Sustainable Power Generation MJ2405

Introduction to the course.
Quick review of classical thermodynamics
for energy conversion and power generation.

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Department of Energy Technology, KTH, Stockholm

Sustainability course block
at the department of Energy Technology, KTH-ITM

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The SPG course proceeds in parallel and is integrated with:

- **Renewable Energy Technology (RET) MJ2411:**
  Focuses specifically on renewable energy resources and technologies – solar, bio, wind, hydro, geo, tidal, etc..
- **Sustainable Energy Utilization (SEU) MJ2407:**
  Concentrates on efficient energy use in buildings, indoor climate, improved refrigeration and air conditioning, etc..
- **Energy & Environment (E&E) MJ2413:**
  Gives a deeper perspective on energy resources & policy, environmental impact, pollution prevention, climate change..

Distribution of course content

- **It's important to define renewability index (RI), life cycle analysis (LCA), environmental impact assessment (EIA)...**
  (The RET and E&E courses will do that)

- **It's important to summarize the human effect on the environment and the availabilty of renewable resources...**
  (The E&E and RET courses will do that)

- **It's important to decrease the consumption of electricity at the user end while improving the indoor environment...**
  (The SEU course will cover that)

- **It's important to understand the power generation system, raise the efficiency, improve the technologies, switch fuels..**
  (Thus, the SPG course concentrates only on the power sector, the thermodynamic cycles and the system view of power production).

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SPG course content

The SPG course will focus on technologies and methods for improving energy conversion for power generation:

- Steam cycles, gas turbine cycles, combined cycles – whatever the fuel.
- Boilers and furnaces, basics of combustion processes and pollutant prevention.
- Quick review of piston engines, fossil fuels' production, energy economy and electrical system aspects.
- Nuclear power – past, present, future – fission and fusion.

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Practical arrangements for the SPG course

- **Students of various backgrounds and with different knowledge base:**

  The course starts from a basic level for the beginners in the field, while additional material is available for advanced students who want to get a deeper insight.

  Try to work in groups and help each-other as much as possible!

- **Literature & suggested reading** – many books cover parts of the course, but there is no single ”best book”. Free online resources are available via KTH Library – take a look at the ”course description” file in CANVAS for a list of e-books.

- **Language of instruction –** English!

  However, it would be good for the Swedish students to train the professional terminology in their own language – therefore teachers will sometimes talk to local students in Swedish..

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SPG scope and sections

- **Period 1 – theory, calculation exercises, homeworks** (lectures, tutorials, home assignments) on:
  Combustion Basics; Steam Cycles; Gas Turbine Cycles; Combined Cycles; Boiler Efficiency.

- **Period 2 – only theory** (lectures) on various additional topics.

- Mid-term exam (control test) on October 26th - see some preliminary details in the ”course description” in CANVAS.

- Home assignments (calculation homeworks) = ÖVN1 (1.5 credits)
- Theory Quizzes (theory MCQ) = ÖVN2 (1.5 credits)

see the ”course description” in CANVAS.

- Course schedule: always check the **detailed schedule** in CANVAS!

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Teacher ≠ Preacher

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- Be sceptic, start discussions, don’t hesitate to ask questions!
  (Provoke your teachers to tell more, to explain deeper, to give examples and discuss alternatives)…

- Be motivated in your studies. Nobody can help you if you don’t have any desire to study.

- Be forgiving to university’s faults and imperfections.
  A single course would not make you professionals. You now learn only how to grow. Later on, you will have the chance to really become professionals after you take advanced courses and actually start working as engineers in the near future…

- Teachers aren’t perfect. You should help them to be better.

Objectivism & Criticism

- Engineers should be objective in their thinking and should demand this also from everybody else around.
- Energy engineers should stay far from political discourse and keep their work outside of any religious beliefs.
  (even if power generation development and research often are a very political matter, unfortunately)
- Engineers should be critical towards everything which isn't properly proven.
  (Don't trust blindly everything you read on the internet. Try to judge it first)
- Criticism becomes constructive (not destructive) when you suggest a way for improvement!

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Laws of classical thermodynamics

- **0th law:** Defines a way to equate (equilibrate) bodies or systems in terms of temperature.
- **1st law:** The change in the internal energy of a system is equal to the heat added to the system minus the work done by the system $\Delta U = \Delta Q - \Delta W$ (energy, heat, and work are measured in the same way).
- **2nd law:** Introduces the concept of entropy (all isolated systems tend towards equilibrium) and explains the notion of ”irreversibility” or the ”value” of energy.
- **3rd law:** …relates the entropy (randomness) of matter to its absolute temperature and defines the ”absolute zero”…

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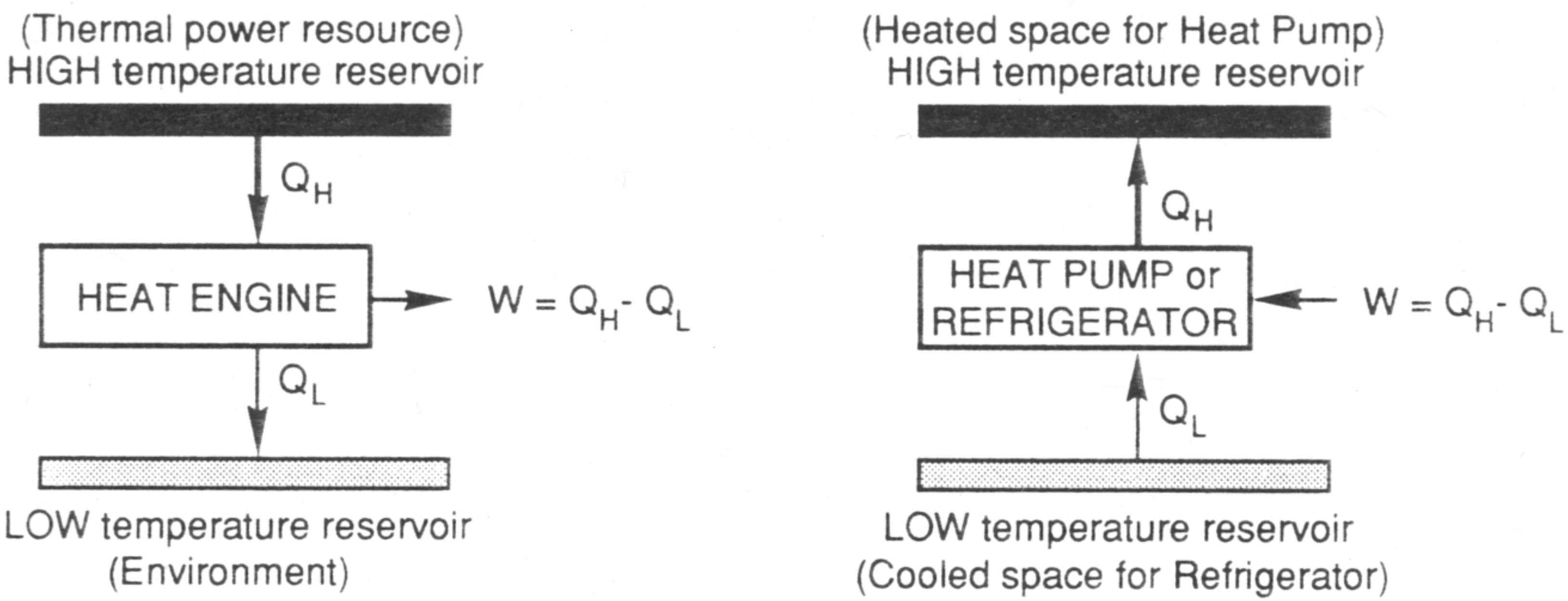
The second law



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CARNOT efficiency: $(T_H - T_L)/T_H$

Interpretations of the second law

From the viewpoint of energy conversion:

- Heat only flows freely (naturally) from a body with higher temperature to a body with lower temperature.
- Converting work into heat is a natural (equilibrium) process, while converting heat into work is a process that brings the system out of its equilibrium and requires efforts for its accomplishment.
- Heat can be transformed into work only through conversion devices which interact with two heat reservoirs – one at higher temperature and another one at lower temperature.
- While converting heat into work, some remaining heat would always need to be dumped (sinked) to the low-temperature reservoir, therefore the conversion of heat into mechanical work can **never** be 100% efficient!

The CARNOT efficiency is the highest possible limit for the efficiency of conversion of heat into mechanical work

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Terminology reminder

- **Energy** (or heat or work) cannot be produced or lost, only converted (transformed) from one form to another!
- The concepts of **entropy** and **exergy** explain the quality (value) of different forms of energy and the inevitable losses during energy transformations. Exergy is always lost while entropy is always produced during inefficient energy transitions!
- **Power** is amount of work or energy released per unit of time.
- *In everyday language we can allow to speak about energy (or power) as being "produced" or "generated" because it is a product, a comodity to be used or sold on the market…*

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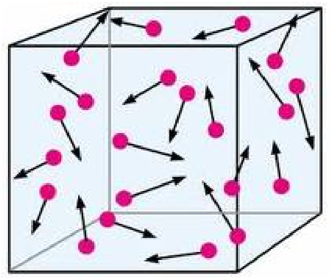
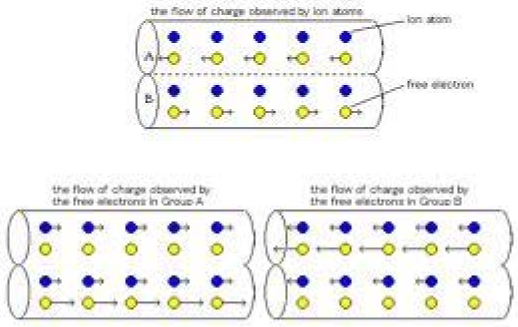
Value of energy





Understanding the concept of ”<u>ordered</u>” and ”<u>disordered</u>” energy:

Exergy = value of energy, i.e. its availability or ”workability”.

- HEAT is disordered (low-value) energy, described by stochastic Brown motion of molecules...
- Electricity (ordered motion of charges), and kinetic or potential energy of flowing fluids or solid objects, are ordered (high-value) energy forms...
- Transformation of ordered energy into disordered energy is easy, the reverse is very difficult, thus the notion of ”value” !!

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Irreversibility = exergy loss

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- Transformation of ”ordered” energy into ”disordered” energy is a **natural process**, always with 100 % efficiency !
- Conversion of ”disordered” into ”ordered” energy is not natural, and is always far **<u>less</u>** than 100 % efficient !
- There is room for improvements in the systems and cycles we apply for conversion of heat into mechanical/electrical power !

Typical examples of exergy loss

- Losses by friction or in electrical conductors – undesired transformation of kinetic or electrical energy into heat.

- Heat exchange through very large temperature differences – dumping high-value heat into low-value such.

- Non-adiabatic compression or expansion processes – undesired transformation of mechanical power into heat.

- Unnecessary throttling of fluids or pressure losses in pipes – the internal energy of the fluid remains the same, but the possibility to produce work by expansion is lost.

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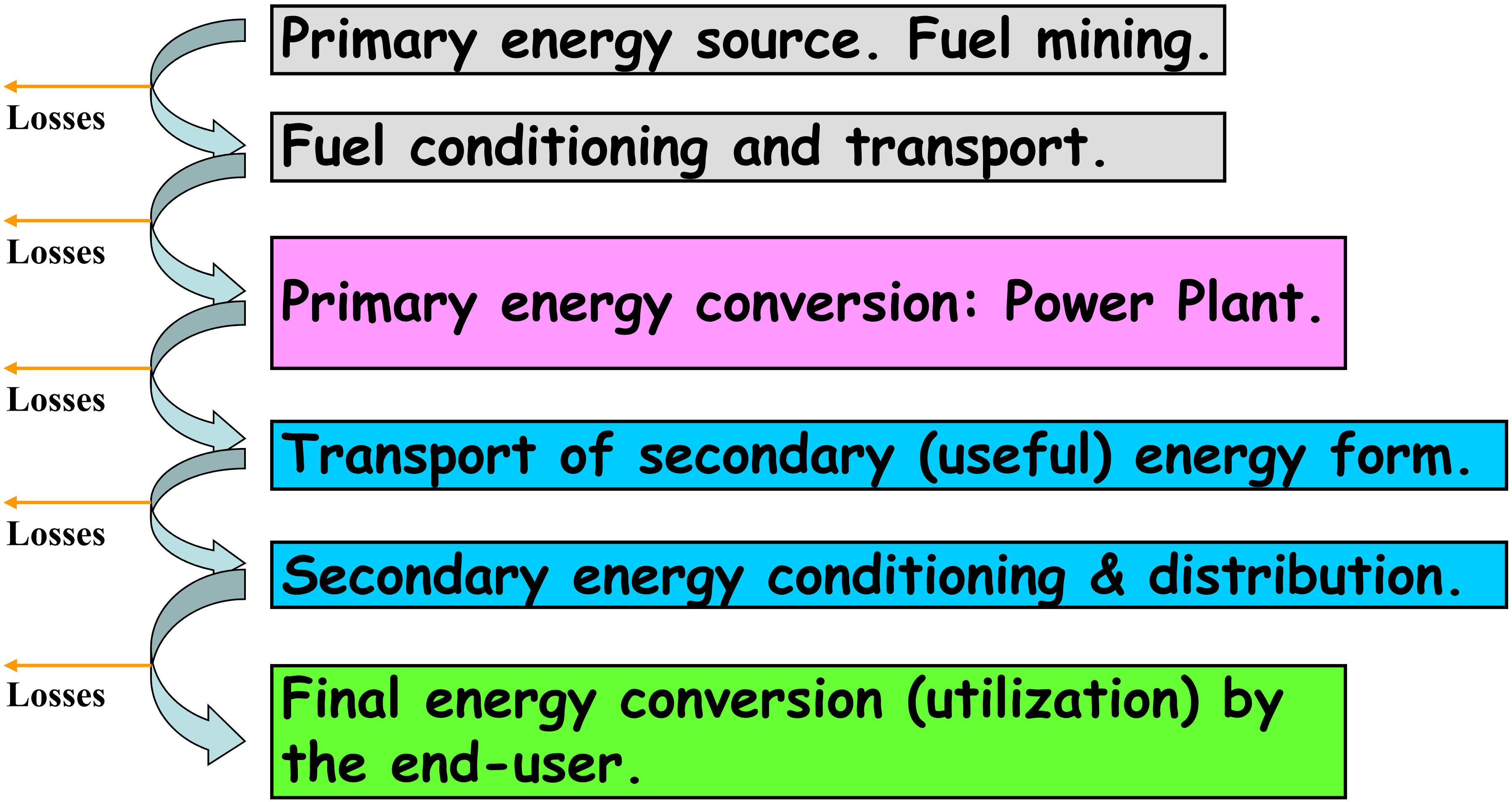
Energy conversion chain



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Efficiency examples of natural processes (1): Photosynthesis

<u>How much is the efficiency of conversion of solar energy to biomass?</u>

- Around $80x10^{12}$ W of solar energy arriving on planet Earth can be used for photosynthesis, **however**:
- 20% of the total insolation reaching the plant's leaf is reflected away,
- 40% has unsuitable wavelengths for photosynthesis,
- 30.8% is a "quantum loss" during the synthetic process,
- 3.7% is a respiration loss for the plant,

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- Thus only 5.5% of the original solar energy can <u>ideally</u> be converted into organic matter = biomass.
- Further practical losses (bad climate, shading, water shortage, physical damage to plants, etc.) brings the final efficiency down to around 0.5 – 2% for temperate regions, and around 1 - 4% for tropical regions.

Efficiency examples of natural processes (2): Food Chain

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Perfect example of an energy conversion chain in its basics: the FOOD CHAIN.

Solar energy → (photosynthesis) → biomass/vegetation/flora → (cellulose to meat & to mech. power) → herbivorous fauna → (meat to meat and meat to power) carnivorous fauna...

From solar energy to mechanical work of this cat:

The overall efficiency is poorly low!

Efficiency examples of natural processes (3): Hydropower

How much is the overall efficiency of energy conversion from solar energy to hydropower potential ?

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- The evaporation of 1 kg/s water by solar energy at 1 bar requires ~ 2500 kW.
- The hydropower potential of 1 kg/s water precipitating and being stored at 1000 m elevation is ~ 10 kW.
- The overall efficiency of energy conversion is ~ 0.4%!

But we assume hydropower as very efficient because we don't care about the primary energy source!

Natural energy sources

<u>*Efficiency of solar energy conversion to:*</u>

- Direct solar power (PV or CSP) ~ 10 - 20%
- Biomass via photosynthesis ~ 0.5 - 4%,
- Wind ~ 2%,
- Hydropower ~ 0.4%,
- Wave power – even less,
- Fossil fuels… – can anybody calculate?

Concentration of energy

HOWEVER: energy concentration rises!

Energy resource availability

Time scale	Natural resource	Conversion technique
SHORT (decades)	Oil	Combustion (heat engine)
↓	Natural gas	Combustion (heat engine)
	Coal	Combustion (heat engine)
	Uranium 235, Thorium	Nuclear fission (heat engine)
	Uranium 238	Nuclear fission (heat engine)
	Deuterium	Nuclear fusion (heat engine)
	Geothermal	Heat engine
LONG (millenia)	Solar *(and its derivatives)*	Heat engine or direct (wind, PV)

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Energy conversion paths

- **Thermal** (via heat engines), limited by the Carnot efficiency and material properties: steam or gas turbines, piston engines, etc.
- **Direct thermal** conversion, also limited by the Carnot efficiency: magnetohydrodynamics (MHD), electrohydro-dynamics, thermoionic, thermoelectric, etc.
- **Non-thermal** conversion methods – avoiding the Carnot limit (!!): Photovoltaics, Fuel Cells.

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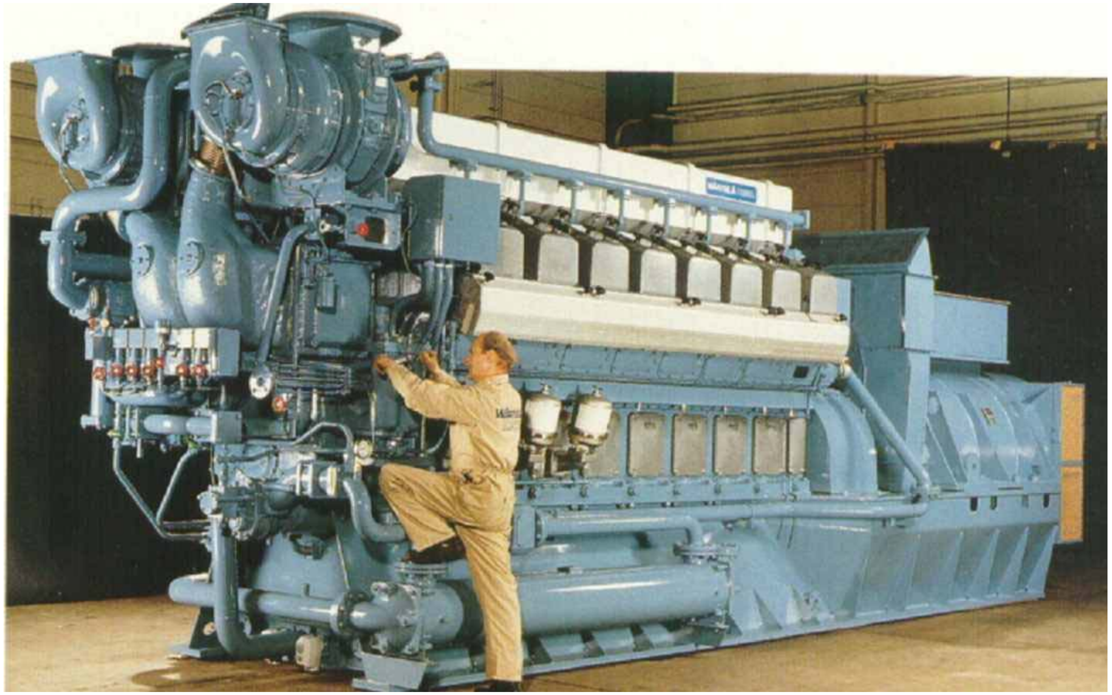
Heat engine examples (1)

Gasoline IC engine for cars: typical efficiency below 20% …

Heat engine examples (2)



Large stationary gas or diesel IC engine: the most efficient **single cycle** heat engine - up to 50%

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Heat engine examples (3)

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Small biomass-fired steam CHP plant (electrical efficiency of ~30%), and a large nuclear power station (electrical efficiency ~33%).

Heat engine examples (4)

Modern coal-fired steam plants can be made efficient and clean, with up to 45% electric efficiency, SOx & NOx reduction and CO2 separation…

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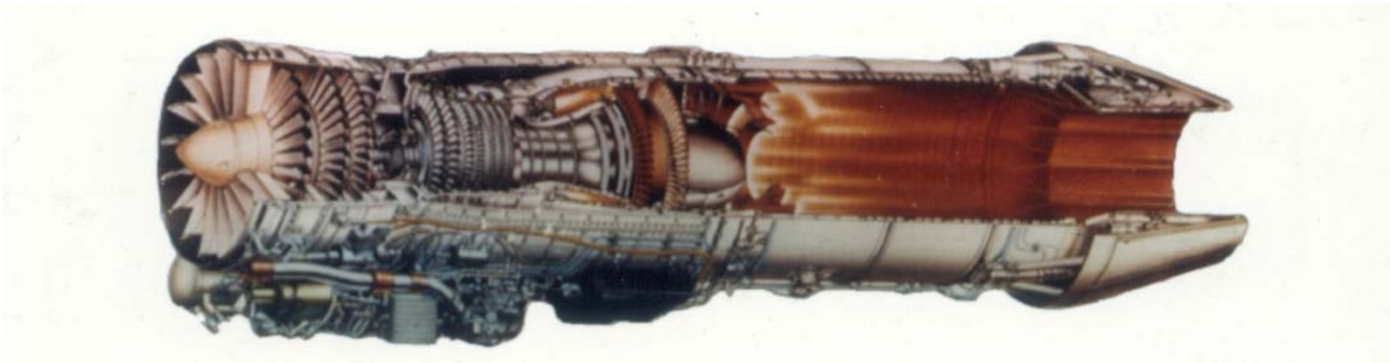
Heat engine examples (5)



Turbojets are the <u>least efficient</u> heat engines we use today!

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Carnot efficiency limit

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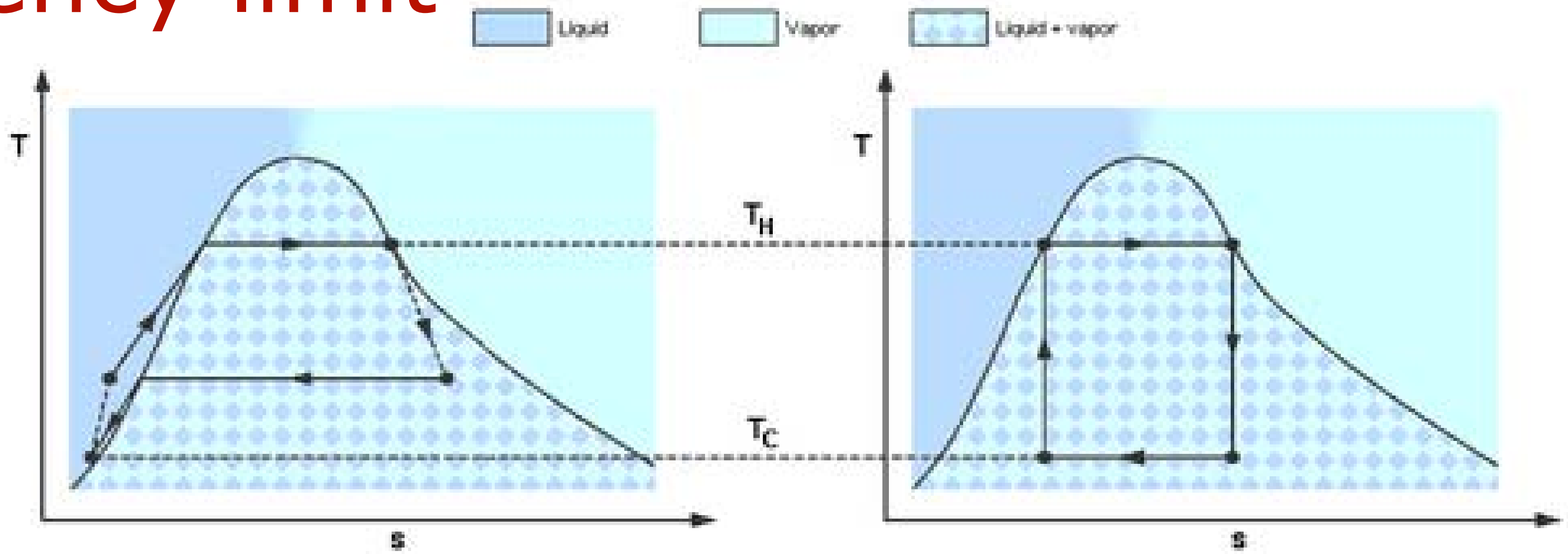

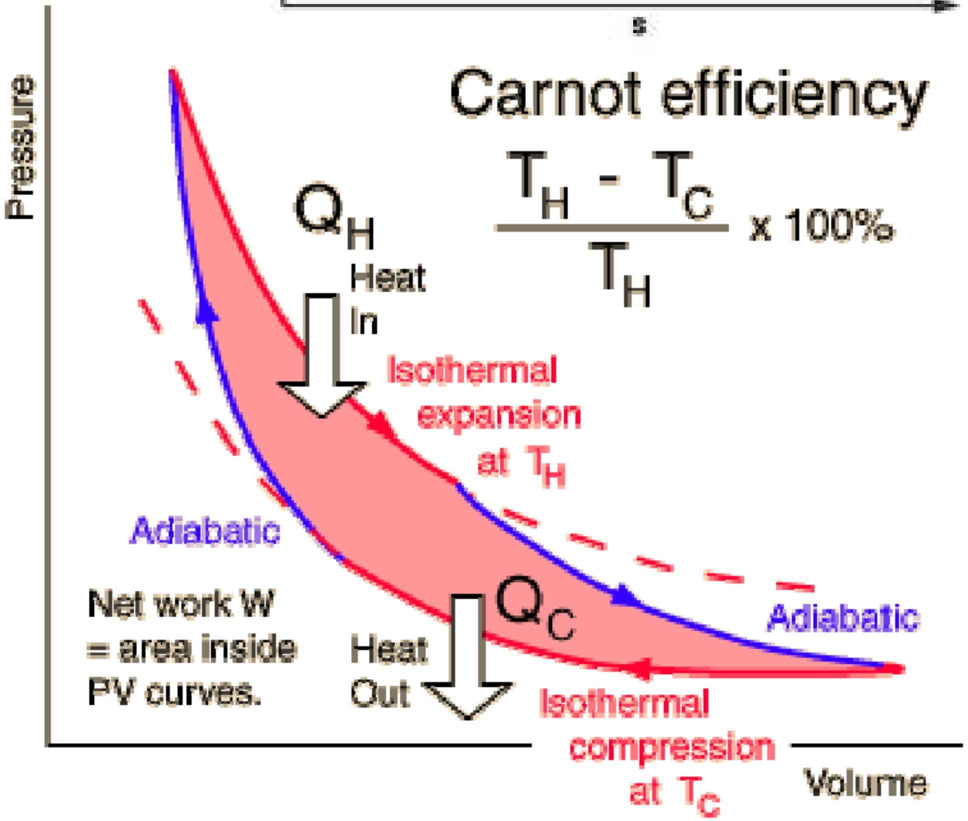

$$\eta = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$$

$$\Downarrow$$

$$\eta = \frac{T_H - T_C}{T_H}$$

Equation of state

Valid for the vapor phase of any substance far from the phase-change region (perfect gas):

$$P.V=n.R.T$$

The specific gas constant R for a given gas is R = **R**/M
where **R** is the universal gas constant: 8.314 [J/mol.K]

state 1: $P_1V_1 = n.R.T_1$
state 2: $P_2V_2 = n.R.T_2$

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Thermodynamic processes (1)

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Isobaric – the pressure is constant: $V_1/V_2 = T_1/T_2$

Isohoric – the volume is constant: $P_1/P_2 = T_1/T_2$

Isothermal – the temperature is constant: $P_1V_1=P_2V_2$

Thermodynamic processes (2)

Adiabatic (isoentropic) – both volume and pressure are changing, but without heat exchange to the environment (not possible in real conditions):

$$PV^{\gamma} = \text{constant} \qquad \gamma = \frac{C_P}{C_V}$$

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Polytropic – a real process – assume it as a abiabatic process with some undesired heat exchange or heat-producing losses

Enthalpy

Enthalpy is a physical property representing the total energy contained by an object or a system. Should always be used when working with fluids that are far from perfect (ideal) gases:

$$H = U + P*V = c_p*T + P*V$$

Enthalpy of a perfect gas: $H = c_p*T$

We are interested in the change of enthalpy, not its absolute value!!

Enthalpy will change either when heat is exchanged or when work is done or absorbed by the considered object or system!

$\Delta H = H_1 - H_2$ for perfect gas: $\Delta H = c_p * \Delta T$

Isoenthalpic process = throttling

Work done by a system

The positive work done by a given mass is expressed by the product of the mass multiplied with the difference of specific enthalpy:

$$W = m*\Delta h = m*(h_1-h_2) \quad [kg*Joule/kg = Joule]$$

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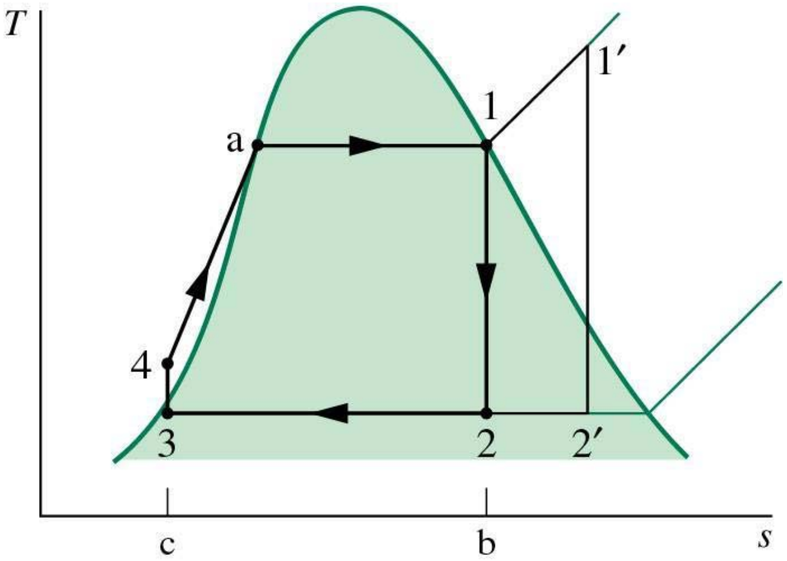
Power is work done per given time. The power output of a thermodynamic cycle (work done by the circulating fluid) is therefore the product of the fluid mass flow rate multiplied with the specific enthalpy difference:

$$P = \dot{m}*\Delta h = \dot{m}*(h_1-h_2) \quad [kg/s*Joule/kg=Joule/s=Watt]$$

Heat engine cycles (1)



Steam cycle
(1′ is for Rankine cycle)

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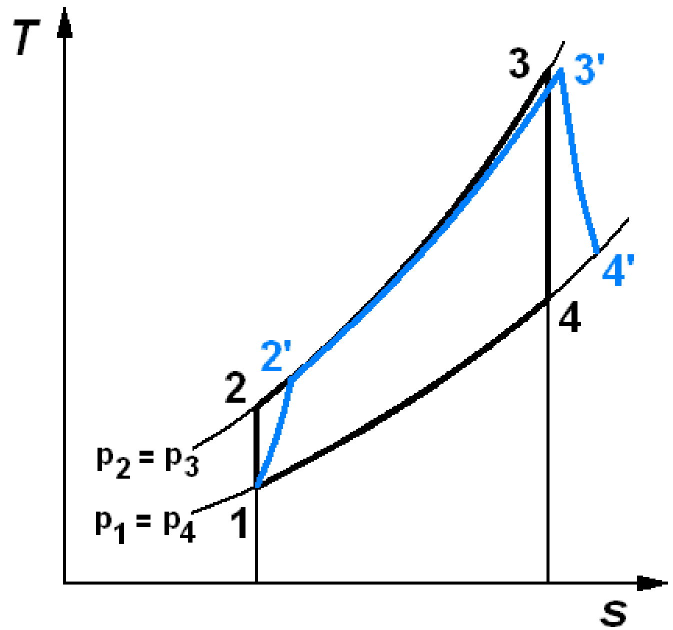
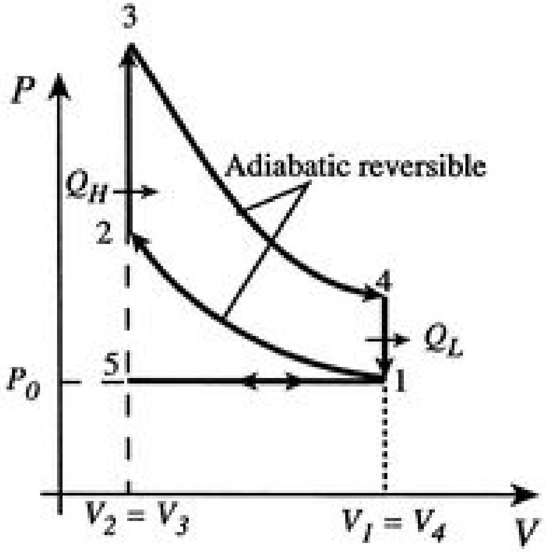


Gas turbine cycle
(Brayton or Joule cycle)

Heat engine cycles (2)



Otto (gas) engine cycle

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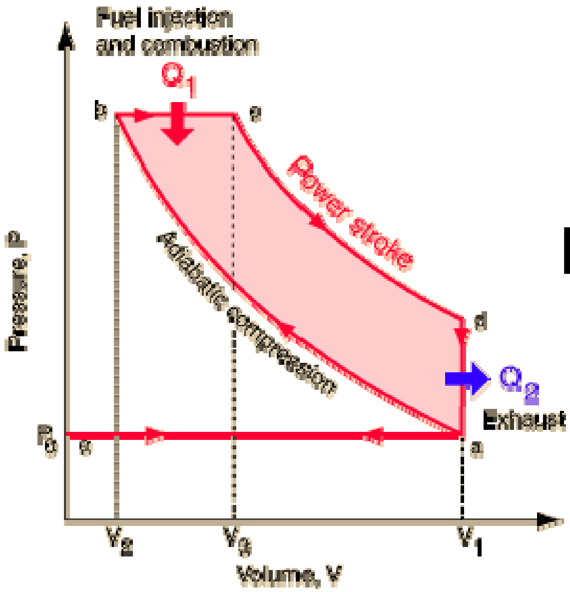
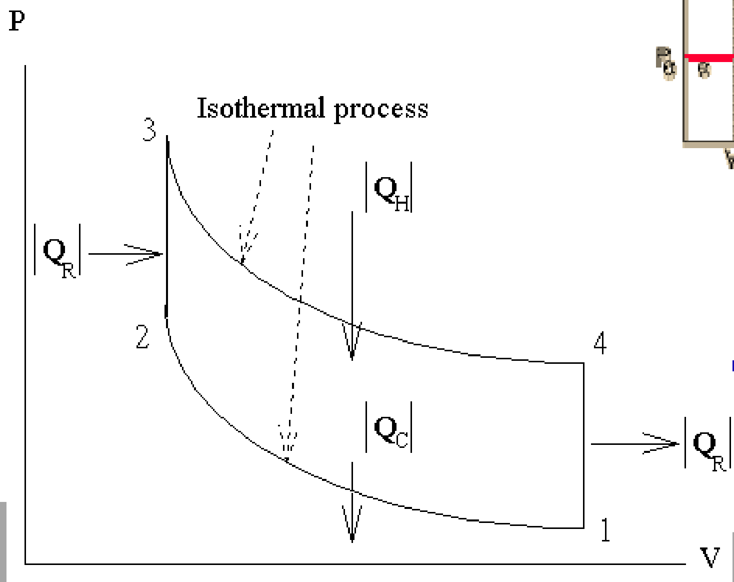


Diesel engine cycle



Stirling engine cycle

Energy conversion matrix

Initial energy form (columns); Final energy form (rows)

	Mechanical	Electrical	Kinetic	Potential	Thermal	Chemical
Mechanical	Gears Pulleys Torque converters	Electric motor	Turbines Water wheels	Spring Expander	Various types of Heat engine	Explosive
Electrical	Electric generator	Rectifier Inverter Transformer	MHD		Thermoelec. Thermionic Photovoltaic	Fuel cell Battery
Kinetic	Propeller	MHD	Molecular collisions	Pendulum Hydropower	Nozzle Solar to wind & waves	Gun
Potential	Lifts Pumps Compressors		Pendulum		Solar to Hydro	
Thermal	Friction	Heater Light bulb	Diffuser		Absorption	Combustion
Chemical		Electrolysis				

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