Facts & Figures

EXERGY

CONCEPT, CHALLENGES AND USAGES FOR INDUSTRY

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ENEA Consulting provides **energy transition and sustainable development consulting services to industry**. ENEA assists companies with strategy development, provides support to innovation and projects, and also offers training and expertise services on these topics.

This publication is part of our policy to share ENEA's essential knowledge, with the aim to propose keys to understanding the main challenges of energy transition and sustainable development at the global scale.

It is the result of the learnings and experience of ENEA experts on the topic of exergy, acquired in the course of our support services and consultancy work with economic actors and from specific research work done in-house.

DEFINITION AND CONCEPT

In the context of growing pressure on natural resources and particularly on energy resources, an essential challenge for the future will be to reduce energy consumption. The concept of exergy creates a global, standard and rigorous framework for the analysis of energy systems, and as such, participates in the comprehension and systemic management of the energy challenge.

Exergy measures the "useful" energy that can be extracted from a reservoir or energy flow. It is also the minimum energy required to create this reservoir or energy flow.

This metric depends on the state of the reservoir or flow (temperature, pressure, composition, etc.) but also the state of the environment (temperature, ambient pressure, etc.) and is expressed in the same unit as the energy (the Joule in the metric system). A thermodynamic definition of exergy is given in annex.

What is "useful" energy?

Energy is said to be "useful" if it can be entirely transformed by an ideal system (i.e. without losses) into any other type of energy. Useful energy, otherwise known as exergy, only represents a fraction of energy.

The greater the "useful" portion of the energy, the higher the "quality" of the energy. The ratio of exergy X ("chi") over energy E is called the exergy index (X/E); it represents a measurement of the quality of an energy, in other words, its degree of usefulness.

Figure 1 presents the exergy indexes of different energies. Electrical and mechanical energies are very "high quality" forms of energy: their exergy index is 100% since exergy is equal to energy. On the other hand, the quality of thermal energy is variable and can be quite low depending on the temperature at which it is available (see box on *Exergy and thermal exchanges* p. 5).

Hence, all forms of energy are not equal and exergy makes it possible to quantify this difference by introducing the notions of energy "quality" and "useful" energy.

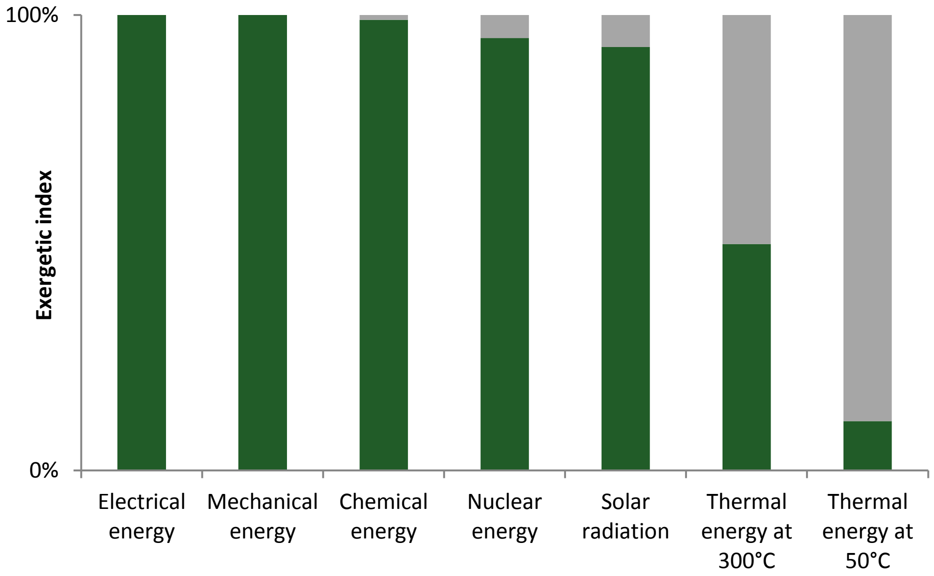

Figure 1: Exergy index of different types of energies. The temperature in the surrounding environment is 15°C

DEFINITION AND CONCEPT

Disequilibrium – the driver of energy systems

The functioning of any energy system can be explained by a disequilibrium between the thermodynamic states of several reservoirs. Figure 2 presents examples of energy systems or processes and the property in disequilibrium that they are based on.

Energy system or process	Property in disequilibrium
Piston	Pressure
Thermal machine	Temperature
Osmosis[1]	Concentration
Battery	Electrochemical potential

Figure 2: Example of the properties whose variance with the surrounding environment is translated into exergy

In fact, exergy measures the functioning potential of a system in the surrounding environment, by evaluating the useful energy that can be extracted from a reservoir or the useful portion of an energy flow. **Exergy quantifies the potential derived from the disequilibrium between a reservoir and the environment via the expression of the useful energy that it is possible to generate based on this disequilibrium.**

The state of the surrounding environment (pressure, temperature, composition, etc.) is not taken into account in the traditional energy approach, which is based on energy levels quantified in absolute terms. The fact that it is taken into consideration in the exergy approach therefore represents a new but requisite complexity required for the evaluation of this useful energy.

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[1] *For more on this topic refer to the ENEA publication on MRE: marine renewable energies*

DEFINITION AND CONCEPT

Exergy and heat exchanges

The temperature difference between a reservoir and the environment contributes to its exergy. If we consider the heat transfer Q between a reservoir at temperature T and the surrounding environment at temperature T_0, the transferred exergy X is given by the following equation:

$$\mathrm{X} = Q\left|1 - \frac{T_o}{T}\right|$$

This relation can be considered as a generalization of the Carnot factor that gives the maximum theoretical efficiency of an internal combustion engine. The graph below illustrates this relation.

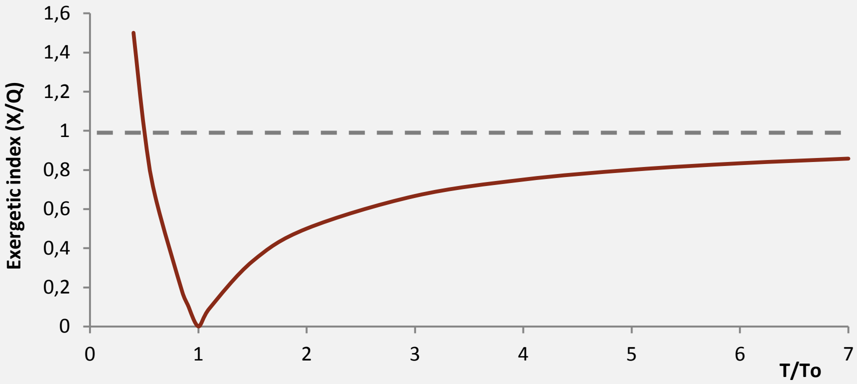


Figure 3: Exergy index as a function of temperature T in a reservoir in an environment at T_0

For high temperatures, exergy and heat tend to merge: the more a heat source is available at a high temperature compared with its environment, the higher its quality is. This is why a high-temperature heat source is more utilizable than a low-temperature heat source.

Moreover, this graph illustrates that the “cold” has an exergy content. From an energy standpoint, a cold system is at a thermal energy level lower than that of it equilibrium state: the lower the temperature of the system, the lower its thermal energy level. The energy analysis therefore qualifies a cold system as a system with an energy deficit relative to its environment. On the contrary, the exergy standpoint shows more clearly that a cold source can be utilizable.

ILLUSTRATIONS

The true measurement of energy flows and resources

Available energy resources can come in very different forms: fuels, rays, wind energy, heat, etc. This diversity of resources and energy transformation processes has led to the development of various metrics specific to the characterization of energy resources. These metrics are difficult to inter-compare: LHV and HHV for fuels, methanogenic capacity, osmotic pressure, etc.

The exergy approach creates an analysis framework for the systematic quantification of energy resources. By taking into account the quality of energy, the **exergy analysis compares different types of energies in a relevant manner**.

For example, this approach enables a relevant representation of energy flows and reservoirs at a planetary level. The diagram below represents energy reservoirs, flows and destruction at the global scale.

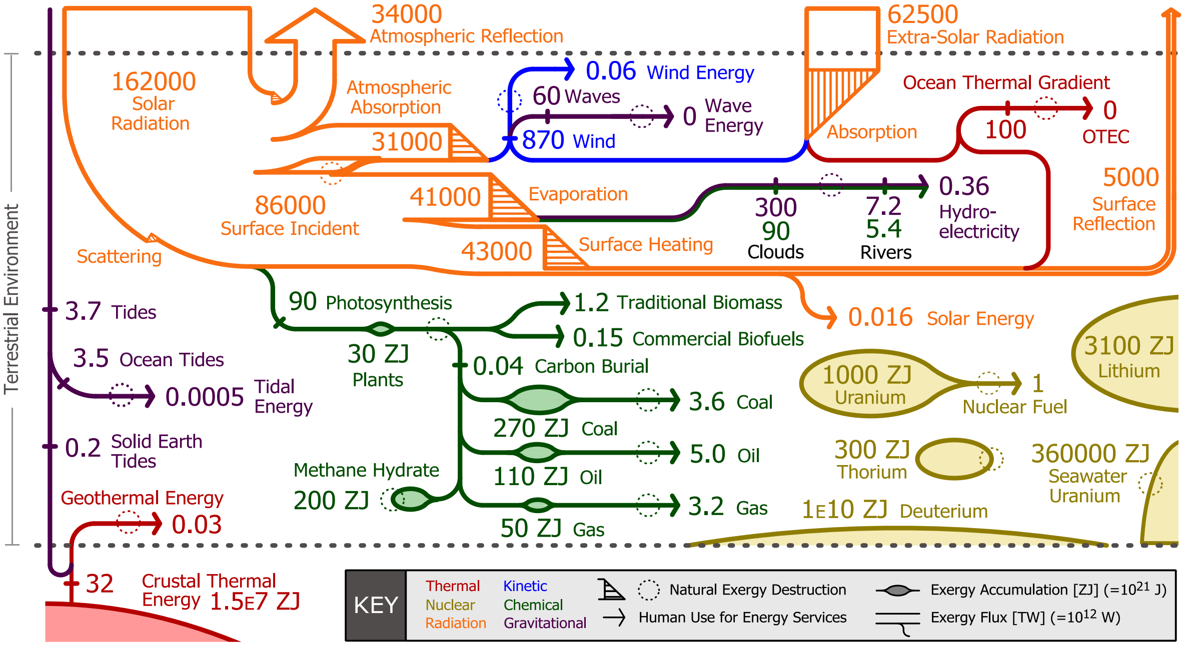


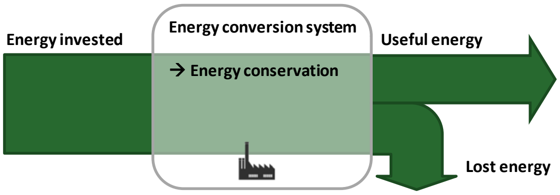
Figure 4: Exergy reservoirs, flux and destruction at the scale of the planet (source: GCEP)

ILLUSTRATIONS

The true measurement of energy conversion efficiencies

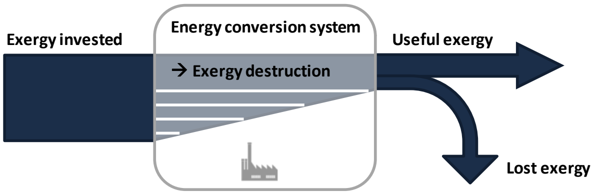
Energy efficiency or yield is defined as the ratio between useful energy and energy invested in a transformation or conversion.

$$\eta_{en} = \frac{Useful\ energy}{Energy\ invested}$$



Exergy efficiency or yield is defined as the ratio between useful exergy[2] and exergy invested in a transformation or conversion.

$$\eta_{ex} = \frac{Useful\ exergy}{Exergy\ invested}$$



As opposed to its energy counterpart, **the exergetic form of efficiency takes into account not only lost energy flows but also the decrease in the quality of energy flows.**

Moreover, since the concept of exergy is a measurement of useful energy allowing the comparison of different types of energy flows, **exergy efficiency is universal in its application and interpretation and enables a considered system to be compared with the best system theoretically possible** (exergy efficiency at 100%)**.**

The basic but informative case of heating demonstrates the contribution of the exergy approach in determining efficiencies:

Technological solution	Energy efficiency	Exergy efficiency
Electric heater	≈ 100%	≈ 7%
Radiator connected to a heating network	≈ 100%	≈ 38%
Heat pump	≈ 300%	≈ 20%

Figure 5: Comparison between energy and exergy efficiencies for different heating solutions. Only the final conversion is taken into account. The details are given in annex.

Indeed, while the statement indicating that the energy efficiency of an electric heater is equal to 100% is in itself correct, it gives the illusion of a “perfect” system and does not help understand that other more efficient systems exist. What’s more, energy efficiency does not differentiate between an electric heater and a radiator connected to a heating network. Finally, an efficiency rating of 300% for heat pumps does not really help gauge the intrinsic efficiency of these systems.

In contrast, the calculation of exergy efficiencies sheds light on the performances of these three types of heating networks: the use of electrical radiators destroys a large quantity of exergy; heat pumps still have substantial room for improvement in terms of efficiency, and radiators connected to heating networks appear to be the most efficient of the three systems.

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[2] *To facilitate understanding, a practical difference is made here between destroyed exergy and lost exergy (i.e. destroyed during an exchange with the environment). From a theoretical standpoint, it’s one and the same notion, that of the destruction of exergy.*

EXERGY AND INDUSTRY

For regulatory and economic reasons, process energy performance measurement, analysis and optimization are proving to be increasingly crucial for industry. The concept of exergy is still rarely used in the industrial world and yet its added value in terms of energy optimization is progressively interesting more actors.

Measuring the performance of an industrial process

In order to optimize the energy performance of an industrial site, one must first be able to assess it. Industrial processes are quite varied in terms of their nature and complexity. Furthermore, energy resources consumed and produced by industry can be of different types, such as electricity or heat. As a result, it is fairly difficult to measure and compare the energy performances of industrial sites due to these disparities.

To measure energy consumption and production, new units have been introduced in industry such as the thermal watt-hour (Wh_{th}), electric watt-hour (Wh_{el}) and ton oil equivalent (T.O.E) whose relevance generally depends on the types of energy in question. The existence of these different units makes comparisons laborious.

In reality, the introduction of these different units of measurement conveys a will to indicate levels of energy quality, which is what the concept of exergy actually expresses.

The concept of exergy is still rarely used in industry to evaluate energy production and consumption and yet it is the relevant value to measure energy consumption and production in a standardized way in industry.

The example of the Oil & Gas sector – the case of E&P

Many industrial sectors do not have a standard energy performance indicator. In the field of Exploration & Production for example there are disparities in the evaluation of site energy efficiency. Most of the oil majors have their own energy performance criteria generally based on plant energy intensity – the ratio between energy consumed and hydrocarbon production. However, the exact definition of this energy intensity varies from one major to the next: inclusion or not of flare gas in consumed energy, accounting for imported utilities, etc.

Moreover, at equivalent production levels, energy intensity largely depends on the characteristics of the oil or gas processed by the site: composition, fluid temperature and pressure levels at the plant entry point. A fluid available at low pressure generally requires a recompression unit at plant entry, representing an increase in energy intensity compared with a plant in which the fluid is available at high pressure. These parameters impact plant energy intensity but are not taken into account in standard energy approaches, which makes the comparison of the energy efficiency of different sites relatively complex in Exploration & Production.

The exergy approach integrates these “extra-process” parameters in the industrial site’s energy performance analysis. It makes it theoretically possible to analyze the efficiency of different industrial sites on a common basis and to compare different types of processes. This is why the definition of new energy performance indicators based on exergy is currently being examined by several industrial companies.

EXERGY AND INDUSTRY

Optimizing the performance of an industrial process

When integrated in a systemic approach, exergy analysis is a powerful tool for the optimization of industrial processes.

Thermal analysis

Energy analyses are commonly used today in industry. A study carried out by ENEA shows that 2/3 of French industrial companies have already carried out energy audits[3].

These are mainly based on a thermal approach. It's true that a comparison of hot and cold flows can potentially be a useful tool to optimize process energy efficiency: it's the principle of heat integration. The pinch analysis, used to identify possible heat exchanges between hot flows (requiring cooling) and cold flows (requiring heating) is a tried and tested approach to improve heat integration.

Exergy and systemic analysis

As opposed to thermal analyses, exergy analysis methods are still quite unknown and rarely used by industrial companies. And yet, exergy analysis makes it possible to go farther in industrial process energy optimization than does the purely thermal approach on which traditional energy analyses are based.

An exergy analysis can, in an overall and systemic way, pinpoint and quantify inefficiencies in an industrial process by taking into account not only energy losses but also losses in the quality of this energy.

As a result, the **exergy approach systematizes research into more efficient breakthrough technologies and processes** (see the case study on gas turbines on the next page).

What's more, this systematization of the **exergy metric allows systemic analysis,** that is to say an approach that takes into account the entire industrial process under consideration and makes it possible to find an overall energy optimum.

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[3] *For more information on this topic, see the ENEA study for the TOTAL-ADEME program: Energy efficiency in Industry: R&D barriers and needs*

CASE STUDY – GAS TURBINES

Single cycle gas turbine

From an energy standpoint, the energy that is not converted into work by a gas turbine is retained in the exhaust gases.

The exergy approach gives a more accurate and precise vision since it quantifies the loss of exergy via the exhaust gases but also the deterioration in energy quality (i.e. exergy destruction) in each of the turbine components (see figure 6). The exhaust system and also the combustion process itself appear to be the two main causes of inefficiency.

Lost exergy capture is a first avenue to improve system efficiency. It's the principle of the combined cycle that utilizes the exergy contained in the exhaust gases in a steam cycle.

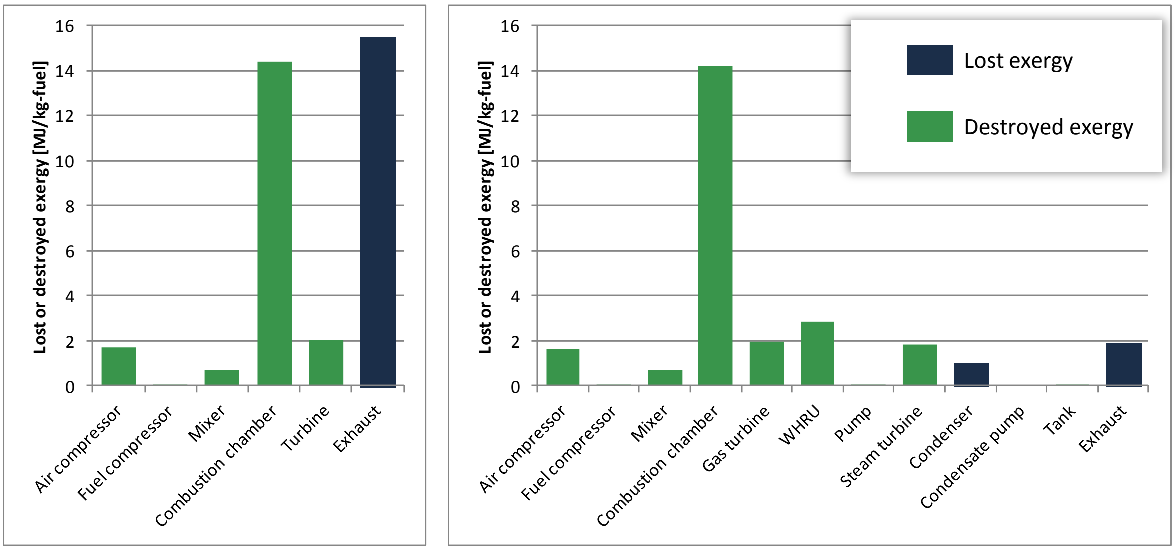

Figure 6: Comparison of the exergy losses of a single cycle gas turbine (left) and a combined cycle turbine right). Lost exergy and destroyed exergy are differentiated.

Combined-cycle turbine and other avenues for improvement

In the case of the combined cycle, the energy approach indicates that the energy not converted into work is contained in the exhaust gases and in the heat flow out of the condenser. This observation, while correct, is insufficient to understand the origin of the residual losses and to envisage ways to improve the system.

The exergy approach shows that for the combined-cycle turbine, exergy losses are lower than exergy destruction: exergy destroyed by combustion itself is the main reason for efficiency loss, well before lost energy flows and other destroyed energy flows (see figure 6).

To significantly improve the efficiency of a combined-cycle turbine, the question is no longer the capture of lost exergy but rather the reduction of exergy destruction during combustion. Systems coupling a solid oxide fuel cell with gas turbines, as well as systems achieving combustion in better conditions (high internal energy) make it possible to meet this challenge and studies aiming at developing a breakthrough technology are underway (see example of GCEP work).

EXERGY IN A NUTSHELL

Key points

Exergy measures useful energy that can be extracted from a reservoir or energy flow. It is an **indicator of the quality of an energy** and allows a **relevant comparison of heterogeneous forms of energy**. Finally, the concept of exergy efficiency gives a **more accurate vision of the real efficiency** of an energy system or process **by quantifying its efficiency with respect to the best system theoretically possible.**

To this end, and compared with energy approaches, the exergy approach allows industrial companies to got further **in optimizing the energy efficiency of industrial processes.** Indeed, this approach gives companies a better understanding of the real efficiency of their processes and can identify and quantify the causes of inefficiencies.

For equipment manufacturers, the exergy approach systematizes **research to find more efficient breakthrough technologies** by identifying sources of efficiency in a systemic manner.

For public authorities, the exergy approach provides **the right metric to value energy flows** by quantifying the energy portion that is useful for society. It's the kWh of exergy that deserves to be valued and not the kWh of energy. For example, it could be wise to consider a feed-in tariff for renewable heat or waste heat on the basis of exergy (thereby appropriately integrating the question of temperature) rather than on the basis of energy.

Thus, exergy is an **accurate metric that is the most appropriate to understand and take into account energy challenges** for all actors involved in energy transition.

For more information:

Göran Wall: Exergetics

GCEP (Global Climate & Energy Project, Stanford University): Global Exergy Resource Chart

GCEP (Global Climate & Energy Project, Stanford University): Low Exergy Loss Chemical Engines

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ANNEX – HEATING EFFICIENCY

Let's consider three heating solutions that can maintain the inside of a room at T=20°C with an outside temperature of T_0=0°C: an electrical radiator, a radiator connected to a heating network and a heat pump system.

Electric heater

Let W_{el} be the electrical energy consumed by the radiator and Q_{out} the heat supplied by the radiator to the room. The electrical energy is entirely converted into heat, so $Q_{out} = W_{el}$. The energy efficiency is therefore 100%:

$$\eta_{en} = \frac{Q_{out}}{W_{el}} = 100\%$$

From an exergy standpoint, the exergy invested X_{in} is exactly equal to the energy invested $E_{in}=W_{el}$, since it's electrical energy (see Figure 1). The recoverable exergy X_{out} is equivalent to the maximum work that can be supplied by the heat produced by the radiator. The radiator's exergy efficiency is thus:

$$\eta_{ex} = \frac{X_{out}}{X_{in}} = \frac{Q_{out}\left(1 - \frac{T_0}{T}\right)}{W_{el}} = \left(1 - \frac{T_0}{T}\right) \approx 7\%$$

From an exergy standpoint, an electrical radiator has a very low level of efficiency as opposed to what is suggested by the energy approach alone. Indeed, an electrical radiator degrades very high quality energy to produce low quality heat. This strong deterioration in energy quality is not visible in the energy analysis that only takes into account energy quantities.

Radiator connected to a heating network

The heating network considered for this analysis has heat available at T_{res}=60°C. With Q_{in} the heat supplied by the heating network to the radiator, we obtain for the energy approach:

$$\eta_{en} = \frac{Q_{out}}{Q_{in}} = 100\%$$

The exergy efficiency is given by the following equation:

$$\eta_{ex} = \frac{X_{out}}{X_{in}} = \frac{Q_{out}\left(1 - \frac{T_0}{T}\right)}{Q_{in}\left(1 - \frac{T_0}{T_{res}}\right)} = \frac{\left(1 - \frac{T_0}{T}\right)}{\left(1 - \frac{T_0}{T_{res}}\right)} \approx 38\%$$

While the energy approach does not make it possible to differentiate the efficiency of an electrical radiator from that of a radiator supplied by a heating network, the exergy approach highlights the clear differences in efficiency between these two systems. Electrical heating is clearly less efficient that the heating network for the same usage since it degrades energy of much higher quality.

ANNEX – HEATING EFFICIENCY

Heat pump

Let's now consider a heat pump based heating system. The energy efficiency of this type of solution is estimated by the Coefficient of Performance (COP) and is equal to the ratio between the heat supplied by the system Q_{out} and the work supplied to the system W_{el} (via the compressor). The energy flow drawn from the environment was not taken into account as invested energy since its "costs nothing". The COP is generally around 300% or more according to the system's performance level.

$$COP_{en} = \frac{Q_{out}}{W_{el}} \approx 300\%$$

Exergy efficiency does take into account the energy flow Q_{in} drawn from the environment at temperature T_0. The fact that this energy "costs nothing" is expressed in the calculation by an associated exergy at nil. The exergy efficiency is thus

$$\eta_{ex} = \frac{\mathrm{X}_{out}}{\mathrm{X}_{in}} = \frac{Q_{out}\left(1-\frac{T_0}{T}\right)}{W_{el} + Q_{in}\left(1-\frac{T_0}{T_0}\right)} = \frac{Q_{out}\left(1-\frac{T_0}{T}\right)}{W_{el}} = COP_{en} \cdot \left(1-\frac{T_0}{T}\right) \approx 20\%$$

The exergy analysis of the heat pump demonstrates the interest of the concept to express efficiency. While the COP does not in fact give any indication of the heat pump's intrinsic performance, the exergy approach reveals a margin for improvement.

ANNEX –THERMODYNAMIC THEORY

Expression of exergy

Exergy is a value indicating the maximum work that a system can provide when it enters into a thermodynamic equilibrium with its environment.

The system is characterized by a temperature T (in K), a pressure P (in bars), chemical potentials μ_i (in $J.mol^{-1}$), as well as internal energy U (in J), a volume V (in m^3), an entropy S (in $J.K^{-1}$), and the quantity of matter of the different elements n_i (in moles). Similarly, the surrounding environment is characterized by T_0, P_0, μ_{i0}, U_0, V_0, S_0, n_{i0}.

If ΔS^{tot} in the maximum creation of entropy resulting from the system entering into equilibrium with its environment, the exergy of a system in its environment is given by the following equation:

$$\mathrm{X} = T_0 \Delta S^{tot}$$

If U_{eq}, V_{eq} S_{eq} and n_{ieq} are internal energy, volume, entropy and the quantities of matter of the different chemical species once the system is in equilibrium with its environment, the following equation is useful to determine the exergy of a system:

$$\mathrm{X} = U - U_{eq} + P_0\left(V - V_{eq}\right) - T_0\left(S - S_{eq}\right) - \sum_i \mu_{i0}\left(n_i - n_{i\,eq}\right)$$

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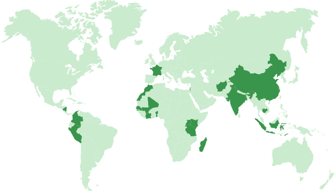

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