Thermodynamics and energetics 1

Prof. Sophia Haussener

Laboratory of Renewable Energy Sciences and Engineering

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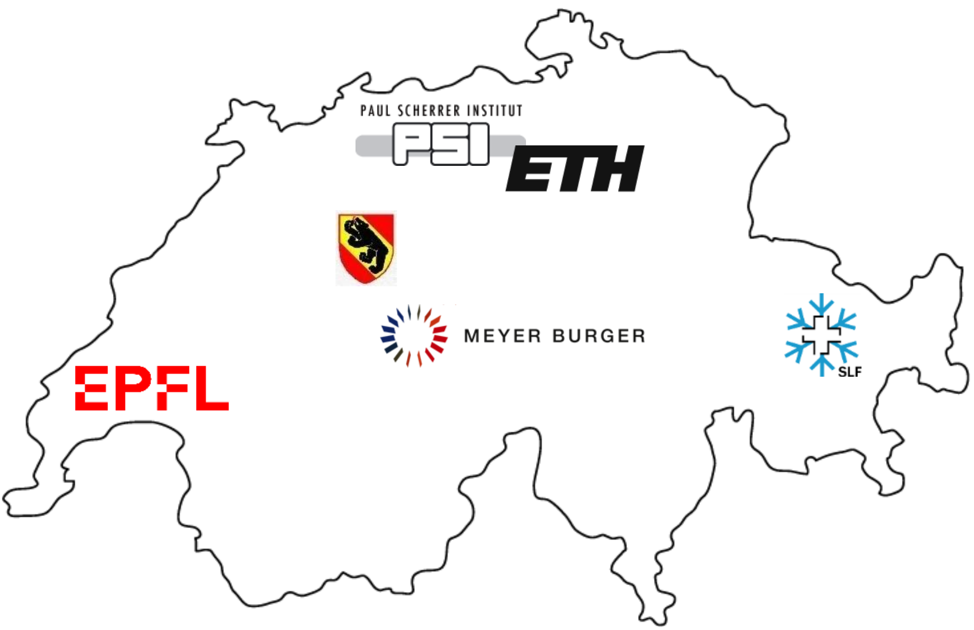
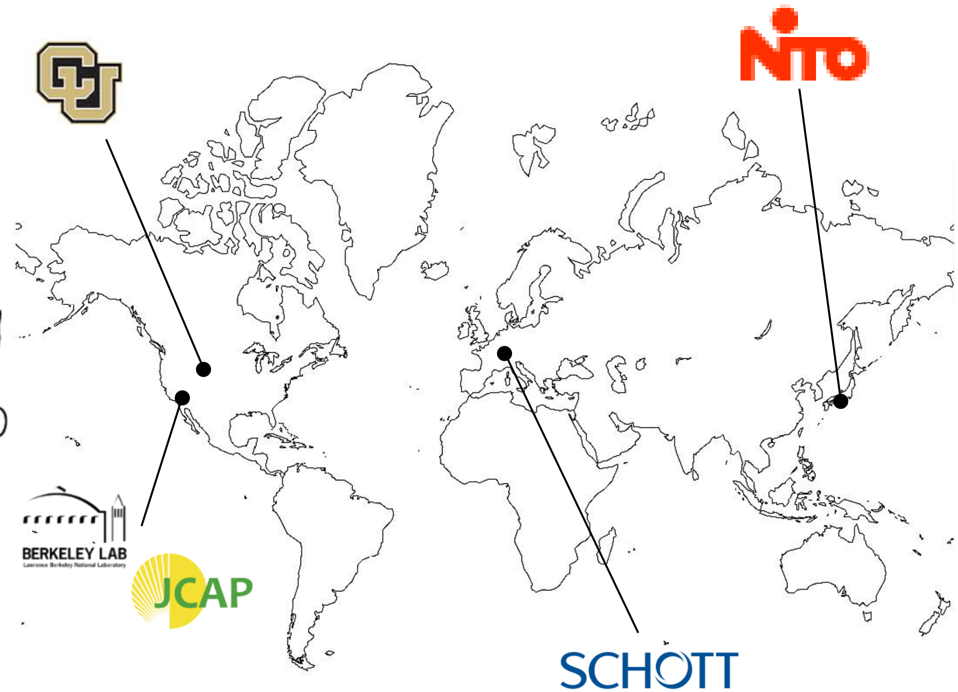
- Head of the Laboratory of Renewable Energy Sciences and Engineering

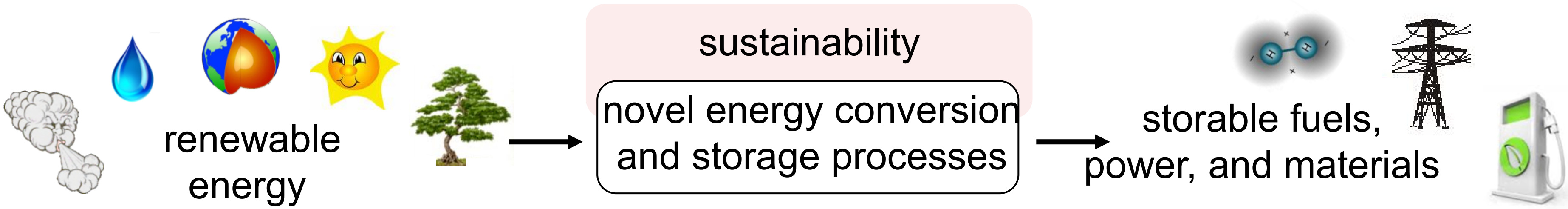




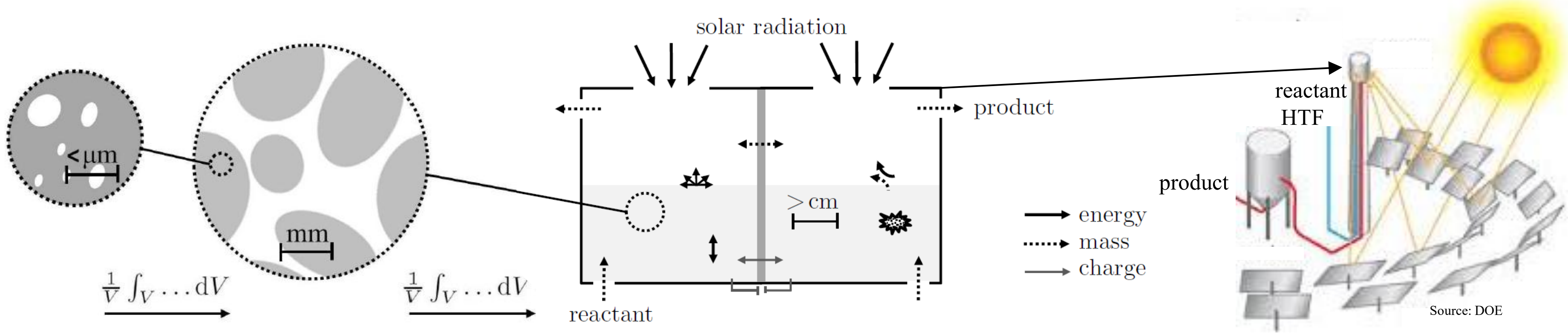
  - 2002 - 2007: BSc/MSc
  - 2007 - 2010: PhD
  - 2011 - 2012: Postdoc
  - 2013 - : Professor at EPFL

Laboratory of Renewable Energy Science and Engineering

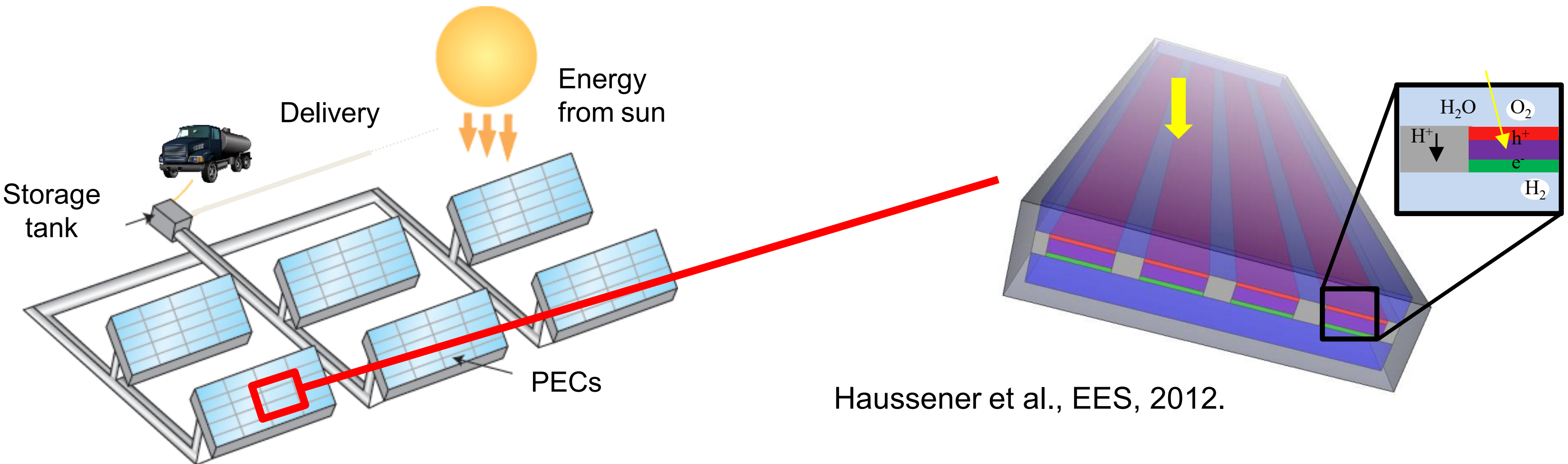
- Laboratory of renewable energy science and engineering – LRESE est. February 2013
- Research area: Efficient, sustainable, robust, and economic conversion of renewable sources into storable fuels, power, materials, or chemical commodities



- Multi-scale numerical and experimental investigations of the multi-physics processes, devices, and systems (from proof of concept to

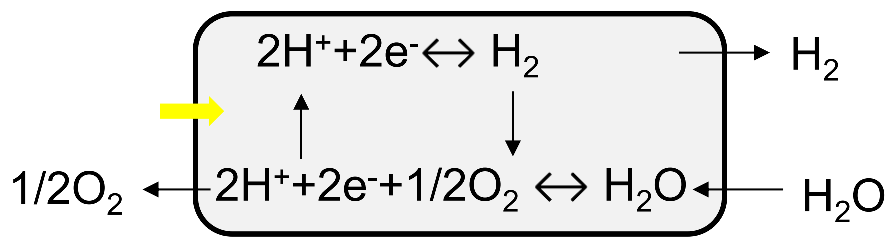


- Photoelectrochemical fuel production



Haussener et al., EES, 2012.

Adapted from *Photovoltaic-solar-power*



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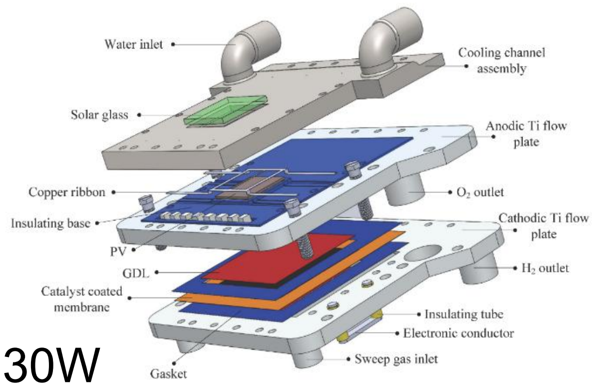

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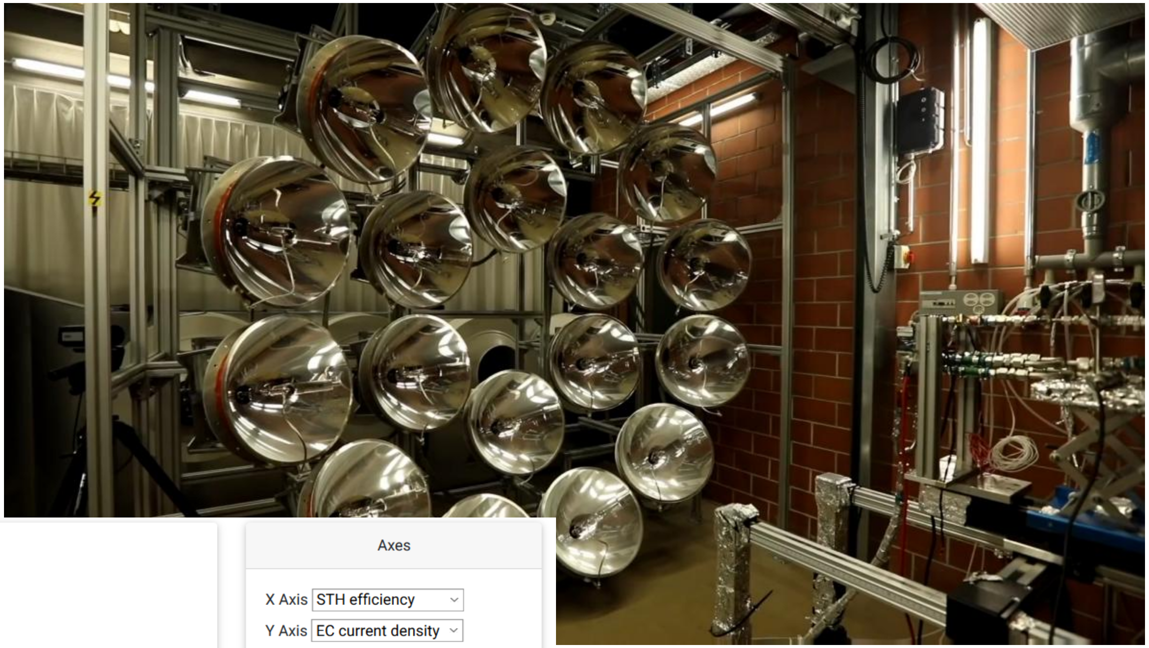
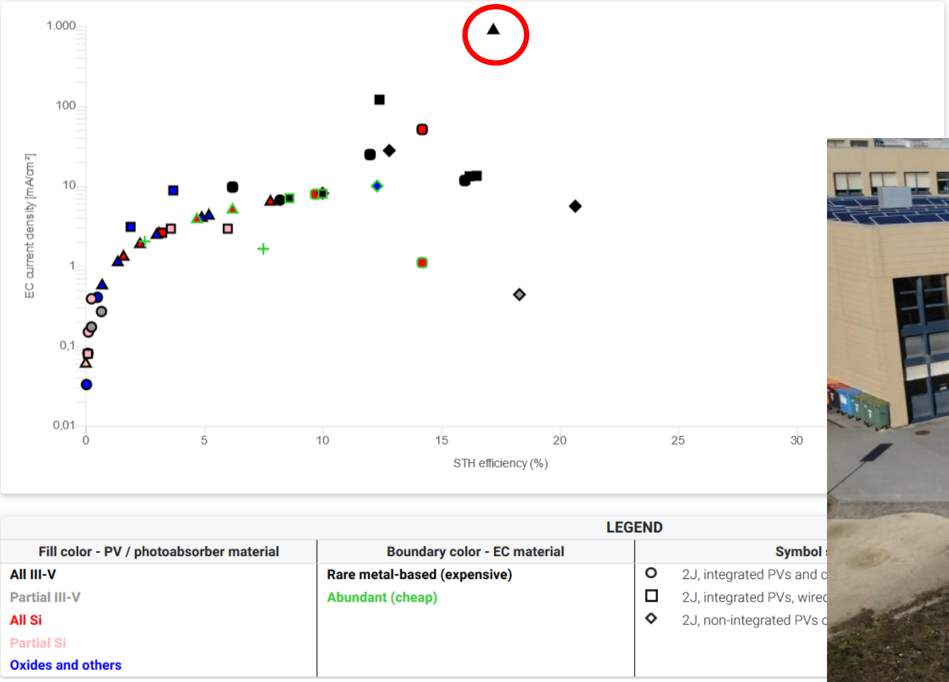




http://specdc.epfl.ch/

Course structure

Outline of course

1. Generalities
2. Energy and 1st law for closed systems
3. Energy transfer by heat
4. Thermodynamic properties
5. 1^{st} law for closed and open systems
6. 2^{nd} law and entropy
7. Exergy
8. Applications
9. Ideal gas mixtures and psychrometry
10. Summary

	Lecture Monday (08:15-10:00), BC 2201	Teacher	Lectures Wednesday (13:15-14:00), RLC	Teacher	Exercise Wed. (14:15-15:00), various rooms
Week 1 (8./10.9)	Generalities, energy, work, 1st law	ZL	Energy, work, 1st law	ZL	Exercise 1
Week 2 (15./17.9)	Energy transfer by heat	ZL	Thermodynamic properties	ZL	Exercise 2
Week 3 (22./24.9)	No lecture	ZL	Thermodynamic properties	ZL	Exercise 3
Week 4 (29.9/1.10)	Thermodynamic properties	ZL	1st law closed systems	ZL	Exercise 4
Week 5 (6./8.10)	1st law close and open systems	ZL	1st law close and open systems	ZL	Exercise 5
Week 6 (13./15.10)	1st law processes, cycles, diagrams, efficiency	ZL	2nd law, entropy	ZL	Exercise 6
-- Teaching break --					
Week 7 (27.10/29.10)	2nd law, entropy	ZL	2nd law, entropy	ZL	Q&A in exercise session
Week 8 (3./5.11)	Entropy and exergy	SH	Exergy	SH	Exercise 7
Week 9 (10./12.11)	Exergy	SH	Exergy / Vapour power systems	sh	Exercise 8
Week 10 (17./19.11)	Vapour power systems	SH	Vapour and gas power systems	SH	Exercise 9
Week 11 (24./26.11)	Gas power systems	SH	Gas power systems, combined	SH	Exercise 10
Week 12 (1./3.12)	Heat pumps	SH	Heat pumps and refrigeration systems	SH	Exercise 11
Week 13 (8./10.12)	Ideal gas mixtures and psychrometry	SH	Ideal gas mixtures and psychrometry	SH	Exercise 12
Week 14 (15./17.12)	Ideal gas mixtures and psychrometry	SH	Summary	SH/ZL	Exercise 13

Summary last lecture

- Interpret Clausius inequality
- Understand key concept of second law
  - Entropy transfer
  - Entropy production
  - Entropy increase
- Evaluate/calculate entropy and entropy change in a process
- Draw temperature-entropy diagrams
- Apply entropy balances to open and closed systems
- Define and evaluate isentropic efficiencies of components (turbines, nozzles, compressors, pumps)

Moran book: chp. 6

Learning outcomes of todays lecture

- Understand and demonstrate key concept of exergy and exergy analysis

- Evaluate exergy at a state and exergy changes between two states

- Apply exergy balances to closed systems

Moran book: chp. 7.1-7.4

EPFL

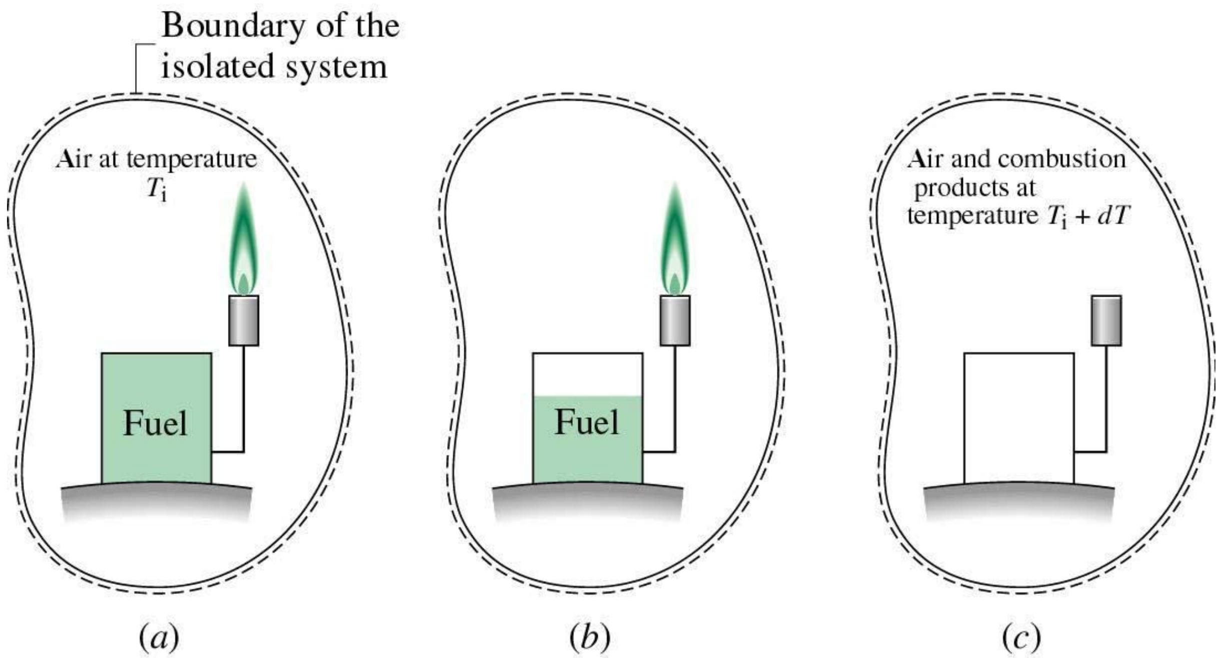
Exergy

- We learned
  - The 1st law of thermodynamics allows us to determine the *quantity* of energy (energy conservation for closed and open systems)
  - The 2nd law of thermodynamics allows us to
    - Describe the potential for converting heat into work (Carnot efficiency)
    - Determine and compare processes/cycles with ideal, reversible processes

  → Energy has a *quality*

Exergy

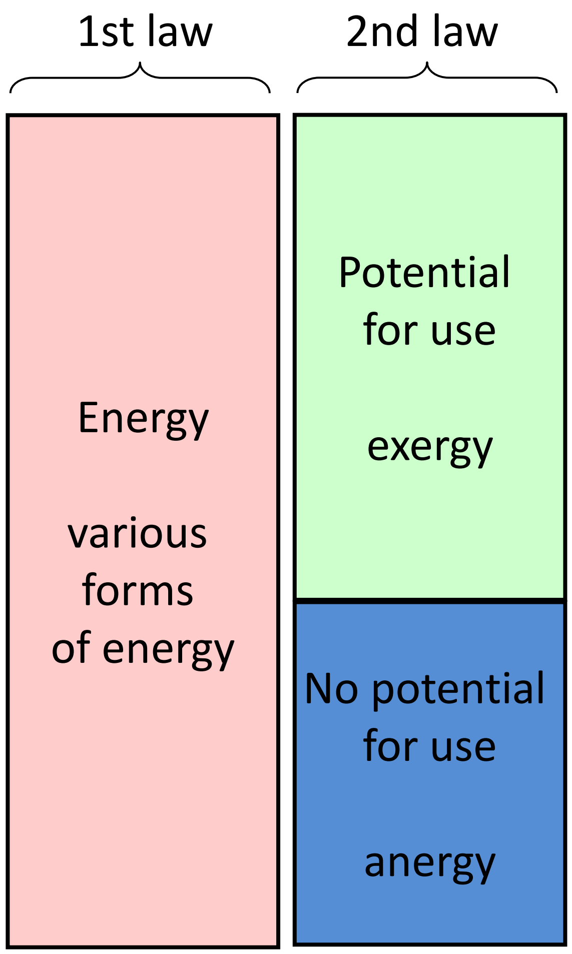
- Isolated system:
  a) Container of fuel
  b) Fuel burns
  c) Slightly warm mixture



- The total energy is conserved
- But potential for use decreases, i.e. initial potential for use is destroyed

Exergy

- What is the potential for use?

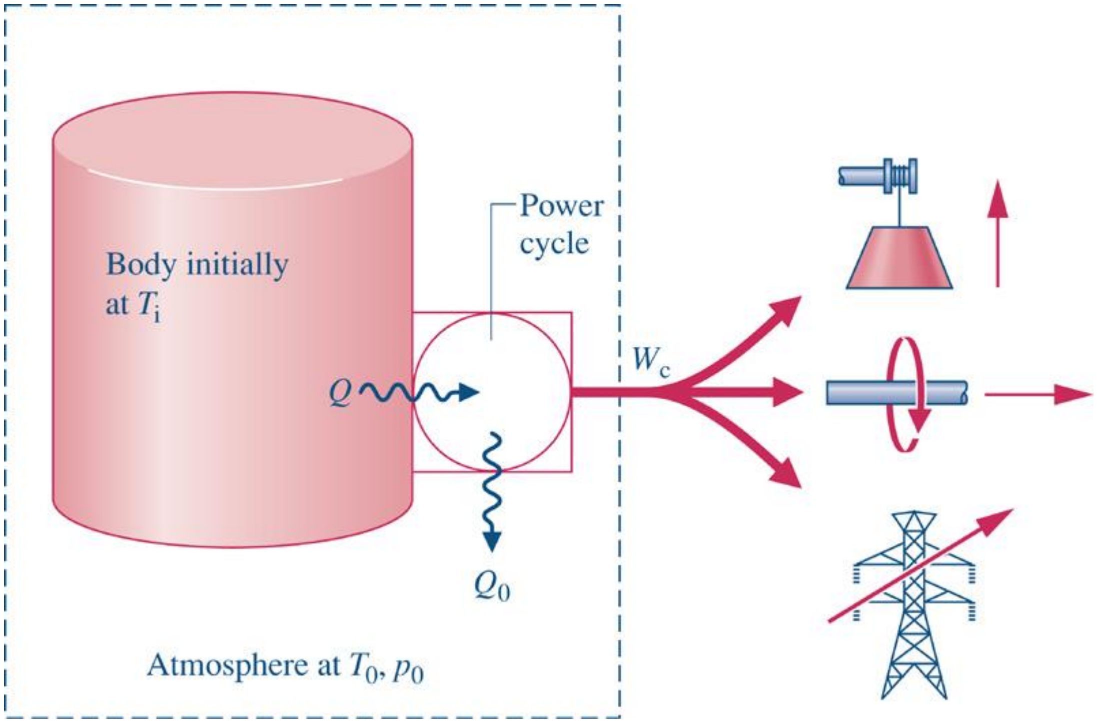


Exergy

- Exergy
  - is a property
  - quantifies the potential for use
  - is not conserved but destroyed by irreversibilities
  - can be transferred to and from systems
  - if transferred from a system to a surrounding without use represents a loss
  - destruction within a system can be reduced by improved energy resource utilization
  - can be linked to economic value (fuel is more valuable than heat)

Exergy

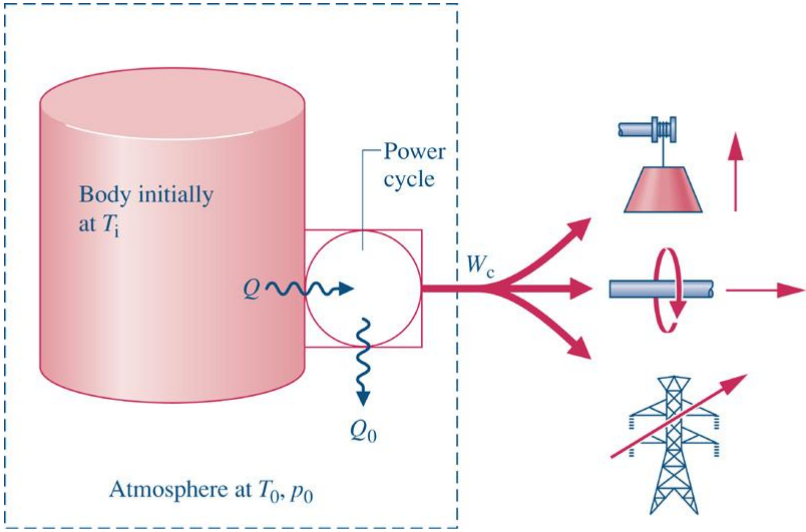
- Developing exergy
  - A potential for developing work exists whenever two systems at different states are brought into contact
  - Work can be developed as the two systems are allowed to come into equilibrium



- Exergy is the maximum theoretical value of such work.

Exergy

- Developing exergy



  - The (exergy reference) environment:
    - Is large
    - Is uniform in temperature and pressure
    - Is usually taken ambient conditions (T_0 = 25°C, p_0 = 1bar)

  - If a system is at rest relative to the environment, and at T_0 and p_0, it is in the *dead state*

Exergy

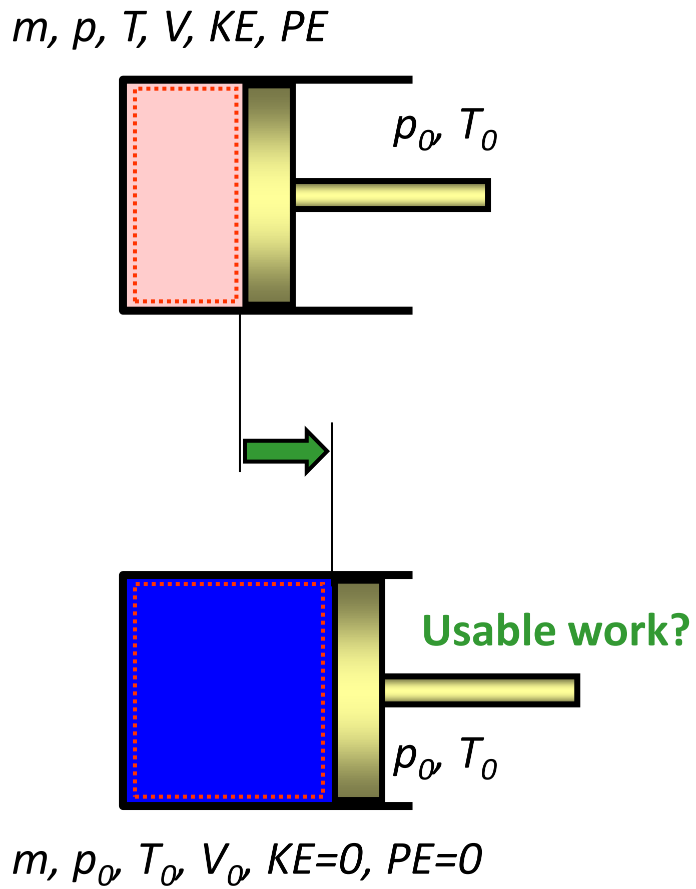
- *Exergy* is the maximum theoretical work obtained from an overall system consisting of a system and the environment as the system comes into equilibrium with the environment (passes to the dead state)

- The energy fraction remaining after achieving the equilibrium - which cannot further be converted into work – is called anergy

- Energy is composed of exergy and anergy
  - Exergy can be converted in anergy
  - Exergy stays constant for reversible processes
  - Anergy cannot be converted in exergy

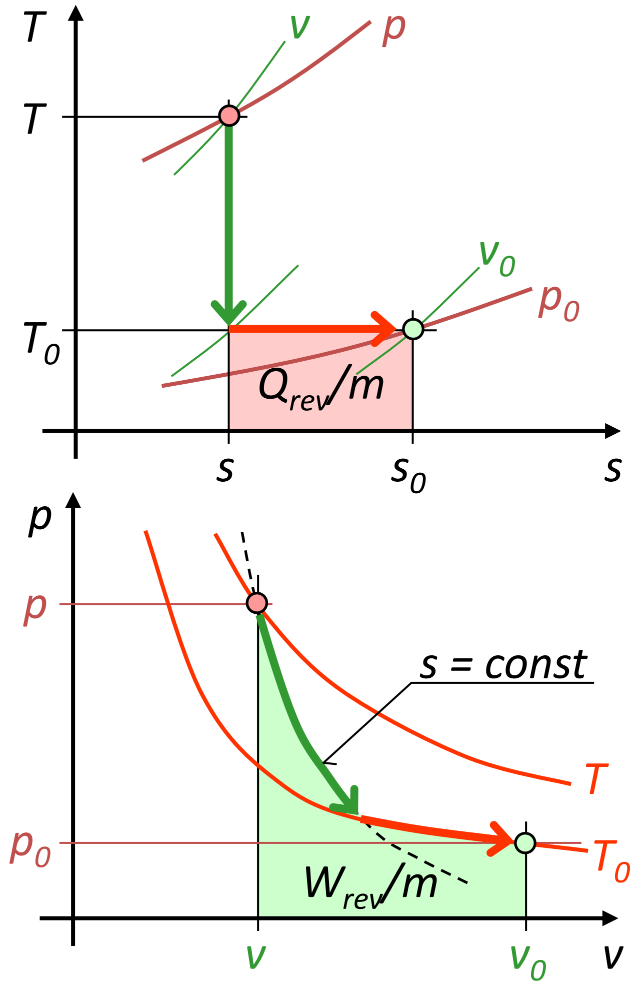
Exergy

- Exergy of a system:
  - A system originally in a defined state
  - A reversible process brings the system into equilibrium with the environment



Exergy

- Exergy of a system:
  - A system originally in a defined state
  - A reversible process brings the system into equilibrium with the environment
    - Isentropic expansion
    - Isothermal heating receiving heat from environment



Exergy

- Exergy of a system:
  - A system originally in a defined state
  - A reversible process brings it into equilibrium with the environment

- First law: $E_0 - E = Q_{rev} - W_{rev}$

$$U_0 + KE_0 + PE_0 - U - KE - PE = Q_{rev} - W_{rev}$$

- Second law: $\delta Q_{rev} = T_0 dS \rightarrow Q_{rev} = T_0 \left(S_0 - S \right)$

- Decomposing work: $W_{rev} = W_{usable} + p_0 \left(V_0 - V \right)$

- The max. usable energy, i.e. exergy:

$$Ex = W_{usable} = U - U_0 + KE + PE - T_0 \left(S - S_0 \right) + p_0 \left(V - V_0 \right)$$

Exergy

(+)

- Exergy of a system:

$$Ex = U - U_0 + KE + PE - T_0\left(S - S_0\right) + p_0\left(V - V_0\right) \qquad \text{[J]}$$

- Specific exergy:

$$ex = u - u_0 + ke + pe - T_0\left(s - s_0\right) + p_0\left(v - v_0\right) \qquad \text{[J/kg]}$$

- Exergy is an extensive property

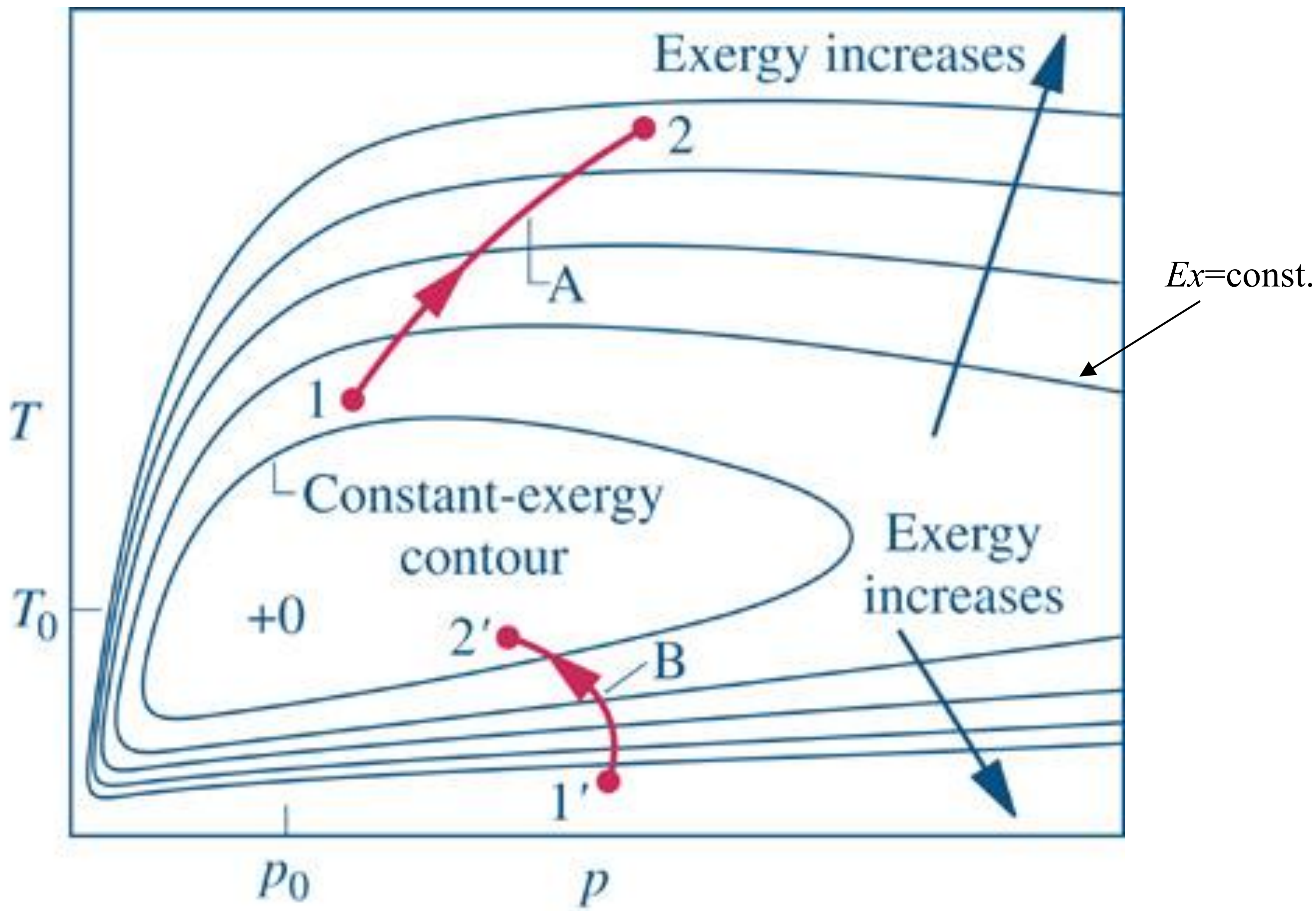
- Difference in exergy:

$$Ex_2 - Ex_1 = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) - T_0\left(S_2 - S_1\right) + p_0\left(V_2 - V_1\right)$$

$$ex_2 - ex_1 = (u_2 - u_1) + (ke_2 - ke_1) + (pe_2 - pe_1) - T_0\left(s_2 - s_1\right) + p_0\left(v_2 - v_1\right)$$

- Exergy change

$$Ex_2 - Ex_1 = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) - T_0\left(S_2 - S_1\right) + p_0\left(V_2 - V_1\right)$$



Exergy

- Exergy:
  - Is a measure of the departure of the state of a system from that of the environment
  - Is an attribute of the system and environment together
  - Can be determined once the environment is specified
  - Cannot be negative
  - Is not conserved but destroyed by irreversibilities
  - Is the maximum theoretical work obtainable form an overall system as the system passes from a state to the dead state
  - Or is the minimum theoretical work required to bring system from dead state to given state
  - Is zero at the dead state, it is in thermal and mechanical equilibrium with the environment

Exergy

- Example (7.1): A cylinder of an internal combustion engine contains 2450 cm^3 of gaseous combustion products (modeled as air) at a pressure of 7 bar and a temperature of 867 °C just before the exhaust valve opens. Determine the specific exergy of the gas. Assume ideal gas, environmental conditions of 300 K and 1.013 bar, and neglect motion and gravity.

ex=368.9 kJ/kg

Exergy

- Exam … ontains
  2450 … at a
  press … e
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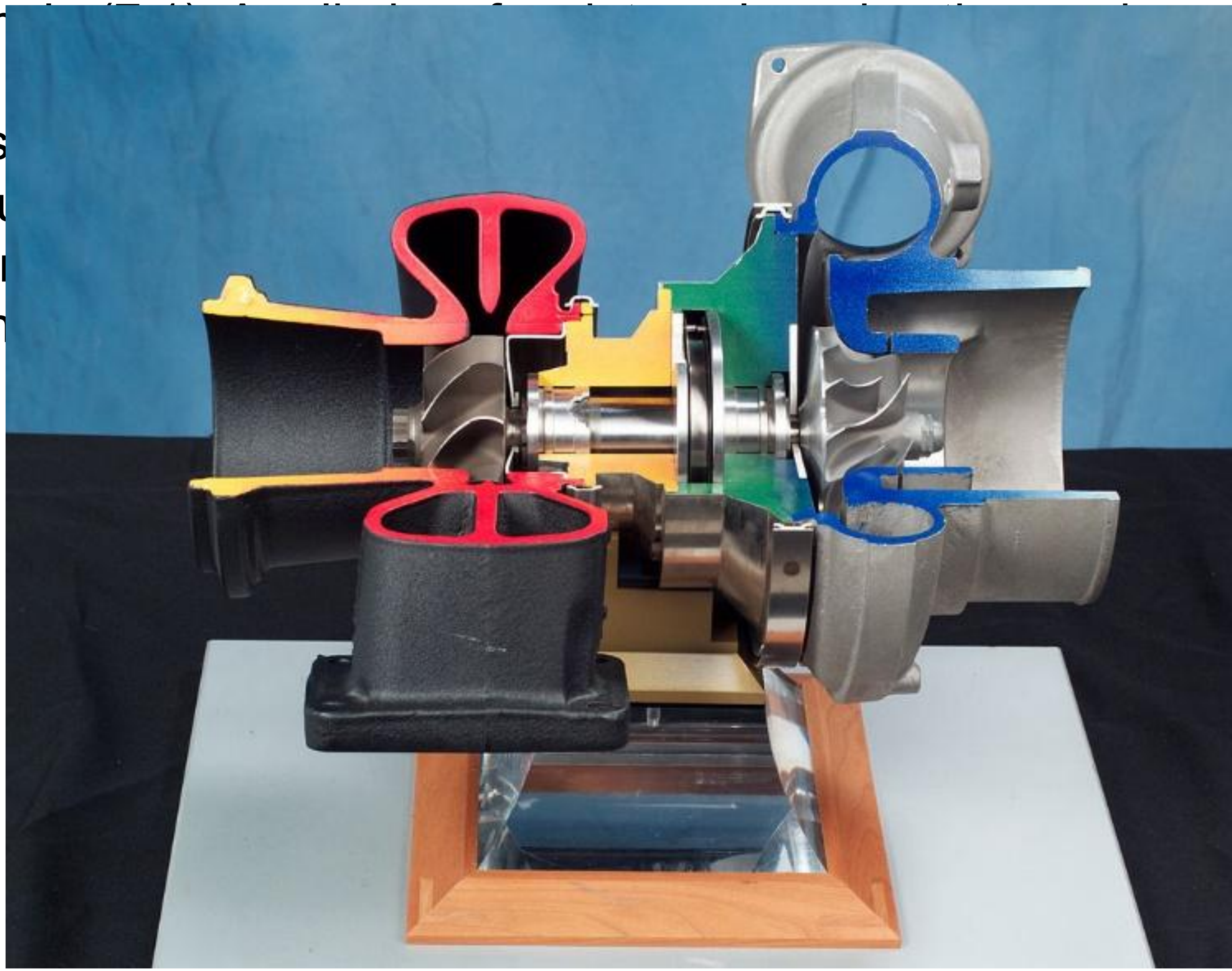
  and n …



$ex = 368.9$ kJ/kg

Exergy balance for closed systems

- Closed systems:
  - 1st law:

$$E_2 - E_1 = \int_1^2 \delta Q - W_{12}$$

  - 2nd law:

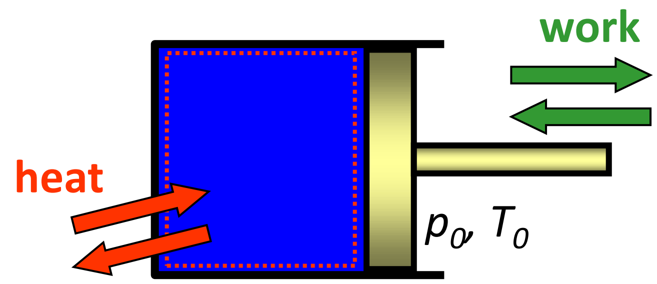
$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + \sigma$$

  - Exergy:

$$Ex_2 - Ex_1 = (E_2 - E_1) - T_0 \left(S_2 - S_1\right) + p_0 \left(V_2 - V_1\right)$$

$$= \int_1^2 \delta Q - W_{12} - T_0 \left(\int_1^2 \frac{\delta Q}{T} + \sigma \right) + p_0 \left(V_2 - V_1\right)$$

$$= \int_1^2 \left(1 - \frac{T_0}{T}\right) \delta Q - \left(W_{12} - p_0 \left(V_2 - V_1\right)\right) - T_0 \sigma$$



Exergy balance for closed systems

- Closed systems:

$$Ex_2 - Ex_1 = \underbrace{\int_1^2 \left(1 - \frac{T_0}{T}\right)\delta Q}_{\text{Exergy transfer by heat transfer}} - \underbrace{\left(W_{12} - p_0\left(V_2 - V_1\right)\right)}_{\text{Exergy transfer by work}} - \underbrace{T_0\sigma}_{\text{Exergy destruction by irreversibilities}}$$

Exergy transfer by heat transfer - **Exergy transfer by work** - **Exergy destruction** by irreversibilities

- Expressed alternatively:

$$Ex_2 - Ex_1 = Ex_q - Ex_w - Ex_d$$

Exergy balance for closed systems

- Closed systems:

$$Ex_2 - Ex_1 = \int_1^2 \left(1 - \frac{T_0}{T}\right)\delta Q - \left(W_{12} - p_0\left(V_2 - V_1\right)\right) - T_0\sigma$$

- Rate form:

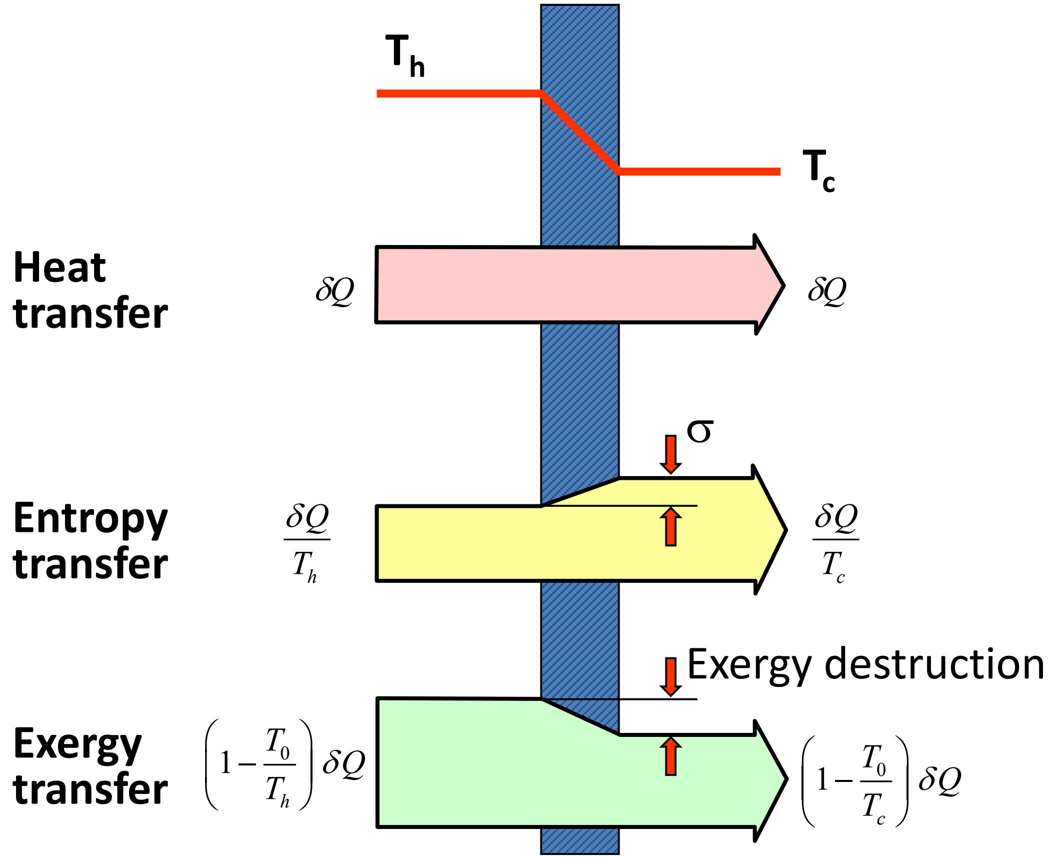
$$\frac{dEx}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W}_{12} - p_0\frac{dV}{dt}\right) - T_0\dot{\sigma}$$

- Steady state:

$$0 = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{12} - T_0\dot{\sigma}$$

Exergy balance for closed systems

- Closed systems, stead state, finite temperature difference:



$$dEx_d = T_0 \frac{T_h - T_c}{T_h T_c}\delta Q = T_0 \frac{\Delta T}{T_h (T_h - \Delta T)}\delta Q \approx T_0 \frac{\Delta T}{T_h{}^2}\delta Q$$

← The higher the better

Exergy balance for closed systems

- Closed systems, isolated:

$$Ex_2 - Ex_1 = -T_0\sigma < 0$$

  - Exergy destruction
  - In accordance to 2nd law

Exergy

- Example (7.2): Water at 150 °C is contained in a piston-cylinder assembly. The water is heated from its saturated liquid state to the saturated vapor state in an internally reversible process. Calculate the exergy change in the system, determine the exergy accompanying heat transfer and work, and the exergy destructed. Environmental pressure is 1 bar and temperature is 293K.

$ex=502.4$ kJ/kg
$Ex_q/m=649.5$ kJ/kg
$Ex_w/m=147.2$ kJ/kg
$Ex_d/m=0$

Learning outcomes of todays lecture

- Understand and demonstrate key concept of exergy and exergy analysis
- Evaluate exergy at a state and exergy changes between two states
- Apply exergy balances to closed