Thermoeconomic Input-Output Analysis applied to Industrial Ecology

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E/E

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Introduction

- The key point of **Industrial Ecology** (IE) is the use of waste flows produced by an industry as inputs for another, in order to **close materials cycles**.
- Thus, a waste becomes a ***by-product***, from the viewpoint of the **producer**
- and a ***resource*** from the new **consumer**.
- Accordingly, the main question arising is:

How fair prices can be determined?

  - They should be based on **production costs** based on physical **roots**.
  - Accurate and objective **accounting methodologies** are needed.
- **Thermoeconomics** is proposed solving this question and other quantification problems within Industrial Ecology.

Outline

- Exergy, Thermoeconomics and Input-Output Analysis.
- Thermoeconomic Input-Output Analysis.
- Example of Application.
- Conclusion.

Exergy, Thermoeconomics and I-O Analysis

- ***Exergy*** is the maximum amount of work that a system or flow could produce while interacting with the environment.
- Concept based on the **Second Law** of Thermodynamics.
- **Key contribution:** It is able to objetify **all** physical manifestations (energy, produts, resources, emmissions) in **energy** units.
- Application of exergy to **Industrial Ecology**:
  - Ayres and Ayres (1996). Quantification.
  - Connelly and Koshland (2001). Resource depletion.
  - Finnveden and Östlund (1997), Cornelissen and Hirs (2002), Dewulf and Langenhove (2002). Life Cycle Assessment (LCA).

Exergy, Thermoeconomics and I-O Analysis

- ***Thermoeconomics*** (Tribus and Evans, 1962), takes a step further by introducing the concept of purpose by means of efficiency:

Exergy Input – Exergy Output = Irreversibility >0

Fuel (F) – Product (P) – Wastes (R) = Irreversibility > 0

- ***Exergy cost*** (Valero et al., 1986) / *Cummulative exergy consumption* (Szargut and Morris, 1987) (amount of resources needed to produce a given flow or system) is a bridge between Thermodynamics and Economics.
- Thermoeconomics has been **applied to** the analysis, optimization and diagnosis of **energy systems**.

Exergy, Thermoeconomics and I-O Analysis

- **Input-Output analysis** (IO) has been aplied to issues related to Industrial Ecology.
- IO traditionally used with **different quantity units** for energy and material fluxes.
- If **monetary units** are used for costs, arbitrariness may be introduced.
- **Exergy IO** allows to measure all flows in the same units (Hau and Bakshi, 2004).
- **Thermoeconomic Input-Output analysis** uses Second Law for cost assessment.
  - It is able to objectively **asses the costs** of products interchanged.
  - It can help to rationalize the general **problem of resources savings** achieved through waste integration.

Thermoeconomic Input-Output Analysis applied to Industrial Ecology

- Physical Structure ⇒ Productive Structure.
- ***Fuel-Product Table:*** each element E_{ij} is the part of the product of component i used as a resource by component j. 0 is the environment.

	F_1	...	F_j	...	F_n	w_s	TOTAL
v_0	E_{01}	...	E_{0j}	...	E_{0n}		
P_1	E_{11}	...	E_{1j}	...	E_{1n}	E_{10}	
...	...	...	...	...	...	...	
P_i	E_{i1}	...	E_{ij}	...	E_{in}	E_{i0}	
...	...	...	...	...	...	...	
P_n	E_{n1}	...	E_{nj}	...	E_{nn}	E_{n0}	
TOTAL							

$$F_j = E_{0j} + \sum_i E_{ij}$$ (Fuel)

$$P_i = E_{i0} + \sum_j E_{ij}$$ (Product)

$$F_i - P_i = I_i > 0$$

$$F_T = \sum_j E_{0j}$$ (External resources)

$$P_T = \sum_i E_{i0}$$ (Final demand)

Thermoeconomic Input-Output Analysis applied to Industrial Ecology

- Processes are characterized by ***unit exergy consumptions***:

$$\kappa_{ji} = \frac{E_{ji}}{P_i} \qquad \langle \mathbf{KP} \rangle = \mathbf{E}\,\hat{\mathbf{P}}^{-1}$$

- **Production of each process** can be obtained from the final demand and unit exergy consumptions:

$$\mathbf{P} = \left(\mathbf{U} - \langle \mathbf{KP} \rangle\right)^{-1} \mathbf{P}_s \qquad |\mathbf{P}\rangle \equiv \left(\mathbf{U} - \langle \mathbf{KP} \rangle\right)^{-1}$$

- **Total fuel** needed for satisfying a given demand:

$$F_T = {}^t\kappa_e \, |\mathbf{P}\rangle \, \mathbf{P}_s$$

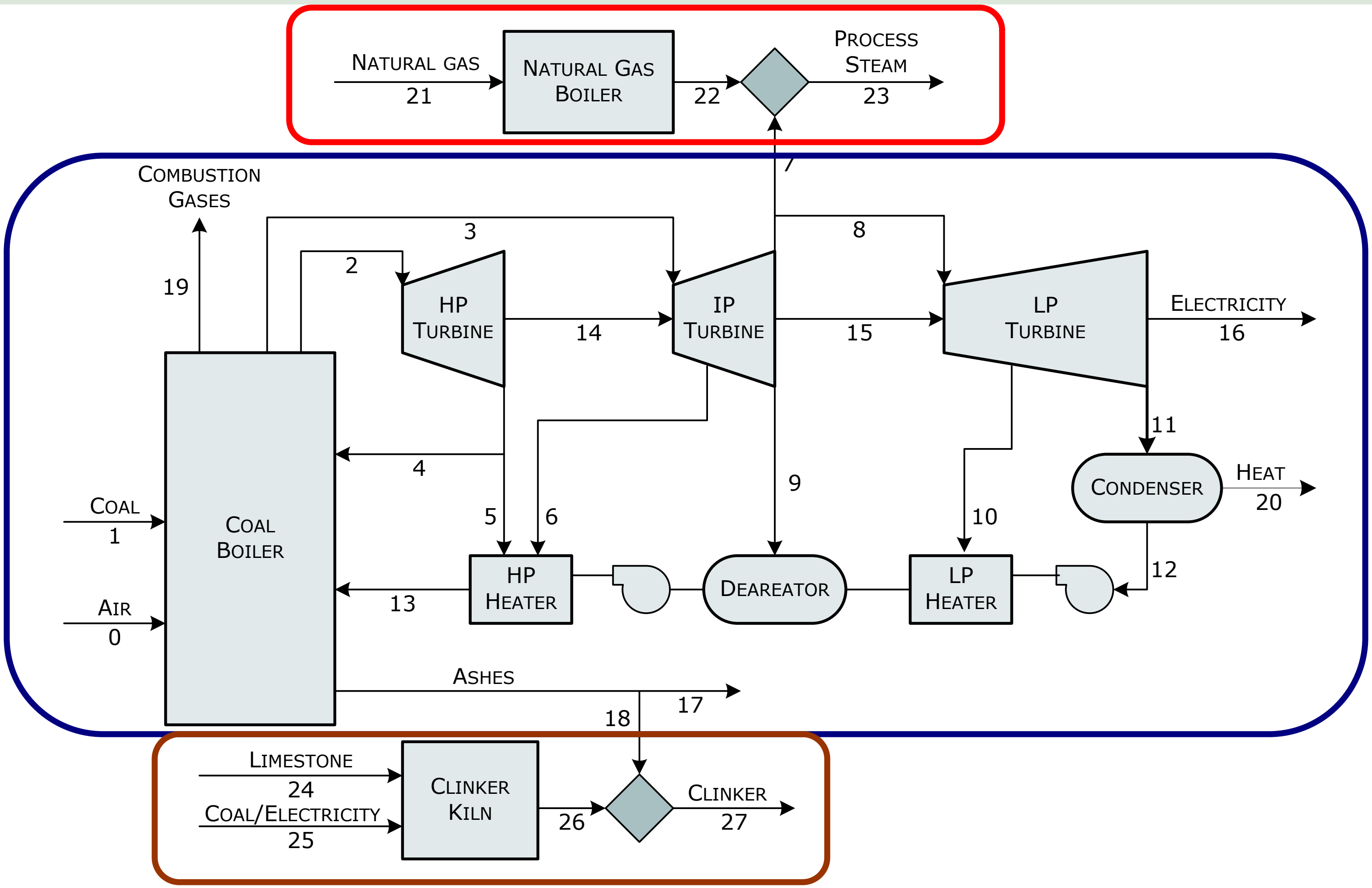
- Calculation of **unit exergy costs:**

$$\mathbf{k}_P^* = {}^t|\mathbf{P}\rangle \, \boldsymbol{\kappa}_e$$

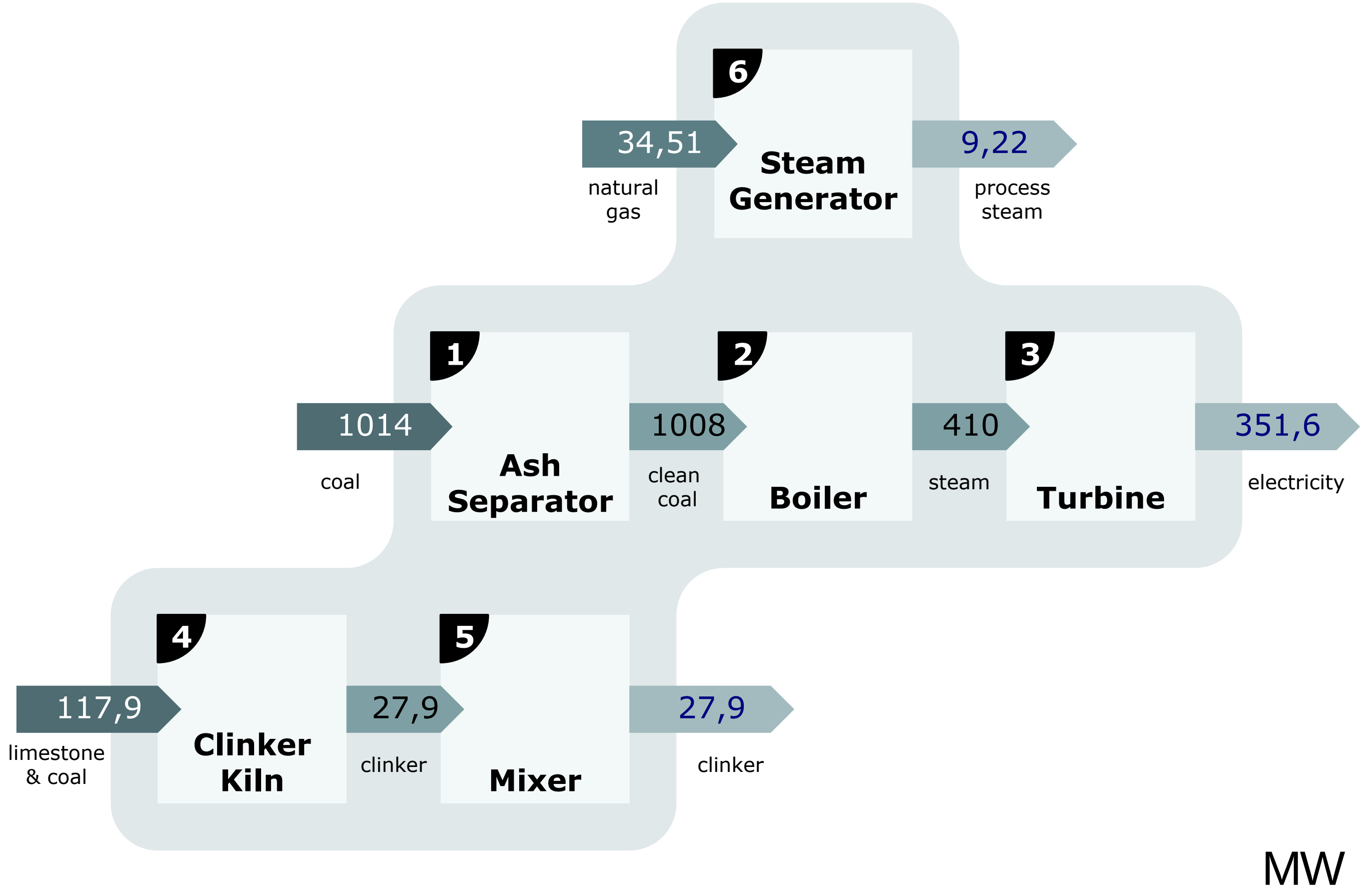
Example of Eco-industrial park

- The park integrates:
  - A **coal fired power plant** producing 350 MW
  - A **cement** factory with a capacity of 650000 ton/year
  - A **gas fired boiler** that produces 10 kg/s of process steam at 8.5 bar and 310ºC
- Flow **integration** analyzed:
  - Replace the **steam** produced in the gas-fired boiler with steam bleeding produced in the power plant.
  - Replace 10% of mass flow rate of **clinker** production **by fly ash** produced in the power plant

Example of Eco-industrial park



Productive structure. Isolated systems.



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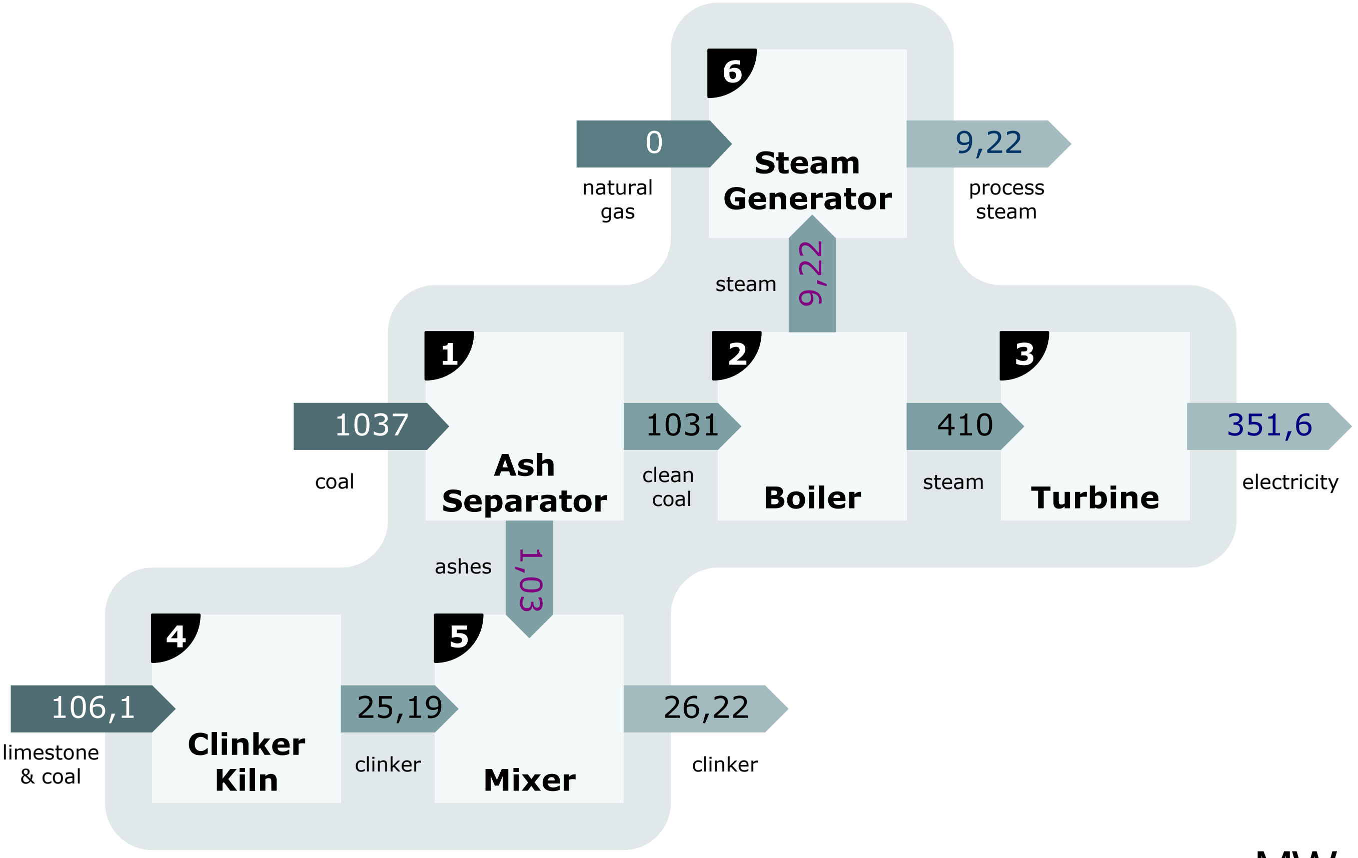
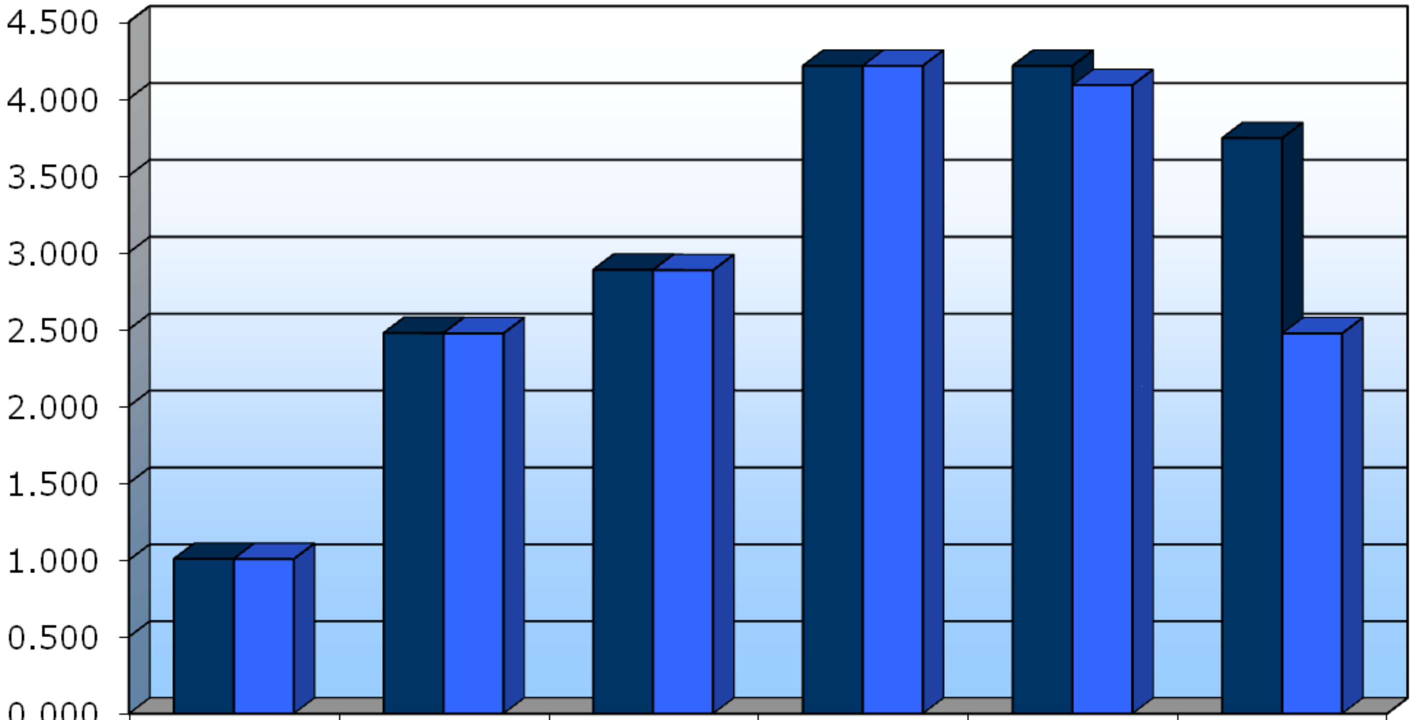


MW

Fuel-Product Table

	F_1	F_2	F_3	F_4	F_5	F_6	w_S	TOTAL
V_0	1015 / 1037,5	0 / 0	0 / 0	118 / 106	0 / 0	34,5 / 0		1167,5 / 1143,5
P_1	0 / 0	1008 / 1031	0 / 0	0 / 0	0 / 1	0 / 0	0 / 0	1008 / 1031
P_2	0 / 0	0 / 0	410 / 410	0 / 0	0 / 0	0 / 9,2	0 / 0	410 / 419,2
P_3	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	351,6 / 351,6	351,6 / 351,6
P_4	0 / 0	0 / 0	0 / 0	0 / 0	28 / 25,2	0 / 0	0	28 / 2,2
P_5	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	28 / 26,2	28 / 26,2
P_6	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	9,2 / 9,2	9,2 / 9,2
TOTAL	1015 / 1037,5	1008 / 1031	410 / 410	118 / 106	28 / 26,2	34,5 / 9,2	388,8 / 387,2	MW

Unit exergy costs



	Ash (P1)	Steam to turbines (P2)	Electricit y (P3)	Clinker (P4)	Clinker + Ash (P5)	Process steam (P6)
Isolated	1.006	2.475	2.887	4.213	4.213	3.743
Integrated	1.005	2.472	2.884	4.213	4.088	2.472

Conclusions

- **Thermoeconomic Input-Output Analysis** is proposed for the analysis of integrations that characterize Industrial Ecology:
  - **Systemic** methodology
  - Based on **physical roots** (Second Law).
- The approach can play a significant role for solving several important **problems of Industrial Ecology**:
  - Guidelines for establishing fair **prices** for by-products
  - **Physical costs** of matter and energy streams
  - Impact on **natural resources consumption** reduction
  - Effect on **waste reduction**
- All **thermoeconomic techniques** developed during years for the analysis, optimization and diagnosis of energy systems can now be applied to Industrial Ecology.

❖Thanks for your attention

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