The exergy approach
in a legal framework

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Preamble

• Introduction of an energy concept including a exergetic performance index, in the energy law of Geneva
• Necessary vulgarisation (engineering offices, architects, diverse customers etc.)
• Concerns large development or retrofit projects but essentially the following services:
  – electricity, heating, air conditioning and refrigeration
History 1: combustion and heating

Simple combustion for heating and cooking (since around 400000 years)

Still today the majority of heating systems (simple fuel or gas boilers, etc.)

Effectiveness (First Law efficiency) in today’s boilers = around 92% of the Lower Heating Value (LHV)
Exergy efficiency = around 16% (for an average heating temperature of 60°C)
History 2: combustion and work (or electricity)

Exergy efficiency (simple engine)

\[ \eta = \frac{\dot{E}^-}{\dot{E}^+} = \frac{\dot{E}^-}{\dot{Q}^+(1 - \frac{T_a}{T})} = \left(1 - \frac{T_a}{T}\right) \]

Entropy and Second Law

\[ dS \geq \frac{\delta Q^+}{T} \]

Effectiveness or First Law efficiency (simple engine)

\[ \varepsilon = \frac{\dot{E}^-}{\dot{Q}^+} = 1 - \frac{T_{cold}}{T_{hot}} \]

- Carnot
- Gouy (bases)
- Diesel
- Heat pump
- Artificial cooling
- Fuel cell

Timeline:
- Thomas Newcomen: 1729
- James Watt: 1769
- Perkins: 1869
- Grove: 1869
- Denis Papin: 1675
- Thomas Savery: 1698
- Machine de Newcomen: 1650
- Machine de Savery: 1714
- Machine de Watt: 1736

Exergy

The exergy linked to a transfer or a storage of energy is defined as the potential of maximum work which could ideally be obtained from each energy unit being transferred or stored (using reversible cycles with the atmosphere as one of the energy sources either hot or cold).

The exergy approach allows to quantify in a coherent way both the quantity and the quality of the different forms of energy considered.

The concept of exergy presents the major advantage of efficiency definitions which are compatible with all cases of conversion of energy resources into energy services (heat and electricity, heat-cold-electricity, refrigeration, heat pumps, etc.) and for all domains of use of energy. These efficiencies are always lower than 100% and give an indication of the relative quality of different technical concepts in competition.
EXERGY BALANCE

First Law

\[ \sum_k (\dot{E}_k^+) + \sum_i (\dot{Q}_i^+) + \sum_j (h_{czj} \dot{M}_j^+) - \frac{d(U_{cz} + P_a V)}{dt} = \dot{Q}_a^- \]

- Second Law

\[ T_a \sum_i \left( \frac{\dot{Q}_i^+}{T_i} \right) + T_a \sum_j \left( s_j \dot{M}_j^+ \right) - T_a dS / dt + T_a \delta S^i / dt = \dot{Q}_a^- \]

\[ \sum_k (\dot{E}_k^+) + \sum_i \left( 1 - \frac{T_a}{T_i} \right) \dot{Q}_i^+ + \sum_j \left( h_{czj} - T_a s_j \right) \dot{M}_j^+ - \frac{d(U_{cz} + P_a V - T_a S)}{dt} - T_a \delta S^i / dt = 0 \]

- Carnot factor
- Total coenthalpy
- Total coenergy
EXERGY BALANCE

First Law

$$\sum_k (\dot{E}_k^+) + \sum_i \dot{Q}_i^+ + \sum_j \left( h_{cz} M_j^+ \right) - d(U_{cz} + P_a V) / dt = \dot{Q}_a^-$$

- Second Law

$$T_a \sum_i \left( \frac{\dot{Q}_i^+}{T_i} \right) + T_a \sum_j \left( s_j M_j^+ \right) - T_a dS / dt + T_a \delta S^i / dt = \dot{Q}_a^-$$

\[
\sum_k (\dot{E}_k^+) + \sum_i \left( 1 - \frac{T_a}{T_i} \right) \dot{Q}_i^+ + \sum_j \left( h_{cz} - T_a s_j \right) M_j^+ - d(U_{cz} + P_a V - T_a S) / dt T_a \delta S^i / dt = 0
\]

Work-exergy

Heat exergy

Transformation exergy (one per network n)

Exergy loss

\[
\sum_k \dot{E}_k^+ + \sum_i \dot{E}_{qi}^+ + \sum_n \dot{E}_{yn}^+ - \dot{L} = 0
\]

In this formulation, each term is either positive, or negative
Coenergy cartoon representation of the heating, cogeneration and heat pumping techniques

Source (partial): Borel L, Favrat D Thermodynamique et énergétique. PPUR 2005
Definition of terms (1)

Terms linked to heat exchange (typically across a wall)

Terms linked to work exchange or electricity (ex: through an engine shaft)

Terms linked to the transformation of masses (typically between inlet and outlet or inside the system between time 1 and time 2)

Convention: exponent $+$ means convention positive entering
exponent $-$ means convention positive exiting

Example: \( \dot{Q}^+ = 2 \text{ kW} \Leftrightarrow \dot{Q}^- = -2 \text{ kW} \)
Definition of terms (2)

**First Law**

\[ \dot{E}^+ \quad \text{Work (in W)} \]

\[ \dot{Q}^+ \quad \text{Heat (in W)} \]

\[ \dot{Y}^+ \quad \text{Transformation energy (in W)} \]

\[ \dot{Y}^+ = \dot{M}^+ \left( h_{cz,in} - h_{cz,out} \right) - \frac{d(U_{cz} + P_a V)}{dt} \]

with specific enthalpy \( h \)

and internal energy \( U \)

**Second Law (exergy)**

\[ \dot{E}^+ \quad \text{Work exergy (in W)} \]

\[ \dot{E}_q^+ \quad \text{Heat exergy (in W)} \]

\[ \dot{E}_y^+ \quad \text{Transformation exergy (en W)} \]

\[ \dot{E}_y^+ = \dot{M}^+ \left( k_{cz,in} - k_{cz,out} \right) - \frac{dJ_{cz}}{dt} \]

with specific coenthalpy \( k = h - T_a s \)

and coenergy \( J = U + P_a V - T_a S \)

\[ \dot{L} \quad \text{Exergy losses (in W)} \]

**In first approximation:**

- indices \( cz \) which represent the kinetic and potential energy are neglected
- except when storage is considered (ex: domestic boiler), the terms of the derivatives with regards to time of the internal energy \( U \) and of its exergy counter part coenergy \( J \) are neglected (hypothesis of steady state)
Examples and simplifications (in a first approach)

\[
\dot{E}_{y,\text{comb}}^+ = M_A \dot{k}_A + M_F (\dot{k}_F + \Delta k^0) - M_G \dot{k}_G \equiv M_F \Delta k^0 \\
\text{EXV}
\]

\[
\dot{E}_q^- = \dot{Q} \left(1 - \frac{T_a}{T}\right) \\
\dot{E}_q^- = 0 \quad \text{si} \quad T = T_a
\]

**Typically applied to cogeneration engines**

\[
\dot{E}_{y,\text{water}}^- = -\dot{M}_{\text{water}}^+ (k_{\text{in}} - k_{\text{out}}) = \dot{M}_{\text{water}}^+ (k_{\text{out}} - k_{\text{in}}) \\
\text{with} \quad k = h - T_a s
\]

\[
\dot{E}_{y,\text{water}}^- \equiv \dot{M}_{\text{water}}^+ c (T_{\text{out}} - T_{\text{in}}) \left(1 - \frac{T_a}{\bar{T}}\right) \quad \text{with} \quad \bar{T} = \frac{T_{\text{in}} + T_{\text{out}}}{2}
\]

Complete exergy balance:

\[
\dot{E}_{y,\text{comb}}^+ - L = \dot{E}_{\text{shaft}}^- + 0 + \dot{E}_{y,\text{water}}^-
\]

Simplified exergy balance:

\[
\dot{E}_{y,F}^+ - L = \dot{E}_{\text{shaft}}^- + \dot{E}_{q,\text{water}}^-
\]

\[
\dot{M}_F \text{EXV} - L = \dot{E}_{\text{shaft}}^- + \dot{Q}_{\text{water}}^- \left(1 - \frac{T_a}{\bar{T}_{\text{water}}}\right)
\]

EXV = exergy value

in first approximation:

\[
\text{EXV} = (\text{LHV}+\text{HHV})/2
\]

where LHV = Lower heating value  \( (\Delta h_i^0) \)

HHV = Higher heating value  \( (\Delta h_s^0) \)
Exergy efficiency of a cogeneration engine (in a first approach)

\[ \dot{E}_{y,\text{comb}}^+ \equiv \dot{M}_F \text{EXV} \]

\[ \dot{E}_{q}^- = \dot{Q}^-(1 - \frac{T_a}{T}) \]

\[ \dot{E}_{q}^- = 0 \quad \text{si} \quad T = T_a \]

Simplified exergy balance:

\[ \dot{E}_{y,\text{comb}}^+ - \dot{L} = \dot{E}_{\text{shaft}}^- + \dot{E}_{q,\text{water}}^- \]

\[ \dot{M}_F \text{EXV} - \dot{L} = \dot{E}_{\text{shaft}}^- + \dot{Q}_{\text{water}}^- \left(1 - \frac{T_a}{T_{\text{water}}} \right) \]

\[ \eta = \frac{\dot{E}_{\text{shaft}}^- + \dot{E}_{q,\text{water}}^-}{\dot{E}_{y,\text{comb}}^+} = \frac{\dot{E}_{\text{shaft}}^- + \dot{Q}_{\text{water}}^- \left(1 - \frac{T_a}{T_{\text{water}}} \right)}{\dot{M}_F \text{EXV}} \]

EXV = exergy value

in first approximation:

EXV = (LHV+HHV)/2

where LHV = Lower heating value

HHV = Higher heating value

\[ (\Delta k_0^0) \]

\[ (\Delta h_0^0) \]
General formulation of the balances
(using only terms which are numerically positive)

Energy (First Law)

\[ \sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ + \sum_n \dot{Y}_n^+ - \dot{Q}_a^- = \sum_k \dot{E}_k^- + \sum_i \dot{Q}_i^- + \sum_n \dot{Y}_n^- \]

- Energy input to the system
- Energy output from the system
- Energy losses

Exergy balance (First and Second Law)

\[ \sum_k \dot{E}_k^+ + \sum_i \dot{E}_{qi}^+ + \sum_n \dot{E}_{yn}^+ - \dot{L} = \sum_k \dot{E}_k^- + \sum_i \dot{E}_{qi}^- + \sum_n \dot{E}_{yn}^- \]

- Exergy input to the system
- Exergy output from the system
- Exergy losses
Effectiveness and exergy efficiency

Effectiveness (First Law)  
(sometimes called thermal efficiency)

\[ \varepsilon = \frac{\sum_k \dot{E}_k^- + \sum_i \dot{Q}_i^- + \sum_n \dot{Y}_n^-}{\sum_k \dot{E}_k^+ + \sum_i \dot{Q}_i^+ + \sum_n \dot{Y}_n^+} \]

Exergy efficiency (First and Second Laws)

\[ \eta = \frac{\sum_k \dot{E}_k^- + \sum_i \dot{E}_qi^- + \sum_n \dot{Y}_n^-}{\sum_k \dot{E}_k^+ + \sum_i \dot{E}_qi^+ + \sum_n \dot{Y}_n^+} \]

Examples:

**Heating heat pump**

\[ \varepsilon_h = \frac{\dot{Q}_{\text{cond}}^-}{E_{\text{elec}}^+} \]

**Cooling heat pump**

\[ \varepsilon_f = \frac{\dot{Q}_{\text{evap}}^+}{E_{\text{elec}}^+} \]

General, so can be applied to both examples

\[ \eta = \frac{\dot{E}_q^-}{\dot{E}^+} \]

\[ \eta = \left( 1 - \frac{T_a}{T_{\text{cond}}} \right) \frac{\dot{Q}_{\text{cond}}^-}{\dot{E}^+} \]

\[ \eta = \left( \frac{T_{\text{evap}}}{T_a} - 1 \right) \frac{\dot{Q}_{\text{evap}}^+}{\dot{E}^+} \]

not general!
Family of engine cycles between two heat sources

\[ \eta = \frac{E - Q}{E_q} + E_q \]

\[ \varepsilon = \frac{E^+ - Q}{E_q} + E_q \]

\[ \eta = \frac{E^+ - E^-}{E_q} + E_q \]

\[ \varepsilon = \frac{E^+ - E^-}{E_q} + E_q \]

\[ \eta = \frac{E^+ - E^-}{E_q} + E_q \]

\[ \varepsilon = \frac{E^+ - E^-}{E_q} + E_q \]
Family of heat pump cycles (in a broad sense) between two heat sources

\[ \varepsilon = \frac{Q^{-} + Q^{+}}{E^{+}} \quad \varepsilon = \frac{Q^{-}}{E^{+}} \quad \varepsilon = \frac{Q^{+}}{E} \]

\[ \eta = \frac{E_{q}^{-}}{E^{+}} \quad \eta = \frac{E_{q}^{-}}{E^{+} + E_{q}^{+}} \]

\[ \varepsilon = \frac{Q^{-}}{E^{+}} \quad \varepsilon = \frac{Q^{-}}{E^{+}} \]

\[ \eta = \frac{E_{q}^{-}}{E^{+}} \quad \eta = \frac{E_{q}^{-}}{E^{+} + E_{q}^{+}} \]

\[ \eta = \frac{E_{q}^{-} + E_{q}^{-}}{E^{+}} \]
**Exergy efficiency**

- Is an indicator of the quality with which men (engineers) convert resources available to them
- Does not:
  - Give indications concerning the use or not of renewable resources,
  - Account for the relative difficulty of conversion of a given primary energy. For example solar energy with its low density of radiation is more difficult to convert than oil or gas hence usually implies lower exergy efficiencies,
  - Give indications on the local environmental impacts (pollutants affecting health) and only indirectly give global environment indications
From local to global

Power plant (away from cities) 1 → Electricity

cogeneration and/or Heat pump + DH 2

Building utility plant 3

(DH heat exchanger, boiler, hp, cogen, etc)

Convector, 4

Radiator, etc

\[ \eta = \eta_1 \eta_2 \eta_3 \eta_4 \]

Example: Combined cycle power plant without cogeneration (1) + District heating heat pump (2) + building DH heat exchanger (3) + convector (4)

\[
\eta = \left( \frac{\dot{E}_{el,1}^{-}}{\dot{E}_{y,1}^{+}} \right) \left( \frac{\dot{E}_{y,2}^{-}}{\dot{E}_{el,2}^{+}} \right) \left( \frac{\dot{E}_{y,3}^{-}}{\dot{E}_{y,3}^{+}} \right) \left( \frac{\dot{E}_{q,4}^{-}}{\dot{E}_{y,4}^{+}} \right) = \frac{\dot{E}_{q,4}^{-}}{\dot{E}_{y,1}^{+}}
\]
Exergy efficiency of heating convectors (sub-system 4)

(winter) (hypothesis: heat input to the convector at the average temperature indiquée en column 1 and heat output at room temperature de pièce, i.e at 20°C, for an average atmospheric temperature of 0°C)

To simplify the year is divided into two seasons: a heating season at an average atmospheric temperature of 0°C and an air conditioning season with an average atmospheric temperature of 30°C. It is however important to point out that it is only an assumption to simplify and these values cannot be used for design.

<table>
<thead>
<tr>
<th>Network</th>
<th>Technologies</th>
<th>Exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low temperature</td>
<td>Floor heating or large convector areas or pulsed air</td>
<td>53</td>
</tr>
<tr>
<td>(45/35°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium temperature</td>
<td>Convectors</td>
<td>38</td>
</tr>
<tr>
<td>(65/55°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature</td>
<td>Convectors</td>
<td>33</td>
</tr>
<tr>
<td>(75/65°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct electrical</td>
<td>Electrical radiators</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Power plants (without cogeneration hence usually out of town) (sub-system 1)

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>32</td>
</tr>
<tr>
<td>Combined cycle</td>
<td>54</td>
</tr>
<tr>
<td>Coal</td>
<td>42</td>
</tr>
<tr>
<td>hydro</td>
<td>88</td>
</tr>
<tr>
<td>Waste incineration</td>
<td>23</td>
</tr>
<tr>
<td>Wind</td>
<td>48</td>
</tr>
<tr>
<td>Solar photovoltaic</td>
<td>11</td>
</tr>
</tbody>
</table>
Example of simple system: direct electric heating (sub-systems 1 et 4)

\[ \eta = \eta_1 \eta_4 \]

Example: combined cycle power plant without cogeneration (1) + electrical radiator (4)

\[ \eta = \left( \frac{\dot{E}_{el,1}^-}{\dot{E}_{y,1}^+} \right) \left( \frac{\dot{E}_{q,4}^-}{\dot{E}_{e,4}^+} \right) = \frac{\dot{E}_{q,4}^-}{\dot{E}_{el,4}^+} \]

\[ \eta = (0.54) \left( \frac{1 - \frac{273}{273 + 20}}{1} \right) = 0.037 \]
Building plant
(sub-system 3)

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal temperatures (supply/return)</td>
<td>45/35°C</td>
</tr>
<tr>
<td>District heating heat exchanger (supply 85°C)</td>
<td>54</td>
</tr>
<tr>
<td>Non condensing boiler</td>
<td>11</td>
</tr>
<tr>
<td>Condensing boiler</td>
<td>12</td>
</tr>
<tr>
<td>Electrical heat pump</td>
<td>45</td>
</tr>
<tr>
<td>Cogeneration gas engine</td>
<td>42</td>
</tr>
<tr>
<td>Cogeneration fuel cell</td>
<td>49</td>
</tr>
<tr>
<td>Cogeneration engine &amp; heat pump</td>
<td>22</td>
</tr>
<tr>
<td>Cogeneration fuel cell &amp; heat pump</td>
<td>25</td>
</tr>
</tbody>
</table>
Towards multistage heat pumps
District heating heat pump (3 stages)

Goteborg: 45 MW\textsubscript{th}

Exergy efficiency > 60%
NH3 heat pump of EPFL district heating (twin-screw with intermediate vapor injection, 3.5 MW$_{th}$)
Effectiveness and exergy efficiency of heating
Simple example: building boiler

\[ \eta = \eta_3 \eta_4 \]

\[ \eta = \frac{\dot{Q}_{ch}}{\dot{M}} \frac{LHV}{EXV} \left(1 - \frac{T_a}{T_{ch}}\right) \left(1 - \frac{T_{\text{pièce}}}{T_{ch}}\right) = 0.92(0.966) \left(1 - \frac{273}{273 + 60}\right) \left(1 - \frac{273}{273 + 20}\right) = 0.7 \]

\[ \eta = (0.16)(0.38) = 0.07 \]
# Power plant with fossil or biomass fuels (sub-system 2)

(with DH network at an average temperature of 85°C)

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cogeneration combined cycle</td>
<td>55</td>
</tr>
<tr>
<td>Cogeneration waste incineration</td>
<td>33</td>
</tr>
<tr>
<td>Boiler</td>
<td>20</td>
</tr>
</tbody>
</table>

## Centralized electrical heat pump (sub-system 2)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>District heating electrical heat pump</td>
<td>61</td>
</tr>
</tbody>
</table>
Example

\[ \eta = \frac{\dot{E}_{el,1}^-}{\dot{M}_{comb}EXV} \left( \frac{\dot{E}_{el,2}^+}{\dot{E}_{el,2}^-} \right) \left( \frac{\dot{E}_{y,3}^-}{\dot{E}_{y,3}^+} \right) \left( \frac{\dot{E}_{q,4}^-}{\dot{E}_{q,4}^+} \right) = \frac{\dot{Q}^-}{\dot{M}_{comb}EXV} \left( 1 - \frac{T_a}{(273 + 20)} \right) \]

\[ \eta = (0.54)(0.61)(0.76)(0.38) = 0.094 \]

\[ \epsilon_{LHV} = 0.58 \text{ (given)} \]
\[ \eta = 0.56 \]
\[ -4\% \text{ grid loss} \]
\[ \eta_1 = 0.54 \]

\[ \text{given for DH HP} \]
Same example but $T_h$ diff.

$$\eta = (0.54)(0.61)(0.76)(0.38) = 0.094$$

Given for HP

$$\eta = (0.54)(0.61)(0.54)(0.53) = 0.094$$

given for HP

9.4% !!
Example:

\[ \eta = \eta_3 \eta_4 \]

Hypotheses:

\[ \eta_3 = \left[ \varepsilon_{el} \frac{LHV}{EXV} \left( \frac{\varepsilon_{hp}}{\varepsilon_{th, hp}} \right) + \left( \varepsilon_{cogen} - \varepsilon_{el} \right) \right] \frac{LHV}{EXV} \left[ 1 - \frac{T_a}{T} \right] \]

\[ \eta_3 = \left[ \frac{\dot{E}_{cogen}^T}{\dot{M}_{comb} LHV} \frac{LHV}{EXV} \eta_{hp} \left( \frac{T}{\Delta T} \right)_{hp} + \left( \frac{\dot{Q}_{cogen}}{LHV} \right) \frac{LHV}{EXV} \right] \left[ 1 - \frac{T_a}{T} \right] \]

\[ \eta_3 = [0.37(0.966)0.45 \frac{273 + 40}{40} + (0.9 - 0.37)0.966] \left[ 1 - \frac{273}{273 + 40} \right] = 0.22 \]

Example: cogeneration gas engine and building heat pump (3) + convector (4)

\[ \eta = \left( \frac{\dot{E}_{q,4}^-}{\dot{E}_{y,3}^-} \right) \left( \frac{\dot{E}_{y,4}^+}{\dot{E}_{y,3}^+} \right) = \frac{\dot{E}_{q,4}^-}{\dot{E}_{y,3}^+} \]

\[ \eta = (0.22)(0.53) = 0.118 \]
Example:

\[ \eta = \eta_1 \eta_3 \eta_4 \]

\[ \eta = \left( \frac{\dot{E}_{el,1}^-}{\dot{E}_{y,1}^+} \right) \left( \frac{\dot{E}_{y,3}^-}{\dot{E}_{el,3}^+} \right) \left( \frac{\dot{E}_{q,4}^-}{\dot{E}_{y,4}^+} \right) = \frac{\dot{E}_{q,4}^-}{\dot{E}_{y,1}^+} \]

\[ \eta = (0.88)(0.45)(0.53) = 0.212 \]

after account of 4% of grid losses
<table>
<thead>
<tr>
<th>Examples of technologies</th>
<th>Power plant</th>
<th>Dist. plant</th>
<th>Building plant</th>
<th>Room convector</th>
<th>Overall exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply/return temperatures</td>
<td></td>
<td></td>
<td>45°/35°</td>
<td>65°/55°</td>
<td>75°/65°</td>
</tr>
<tr>
<td>Direct electric heating (nuclear power)</td>
<td>0.32</td>
<td></td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Direct electric heating (combined cycle cogeneration)</td>
<td></td>
<td>0.55</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
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<tr>
<td>Direct electric heating (hydro power)</td>
<td>0.88</td>
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<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
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<td>District boiler</td>
<td></td>
<td>0.2</td>
<td>0.54</td>
<td>0.76</td>
<td>0.86</td>
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<tr>
<td>Building non-condensing boiler</td>
<td></td>
<td>0.11</td>
<td>0.16</td>
<td>0.18</td>
<td>0.53</td>
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<tr>
<td>Building condensing boiler</td>
<td></td>
<td>0.12</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>District heat pump (nuclear power)</td>
<td></td>
<td>0.32</td>
<td>0.61</td>
<td>0.54</td>
<td>0.76</td>
</tr>
<tr>
<td>Domestic heat pump (nuclear power)</td>
<td></td>
<td>0.32</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Domestic cogeneration engine and heat pump</td>
<td></td>
<td>0.22</td>
<td>0.25</td>
<td>0.26</td>
<td>0.53</td>
</tr>
<tr>
<td>District heat pump (combined cycle power)</td>
<td></td>
<td>0.54</td>
<td>0.61</td>
<td>0.54</td>
<td>0.76</td>
</tr>
<tr>
<td>Domestic heat pump (combined cycle power)</td>
<td></td>
<td>0.54</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Domestic heat pump (cogeneration combined cycle power)</td>
<td></td>
<td>0.55</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Cogeneration fuel cell and domestic heat pump</td>
<td></td>
<td>0.55</td>
<td>0.25</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>District heat pump (hydropower)</td>
<td></td>
<td>0.88</td>
<td>0.61</td>
<td>0.54</td>
<td>0.76</td>
</tr>
<tr>
<td>Domestic heat pump (hydropower)</td>
<td></td>
<td>0.88</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Air conditioning or refrigeration convector

(Summer hypothesis: cold input to the convector at an average temperature given in column 1 and cold output to the room at 20°C, for an average atmospheric temperature of 30°C)

<table>
<thead>
<tr>
<th>Network temperatures</th>
<th>Technologies</th>
<th>Exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/15°C</td>
<td>Water or air</td>
<td>56</td>
</tr>
<tr>
<td>5/10°C</td>
<td>Water or glycol water</td>
<td>43</td>
</tr>
<tr>
<td>0/5°C</td>
<td>glycol water</td>
<td>34</td>
</tr>
<tr>
<td>-5/0°C</td>
<td>glycol water /ice slurry</td>
<td>28</td>
</tr>
<tr>
<td>-10/–5°C</td>
<td>glycol water</td>
<td>24</td>
</tr>
<tr>
<td>-15/–10°C</td>
<td>glycol water</td>
<td>21</td>
</tr>
<tr>
<td>-20/–15°C</td>
<td>glycol water</td>
<td>18</td>
</tr>
</tbody>
</table>

Example of calculation

\[ \eta = \frac{(\frac{T_a}{T} - 1) \dot{Q}^-}{(\frac{T_a}{T} - 1) \dot{Q}^+} = \frac{(\frac{273 + 30}{273 + 20} - 1)}{(\frac{273 + 30}{273 + 12.5} - 1)} = 0.56 \]
Air conditioning / refrigeration

(hypothesis: electric compression chiller with an exergy efficiency of 40%)

<table>
<thead>
<tr>
<th>Power plant technologies</th>
<th>Power plant</th>
<th>Dist. plant</th>
<th>Building plant</th>
<th>Room convector</th>
<th>Overall exergy efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply/return temperatures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear power</td>
<td>0.32</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.56 0.43 0.34 7.1 5.4 4.3</td>
</tr>
<tr>
<td>Gas motors</td>
<td>0.36</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.56 0.43 0.34 8.1 6.2 4.9</td>
</tr>
<tr>
<td>Combined cycle power plant without cogeneration</td>
<td>0.54</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.07 0.07 0.07 12.1 9.3 7.3</td>
</tr>
<tr>
<td>hydropower</td>
<td>0.88</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.53 0.38 0.33 19.8 15.2 12.0</td>
</tr>
</tbody>
</table>
Conclusions

• Introducing an exergy indicator exergie in a law on energy highlights:
  – The importance of a low temperature heating, respectively of a high temperature cooling
  – The weak efficiencies of today’s dominant heating technologies and the prospect for improvement
  – A coherent ranking of the alternatives facilitating a better planning of future energy systems

• After this first step a major effort is still required to educate stakeholders and secure its implementation at all levels

• It is vital to ensure a rigorous teaching of exergy at all professional and university levels