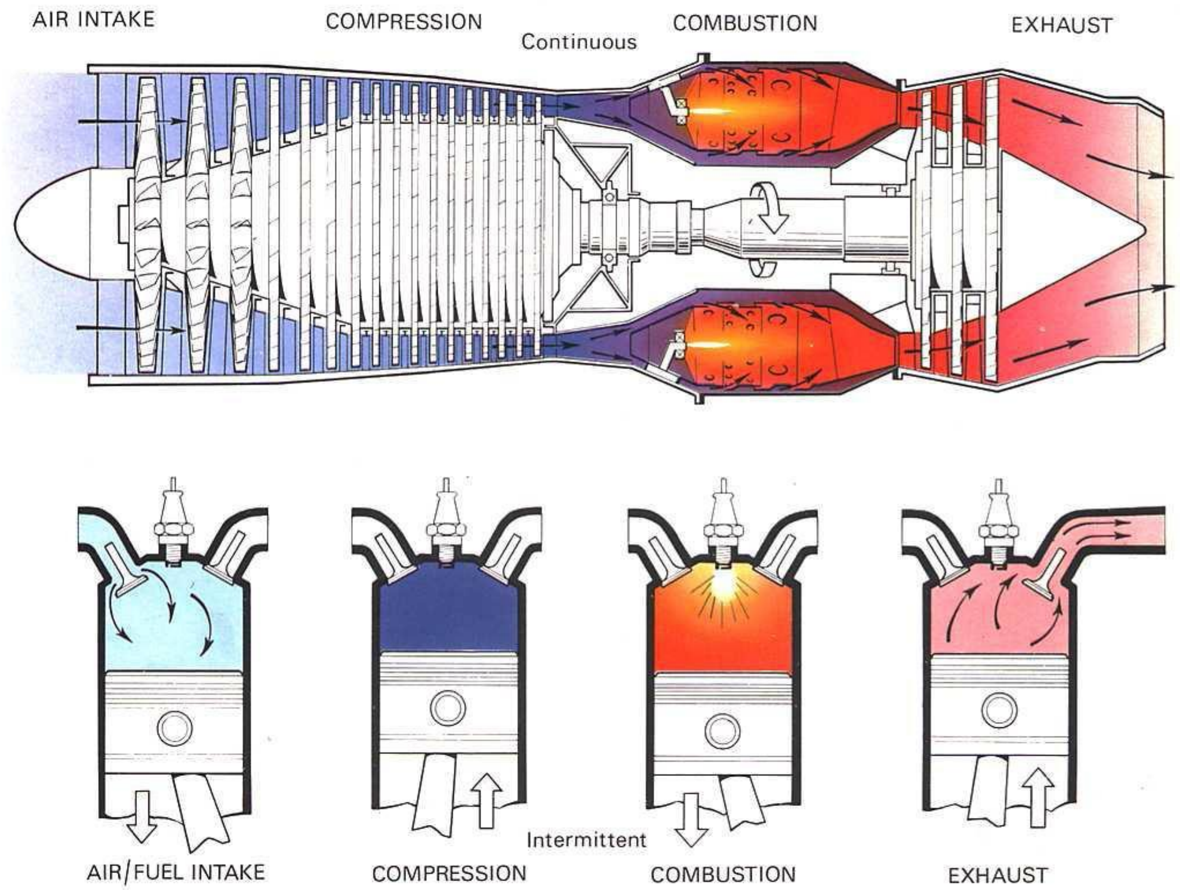
1-2: compression (isentropic)

2-3: ignition (**isobaric**)

3-4: expansion (isentropic)

4-1: ideal heat rejection (**isobaric**)

(exhaust)



Brayton / Joule cycle - theory

intake

1-2: compression (isentropic)

2-3: ignition (**isobaric**)

3-4: expansion (isentropic)

4-1: ideal heat rejection (**isobaric**)

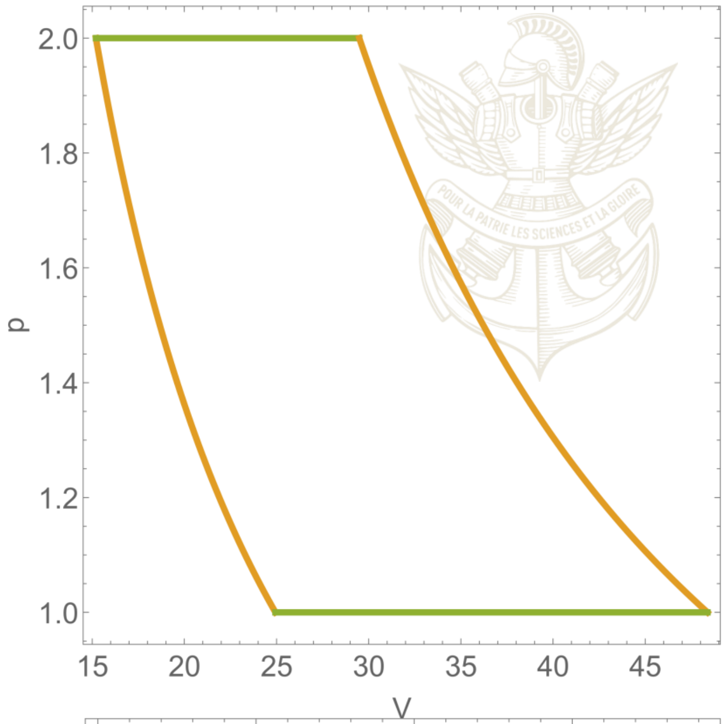
exhaust

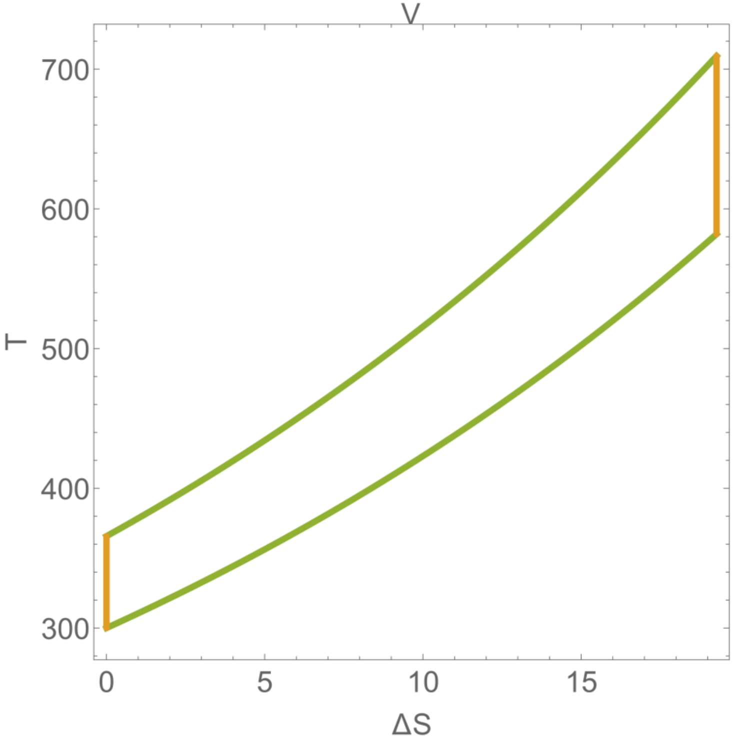
(Pressure) compression ratio

$$r_p = \frac{p_2}{p_1}$$

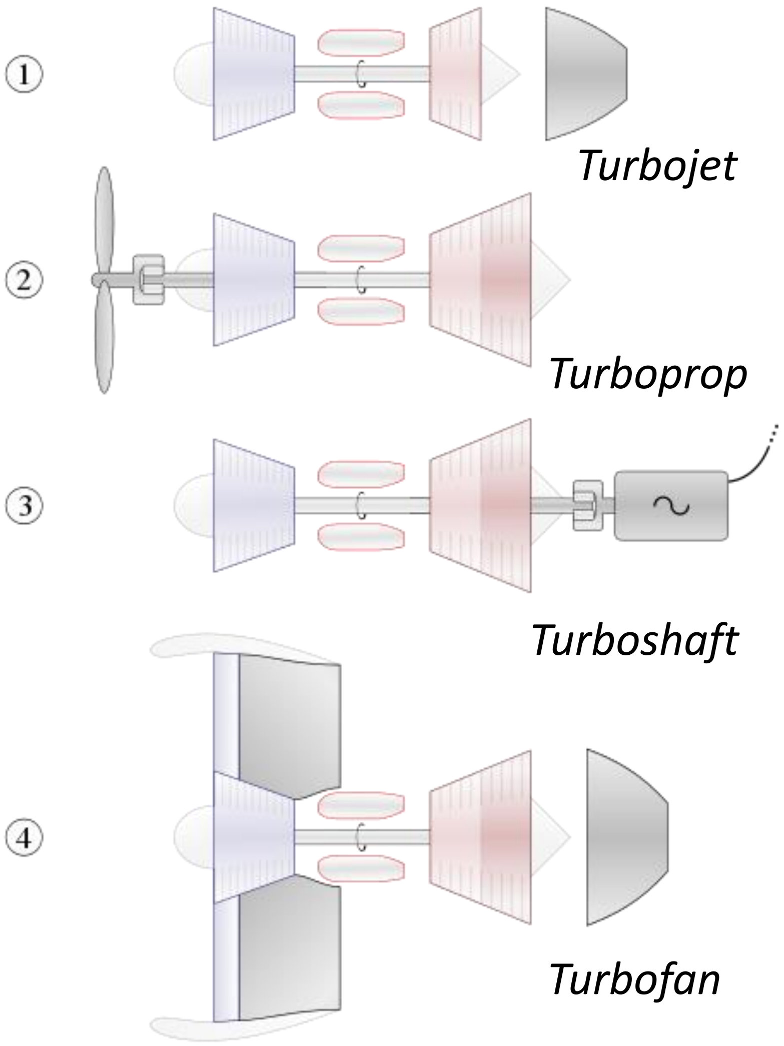
Efficiency

$$\eta = 1 - \frac{1}{{r_p}^{\frac{\gamma-1}{\gamma}}}$$



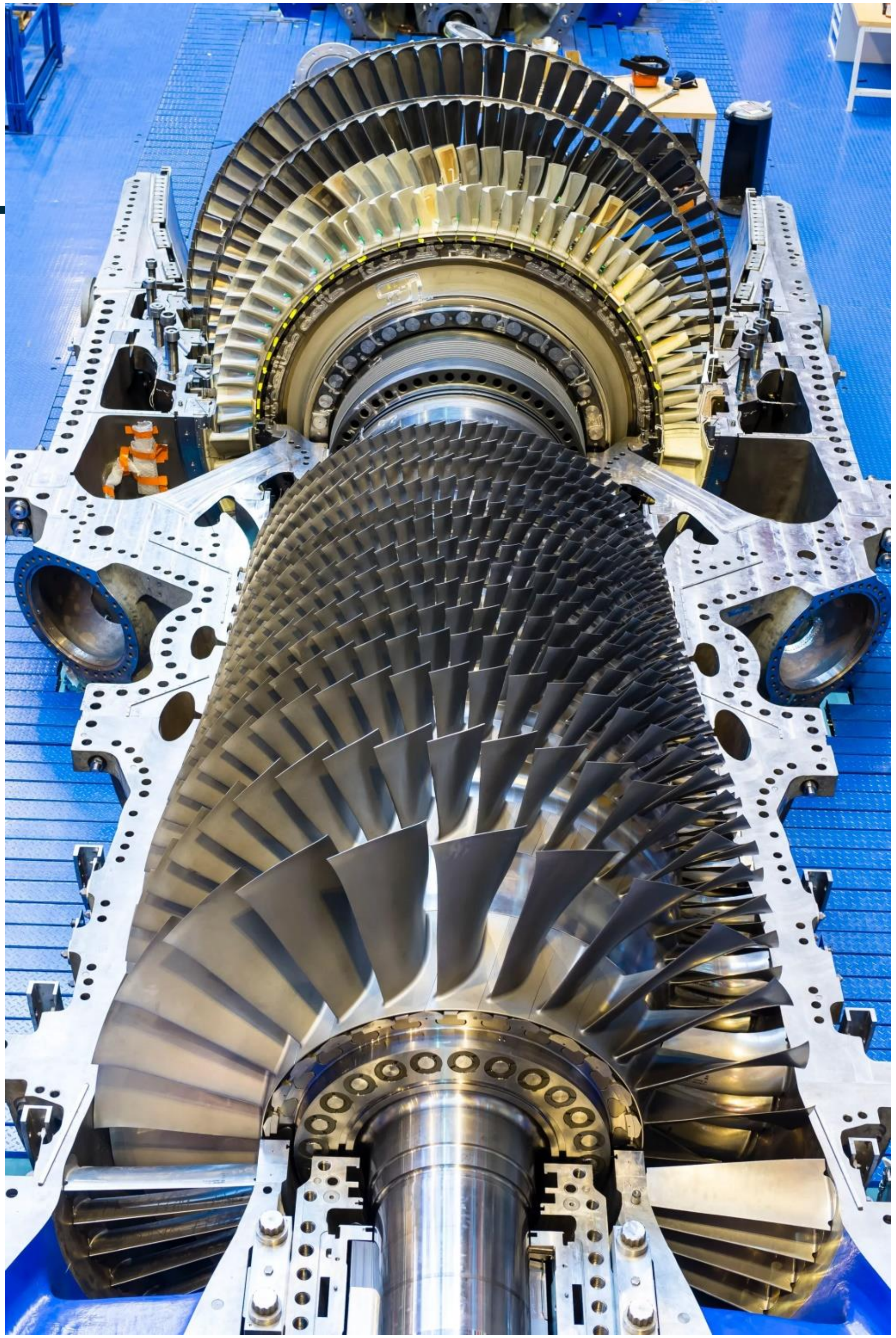


Brayton cycle - application



Source : wiki

GE Harriet 9HA
571 MW – 44% efficiency
Ramp rate: 88 MW/min



Improving gas turbine efficiency

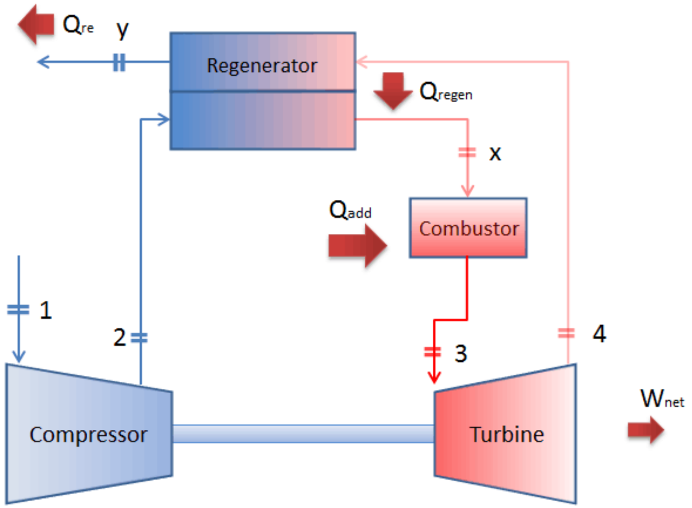
Avoid wasting exhaust heat

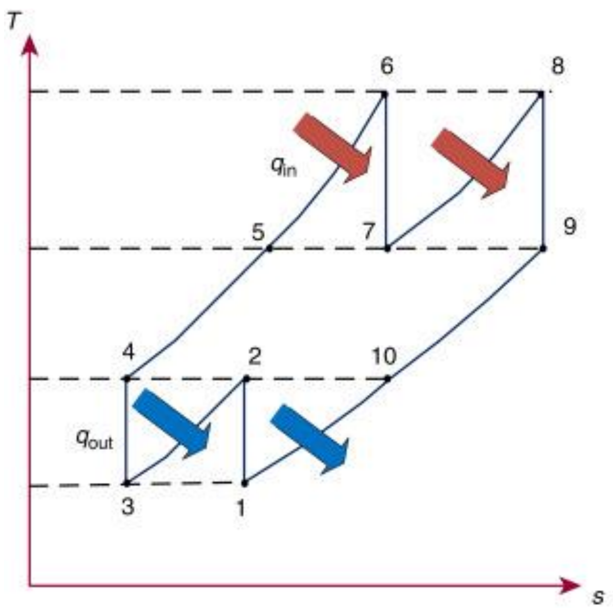
Reduce compression work :

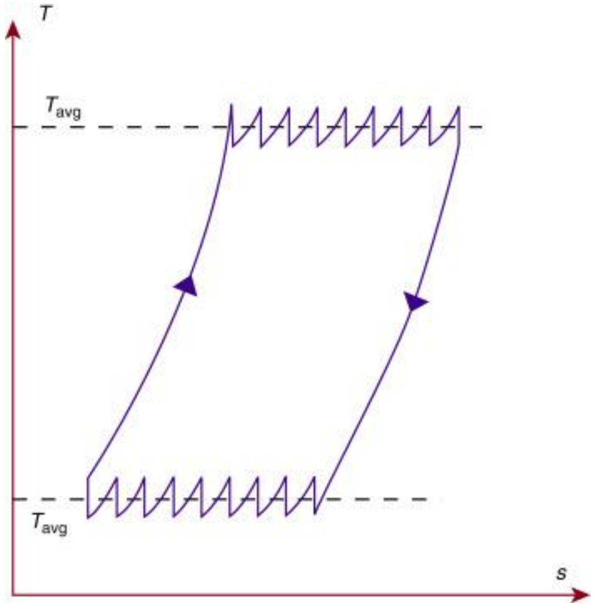
multi stage compressor with intercooler

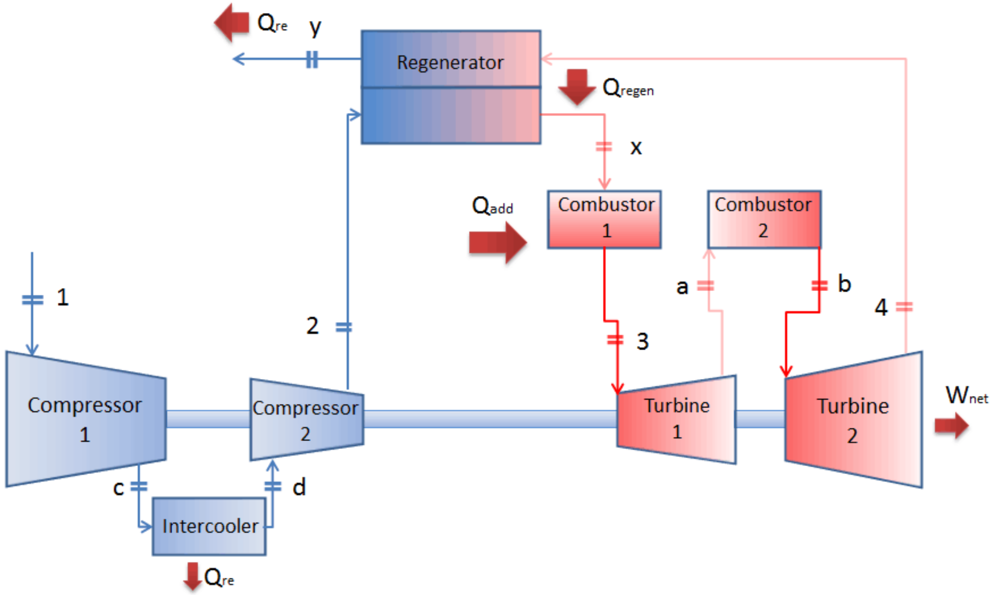
Increase expansion work :

multi stage combustion with reheaters









Rankine cycle - theory

External combustion engine

1-2: **liquid** compression (isentropic)

2-3: heated and vaporized (isobaric)

3-4: expansion in a turbine (isentropic)

4-1: wet vapour condensation (isobaric)

$$\eta = \frac{W_{\mathrm{out}} - W_{\mathrm{comp}}}{Q_{\mathrm{in}}} = 1 - \frac{h_2 - h_3}{h_1 - h_4} \simeq 34 - 40\%$$

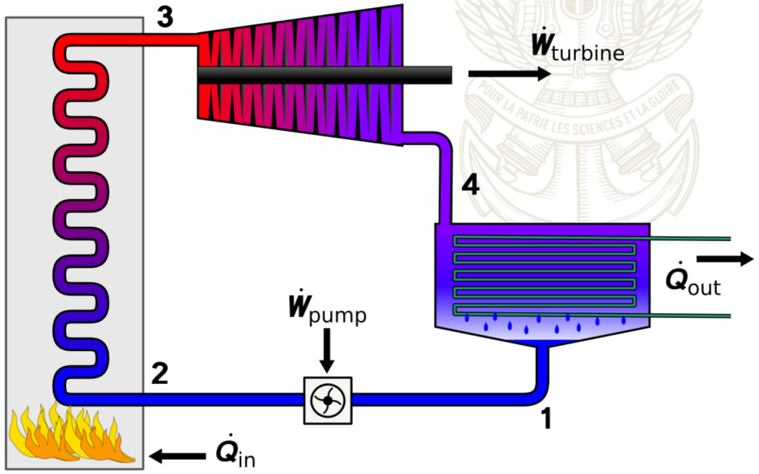
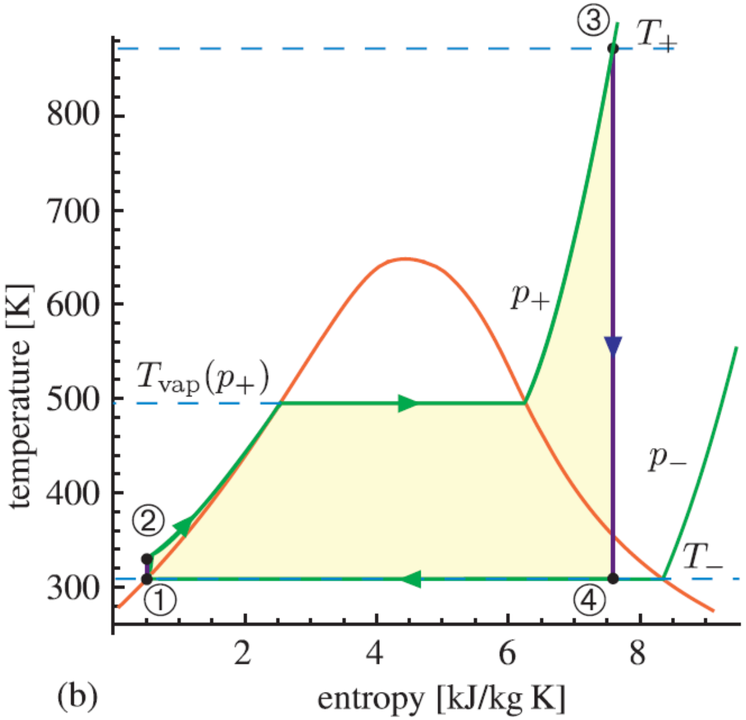
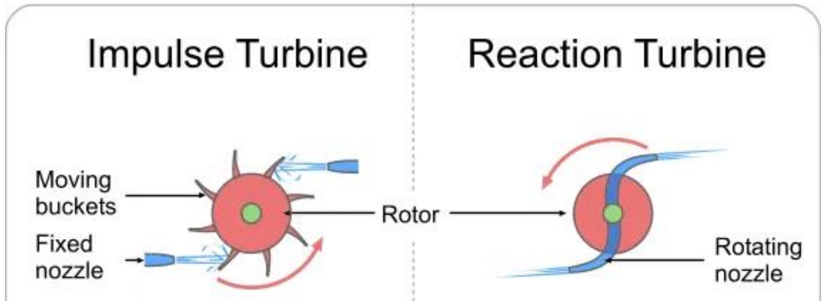


Figure : wikipedia



Jaffe & Taylor

Turbine design – impulse turbine



Driving force :
velocity

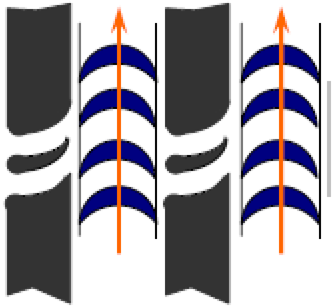
Fixed Nozzle
converts p → v

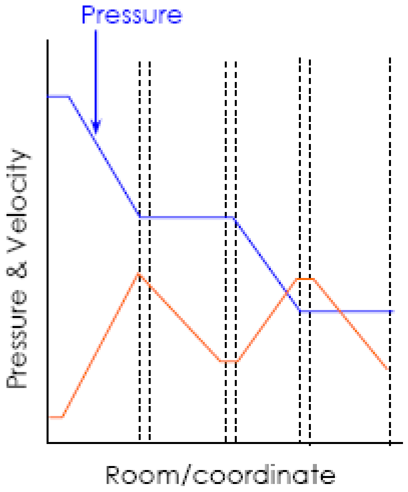
Moving blades
extract velocity
at cst pressure

Fixed blades
redirect velocity
at cst pressure

Rateau turbine

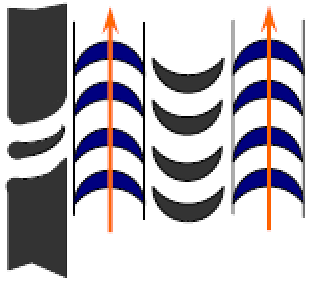
Pressure compounding

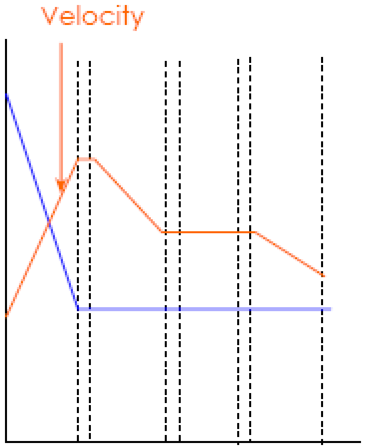




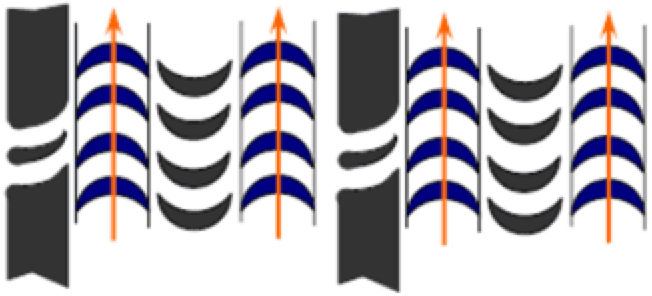
Curtis turbine

Velocity compounding



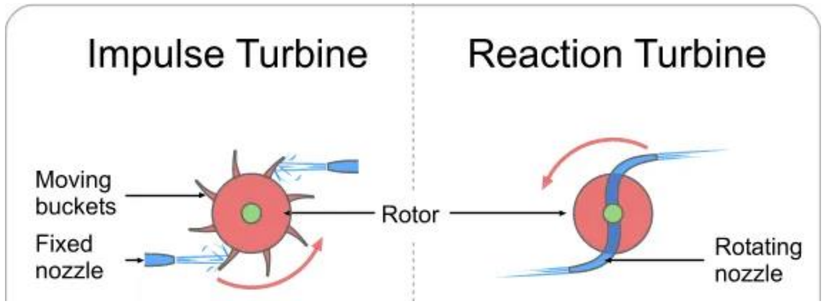


Pressure – velocity compounding

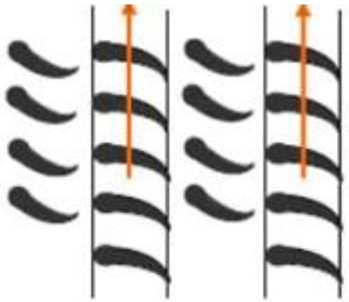


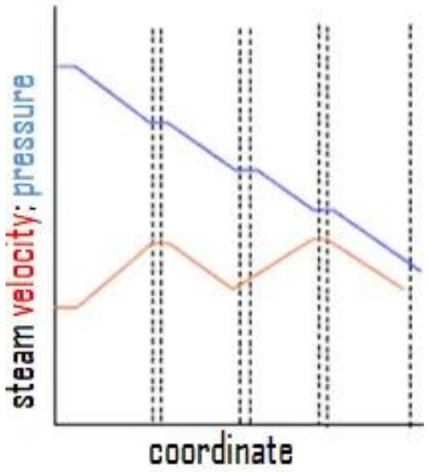
Lecture 8 : Pelton turbine

Turbine design – reaction turbine



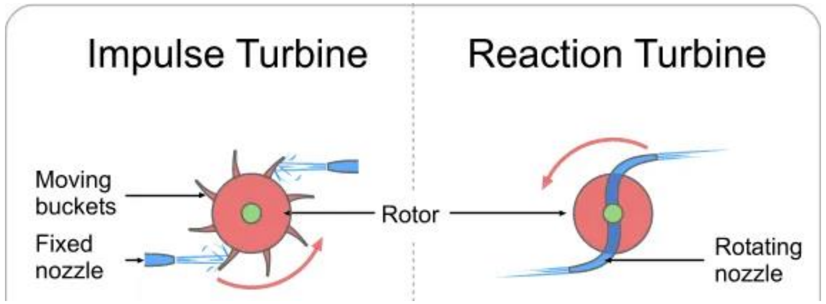
Driving force : velocity	Driving force : pressure
Fixed Nozzle converts p → v	No ‘‘nozzle’’
Moving blades extract velocity at cst pressure	Moving blades due to pressure gradient
Fixed blades redirect velocity at cst pressure	Fixed blades due to pressure gradient





Lecture 8 : Kaplan, Francis turbine

Turbine design – in practice



Driving force : velocity	Driving force : pressure
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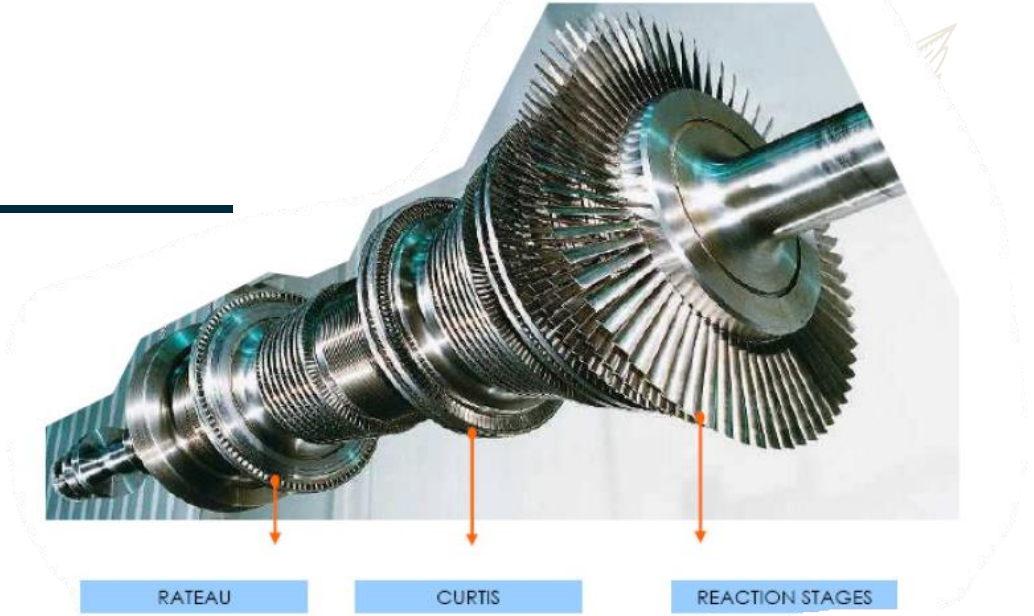
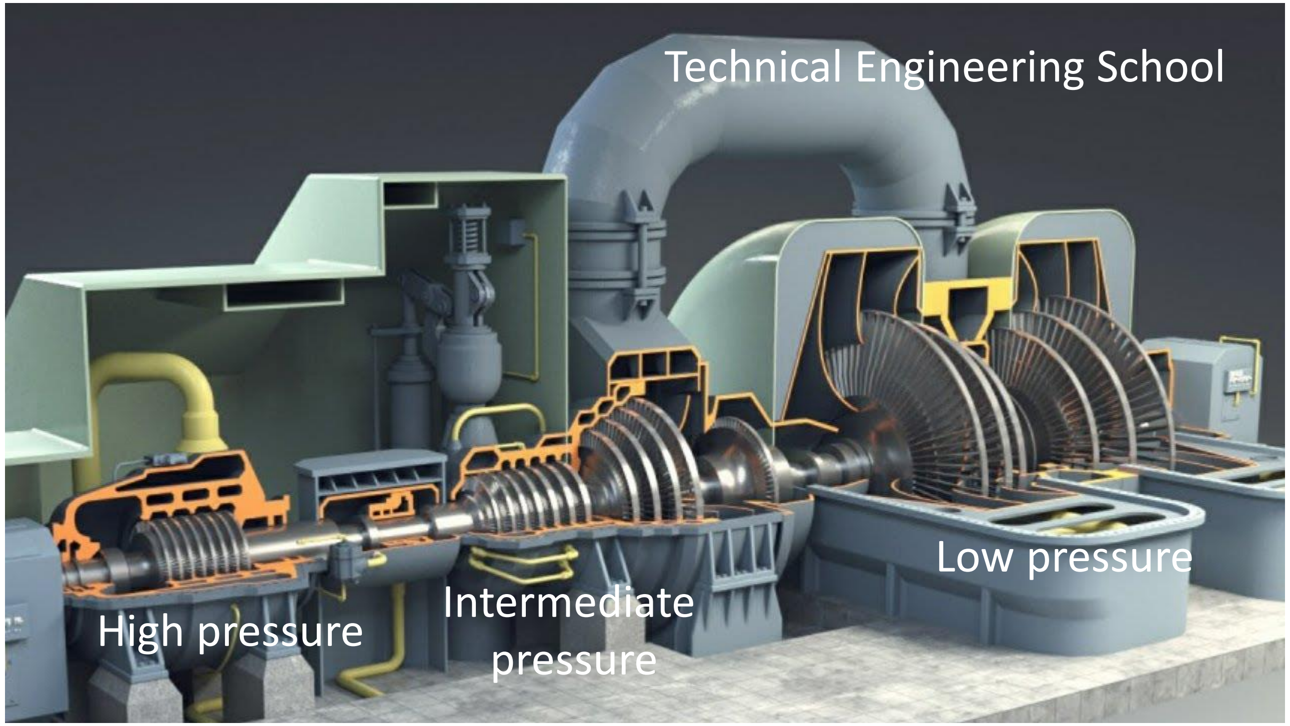
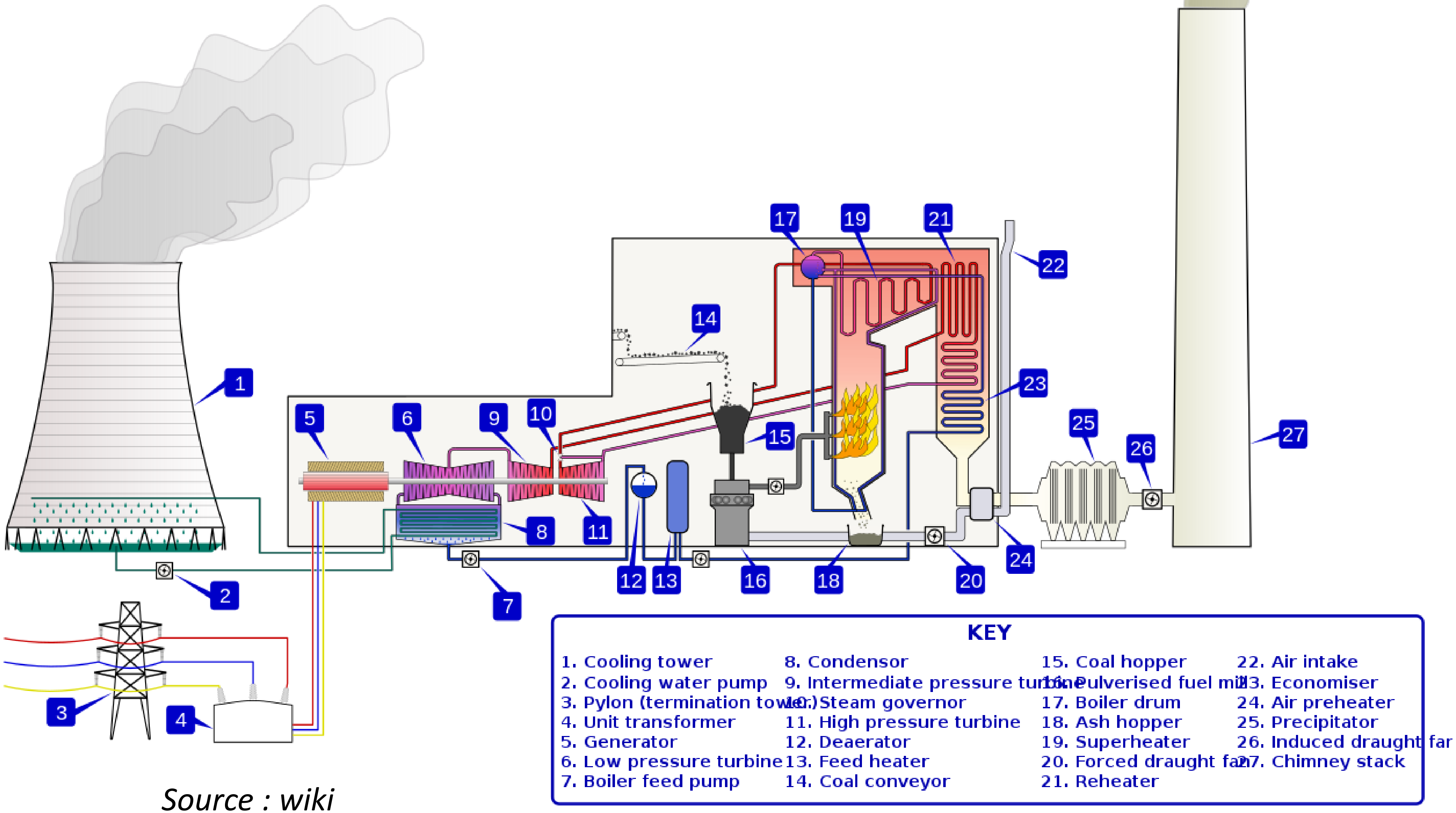




Coal (and nuclear) power plant



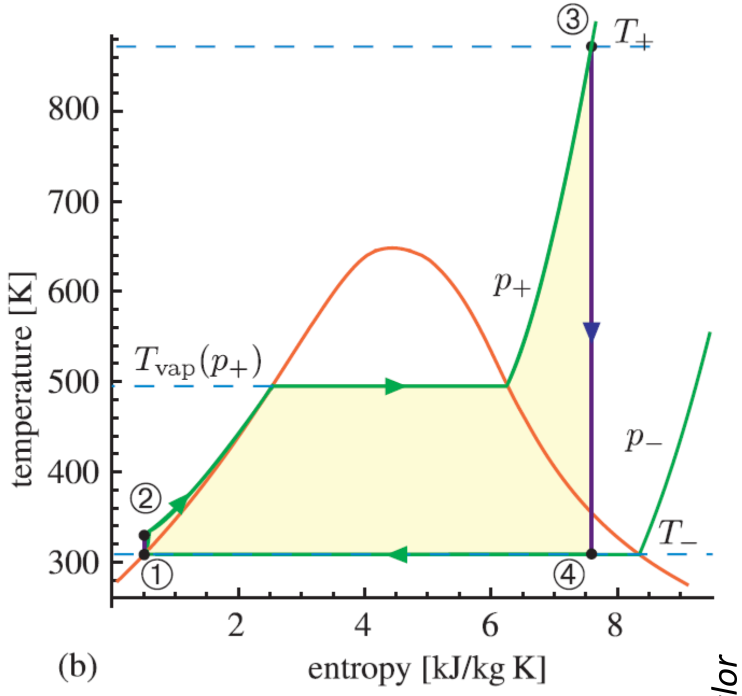
KEY

1. Cooling tower
2. Cooling water pump
3. Pylon (termination tower)
4. Unit transformer
5. Generator
6. Low pressure turbine
7. Boiler feed pump
8. Condensor
9. Intermediate pressure turbine
10. Steam governor
11. High pressure turbine
12. Deaerator
13. Feed heater
14. Coal conveyor
15. Coal hopper
16. Pulverised fuel mill
17. Boiler drum
18. Ash hopper
19. Superheater
20. Forced draught fan
21. Reheater
22. Air intake
23. Economiser
24. Air preheater
25. Precipitator
26. Induced draught fan
27. Chimney stack

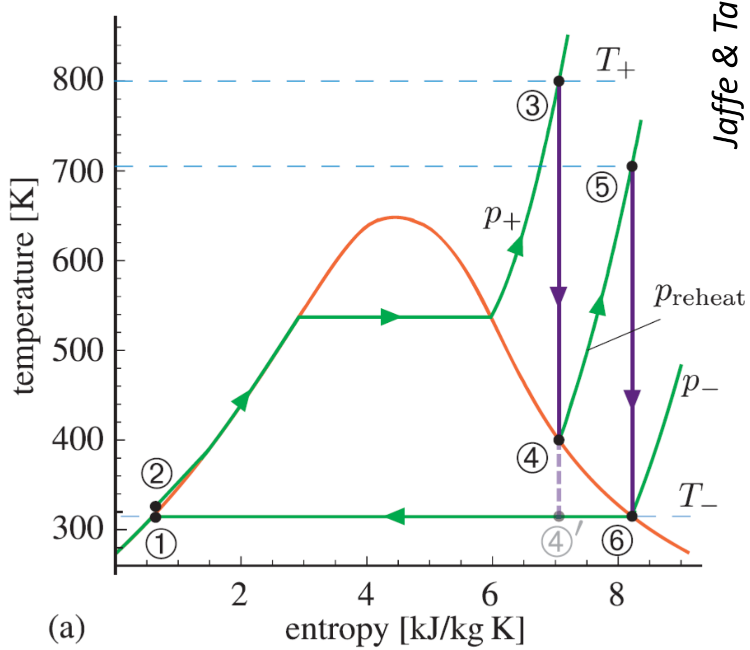
Source : wiki

Rankine cycle - improvements

Why is the last stage of the turbine most subject to eroding ?



(b)



(a)

Jaffe & Taylor

Rankine cycle - improvements

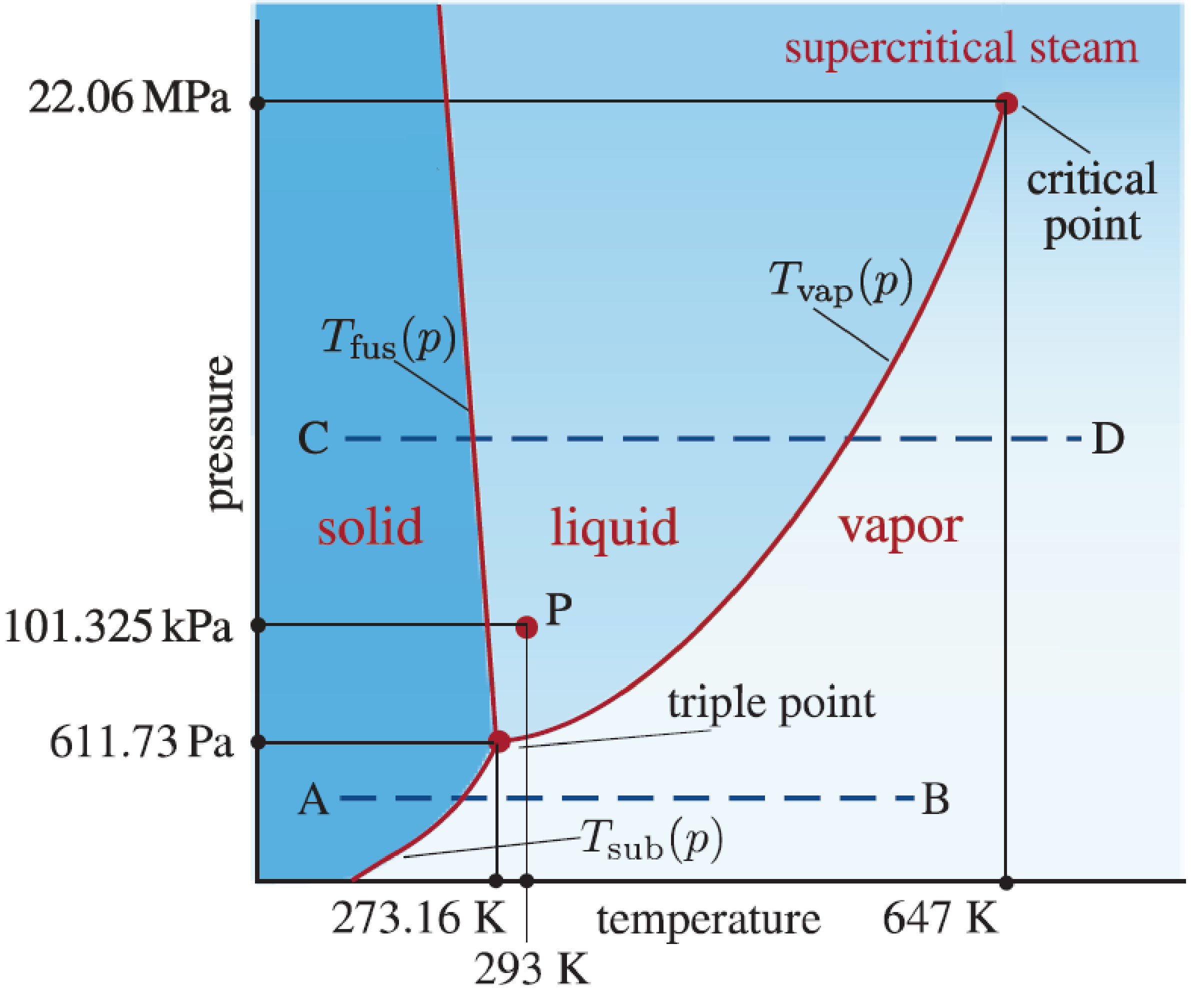
Above the critical point (221 bar, 374°C)
no liquid – vapor phase change

Requires less enthalpy to reach high temperatures
→ less heat input

Less entropy after the ''boiler''
→ more heat input

Efficiency : 42-45%

But strong material requirements !



Jaffe & Taylor

Rankine cycle - improvements

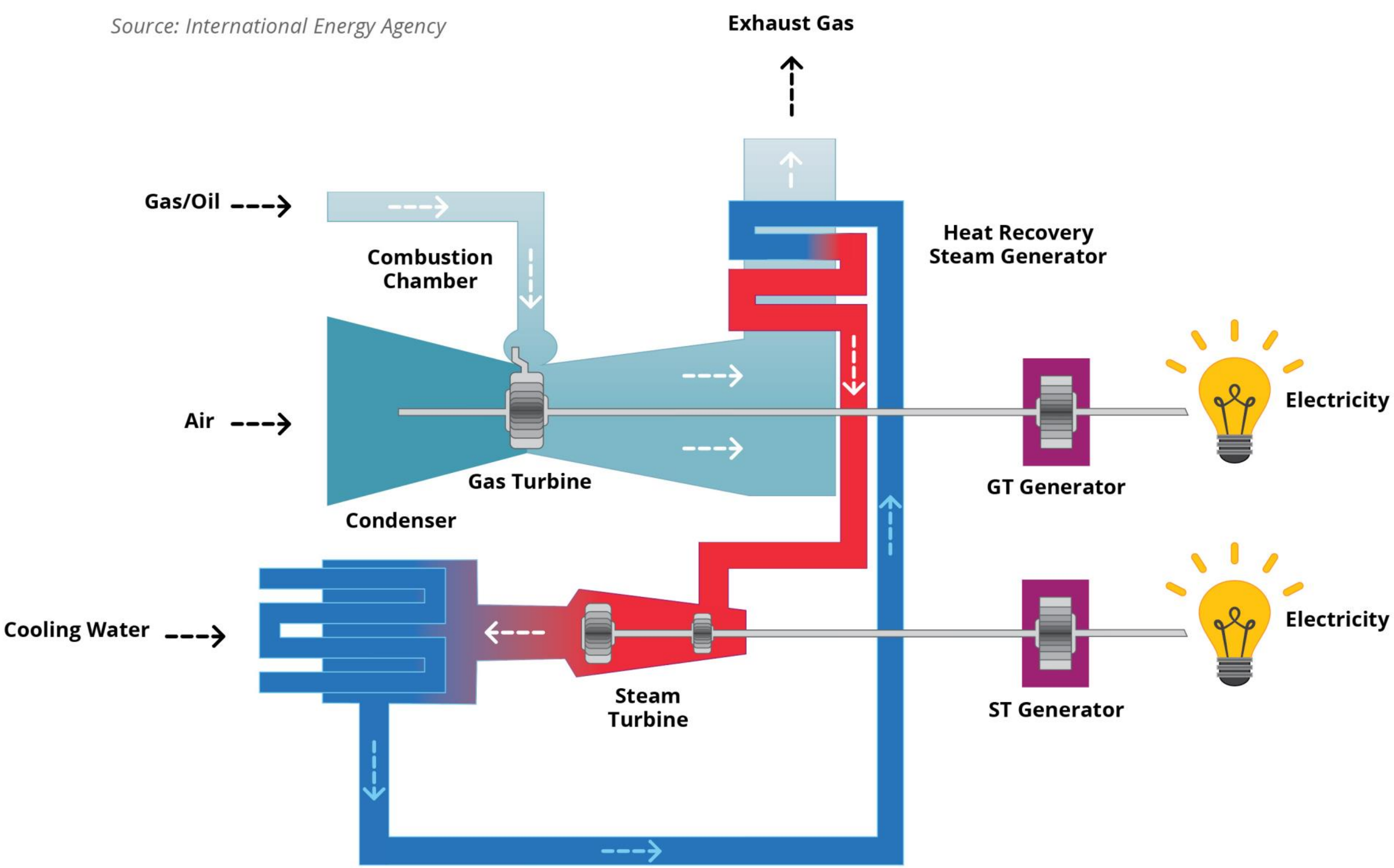
1957: first supercritical steam-electric generating unit in the world (Philo Power Plant, Ohio, USA)

2010 : Rheinhafen steam power plant (Karlsruhe, Germany)

47.5% net thermal efficiency
919 MW of electricity (+220 MW heat)

Steam > 600°C
275 bar

Combined cycle (CCGT)



Gaz turbine efficiency	η_{GT}
Steam turbine efficiency	η_{ST}
Heat exchange efficiency	β

$$\eta_{\text{CCGT}} = \frac{W_{\text{GT}} + W_{\text{ST}}}{Q_{\text{combustion}}}$$

$$= \eta_{\text{GT}} + \beta(1 - \eta_{\text{GT}})\eta_{\text{ST}}$$

Up to 60%

Combine cycle - application

Gas turbine : Siemens SGT5-8000H (« H » class)

Gross Power Output	340 MW
Pressure ratio	19.2
Exhaust temperature	625 °C
Exhaust mass flow	820 kg/s
Net power output	530 MW

Vapour turbine : Siemens SST-5000

Combined Cycle	120 MW to 500 MW
Conventional Steam	120 MW to 700 MW
Steam Temperature:	Up to 600° C
Pressure:	Up to 177 bar
Reheat Steam T :	Up to 600°

Gas and vapour on same rotation shaft

Net efficiency (in CC) 60%

Lecture 4
Heat engines

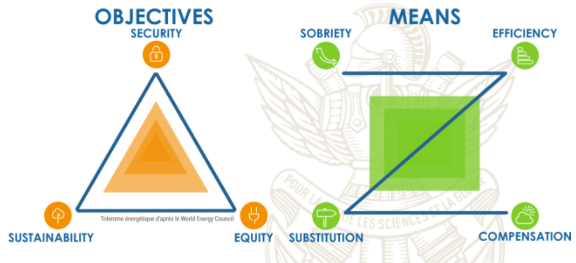
I. What, why, where ?

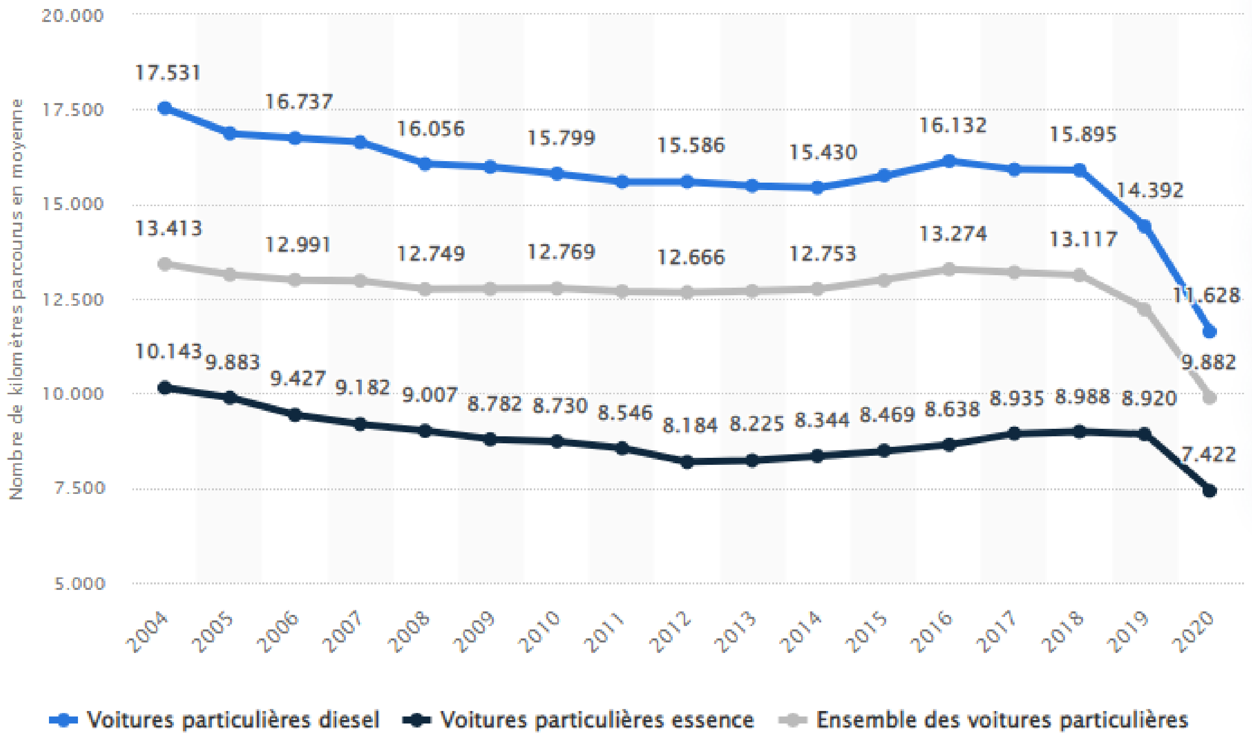
II. Thermodynamics framework

III. Standard cycles and their applications

IV. Perspectives

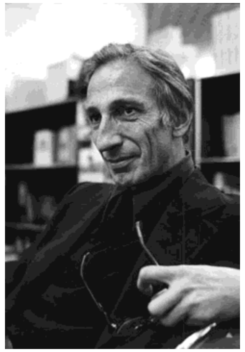
Sufficiency - transport



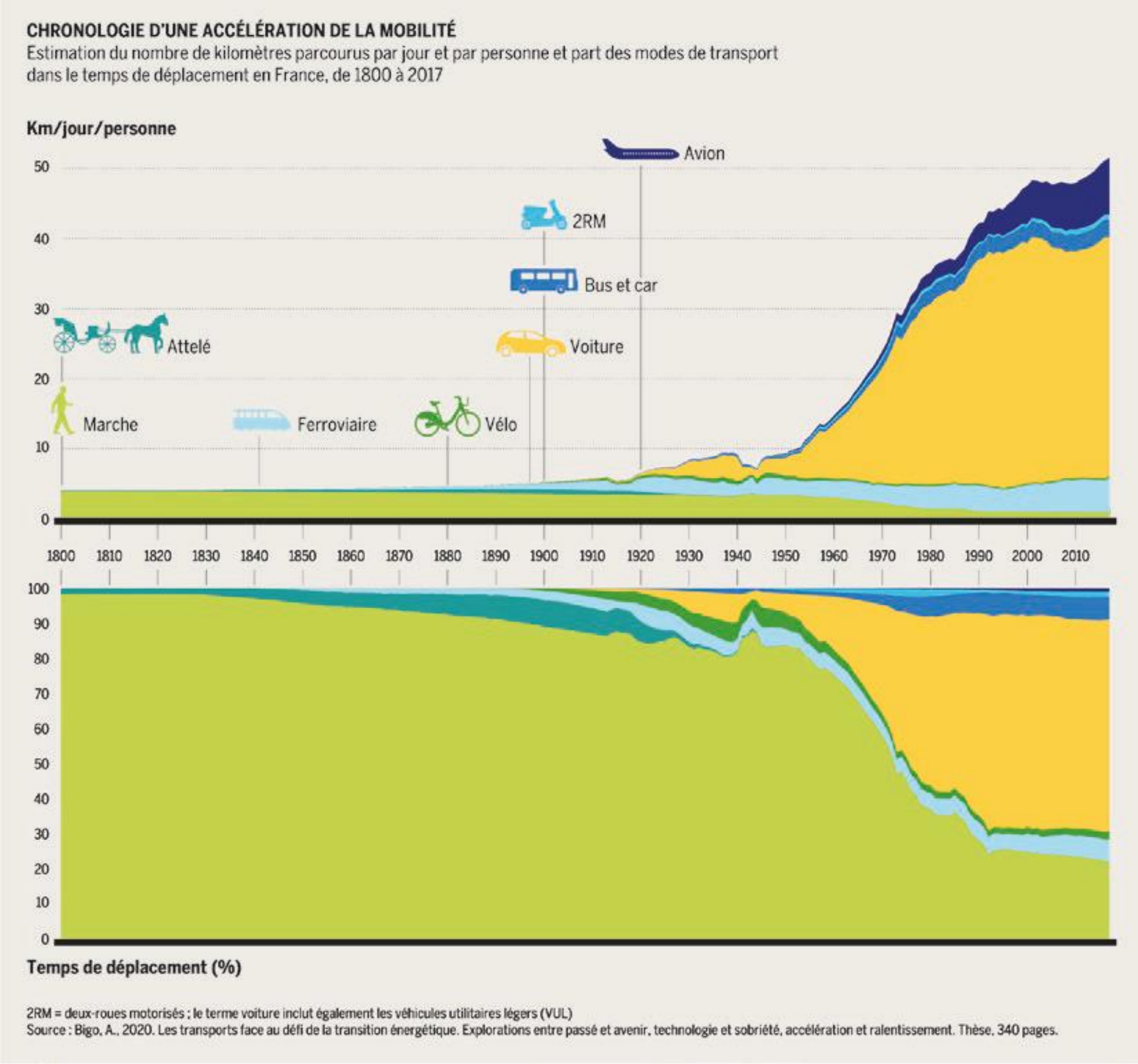


13 000 km/year = 35 km/day

Infrastructures ?
Daily planning ?



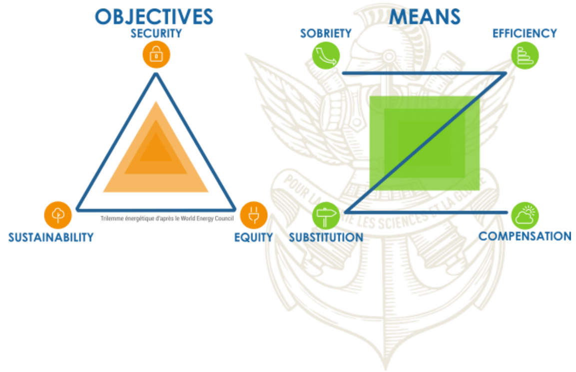
Ivan Illich, Energy & equity

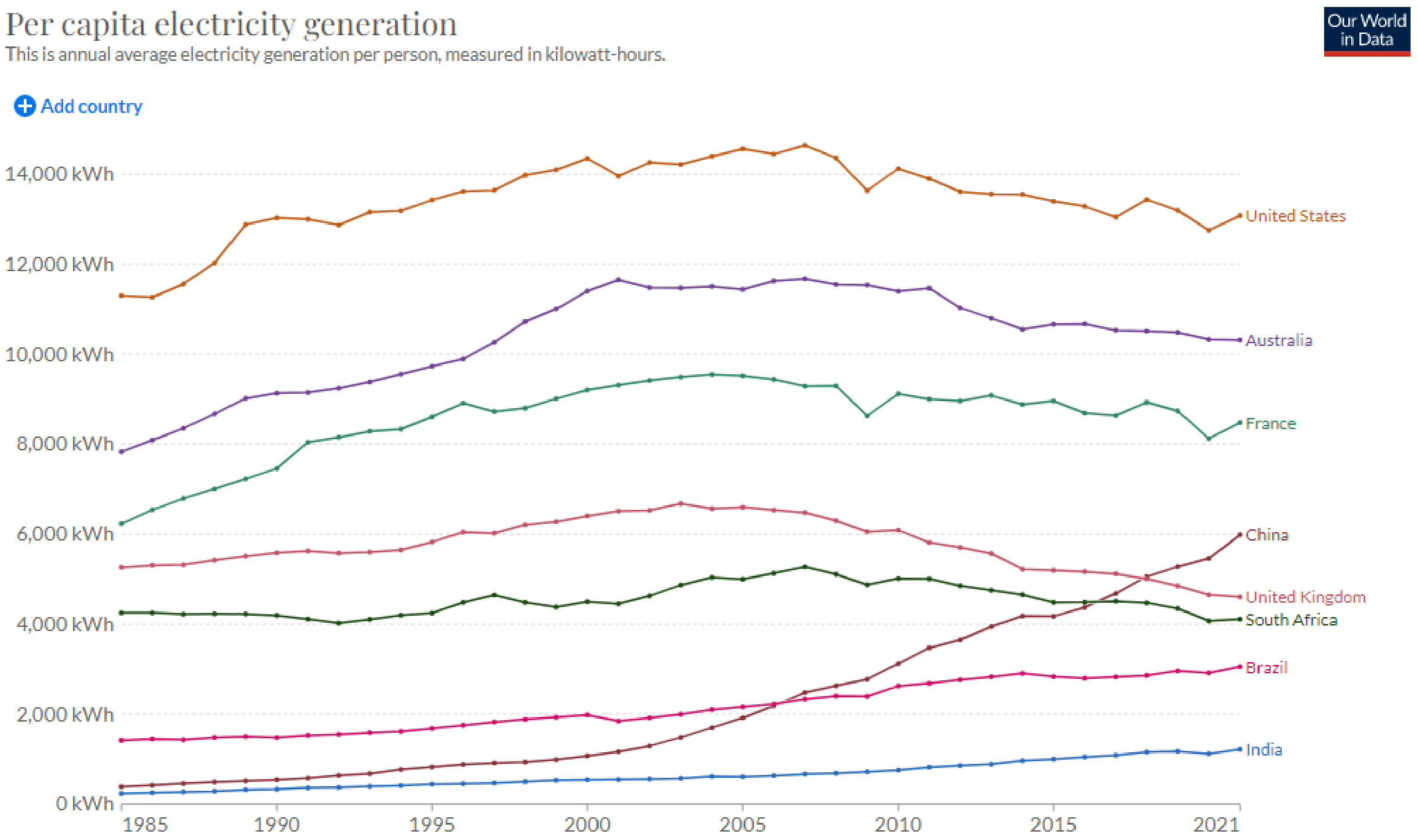


CHRONOLOGIE D'UNE ACCÉLÉRATION DE LA MOBILITÉ
Estimation du nombre de kilomètres parcourus par jour et par personne et part des modes de transport dans le temps de déplacement en France, de 1800 à 2017

2RM = deux-roues motorisés ; le terme voiture inclut également les véhicules utilitaires légers (VUL)
Source : Bigo, A., 2020. Les transports face au défi de la transition énergétique. Explorations entre passé et avenir, technologie et sobriété, accélération et ralentissement. Thèse, 340 pages.

Sufficiency electricity

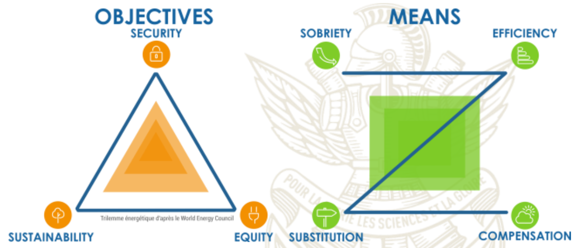




Per capita electricity generation

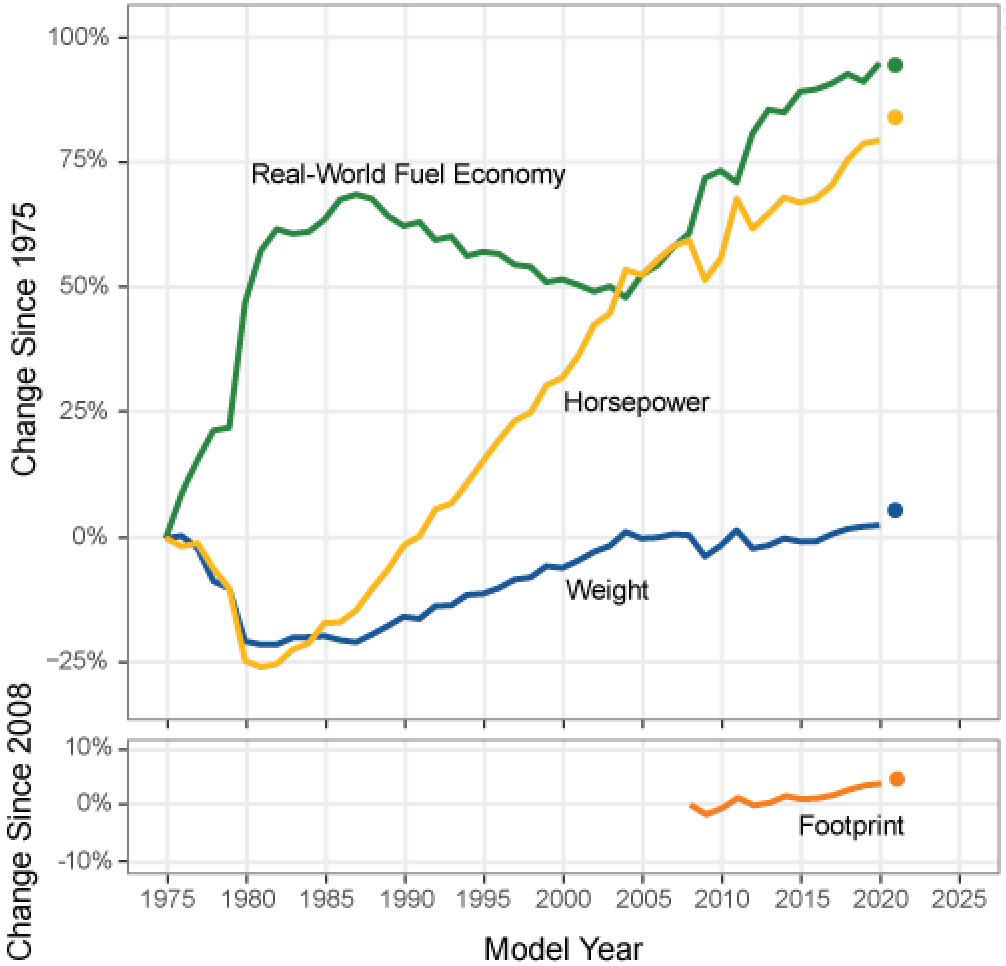
This is annual average electricity generation per person, measured in kilowatt-hours.

Efficiency - transport



How far can you go with 1L of gasoline ?

3800 km / L !

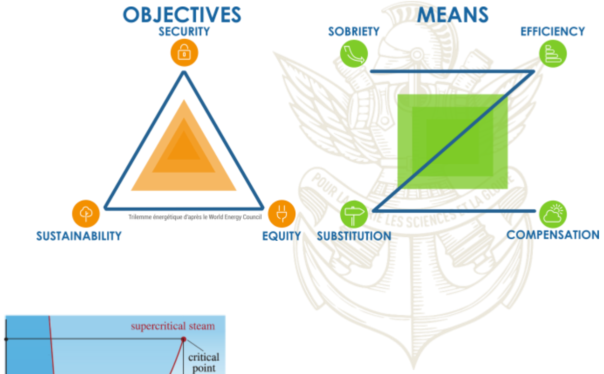


Data : EPA

Individual transport technology ?

Individual transport behavior (car sharing) ?

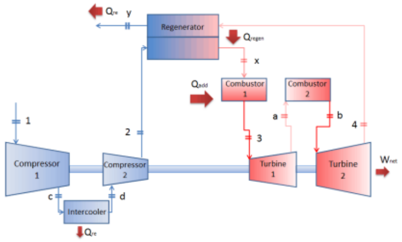
Public transport ?

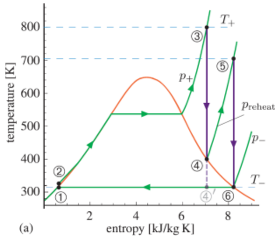


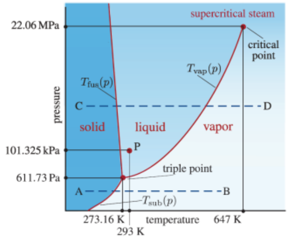
Efficiency - power

Improving technologies

Production







Distribution See lecture 9

Demand Efficient electronics…

Improving usage

Combined cycle, cogeneration

Substitution - combustion

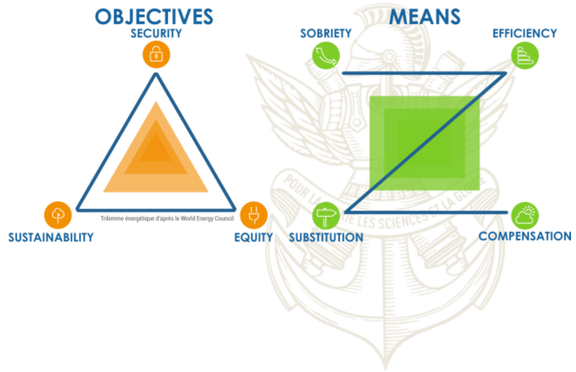
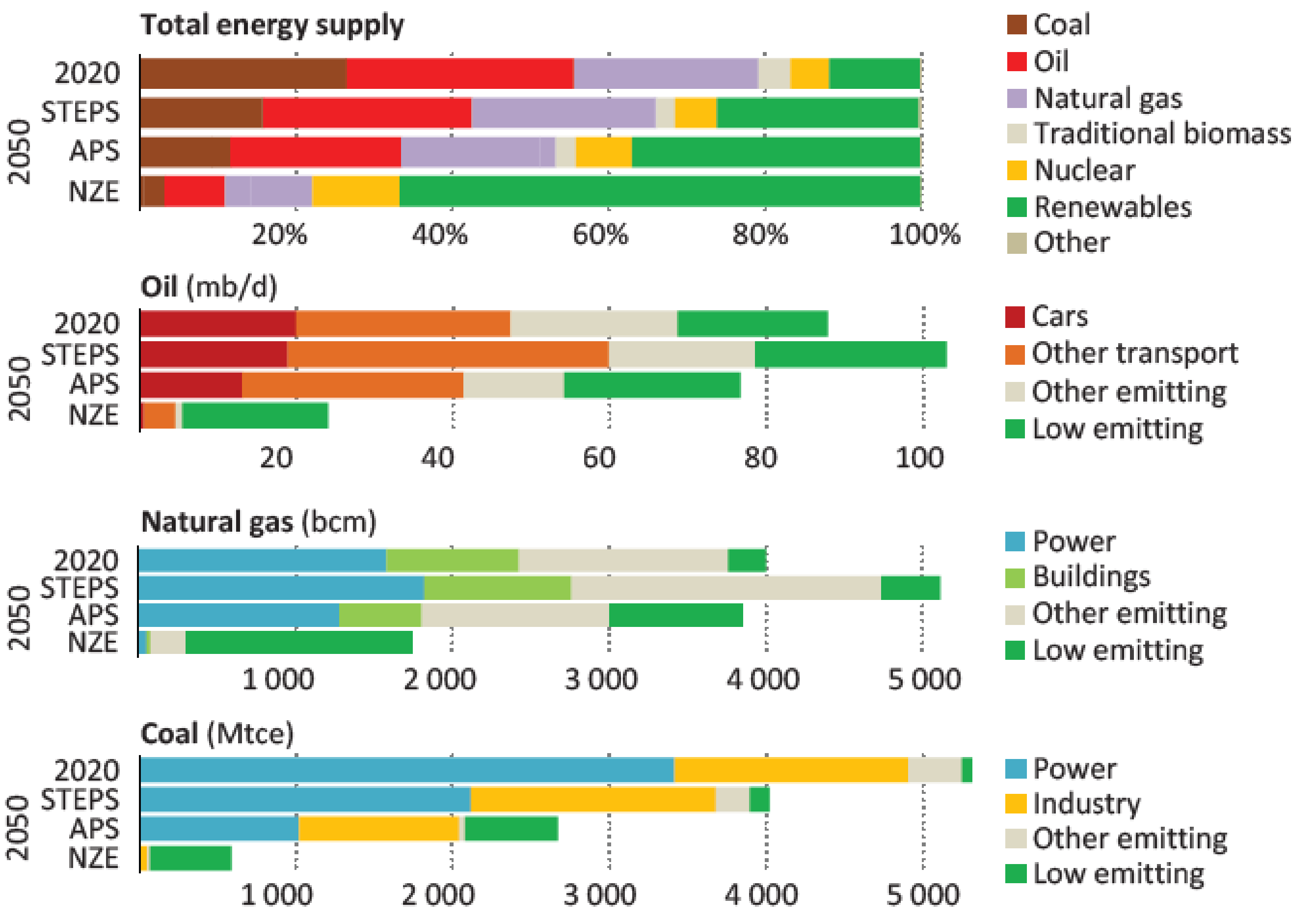


Figure 4.15 ▷ Energy supply and demand by fuel and sector, 2020 and 2050



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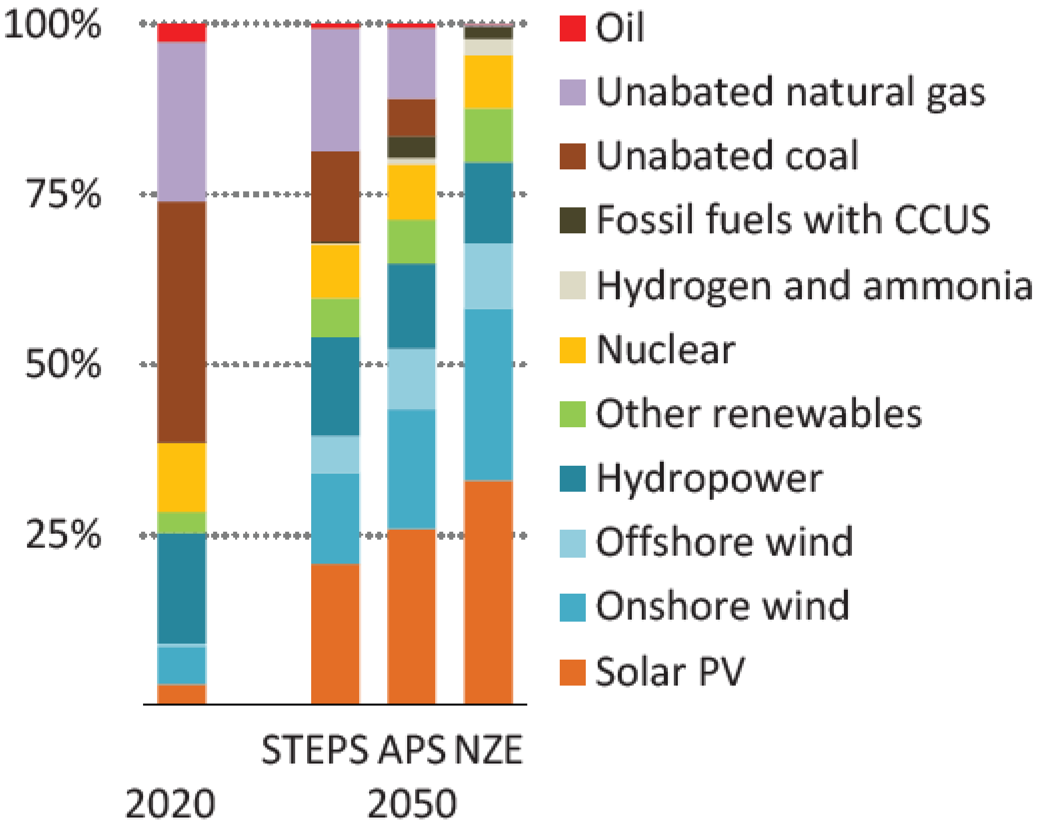
Electricity production



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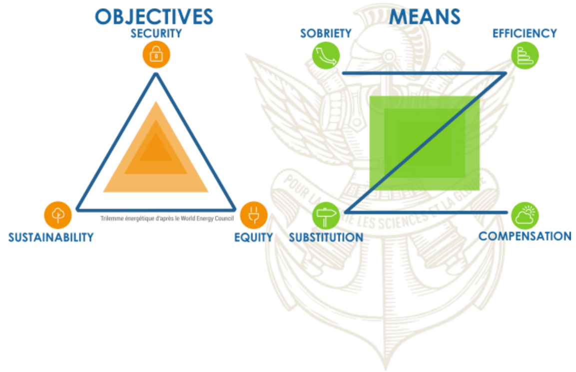
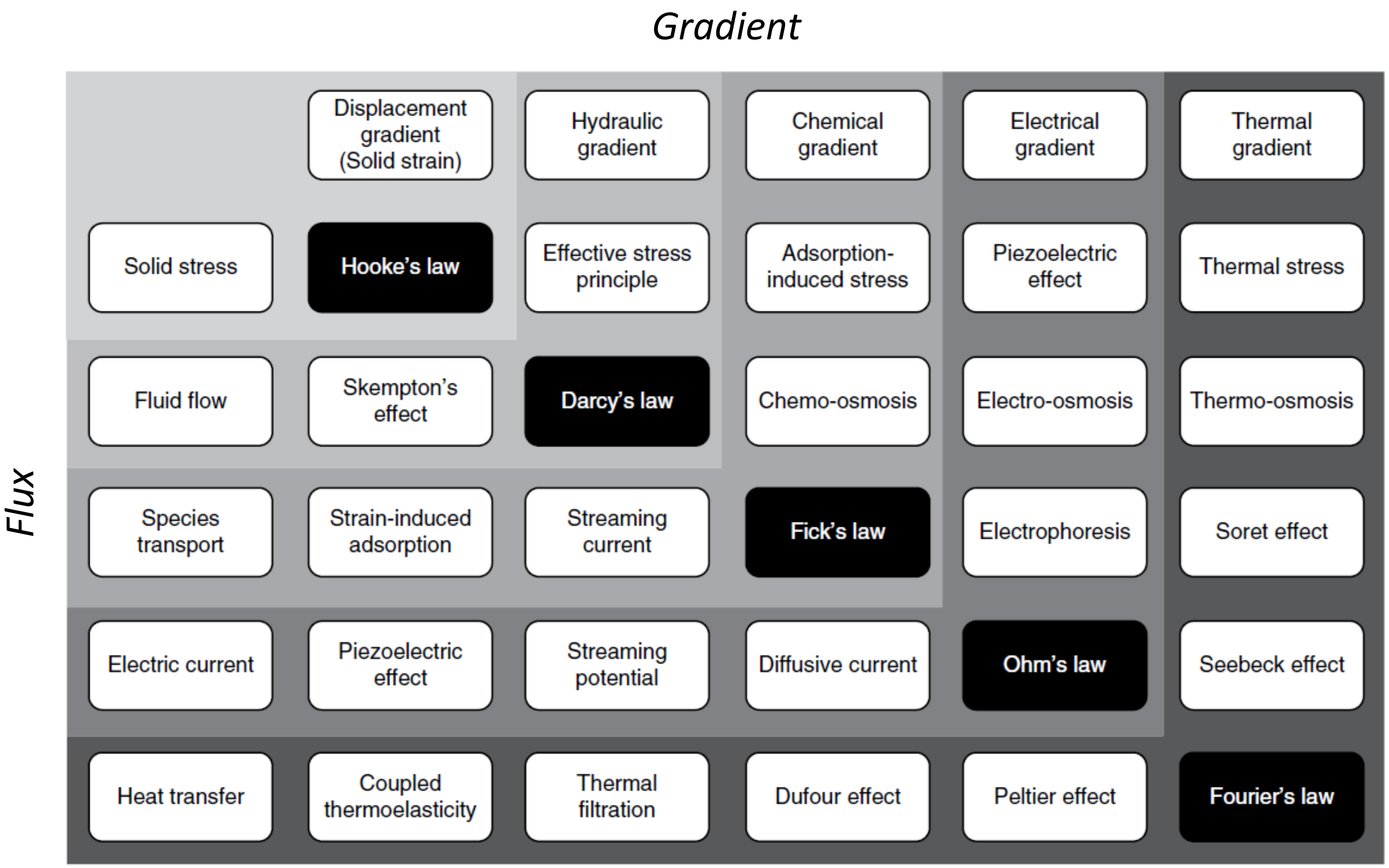


Substitution – direct conversion

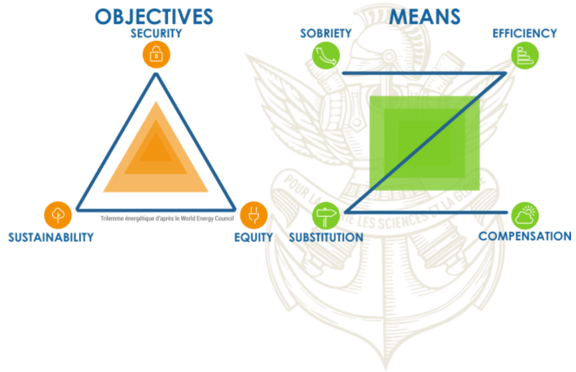


Gradient

Flux

	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**

Compensation



« no unabated coal » : still coal, but « clean » coal ?

Work required to get 1 mole of CO2 from a mixture with concentration x

$$W = RT(1 - \ln x)$$

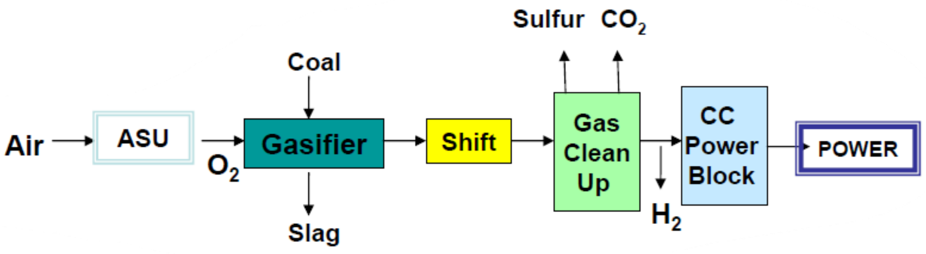
Concentrate even more CO2 ?

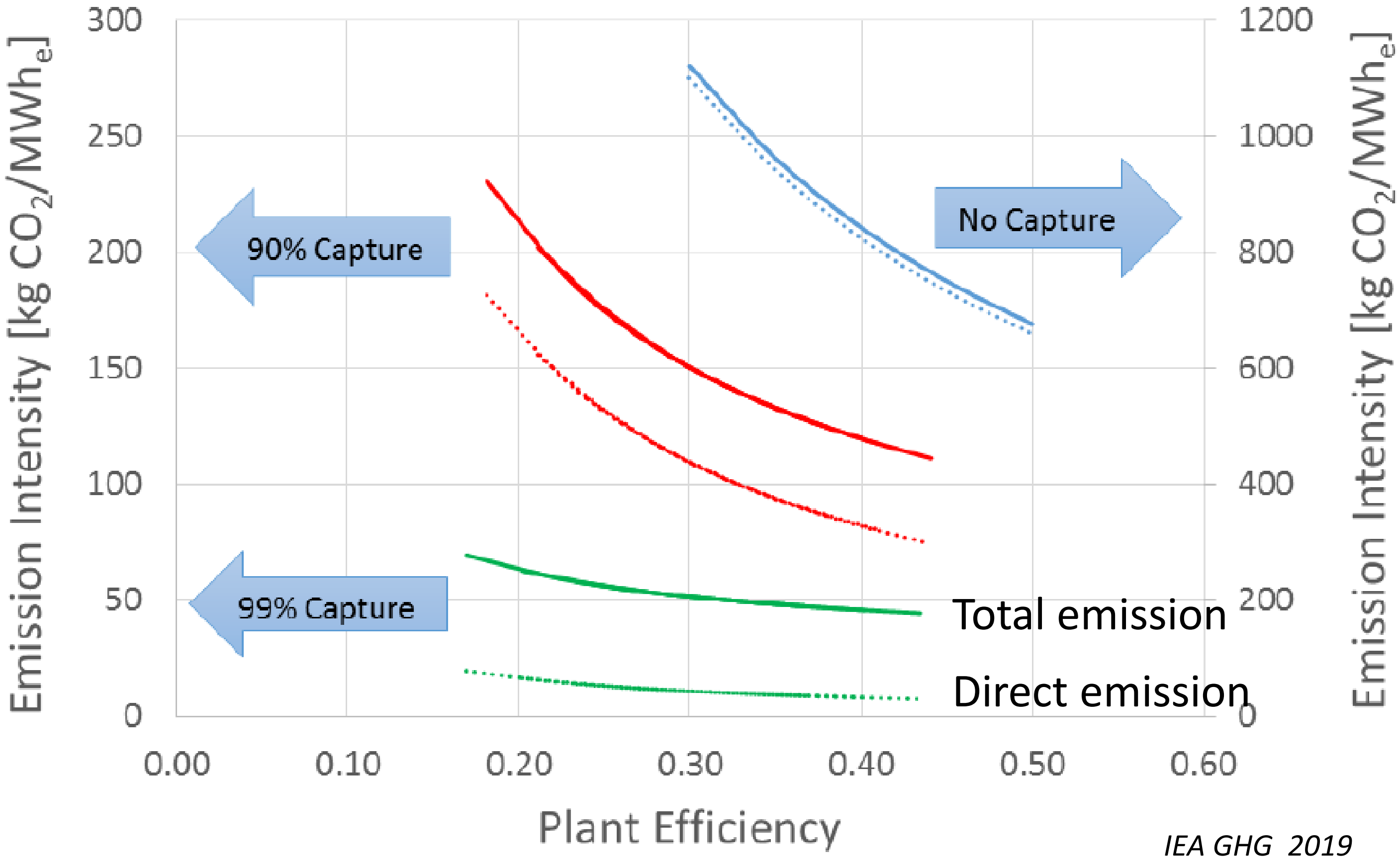
Integrated gasification combined cycle

$$3C + O_2 + H_2O \rightarrow \underbrace{H_2 + 3CO}_{\textit{syngas}}$$

water-gas shift reaction

$$CO + H_2O \leftrightarrow CO_2 + H_2$$





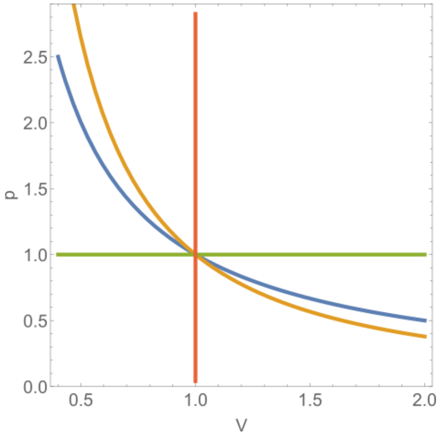
IEA GHG 2019

Take home message

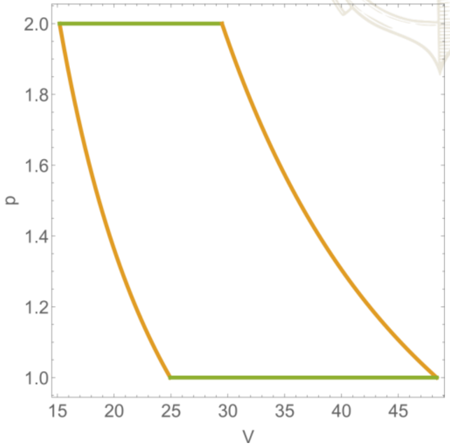
$$dU = \delta W + \delta Q$$

$$dS = \frac{\delta Q}{T_{\text{ext}}} + \delta S_{\text{cr}}$$

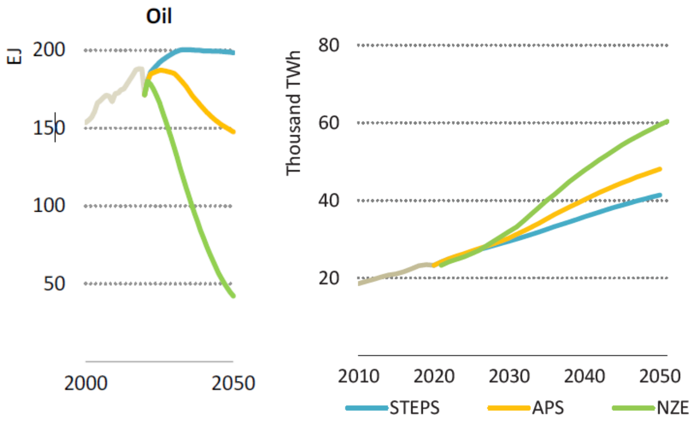
Heat, work
Conversion efficiency
Power



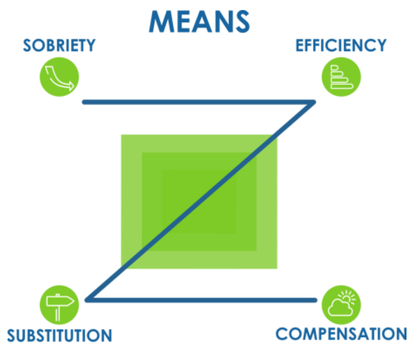
Ideal gas properties
Basic diagrams



4 standard cycles
Specificities, usage…



Perspective


MEANS

SOBRIETY

EFFICIENCY

SUBSTITUTION

COMPENSATION

Solutions