

Exergy analysis

Measuring the Physical Value of Resources

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Objectives of the lecture

- **Understand the concept of exergy and the reference environment**
- **Define the concept of irreversibility**
- **Introduce the exergy balance for closed systems**
- **Define exergy efficiency**

A review of the first and second laws

- **First law: energy is conserved**
- **Second Law: Entropy of a system+ surroundings always increase (or remains constant ideally)**

$$\Delta S_{\text{universe}} > 0 ; \Delta S_{\text{universe}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}}$$

The second law and entropy

The Second Law :Natural processes increase total entropy and cannot reverse themselves spontaneously.

Entropy: is an extensive state variable that can be defined for any material substance or any system and which indicates its degree of disorder

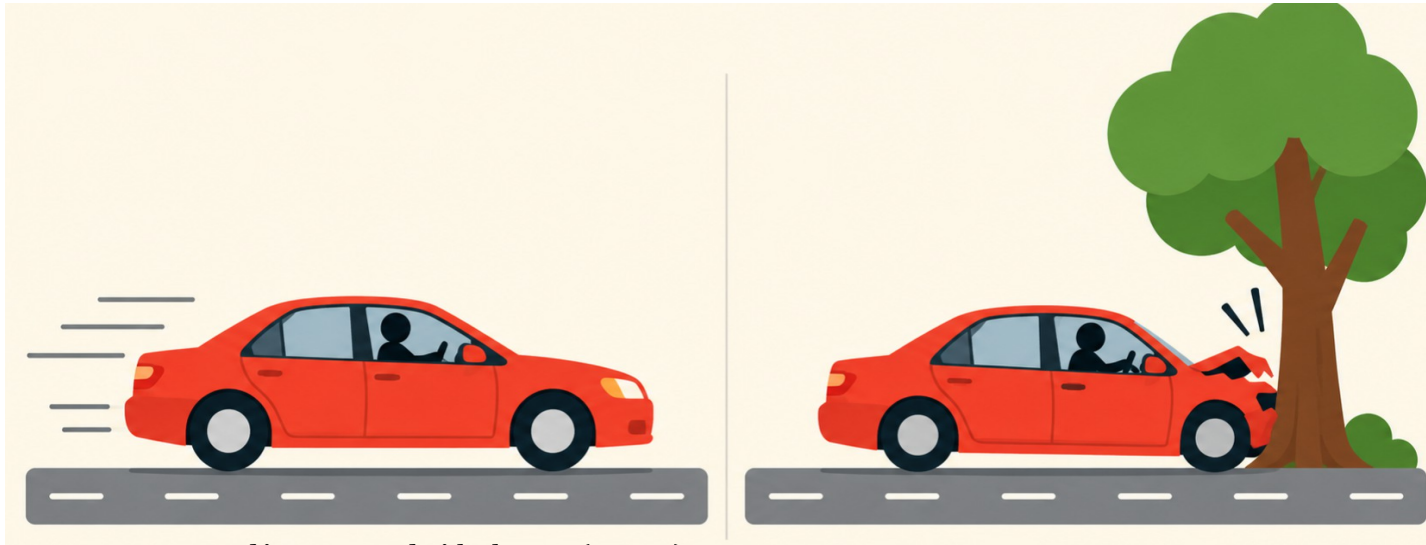
$$\text{Entropy generation} = \sum (\text{dissipated heat} / T)_i$$

- What goes up, comes down
 - What is cold, gets warm
 - What is hot, cools down
 - What is concentrated becomes diluted
 - What is pure, rusts
 - What is alive, dies
- *Entropy is generated , $S_g > 0$ = Irreversibility*

But...the units of entropy (kW/K) are unintelligible by non experts

Where is the degraded energy?

- If everything degrades and energy is conserved => there are forms of energy that are more useful and less degraded than others.



Source: AI-generated image created with ChatGPT (OpenAI),

- All "noble energy" transforms into heat at the lowest possible temperature => thermal energy is the "dump" for all other forms of energy.

Which source of energy would you choose?



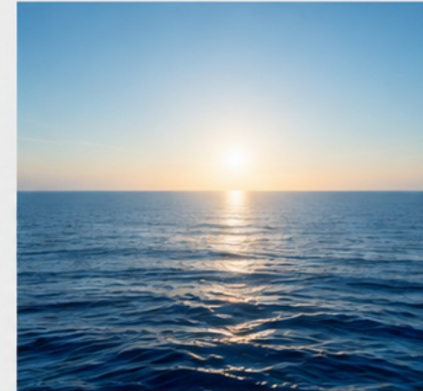
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VS



Source: AI-generated image created with ChatGPT (OpenAI),

Exergy as a combination of the two laws

- **First Law: evaluates the quantity of energy.**
- **Second Law: gives us the direction of transformation. Energy will only transform if "quality" is consumed. The entropy of the universe will always increase.**
- **The combination of both laws indicates that it is not a matter of the quantity of mass or energy in a system, but the quality of that matter or energy, i.e., its exergy content.**

Exergy characteristics

- **Exergy is a thermodynamic quantity that indicates the maximum theoretical work that can be achieved through the spontaneous interaction between a system and its surroundings.**
- **Alternatively, it can also be expressed as the minimum theoretical work required to bring a system from its equilibrium state to a predefined state.**
- **All resources have a defined and calculable amount of exergy relative to a reference environment.**
- **It provides information about the potential usefulness of the system as a source of work.**

Exergy characteristics

- **It is an extensive property with the same units as energy (universal).**
- **It is not conserved; instead, it is destroyed due to irreversibilities.**
- **In all matter or energy transformations, exergy is always lost.**
- **To define it, the Reference Environment must first be established.**

Types of exergy

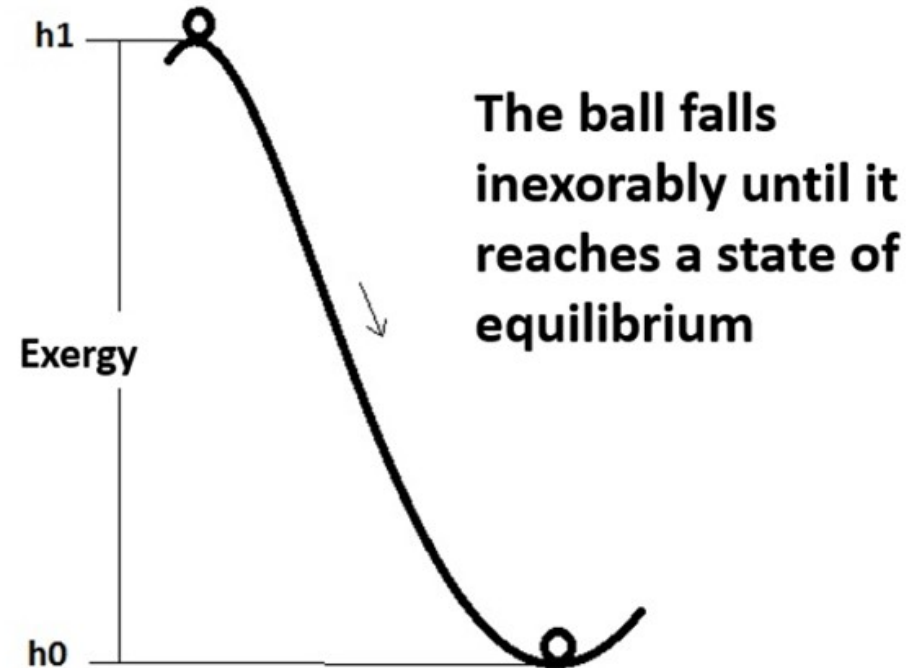
Exergy: The maximum amount of *work* that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly.

- What goes up, comes down = Destruction of **Mechanical Exergy**
 - What is cold, gets warm = *Destruction of Thermal Exergy*
 - What is hot, cools down = Destruction of **Thermal Exergy**
 - What is concentrated becomes diluted = Destruction of **Chemical Exergy**
 - What is pure, rusts = Destruction of **Chemical Exergy**
 - What is alive, dies = Destruction of **Chemical Exergy**
 - Waste is dispersed = **Destruction of any type of Exergy**
- } ➤ **Spontaneously**

The Gouy –Stodola theorem : Exergy destruction = $T_0 S_g \equiv$ Irreversibility !!!

The units of exergy (**kWh**) are knowledgeable, BUT WE NEED a REFERENCE

The Reference Environment



The limit of the system's spontaneous evolution is to reach equilibrium with its environment (dead state)

Characteristics of the Reference Environment

- The reference environment (dead state) is the region located beyond the immediate surroundings of the system and whose properties are not affected by the process.
- Different reference environments generate different exergies.
- The properties in the dead state are denoted by T_0 , P_0 , h_0 , u_0 , and s_0 .
- For engineering applications, $T_0=20$ or 25°C ; $T_0=20$ or 25°C and $P_0=1$ bar $P_0=1$ bar.
- In the reference environment, $E_k=E_p=0$ $E_k=E_p=0$ exergy and kinetic and potential energy coincide.

The purpose of the Reference Environment



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Specific exergy

$$b = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + \frac{c^2}{2} + gz \quad [\text{J/kg}]$$

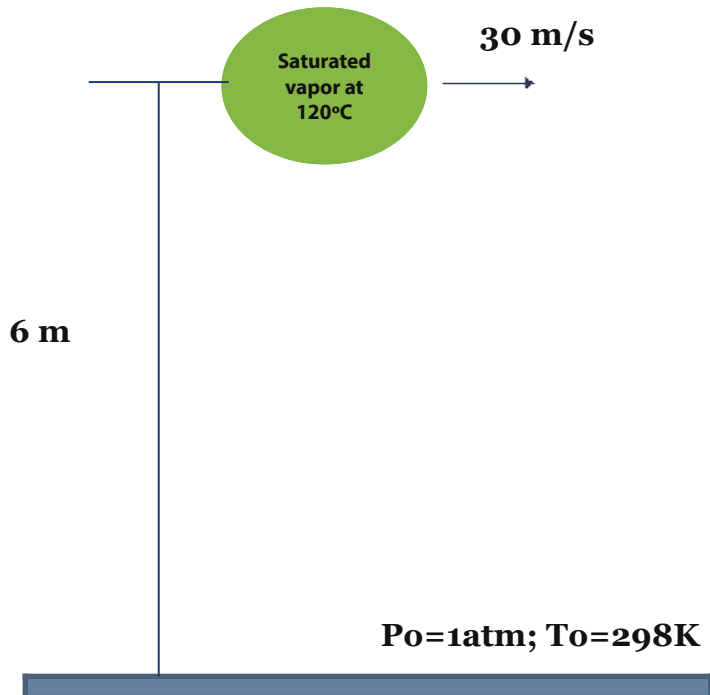
Variation of exergy:

$$B_1 = (U_1 - U_0) + p_0(V_1 - V_0) - T_0(S_1 - S_0) + KE_1 + PE_1$$

$$B_2 = (U_2 - U_0) + p_0(V_2 - V_0) - T_0(S_2 - S_0) + KE_2 + PE_2$$

$$B_2 - B_1 = (U_2 - U_1) + p_0(V_2 - V_1) - T_0(S_2 - S_1) + (KE_2 - KE_1) + (PE_2 - PE_1) \quad [\text{J}]$$

- Calculate the specific exergy of a saturated vapor bubble at 120°C, with a velocity of 30 m/s and a height of 6 m. Properties of the reference environment: $T_0=298$ K, $P_0=1$; liquid water.



$$b = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + \frac{c^2}{2} + gz$$

	Saturated vapor ($T=120^\circ\text{C}$; $x=1$)	Water in the R.E. ($T_0=25^\circ\text{C}$; $p_0=1\text{atm}$)
Internal energy, kJ/kg	2529,3	104,88
Specific volume, m ³ /kg	0,892	$1,0029 \times 10^{-3}$
Specific entropy, kJ/kgK	7,1296	0,3674

$$b = (2529,3 - 104,88) + 1,01 \times 10^5 (0,892 - 1,00 \times 10^{-3}) / 1000$$

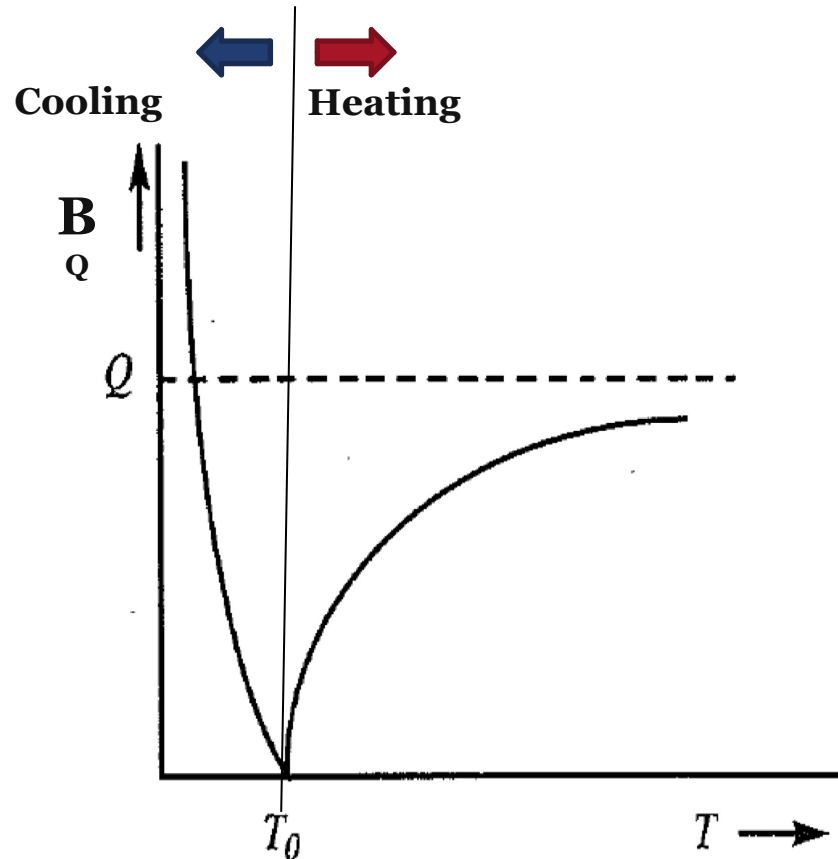
$$- 298(7,1296 - 0,3674) + \frac{30^2}{2 \cdot 1000} + \frac{9,8 \cdot 6}{1000}$$

$$b = 2424 + 89,5 - 2015 + 0,45 + 0,05$$

$$b = 499 \text{ kJ/kg}$$

Exergy transfer through heat

$$B_Q = Q(1 - T_0 / T_f) \quad [\text{J}]$$



- In heating or cooling processes:
 - A $T_f > T_0$. $Q > 0$ (heating: obtaining exergy from heat)
 - A $T_f < T_0$. $Q < 0$ (cooling: extraction of heat from exergy)
- In heating processes, exergy is always less than Q . They are equal when $T_f = T_\infty$.
- In cooling processes, the exergy required to cool is infinite when $T_f = 0$.
- It is very difficult to cool a body below the ambient temperature. Be careful not to lower the ambient temperature more than necessary in summer!

Fuente: Moran y Shapiro (2014)

- Energy balances indicate Losses crossing the limits of the system. But they do not locate causes.

$$\text{Energy in} - \text{Energy out} = \text{Losses crossing limits}$$

- Exergy Balances indicate Degradations and their Location

$$\text{Exergy in} - \text{Exergy out} = \text{Degradations within the system}$$

- Differential Exergy balances indicate Causes of Degradation and Avoidable Losses

Exergy balance is not conservative

$$B_2 - B_1 = \int_1^2 \left(1 - \frac{T_0}{T_f}\right) \delta Q - [W - p_0 (V_2 - V_1)] - T_0 S_g \quad [\text{J}]$$

$$\frac{dB}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \left[\dot{W} - p_0 \frac{dV}{dt}\right] - T_0 \dot{S}_g \quad [\text{W}]$$

$$B_2 - B_1 = \int_1^2 \left(1 - \frac{T_0}{T_f}\right) \delta Q - [W - p_0 (V_2 - V_1)] - T_0 S_g$$

ΔB
**Exergy
variation**

B_Q
**Exergy
transfer
associated
with heat**

B_W
**Exergy transfer
associated with
work**

I
**Exergy
destruction/
Irreversibility**

$$B_2 - B_1 = \int_1^2 \left(1 - \frac{T_0}{T_f}\right) \delta Q - [W - p_0 (V_2 - V_1)] - T_0 Sg$$

➤ Irreversibility (I) or exergy destruction satisfies:

$$I = T_0 Sg$$

- **Starting from the concept of equilibrium (p, T, μ), one can distinguish between mechanical, thermal, and chemical irreversibilities.**
 - **Mechanical irreversibility: Caused by friction.**
 - **Thermal irreversibility: Caused by temperature gradients. To be efficient, small temperature increments and exchangers with large heat exchange surfaces are preferred.**
 - **Chemical irreversibility: Occurs due to chemical imbalances, such as in mixtures, solutions, or chemical reactions.**

Exergy Efficiency

- Since losses are not located in the component, energy efficiency using the first law of Thermodynamics may be misleading.
- The Second Law Efficiency or Exergy Efficiency is defined as:

$$\eta = \frac{\text{Product Exergy}}{\text{Exergy of Fuels}}$$

- The Product exergy is also named recovered exergy and the exergy of Fuels are the supplied exergies to the component.
- This is a universal definition of “true efficiency” and its value ranges between 0 and 1.
- Second Law of Thermodynamics can also be written as

$$F - P = I \geq 0 \quad \text{and}$$

- In such a way that the inverse of the exergy efficiency (η) is named “unit exergy consumption, k ”, and is in fact a “local cost”.

Improving Efficiencies

Exergy Analysis can be used in many ways to improve efficiencies

1. Process design and improvement.
2. Process optimization.
3. On-line Thermoeconomic Diagnosis: Detection of inefficiencies and calculation of their economic effects in operating plants.
4. Rational cost assessment of plant products based on physical criteria.
5. Evaluation of alternatives among various designs or operation decisions and profitability maximization. Energy (Exergy) audits.
6. Industrial Simbiosis and price setting of interchanged commodities.
7. Setting rational legislation about commercially efficient solutions.

Sama-Szargut Second Law rules

- **1. Do not use excessively large or excessively small thermodynamic driving forces in process operations.**
- **2. Minimize the mixing of streams.**
- **3. The rejection of heat to the environment, is a reflection of the irreversibilities within the plant.**
- **4. Fans or compressors should operate on the process coolest streams.**

J. Szargut, D.A. Sama, 1995: Practical Rules of the Reduction of Energy Losses Caused by the Thermodynamic Imperfections of Thermal Processes, Proc. of The II Int. Thermal Energy Congress, Agadir, Morocco, June, v. 2, 782-785

Sama-Szargut Second Law rules

- **5. Avoid the compression of steam which has been previously expanded**
- **6. Introduce polygeneration**
- **7. A malfunction in a component induces malfunctions in the others. Analyze it. Use a simulator.**
- **9. Do not discard heat at high temperature to the ambient or to cooling water, and do not heat refrigerated streams with hot streams or with cooling water. Use instead energy cascades.**

Sama-Szargut Second Law rules

- **10. In heat exchangers, try to match streams where the final temperature of one is close to the initial temperature of the other.**
- **11. The flow heat capacities of the streams exchanging heat should be similar. Consider partitioning in two or more exchangers otherwise.**
- **12. Any counter-current process is generally more thermodynamically efficient than its parallel equivalent.**
- **13. Exergy destructions due to hydraulic friction or irreversible heat transfer are the larger, the lower is the temperature in the process. Minimize these destructions especially below the ambient temperature.**

- **14. Minimize the throttling.**
- **15. Eliminate leaks.**
- **16. 17. 18. Avoid large chain processes. The exergy costs increase “downstream”. Recirculate streams. Integrate processes., make systems multifunctional...**
- **19. ... Concentrate in exergy destructions with higher costs. The more advanced the production process is, the greater the cost of the irreversibility malfunction, and the greater its fuel impact.**
- **20.21....**
- **and more See:**

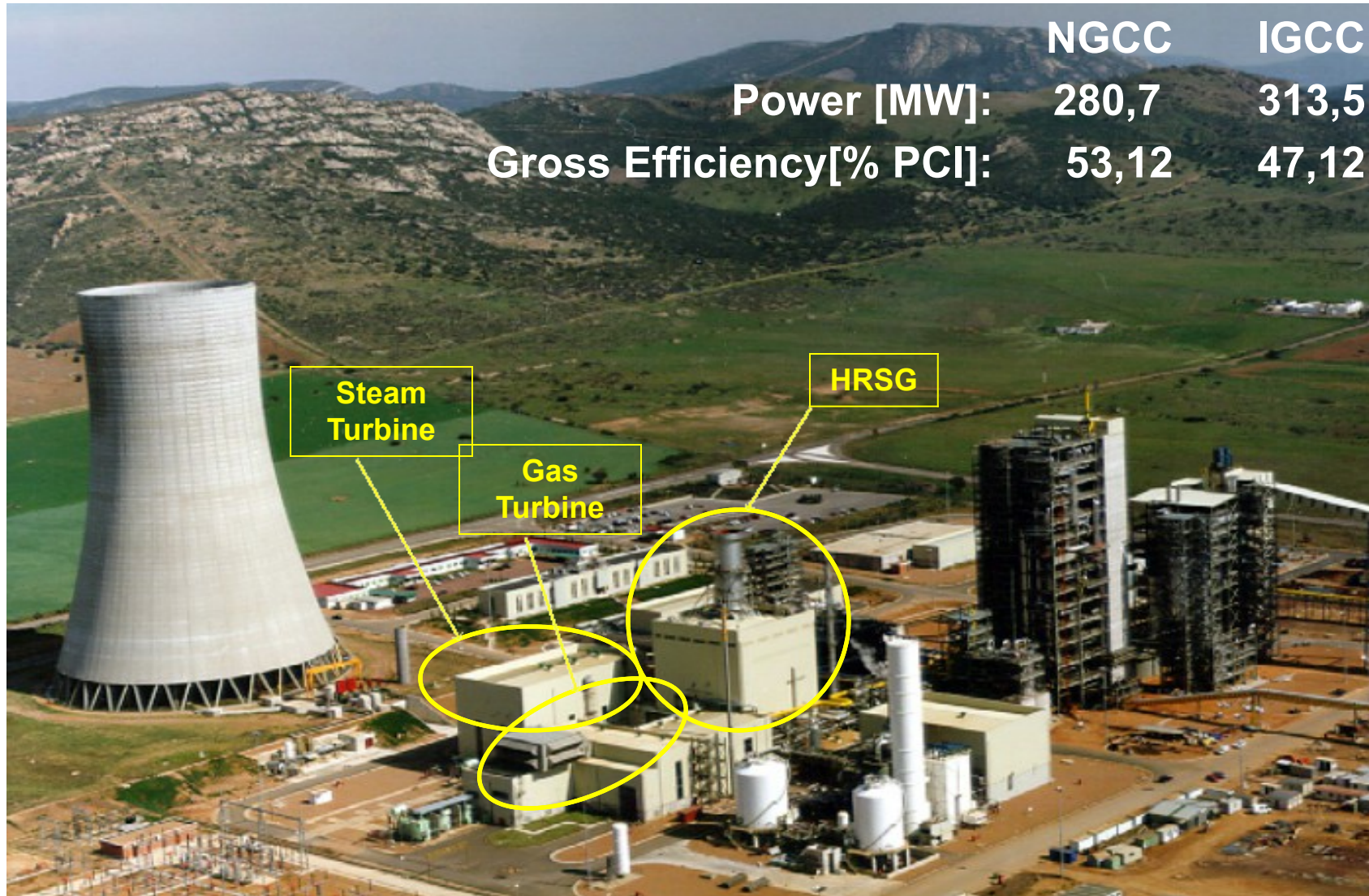
The Principles of Resource Efficiency . Ch 16. in A Valero and Al. Valero D. “Thanatia: The Destiny of Mineral Resources” World Sci. ,The Imperial College Press, 2014. ISBN 9789814273930

Sama-Szargut Second Law rules

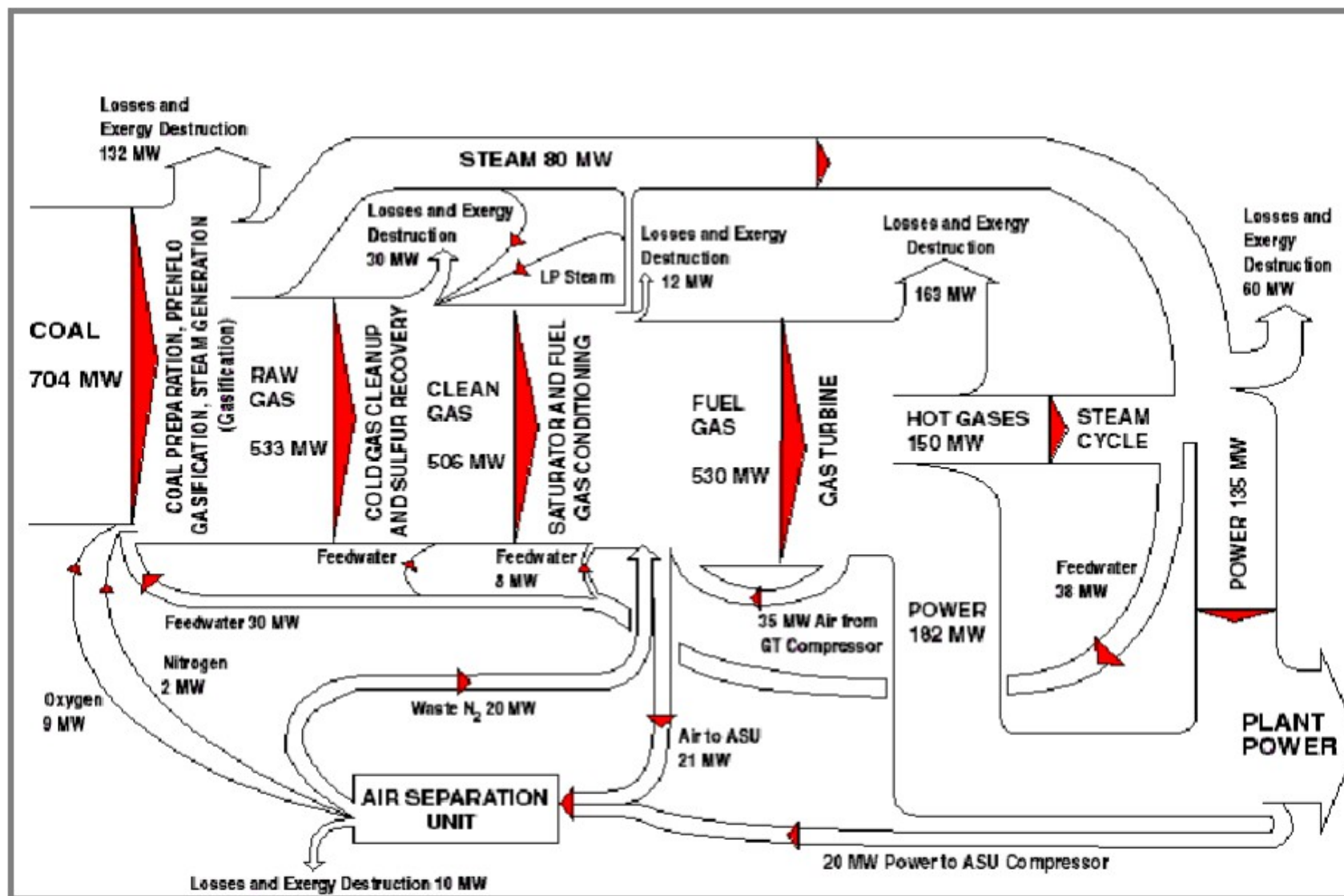
- ***One would expect that most, if not all, of the rules be routinely implemented in new designs and in retrofit projects. It turns out, that the contrary is rather true: even a superficial survey of some of the current most common energy conversion installations shows that most of the rules are actually disregarded in practice.***

E. Sciubba. Why are some of the Sama-Szargut Second Law rules routinely violated in practical applications? Conference Proceedings Paper - Energies „Whither Energy Conversion? Present Trends, Current Problems and Realistic Future Solutions” 1st International e-Conference on Energies, March 2014, <http://sciforum.net/conference/ece-1>

IGCC Plant



Grassman diagram of the plant



Summary

Exergy

It measures the quality of energy and resources in general: máximo theoretical work of a system as it interacts spontaneously with the environment.

Exergy of a system

[J]

Exergy balance closed systems

= [J]

Irreversibility (I₀)

[J]

Maximum power

=() [W]

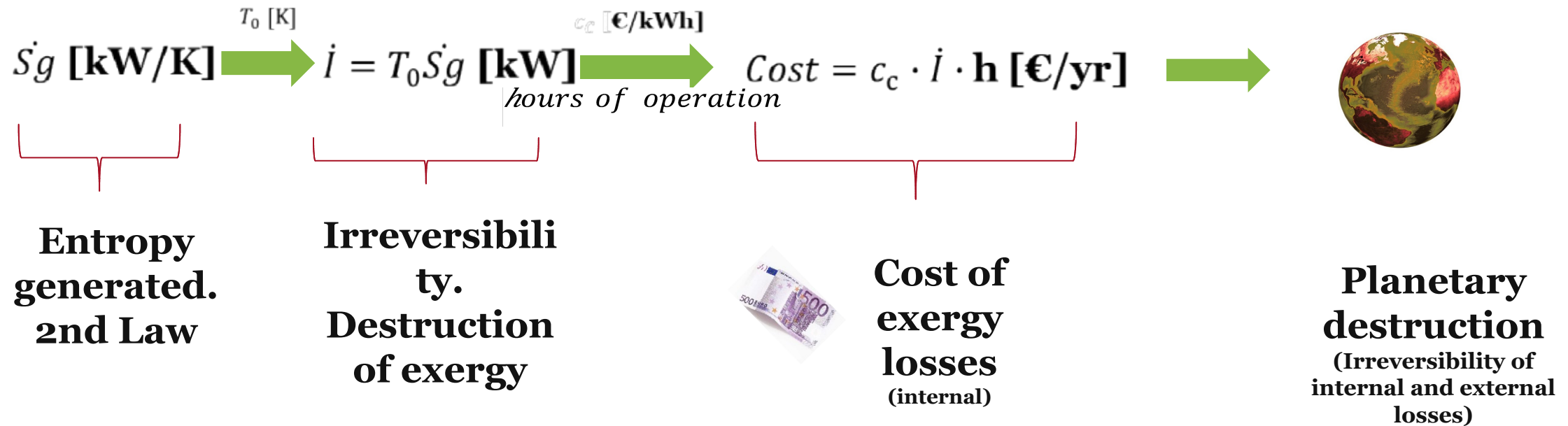
Exergy balance open systems

= [W]

Exergy efficiency

$$\varepsilon = \frac{B_{recovered}}{B_{supplied}} \quad [-]$$

Message of the seminar



Thank You

Physics, Economics and Responsible Resource Use