Lecture # 2

Thermodynamics and
Tools to Analyze Conversion Efficiency

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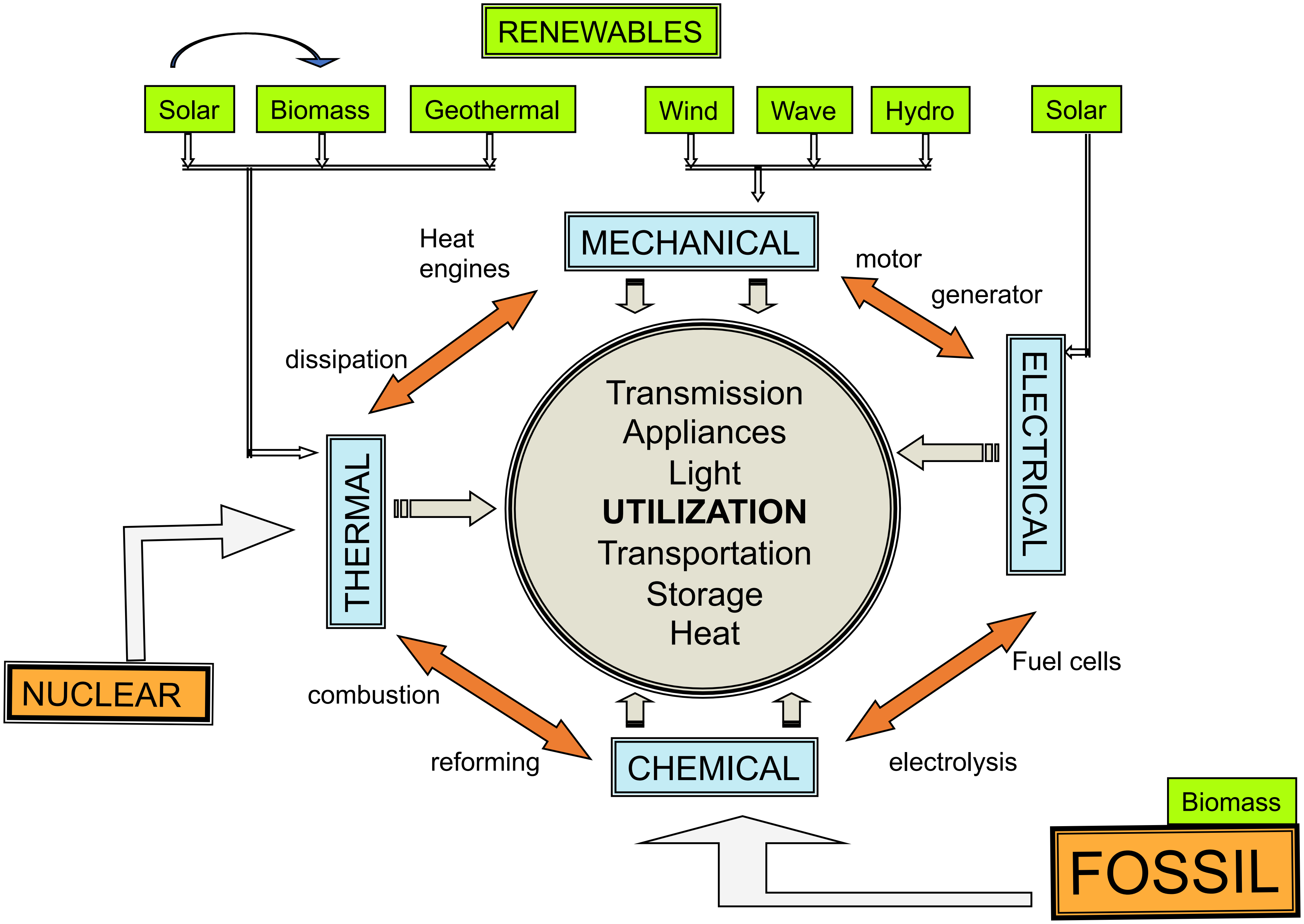
- Conservation laws
- Limits on conversion
- Availability
- Efficiency

Ghoniem, AF Energy Conversion Engineering, Chapter II, Thermodynamics.



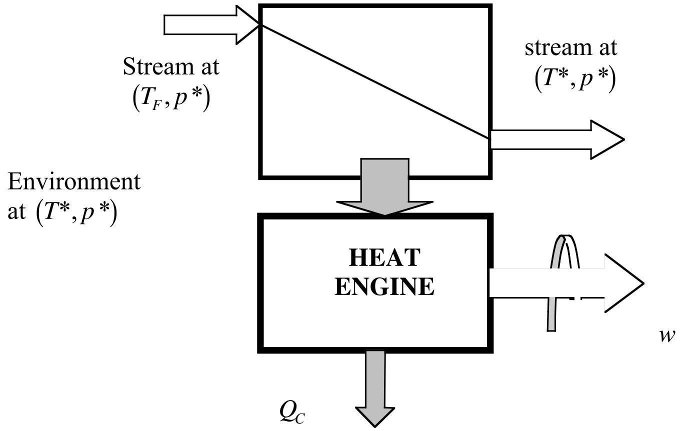
RENEWABLES
Solar
Biomass
Geothermal
Wind
Wave
Hydro
Solar
MECHANICAL
Heat engines
dissipation
motor
generator
THERMAL
ELECTRICAL
Transmission
Appliances
Light
UTILIZATION
Transportation
Storage
Heat
NUCLEAR
combustion
reforming
Fuel cells
electrolysis
CHEMICAL
Biomass
FOSSIL

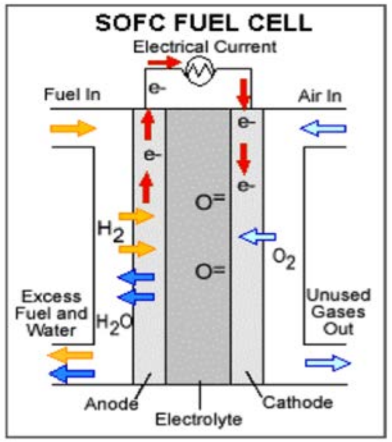
Some Thermodynamics

"Classical Thermodynamics is the only physical theory of universal content which, … within the framework of its basic notions, will never be toppled." *Albert Einstein.*

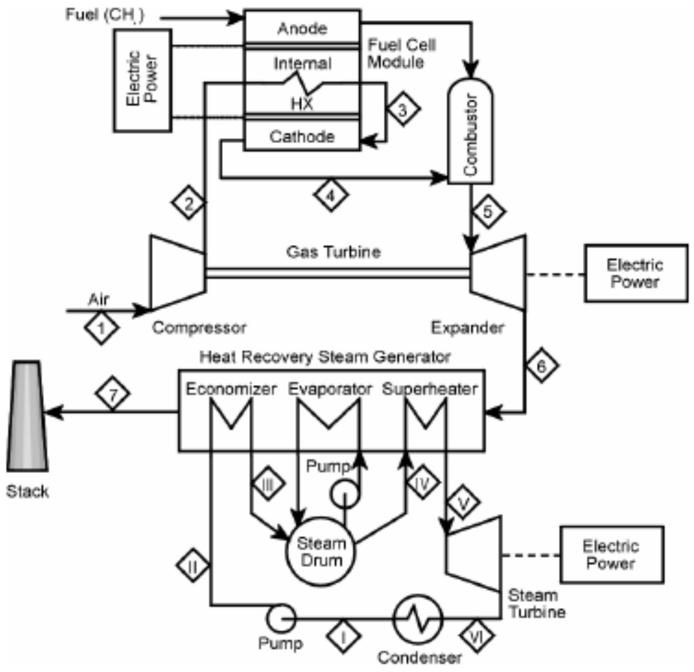
- Energy conversion is governed by conservation principles, and often involves "availability" loss.
- This translates to the all important "efficiency".
- How to maximize conversion efficiency, identify sources of loss and minimize them?

Heat Engine & Fuel Cell, Efficiency?





Integration of Thermomechanical
and Electrochemical Systems



$$\eta_{car} = 1 - \ell n \frac{T_F}{T^*} / \left(\frac{T_F}{T^*} - 1\right)$$

$$= 70\% \ for\ T_F / T^* = 8$$

$$\mathcal{E}(T,p,X_i) = \mathcal{E}^o(T) + \frac{\Re T}{2\Im}\left(\frac{1}{2}\ell n\, p + \ell n\left(\frac{X_{H_2} X_{O_2}^{1/2}}{X_{H_2O}}\right)\right)$$

$$\eta_{OC} = \frac{w_{max}}{\Delta H^o_{R,H_2O}} = \frac{\Delta G_{R,H_2O}}{\Delta H^o_{R,H_2O}}$$

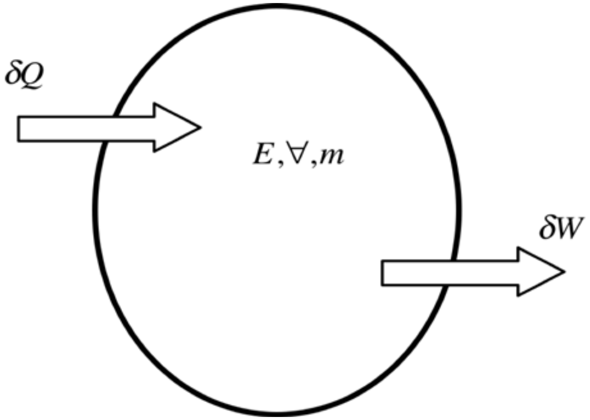
Ideal thermomechanical vs. electrochemical systems, governing principles and efficiency, and their integration for maximizing the latter

First Law: Energy Conversion, heat and work transfer, control mass

$$\Delta Q - \Delta W = E_2 - E_1$$

Stored Energy (in terms of state properties, V, $u = U/m$, Z, ς, ...)

$$E = \underbrace{KE}_{\frac{1}{2}m\mathbf{V}^2} + \underbrace{PE}_{mg_r Z} + \underbrace{U}_{U_{th} + U_{ch}} + \underbrace{E_{elas}}_{\frac{1}{2}k_s x^2} + \underbrace{E_{elect}}_{\varepsilon\varsigma} + E_{mag} + E_{nuc}$$

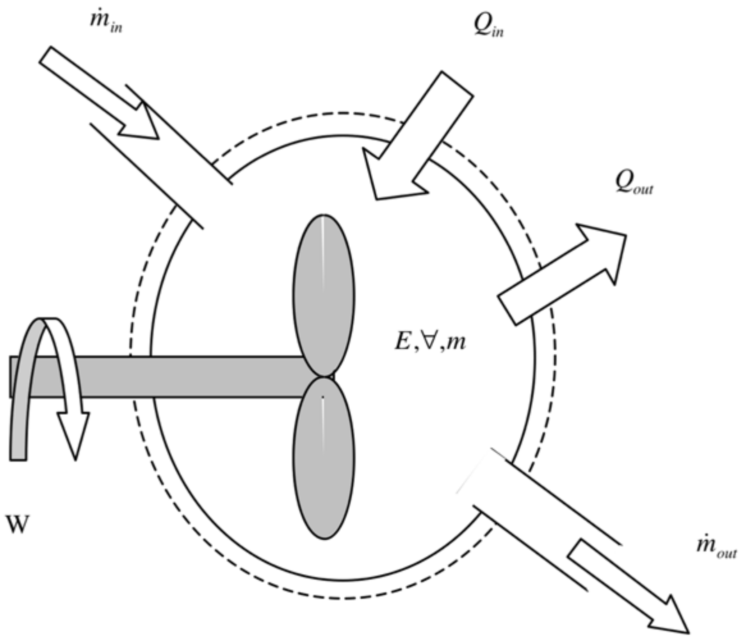


$$-\delta W_{mech} = \vec{F}.d\vec{x} = -p\,d\forall$$

$$-\delta W_{el} = \mathcal{E} d\varsigma$$

$$-\delta W_{mag} = \mathrm{H}\,dM_g$$

Control Volume:



Need mass conservation as well

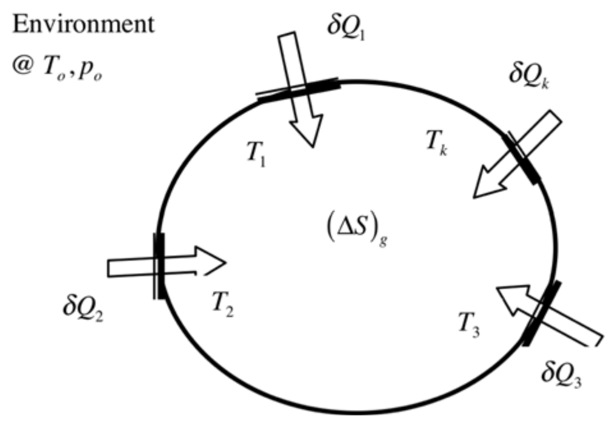
$$\frac{dm_{CV}}{dt} = \sum_{in} \dot{m}_i - \sum_{out} \dot{m}_i$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}_i (h + ke + pe + ...) - \sum_{out} \dot{m}_i (h + ke + pe + ...)$$

$$E_2 - E_1 = Q - W + \sum_{in} m_i (h + ke + pe + ...) - \sum_{out} m_i (h + ke + pe + ...)$$

Second Law: Entropy
Control mass

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + (\Delta S)_g \quad \text{or} \quad S_2 - S_1 = \sum_{k=1}^{K} \frac{\Delta Q_k}{T_k} + (\Delta S)_g$$



Entropy is generated when:

- Heat is transferred across a finite temperature gradient
- Fluid expands across a finite pressure drop
- Mixing of different fluids (or same fluid volumes with different T)
- Chemical reactions causing temperature rise (or drop)

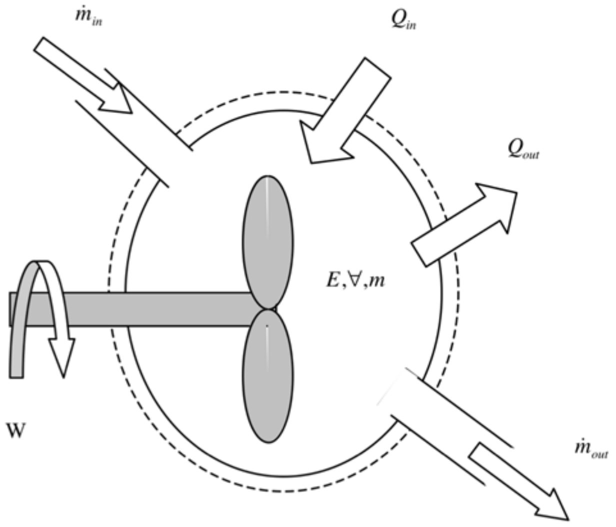
Informally: entropy is generated when a process is performed without work transfer when work could have been obtained (or when it is less than the maximum possible).

One of the original statements: a cyclic machine cannot be used to convert heat into work at 100% efficiency.

Second Law: Entropy
Control volume

$$\frac{dS_{cv}}{dt} = \int_1^2 \frac{\delta \dot{Q}}{T} + \sum_{in} s_i \dot{m}_i - \sum_{out} s_i \dot{m}_i + \left(\frac{dS}{dt}\right)_g$$

$$(S_2 - S_1)_{CV} = \sum \frac{\Delta Q_i}{T_i} + \sum_{in} s_i m_i - \sum_{out} s_i m_i + (\Delta S)_g$$



Entropy generation is a quantitative measure of “loss of work”!?

The lost work is measured by the “availability” or “exergy” loss.

Maximum Work, Availability and limits on energy conversion:

System (with fixed mass)

“Add” the first and second laws
For a system with heat transfer at fixed temperatures

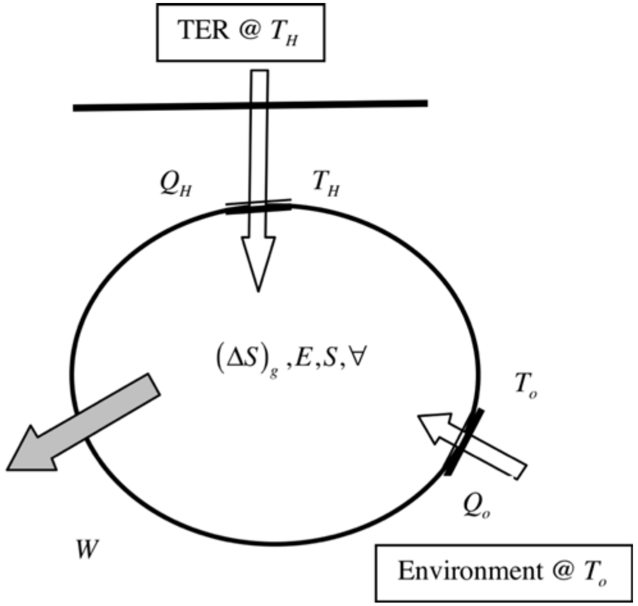
$$W_{use} = Q_H \left(1 - \frac{T_o}{T_H}\right) + \Xi_1 - \Xi_2 - I_{ir}.$$

system availability is:

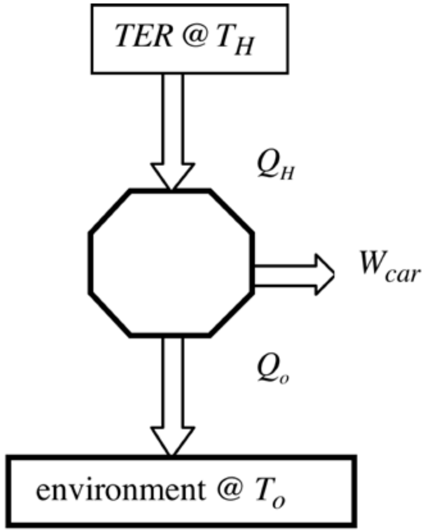
$$\Xi = (E - U_o) + p_o(\forall - \forall_o) - T_o(S - S_o).$$

Changes in internal energy, volume or entropy can produce work

$I_{ir} = T_o(\Delta S)_g \rightarrow$ internal irreversibility or lost work



Examples:



Heat Engine, work produced by heat transfer only:

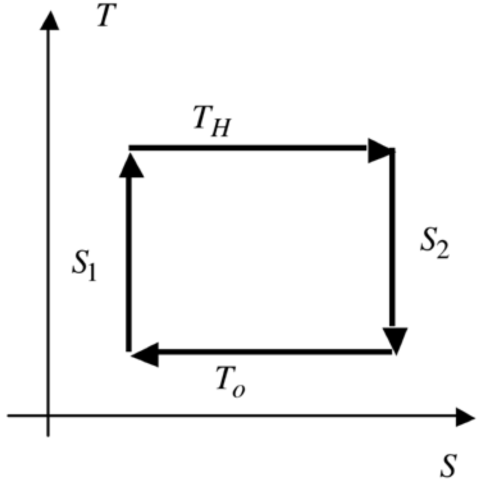
2 TER*, high TER fixed at T_H

$$W_{\max} = \left(1 - \frac{T_o}{T_H}\right) Q_H = W_{car}$$

* it is easy to fix T_o, but not T_H

Can only be realized with:

- Isothermal heat transfer from sources (with zero ΔT)
- Ideal expansion/compression



The Carnot cycle is an ideal heat engine

(as well as the Stirling and Ericsson cycles)

For a control volume

Fixed Mass interacting with single TER@T_0:

$$W_{\max} = \left(E_1 - T_0 S_1 + p_0 \forall_1\right) - \left(E_2 - T_0 S_2 + p_0 \forall_2\right)$$

$$= \Xi_1 - \Xi_2$$

Ξ : total exergy or availability difference

in case only internal energy is utilized, $E = U$

with no change of chemical state, $U = U_{th}$.

For $\max\left|W_{\max}\right|$, final state (2) must be in equilibrium

with environment (restricted dead state), $T_2 = T_0, p_2 = p_0$

$$\dot{W}_{cv} = \sum_{TERs}\left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i - \left(\frac{d\Xi_{cv}}{dt} - p_o \dot{\forall}_{cv}\right) + \sum_{in} \dot{m}_i \xi_i - \sum_{out} \dot{m}_i \xi_i - \dot{I}_{ir}$$

$$\xi = \left(\tilde{h} - h_o\right) - T_o\left(s - s_o\right)$$

(flow exergy/availability per unit mass)

$$\tilde{h} = h + ke + pe$$

for an ideal gas, fixed c_p

$$\Delta h = c_p\left(T_2 - T_1\right),$$

$$\Delta s = c_p \ell n\left(\frac{T_2}{T_1}\right) - \Re \ell n\left(\frac{p_2}{p_1}\right)$$

For steady operation of a CV interacting with 2 TER and stream:

$$\dot{W}_{cv} = \underbrace{\left(1 - \frac{T_o}{T_H}\right)\dot{Q}_H}_{\text{Carnot Engine heat availability}} + \underbrace{\dot{m}\left(\xi_{in} - \xi_{out}\right)}_{\text{flow stream flow availability}} - \dot{I}_{ir} \qquad \xi = \left(\tilde{h} - h_o\right) - T_o\left(s - s_o\right)$$

For maximum work:

- zero irreversibility, $I_{ir} = 0$
- equilibrium with enviroment, $\xi_{out} = \xi_{env}$

For steady operation of a CV interacting with a stream only: $\dot{Q}_H = 0$

Entropy and exergy analysis serve the same purpose, they are interchangable

Either can be used to determine the source of inefficiency in a complex system

Example 2.8. (subcooled) Water at 200 kPa and 100^{o}C is expanded in an adiabatic throttle valve to a final pressure of 20 kPa. The process does not involve any work transfer. An inventor claims to have designed a device that generates work of 10 kJ/kg of water while maintaining the same inlet and outlet conditions of the throttle and exchanging heat with the environment at 25^{o}C. Is this claim feasible?

assume steady operation, neglect changes in the kinetic and potential energies.
At 200 kPa and 100 ^{o}C, $h_1 = h_{f@100°C} = 419.17$ kJ/kg and $s_1 = s_{f@100°C} = 1.3072$ kJ/kg-K.
energy balance across an adiabatic throttle is: $h_2 = h_1 = 419.17$ kJ/kg.
The final state is determined by knowing the final pressure, p_2, and the final enthalpy, h_2.
Since the enthalpy falls between the saturated liquid and the saturated vapor values at 20 kPa, $h_{f@20\text{kPa}} = 251.42$ kJ/kg and $h_{g@20\text{kPa}} = 2608.9$ kJ/kg,
the quality of the mixture is $x_2 = \left(h_2 - h_f\right)/h_{fg} = 0.0712$,
and the entropy is $s_2 = s_f + x_2\ s_{fg} = 0.8320 + 0.0712 \times 7.9073 = 1.3354$ kJ/kg-K.

maximum work is the difference between the availability between initial and final states:

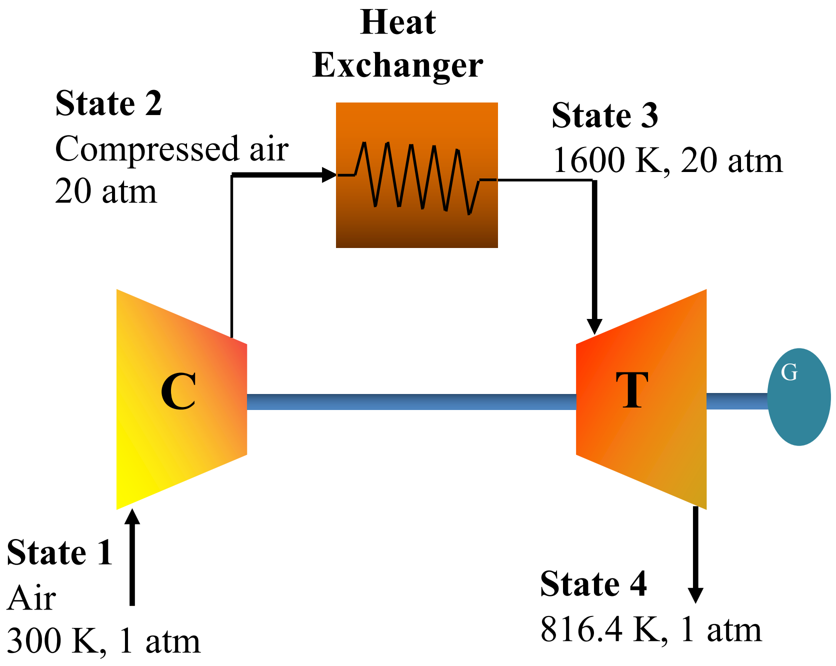
$$w_{\max} = \left(h_1 - T_o s_1\right) - \left(h_2 - T_o s_2\right) = T_o\left(s_2 - s_1\right) = 8.417 \quad kJ/kg$$

work output claimed by the inventor is higher than maximum value, not possible.

Using exergy analysis to determine the performance of a system and how to improve it

A closed-cycle gas turbine power plant, shown in the following figure, operates with air as a working fluid. Conditions are shown in figure. Analyze the losses and propose improvements

State	T(K)	p (atm)	h (kJ/kg.K)	ξ (kJ/kg)
1	300	1	0	0
2	808.3	20	510.4	469.8
3	1600	20	1305.2	1058.9
4	816.4	1	519.4	217.5



Energy (and availability) are added (from outside) in process 2-3 only.
For maximum work all availability added should be used as work
How much is lost in each component and with the exit stream?

To determine performance

of individual components:

For a flow process:

$$Q - W = \Delta h$$

Maximum work

= change in availability

$(W_{\max})_{turbine} = \xi_4 - \xi_3,\ (W_{\max})_{compr} = \xi_2 - \xi_1,$

$(W_{\max})_{exitstream} = \xi_4 - \xi_1,$

state 1 taken as reference

	Enthalpy change (kJ/kg)	Availability change (kJ/kg)
Heat Exchanger	$h_3 - h_2$=794.8	$\xi_3 - \xi_2$=**589.1**
Compressor	W_c =510.4	-469.8
Turbine	W_t =785.8	841.4
Net Work	$(h_3 - h_4) - (h_2 - h_1)$=**275.4**	
Air out at 4	$h_4 - h_1$= 519.4	**217.5**

to find maximum work by system

$$W_{sys} = \left(1 - \frac{T_o}{T_i}\right) Q_i + \xi_1 - \xi_4 - I_{ir}$$

for max work, ξ_4 should be equal to ξ_1

and $I_{ir} = 0$. $W_{sys,\max} = \left(1 - \frac{T_o}{T_i}\right) Q_i$

to determine the RHS, apply the same to HX, with $I_{ir} = 0$:

$0 = \left(1 - \frac{T_o}{T_i}\right) Q_i + \xi_2 - \xi_3$, and substitute: $W_{sys,\max} = \xi_3 - \xi_2$

First law efficiency is 275.4/794.8 =34.6%

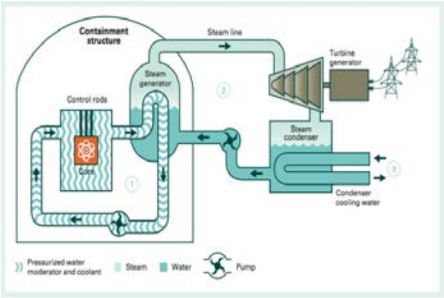
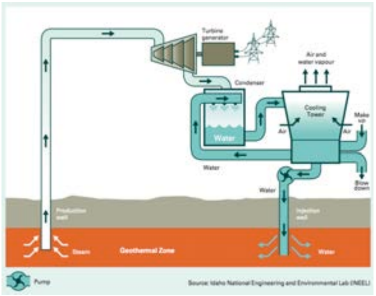
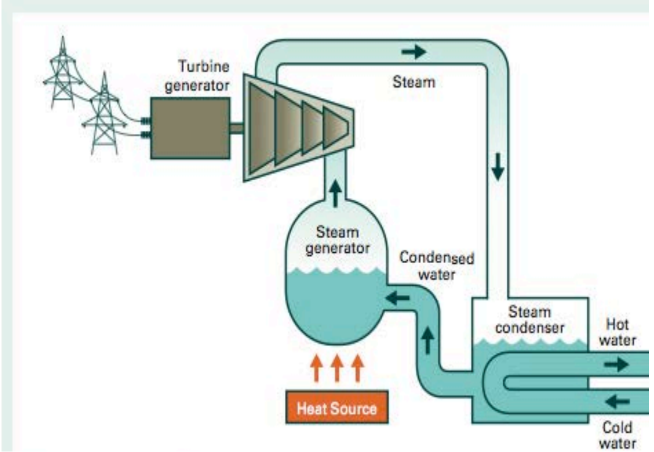
Second law efficiency is 275.4/589.1=46.7%

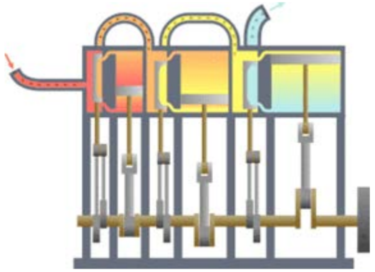
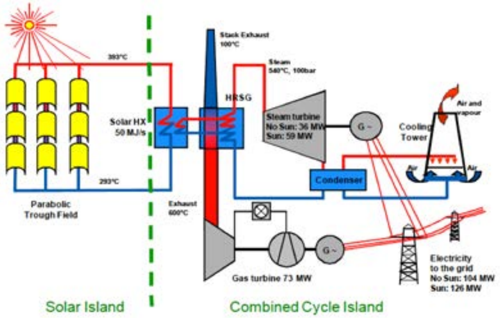
Compressor irreversibility $\frac{\dot{I}}{\dot{m}} = -\frac{\dot{W}}{\dot{m}} + \xi_1 - \xi_2$=40.6 kJ/kg

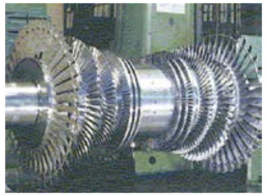
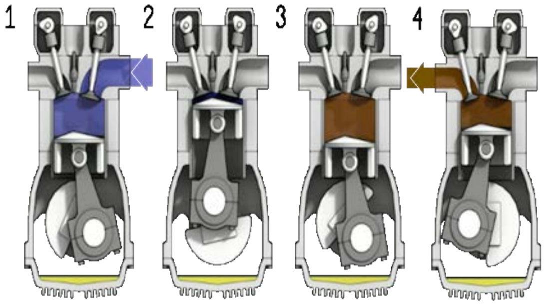
Turbine irreversibility $\frac{\dot{I}}{\dot{m}} = -\frac{\dot{W}}{\dot{m}} + \xi_3 - \xi_4$=55.6 kJ/kg

losses with exit stream = 217.5 kJ/kg

Many Heat Engines since …

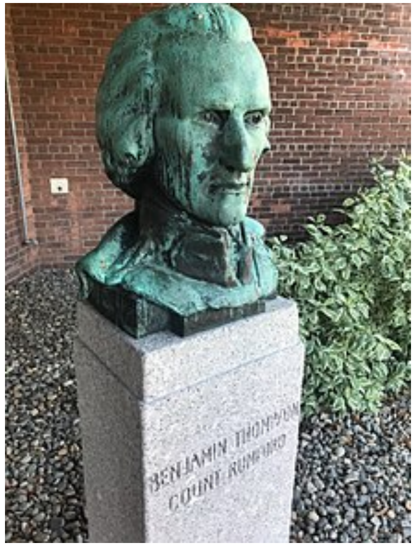



Gas turbine engines and turbo jet engine


GEnx Engine 53,000-75,000 pounds thrust

Benjamin Thompson/Lord Rumford established the equivalency of heat and work, worked on cannons, invented the modern fireplace, drip coffee maker, etc., his bust in Rohde Island (and a historical society named after him)



Rumford birthplace (1753) and museum, Elm St, Woburn MA

Image courtesy of Mass.gov.

Benjamin Thompson born 1753 in Woburn, MA, educated in Harvard, married Sarah Rolfe from Concord NH, then called Rumford. Worked on boring cannons, helped the British during the revolutionary war, and ran to England, where became Lord Rumford, eventually moved to Munich and contributed much to physics and thermodynamics.

The inverse of a heat engine is refrigerators and air conditioners, arguably the most important invention of engineering in the 20th century.

Power Plant Efficiency

Do we have an Energy or an Entropy Crisis?

What have engineers been doing over the past 200 yeas?

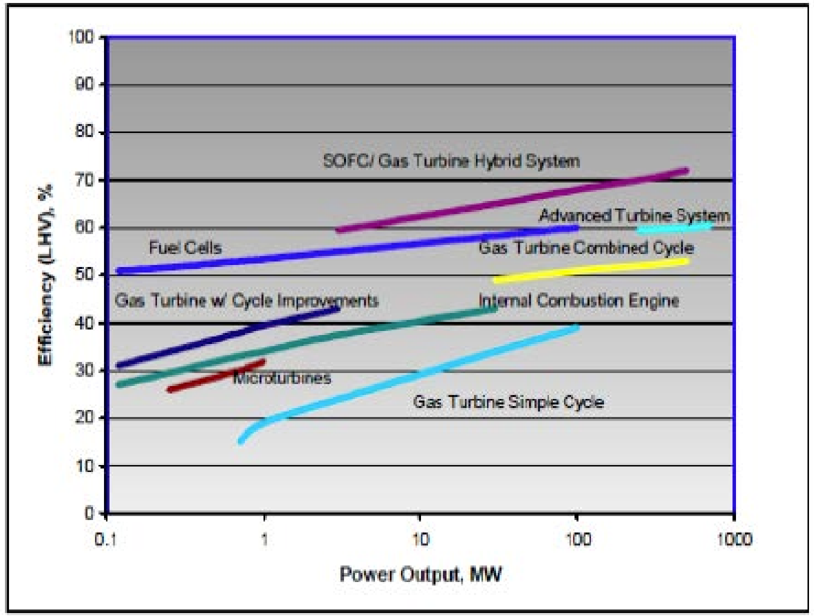
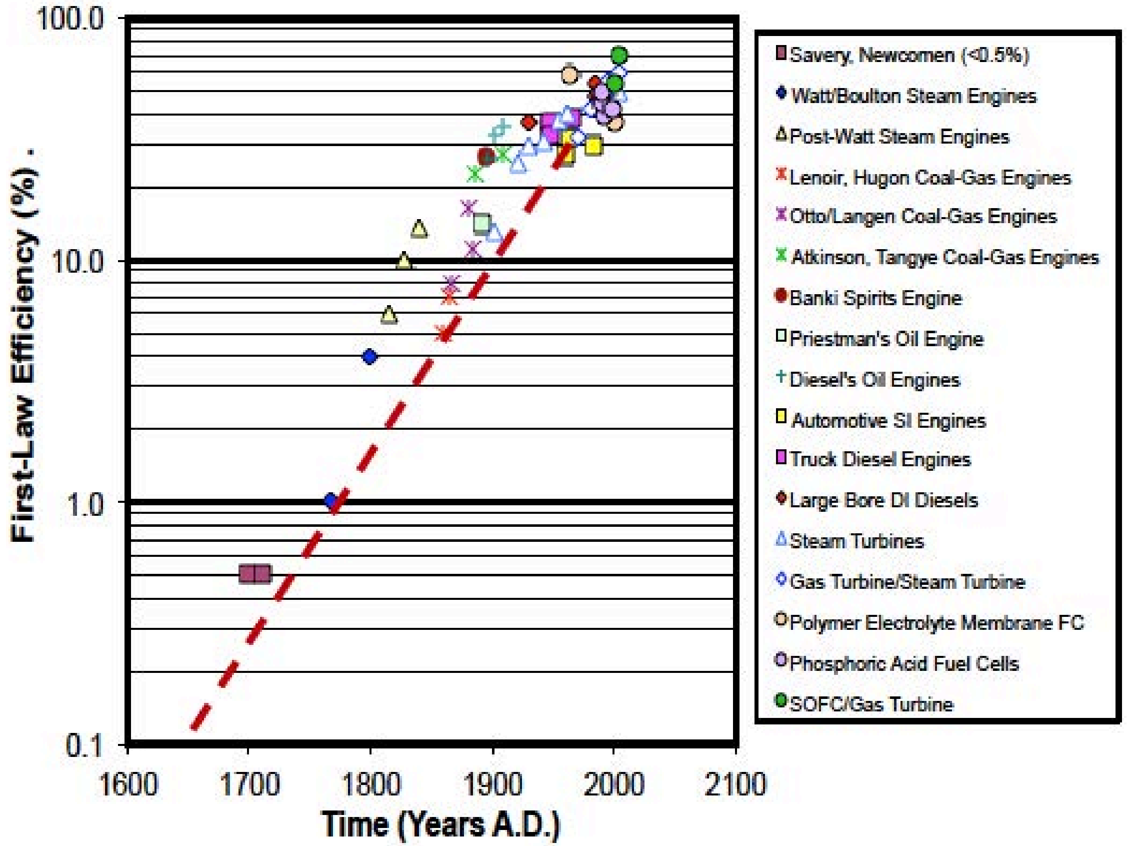


Figure 8-41 Estimated performance of Power Generation Systems

Image courtesy of DOE.

Fuel Cell Handbook, 7th Ed., by EG&G Technical Services, U.D. DOE, Office of Fossil Energy, NETL, Morgantown, W Va, Nov 2004, p. 8-91.



The best **heat engine** (thermal to mechanical) is a Carnot engine operating between two fixed temperatures:

the (thermo-mechanical) converison efficiency of the engine is

$$\eta_I = \frac{W_{net}}{Q_H} = 1 - \frac{Q_o}{Q_H}$$, also called the first law efficiency

$$\eta_{car} = 1 - \frac{T_o}{T_H}$$

temperatures are in absolute, e.g., in K=273+C

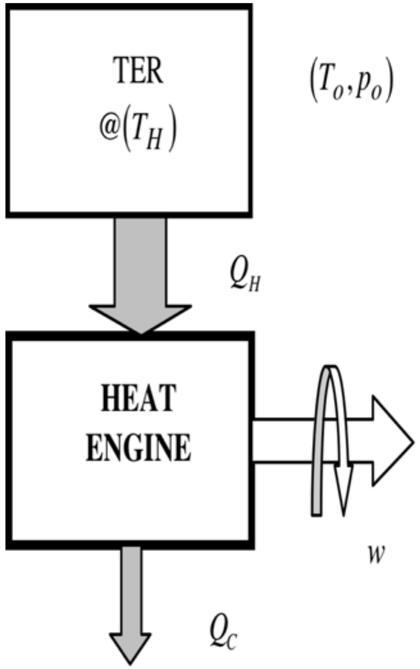
$T_o \sim 300$ K,

maximum fuel combustion temperature ~ 1800-2400 K

$T_H / T_o = 6 - 8, \quad \eta_{car} = 84 - 88\%$

the efficiency depends critically on T of the heat source!

also on the cold side T



A heat engine operating between a continuous stream starting at a high temperature and the environment has a lower efficiency.

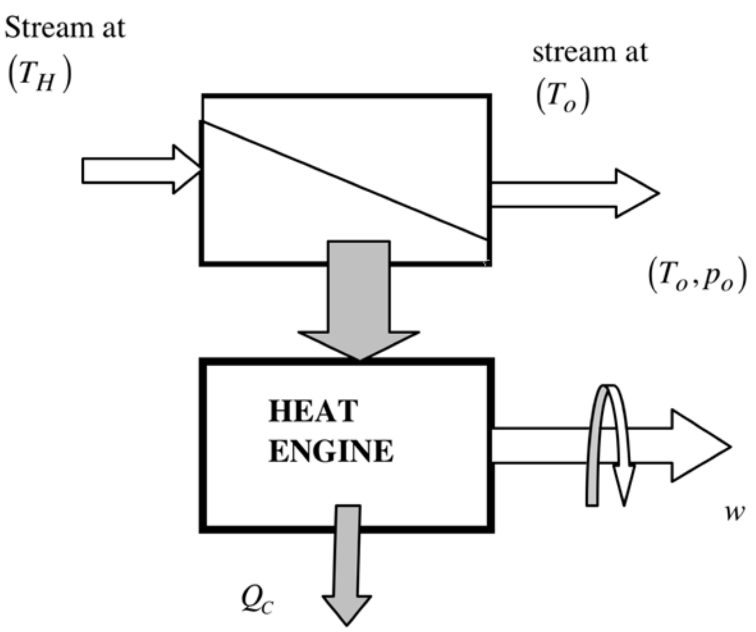
If the stream pressure is fixed:

$$W_{\max} = \int_{T_o}^{T_H} \left(1 - \frac{T_o}{T}\right) dQ = \int_{T_o}^{T_H} \left(1 - \frac{T_o}{T}\right) C dT$$

$$= C\left[(T_H - T_o) - T_o \ell n \frac{T_H}{T_o}\right]$$

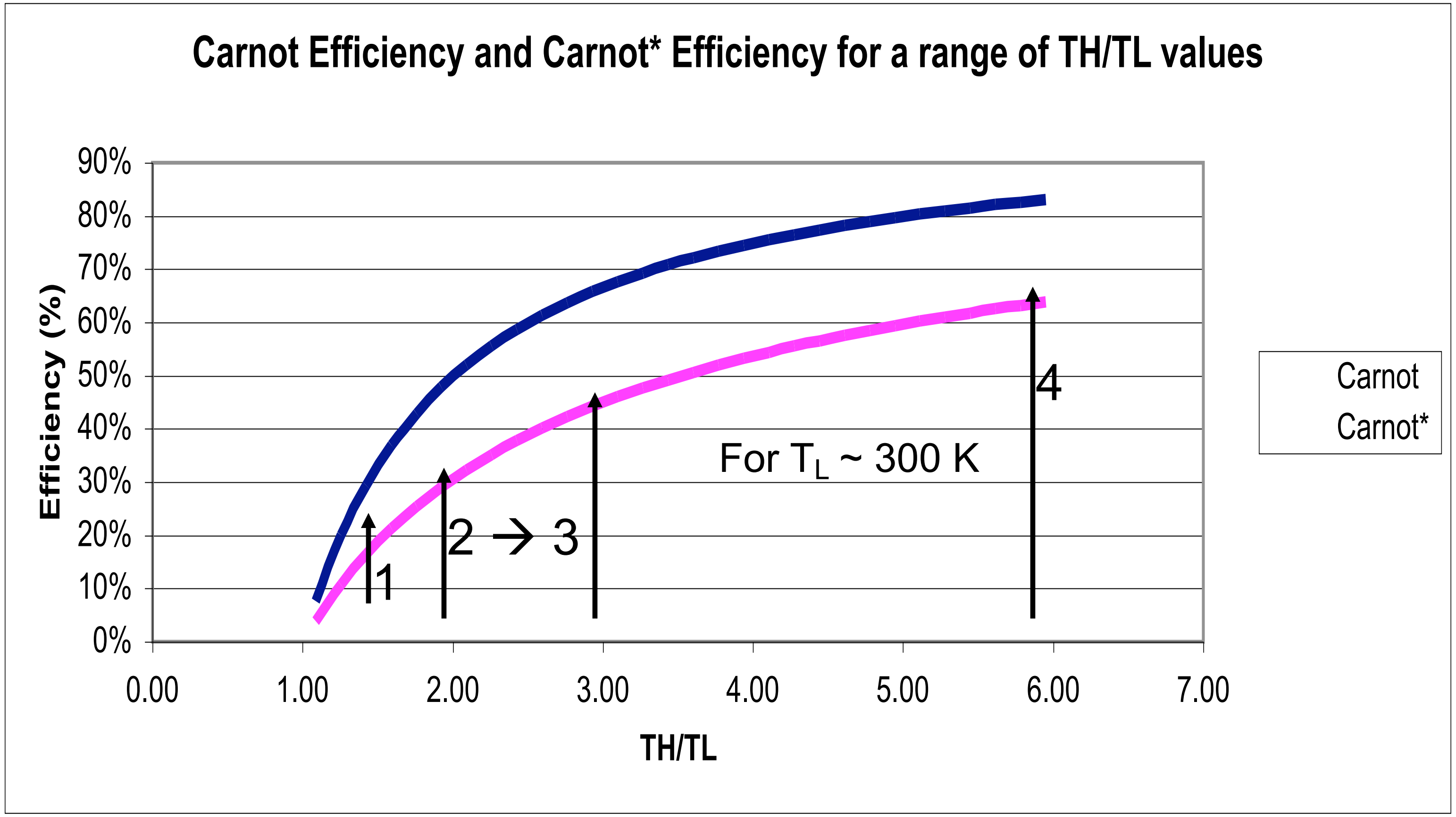
OR (since streams at same p_o)

$$W_{\max} = \xi_H - \xi_o = (H_H - H_o) - T_o (S_H - S_o)$$



$$\eta_{car}^{*} = 1 - \ell n\left(\frac{T_H}{T_o}\right) / \left(\frac{T_H}{T_o} - 1\right)$$

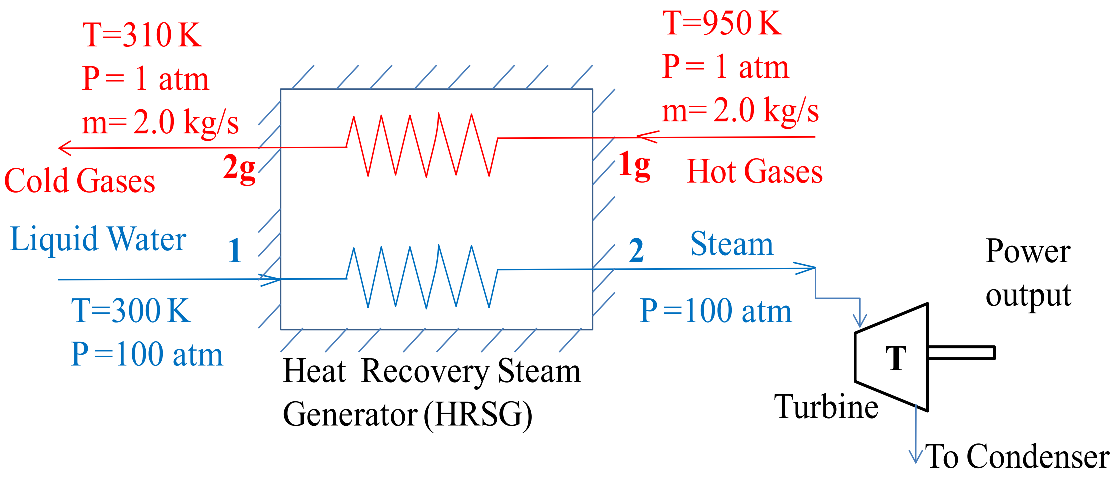
$$T_H / T_L = 6 - 8,\ \eta_{car}^{*} = 70\%$$

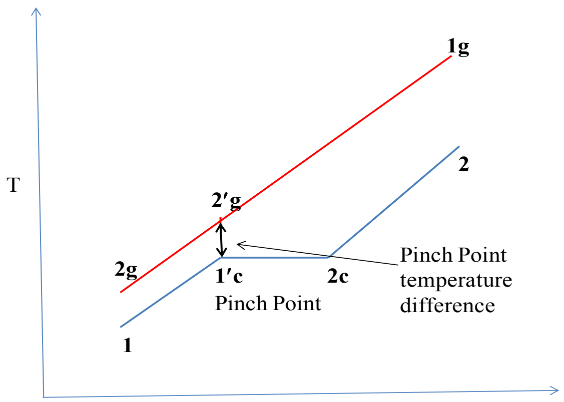


1. Geothermal heat @ T_H ~ 100-150 C
2. Solar concentrators produce heat @ T_H ~ 300 - 600 C
3. Nuclear reactors T_H ~ 300- 600 C
4. Combustion, only limited by material, T_H ~ 1400- 2100 C.

Example 2.10

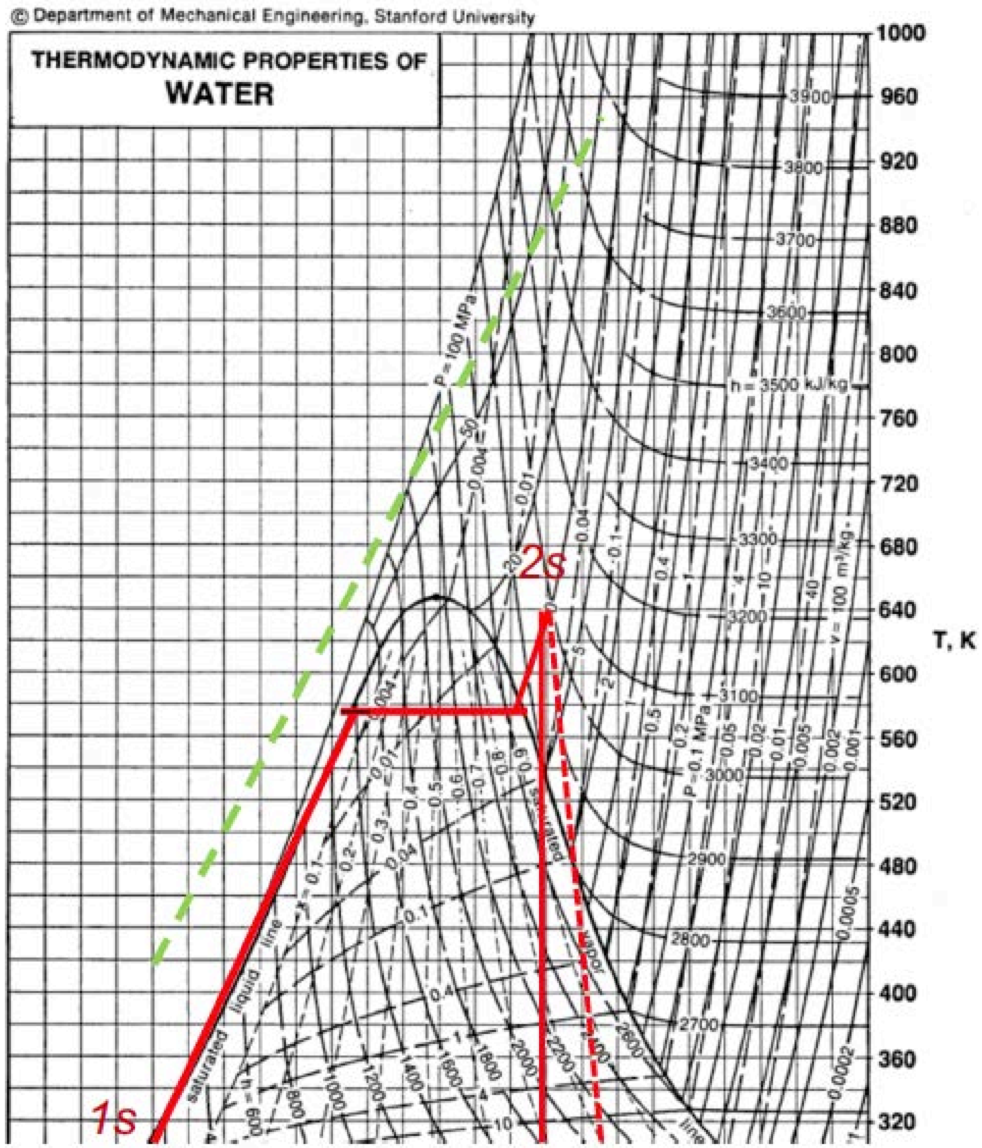
An industrial plant requires high temperature heat, which it generates by burning kerosene. After extracting the “useful” high temperature heat from the combustion products, the plant discharges gases at 950 K and 1 atm. The flow rate of combustion gases is 2.0 kg/s. A waste heat-recovery system (WHRS) is proposed for the utilization of the energy in the hot exhausted gases. It consists of a steam generator, the heat recovery steam generator (HRSG) and a steam turbine. The isentropic efficiency of the turbine is 94%, and steam exits the turbine at 40 ^oC. Assume the pinch point temperature difference of10 ^oC. Atmospheric conditions are at 1 atm. and 300 K. Assume the hot combustion products as an ideal gas with the same properties as air, specific heat is $c_{p,GAS}$ = 1.048 kJ/kg-K. Calculate the exergy losses in this system.





Temperature-heat transfer plot

Green, gas
Red, steam



Maximum work from the stream is obtained using the availability of the hot gases:

$$\text{Maximum Work} = \dot{\Xi}_{GASES} = \dot{\Xi}_{1g} = \dot{m}_{1g}[(h_{1g} - h_{0g}) - T_0(s_{1g} - s_{0g})] = 638.1 \text{ kW}$$

Now we calculate the mass flow rate of turbine water (do not yet know exit conditions of steam): energy balance between the two streams from the cold side of HRSG to pinch point (PP),

$$\dot{m}_{1g}(h_{2'g} - h_{2g}) = \dot{m}_w(h_{1'c} - h_1)$$

from tables, specific enthalpy of saturated water at 100 atm: $h_{1'c}$ = 1413.0 kJ/kg.
Looking at enthalpy of water at T = 300 K and p=101325 kPa: h_1 = 121.8 kJ/kg.
From the steam tables, the saturation temperature $T_{1'c}$ at 10132.5 kPa is 585.2 K.

Pinch point temperature difference is 10 K. $T_{2'g} = T_{1'c} + 10 = 595.2$ K

Therefore, mass flow of water is:

$$\dot{m}_w = \frac{\dot{m}_{1g} C_{P,GAS}(T_{2'g} - T_{2g})}{(h_{1'c} - h_1)} = \frac{2.01.048(595.2 - 310)}{(1413 - 121.8)} = \mathbf{0.4629} \text{ kg/s}$$

After knowing mass flow rate of water, we apply energy equation for the entire HRSG

$$\dot{m}_{1g}(h_{1g} - h_{2g}) = \dot{m}_w (h_2 - h_1)$$

This gives $h_2 = 3020$ kJ/kg.

With $h_2 = 3020$ kJ/K and $p_2 = 100$ atm, from steam tables, we get $\underline{T_2 = 650.7 \text{ K}}$.

Loss of work/irreversibility in HRSG:

$$0 = \sum \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{CV} + \dot{\Xi}_{1g} - \dot{\Xi}_{2g} + \dot{\Xi}_1 - \dot{\Xi}_2 - \dot{\Xi}_{DESTRUCTION}$$

First two terms are zeros

Irreversibility $= \dot{\Xi}_{DESTRUCTION} = 637.7 - 549.8 = 87.48\ k\text{W}$

For the turbine, exit temperature T = 273+40 =313 K (we know it is 2 phase), from tables, saturation pressure is 7.323 kPa.

$T_2 = 650.7$ K, $p_2 = 10132.5$ kPa, $h_2 = 3020$ kJ/kg and $s_2 = 6.091$ kJ/kg-K

Isentropic conditions of steam exiting turbine are: $p_3 = 7.323$ KPa, $s_{3s} = s_2 = 6.091$ kJ/kg-K.

From steam tables, isentropic enthalpy is $h_{3s} = 1895$ kJ/kg.

The actual conditions (enthalpy) of steam exiting turbine can be found from

$$\eta_T = \frac{(h_2 - h_3)}{(h_2 - h_{3s})} \Rightarrow 0.94 = \frac{(3020 - h_3)}{(3020 - 1895)}$$

This gives h_3 = 1962 kJ/kg. Using h_3 and p_3 and T_3 = 313 K, from steam tables: s_3=6.307 kJ/kg-K (less than $s_{3\text{sat steam}}$, verifying it is a two-phase flow mixture).

Turbine work rate is 489.5 kW.

But $0 = -\dot{W}_{turbine} + \dot{\Xi}_{in} - \dot{\Xi}_{out} - \dot{I}$

Change of Availability in the turbine is:

$$\Delta\dot{\Xi} = \dot{m}_w\left[\left(h_2 - h_3\right) - T_o\left(s_2 s_3\right)\right] =$$

$$0.4629\left[\left(3020 - 1962\right) - 300\left(6.091 - 6.307\right)\right] = 519.4\ kW$$

Exergy loss is the difference between change and work, **29.88 kW**

This is much less that exergy destroyed in HRSG.

Thermodynamic Efficiencies

$$\text{Conversion Efficiency or first law efficiency } \eta_I = \frac{\text{All what you get}}{\text{All what you pay}}$$

$$\text{heat engines } \eta_I = \frac{\text{net work out}}{\text{Heat in}}$$

$$\text{Electrochemical Efficiency for battery or fuel cell} \rightarrow \frac{\text{Work (Electrical Energy) out}}{\text{Chemical Energy in/used}}$$

$$\text{electrochemical efficiency for charging battery or electrolyzer} \rightarrow \frac{\text{Chemical Energy stored}}{\text{electrical Energy in}}$$

$$\text{Co-generation efficiency(bad definition but it is used)} \rightarrow \frac{\text{Work + Heat}}{\text{Chemical Energy}}$$

$$\text{a better definiton is } \rightarrow \frac{\text{Work} + (1-\frac{T_o}{T_H})Q_H}{\text{Chemical Energy}}$$

Thermodynamic Efficiencies

$$\text{Conversion Efficiency or first law efficiency } \eta_I = \frac{\text{Work/Energy/Heat OUT}}{\text{Heat/Energy/Work IN}}$$

$$\text{Thermomechanical Efficiency of a Heat Engine} \rightarrow \frac{\text{Work (Mechanical)}}{\text{Heat}}$$

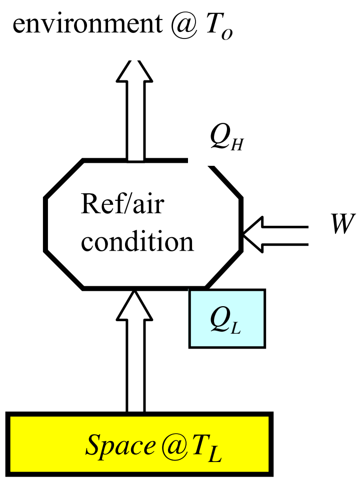
$$\text{Combustion Efficiency} \rightarrow \frac{\text{Thermal Energy}}{\text{Chemical Energy}}$$

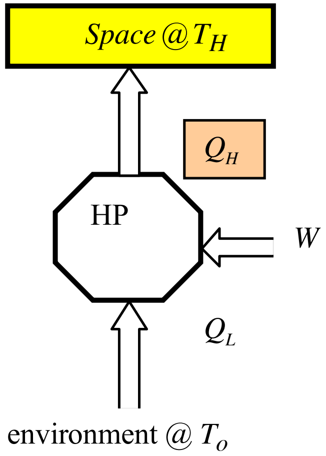
$$\text{Reforming Efficiency} \rightarrow \frac{\text{Chemical Energy Out}}{\text{Chemical Energy In}}$$

$$\text{Fuel Utilization Efficiency of a combustion engine} \rightarrow \frac{\text{Power (Mechanical)}}{\text{Rate of Chemical Energy in}}$$

In heating and cooling equipment, we define:

The Coefficient of Performance (can be larger than 1)





$$\beta_{ref/aircondition} = \frac{Q_L}{W} \qquad \beta_{HeatPump} = \frac{Q_H}{W}$$

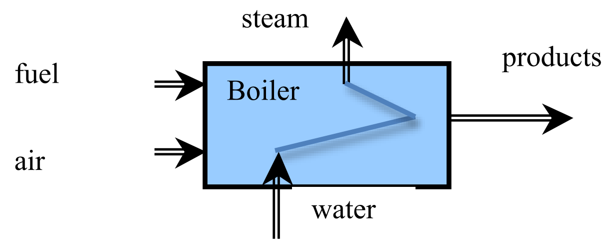
Carnot like expressions still define the best performance

In combustion
we use the stored chemical energy to define efficiencies:

Boiler efficiency:

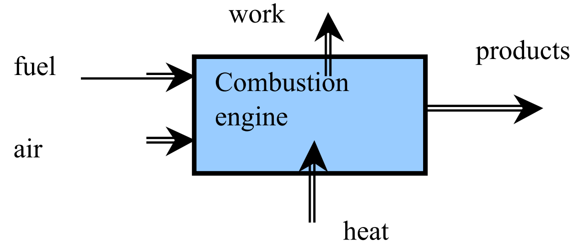
$$\eta_{Boiler} = \frac{\dot{m}_{steam}\left|\Delta H_{steam}\right|}{\dot{m}_{fuel}\left|\Delta H_{r,fuel}\right|}$$

$\left|\Delta H_{r,fuel}\right|$ is the energy (thermal) gained by converting a unit mass of fuel to products



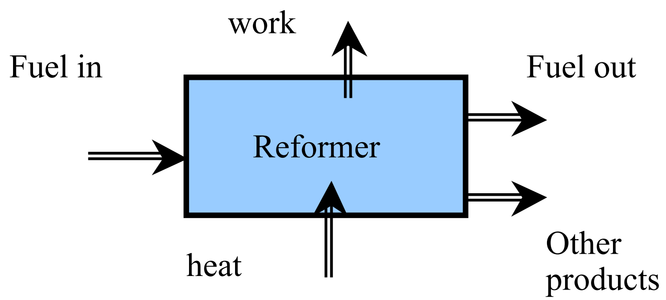
Combustion engine:

$$\eta_{fuelutilization} = \frac{P_{out}}{\dot{m}_{fuel}\left|\Delta H_{r,fuel}\right|}$$



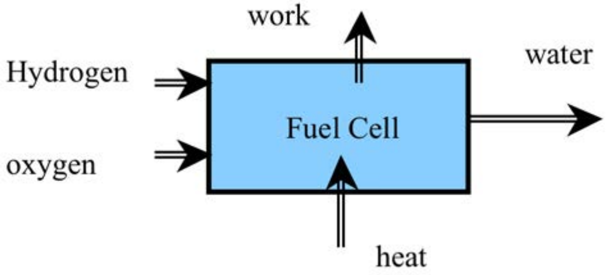
Reformer

$$\eta_{reformer} = \frac{\dot{m}_{fuelout}\left|\Delta H_{r,fuelout}\right|}{\dot{m}_{fuelin}\left|\Delta H_{r,fuelin}\right|}$$

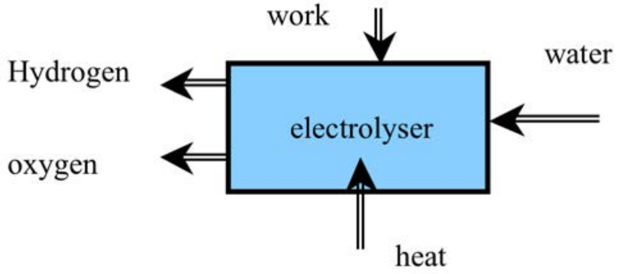


In direct conversion between chemical and electrical energy (fuel cells and electrolysis), we use the stored chemical energy of the fuel to define efficiencies:

$$\eta_{FC} = \frac{P_{out}}{\dot{m}_{H2}\left|\Delta H_{r,H2}\right|}$$

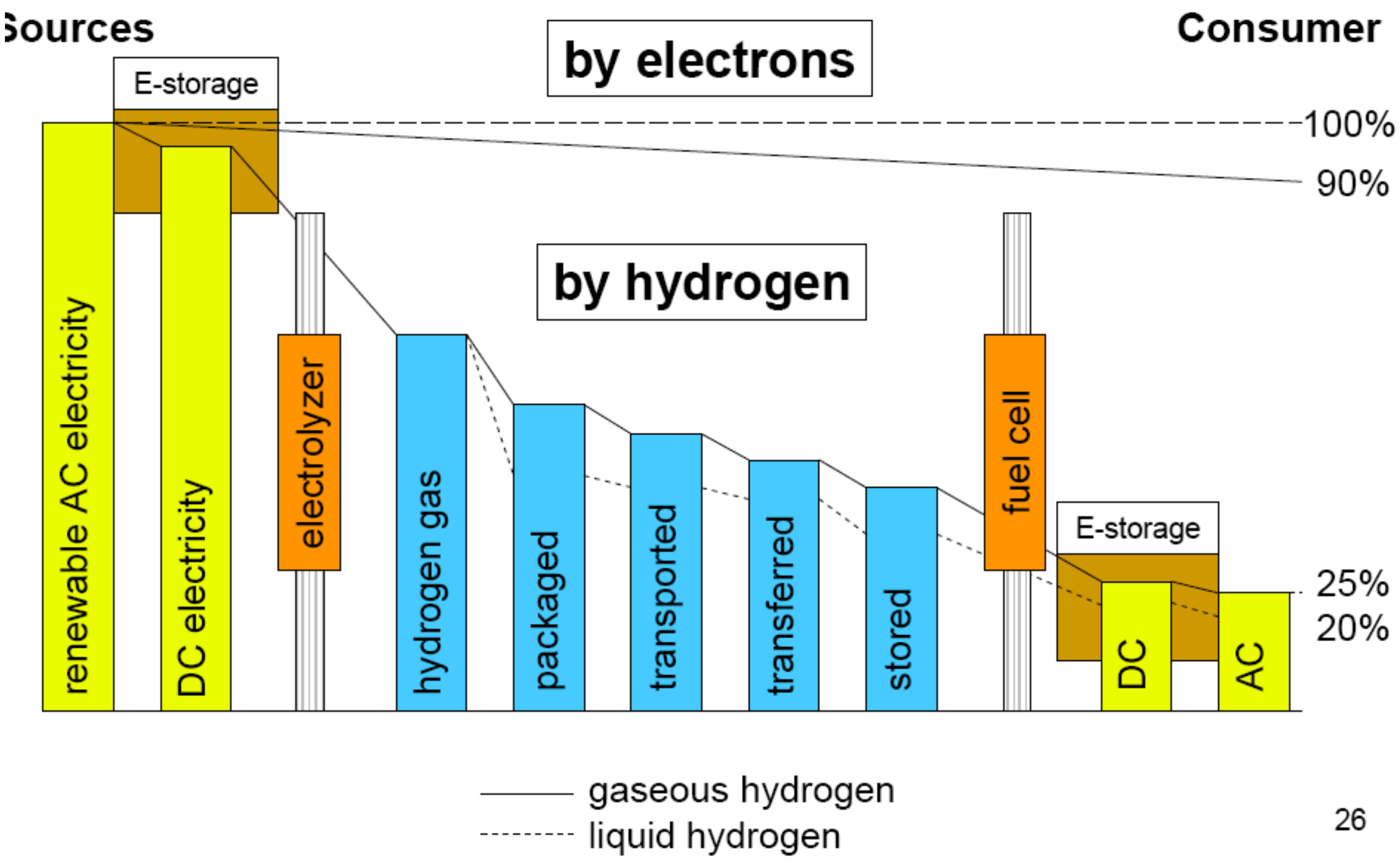


$$\eta_{electrolysis} = \frac{\dot{m}_{H2}\left|\Delta H_{r,H2}\right|}{P_{in}}$$



$\left|\Delta H_{r,H2}\right|$ is the energy (thermal) gained by converting a unit mass of hydrogen to water

WTW or LCA requires knowledge of process efficiency and overall integration of processes and systems …



Bossel, Towards a Sustainable Energy Future, Oct 2004

Effectiveness, or Second Law Efficiency $= \dfrac{\text{actual efficiency}}{\text{maximum efficiency}} = \dfrac{\text{work}}{\text{maximum work}}$

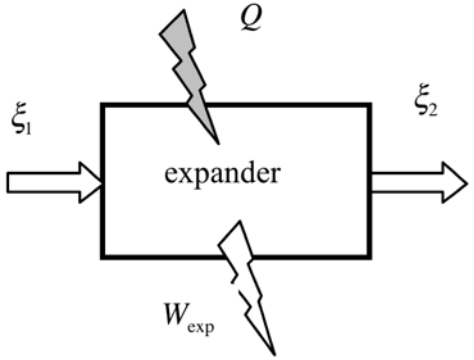
System interacting with 2 TER only: $\eta_{II} = \dfrac{W_{net}}{W_{\max}} = \dfrac{W_{net}/Q_H}{1 - T_L/T_H}$

System processing a stream: $\eta_{II} = \dfrac{W_{net}}{W_{\max}} = \dfrac{W_{net}}{\Delta \Xi} \rightarrow$ work producing cycle (system)

Device expanding a stream: $\eta_{II} = \dfrac{w_{net}}{w_{\max}} = \dfrac{w_{net}}{\Delta \xi} \rightarrow$ work producing cycle

In an isothermal process with an ideal gas:

$$\hat{w}_{\max} = \Delta\hat{\xi} = \Delta\hat{h} - T_o \Delta\hat{s} = \Re T_o \ell n \left(\frac{p}{p_o} \right)$$



other important efficiencies (related to the second law)

turbine isentropic efficiency $\eta_T = \frac{W}{W_{\max}} = \frac{W}{W_{is}}$

note that for an adiabatic turbine,

$$W_{\max} = \xi_1 - \xi_2 = \left(h_1 - h_2\right) - T_o\left((s_1 - s_2)\right) = \left(h_1 - h_2\right)$$

compressor isentropic efficiency $\eta_T = \frac{W_{\min}}{W} = \frac{W_{is}}{W}$