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Hybrid Thermoeconomic Input–Output Analysis of a Waste-to-Energy power plant

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Dedicatio

"If you think you're too small to make the difference,
you haven't spent a night with a mosquito"

African proverb

We rich nations, for that is what we are, have an obligation not only to the poor nations, but to all the grandchildren of the world, rich and poor. We have not inherited this Earth from our parents to do with it what we will. We have borrowed it from our children and we must be careful to use it in their interests as well as our own. Anyone who fails to recognize the basic validity of the proposition put in different ways by increasing numbers of writers, from Malthus to The Club of Rome, is either ignorant, a fool, or evil.

Moses Henry Cass
Australian Minister for the Environment, Heritage and the Arts
Address speech to the Environment Committee of the OECD
Paris, November 13, 1974

Acknowledgments

Milan, 29/04/2015

This work represents a milestone in my life. Special dedication is reserved to my family: without the love and support from my parents, Matteo, and Mara, this important achievement would not feel so special.

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Abstract (ENG)

Given the crucial role played by natural resources in supporting economic activities, rational use of non-renewable energy sources has arisen as a major need as environmental concern is increasing worldwide.
This thesis deals with the concept of primary energy savings. Indeed, its main objective is to propose a novel methodology for the evaluation of the overall natural-resources consumption occurring in energy-conversion systems. Primary requirements can be either *direct*, if directly utilized in the considered system, or *indirect*, related to the implicit effects of the supply chains.
This technique could be exploited to understand the impact of energy generation in terms of fossil-fuels requirements, in the pursuit of a smarter management of non-renewable energy sources.

Keywords

Thermoeconomics; Input-Output Analysis; Hybrid LCA; Waste to Energy; Primary Resources Consumption.

Abstract (ITA)

Dato il ruolo cruciale svolto dalle risorse naturali nel supportare le attività economiche, l'utilizzo razionale delle fonti energetiche non rinnovabili appare una necessità sempre più rilevante con l'aumento dell'interesse verso l'ambiente in ogni parte del mondo.

Questa tesi affronta il concetto di risparmio di energia primaria. L'obbiettivo principale è infatti di proporre una metodologia innovativa per la valutazione del consumo complessivo di risorse naturali dovuto ai sistemi di conversione energetica. Il fabbisogno di risorse primarie può essere *diretto*, se questi sono utilizzati direttamente dall'impianto considerato, oppure *indiretto*, relativo agli effetti impliciti della catena degli approvvigionamenti.

Questa tecnica può essere utilizzata per comprendere l'impatto della generazione energetica in termini di fabbisogno di combustibili fossili, con l'intento di perseguire una gestione più efficiente delle fonti energetiche non rinnovabili.

Parole chiave

Termoeconomia; Analisi Input–Output; Analisi Ibrida del Ciclo di Vita; Energia da Rifiuti; Consumo di Risorse Primarie.

Summary

Context and motivation

Energy data gathered from authoritative institutions suggest that, among the broader set of natural resources, the class of *fossil fuels* plays a major role in supporting human activities.
Nonetheless, considering actual depletion rates, it can be claimed how these sources are scarce and valuable. Stocks and reserves are present in a finite amount on our planet, and sooner or later they will be completely depleted. Furthermore, growing awareness about the effect of energy-related emission on climate change contributed in a broader concern about non-renewable energy-sources consumption.
In recent times, political institutions began to agree on the need for *sustainable development*, thus including environmental care. Energy sustainability is part of this need, as the seventh Millennium Development Goal points out. Two simultaneous actions are being claimed:

- Migration towards alternative sources to satisfy the increasing level of final demand for energy (Security of Supply, SoS);
- Rational use of energy to reduce the consumption of non-renewable fossil fuels (primary energy saving).

For this reason, there is a need for analytical techniques capable of evaluating the total amount of primary resources embodied in the product of economic activities, assessing what can be considered a "cost" in terms of direct and indirect fossil-fuels requirements.

Objectives of the thesis

This thesis deals with the concept of primary energy savings. Indeed, its main objective is to propose a novel methodology for the evaluation of both direct and indirect natural-resources consumption occurring in energy-conversion systems. More specifically:

- Standard Thermoeconomic Analysis, formalized with an Input–Output approach, is enhanced. The issues of reallocating the cost of residues to the final demand and accounting for supply chains and life-cycle phases are properly considered, hence defining a *hybrid* model.

- An iterative methodology for the economic optimization of energy systems is proposed, based on Exergoeconomic Design Evaluation but validated with the novel technique assessed in this thesis. This improved procedure is then applied to the case study of a Waste-to-Energy (WtE) power plant, which provides a relevant example of indirect fossil-fuels consumption.

Achievements of the thesis

Hybrid Thermoeconomic Input–Output Analysis (H–TIOA) has been developed, and results a flexible tool to enquiry the extent of resources-consumption of a given system, thanks to its *comprehensiveness* and its *simple formulation*. The main drawbacks affecting H–TIOA are related to the use of MIOTs to model the supply chains, and determine the trustworthiness of the results; however, *Sensitivity* and *Uncertainties* represent topics that are still to be deeply investigated. Indeed, the mathematical structure of the method is already suitable to such evaluations, but these aspects have not been examined in this thesis.

Results confirm the expectations that WtE is a valuable technology in terms of primary-resources savings, since it can pay-back its total primary exergy cost in less than one year of operation. Moreover, the Exergoeconomic Design Evaluation and Optimization procedure allowed to easily increase the performance of the system.

Despite much effort is needed to overcome known issues of thermoeconomic procedures, H–TIOA could constitute a support tool for environmental impact assessments, especially when newer technologies, based on renewable energy sources, are analyzed.

Chapter 1
Introduction and Objectives of the thesis

1.1 The issue of Natural Resources

As Figure 1.1 points out, economic wellness is strictly related to the amount of primary energy supply. This connection can be explained with the important role that energy resources play in sustaining economic activities [1, 2].

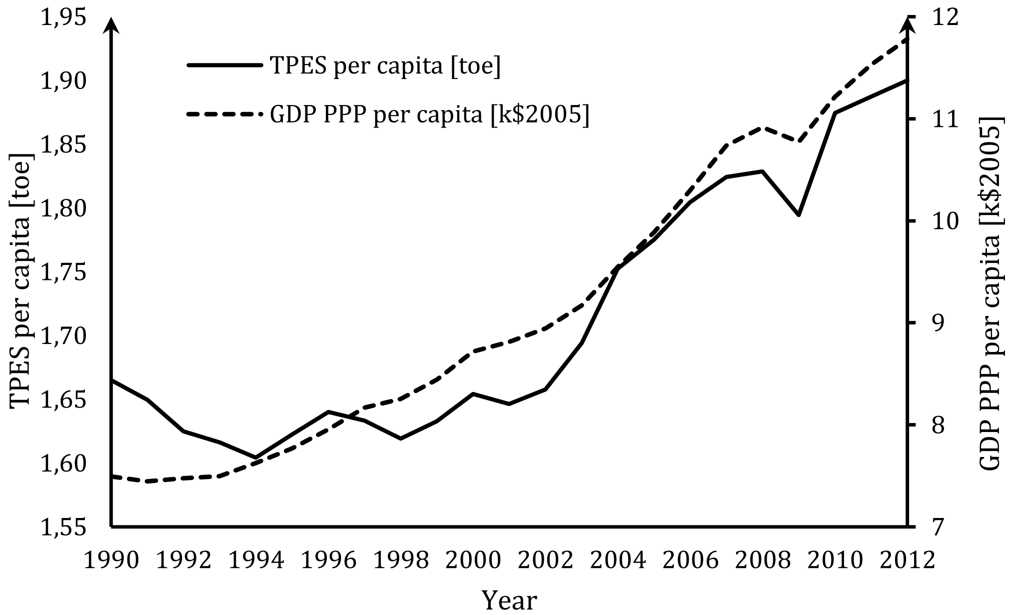


Figure 1.1. Primary energy and economic per capita indicators for the World [1].

Studies such as the *Millennium Ecosystem Assessment* has raised reasonable concern about the impact of human activities on natural ecosystems: «*Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any other comparable period of time in human history*» [3]. This concern has been effectively conveyed on the technical standpoint by Valero [4, p. 4]:

> *«We live in a finite and small world for the people we are and will be, and natural resources are scarce. If we want to survive, we must conserve them. [..] We must know the mechanisms by which energy and resources degrade; we must learn to judge which systems work better and systematically improve designs to reduce the consumptions of natural resources and we must prevent residues from damaging the world."*

As natural resources are recognized to play a crucial role in sustaining economic activities, various methodologies and analytical tools have been developed in the attempt to address environmentally-conscious decisions [5]. The proposed metrics must take proper consideration of the laws of nature, in order to have a solid basis, as well as to provide effective guidance for further improvements [2]. An important example is given by the Second Law of Thermodynamics: advances in the field of energy conversion have traditionally been driven by attainment of the maximum thermodynamic efficiency, expressed as the minimum fuel consumption to satisfy a given level of production. Starting from the beginning of last century, *exergy*[1] has arisen as the best indicator for thermodynamic analyses, and is nowadays broadly accepted by literature [5–7]. Since exergy is defined over both First and Second Laws of Thermodynamics, it takes in consideration both quantity and quality of energy interactions [7]. For this reason, standard *Exergy Analysis* (EA) has been broadly accepted by literature as the suited method for thermodynamic performance evaluation and design optimization of energy conversion systems [8].

1.2 Thermoeconomics

EA carries a relevant advantage: it allows to locate and evaluate the real thermodynamic inefficiencies that concur in reducing the amount of useful product delivered by a given system. Nonetheless, this tool is purely thermodynamic, and neglects the economic perspective of energy-conversion facilities. Indeed, in engineering practice, it is not uncommon that thermodynamic design and optimization methods are subject to monetary constraints, as *money* can still be considered a resource fueling the considered system in order to deliver its final products.

More recently, *Thermoeconomics*[2] has emerged in the attempt to bring together thermodynamic and economic principles, in order to evaluate the

---

[1] *Exergy e* is defined as the maximum theoretical amount of work that it would be possible to extract from a given system through a reversible process that would bring it in equilibrium with its reference environment. Denoting enthalpy with *h*, entropy with *s*, and temperature with *T*, and specifying environment conditions with the subscript *0*, it results:

$$e = h - h_0 - T_0 \left(s - s_0 \right)$$

[2] This term was coined by Tribus and Evans [19] to underline the combination between Thermodynamics and Economics when the concept of *cost* is applied to exergy.

impact that inefficiencies have on the cost of the product of the considered system. As stated by Tsatsaronis [9], this method is able to:

- determine location, magnitude, causes, and costs of thermodynamic inefficiencies occurring in complex systems;
- allocate the cost of resources to the different final products (in accordance with economic practice).

In the most general acceptation, *Thermoeconomic Analysis* (TA) can be claimed to be a cost-accounting procedure that relies on physical relations to determine the cost of *final products* in terms of the specified *resources*. In this perspective, TA has been intensively used in literature with the aim to evaluate and to optimize the cost of a system's product. Two main branches have been consequently developed:

- *Exergy Cost Analysis* (ExCA): resources include the exergy directly fueled to all the components of the system [10, 11];
- *Exergoeconomic Cost Analysis* (EeCA): resources are expressed in terms of economic expenses borne build and operate the system [9, 12].

As Valero suggests in [4], one of the main feature of TA is the possibility to perform global and local optimization of a system component, as well as iterative Design Evaluation procedures of the overall facility: in both cases, the *objective function* is built over the specified cost of final products.

Thermoeconomics has developed as a technique to allocate, on a thermodynamic basis, the costs of production to the final demand of the system; these costs are expressed in terms of the exogenous resources that are specified to fuel the considered system. This means that the analytical boundaries are restricted to the physical system itself; indeed, Thermoeconomics was originally formulated to analyze a single unit/system. Nowadays, this approach is known to suffer from two main failures.

1. *Indirect primary resources consumption*. The case of ExCA deals with direct exergy intakes from the environment. This implies that:
    - Indirect resource-consumption, related to all the supply chains that feed the analyzed system, are neglected;
    - The system configuration is kept fixed, i.e. only the operation phase is considered, while other life-cycle phases are omitted.

Literature points out that neglecting the aforementioned contributions could lead to warped results [13], especially for systems that do not exhibit direct fossil-fuels consumptions. This is typically the case of power-generating systems based on renewable energy sources. To include supply chains in thermoeconomic evaluations of energy systems, *hybrid* methods have been proposed [14–16].

2. *Reallocation of the cost of residues*. In complex thermodynamic systems, specific components can be found whose purpose is to dissipate the residue of productive components, without providing a direct contribution to the production of final demand. Application of standard TA requires these dissipations to be treated as *products* of dissipative components, hence determining their costs in terms of exogenous resources. However, in economic practice it is common to allocate all the costs to the final demand. For this reason, Valero and colleagues [17] proposed a method to include this reallocation issue in standard TA. Nonetheless, this improvement is not usually included in the standard hybrid procedures discussed above.

1.3 Objectives of the thesis

From the first attempts to formulate theories based on the Second Law of Thermodynamics in cost accounting and optimization of energy systems, such as [18, 19], Thermoeconomic Analysis is currently open to developments and perfections, and important research efforts are needed in order to improve and enhance this tool. This thesis is aligned to this point of view.

- ***Theory***. The main objective of this thesis is to propose *Hybrid Thermoeconomic Input-Output Analysis* (H–TIOA) as an improved thermoeconomic technique to assess the primary exergy consumption of energy-conversion systems. More specifically, the aim is to overcome the two issues of standard Thermoeconomics highlighted in previous paragraph:

  1. *Indirect requirements*. Supply chains fueling the system are accounted for exploiting the matrix formulation of *Input-Output Analysis* (IOA); the resulting *hybrid* model is then extended to consider all the Life-Cycle phases of the system.

2. *Reallocation*. The procedure to reallocate to the final demand the cost of residues-dissipations is included as it has been introduced by Valero et al. [17];

- ***Practice***. The novel method is applied to the case study of a Waste-to-Energy power plant, in order to perform a complete and thorough iterative optimization procedure guided by thermoeconomic considerations. Numerical examples of such analysis are hardly retrievable in literature. A comparison is carried out between the enhanced method and a more traditional optimization process.

1.4 Structure of the thesis

This thesis is settled according to the following outline.

- **Chapter 2** presents the standard formulation of Thermoeconomic Input–Output Analysis and its application to cost accounting procedures, dealing with the procedure to reallocate the cost of residues to the final demand.
- **Chapter 3** describes Monetary Input–Output Tables and their use to model the entire supply chain of a given system, providing the necessary extension to a Hybrid formulation of TIOA (H–TIOA);
- **Chapter 4** introduces the issue and the potential of a sustainable waste management, and provides a broad overview of the state of the art of Waste-to-Energy technology. The case study of a Waste-to-Energy power plant, based on the well-known method of waste incineration, is described, while main differences between the physical structure and the thermodynamic model are clarified.
- **Chapter 5** contains a detailed explanation of the methodology followed to apply H–TIOA to the specific case study. Performance evaluation of the system is numerically performed, and main results are highlighted.
- **Chapter 6** performs a critical evaluation of the results obtained in previous chapter, assessing the main conclusions that arise from the analysis, and providing suggestions for further investigations.

Chapter 2
Thermoeconomic Input–Output Analysis

In this chapter, standard formulation of Thermoeconomic Analysis and Input-Output Analysis are presented, and the formalization of Thermoeconomic Analysis with an Input–Output approach is discussed. Determination of exergy costs and exergoeconomic costs is accomplished, and special attention is given to the problem of reallocating the cost of residues to those components responsible for their generation.

2.1 Thermoeconomic Analysis

According to Lozano and Valero [20], Thermoeconomics is grounded on the consequences of the Second Law of Thermodynamics. The *Exergy Cost Theory* is based on the concept that the process of exergy cost formation is closely related to the destruction of exergy occurring when a system transforms resources into products. In accordance to the *exergy-costing principle*, exergy represents the most accurate and truthful basis for allocating "values" (with an economic meaning) to resources and products of any energy system and each of its components. Indeed, since exergy is defined over both enthalpy and entropy, it is not subject to any conservation principle, and therefore its magnitude tends to decrease undergoing energy interactions. This observation leads straightforwardly to the concept of *exergy cost* as the amount of exergy needed to produce a given stream. Exergy cost is symbolized with C and it is expressed in the same units as exergy.

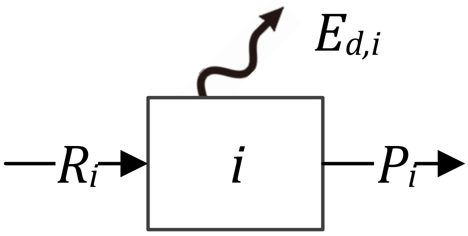


Figure 2.1. Generic component with its main streams of exergy.

With reference to the general component depicted in Figure 2.1, Thermoeconomic Analysis is based on the following three main assumptions, according to Tsatsaronis [9].

- *Exergy balance*. A direct consequence of the Second Law of Thermodynamics is that the exergy of the resource equals the exergy of the product, except for unavoidable dissipations occurring in non-reversible processes.
- *Cost balance*. As in economic practice, conservation is respected: cost of product is equal to the sum of the cost of resources, increased by eventual expenditures referring to disposal of residues concurrently produced.
- *Exergy-Costing Principle*. Exergy cost of a given stream is proportional to its exergy flow through coefficient c_i, named *unit exergy cost*, which represents the amount of exergy needed to produce one exergy unit of that stream. Cost of exogenous resources is usually assumed as known. When more detailed data are not available, common practice suggests to set the unit exergy cost equal to one:

$$c_{0i} = 1 \qquad \Leftrightarrow \qquad C_{0i} = \dot{E}_{0i} \tag{2.1}$$

The previous statements can be translated in the following system of linear equations:

$$\begin{cases} \dot{R}_i = \dot{P}_i + \dot{E}_{d,i} & \text{Exergy balance} \\ C_P = C_R + C_W & \text{Cost balance} \\ C_{ij} = c_i \cdot \dot{E}_{ij} & \text{Constitutive relation} \end{cases} \tag{2.2}$$

Substituting the exergy balance in the cost balance, and applying one constitutive relation for each stream, the cost of the product can be determined as a function of all the other terms. For the case of the single unit depicted in Figure 2.1 the cost balance hence results:

$$c_P \dot{P}_i = c_R \dot{P}_i + c_R \dot{E}_{d,i} \qquad \rightarrow \qquad c_P = c_R + c_R \frac{\dot{E}_{d,i}}{\dot{P}_i} \tag{2.3}$$

Eq. (2.3) shows how the cost of the product of a single component is given by the cost of its resource, increased by the term that represents the *cost of exergy destruction* occurring in that process.

As it can be understood, the case of a single unit is quite easy to handle. However, a complex energy system is usually composed of *n* components connected to each other and to the reference environment by *m* streams of exergy. In this case, a set of n exergy balances, n cost balances, and m constitutive relations can be determined. If the size of this system is large, easier and faster matrix formulation is necessary in order to achieve the solution; this leads straightforwardly to the use of Input–Output Analysis.

2.2 Input–Output Analysis

Input–Output Analysis (IOA) is a well-established tool for economic analysis [21], for which Russian economist W. W. Leontief was awarded the Nobel Prize in 1973. He originally developed this theory in 1930s [22] for the study of direct and indirect requirements of interrelated industrial sectors to satisfy a given final demand for weaponry, in the light of the upcoming World War II.

2.2.1 Single process

Let the example of a single productive process be considered, as depicted in Figure 2.2. Process i produces a net final demand f_i of the useful product, requiring exogenous resources r_i and intermediate consumption x_{ii} (endogenous resources) of its own product.

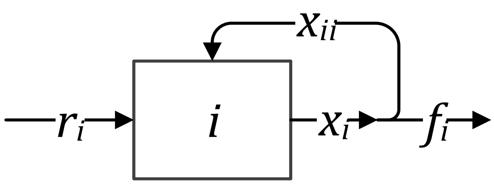


Figure 2.2. Generic single productive process

2.2.1.1 Leontief Quantity Model (LQM)

As it can be devised from Figure 2.2, total production is given by the sum of intermediate and final demand:

$$x_i = x_{ii} + f_i \tag{2.4}$$

The amount of endogenous resources required to satisfy a given level of final demand can be seen as a sort of *efficiency* that characterizes the process; this feature is expressed by the *technological coefficient* defined as follows:

$$a_i = \frac{x_{ii}}{x_i} \tag{2.5}$$

Definition (2.5) can be substituted into the production balance (2.4), resulting in the formulation of the *Leontief Quantity Model (LQM):*

$$x_i = a_i x_i + f_i \quad \rightarrow \quad x_i = (1 - a_1)^{-1} f_i \tag{2.6}$$

From eq. (2.6), the *output multiplier* can be defined as follows:

$$l_i = (1 - a_i)^{-1} \tag{2.7}$$

The factor defined in (2.7) is named *Leontief Inverse Coefficient*, and represents the amount of production that process *i* is required to fulfill in order to deliver one unit of its final demand.

2.2.1.2 Leontief Cost Model (LCM)

Referring to Figure 2.2, it can be claimed that production of final demand f_i, for which the total production x_i has been determined with eq. (2.6), requires provision of exogenous resources r_i. The amount of exogenous resources required to deliver one unit of final demand can be seen as a sort of *efficiency* characterizing the considered process; this feature is expressed by the *input factor* defined as follows:

$$b_i = \frac{r_i}{x_i} \tag{2.8}$$

According to economic practice, the cost of the product is given by the sum of the cost of exogenous resources and of the other intermediate inputs; furthermore, it is obvious that the product of a given process has the same cost no matter what use it will be destined to. Hence, the following balance holds:

$$c_i x_i = c_i x_{ii} + r_i \tag{2.9}$$

Eq. (2.5) and (2.8) can be substituted into (2.9), and the total production x_i can be simplified, resulting in the formulation of the *Leontief Cost Model* (LCM):

$$c_i = c_i a_i + b_i \quad \rightarrow \quad c_i = b_i (1 - a_i)^{-1} \tag{2.10}$$

Eq. (2.10) allows to compute the amount of exogenous resource needed to deliver one unit of final demand, both directly (direct production of final demand) and indirectly (production of endogenous inputs).

2.2.2 Multiple process

A complex system can be generally outlined as a set of *n* components connected to each other and to the environment by flows of resources and products, as shown in Figure 2.3.

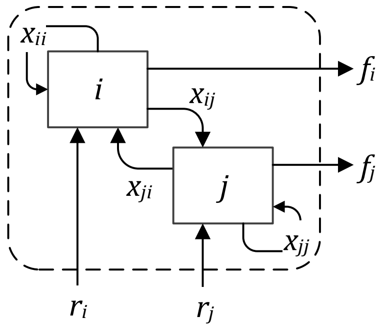


Figure 2.3. General outline of a complx system with multiple components.

2.2.2.1 Leontief Quantity Model (LQM)

For each *i*-th component, a production balance can be written according to eq. (2.4). Total production is given by final demand plus the sum of all the intermediate production fueled to other components:

$$x_i = \sum_{j=1}^{n} x_{ij} + f_i \tag{2.11}$$

Production balance (2.11) can be written for each of the *n* components; the resulting set of equations can be collected in a system as follows.

$$\begin{cases} x_1 = x_{11} + \ldots + x_{1n} + f_1 \\ \vdots \\ x_n = x_{n1} + \ldots + x_{nn} + f_n \end{cases} \tag{2.12}$$

If the *Production vector* $\mathbf{x}(n \times 1)$, the *Transaction matrix* $\mathbf{Z}(n \times n)$, and the *Final Demand vector* $\mathbf{f}(n \times 1)$ are defined, system (2.12) can be represented in a more compact matrix notation, as follows:

$$\begin{gathered} \mathbf{x} = \mathbf{Z} \cdot \mathbf{1}_{n\times1} + \mathbf{f} \\ \begin{vmatrix} x_1 \\ \vdots \\ x_n \end{vmatrix} = \begin{vmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{vmatrix} \cdot \begin{vmatrix} 1 \\ 1 \\ 1 \end{vmatrix} + \begin{vmatrix} f_1 \\ \vdots \\ f_n \end{vmatrix} \end{gathered} \tag{2.13}$$

where $\mathbf{1}_{n\times1}$ is called *summation vector* [23], having every element equal to 1.

In analogy with eq. (2.5), the *Technical Coefficients matrix* $\mathbf{A}(n \times n)$ can be defined to collect in matrix form the technical coefficients:

$$\mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1} \qquad \rightarrow \qquad a_{ij} = \frac{x_{ij}}{x_j} \tag{2.14}$$

Substituting eq. (2.14), eq. (2.13) can be written similarly to eq. (2.6), resulting in the matrix form of the *Leontief Quantity Model* (LQM):

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{f} \qquad \rightarrow \qquad \mathbf{x} = \left(\mathbf{I} - \mathbf{A}\right)^{-1} \cdot \mathbf{f} \tag{2.15}$$

The symbol **I** represents the *Identity matrix* with appropriate dimension.
In analogy with eq. (2.7), the *Leontief Inverse matrix* $\mathbf{L}(n \times n)$ can be introduced to collect in matrix form all the output multipliers of the system:

$$\mathbf{L} = \left(\mathbf{I} - \mathbf{A}\right)^{-1} \tag{2.16}$$

2.2.2.2 Leontief Cost Model (LCM)

Figure 2.3 shows how each component is completely characterized in terms of the exogenous resources received from the environment. In general, m different resources could be considered, assessing the cost of final demand in terms of each one, thus obtaining m different costs for each final product.
For each k-th resource, a cost balance similar to eq. (2.9) can be written, expressing the cost of the product of the i-th component as the sum of the exogenous resources and all the intermediate consumptions:

$$c_{ki} x_i = \sum_{j=1}^{n} c_{kj} x_j + r_{ki} \tag{2.17}$$

Production balance (2.17) can be written for each of the n components; the resulting set of equations can be collected in a system as follows.

$$\begin{cases} c_{k1} x_1 = c_{k1} x_{11} + \ldots + c_{kn} x_{n1} + r_{k1} \\ \vdots \\ c_{kn} x_n = c_{k1} x_{1n} + \ldots + c_{kn} x_{nn} + r_{kn} \end{cases} \tag{2.18}$$

The *Resources matrix* $\mathbf{R}(m \times n)$ can be defined as in eq. (2.20) to collect all the exogenous resources fueling the system. Each row refers to one type of resource and is hence expressed in homogenous units. Conversely, each column refers to all the different resources fueling one given component.

$$\mathbf{R} = \begin{vmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{vmatrix} \tag{2.19}$$

In a similar fashion, the *Unit* and *Total Cost matrices* $\mathbf{c}(n \times m)$ and $\mathbf{C}(n \times m)$ are introduced as in eq. (2.20) to collect the specific and total costs of the j-th product in terms of the i-th exogenous resource.

$$\mathbf{c} = \begin{vmatrix} c_{11} & \cdots & c_{1m} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nm} \end{vmatrix} \qquad \mathbf{C} = \begin{vmatrix} C_{11} & \cdots & C_{1m} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nm} \end{vmatrix} \tag{2.20}$$

In analogy with definition (2.8), the *Input matrix* $\mathbf{B}(m \times n)$ can be defined to collect in matrix form the input factors:

$$\mathbf{B} = \mathbf{R} \cdot \hat{\mathbf{x}}^{-1} \qquad \rightarrow \qquad \left|\mathbf{B}\right|_{kj} = b_{kj} = \frac{r_{kj}}{x_j} \tag{2.21}$$

Exploiting definitions given by eq. (2.13), (2.19), and (2.20), system (2.18) can be written in a more compact matrix form as follows:

$$\hat{\mathbf{x}} \cdot \mathbf{c} = \mathbf{Z}^T \cdot \mathbf{c} + \mathbf{R}^T \tag{2.22}$$

Recalling eq. (2.14) and (2.21), balance (2.22) can be written as:

$$\hat{\mathbf{x}} \cdot \mathbf{c} = \hat{\mathbf{x}} \cdot \mathbf{A}^T \cdot \mathbf{c} + \hat{\mathbf{x}} \cdot \mathbf{B}^T \qquad \rightarrow \qquad \mathbf{c} = \mathbf{A}^T \cdot \mathbf{c} + \mathbf{B}^T \tag{2.23}$$

Solving for the unit cost vector leads to the matrix formulation of the *Leontief Cost Model* (LCM) for the case of complex productive processes:

$$\mathbf{c} = \left(\mathbf{I} - \mathbf{A}^T\right)^{-1} \cdot \mathbf{B}^T \tag{2.24}$$

Recalling definition (2.16), unit and total costs of final demand can be determined as follows:

$$\mathbf{c} = \mathbf{L}^T \cdot \mathbf{B}^T = \left(\mathbf{B} \cdot \mathbf{L}\right)^T \qquad \rightarrow \qquad \mathbf{C} = \hat{\mathbf{f}} \cdot \mathbf{c} \tag{2.25}$$

A final check could be performed to assess the correctness of this procedure. For each k-th resource, since cost is conservative, the sum of the resources fueled to the system must equal the sum of the costs of final demand, and the following relation must be true.

$$\mathbf{R} \cdot \mathbf{1}_{n\times 1} = \left(\mathbf{1}_{1\times n} \cdot \mathbf{C}\right)^T \tag{2.26}$$

The LCM hence results a universal cost accounting method, used in Economics to assess the costs of the final demand of complex systems in terms of the specified exogenous resources that are fueled to it. Physical interconnection between the components of the system constitute the allocation pattern, while different definitions of the exogenous resource vector allows for different types of cost assessments/impact analyses [24] (inputs consumption, emissions, land/water/labor requirements, etc.).

2.2.3 Meaning of the Leontief Inverse coefficients

Eq. (2.15) is representative of a system of n linear equations with the following structure:

$$\begin{cases} x_1 = \mathbf{l}_{11} w_1 + \ldots + \mathbf{l}_{1n} w_n \\ \vdots \\ x_n = \mathbf{l}_{n1} w_1 + \ldots + \mathbf{l}_{nn} w_n \end{cases} \tag{2.27}$$

These equations explain how the Leontief coefficients l_{ij} represent the share of contribution of the *j*-th final demand in the total production of the *i*-th component; that is, the amount of production that the *i*-th component has to produce for each unit of final demand delivered by the *j*-th component. For this reason, these coefficients are claimed to account for the real, entire production, both *direct* (direct production of final demand) and *indirect* (intermediate production that is fueled to other components concurring in meeting the final demand).

Further details about the significance of the Leontief inverse coefficients in Input–Output Analysis can be retrieved in literature [25].

Technical coefficient a_i represents the amount of production that the process has to fulfill for self-consumption in order to deliver one unit of final demand. Production of the exceeding amount a_i requires an additional production in the amount of $a_i \cdot a_i = a_i^2$, and so on indefinitely. This process is represented by the production scheme reported in Figure 2.4.

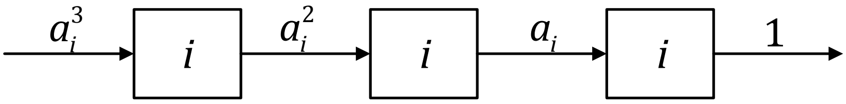


Figure 2.4. Meaning of the Leontief Inverse Coefficients.

The total requirements to deliver one unit of final demand through this infinite loop can be evaluated with the *power series approximation*:

$$l_i = \underbrace{1}_{direct} + \underbrace{a_i + a_i^2 + a_i^3 + \ldots}_{indirect} = \sum_{t=0}^{+\infty} a_i^t = \left(1 - a_i\right)^{-1} \tag{2.28}$$

Conversely, condition (2.28) is not necessary for extra-diagonal elements, since different physical units could eventually be involved in different rows of the Transaction matrix, and still the system could result economically productive.
Eq. (2.28) can be extended to the generic case of n interconnected processes considering the technological coefficients matrix $\mathbf{A}(n \times n)$:

$$\mathbf{L} = 1 + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots = \sum_{t=0}^{+\infty} \mathbf{A}^t = \left(\mathbf{I} - \mathbf{A}\right)^{-1} \tag{2.29}$$

If the order of the system is *large* and the technical coefficients matrix is *dense*, eq. (2.29) provides an approximate method to bypass the process of matrix inversion, which would otherwise result numerically demanding.

2.3 Thermoeconomic Input–Output Analysis

In this section, standard Thermoeconomic Analysis is presented and formalized with an Input–Output formulation. Specifically, procedures to assess *exergy costs* and *exergoeconomic costs* are detailed.
Input–Output Analysis requires all the components of the system to produce a positive final demand, thus computing the cost also of residues out of dissipative components. Taking these costs as the genuine costs of final demand would be misleading, because economic practice requires all the production costs to be allocated to the useful products. For this reason, standard formulation of TIOA has been enhanced by Valero and colleagues [17] to take the issue of reallocation in proper consideration, and this approach is included in this chapter.

2.3.1 Resource–Product representation

A generic energy system can be represented as a set of sub-systems (*components*) linked to each other and to the environment by material and/or non-material flows (mass, energy, entropy, exergy, etc.). This "energetic" arrangement does not always resemble the physical structure of the system; instead, it is a representation of its "economic purpose". This distinction has been formalized by Tsatsaronis [26] with the introduction of the *Fuel-Product-Loss* (FPL) *criterion*. In this work, according to Querol et al. [27], the term *Fuel* is replaced with *Resource*, in order to avoid the sense of limitation to power-generation technologies and keep a more general formulation. Moreover, *Loss*, which include physical wastes and residues outflows to the environment, is accounted together with the strictly thermodynamic inefficiencies in the value of *Exergy destruction*.
Hereinafter, this classification is referred to as *Resource–Product* (RP).

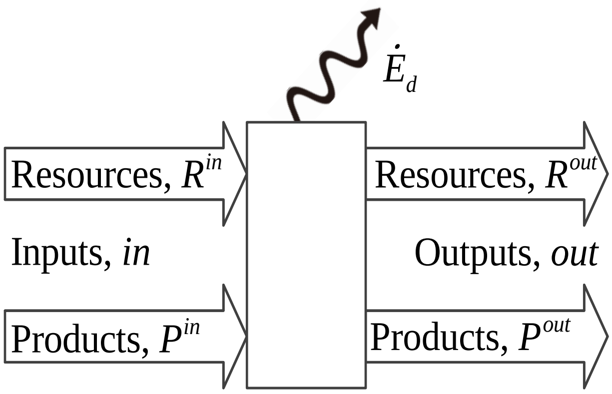


Figure 2.5. Resource–Product representation of a generic component.

When the economic purpose of a generic component (Figure 2.5) is considered, the following definitions can be expressed, according to [27].

- *Resource* is defined as the net exergy balance between inlet and outlet flows classified as resources:

$$\dot{R} = \sum_{input} \dot{E}_R^{in} - \sum_{output} \dot{E}_R^{out} \tag{2.30}$$

- *Product* is defined as the net exergy balance between outlet and inlet streams classified as products:

$$\dot{P} = \sum_{output} \dot{E}_P^{out} - \sum_{input} \dot{E}_P^{in} \tag{2.31}$$

- *Exergy destruction* is defined as the net balance between resource and product. This terms includes both physical losses and thermodynamic inefficiencies:

$$\dot{R} = \dot{P} + \dot{E}_d \quad \Leftrightarrow \quad \dot{R} - \dot{P} = \dot{E}_d \tag{2.32}$$

- *Efficiency*, from the perspective of the Second Law of Thermodynamics, is the ability of a given component to transfer exergy from resources to products:

$$\eta = \frac{\dot{P}}{\dot{R}} \tag{2.33}$$

- *Unit exergy consumption* is defined as the inverse of efficiency, and indicates the amount of exergy needed to produce one exergy unit of useful product:

$$k = \frac{1}{\eta} = \frac{\dot{R}}{\dot{P}} \tag{2.34}$$

Components within the same energy system can be classified in accordance to their economic purpose as follows:

- *Productive* components, designed to generate a useful product;
- *Dissipative* components, which do not generate any final product, but are responsible for disposing of the residues originated by production processes (condensers, filters, SCRs, stacks, etc.).

For each of them, an RP classification can be devised as in Table 2.1.

Table 2.1. Resource–Product representation of a generic component.

	Component	Resource	Product	Exergy Destruction	Efficiency
Productive	...				
	i	$\dot{R}_i$	$\dot{P}_i$	$\dot{E}_d = \dot{R}_i - \dot{P}_i$	$\eta_i = \frac{\dot{P}_i}{\dot{R}_i}$
Dissipative	...				

As it arises from Figure 2.5, inlet and outlet flows can be simultaneously part of both the resource and the product of the same component. The heat exchanger from Figure 2.6 provides a simple yet clear example to understand this distinction. Physical description suggests that flows 1 and 3 are the inputs, while flows 2 and 4 are the outputs. However, the purpose of this component is to transfer heat from the hot stream (e.g. 1-2) to the cold stream (e.g. 3-4); with this approach, the change of state from 1 to 2 (cooling) is the *resource*, while the opposite change of state from 3 to 4 (heating) is the *product* of the heat exchanger (assuming that operation temperatures are higher than that of the environment).

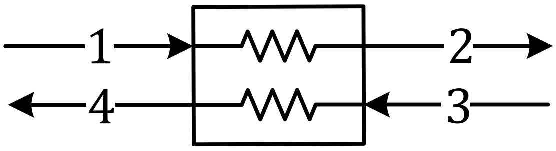


Figure 2.6. Sketch of a generic counter-flow heat exchanger.

2.3.2 Exergy Cost Analysis

Let a generic system be composed of n_P productive components $\mathbb{P} = \{1, \dots, n_P\}$ and n_D dissipative components $\mathbb{D} = \{n_P + 1, \dots, n_P + n_D\}$, with $n_P + n_D = n$. Total production of i-th component can be determined as the sum of the exergy exchanges towards other components and the environment:

$$\dot{P}_i = \sum_{j=1}^{n} \dot{E}_{ij} + \dot{E}_{i0} \tag{2.35}$$

Each term $\dot{E}_{ij}$ represents the amount of exergy produced by the i-th component and fueled as a resource to the j-th component within a defined time frame (usually one second). Similarly, total resource includes contributions from other equipment, as well as direct resources fueled from the environment; therefore, it can be expressed as in eq. (2.36).

$$\dot{R}_i = \dot{E}_{0i} + \sum_{j=1}^{n} \dot{E}_{ji} \tag{2.36}$$

Dividing by the component's total product yields an expression for the unit exergy consumption:

$$\frac{\dot{R}_i}{\dot{P}_i} = \frac{\dot{E}_{0i}}{\dot{P}_i} + \sum_{j=1}^{n} \frac{\dot{E}_{ji}}{\dot{P}_i} \qquad \rightarrow \qquad k_i = \kappa_{0i} + \sum_{j=1}^{n} \kappa_{ji} \tag{2.37}$$

Elements κ_{ij} in eq. (2.37) represent the amount of exergy from the i-th component, needed to produce one exergy unit in the j-th component.

Substituting eq. (2.37), eq. (2.35) can be rewritten as follows:

$$\dot{P}_i = \sum_{j=1}^{n}\left(\kappa_{ij}\dot{P}_i\right) + \dot{E}_{i0} \tag{2.38}$$

This procedure results in system of n linear equation with n variables, which can be easily managed with a matrix formulation.
Exergy inter-exchanges among all the system components are collected in the *Transaction Matrix* $\mathbf{Z}(n \times n)$:

$$\mathbf{Z} = \left|\dot{E}_{ij}\right| \qquad i,j \in \mathbb{P} \cup \mathbb{D} \tag{2.39}$$

The amount of exergy provided to the environment from productive component and dissipative components is respectively collected in the *Final Demand vector* $\mathbf{f}(n_P \times 1)$ and in the *Residue vector* $\mathbf{g}(n_D \times 1)$: these vectors define the *Output vector* $\mathbf{w}(n \times 1)$ according to eq. (2.40).

$$\mathbf{w} = \begin{vmatrix}\mathbf{f}\\ \mathbf{g}\end{vmatrix} \quad \rightarrow \quad \begin{cases}\mathbf{f} = \left|\dot{E}_{i0}\right| & i \in \mathbb{P}\\ \mathbf{g} = \left|\dot{E}_{i0}\right| & i \in \mathbb{D}\end{cases} \tag{2.40}$$

The *Production vector* $\mathbf{x}(n \times 1)$ collects the product of each component:

$$\mathbf{x} = \left|\dot{P}_i\right| \qquad i \in \mathbb{P} \cup \mathbb{D} \tag{2.41}$$

The balance from eq. (2.35) can be expressed in matrix notation as follows:

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{1}_{n\times 1} + \mathbf{w} \tag{2.42}$$

where $\mathbf{1}_{n\times 1}$ represents a column vector with every component equal to one.
The *Technical Coefficients matrix* $\mathbf{A}(n \times n)$ can be defined as follows[3]:

$$\mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1} \qquad \rightarrow \qquad \left|\mathbf{A}\right|_{ij} = \frac{\left|\mathbf{Z}\right|_{ij}}{\left|\mathbf{x}\right|_j} = \frac{\dot{E}_{ij}}{\dot{P}_j} = \kappa_{ij} \tag{2.43}$$

[3] The *caret* grapheme ^ above a vector represents the diagonal matrix whose main diagonal elements are the elements of that vector, while all the extra-diagonal elements are null:

$$\mathbf{A} = \left|a_i\right| \quad \rightarrow \quad \hat{\mathbf{A}} = \left|a_{ii}\right|$$

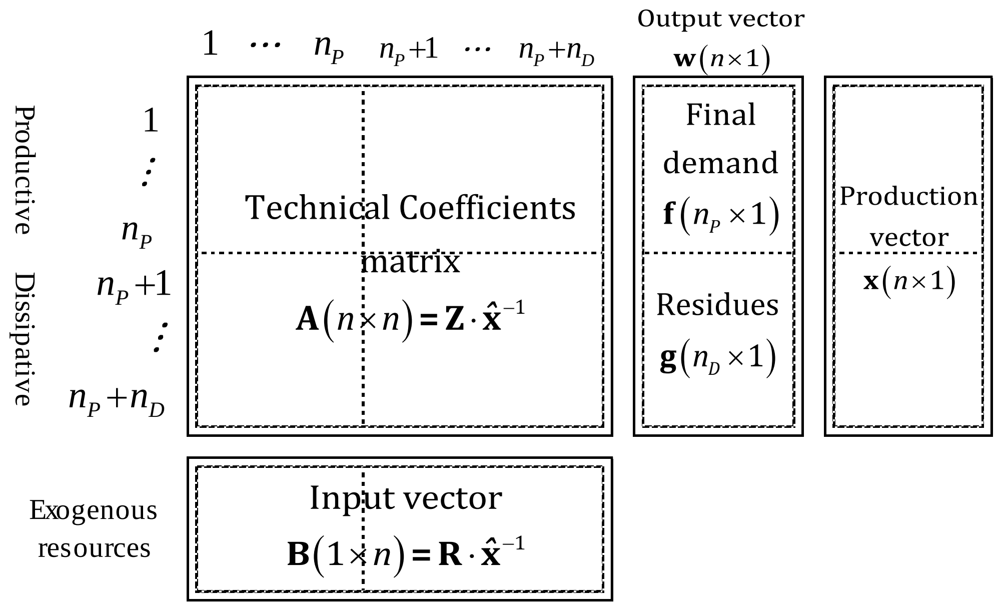


Figure 2.7. Layout of the Input-Output model matrix formulation.

Eq. (2.38) can be expressed in matrix notation as:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{w} \tag{2.44}$$

Solving for $\mathbf{x}$, matrix $\mathbf{I}$ being the identity matrix with appropriate dimension:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{w} \tag{2.45}$$

The *Leontief's inverse matrix* $\mathbf{L}(n \times n)$ can be defined as:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{2.46}$$

so that eq. (2.45) can be rewritten in a more compact form:

$$\mathbf{x} = \mathbf{L} \cdot \mathbf{w} \tag{2.47}$$

For the i-th productive component, the cost balance from eq. (2.2) can be written as follows:

$$C_{P,i} = C_{R,i} + C_{W,i} \qquad i \in \mathbb{P} \tag{2.48}$$

Applying eq. (2.1) and (2.2) to eq. (2.36), cost of resource can be expressed as:

$$C_{R,i} = C_{0i} + \sum_{j=1}^{n} C_{ij} = \dot{E}_{0i} + \sum_{j=1}^{n} \left(c_i \dot{E}_{ij} \right) \qquad i \in \mathbb{P} \tag{2.49}$$

Residues dissipation expenditures are computed as a sum over the entire set of dissipative components:

$$C_{W,i} = \sum_{j \in \mathbb{D}} C_{W,ij} \qquad i \in \mathbb{P} \tag{2.50}$$

so that each term $C_{W,ij}$ represents the cost of residues originated in the i-th productive component and dismissed in the j-th dissipative component. These terms can be considered proportional to the product of the corresponding dissipative component:

$$C_{W,ij} = \psi_{ji} \cdot C_{P,j} \qquad j \in \mathbb{D} \tag{2.51}$$

Hence, each *residues cost distribution ratio* ψ_{ij} denotes the share of the cost of the j-th dissipative component's output arising from residues originated in the i-th productive component. Since cost is conservative, for each dissipative component, the sum of the residues costs deriving from all the productive components must be equal to its own product cost, and eq. (2.52) must be satisfied.

$$\sum_{i \in \mathbb{P}} C_{W,ij} = C_{P,j} \qquad j \in \mathbb{D} \tag{2.52}$$

From eq. (2.51) and (2.52), it can be demonstrated that coefficients ψ_{ij} must show the following feature:

$$\sum_{i \in \mathbb{P}} \psi_{ji} = 1 \qquad j \in \mathbb{D} \tag{2.53}$$

Different arbitrary definitions of the residues cost distribution ratios have been proposed, showing coherent eligibility and featuring the property presented in eq. (2.53), but so far it has not yet been identified a universal one, which applies perfectly to every type of energy system. Four different definitions are proposed in [17], which base the allocation pattern on either:

a) the exergy of the flow processed in the dissipative component;
b) the cost of the residue dissipated in the dissipative component;
c) the cost of exergy destroyed in the dissipative component;
d) the amount of external resources embodied in the residue.

The simplest from list above is option *a*, which considers these ratios directly proportional to the resource fueled to the corresponding dissipative component, as formulated by eq. (2.54).

$$\psi_{ji} = \frac{\dot{E}_{ij}}{\dot{R}_j} \qquad \begin{matrix} i \in \mathbb{P} \\ j \in \mathbb{D} \end{matrix} \tag{2.54}$$

To better understand the theoretical principle underlying in eq. (2.54), let the example depicted in Figure 2.8 be considered.

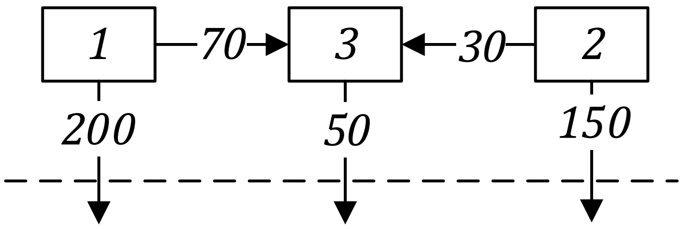


Figure 2.8. Numeric example of residues cost reallocation.

Final demand is manufactured by productive components *1* and *2*, with a total (*non-reallocated*, or *original*) cost of $200kJ$ and $150kJ$, respectively. At the same time, they fuel $70kJ$ and $30kJ$ to dissipative component *3* as residues to be disposed of. Hence, the total cost of dissipation, $50kJ$, has to be reallocated to the product of *1* and *2*. Reallocation is accomplished in proportion to the contribution of components *1* and *2* in providing exergy to component *3*: this means that the term of $50kJ$ is assigned 70% ($35kJ$) to *1* and 30% ($15kJ$) to *2*. Therefore, the cost of final demand is correspondingly increased: from 200 to $235kJ$ for final demand *1*, and from 150 to $165kJ$ for final demand *2*.

This is not the only nor the best possible definition, but carries a relevant advantage: it can be straightforwardly devised from the Resource–Product Table previously defined. For this reason, (2.54) is the definition adopted in the present work.

A possible and frequently selected alternative is the allocation based on the amount of *entropy* generated along the process. The main drawback of this method is that, although it works conveniently for closed cycles, it fails when applied to open cycles.

Applying eq. (2.49), (2.50), (2.51) and (2.54), cost balance (2.48) becomes:

$$c_i \dot{P}_i = C_{0i} + \sum_{j \in \mathbb{P}} C_{ji} + \sum_{j \in D} \left(\psi_{ji} C_{P,j} \right) \tag{2.55}$$

Dividing by $\dot{P}_i$ and applying eq. (2.37), eq. (2.55) can be written as:

$$c_i = \kappa_{0i} + \sum_{j \in \mathbb{P}} \left(c_j \cdot \kappa_{ji} \right) + \sum_{j \in \mathbb{D}} \left(\psi_{ji} \cdot c_j \cdot \frac{\dot{P}_j}{\dot{P}_i} \right) \tag{2.56}$$

The following definition can be introduced:

$$\rho_{ji} = \begin{cases} 0 & j \in \mathbb{P} \\ \psi_{ji} \dfrac{\dot{P}_j}{\dot{P}_i} & j \in \mathbb{D} \end{cases} \tag{2.57}$$

From eq. (2.53), the following is demonstrated:

$$\sum_{i \in \mathbb{P}} \left(\rho_{ji} \cdot \dot{P}_i \right) = \sum_{i \in \mathbb{P}} \left(\psi_{ji} \cdot \dot{P}_j \right) = \sum_{i \in \mathbb{P}} \left(\frac{\dot{E}_{ij}}{\dot{R}_j} \dot{P}_j \right) = \frac{\dot{P}_j}{\dot{R}_j} \underbrace{\sum_{i \in \mathbb{P}} \dot{E}_{ij}}_{\dot{R}_j} = \dot{P}_j \qquad j \in \mathbb{D} \tag{2.58}$$

Therefore, each term ρ_{ji}, called *residues production coefficient*, represents the fraction of the total production of the *i*-th productive component which becomes residue dissipated in the *j*-th dissipative component.
Substituting eq. (2.57), eq. (2.56) becomes:

$$c_i = \kappa_{0i} + \sum_{j=1}^{n} \left(c_j \cdot \kappa_{ji} \right) + \sum_{j \in \mathbb{D}} \left(\rho_{ji} \cdot c_j \right) \tag{2.59}$$

Since, by definition, dissipative components show no interactions towards productive ones, eq. (2.60) holds.

$$\kappa_{ji} = 0 \qquad \begin{matrix} i \in \mathbb{P} \\ j \in \mathbb{D} \end{matrix} \tag{2.60}$$

As a consequence, eq. (2.59) can be written in a more compact form:

$$c_i = \kappa_{0i} + \sum_{j=1}^{n} \left[c_j \left(\kappa_{ji} + \rho_{ji} \right) \right] \tag{2.61}$$

In analogy with eq. (2.38), eq. (2.61) is representative of a system of n linear equation, whose solution can be nimbly determined with a matrix formulation.

An appropriate *Resources vector* $\mathbf{R}(1 \times n)$ can be defined to collect the amount of exergy directly fueled to each component from the environment:

$$\mathbf{R} = \left| \dot{E}_{0i} \right| \tag{2.62}$$

In analogy with eq. (2.43), the *Input vector* $\mathbf{B}(1 \times n)$ can be defined so that its elements represent the unit consumption of external resources characterizing the i-th component, as follows:

$$\mathbf{B} = \mathbf{R} \cdot \hat{\mathbf{x}}^{-1} \qquad \rightarrow \qquad \left|\mathbf{B}\right|_i = \frac{\left|\mathbf{R}\right|_i}{\left|\mathbf{x}\right|_i} = \frac{\dot{E}_{0i}}{\dot{P}_i} = \kappa_{0i} \tag{2.63}$$

The *Residues Production matrix* $\mathbf{W}(n \times n)$ can be defined to collect in matrix form, as shown in Figure 2.9, the residues production coefficients ρ_{ji} defined by eq. (2.57):

$$\mathbf{W} = \left| \rho_{ji} \right| \tag{2.64}$$

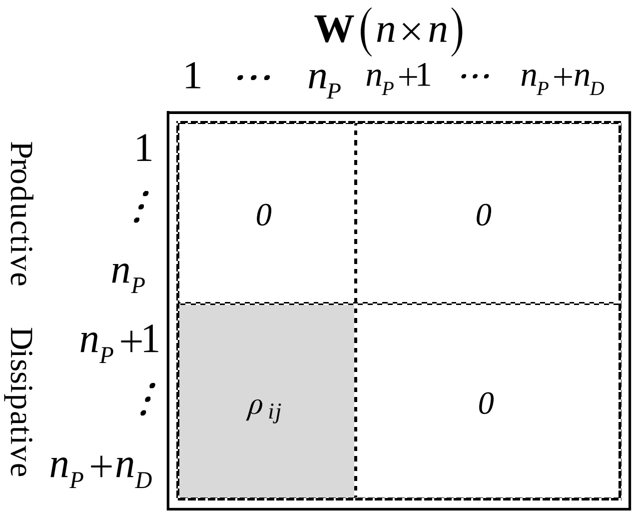


Figure 2.9. Layout of the Residues Coefficients matrix defined in eq. (2.64).

The *Unit Costs vector* $\mathbf{c}(n \times 1)$ can be defined to collect the unit exergy costs of each component of the system:

$$\mathbf{c} = \left| c_i \right| \qquad i = 1, \ldots, n \tag{2.65}$$

Eq. (2.61) can be expressed in compact matrix form as follows:

$$\mathbf{c} = \mathbf{B}^T + \left(\mathbf{A}^T + \mathbf{W}^T \right) \cdot \mathbf{c} \tag{2.66}$$

which can be solved for the unit cost vector:

$$\mathbf{c} = \mathbf{B}^T \cdot \left(\mathbf{I} - \mathbf{A}^T - \mathbf{W}^T\right)^{-1} \tag{2.67}$$

Introducing the *Modified Leontief Inverse matrix* $\mathbf{L_R}(\mathrm{n} \times \mathrm{n})$:

$$\mathbf{L_R} = \left(\mathbf{I} - \mathbf{A} - \mathbf{W}\right)^{-1} \tag{2.68}$$

Eq. (2.67) assumes the form[4] known as the *Leontief Cost Model* (LCM):

$$\mathbf{c} = \mathbf{L_R}^T \cdot \mathbf{B}^T = \left(\mathbf{B} \cdot \mathbf{L_R}\right)^T \tag{2.69}$$

The unit exergy costs computed by means of eq. (2.69) represent the marginal costs of the products delivered as final demand. Terms referring to dissipative components have no practical meaning, since costs of their products have been reallocated to the productive components responsible for residues generation. Denoting with $\mathbf{c}_{n_P}$ the restriction of the unit cost vector $\mathbf{c}$ to the first n_P (productive) components, total costs of final products can be determined as:

$$\mathbf{C} = \left|c_i \cdot \mathbf{f}_i\right| = \hat{\mathbf{f}} \cdot \mathbf{c}_{n_P} \qquad i \in \mathbb{P} \tag{2.70}$$

The remaining n_D terms of the unit cost vector represent the unit costs of the product of dissipative components, having no practical meaning, since they have already been reallocated to productive components.
As stated by eq. (2.26), the sum of the costs of exogenous resources fueling the system must equal the sum of the costs of final demand, and the following relation must be true:

$$\mathbf{R} \cdot 1_{n \times 1} = 1_{1 \times n_P} \cdot \mathbf{C} \tag{2.71}$$

2.3.3 Exergoeconomic Cost Analysis

Economic Life Cycle Assessment is a well-established and standardized procedure to evaluate the total expenditures borne to construct, operate, and dismantle a generic energy system [28]. These expenditures can be interpreted as a resource fueling the system in order to fulfill its productive purpose. In this light, a monetary resource vector can be defined, and the same

[4] Since matrix $\mathbf{I}$ is symmetric, the following is demonstrated:

$$\left(\mathbf{I} - \mathbf{A}^T - \mathbf{W}^T\right)^{-1} = \left(\mathbf{I}^T - \mathbf{A}^T - \mathbf{W}^T\right)^{-1} = \left[\left(\mathbf{I} - \mathbf{A} - \mathbf{W}\right)^T\right]^{-1} = \left[\left(\mathbf{I} - \mathbf{A} - \mathbf{W}\right)^{-1}\right]^T = \mathbf{L_R}^T$$

cost accounting procedure explained in previous paragraphs can be performed [9]. Result of this operation will be a vector of monetary costs per unit of final demand, named *Exergoeconomic costs*.

Likewise the definition of exergy costs given by eq. (2.2), an *exergoeconomic cost* $\dot{\Pi}_j$ can be assigned to each stream in the system, representing that cost, in terms of monetary units per unit of time, required to produce that stream. Therefore, the *unit exergoeconomic cost* expresses the amount of monetary resources needed to produce one exergy unit of the considered stream:

$$\pi_j = \frac{\dot{\Pi}_j}{\dot{E}_j} \tag{2.72}$$

Considering the RP classification depicted in paragraph 2.3.1, the unit exergoeconomic costs of resource and products can be defined:

$$\pi_i = \frac{\dot{\Pi}_{P,i}}{\dot{P}_i} \qquad \pi_{R,i} = \frac{\dot{\Pi}_{R,i}}{\dot{R}_i} \qquad i = 1,\ldots,n \tag{2.73}$$

Denoting with $\dot{Z}_i$ the terms, in monetary units per unit of time, accounting for capital investment and depreciation, as well as operating and maintenance expenses, an exergoeconomic balance can be expressed for every component:

$$\dot{\Pi}_{P,i} = \dot{\Pi}_{R,i} + \dot{Z}_i \qquad i = 1,\ldots,n \tag{2.74}$$

Substituting eq. (2.34) and (2.73) in (2.74), the balance becomes:

$$\pi_i \cdot \dot{P}_i = \pi_{R,i} \cdot \dot{R}_i + \dot{Z}_i = \pi_{R,i} \cdot \kappa_i \cdot \dot{P}_i + \dot{Z}_i \tag{2.75}$$

Dividing by the component's total product, the resultant unit balance is:

$$\pi_i = \pi_{R,i} \cdot \kappa_i + \frac{\dot{Z}_i}{\dot{P}_i} \tag{2.76}$$

The Leontief Cost Model presented in paragraph 2.3.2 can be applied to the *Monetary Resources vector* $\mathbf{R}_m(1 \times n)$, whose compilation is described in paragraph 2.3.3.1 below:

$$\mathbf{R_m} = \left|\dot{Z}_i\right| \qquad i = 1,\ldots,n \tag{2.77}$$

leading to the following computation of the *unit exergoeconomic costs*:

$$\boldsymbol{\pi} = \left(\mathbf{I} - \mathbf{A}^T - \mathbf{W}_\mathbf{R}^T\right)^{-1} \cdot \mathbf{B}_\mathbf{m}^T = \mathbf{L}_\mathbf{R}^T \cdot \mathbf{B}_\mathbf{m}^T = \left(\mathbf{B}_\mathbf{m} \cdot \mathbf{L}_\mathbf{R}\right)^T \tag{2.78}$$

Denoting with $\boldsymbol{\pi}_{n_p}$ the restriction of the unit exergoeconomic cost vector $\boldsymbol{\pi}$ to the first n_p (productive) components, total exergoeconomic cost of the final demand can be computed as:

$$\boldsymbol{\Pi} = \left|\pi_i \cdot f_i\right| = \hat{\mathbf{f}} \cdot \boldsymbol{\pi}_{n_p} \qquad i \in \mathbb{P} \tag{2.79}$$

Also in this case, unit costs of the product of dissipative components have no practical meaning, because they have already been reallocated to the product of productive components.

2.3.3.1 Monetary Resource vector build-up

A traditional economic analysis is usually accomplished when a project is being designed. Independently on the exact procedure followed, this investigation allows the identification of the following two main terms:

- *Investment cost*, usually known as Total Capital Investment (TCI). In order to determine the flow per unit of time, an equivalent annualized cost A_{eq} has to be outlined through the *capital recovery factor* f_I, as described in [27] and shown in eq. (2.80).

  $$f_I = \frac{m\left(1+m\right)^{LT}}{\left(1+m\right)^{LT}-1} \tag{2.80}$$

  where m is the *unit cost of capital* and LT is the prospected *lifetime* of the project in years. Therefore, the equivalent annualized investment cost results:

  $$A_{eq}\left[\frac{€}{year}\right] = f_I \cdot TCI \tag{2.81}$$

- *Variable costs*, comprising unavoidable annual costs that are independent on the production rate. Usually this term is referred to with the name *Operation and Maintenance* (O&M), although other types of cost can be included. When the annual variable cost VC is known, the *variable cost factor* f_V can be defined as:

$$f_V = \frac{VC}{TCI} \tag{2.82}$$

The sum of the annual *investment* and *variable* costs gives the *total annual fixed cost* (FC), which can be determined as follows:

$$FC\left[\tfrac{€}{year}\right] = A_{eq} + VC = TCI \cdot \left(f_I + f_V\right) \tag{2.83}$$

This total cost is then distributed to each component with a suitable proportional basis. Common practice suggests to adopt the share of the component in the total *Purchased Equipment Cost* (PEC), which is usually the most significant part of the TCI:

$$p_i = \frac{PEC_i}{PEC} \tag{2.84}$$

and hence the *fixed cost flow* can be determined for each component:

$$\dot{Z}_i^F\left[\tfrac{€}{year}\right] = p_i \cdot FC \tag{2.85}$$

Denoting by $\dot{Z}_i^V$ the amount of operating costs per unit of time directly absorbed by each component from the environment (comprising, for instance, raw materials, fuels, reagents, and utilities), the monetary resources fueled to each component will result as the sum of the fixed cost flow and the variable operating costs:

$$\dot{Z}_i = \dot{Z}_i^F + \dot{Z}_i^V \qquad \rightarrow \qquad \left|\mathbf{R}_m\right|_i = \dot{Z}_i \tag{2.86}$$

Obviously, the same analysis could be restricted to a different timeframe; a common alternative is to set the time unit to one second, in order to directly couple these definition with the thermodynamic output in power units. In this case, computation of monetary cost vector is performed according to the procedure presented above, the only difference being the conversion of eq. (2.87) from units of year to units of second, knowing the *Full-Time equivalent hours* $H_{eq}[h/year]$. This parameter indicates the amount of hours that the power plant is required to operate at nominal power in order to produce the same amount of useful product it actually produces during one year, and is usually known or prospected.

$$FC\left[\frac{€}{s}\right]=\frac{FC\left[\frac{€}{year}\right]}{3600\left[\frac{s}{h}\right]\cdot H_{eq}\left[\frac{h}{year}\right]} \tag{2.87}$$

2.3.4 Design Evaluation and Optimization

Literature regarding optimization of energy systems is very large; several mathematical tools and procedures have been proposed [29–34]. In general, two models have to be defined for the system to be optimized: a *thermodynamic model* and an *economic model*. In theory, proper coupling of these abstracted representations of the system should allow to simulate how economic costs are affected by a change in the value of the main thermodynamic parameters. However, thermodynamic models are usually more reliable and easier to define than economic ones; detailed and flexible information about cost terms are in general uncertain and/or difficult to obtain in the required shape [35]. Moreover, traditional mathematical methods become unstable and ineffective to practical use when the system to be analyzed is made up by a large set of components, particularly in case of non-linear and/or non-explicit relations among the variables [35].

Thermoeconomics provides excellent and effective techniques for the Design Evaluation and Optimization of energy systems, no matter how complex and interconnected they are. Useful information about the performance of a single component or of the energy system as a whole, and about possibilities for further improvements, can be devised from the Exergoeconomic Cost Analysis. Traditional economic standpoint commit engineering optimization procedures to focus on the minimization of the economic cost. Nonetheless, improvements in economic performance are guided by thermodynamic enhancements, which, in turn, are motivated on a thermoeconomic basis.

2.3.4.1 Exergy Cost Analysis

When the Exergy Cost Analysis is considered, components are arranged in decreasing order of ***Exergy cost of exergy destruction***, defined by eq. (2.88).

$$C_{d,i}=c_i\cdot\dot{E}_{d,i} \qquad \rightarrow \qquad \mathbf{C_d}=\hat{\mathbf{E}}_\mathbf{d}\cdot\mathbf{c} \tag{2.88}$$

In common practice, exergy destruction is evaluated as an additional amount of resource required to pursuit the given output; therefore, it is usually evaluated at the unit cost of the resource. Nevertheless, in this work, a WtE power plant is considered, whose design is commonly Fuel-Driven, so that exergy destruction can be seen as a reduction in output. For this reason, definition (2.88) is based on the exergy cost of the product. Components with higher values are indicated as those with the most important impact in increasing inefficiencies in the system, and therefore those on which top priority efforts should be addressed to increase exergy efficiency.

Components having major upgrade potential are characterized by a high value of the ***Relative Cost Difference***, expressed as the unit exergy cost increase across such component, relative to the unit exergy cost of its resource[5], as stated by eq. (2.89).

$$r_i = \frac{c_i - c_{R,i}}{c_{R,i}} = \frac{1-\eta_i}{\eta_i} \tag{2.89}$$

Therefore, optimization processes should focus on components with the highest values of C_d, giving priority to those showing a concurrently important value of r.

2.3.4.2 Exergoeconomic Cost Analysis

When the Exergoeconomic Cost Analysis is taken in consideration, the exergy balance stated by eq. (2.32) can be substituted in the thermoeconomic balance expressed by eq. (2.76), resulting in:

$$\pi_i = \frac{\pi_{R,i}\left(\dot{P}_i + \dot{E}_{d,i}\right) + \dot{Z}_i}{\dot{P}_i} = \pi_{R,i} + \frac{\pi_{R,i} \cdot \dot{E}_{d,i}}{\dot{P}_i} + \frac{\dot{Z}_i}{\dot{P}_i} \tag{2.90}$$

Previous equation shows how the unit cost of product is given by the unit cost of resource increased by exergy destruction (thermodynamic effect) and monetary costs (economic effect). To refer to this cost rise occurring in the *i*-th component, the ***Relative Cost Increase*** can be defined as:

$$\gamma_i = \frac{\pi_i - \pi_{R,i}}{\pi_{R,i}} = \frac{\dot{E}_{d,i}}{\dot{P}_i} + \frac{\dot{Z}_i}{\pi_{R,i} \cdot \dot{P}_i} \tag{2.91}$$

[5] From eq. (2.2) and (2.33), unit cost of resource can be determined as follows:

$$C_P = C_R \quad \rightarrow \quad c_i \cdot \dot{P} = c_{R,i} \cdot \dot{R} = c_{R,i} \cdot \frac{\dot{P}}{\eta_i} \quad \rightarrow \quad c_{R,i} = c_i \cdot \eta_i$$

which clearly depicts the combined effect of thermodynamic inefficiencies and economic expenses. Higher values reveal an important role of that component in increasing the unit cost of the product, hence suggesting that there exist possibilities for upgrades.

If aggregated quantities are used instead of unit ones, the thermoeconomic balance from eq. (2.75) can be rewritten as follows:

$$\dot{\Pi}_i = \pi_{R,i} \cdot \left(\dot{P}_i + \dot{E}_{d,i} \right) + \dot{Z}_i \tag{2.92}$$

If the Exergoeconomic cost of exergy destruction is defined as:

$$\dot{\Pi}_{d,i} = \pi_{R,i} \cdot \dot{E}_{d,i} \qquad \rightarrow \qquad \mathbf{\Pi_d} = \mathbf{\hat{E}_d} \cdot \boldsymbol{\pi}_R \tag{2.93}$$

the ***Absolute Cost Increase*** can be introduced as stated by eq. (2.94), representing the effective rise between the cost of the product and the cost it would have if it was valued at the cost of resources: once again, this increase is given by both thermodynamic and economic effects.

$$\Gamma_i = \dot{\Pi}_i - \pi_{R,i} \cdot \dot{P}_i = \dot{\Pi}_{d,i} + \dot{Z}_i \tag{2.94}$$

Components with the highest *absolute* cost increase should be the first ones to be subject to enhancements, focusing on those showing a concurrent high *relative* cost increase. This procedure points out those components with the most compelling need to be improved and the highest impact on the cost increase processes.

In different components, *thermodynamic* and *economic* contributions to cost increase may have different relevance; to weight this disparity, the ***Exergoeconomic Factor*** in eq. (2.95) can be introduced as the share of the economic effect:

$$\varphi_i = \frac{\dot{Z}_i}{\Gamma_i} = \frac{\dot{Z}_i}{\dot{\Pi}_{d,i} + \dot{Z}_i} \tag{2.95}$$

Thermoeconomic variables introduced with eq. (2.91), (2.94) and (2.95) provide guidance for an iterative optimization process: Once these main components are detected, the corresponding exergoeconomic factor is observed to identify the strategy to prefer.

- A high value of φ deceives an important economic effect, so it makes recommendable to reduce the monetary costs (e.g. with a simpler design) even if this procedure will affect exergy efficiency negatively;
- A low value of φ discloses the relevance of thermodynamic inefficiencies, so it would be advisable to aim for a more efficient design to reduce exergy destruction, although this will correspond to higher costs.

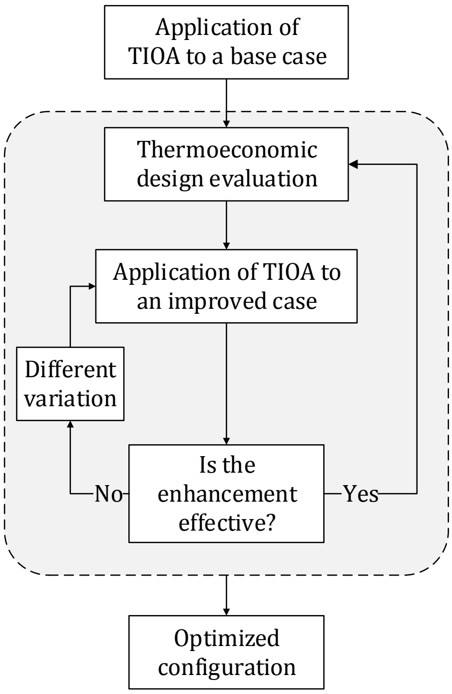


Figure 2.10. Outline of the iterative optimization routine.

An iterative procedure of this kind can be a powerful tool when performing a Design Evaluation and Optimization over an existing system configuration, with the purpose of detecting the most inefficient equipment and hence identifying the suggested strategies to enhance their performance. It must be remembered that, in economic practice, optimization involves the minimization of the production cost, which constitutes the objective function of the analysis; nonetheless, TIOA provides a set of indication that supports the analyst and lead the optimization process by suggesting where efforts should be focused in the attempt to obtain the most effective enhancements.

2.4 Example: Gas Turbine Cogeneration power plant

For didactical purpose, the simplified example of a Gas Turbine is here presented and analyzed with the procedure previously presented in this chapter. The aim is to provide a guided step-by-step application of standard Thermoeconomic Input–Output Analysis, in order to allow for an easier and deeper understanding of the theoretical basis and mathematical framework of this method, together with its advantages and drawbacks, in order to foster the subsequent extension to the hybrid approach.

Although the example tries to keep as close as possible to a real case, numeric values have only a didactical purpose and should not be taken as reliable representation of the considered technology.

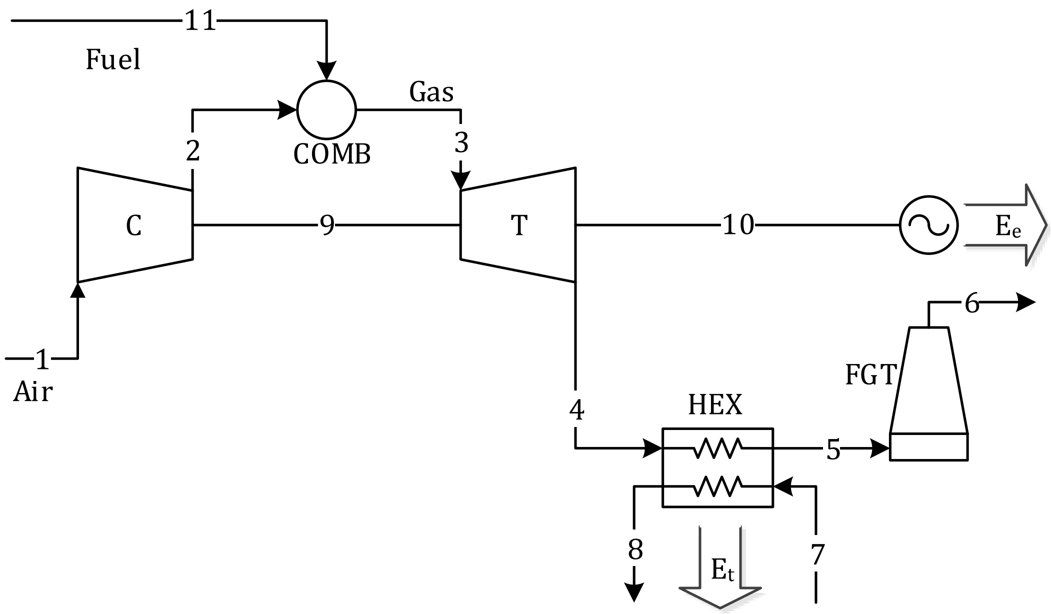


Figure 2.11. Simplified layout of a GT-Cog power plant.

This case is loosely based on the *tgas* example included in [36], but has been further elaborated to increase its didactical relevance. Figure 2.11 reports the simplified physical layout of the plant, highlighting its main components and material streams, while Table 2.2 summarizes values of their exergy flows.

Table 2.2. Exergy of the flows from Figure 2.11.

Flow	$\dot{E}\ [kW]$	Flow	$\dot{E}\ [kW]$
1	0	7	63
2	1984	8	1260
3	7756	9	2185
4	2331	10	1000
5	754	11	6605
6	523		

Natural Gas is the main fuel input, while Electric Energy and Heat constitute the useful products of the plant; a stream of Flue-Gases undergo a Treatment (FGT) process before being rejected into the environment as waste material. Table 2.3 reports the main input and output flows of the plant.

Table 2.3. Inputs and Outputs of the GT-Cog example.

Input	Stream	$\dot{E}\ [kW]$	Output	Stream	$\dot{E}\ [kW]$
Air	1	0	Electricity	10	1000
Fuel	11	6605	Heat	8-7	1197
			Flue-Gas	6	523

2.4.1 Resource–Product representation

Following the procedure described in paragraph 2.3.1, each component is classified according to the RP criterion. Assignment of Resource, Product and Exergy Destruction must adhere to the economic purpose of the component, as shown by Table 2.4. Among the five components, the Flue-Gas Treatment (FGT) section is the one designated to dissipate the residual exergy of the gas stream; therefore, it is the only dissipative component.

Table 2.4. RP classification of the GT-Cog example.

	Component	$\dot{R}$	$[kW]$	$\dot{P}$	$[kW]$	$\dot{E}_d\ [kW]$	η [%]
Productive	C	*9*	2185	*2-1*	1984	201	90,8
	Comb	*11*	6605	*3-2*	5772	833	87,4
	GT	*3-4*	5425	*9+10*	3185	2240	58,7
	HEX	*4-5*	1577	*8-7*	1197	380,2	75,9
Dissipative	FGT	*5*	754	*6*	523	230,8	69,4

2.4.2 Input–Output Analysis

Definition of the Transaction matrix requires to understand origin and destination of each component's resource and product. This task is accomplished with the aid of the RP diagrams of Figure 2.12 and Figure 2.13.

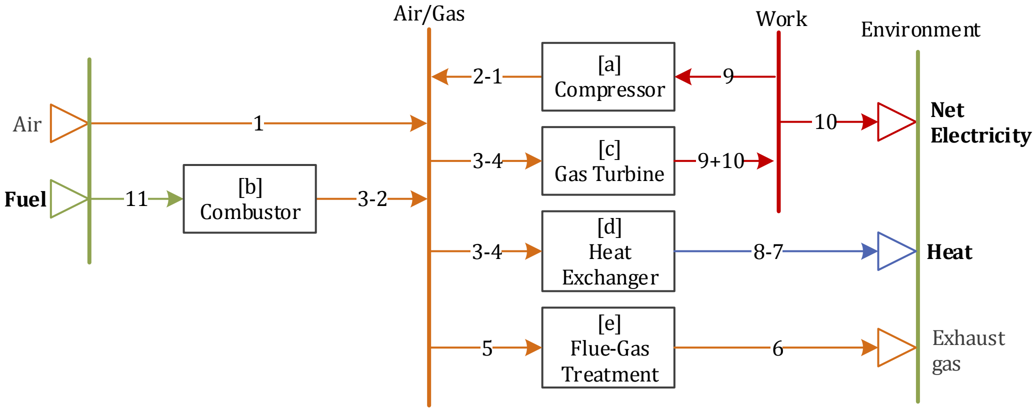


Figure 2.12. Rational Resource–Product diagram of the GT-Cog plant.

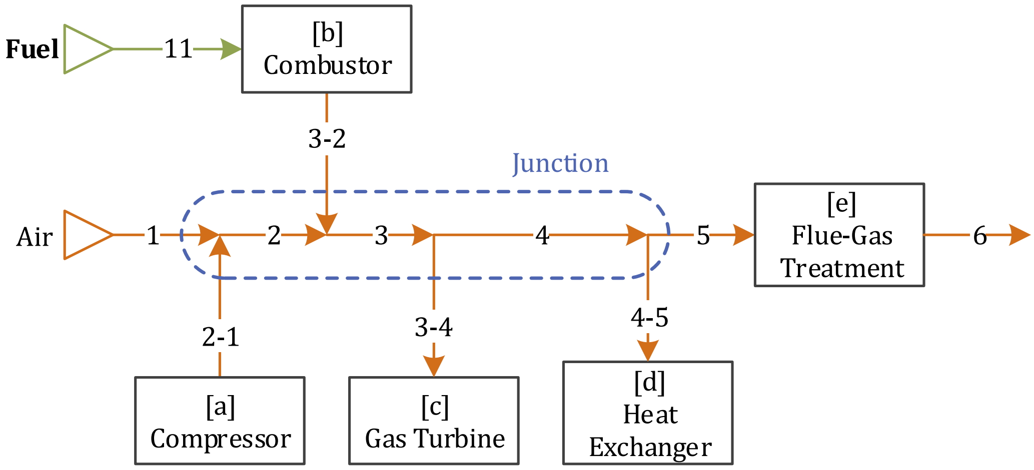


Figure 2.13. Functional Resource–Product diagram of the GT-Cog plant.

Figure 2.13 points out the presence of an exergy junction: indeed, the product of the Compressor and the Combustor is simultaneously used as a resource in the three other components.

Table 2.5. Determination of the junction ratios for the GT-Cog example.

Component	Resource from the junction	$[kW]$	Junction ratios	[%]
c) GT	*3-4*	5425	r_c	69,9%
d) HEX	*4-5*	1577	r_d	20,3%
e) FGT	*5*	754	r_e	9,7%
Total		7756		100,0%

Table 2.6. Layout of the Input–Output tables of the GT-Cog example.

Z	a	b	c	d	e		w		x
a	-	-	$r_c \cdot P_a$	$r_d \cdot P_a$	$r_e \cdot P_a$		-		P_a
b	-	-	$r_c \cdot P_b$	$r_d \cdot P_b$	$r_e \cdot P_b$		-		P_b
c	9	-	-	-	-		10		P_c
d	-	-	-	-	-		8-7		P_d
e	-	-	-	-	-		6		P_e
	1	11	-	-	-				

Table 2.7. Compiled Input–Output tables of the GT-Cog example.

Z	a	b	c	d	e		w		x
a	-	-	1388	403	193		-		1984
b	-	-	4037	1174	561		-		5772
c	2185	-	-	-	-		1000		3185
d	-	-	-	-	-		1197		1197
e	-	-	-	-	-		523		523
R	0	6605	-	-	-				

Table 2.8. Technical Coefficients matrix and Input vector of the GT-Cog example.

A	a	b	c	d	e
a	-	-	0,44	0,34	0,37
b	-	-	1,27	0,98	1,07
c	1,10	-	-	-	-
d	-	-	-	-	-
e	-	-	-	-	-
B	0	1,14	-	-	-

Table 2.9. Leontief Inverse matrix of the GT-Cog example.

L	a	b	c	d	e
a	1,92	-	0,84	0,65	0,71
b	2,68	1,00	2,44	1,89	2,06
c	2,12	-	1.92	0,71	0,78
d	-	-	-	1,00	-
e	-	-	-	-	1,00

Hence, three junction ratios must be defined as shown in Table 2.5: they reflect how the exergy of the junction is distributed among the three user components. The exergy junction ratios allow to distribute the product of the Compressor and the Combustor on a coherent proportional basis. Recalling the definitions given in section 2.3, the Input–Output model can be devised as shown in Table 2.6-Table 2.9.

It can be interesting to analyze the differences arising between Table 2.8 and Table 2.9. The Technical Coefficients matrix accounts only for *direct* production: it collects the amount of exergy that each *i*-th component is required to produce to provide one exergy unit to each *j*-th component that is directly fueled by it. For example, element $a_{31} = 1{,}10$ means that the Gas Turbine has to produce $1{,}10kJ$ of exergy for each kJ of exergy it directly fuels to the Compressor, since there is a direct exergy exchange from GT to C. This is why the layout of matrix A exactly reflects that of matrix Z.

On the other hand, the Leontief Inverse matrix accounts for both *direct* and *indirect* requirements: it collects the amount of exergy that each *i*-th component must produce to satisfy one exergy unit of the *j*-th final demand. It can be noticed that for each *ij*-th element, eq. (2.96) and (2.97) hold:

$$l_{ij} \geq a_{ij} \qquad i,j = 1,\ldots,5 \tag{2.96}$$

$$0 \leq a_{ii} \leq 1 \quad \rightarrow \quad l_{ii} \geq 1 \qquad i = 1,\ldots,5 \tag{2.97}$$

Eq. (2.96) explains that unit production of the *i*-th component must increase to satisfy not only the direct exergy transactions, but also the indirect requirements that support the final demand. For example, $l_{31} = 2{,}12$ means that the Gas Turbine has to produce $2{,}12kJ$ of exergy for each kJ of exergy delivered by the Compressor as final demand. This term considers both the previous $1{,}10kJ$ direct consumption, and the remaining $1{,}02kJ$ of indirect requirements, as summarized by eq. (2.98).

$$l_{31} = \begin{Bmatrix} \text{direct:} & a_{31} = 1{,}10 \\ \text{indirect:} & l_{31} - a_{31} = 1{,}02 \end{Bmatrix} = 2{,}12 \tag{2.98}$$

This indirect consumption is needed to fuel the Compressor, so that it can provide exergy to all the other components that, in turn, concur in fueling the Gas Turbine and deliver its final demand.

Eq. (2.97) represents the *productiveness condition*: in order to be economically productive, direct exergy requirements for self-consumption must be lower than the total production of each considered component. This implies that to deliver one exergy unit of the *i*-th final demand, at least one unit of it has to be produced by the *i*-th component.

2.4.3 Exergy Cost Analysis

The Resource vector is defined in terms of exergy that is directly fueled to the system from the environment, and is reported in Table 2.7. The resulting Input vector is shown in Table 2.8.

The Flue-Gas Treatment section is considered a *dissipative* component: the cost of its product has to be properly reallocated to the final demand of the system, thus specifically to the products of the Gas Turbine and of the Heat Exchanger.

As it can be noticed from the Transaction matrix, component FGT is directly fueled from the exergy junction, so its resource is made-up by the product of the Compressor and of the Combustor (in a proportion given by the exergy junction ratios). Therefore, the cost of the product of these last components is increased by the term that represent the cost of this residues dissipation, as in eq. (2.48). Recalling the definition given by eq. (2.54), the following Residues Cost Distribution ratios are defined:

$$\psi_{51} = \frac{\dot{E}_{15}}{\dot{R}_5} = \frac{193kW}{754kW} = 0{,}256 \tag{2.99}$$

$$\psi_{52} = \frac{\dot{E}_{25}}{\dot{R}_5} = \frac{561kW}{754kW} = 0{,}744 \tag{2.100}$$

The feature of eq. (2.53) is straightforwardly respected:

$$\sum_{i \in \mathrm{P}} \psi_{5i} = \psi_{51} + \psi_{52} = 0{,}256 + 0{,}744 = 1 \tag{2.101}$$

Subsequently, from eq. (2.57), the following Residues Production coefficients can be introduced:

$$\rho_{51} = \psi_{51} \cdot \frac{\dot{P}_5}{\dot{P}_1} = 0{,}256 \cdot \frac{523kW}{1984kW} = 0{,}067 \tag{2.102}$$

$$\rho_{52} = \psi_{52} \cdot \frac{\dot{P}_5}{\dot{P}_2} = 0{,}744 \cdot \frac{523kW}{5772kW} = 0{,}067 \tag{2.103}$$

Table 2.10. Residues Coefficients matrix of the GT-Cog example.

W	a	b	c	d	e
a	-	-	-	-	-
b	-	-	-	-	-
c	-	-	-	-	-
d	-	-	-	-	-
e	0,067	0,067	-	-	-

As in eq. (2.64), the Residues Coefficients matrix can be determined; the result is shown in Table 2.10. From eq. (2.68), the Modified Leontief Inverse matrix can be computed as in Table 2.11.

Table 2.11. Modified Leontief Inverse matrix of the GT-Cog example.

L_R	a	b	c	d	e
a	2,19	0,06	1,03	0,80	0,87
b	3,47	1,17	3,00	2,32	2,54
c	2,42	0,06	2,13	0,88	0,96
d	-	-	-	1,00	-
e	0,38	0,08	0,27	0,21	1,23

The unit exergy costs of the final demand can be revealed from eq. (2.69); the result is reported in Table 2.12, together with the respective Exergy Design Evaluation procedure from paragraph 2.3.4.1.

Table 2.12. Exergy Cost Analysis of the GT-Cog example.

	c $[kJ/kJ]$	C $[kJ]$	C_d $[kJ]$	Rank C_d	c_R $[kJ/kJ]$	r [%]
a) C	3,97	-	798	4	3,61	10,1
b) Comb	1,34	-	1116	2	1,17	14,4
c) GT	3,43	3429	7682	1	2,01	70,3
d) HEX	2,65	3176	1009	3	2,01	31,8

Final check from eq. (2.71) results satisfied: $3429kW + 3176kW = 6605kW$.

Results from Table 2.12 suggests that, from a purely thermodynamic point of view, the Gas Turbine and the Combustor are the most exergy-destroying components; therefore, efforts for enhancement should primarily focus on them. This result is in line with expectations. Moreover, respective values of the Relative Cost Difference r suggest that the Combustor has a much larger potential for thermodynamic improvements than the Gas Turbine.

2.4.4 Exergoeconomic Cost Analysis

The Exergoeconomic Cost Analysis procedure follows systematically the outline of previous paragraph. The only difference is represented by the Exogenous Resources vector: in this case, it is defined in monetary units, as explained in paragraph 2.3.3.1

Purchased Equipment Costs have been roughly determined based on the cost functions included in [37]. Specific adjustments and rounding have been performed in order to suit the didactical purpose of the example, so the resulting values should not be considered reliable representation of the average market prices.

The Total Capital Investment has been determined as 1,9 times the total PEC: $TCI = 1{,}9 \cdot PEC = 1{,}9 \cdot 22{,}8M€ = 43{,}32M€$.

Assuming a Weighted Average Cost of Capital (WACC, or depreciation rate) $m = 8\%$ and a prospected lifetime $LT = 30\ years$, the Capital Recovery factor can be computed with the aid of eq. (2.80), resulting $f_I = 0{,}089$. Instead, the Variable Cost factor has been assumed $f_V = 0{,}011$.

Previous hypotheses, with an Equivalent Full-Time $H_{eq} = 7000\ h/year$, allow to compute the total fixed cost flow:

$$FC = TCI \frac{f_I + f_V}{3600 \cdot H_{eq}} = 0{,}1716 \frac{€}{s} \tag{2.104}$$

This term has to be redistributed to each component in proportion to its share in the total PEC, as explained by eq. (2.85) and reported in Table 2.13. Addition, as in eq. (2.86), of the variable cost flow for each component (in this case, only the cost of the fuel for the Combustor, and reagents and maintenance for the FGT) result in the full definition of the Monetary Resources vector.

Table 2.13. Detail of the cost terms of the GT-Cog example.

	$PEC\ [M€]$	p [%]	$\dot{Z}_F\ [€/s]$	$\dot{Z}_V\ [€/s]$	$\dot{Z}\ [€/s]$
a) C	5,2	22,8	0,039	-	0,0391
b) Comb	0,8	3,5	0,006	1,5E-05	0,0060
c) GT	10,3	45,2	0,078	-	0,0775
d) HEX	0,9	3,9	0,007	-	0,0068
e) FGT	5,6	24,6	0,042	4,2E-06	0,0422
Total	22,8	100	0,1716		

Table 2.14. Monetary Resources and Input vectors for the GT-Cog example.

Comp	a	b	c	d	e
R_m	0,0391	0,0060	0,0775	0,0068	0,0422
B_m	2,0E-05	1,0E-06	2,4E-05	5,7E-06	8,1E-05

Application of the LCM leads to the Exergoeconomic Costs and Design Evaluation reported in Table 2.15.

Table 2.15. Exergoeconomic Cost Analysis of the GT-Cog example.

	π [€/GJ]	Π [€/s]	Π_d [€/s]	Γ [€/s]	Rank Γ	π_R [€/GJ]	γ [%]	φ [%]
a) C	136,48	-	0,0249	0,0640	2	123,93	10,1	61,1
b) Comb	10,64	-	0,0077	0,0138	4	9,30	14,4	43,8
c) GT	97,30	0,097	0,1280	0,2055	1	57,12	70,3	37,7
d) HEX	62,10	0,074	0,0179	0,0247	3	47,13	31,8	27,4

Table 2.15 shows that, from a thermoeconomic perspective, the most important components of the system are the Gas Turbine and the Compressor. Corresponding values of the exergoeconomic factor suggest that attempts for enhancements should be addressed on thermodynamic efficiency for the GT and on investment cost for the C, respectively.

Chapter 3
Hybrid Thermoeconomic IO Analysis

The cost accounting method formalized in section 2.3 has been traditionally applied to energy systems [27, 38–42], assessing the cost of final products in terms of direct exogenous-resources requirements. However, it must be noticed that these inputs are usually outputs of other productive systems. According to international standards [43, Sec. 5.2.3]:

> *"Ideally, the product system should be modeled in such a manner that inputs and outputs at its boundary are elementary flows. However, resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study."*

"Elementary flows" are defined as material and non-material flows either:

- Entering the system after having been drawn from the environment with no previous artificial transformation or human manipulation;
- Leaving the system, discarded to the environment with no subsequent artificial transformation or human manipulation.

These definitions imply that, in practice, closed clusters, which treat only elementary flows and receive elaborated products only from themselves, cannot exist. Instead, given the tangled amount of physical and commercial relationships among all the producing systems of current economies, it could be easily assumed that in general any system is deeply interrelated to many others, exchanging intermediate and/or final products.

Refined methods have been developed and standardized for environmental *Life-Cycle Assessments* (LCA), e.g. of emissions [28, 43]; nevertheless, techniques for assessing the impact of total resources consumptions have been somehow disregarded until recently [5]. It is undoubted that standard Thermoeconomics could benefit from a LCA formulation; however, the earlier process-based methods, although broadly used, have proved excessively exacting and demanding in the effort to follow the supply chain *from-cradle-to-grave*. Time and resources constraints force some parts of the system to be neglected from the analysis, resulting in unavoidable truncation errors that are reported to have a relevant impact, particularly in capital-intensive sectors [13–15]. To overcome these limitations, newer methods are based on *Input–Output Analysis* (IOA), developed by Leontief in 1930s [21, 22], which allows the supply chains to be modeled in a matrix framework. With this approach, it is possible to extend the boundaries of the analysis up to the direct extraction of the resources from the environment, avoiding the aforementioned cut-off errors and providing more reliable and accurate results. In the last decades, development of TA with an IO formulation has been successfully performed, leading to the definition of *Thermoeconomic Input-Output Analysis* (TIOA) [17, 44, 45]. However, standard TIOA is still unsuitable to LCA, since it does not adapt to its previously stated purposes. Attempts to enhance TIOA, encompassing the entire supply chains and all the Life Cycle phases of a system, can be retrieved in literature [46]. As for other LCA methods, *hybrid* formulations have been introduced [14, 16]. The adjective *hybrid* refers to the concept of integrating the system's physical description with its embedding economic environment, providing the necessary level of disaggregation that allows to estimate the system's real performances.

Therefore, to avoid truncation errors in process-based LCA the system boundaries should be broadened until the whole economy is encompassed, as Figure 3.1 points out; this would require a huge computational effort, as cut-off errors have been proved to have a relevant impact on the result of this type of analysis [13, 14].

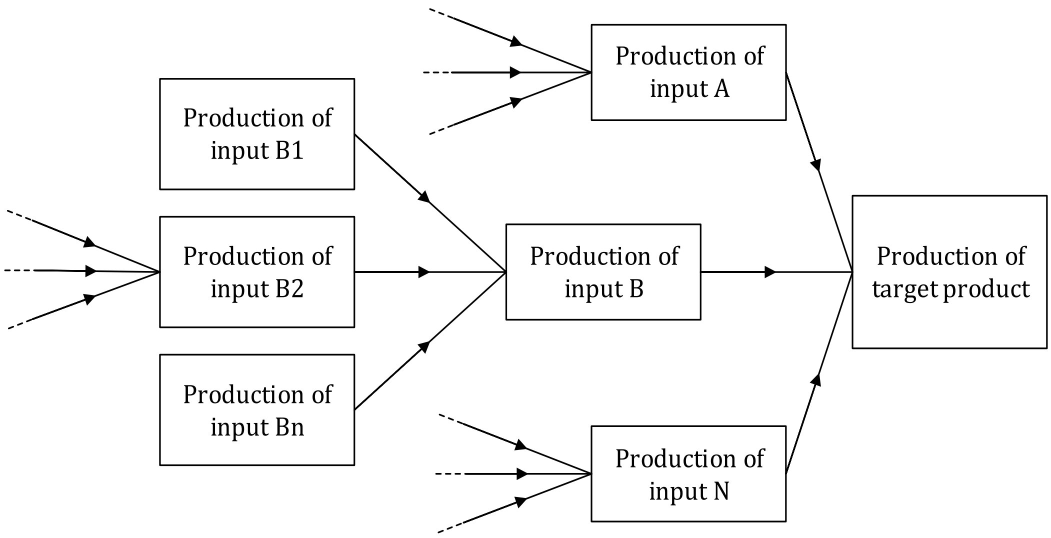


Figure 3.1. Outline of a generic process-based procedure to assess the whole supply-chain requirements characterizing a target production process [47].

To overcome these flaws, monetary-based Input–Output approach has been developed [16], relying on national economic data derived from *Monetary Input-Output Tables* (MIOTs). These tables are sectorial monetary transaction matrices accounting for the intricate interdependence of producing sectors within the same economic system, and are updated on a regular basis by national statistics offices.

3.1 Monetary Input–Output Tables

In the last decades, Input–Output Analysis has become an important and useful tool in national economic statistics, and Input–Output Tables (IOTs) are periodically devised by national agencies. These tables contain, in monetary values, the product that each economic activity (*producing sectors*, *segments*, or *branches*) delivers to each other and to the national final demand.
National MIOTs, with s different branches $\mathbb{S} = \{1, \dots, s\}$, have the simplified outline shown in Figure 3.2.

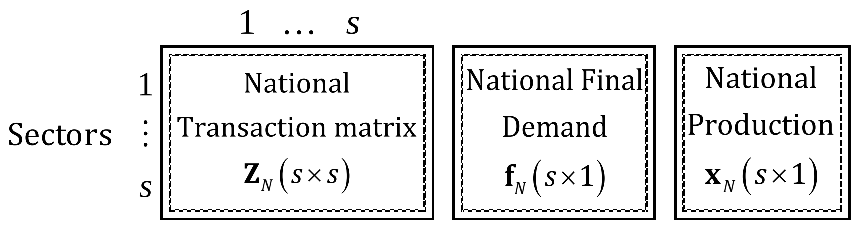


Figure 3.2. General outline of a MIOT with internalized import.

Direct inter-industry relations are collected in the total *National Transaction matrix* $\mathbf{Z}_\mathrm{N}(s \times s)$:

$$\mathbf{Z}_N = \begin{vmatrix} x_{11} & \cdots & x_{1s} \\ \vdots & \ddots & \vdots \\ x_{s1} & \cdots & x_{ss} \end{vmatrix} \tag{2.105}$$

The *National Production vector* $\mathbf{x}_\mathrm{N}(s \times 1)$ accounts for production fueled to other sectors (intermediate production) and to households (final demand):

$$\mathbf{x}_N = \mathbf{Z}_N \cdot \mathbf{1}_{s\times 1} + \mathbf{f}_N \quad \rightarrow \quad x_i = \underbrace{\sum_{j=1}^{s} x_{ij}}_{\text{intermediate production}} + \underbrace{f_i}_{\text{final demand}} \qquad i = 1, \dots, s \tag{2.106}$$

Recalling the cost accounting procedure from paragraph 2.3.2, elementary flows to the economic system are properly determined and collected in the *National Resources vector* $\mathbf{R}_N(1 \times s)$:

$$\mathbf{R}_N = \left|\dot{E}_{0i}\right| \qquad i = 1, \dots, s \tag{2.107}$$

For Exergy Cost Analysis purposes, the exogenous resources vector is defined in terms of primary fossil exergy, resulting in a homogenous vector showing the national production of Coal, Oil, and Natural Gas (and, eventually, Nuclear power), derived from energy statistics for the reference year. These terms are given in Lower Heating Values basis, and have to be converted in exergy basis. For this purpose, literature provides reference values for β_i (the ratio of chemical exergy to LHV) that can be used for quick, low-order estimations. Each resulting value will then be assigned to the corresponding productive sector according to [48]; all the other cells will be null.
Table 3.1 reports the case of Italian data for 2010, which is valid for the case study developed in the proceeding of this work.

Table 3.1. Determination of the national resource vector in terms of fossil fuel exergy.

	Unit	Coal	Crude Oil	Natural Gas	Ref
LHV	$[ktoe]$	64	5620	6883	[49]
Range β	$[-]$	1,06 – 1,10	1,04 – 1,08	1,04	[50]
Selected β	$[-]$	1,08	1,06	1,04	
E^{CH}	$[ktoe]$	69,12	5957,20	7158,32	
Assigned to sector		ISIC B 05 Mining of coal and lignite	ISIC B 0610 Extraction of crude petroleum	ISIC B 0620 Extraction of natural gas	[48]

3.1.1 Import Internalization

The general outline of a national MIOT is presented in Figure 3.3.

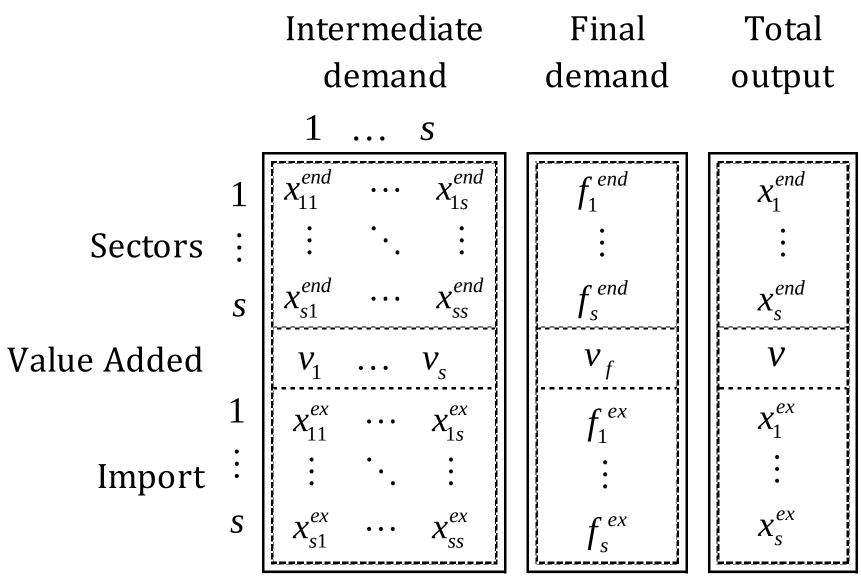


Figure 3.3. General structure of a national Monetary Input–Output Table.

Value added comprises labor compensation, public services, interests, and other features that are not directly related to productive performance; for this reason, it is not considered in this IO model.
MIOTs makes a distinction between the *endogenous* production, directly produced by national sectors, and the *exogenous* production, which includes import of goods and services from foreign countries to fuel internal production. Imported goods and services are produced in other economic systems that have, in the most general case, different efficiencies. Therefore, an accurate analysis should take in consideration that similar products may have different production efficiencies. This operation would require a considerable computational effort, since national economies nowadays result widely interrelated by trade and commerce. A simple methods consists in the assumption of *constant input matrix* [24]: competitive[6] imported products are characterized by the same production efficiency as if they were manufactured internally [51]:

$$x_{ij} = x_{ij}^{end} + x_{ij}^{ex} \tag{2.108}$$

$$f_i = f_i^{end} + f_i^{ex} \tag{2.109}$$

This approximation is acceptable as long as the import originates from countries with similar technology and expertise as the considered economy, hence having comparable technology coefficients.

3.1.2 Advantages and drawbacks

Use of MIOTs to model the supply chains of the physical system is controversial, and it is responsible of some of the main drawbacks of the hybrid IO model extended afterwards. The most important sources of uncertainty are related to [13]:

- *Aggregation*. National MIOTs are compiled by aggregation of all the productive processes in a smaller set of *sectors*, since a detailed account of every economic transaction between single units would require an overwhelming effort. Therefore, resulting information are easier to handle, but represent the average performance of the entire sector, and more precise data regarding one given process cannot be extrapolated.

[6] For the sake of completeness, also non-competitive import should be considered, which is not eligible of internalization since by definition, a corresponding producing sector does not exist in the considered economy. It is usually neglected.

- *Proportionality.* Monetary values in the MIOT represent physical flows of goods and services based on linear proportionality assumption. This fact is cause of uncertainties, because monetary values are recognized as a poor indicator for physical transactions. Indeed, price of the same good/service can be subject to noteworthy variations in time and space that have no relation with its physical nature.
- *Import internalization*. The hybrid model assumes that competitive goods and services from foreign economies are produced with the same efficiency of the corresponding national sector. This approximation may not always be acceptable, especially when the considered economies show significant differences in technology, know-how and expertize. For most cases, uncertainties arising from this assumption are negligible with respect to others.
- *Delay*. National MIOTs are usually published with a consistent delay with respect to the year they refer to. Differences of several years in the time reference can be responsible for consistent errors when analyzing products and technologies undergoing to fast development.
- *Source data*. A non-negligible contribution to uncertainties can be sought in the incompleteness or untrustworthy of the original data. Information about economic transactions are gathered by industrial surveys that can go through a tangled communication process, which can eventually mine the accuracy of the final results.

Despite the drawbacks highlighted above, a number of advantages contribute to the great potential of using MIOTs to extend Thermoeconomic IO models:

- *Simplicity*. Among the reasons that contributed in favor the broad acceptance of Input–Output Analysis, ease of application plays a crucial role. Fewer data are required to accomplish the examination, and the underlying mathematical structure relies on matrix notation, easier to manage with respect to other formulations.
- *Comprehensiveness*. Since the table accounts for all the trades occurring within the considered economic system with a matrix formulation, it is generally argued that IOA is more complete than other kinds of analysis [13, 14, 52]. Indeed, Upstream Cut-offs are reported to be significantly reduced, although Downstream phases are usually neglected.

3.2 H–TIOA: a revised formulation

This section presents the original contributions of the thesis:

- Evaluation of the total Life-Cycle primary-resources cost of the product of a generic energy-conversion system, taking proper consideration of the issue of reallocating the cost of residues to the final demand;
- Introduction of coherent performance indicators, and proposal of an iterative optimization procedure.

3.2.1 Primary-Resources Cost evaluation

Aggregation is possibly the main source of uncertainties related to the use of MIOTs to model the supply chain of a productive system, since it implies the evaluation of sectorial average values that do not usually reflect the actual performance of each system included therein. However, it is claimed that cut-off errors of process-based analysis can be an even larger source of error [13, 14]. Therefore, hybrid procedures have been introduced in the attempt to merge completeness of IOA with accuracy of process-based methods. First adoption of a *Hybrid Input-Output Analysis* dates back to 1975 [47]. In hybrid models, the process is represented by its technology matrix (in physical units), the same one that has been computed by means of eq. (2.43); instead, the embedding economic environment is denoted by its national MIOT (in monetary units), taken from available national data referred to proper year, and corrected to account for the extraction of the system under study (procedure cited as *normalization*) to avoid double-counting errors.
Application of Hybrid Thermoeconomic Input–Output Analysis requires a mathematical formulation very similar to that of the standard procedure formerly depicted. The core of the method is the proper definition of the transaction matrix, which merges the national MIOT (s sectors, in monetary units) and the RP table of the system (n components, in physical units).
In the national account, the system is included in one of the economic sectors. The method consists in disaggregating the physical system from the national MIOT; therefore, this last has to be adjusted in order to avoid double counting. Adjustment mechanism involves proper definition of the:

- *Upstream Cutoff Matrix* $\mathbf{E}_{NS}(s \times n)$, characterizing monetary interactions from national economy to the physical system.
- *Downstream Cutoff Matrix* $\mathbf{E}_{SN}(n \times s)$, describing physical linkages from the system to its economic surroundings.

These matrices provide the connection between the national account and the disaggregated system; each stream fueled to the system must be subtracted from the same row of the National MIOT, in correspondence to the column referring to receiving component.

$$\left|\widehat{\mathbf{Z}}_N\right|_{ij} = \left|\mathbf{Z}_N\right|_{ij} - \sum_{j=1}^{n} \left|\mathbf{E}_{NS}\right|_{ij} \qquad \text{for selected segment } i \qquad (2.110)$$

For example, a steam turbine provided to a power plant will be assigned from ISIC sector C 2811 ("Manufacture of engines and turbines, except aircraft, vehicle and cycle engines") to the energy system; therefore, this term has to be subtracted in the same row of the MIOT, in the cell matching column ISIC D 3510 ("Electric power generation, transmission and distribution").
Similarly, adjustment of national final demand, total production, and exogenous resources is performed as exemplified in (2.111), subtracting, in the proper rows and columns, monetary values corresponding to the physical terms of the energy systems:

$$\left|\widehat{\mathbf{f}}_N\right|_{i} = \left|\mathbf{f}_N\right|_{i} - \left|\mathbf{f}\right|_{j} \qquad \text{for matching segments } i \text{ and } j \qquad (2.111)$$

As an example, monetary value of the net electricity produced by a power plant has to be deducted from the national final demand for electricity (ISIC D 3510). It must be noticed that, since H–TIOA computes the cost of final demand, useful products of the system must be assigned to its final demand, despite the fact that they might be recirculated into national economic system; otherwise, it would not be possible to estimate its primary resources cost. For example, electricity generated by a power plant is assigned to the system final demand vector, despite the fact that it is practically fueled to the national electricity distribution system.
The system *Resource vector* **R**, when the exergy of fossil fuels is considered, is usually composed of null elements, unless the energy system is designed to operate in the field of natural resources extraction from the environment.

$$\left|\widehat{\mathbf{R}}\right|_{i} = 0 \qquad i = 1,\ldots,n \qquad (2.112)$$

Conversely, fossil fuels are determined as monetary flows coming from their respective ISIC sector, as it is highlighted in Table 3.1.

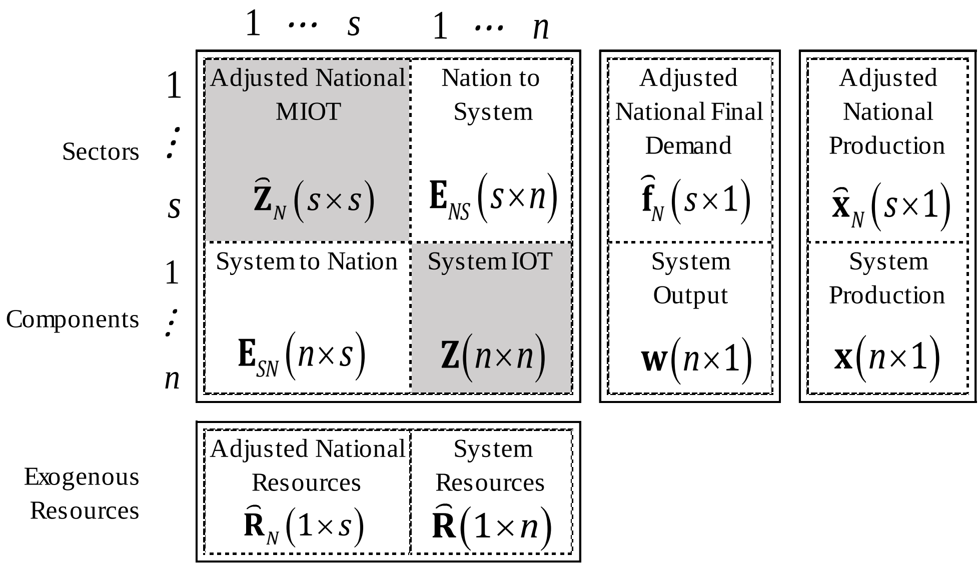


Figure 3.4. General set-up of a Hybrid Input–Output Table.

Referring to Figure 3.4, the *Hybrid Transaction* $\mathbf{Z}_H(s+n\times s+n)$ and *Technical Coefficients* $\mathbf{A}_H(s+n\times s+n)$ matrices, and the *Hybrid Final Demand* $\mathbf{f}_H(s+n\times 1)$, *Production* $\mathbf{x}_H(s+n\times 1)$ and *Resource* $\mathbf{R}_H(1\times s+n)$ vectors can be defined.
With these definitions, it is possible to apply the LCM and compute the cost of final demand in terms of primary fossil fuels exergy, as follows.

$$\left.\begin{aligned}\mathbf{B}_H &= \mathbf{R}_H\cdot\hat{\mathbf{x}}_H^{-1}\\ \mathbf{L}_H &= \left(\mathbf{I}-\mathbf{A}_H-\mathbf{W}_H\right)^{-1}\end{aligned}\right\}\quad\rightarrow\quad \mathbf{c}_H=\left(\mathbf{B}_H\cdot\mathbf{L}_H\right)^T \qquad (2.113)$$

It must be noticed that only the first $s+n_P$ of vector $\mathbf{c}_H$ are noteworthy, since they refer to the final demand of the national economy and of the system. The remaining n_D terms arise as a consequence of the mathematical formulation, but they have no practical meaning, as long as they refer to residues whose cost has already been reallocated. For this purpose, a proper redefinition of the *Residues Coefficients matrix* in a hybrid framework is necessary in order to account for the increased matrix dimension of the model. Therefore, the matrix depicted in Figure 2.9 must be extended recalling the definition given by eq. (2.57), as in eq. (2.114) and shown in Figure 3.5.
The system residues coefficients matrix is extended with *null elements*, except for those rows referred to dissipative components.

$$\rho_{ji} = \begin{cases} 0 & j \in \mathbb{S} \\ 0 & j \in \mathbb{P} \\ \psi_{ji} \dfrac{\dot{P}_j}{\dot{P}_i} & j \in \mathbb{D} \end{cases} \tag{2.114}$$

Indeed, it is possible that some dissipative components receive input from national sectors; these interactions are characterized by a cost that needs to be reallocated to the final demand of the system.

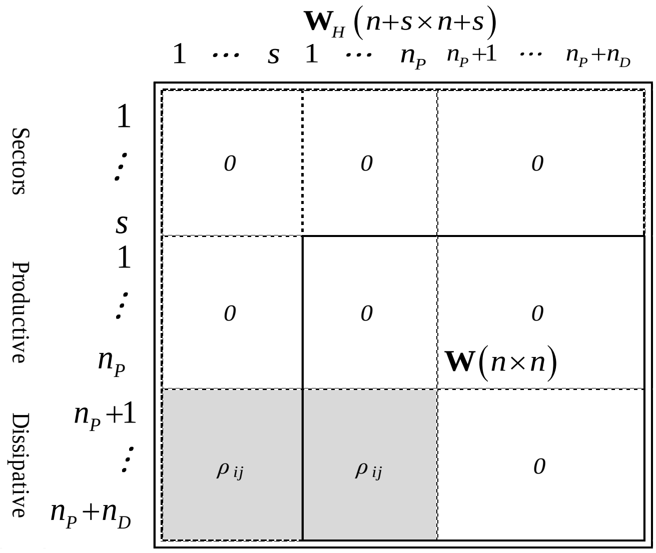


Figure 3.5. Layout of the Hybrid Residues Coefficients matrix.

Output of this procedure is the *Unit Hybrid Costs vector* $\mathbf{c}_H$, which contains the unit cost of the integrated economy-system's final demand in terms of primary exergy of fossil fuels. The most interesting elements of this vector are those concerning the final demand of the energy system, since they are representative of the system's performance in converting primary exergy. *Total Hybrid cost* of final products can therefore be determined as:

$$\mathbf{C}_H = \left| c_{H,i} \cdot f_{H,i} \right| = \hat{\mathbf{f}}_H \cdot \mathbf{c}_{H,SN} \tag{2.115}$$

Differently from the Exergy Cost and Exergoeconomic Cost analyses, in this case the equivalence between the sum of the total cost of final demand and the sum of the resources cannot be verified, only the order of magnitude can be expected to be the same. This is ascribed to the approximation introduced when evaluating the impact of imported goods and products as if they were endogenously produced, hence sharing the same technological coefficient of competitive national products. Indeed, this approximation leads to errors that increase with the difference between the performances of the competitive sectors of national and foreign economies.

3.2.1.1 Adjustments to Life-Cycle Assessment

The Hybrid Thermoeconomic Input–Output framework clearly states the spatial boundaries of the analysis (from the final product up to the entire supply chain), but is limited in the temporal rim, usually one year. This is due to the use of national MIOTs, which are computed over one year. For accurate LC evaluations through H–TIOA, the proper MIOT ought to be implemented for the respective year of analysis. However, this feature is impossible to achieve, mainly due to the following reasons.

- MIOTs are usually updated every 5 years, and delivered with a significant delay. Therefore, yearly detail is unavailable;
- Monetary value of goods and services can be subject to fluctuations due to financial/currency trends, that results substantially independent from technological factors;
- Predictions about future situations are unavoidably characterized by considerable uncertainty.

Best available data usage is always recommended; therefore, application of H–TIOA to existing or projected energy systems involves the important approximation of *constant technological coefficient*: the Hybrid Transaction matrix is kept constant throughout the entire timespan of the LC. Nonetheless, this rough estimation has proved not to drastically influence the results of the analysis [52]. Next paragraphs specify the conditions that ought to be respected to coherently apply H–TIOA in every LC phase of a system.

Table 3.2. The three phases of an energy system Life Cycle.

Phase	Duration
Construction	
Operation	
Disposal	

- ***Construction***. For the Construction phase, the Input–Output method is specifically adjusted, so that the entire energy system is accounted as a single unit. The result will be the total primary exergy required to build one unit of energy systems, i.e. the considered power plant. The physical Transaction matrix of the system consists of a single cell. The

only final product is the unit of power plant, while the exogenous resource is the Total Capital Investment in the form of different factors coming from other economic sectors. These terms are included in the Upstream Cutoff matrix, as Nation-to-System economic flows.
The resulting Hybrid Input–Output matrix is outlined in Figure 3.6.

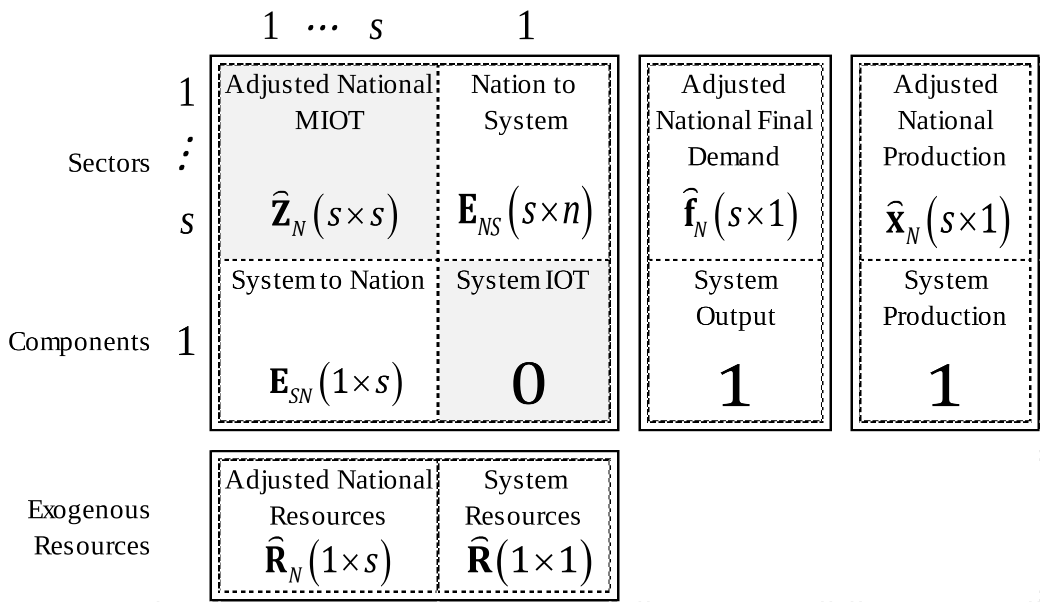


Figure 3.6. Layout of the Hybrid IO matrices for Construction and Disposal phases.

The same H–TIOA depicted in paragraph 3.2 can be applied in the simplified version, since no dissipative element appear in the physical system. The obtained cost of final demand represents the exergy cost $E_C > 0$ for the construction of one power plant, in terms of primary fossil exergy; with an economic analogy, it might represent a total exergy investment.

- ***Operation***. In the Operation phase, the Hybrid Thermoeconomic method systematically follows the procedure described in section 3.2, using a levelized yearly average configuration that remains valid for the entire lifetime of the project. The hybrid IO tables resemble the general structure depicted in Figure 3.4. With an economic analogy, it is possible to account for exergy *passivity* E^- (the yearly exergy consumption) and exergy *activity* E^+ (the yearly exergy production):

$$E_O = E^- - E^+ \tag{2.116}$$

The net balance (2.116) provides the *yearly net exergy* that is either:

- *Consumed*, when passivity is greater than activity ($E_O > 0$). This is usually the case of traditional power plants running on fossil fuels;
- *Produced*, when activity exceeds passivity ($E_O < 0$). This is the expected behavior of power-generating technologies based on renewable energy sources.

- ***Disposal***. Analysis of Disposal phase follows the same basic structure of Construction phase. The result is a unique value of exergy cost ($E_D > 0$), which represents the amount of exergy required for the *End-of-Life* (EoL) operations: dismantling the plant and recovering the site up to green-field conditions. This value ought to be considered as a future expenditure in the design phase of the project, in order to achieve better long-term profitability predictions. Neglecting this phase can cause important evaluation errors, especially in case of energy systems, which are responsible of an extensive land impact.

Traditional Economic Analysis provides the linkage between the system and the national economy, allowing to compile the Hybrid table with the Upstream Cut-off matrix. Conversely, detailed discussion about the Downstream Cut-off matrix has been left aside as a consequence of the following reasons:

- In most cases, products of the system's components should be assigned to the final demand vector, in order to determine their cost with an Input–Output procedure, neglecting the fact that, in the real case, they might be recirculated into the national economy as a resource to other productive sectors;
- Terms of the Downstream Cut-off matrix have a physical nature and are hence expressed in physical units; no particular procedure is needed to compile this table;
- For the purpose of the case study analyzed in this work, the Downstream Cut-off matrix is considered to have a negligible impact: in the whole 20×63 table, only one single cell has a non-zero value, and it also results very small in comparison to the final demand.

More details about the importance of the Downstream Cut-off matrix in Hybrid Input–Output Analysis can be retrieved in literature [53].

3.2.2 Performance indicators

The main information regarding performance, in terms of fossil fuels directly and indirectly consumed, attained by the energy system under consideration can be expressed by the three following indicators that have been specifically detailed for the purpose.

- ***C_{PR}* – *Primary Resource Cost*** is defined as the total cumulative amount of primary exergy required for construction (C), operation (O) and disposal (D) phases:

$$C_{PR} = E_C + LT \cdot E_O + E_D \tag{2.117}$$

  This quantity is the most interesting output of this novel procedure, since it can be evaluated for <u>any energy-conversion system</u>. It is expected to assume positive values for traditional power plants based on fossil fuels. Conversely, newer power-generating technologies based on renewable energy sources are designed to produce more exergy than it is required for their operation; therefore, in these cases C_{PR} is expected to assume small values, even negative, and result in a long-term exergy benefit.
- ***ExROI* – *Exergy Return On (exergy) Investment*** can be defined only if C_{PR} results negative, that is, only if the system produces a net exergy benefit; hence, it can be evaluated only in the case of energy-conversion systems based on <u>renewable energy sources</u>. In this case, $ExROI$ is defined as the ratio between the absolute value of the Primary Resource Cost, and the total exergy expenditure of the construction phase.

$$ExROI[-] = \frac{-C_{PR}}{E_C} > 0 \tag{2.118}$$

  This indicator represents, in percentage, the cumulated exergy benefit that is projected to arise from an initial exergy investment. In other words, it indicates how many times the net exergy benefit produced throughout the system's lifetime can pay-back the initial exergy investment. Indeed, only if the net exergy balance (2.116) in the Operation phase is positive, a complete exergy pay-back can eventually be achieved. In analogy with economic routines, the inverse ratio of the

$ExROI$ (2.119) could be defined *Exergy Pay-Back Time*, since it expresses the number of years required for the plant to save enough primary exergy to account for all the phases of its own Life Cycle.

$$ExPBT\left[-\right]=\frac{1}{ExROI} \tag{2.119}$$

- ***LexCOE – Levelized Exergy Cost Of Exergy*** represents the cost of a unit of exergy production in terms of the cumulated requirements of the plant over its entire life-time; therefore, it can be evaluated only for power-generating systems, which are specifically designed to provide useful energy (whether *electrical* or *thermal*) as final product. $LExCOEx$ is defined as the ratio between the cumulated consumption of exergy to support the whole Life Cycle of the system, and its cumulated useful effect:

$$LExCOEx\left[\tfrac{J}{J}\right]=\frac{\left|E_C+E_D\right|+\sum_{i=1}^{LT}E_i^-}{\sum_{i=1}^{LT}E_i^+} \tag{2.120}$$

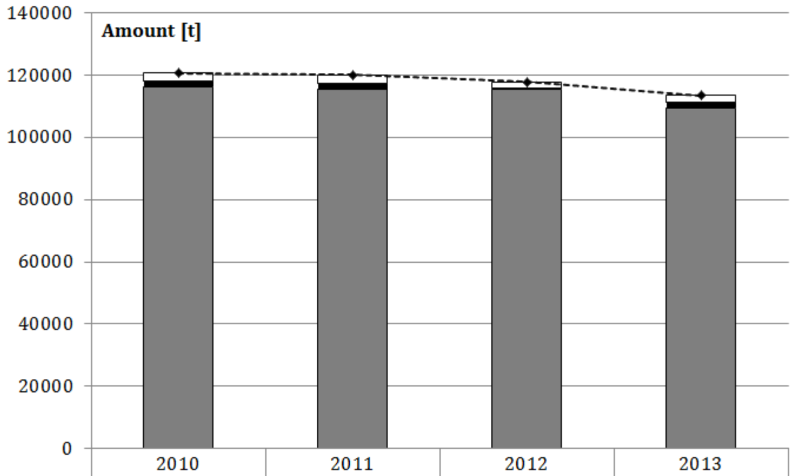
Although optimization of energy systems usually focuses on the economic production cost, $ExROI$ and $LExCOEx$ can provide a homogeneous basis to perform speculative comparisons among power-generating technologies, and therefore help policy-makers in addressing the best strategies within the energy sector management.
It is noteworthy to understand that the hybrid LCA–TIOA provides a final result that is useful for evaluating the performance of the considered system. Nonetheless, discriminating, as discussed in paragraph 2.3.4, among thermodynamic and economic effects on global inefficiencies is possible only when the costs are given in homogeneous units. In a hybrid approach, which aggregates monetary resources in the Upstream Cut-off matrix as part of the Hybrid Transaction matrix, a clear distinction of the two clouts is not possible. This is why eventual optimization processes ought to be performed relying on information arising from standard thermoeconomic procedures, as devised in paragraph 2.3.4.

Chapter 4
Tecnoborgo power plant and review of Waste-to-Energy technology

4.1 Focus on Tecnoborgo (PC, Italy)

Tecnoborgo is a waste incineration power plant located in Piacenza (PC), in northern Italy. While the society (Tecnoborgo S.p.A.) was founded in 1996, the power plant was set in operation in 2002 [54] to serve the whole district of Piacenza (260′000 inhabitants targeted [55]). The facility has a nominal capacity of 15 t/h, and it is designed to treat 120’000 $t/year$ of waste (expecting an availability factor exceeding 91%, corresponding to 8’000 $h/year$), mainly *Municipal Solid Waste* (MSW) and *Assimilated* (MSW&A), with small fractions of *Clinical Waste* (CW), and *Sewage Sludge* (SS)[7]. Table 4.1 reports the amount of waste treated between 2010[8] and 2013, showing undoubtedly how MSW&A is the predominant fraction in the total feedstock.

Table 4.1. Amount of waste treated in Tecnoborgo [56].



	2010	2011	2012	2013
SS	2520	2698,39	2179,32	2119,32
CW	1857	1979,23	194,81	1904,29
MSW&A	116284	115320,43	115407,41	109442,21
Tot	120661	119998,05	117781,54	113465,82

[7] Treating capacity is limited to 2’000 $t/year$ for Clinical Waste and 3’500 $t/year$ for Sewage Sludge.
[8] The value for year 2010 exceeds the limit of 120’000 $t/year$ due to special authorizations for the management of two emergency situations.

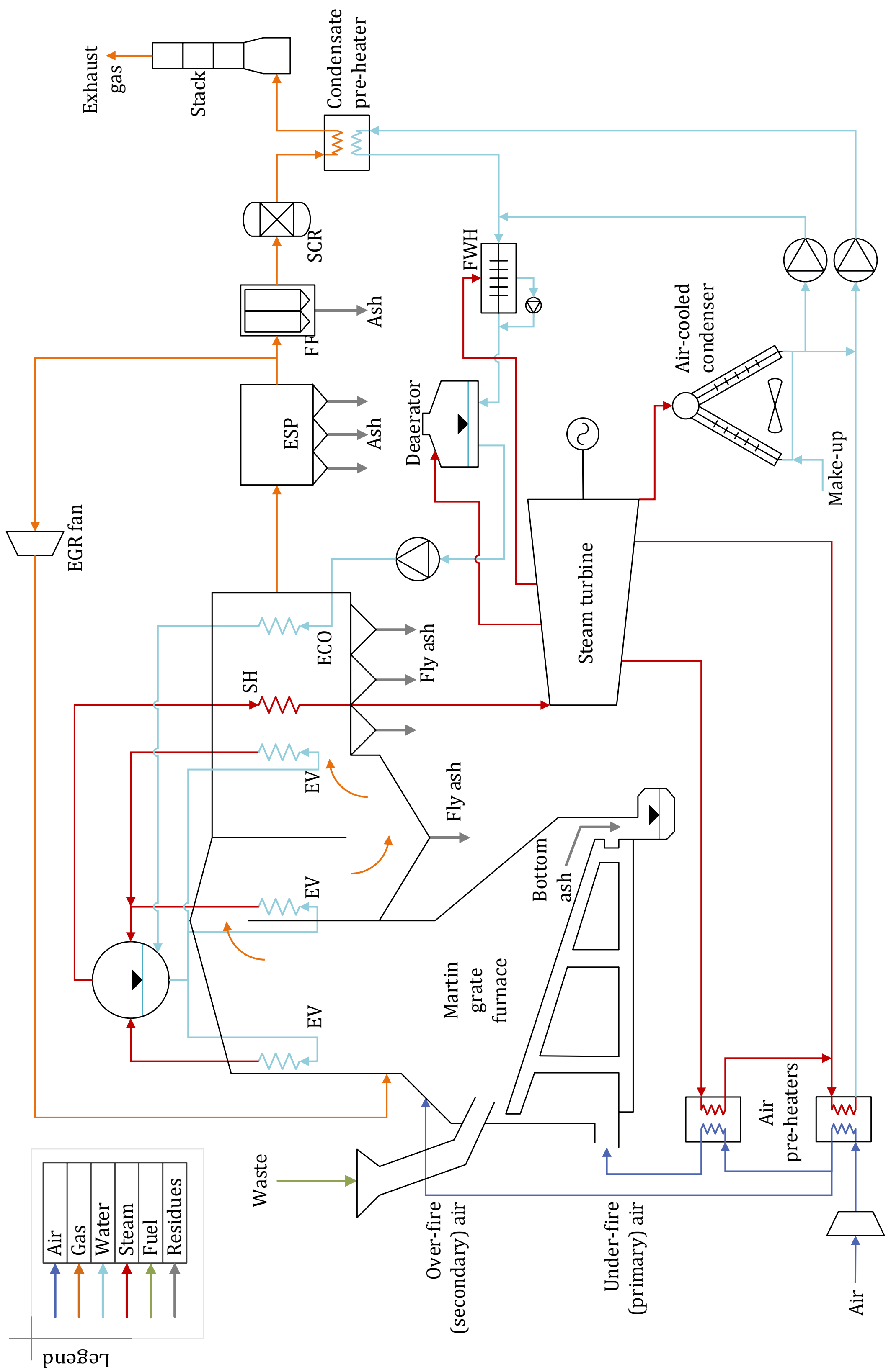


Figure 4.1. Layout of Tecnoborgo WtE power plant.

Table 4.2 summarizes the nominal value and the allowed range of variation for the waste flow per line and its LHV, which are influenced by the actual composition of the refuse to be treated.

Table 4.2. Authorized range for two main operating parameters of the plant [54, 56].

	Unit	Minimum	Nominal	Maximum
Waste capacity per line	t/h	6,0	7,5	8,5
Lower Heating Value	MJ/kg	9,6	10,881	13,6

4.1.1 Layout of the structure

The received MSW is weighted and discharged in a pit, where two loading claws are used to fluff it and load it in the hoppers. CW loaded directly in the hoppers via automatic chargers. SS undergo two steps of physical dewatering through dedicated centrifuges and an indirect thermal drying (whose heat is supplied by a certain amount of steam tapped from the turbine) before being introduced in the incinerator.

The facility is endowed with two parallel lines, both implementing an air cooled downward reverse-reciprocating grate (*Martin grate*) with a counter-flow arrangement of the combustion chamber. An hydraulic piston drives the alternate motion of the moving grate bars, and the relative movement against the fixed bars causes the waste to move downward. Auxiliary burners fed with methane gas are set in operation whenever the temperature in the chamber would otherwise drop under the minimum temperature of $850°C$.

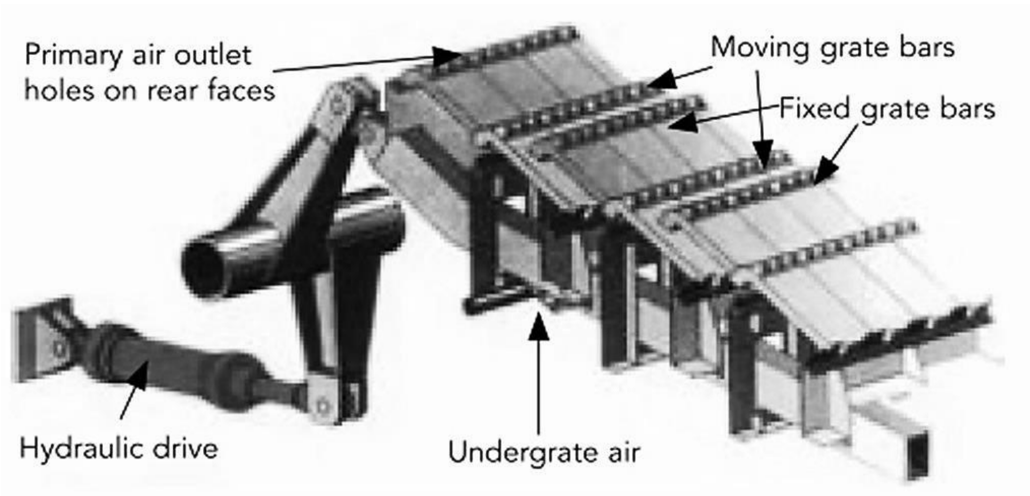


Figure 4.2. Detail of a reverse reciprocating grate mechanism [57].

Superheated steam at $390°C/40bar$ is collected from the two lines and expanded in the single steam turbine from $385°C/40bar$ to $53,5°C/0,147bar$ conditions. On the same shaft, a three-phase bipolar synchronous alternator is attached, converting this mechanical power into electrical power at $15kV$. A subsequent transformer raises voltage up to $132kV$ before sending the electricity to the national grid system. Gross electrical capacity of the turbo-alternator is $11,73MW$, while the net production reduces to around $10MW$ after accounting for internal auxiliary consumptions.
Three bleedings at intermediate pressure levels are designed to provide the necessary heat input to:

- $12,52bar$ → *combustion air pre-heater*, high temperature section, designed to increase temperature of the air fed to the furnace from 105°C to $150°C$, and *sewage sludge indirect dryer*;
- $2,74bar$ → *combustion air pre-heater*, low temperature section, designed to increase temperature of the air fed to the furnace from ambient temperature ($20°C$) to $105°C$, and *deaerator*, to remove non-condensable gases eventually collected in the liquid water stream;
- $0,92bar$ → condenses heater (*regenerator*), which allows to increase the overall energetic efficiency of the process.

At the exit of the turbine, a 3-cell air cooled condenser promotes the condensation of the two-phase flow at $0,142bar$ (corresponding to a saturation temperature of $52,87°C$), completed in the underlying condensate tank. After a regenerative section follows the deaerator, from where liquid water is pumped to the economizer section of the boiler at $131°C$ (saturation temperature at $2,74bar$).
The Flue-Gas Treatment section features a Dry Process type on both lines and originally included, for NO_x removal, only a SNCR system running with ammonia solution; in 2009 and 2011 respectively, lines 1 and 2 were endowed with an additional SCR at the exit of the boiler. Coarse particles are then separated by the $15kV$ electric field set up inside an ESP. Sodium bicarbonate, or lime, and activated carbon are added afterwards to promote acid-gases and VOCs removal. Solid products and unreacted reagents, together with finer particulate matter, are subsequently separated in a FF system before the purified gas flow is blown into the atmosphere from the top of two stacks at the height of $70m$, avoiding condense formation.

At the end of the grate, bottom ashes from the combustion process fall in the bottom ash discharger, where cooling and solidification occurs. A subsequent vibrating belt conveys this inert, non-hazardous substance to the material recovery section: ferrous and other metal are completely recovered, while the remaining material is almost entirely recovered for cement production; only a small fraction is landfilled. Also the fly-ash separated from the boiler and the ESP will be sent to landfilling after inertization. Residues from the FF are mainly composed of Sodium and Calcium residues that can be recovered, while a minor fraction will be landfilled. Figure 4.3 summarizes the output from a unit of unsorted waste treated in Tecnoborgo, showing that only a very small amount (5,5– 6%) of matter is destined to the final landfill disposal.

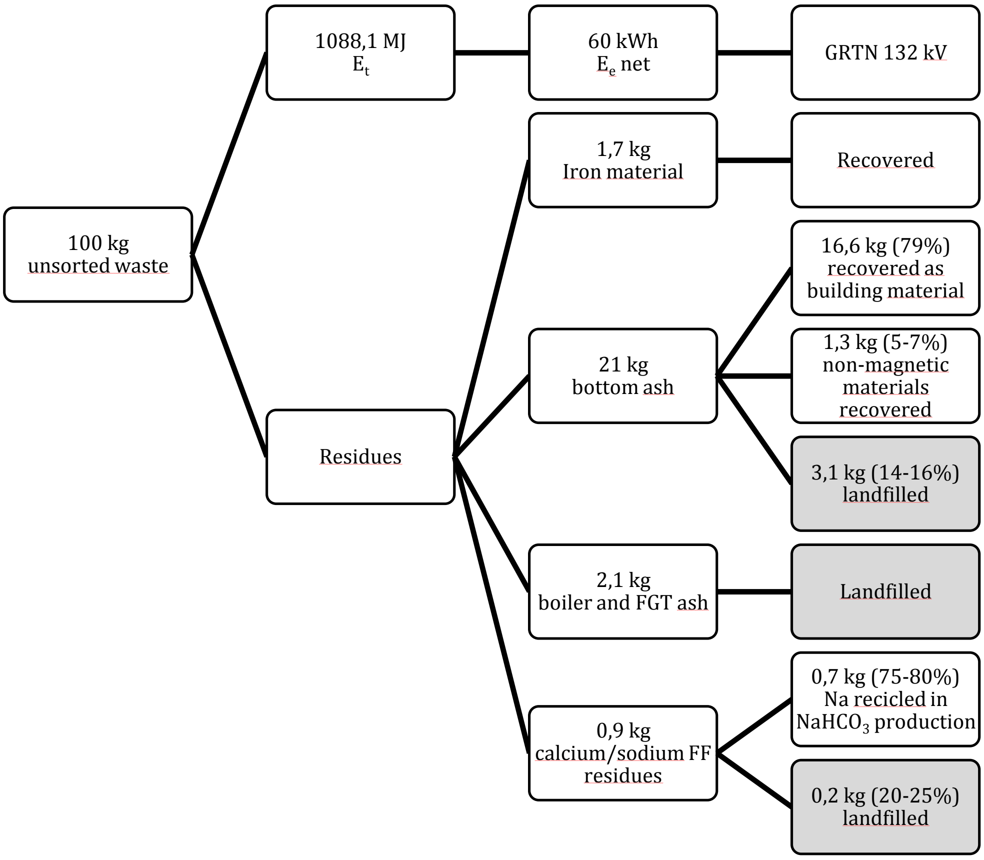


Figure 4.3. Output from waste treatment obtained by Tecnoborgo [54, 56, 58].

4.1.2 Thermodynamic model

This section provides a description of the thermodynamic cycle implemented in Tecnoborgo Waste-to-Energy facility. The system has been modeled using *ThermoFlex*® by *Thermoflow, Inc*., and has been adjusted from the basic model provided by the *Group of Energy COnversion Systems* (GECOS) of Politecnico di

Milano, Department of Energy, which is gratefully acknowledged. Environment conditions have been set as reported in Table 4.3.

Table 4.3. Environment conditions set-up.

Parameter	Unit	Value	Description
T_0	$°C$	15	Environmental temperature
p_0	bar	1,11	Environmental pressure
$r.h.$	%	60	Environmental relative humidity

Two boilers, characterized by a horizontal configuration with water-wall bundles based on a natural circulation system, provide the necessary heat input to a single Rankine steam cycle. The system operates with a 4,2 kg/s constant feedstock input, so that electric energy production results Fuel-Driven; this means that any simulation and design optimization procedure will consider a constant amount of fuel input. Conversely, a Product-Driven model, which varies the amount of fuel intake to maintain a constant production rate, would not be suitable, since a WtE plant is designed to operate with a given fuel input, while the concurrent electrical generation is just a by-product, though useful and valuable.
The main thermodynamic parameters are summarized in Table 4.4.

Table 4.4. Main thermodynamic parameters characterizing Tecnoborgo power plant.

Parameter	Unit	Value	Description
$\dot{m}_1$	kg/s	4,2	Feedstock flow rate
LHV	MJ/kg	10,8	Lower Heating Value of the waste
E^{CH}	MJ/kg	12,9	Estimated chemical exergy of the waste
p_{in}^{ST}	bar	40	Steam turbine inlet pressure
T_{in}^{ST}	$°C$	390	Steam turbine inlet temperature
FGR	–	15%	Flue-Gas Recirculation ratio

The model performs control checks in order to:

- maintain underfire and overfire air temperatures around to the specified values of 150$°C$ and 90$°C$, respectively, in order to reach the necessary temperatures in the grate to promote combustion;
- reach the super-heated steam conditions, in terms of temperature and pressure, specified for each simulation. These conditions represent one of the design variable, since the entire heat-recovery section that follows is designed accordingly;
- avoid temperature to fall below 120$°C$ at the exit of the stack, to avoid condensation of acid gases that would induce corrosion issues;
- perform pollutant abatement required by environmental legislation.

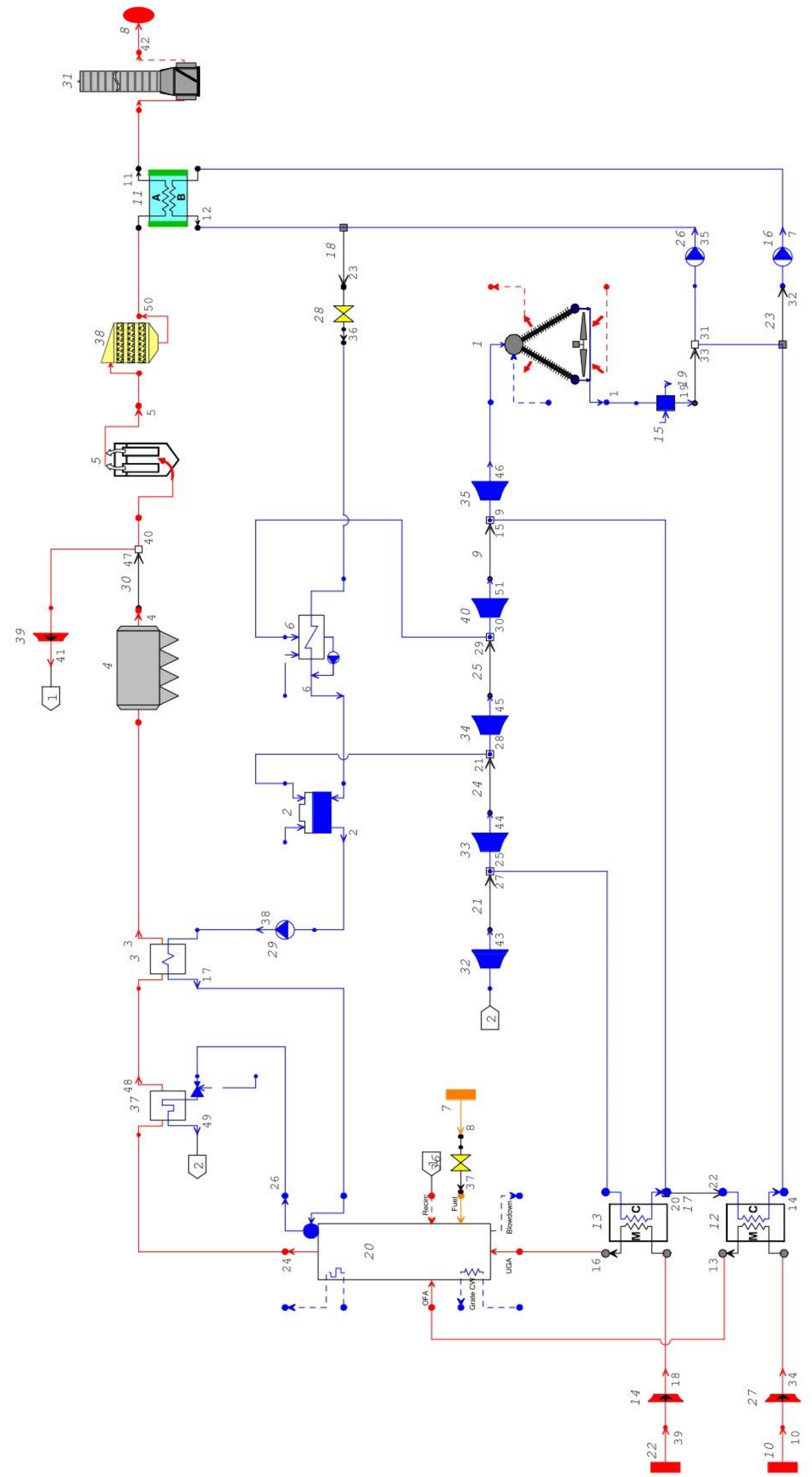


Figure 4.4. Layout of the Thermoflex® model.

4.1.2.1 Elaboration of case-study MSW properties

The fuel of the analyzed Waste-to-Energy power plant mainly consists in the fraction of domestic *trash* or *garbage* that remains after recycling and material recovery. A careful evaluation of its composition is compulsory in order to assess its thermal properties, since these directly affect the plant thermodynamic performance, and therefore the entire economic appraisal of the project. Many approximate correlations for estimation of the Higher Heating Value of substances exist in literature, primarily based on proximate or ultimate analysis.

In this work, average data from regional reports [59] have been used to estimate the fuel composition in terms of materials, summarized in Table 4.5.

Table 4.5. Emilia-Romagna waste average composition in 2010 [59, Fig. 10].

Material	[% wt]
Cellulose	26
Wood	6
Plastics	13
Glass, Metals, Inerts	9
FORSU	13
Green	15
Textiles	18

Proximate analysis of waste "as received" has been determined with the aid of data from [54], presented in Table 4.6.

Table 4.6. Composition and Lower Heating Values of waste materials.

Material	Proximate analysis as received $[\%wt]$								$LHV\left[\frac{MJ}{kg}\right]$
	C	Cl	H	O	N	S	Ash	H_2O	
Cellulose	32,91	0,13	4,56	31,55	0,17	0,10	8,58	22,00	10,71
Wood	37,98	0,08	4,59	31,87	0,45	0,07	2,96	22,00	13,6
Plastics	49,44	1,60	7,10	6,59	0,58	0,14	4,55	30,00	20,64
Glass, Metals, Inerts	-	-	-	-	-	-	95,00	5,00	-0,12
FORSU	18,13	22,00	2,46	13,53	0,96	0,10	4,60	60,00	5,51
Green	14,14	6,00	1,78	11,49	0,48	0,05	12,00	60,00	3,82
Textiles	41,89	24,00	5,45	30,13	2,83	0,21	4,25	15,00	15,69

Let $\mathbf{y}(7 \times 1)$ be the vector of materials characterization in Table 4.5, and $\mathbf{M}(7 \times 8)$ the matrix of materials proximate analysis from Table 4.6. The following matrix multiplication returns the relative atomic composition of the average waste selected for the case-study $\bar{\mathbf{y}}^{MSW}(8 \times 1)$:

$$\bar{\mathbf{y}}^{MSW} = \mathbf{M}^T \cdot \mathbf{y} \tag{4.1}$$

This is not a proximate analysis since the sum does not add up to unity, the obtained values must be normalized. It has arbitrarily chosen to neglect the small contribution of Chlorine, in order to allow properties calculation with the approximate functions presented above:

$$\begin{cases} y_i^{MSW} = \dfrac{\bar{y}_i^{MSW}}{\sum_i \left(\bar{y}_i^{MSW}\right) - \bar{y}_{Cl}^{MSW}} \\ y_{Cl}^{MSW} = 0 \end{cases} \tag{4.2}$$

$$y_{i,d}^{MSW} = y_i^{MSW}\left(1 - y_{H_2O}^{MSW}\right) \tag{4.3}$$

Results of this approximate procedure are presented in Table 4.7.

Table 4.7. Determination of composition and properties for the case-study MSW.

MSW WtE [$\%wt$]	C	H	O	N	S	Ash	H_2O	Cl	Sum
$\bar{y}^{MSW}$	29,28	3,95	19,88	0,85	0,11	14,71	30,89	8,33	108,00
y^{MSW}	29,38	3,96	19,94	0,86	0,11	14,76	30,99	-	100,00
y_d^{MSW}	42,56	5,75	28,90	1,24	0,16	21,39	-	-	100,00

while thermal properties are summarized in. The Lower Heating Value resulting from Thermoflex estimation is similar to the value given in Tecnoborgo official reports [56]: relative error results 0,38%, which is considered acceptable.

Table 4.8. Properties of the selected waste determined with approximate methods.

[MJ/kg]	Dry base	Wet base	Source
e^{CH}	18,741	12,933	[60]
HHV	18,188	12,551	[61]
LHV		10,922	Thermoflex®
		10,881	Tecnoborgo

4.1.3 Economic model

The economic assessment of the system under study is an important part of Thermoeconomic Analysis, since it provides the necessary linkage between traditional thermodynamic model and monetary evaluations, which constitute the input data for Exergoeconomic Cost Analysis and Hybrid Thermoeconomic Analysis. Therefore, economic analysis ought to be accomplished in order to result as complete and detailed as possible. It should be remembered that errors made in this section are transferred and amplified in the proceeding of

the analysis, and can lead to severe distortion of results; on the other side, results from thermoeconomic techniques have to be properly interpreted, taking into account the approximate nature of economic base data from which they have been devised.
For Thermoeconomic Analysis purposes, every economic cost term should be, in all possible cases, related to thermodynamic parameters, so that a variation in these values addresses a direct variation the Total Capital Investment, allowing a more reliable and detailed analysis.

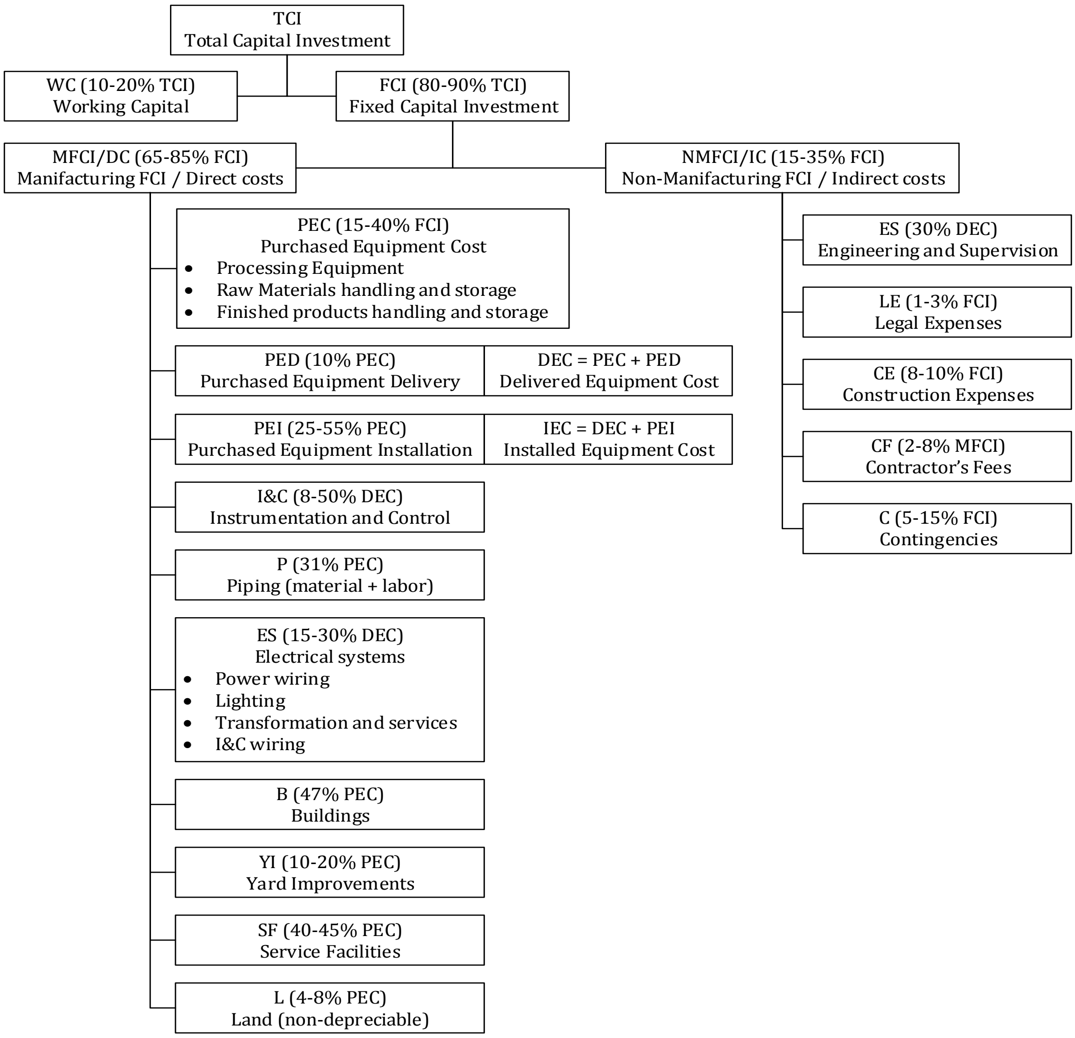


Figure 4.5. Reference build-up of the Total Capital Investment [30].

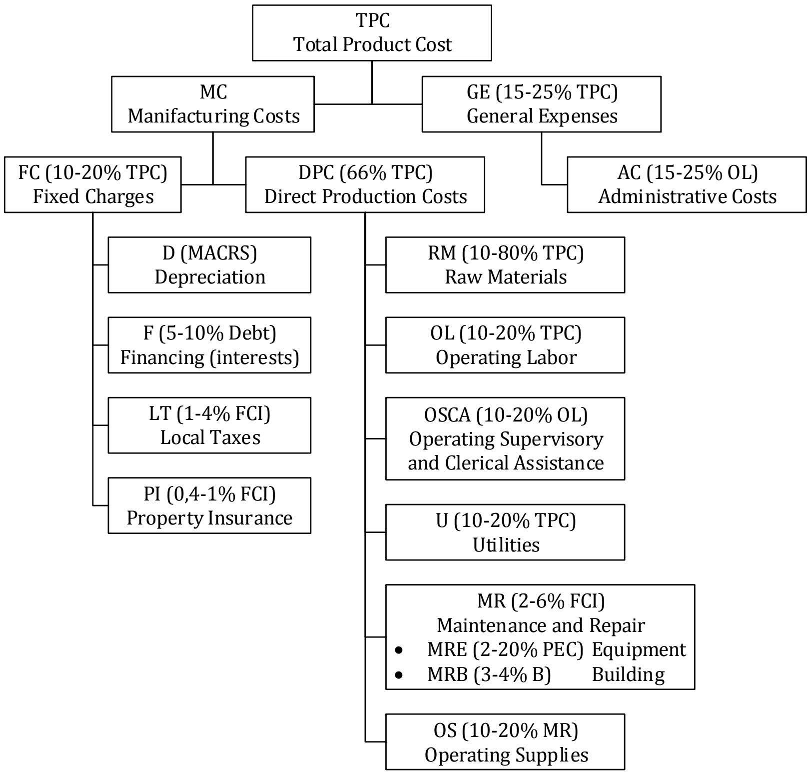


Figure 4.6. Reference build-up of the yearly production cost [30].

The economic assessment performed in this work follows the procedure described by Peters, Timmerhaus, and West [30]. Technical literature provides functional relations between the cost of equipment and the main thermodynamic parameters that affect their respective performance, and further details are given in Appendix A.2.. Other terms of the Total Capital Investment are derived, directly or indirectly, from equipment cost, as highlighted in Figure 4.5. Total yearly production cost is evaluated following the structure reported in Figure 4.6.

In this work, only an average value is determined for each economic term, in order to simplify the analysis. Indeed, deeper and more detailed estimates are required to perform a more precise analysis. Indeed, analysis of uncertainties is an essential feature that needs to be developed in order to assess the reliability of this technique. Whenever possible, data collected from similar case-studies or sectorial reports are used instead of approximate estimates.

With reference to Figure 4.5 and Figure 4.6, the selected values for the determination of the TCI and the TPC are summarized in Table 4.9.

Table 4.9. Selected values for the Economic Analysis.

Cost term		Evaluation
TCI	Purchased Equipment Delivery (PED)	5% PEC
	Purchased Equipment Installation (PEI)	20% DEC
	Piping (P)	20% PEC
	Electrical Systems (ES)	15% DEC
	Engineering and Supervision (E&S)	20% DEC
	Legal Expenses (LE)	0,5% FCI
	Construction Expenses (CE)	8% FCI
	Contractor's Fees (CF)	2% MFCI
	Contingencies (C)	5% FCI
	Working Capital	1% TCI
TPC	Maintenance and Repair: Equipment (MRE)	2% PEC
	Maintenance and Repair: Building (MRB)	3% B
	Operating Supplies (OS)	10% MR
	Property Insurance (PI)	0,5% FCI
	Administrative Costs (AC)	15% OL

The main economic assumptions for the determination of the investment and production cost and for their discount on the system's life cycle are reported in Table 4.10.

Table 4.10. Main economic assumptions. Based on [62].

Parameter		Value
Equivalent working hours per year	H_{eq} $[h/year]$	8'000
Prospected lifetime	LT $[years]$	25
Yearly average interest rate	f [%]	3
Debt fraction on investment	R_d [%]	65
Equity fraction on investment	R_r [%]	35
Interest rate on Debt	d [%]	6
Interest rate on Equity	r [%]	4
Tax rate	t [%]	30
Gate fee	c_f [€/t]	100

Based on these data, the *unit cost of capital* can be evaluated as *Weighted Average Cost of Capital* (WACC) as follows [63]:

$$m = R_d \cdot d + R_r \cdot r = 5{,}4\% \tag{4.4}$$

Hence, the *capital recovery factor* is computed as in eq. (2.80), resulting:

$$f_I = \frac{m(1+m)^{LT}}{(1+m)^{LT} - 1} = 8{,}12\% \tag{4.5}$$

4.2 State of the art of Waste-to-Energy technology

This section reports a brief focus on the technology of energy-recovery from waste. Although not directly related to the main purpose of this thesis, this part represents an interesting overview of the technology, allowing a better understanding of the working principle and of the possible alternatives for waste management coupled with energy recovery.

4.2.1 Introduction to waste management

The concept of exploiting the energy content of waste materials is not a recent idea, but modern conversion technologies are based on experiments carried out during the 1970s mostly in the USA, aiming at contrasting the first of various energy crisis [64].

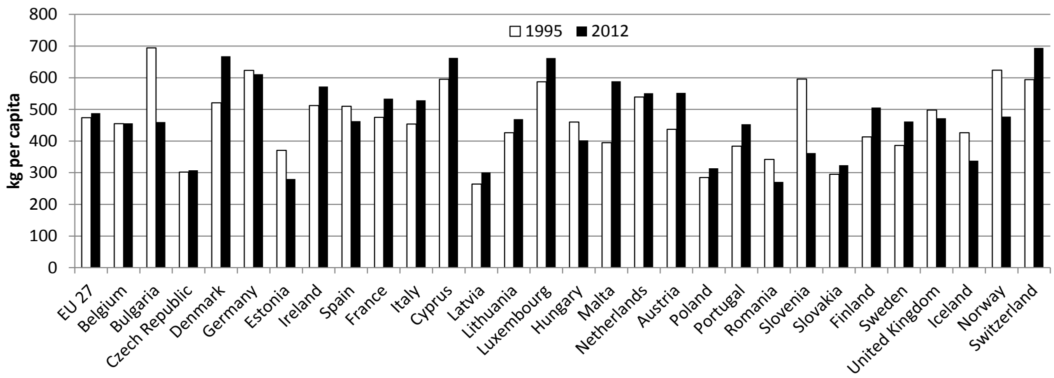


Figure 4.7. MSW generation in Europe, selected sample. Adapted from [65].

As Figure 4.7 points out, the last two decades are characterized by an average increase in per-capita generation of Municipal Solid Waste in Europe, apart from a few excellent exceptions. The average value for the European Union (27 countries) remains slightly below 500 $kg/year$ per capita.

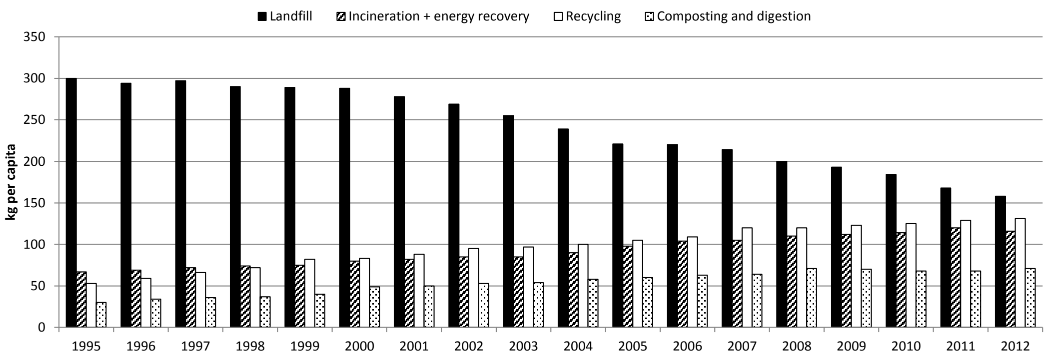


Figure 4.8. Amount of MSW per capita disposed of from 1995 to 2012, by type of treatment method. Average of the 27-countries European Union. Adapted from [65].

Figure 4.8 shows that, among the most important waste treatment methods, *landfilling* still remains the most relevant option; nonetheless, alternatives such as *composting*, *recycling*, and *material recovery* are playing an increasing role. *Incineration* (especially combined with energy recovery), is expected to have the major growing potential [65].
The trend summarized in Figure 4.8 confirms the disposition originally introduced by European Community directives [66, 67]: a sustainable waste management must aim at reducing traditional landfilling, exploiting valid alternatives such as recycling, composting, and energy recovery.

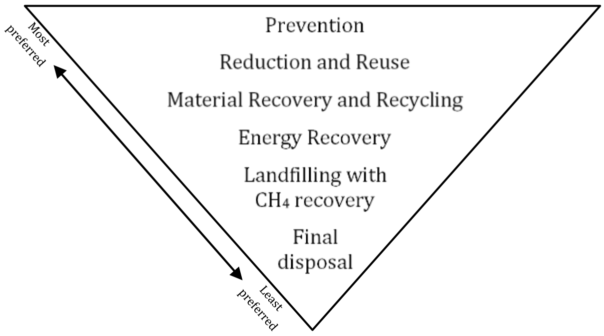


Figure 4.9. Waste Management Hierarchy pyramid. Adapted from [67].

In the light of the data presented above, it results clear that *Waste-to-Energy* (WtE) can play a major role in the wide range of options for waste management. Figure 4.10 shows the potential of MSW as a fuel in combustion systems. Depending on moisture content, a number of materials usually contained in MSW are characterized by interesting values of the Lower Heating Value.

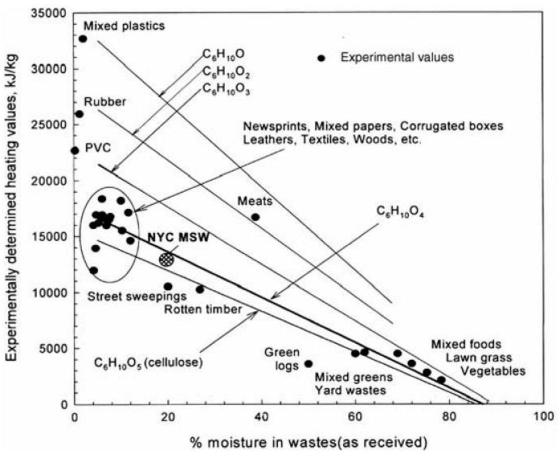


Figure 4.10. Comparison of empirically determined Lower Heating Values of various waste materials. Lines show respective values for chemicals $C_6H_{10}O_x$ [68].

To understand the powerfulness of WtE, let 500 $kg/year$ per capita be the average production of waste in Europe, with a level of material recovery and recycling around 40%; the remaining 300 $kg/year$ per capita can be assumed to have $LHV \approx 10\ MJ/kg$, resulting in a total energy content of 3 $GJ/year$ per capita, equivalent to 0,072 $toe/year$ per capita[9]. This value, compared to 4,28 $toe/year$ (Total Primary Energy Supply per capita, OECD average [1]), reveals that, even today, Waste-to-Energy can cover around 1,5– 2% of the current primary energy demand in developed countries.
An important distinction has to be made between the new concept of *energy recovery from waste* and the traditional technology of *waste incineration*. The latter deals only with mass combustion of useless material before landfilling; benefits are achieved in reducing mass and volume of the waste to be landfilled (about $70-75\%$ and 90% respectively [69]), and also in making it inert and stable over time, but no useful side effect is given; besides, the very low pollutant-emission levels from incineration plants are just recent achievements of abatement technology.
WtE goes further beyond this concept, recovering energy from the thermal treatment of waste, in the form of heat and/or mechanical/electrical power. Benefits in this case become even greater: reducing the need for traditional power plants based on fossil fuels is essential to meet long-run goals for primary-resources saving.

4.2.2 General structure of a WtE facility

Scope of this section is to report the state of the art of the most relevant Waste-to-Energy technologies for Municipal Solid Waste management, for it is of greatest concern in the waste management sector.
One line of a Waste-to-Energy power plant is commonly made up of four main operations [70]:

1. Thermal treatment
2. Energy recovery
3. Flue-gas treatment
4. Pre-treatment

What follows is a brief and not exhaustive description of each of these stages.

[9] $1toe = 41{,}868GJ$.

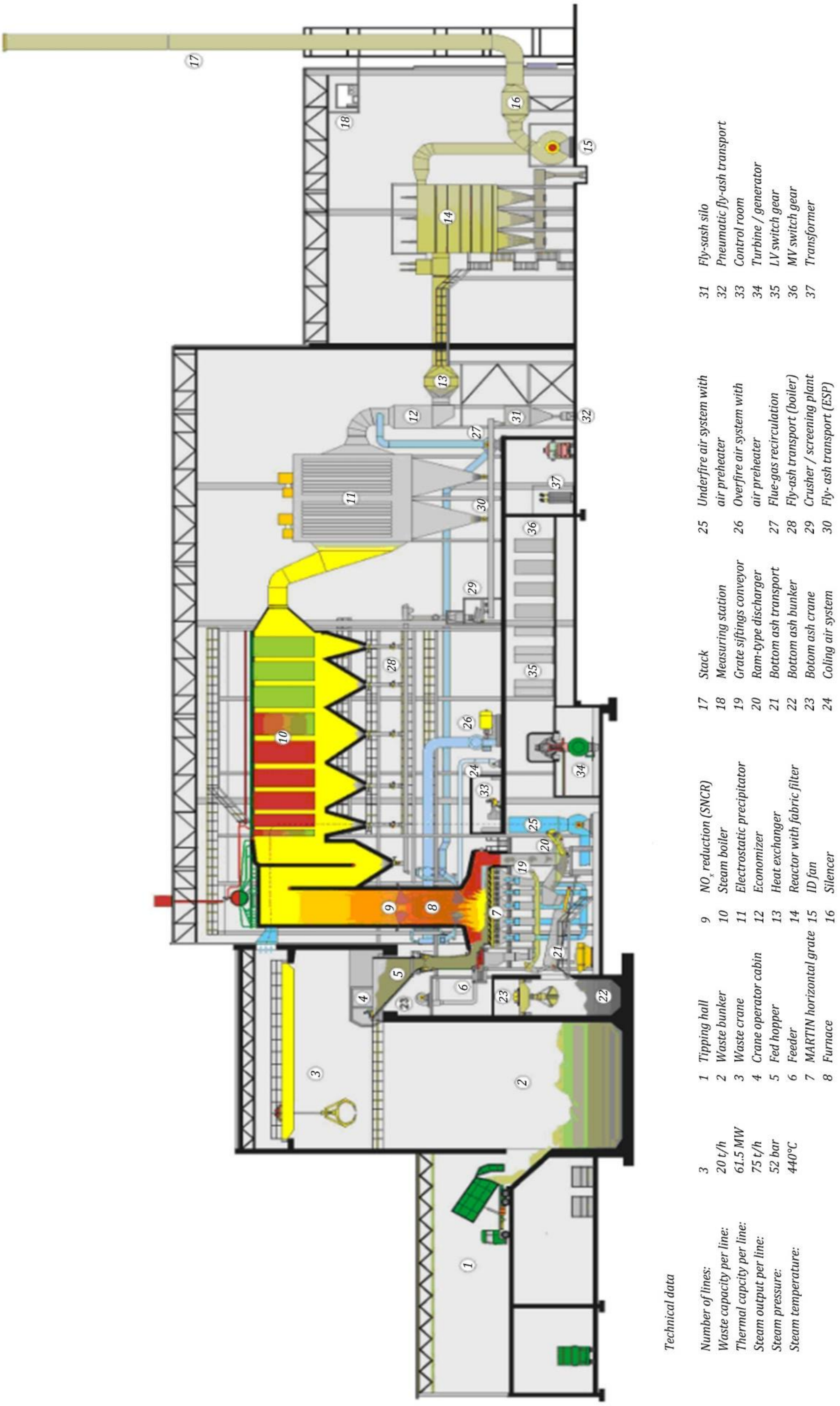


Figure 4.11. Typical new generation WtE power plant [71].

4.2.3 Thermal treatment stage

Despite the fact that incineration is the most widely applied [72], it is only one among the whole set of thermal treatment options that can be carried out in a WtE facility. The most exploited alternatives include gasification and pyrolysis. As a general concept, gasification and pyrolysis differ from combustion in the fact that they are only partial oxidation processes, and the output consists in a flow of combustible gases that will be further oxidized in a second step; instead, combustion is a complete oxidation, whose output is a high temperature stream of inert gases. This temperature ranges a wide span of values due to parameters optimization needed as waste coming from different sources may present different characteristics.

Table 4.11. Raw characterization of the main thermal treatments with interesting applications in MSW management [70].

	Reaction temperature (°C)	Pressure (bar)	Stoichiometric ratio
Incineration	800–1450	1	>1
Gasification	500–1600	1–45	<1
Pyrolysis	250–700	1	0

The type of thermal treatment accomplished is relevant to determine the overall structure and efficiency of the plant, because it is responsible for converting waste into useful energy in the form of a gaseous stream embodied of either a physical or a physical-chemical energy (or, better, exergy) content.

4.2.3.1 Incineration

Mass burn incineration of as-received waste in a grate combustor is the oldest option, and it is shown in Figure 4.12. Hearth of the system is the *grate*, whose duty is to fulfill a good contact between the waste and the primary combustion air blown from below; this is the reason why newer plants rely on innovative grate designs in the attempt to achieve better performances. Some examples are reported in Figure 4.13.

To guarantee good conversion efficiencies, usually grate incinerators adopt $50-100\%$ excess air. Primary (under-fire) air accounts for $50-70\%$ of the total, and is taken from the storage bunker (to minimize odor emissions) and blown underneath the grate with a three-fold purpose: provide oxidant, cool the grate, and avoid slag formation. The remaining fraction is secondary (over-fire) air, injected at higher velocity in the upper part of the combustion chamber to complete combustion and mix the flue-gas.

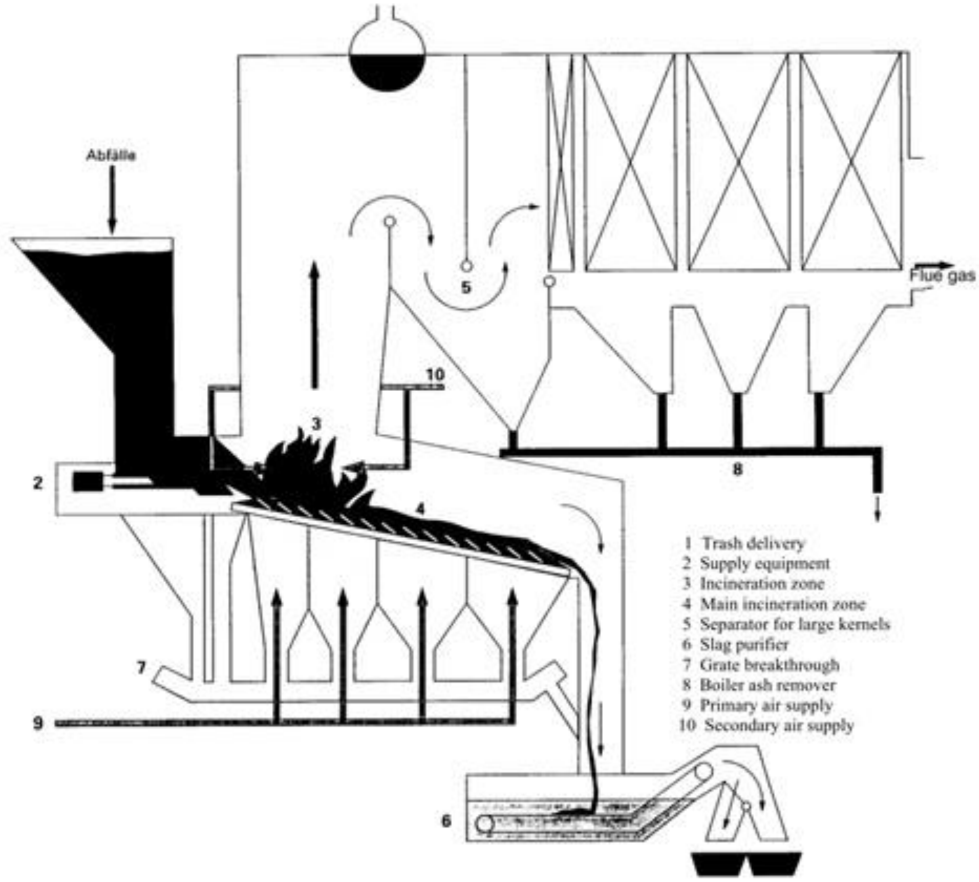


Figure 4.12. General structure of an incineration furnace with energy recovery [73].

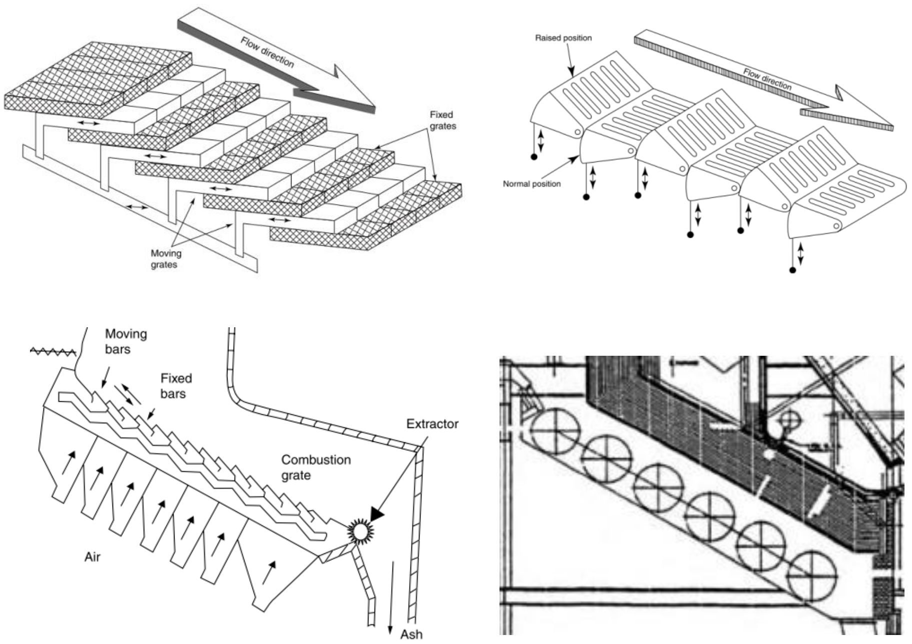


Figure 4.13. Different grate designs. Motion is designed in order to maximize tumbling and mixing of the waste [74].

Legislation [75, Sec. 6.1] establishes that, in case of non-hazardous waste:

> *"Incineration plants shall be designed, equipped, built and operated in such a way that the gas resulting from the process is raised, after the last injection of combustion air, in a controlled and homogeneous fashion and even under the most unfavourable conditions, to a temperature of 850°C, as measured near the inner wall or at another representative point of the combustion chamber as authorized by the competent authority, for two seconds."*

At the end of the grate, ashes and unburnt particles at temperatures around $450°C$ are cooled down in the *bottom ash discharger*, a water-filled piston that allows for a safe handling of solid residues and acts as an air-seal for the furnace (the other sealing is guaranteed by the waste filling the hopper).
The choice of the grate is usually performed together with the design of the *combustion chamber*. This optimization process is based on waste characteristics, and is of great relevance since the utmost part of the combustion process happens above the grate. Different general designs can be distinguished as in Figure 4.14.

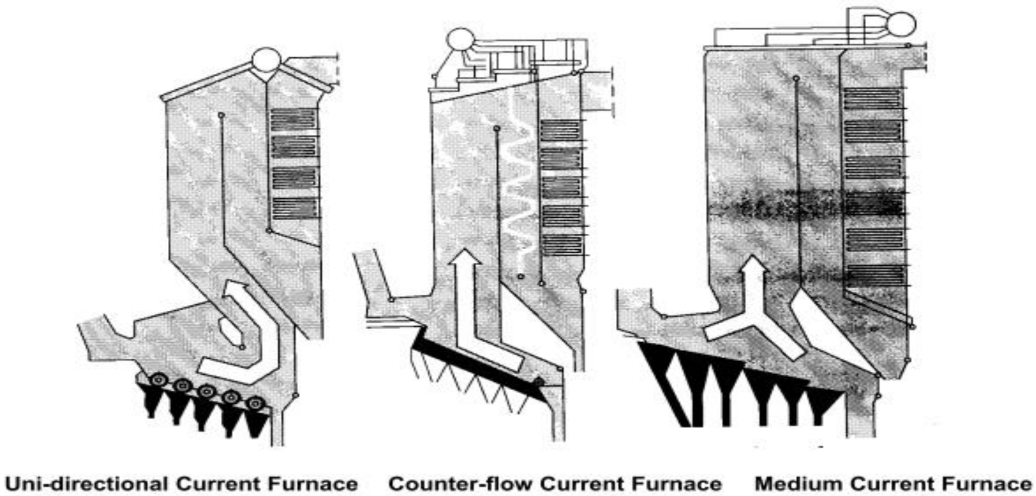


Figure 4.14. Various designs for the combustion chamber [73].

Uni-directional current (or parallel flow) reaches the highest residence times and temperatures, so the highest conversion efficiencies, but needs an important pre-heating of the primary air. Conversely, the counter-flow (or countercurrent) arrangement has the lowest residence times and temperatures, thus requiring secondary air to abate unburnt particles in the flue-gas. The medium current (or center-flow) represents a good compromise between advantages and drawbacks of the previous two options.

An alternative to the traditional grate combustor is the *rotary kiln* (or rotary combustor), shown in Figure 4.15. This apparatus consists in a cylindrical vessel, whose slight tilt and rotation around its axis provide the waste with the necessary tumbling action and horizontal motion from one end to the other. As the waste exits the kiln, it is introduced in a post-combustion chamber, where secondary air injections achieve a better burnout.

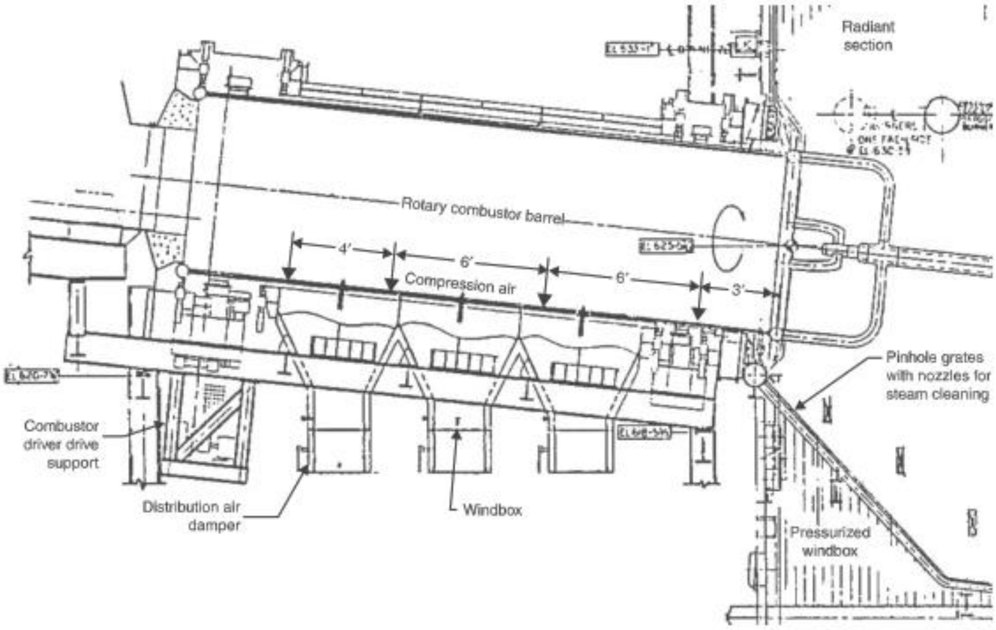
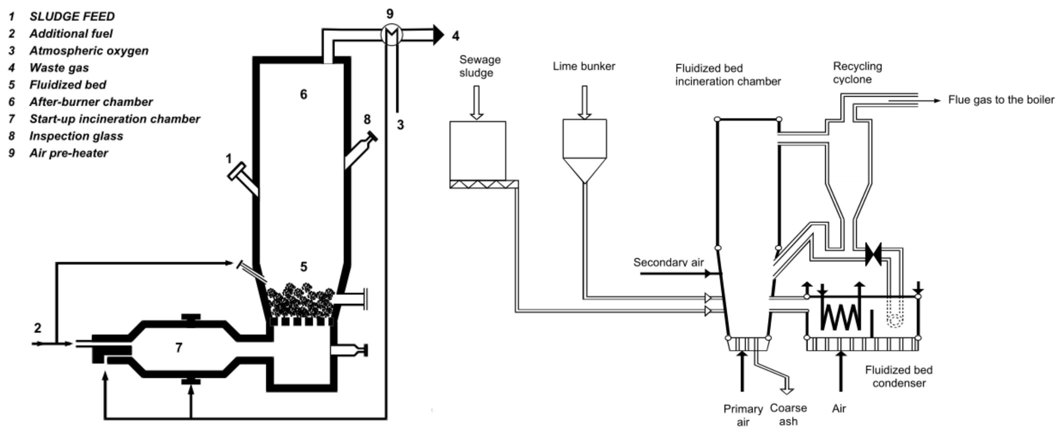


Figure 4.15. Cross section of a rotary combustor with the detail of the primary air distribution system and the connection to the secondary combustion chamber [76].

Another opportunity, of wider application for *Refuse-Derived Fuel* (RDF)[10] and *Sewage Sludge* (SS), is the *fluidized bed* incinerator, either stationary (Bubbling, BFB) or Circulating (CFB), shown in Figure 4.16.
In both cases, waste is fed continuously as finely subdivided particles (significant pre-treatment may be necessary, particularly in the case of unsorted MSW). Combustion happens in a bed of inert materials which is maintained in fluidized conditions by an injection of high-velocity under-fire air inside a vertical cylindrical vessel. The empty space at the top of the vessels is called *freeboard* and must provide temperature conditions coherent with cited legislation.

[10] RDF is a homogenous fuel derived after a series of pre-treatments carried out on waste with the purpose to increase its combustion properties and performances. *Cfr.* Section 4.2.6 below.



Bubbling Fluidized Bed Circulating Fluidized Bed

Figure 4.16. Different Fluidized Bed technologies [73].

An additional heat exchanger is usually implemented to pre-heat the under-fire air. A special version of the BFB aims at increasing tumbling and mixing of the inert bed providing the vessel with a rotational motion.

4.2.3.2 Gasification and pyrolysis

Traditional incinerators can be straightforwardly converted to operate under air-deficient conditions. The aim is to perform a thermal degradation that converts the organic matter of waste into a syngas, mostly composed of CO and H_2, while inorganic materials is discarded as slag. This syngas can be conveniently used as fuel in a subsequent thermodynamic cycle to recover its energy content.

Noticeable advantages comprise smaller gas volumes, bringing about smaller and cheaper components and minor needs for the flue-gas treatment section, rejection of solids as an inert slag, and lower emissions ensured by lower excess air and easier temperature control. On the other side, these systems usually require some stricter pre-processing of waste, resulting in an increase of costs. Table 4.12 shows that pyrolysis provides a better quality than gasification, due to the higher fraction of valuables molecules (CO and H_2) and the lower dilution in inert gases (CO_2 and N_2).

Table 4.12. Typical compositions and HHV of syngases from pre-processed MSW [57].

[%]	CO	CO_2	H_2	CH_4	C_xH_y	N_2	$HHV\left[\frac{MJ}{Nm^3}\right]$
FB gasification (air)	10	26	7	5	4	54	5–7,5
Pyrolysis	34	19	33	6	3	5	11

A more recent and promising technology is *plasma arc gasification*, a very high temperature thermal process that exploits the electric arc created in a special torch as the energy source to convert waste into syngas. *Plasma* is a state of matter corresponding to a hot ionized gas generated by interaction of an inert gas (e.g. Argon) with an electro-magnetic field. Because of the extreme temperatures generated ($5'000 - 15'000°C$) [70], this technology can accept (almost) un-processed waste, showing very low emissions of hazardous contaminants [70, 77]. Inorganic materials is rejected as a vitrified slag, which still has a commercial value. For these reasons, this process can reach very high efficiencies, as can be seen from Figure 4.17. Indeed, reducing the need for special pre-treatments of the feedstock and for subsequent flue-gas cleaning systems is an enormous benefit in economic terms.

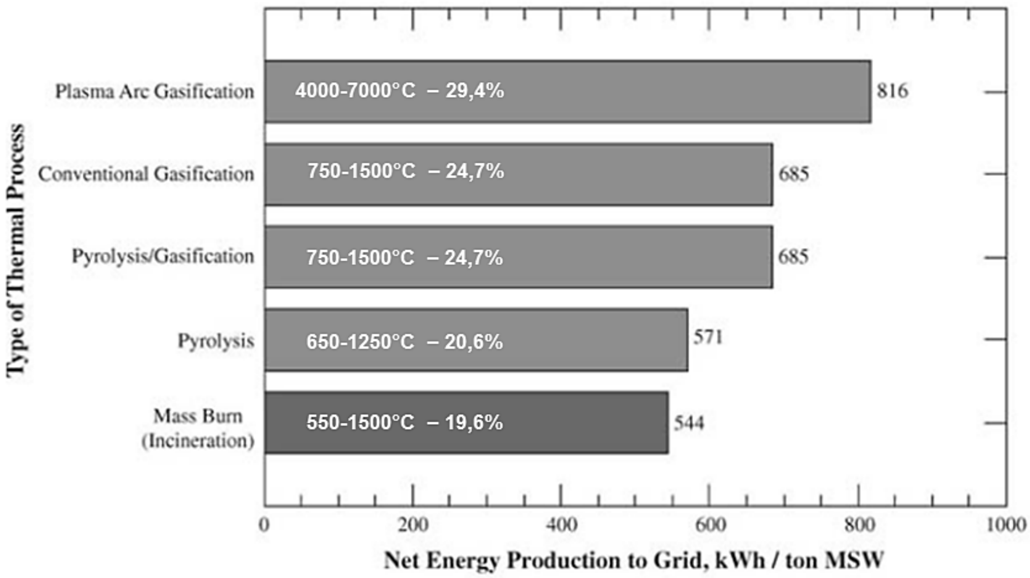


Figure 4.17. Comparison between various thermal processes in terms of Net Electrical production, Temperature ranges and Net Efficiencies (based on a 10 MJ_{LHV}/kg waste feedstock). Adapted from [77].

4.2.4 Energy recovery stage

Independently on the thermal process carried out, the output will be a hot stream of inert flue-gas, originated from the exothermic reactions involved in the overall combustion process. It is necessary to cool down this stream in order to perform subsequent cleaning treatments before releasing it into the atmosphere. Therefore, recovering this excess heat results a smart and efficient solution. This is conveniently performed by a *heat-transfer fluid* evolving through a thermodynamic power cycle, whose output will be the generation and supply of electricity and/or heat.

As Figure 4.18 points out, the level of integration between the thermodynamic cycle and the furnace is remarkable.

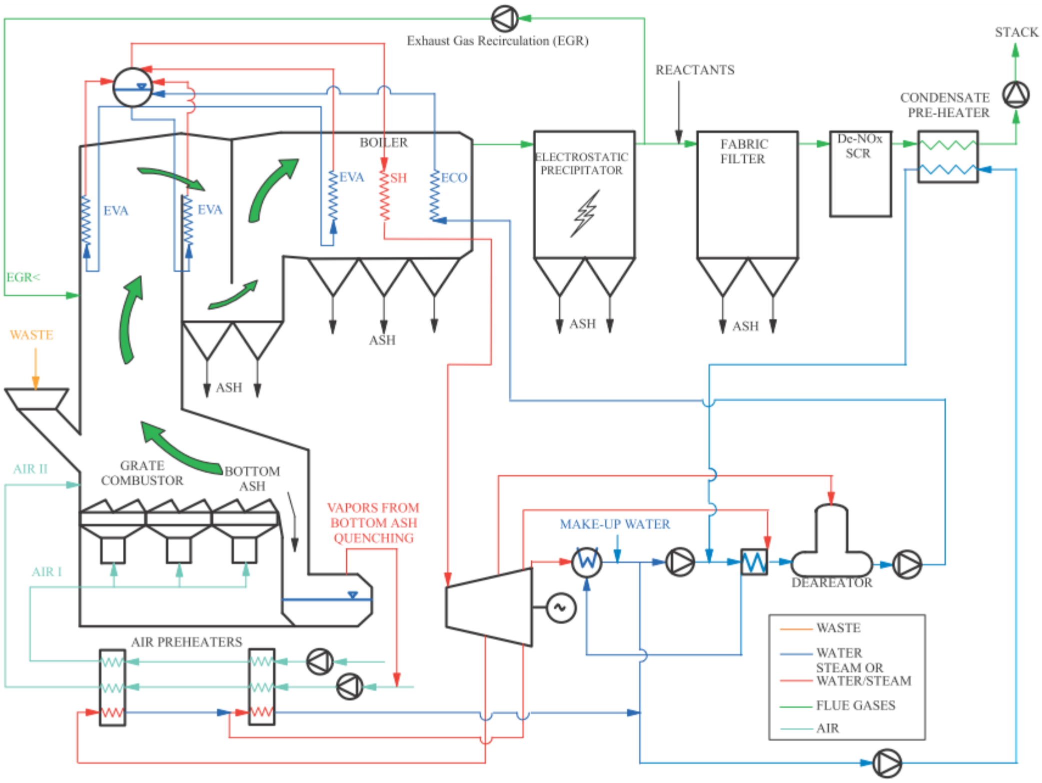


Figure 4.18. Layout of a conventional Grate Combustor integrated with a Rankine power cycle producing superheated steam for electrical generation [78].

The core of the heat recovery process is the *boiler*, responsible for heating water up to the conditions of high-pressure steam that will be expanded in the steam turbine. Figure 4.19 shows common designs for a WtE boiler.

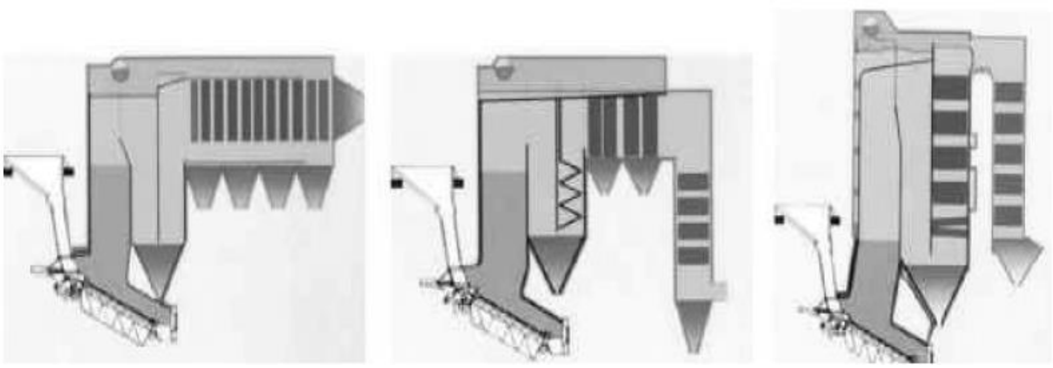


Figure 4.19. Various boiler design, with different dispositions of the heat exchangers. From left to right: horizontal, combined, and vertical [73].

Because of the high temperatures reached during combustion, usually a radiant pass above the grate is included, with *waterwall bundles* in which the evaporative process occurs at $20 - 60 bar$ [79].
Since waste incineration generates a high quantity of fly-ash, a first empty pass is designed to abate dust entrainment in the flue-gas flow, protecting the successive heat exchanger tubes from fouling and corrosion, and increasing the overall availability of the equipment.
The convective section begins with the *superheater*, where saturated steam is brought to temperatures around 400–500°C [79], and proceeds with the *economizer*, which pre-heats the liquid phase of the working fluid before sending it to the evaporator. A common shrewdness to gain in efficiency is to design a final heat-exchange step to pre-heat the air to be blown in the combustion chamber up to about 250°C [64].
It is not infrequent that a water-cooling system is implemented in the grate and integrated with the thermodynamic cycle. This complication allows temperatures in the combustion chamber to be controlled independently from the primary air supply.

4.2.5 Flue–Gas Treatment stage

At the end of the Energy Recovery section, the flue-gas temperature results roughly around $140 - 200°C$ [10, 19]. Lower temperatures would lead to corrosion problem due to condensation of acid gases; higher temperatures would not be tolerated by the Flue–Gas Treatment system. Usually, modern facilities tend to optimize the boiler outlet temperature of the flue-gas to match FGT requirements.
Table 4.13 summarizes some of the limit value for emissions of pollutants in the atmosphere as stated in the European Union legislation, where more precise and complete information are detailed [75, Sec. 7.1].

Table 4.13. Restrictions to emissions of pollutants into the atmoshpere from waste incineration plants (daily average values). Adapted from [75].

Pollutant	Air emission limit value $[mg/Nm^3]$
Total dust	10
Volatile Organic Compounds (as Total Organic Carbon)	10
Hydrogen Chloride (HCl)	10
Hydrogen Fluoride (HF)	1
Sulphur Dioxide (SO_2)	50
Nitrogen monoxide (NO) and nitrogen dioxide (NO_2)	200

4.2.5.1 Particulate removal

The first step in a FGT is usually a filter to remove coarse particles, dust and ashes. Depending on the average size of the particles (which is strictly related to the original waste composition) and the desired removal efficiency, different types of filter can be adopted. Among others:

- *ElectroStatic Precipitator* (ESP) induces an electric field to charge solid particles that will perceive an attractive force towards one of the two electrodes and will be thus captured. Usual operating temperature ranges $160 - 260°C$; removal efficiency is highly influenced by electric resistivity of the particles.
- *Fabric Filter* (FF) or BagHouse is subject to a widespread use because of its very high efficiency across a broad range of particle sizes. The filter medium is usually a woven or felted fabric, made either with cotton or artificial materials, and has to be accurately chosen to match with the requirements imposed by the composition and characteristics of the dust, the flue-gas velocity, and the operating temperature.
- *Cyclone* (CY) is characterized by a robust structure and a wide temperature range with almost no pressure drop. The flue-gas is fed from the side and raised from a central point; the resulting centrifugal force separates the gas from solid matter, which is easily collected in a lower hopper. Major drawback is the low efficiency, but cyclones can still be conveniently applied as a first-step de-duster before other stages.

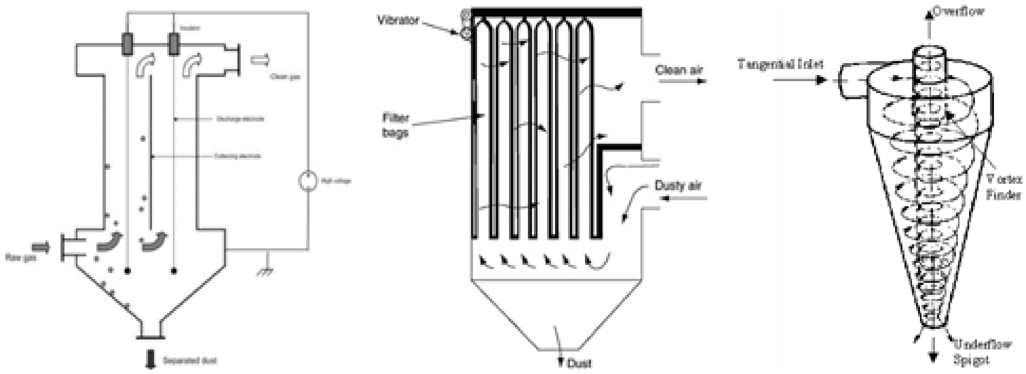


Figure 4.20. Diagrams of the most common devices for particulate matter removal. From left to right: ESP, FF, CY. Images taken from the Internet.

4.2.5.2 Nitrogen Oxides removal

Techniques aiming at removing NO_x can be discriminated among:

- *Primary*, intended to prevent the generation of such molecules. Figure 4.21 shows how NO_x formation mechanisms are variously, but noteworthy, dependent on temperature conditions. A decrease in the operating temperature ensures lower levels of these pollutants in the flue-gas stream flow. In this perspective, primary techniques aim at promoting even temperature gradients in the combustion chamber: optimal distribution of under-fire and over-fire air, adoption of Flue-Gas Recirculation (FGR), and staged combustion are common solutions for many WtE facilities.

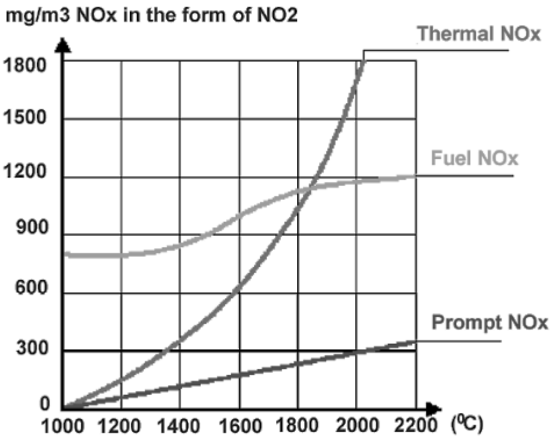


Figure 4.21. Different NO_x formation mechanisms [81].

- *Secondary*, with the purpose to reduce the NO_x already formed in the combustion section, in order to fulfill limitations imposed by legislation. Ammonia or urea are exploited as reducing agents:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (4.6)$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \quad (4.7)$$

Two basic processes can be distinguished [70], depending on the method adopted to supply the reducing agent to the system:

- *Selective Non-Catalytic Reduction* (SNCR) consists in the direct injection of the reducing agent in the combustion chamber, so that NO_x are reduced at temperatures around $850 - 1000°C$. To avoid emission of NH_3 (*ammonia slip*), removal efficiency cannot exceed $60 - 80\%$.

- *Selective Catalytic Reduction* (SCR) consists in adding an ammonia-air mixture to the flue-gas. Reactions with NO_x are catalyzed in a dedicated device, with typical efficiencies over 90% and temperatures ranging $250 - 450°C$. In WtE facilities, application of SCR after de-dusting and acid-gas removal is a common practice; in such cases, re-heating of the flue-gas may be required. Moreover, it is not uncommon that both SNCR and SCR are applied simultaneously, as shown in Figure 4.22; in this case, SCR utilizes the fraction of reducing agent which has not been converted in the previous SNCR stage.

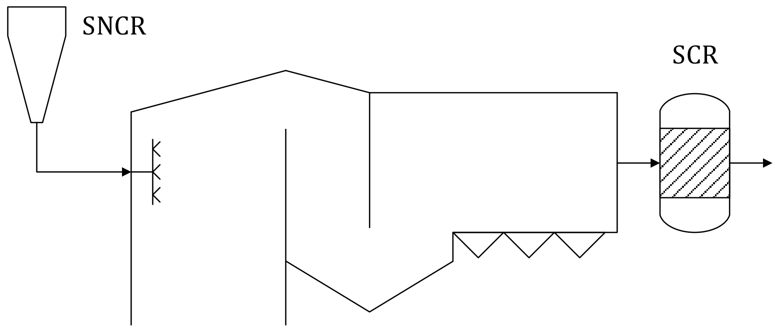


Figure 4.22. Detail of the boiler with both NO_x removal technologies.

4.2.5.3 Acid-gas removal

Substances such as HCl, HF, and SO_x, are treated with alkaline reagents (usually lime or sodium bicarbonate), to perform chemical or physical sorption. Beside the direct addition of sorbents in the combustion chamber (*direct desulphuration*), three main strategies can be differentiated [57, 70]:

- *Dry process*: sorbents are mixed in the flue-gas flow as a dry powder. Solid products a unreacted reagents will be separated in a subsequent filter (commonly a FF);
- *Semi-wet* (or *semi-dry*) process: sorbents are added to the flue-gas flow as an aqueous solution or suspension in the form of a spray. The higher active surface ensures better utilization of the reagents, while evaporation of the solvent allows for a further cooling of the flue-gas. Solid products will be collected in a subsequent filtering stage;
- *Wet process*: this technique adopts various types of scrubber systems, with different solutions to maximize affinity with the diverse substances to remove. It results a multi-stage process, producing an important quantity of waste-water needing special treatments.

4.2.5.4 Volatile Organic Compounds

The most relevant organic pollutants are those known as *dioxins* (polychlorinated dibenzo-p-dioxins, PCDD) and *furans* (polychlorinated dibenzofurans, PCDF). These substances (PCDD/F) are supposed to originate from fly-ash or dust from incineration, at temperatures around $200 - 450°C$ [70]. A widely adopted and very effective option is *absorption* carried out by particles of *activated carbon*, either in the form of a powder injected in the flue-gas flow before particulate filters, or in the form of a dedicated fixed bed with a honeycomb structure. Solid particles will then be collected by the subsequent filtering stage. Activated carbon has been testified to reduce also heavy metals emissions.

Another solution is to specifically modify the SCR design to perform also catalytic oxidation of organic compounds, with efficiencies of $98 - 99{,}9\%$ [70].

4.2.5.5 Situation of Italian facilities

Figure 4.23 presents the situation of FGT systems currently implemented in Italian waste incinerators.

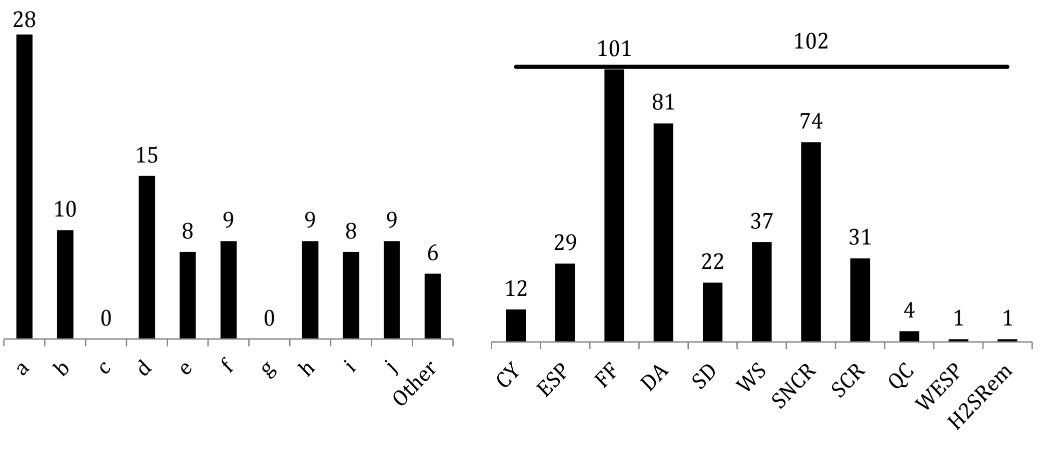


Figure 4.23. Flue-Gas Treatment statistical analysis [55]. Left: number of lines adopting one the varoius configuration. Right: number of lines implementing selected equipments (*CY*: Cyclone, *ESP*: ElectroStatic Precipitator, *FF*: Fabric Filter, *DA*: Dry process, *SD*: Semi-Dry process, *WS*: Wet Scrubber, *SNCR*: Selective Non-Catalytic Reduction, *SCR*: Selective Catalytic Reduction, *QC*: Quench, *WESP*: Wet Electro-Static Precipitator, *H2SRem*: H_2S removal).

Selected sequences have been identified and summarized in Table 4.14, which is the reference for the left-hand side diagram. As it is shown, most of the sample implement a Dry process, with Fabric Filters and a SNCR (option a). The main FGT stages recognized include acid-gas removal, NO_x removal, and particulate removal. The latter in particular can be designed as a double-stage process, especially when the second step is dedicated to the recovery of reaction products and unreacted reagents for eventual reuse.

Table 4.14. Selected sequences for FGT adopted in Italian waste incinerators.

<table>
<tr><th>FGT</th><th>DeNO$_x$</th><th>DeDust</th><th colspan="2">Acid gas removal</th><th>DeNO$_x$</th></tr>
<tr><td>a</td><td rowspan="4">SNCR</td><td></td><td rowspan="2">DA (SD) + FF</td><td rowspan="3"></td><td rowspan="4"></td></tr>
<tr><td>b</td><td rowspan="6">ESP</td></tr>
<tr><td>c</td><td>WS</td></tr>
<tr><td>d</td><td rowspan="3">DA (SD) + FF</td><td>WS</td></tr>
<tr><td>e</td><td rowspan="4"></td><td></td><td rowspan="5">SCR</td></tr>
<tr><td>f</td><td>WS</td></tr>
<tr><td>g</td><td>WS</td><td rowspan="3">DA + FF</td></tr>
<tr><td>h</td><td rowspan="3"></td><td>DA (SD) + FF</td></tr>
<tr><td>i</td><td rowspan="2">SNCR</td><td></td></tr>
<tr><td>j</td><td>DA (SD) + FF</td><td>WS</td><td></td></tr>
</table>

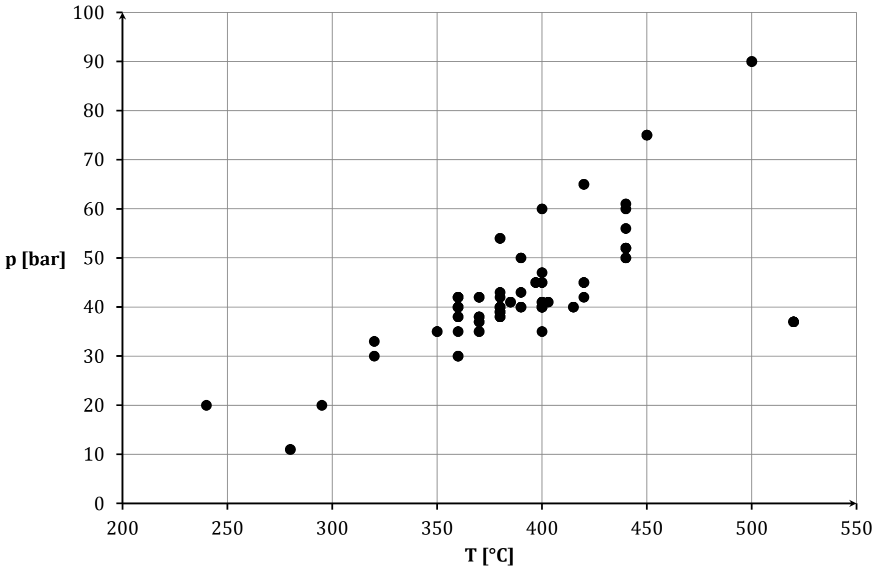


Figure 4.24. Steam parameters of Italian Waste-to-Energy power plants [55].

4.2.6 Pre-treatment stage

Every kind of waste treatment facility implements a certain set of preliminary processes before feeding the waste to the Thermal Treatment section. Some of these pre-treatments are necessary to ensure safer operating conditions and a higher availability of the plant, other are supplementary, adopted in special cases with the objective to minimize the environmental impact and to increase the overall efficiency of the power cycle [82]. Although the recognized benefits in terms of material and energy recovery, adoption of pre-treatments has not yet been demonstrated as more profitable with respect to direct mass burn of unsorted waste.

Mass-burn incineration is the option requiring the least amount of pre-processing. It involves the basic treatments performed in every kind of waste treatment facility, namely:

- A *visual screening* is usually accomplished by human operators when the waste is received, removing undesired refuse such as white goods (stoves, refrigerators and other domestic appliances).
- *Pit fluffing* is commonly performed to roughly reduce the size of the bulkiest materials with the same crane used to load the hoppers.

Many other technologies (such as fluidized beds, gasification, pyrolysis, and RDF) are not able to operate with untreated waste and require an enhanced fuel. Therefore further operations are carried out on the feedstock, aiming to reduce its average size and size distribution, homogenize its characteristics and increase its heating value. Subsequent benefits include additional material recovery, reduction of environmental impact and easier handling.

- A common first-step screening is performed by a *trommel*, a tubular sieve, endowed with openings on its sides, that rotates on a tilted axis. Waste is charged in the inner side and proceeds from one end to the other, so that objects, that are smaller than the openings, fall and are separated from the rest.

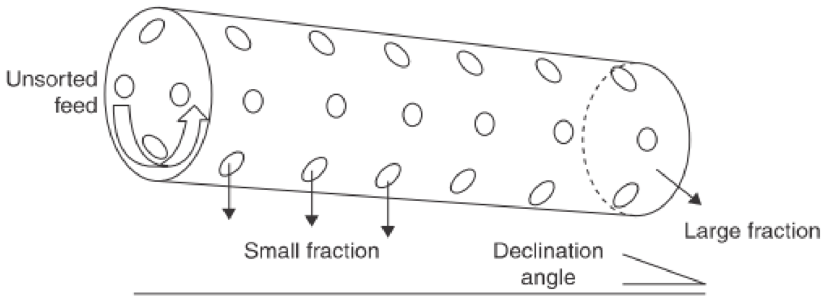


Figure 4.25. Basic design of a Trommel screening device. [82]

- *Magnetic separation* is applied to recover valuable ferrous materials: a magnetic drum attracts and separates iron and steel from unsorted waste and releases them on a conveyor belt.
- A similar process, known as *Eddy current separation*, is targeted to separate non-magnetic metals such as aluminum, copper, and brass.
  A rotating magnet is used to induce a variable magnetic field, which induces eddy currents in the electrically conductive materials.

Therefore, these last materials feel a repulsive force and are pushed away from the main flow.

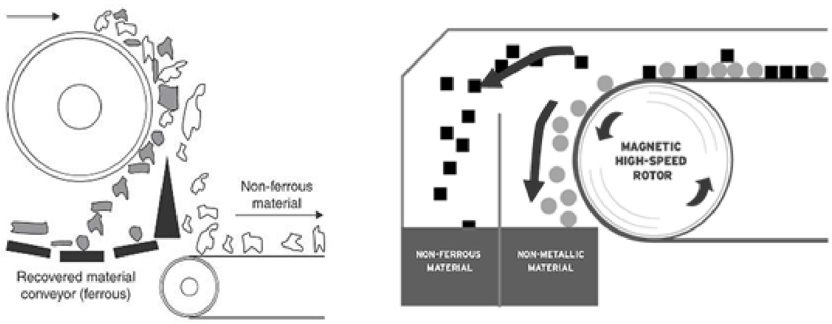


Figure 4.26. Metal removal processes.
Right: Magnetic separation [82]. Left: Eddy current separation [internet].

- The organic fractions of MSW can be conveniently converted by *Mechanical-Biological Treatments* in order to make waste inert and stable, reducing pollution issues in landfill sites. A combination of aerobic/anaerobic digestion processes will ensure lower release of landfill gases (particularly CH_4) and liquids (leachate).
- A set of operation applicable on the inert, separated fraction of MSW is the sequence of *Shredding*, *Pelletization* and *Torrefaction*. The first one is an arrangement of size-reduction processes that aims to homogenize the size of the feedstock. The second one takes the homogeneous material coming from the shredding section, and compresses it to produce a solid and easy-to-handle fuel in the form of small compact pellets. The third one is an optional thermal treatment that pellets can undergo to improve storage/handling properties and heating value. It is an intermediate form between drying and pyrolysis, performed in the temperature range 200-300°C to remove oxygen and humidity from the waste.

Figure 4.27. Products of Shredding, Pelletizing, and Torrefaction [Internet].

Chapter 5
Case study: H–TIOA and Design Evaluation

In this chapter, standard Exergoeconomic Cost Analysis (EeCA) and Hybrid Thermoeconomic Input–Output Analysis (H–TIOA) are applied to the case study of the Waste-to-Energy power plant presented in previous chapter, aiming at assessing the actual performance of the base configuration, and at evaluating the range of possibilities for improvements.

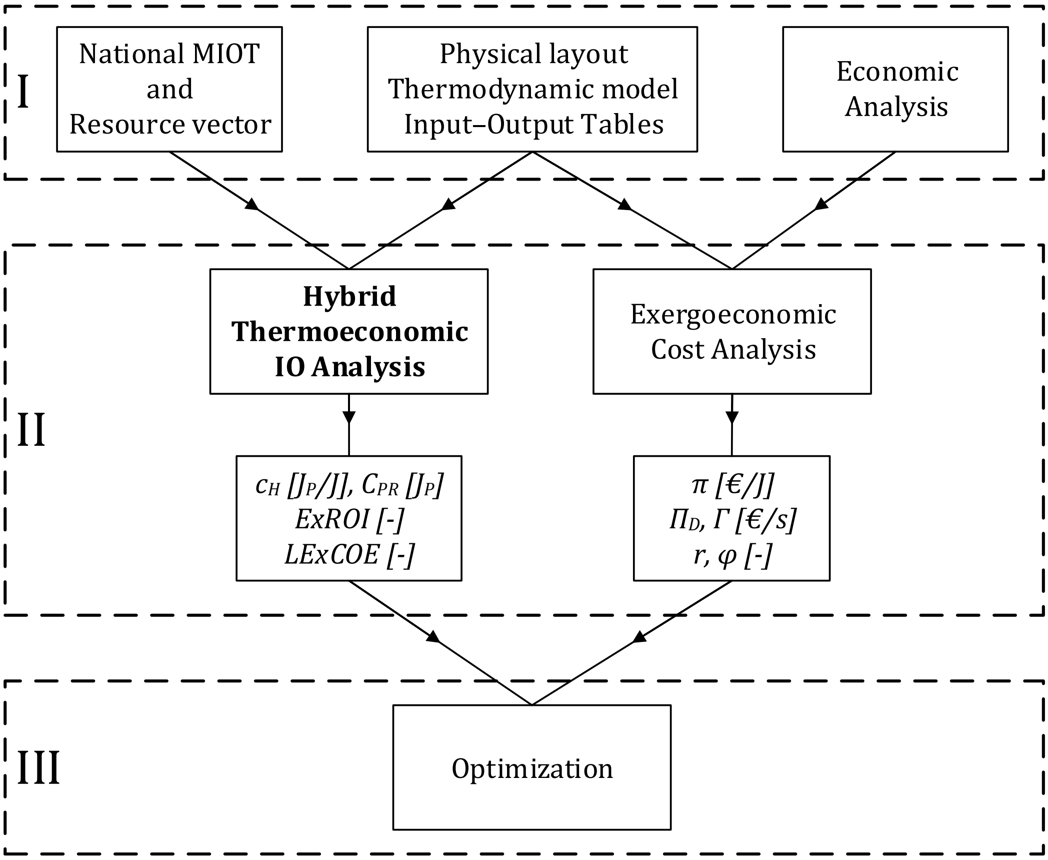


Figure 5.1. Flow diagram for the application of H–TIOA.

The general structure of the procedure follows the schematic representation of Figure 5.1, hence it includes:

- Standard Exergy and Exergoeconomic Cost Analyses, whose output consists in the primary cost of the final demand of the system, as well as in the exergoeconomic indexes that will be considered afterwards to perform Design Evaluation and Optimization;

- The Hybrid Thermoeconomic Input–Output Analysis, which provides indications on the environmental performance of the system by evaluating the total Primary Resources Cost (C_{PR}), the Exergy Return On Investment (*ExROI*), and the Levelized Exergy Cost Of Exergy (*LExCOEx*), as introduced in section 3.2.2;
- The novel optimization procedure, performed iteratively and guided by the exergoeconomic parameters previously evaluated.

As Figure 5.1 points out, the process for the application of the hybrid model can be partitioned in three different phases.

I. In the first step, all the models involved in the representation of the system are defined: the system is shaped both from a physical-thermodynamic and from an economic perspective, and its entire supply chain is considered through the national MIOT.
II. In the second stage, Hybrid Thermoeconomic Input–Output Analysis is carried out as described in section 3.2, assessing the performance of the system in terms of its direct and indirect fossil-fuels consumption. This part ought to be coupled with a standard Exergoeconomic Cost Analysis, since this last provides the necessary guidelines for the subsequent optimization procedure through the Design Evaluation indicators described in paragraph 2.3.4.2.
III. The third phase refers to the application of an enhanced optimization procedure accomplished from a thermoeconomic viewpoint, as detailed in paragraph 2.3.4.

The WtE example is considered relevant for the following reasons:

- Direct fuel intake consists in a renewable source, while fossil fuels are consumed only indirectly; hence, it provides an didactical application of primary-resource accounting based on indirect consumption;
- It can provide a contribution to the literature about Thermoeconomic Analysis of Waste-to-Energy technology, whose potential in the current national energy supply systems needs to be deepened.

Thermodynamic simulation accomplished in Thermoflex® provides an output that is imported in a spreadsheet, appropriately designed to perform the Exergy Cost and Exergoeconomic Cost analyses depicted in Chapter 2, and Hybrid Thermoeconomic Input-Output Analysis described in Chapter 3.

5.1 Preliminary operations

Definition of the model for Thermoeconomic Analysis purpose does not resemble the physical structure of the power plant: aggregation level of the system is defined according to economic cost data availability.

Each component thus recognized is classified according to the RP criterion introduced in paragraph 2.3.1. In this specific case, 15 productive and 5 dissipative components have been depicted, and the resulting productive structure is shown in Figure 5.2. It is straightforward to notice the differences between this diagram, the physical arrangement in Figure 4.1, and the simulation layout in Figure 4.4.

With reference to Figure 5.2, the RP classification reported in Table 5.1 can be accomplished; each number represents the exergy of the respective flow.

Table 5.1. Resource–Product classification of the case-study.

	Component		Resource	Product
Productive	a)	Grate Furnace	1+4+7+12+45	8+(27-26)+49
	b)	Deaerator	30	24-23
	c)	Feedwater Heater	31+44	23-(22+19)
	d)	Economizer	9-10	26-25
	e)	SuperHeater	8-9	28-27
	f)	Steam Turbine	28-29-...-33	36+...+48
	g)	Pump26	38	19-18
	h)	Pump16	39	2-(20+35)
	i)	Pump29	40	25-24
	j)	Fan14	41	3-2
	k)	Fan27	42	6-5
	l)	Fan39	43	12-11
	m)	AirHEX13	29-34	4-3
	n)	AirHEX12	32+34-35	7-6
	o)	Heat Exchanger	15-16	22-21
Dissipative	p)	AeroCondenser	33-(18+20)+ 37	58
	q)	ES Precipitator	10-(11+13)+ 46+52-53	55
	r)	Fabric Filter	13-14+47+53-54	56
	s)	SC Reactor	14-15+48+54	57
	t)	Stack	16	17

Information provided by this table are visually reported in Figure 5.3, in which it is highlighted which flows each component takes exergy from (Resource) or gives exergy to (Product). Since no exergy could neither disappear nor accumulate outside the components, each stream node must result balanced.

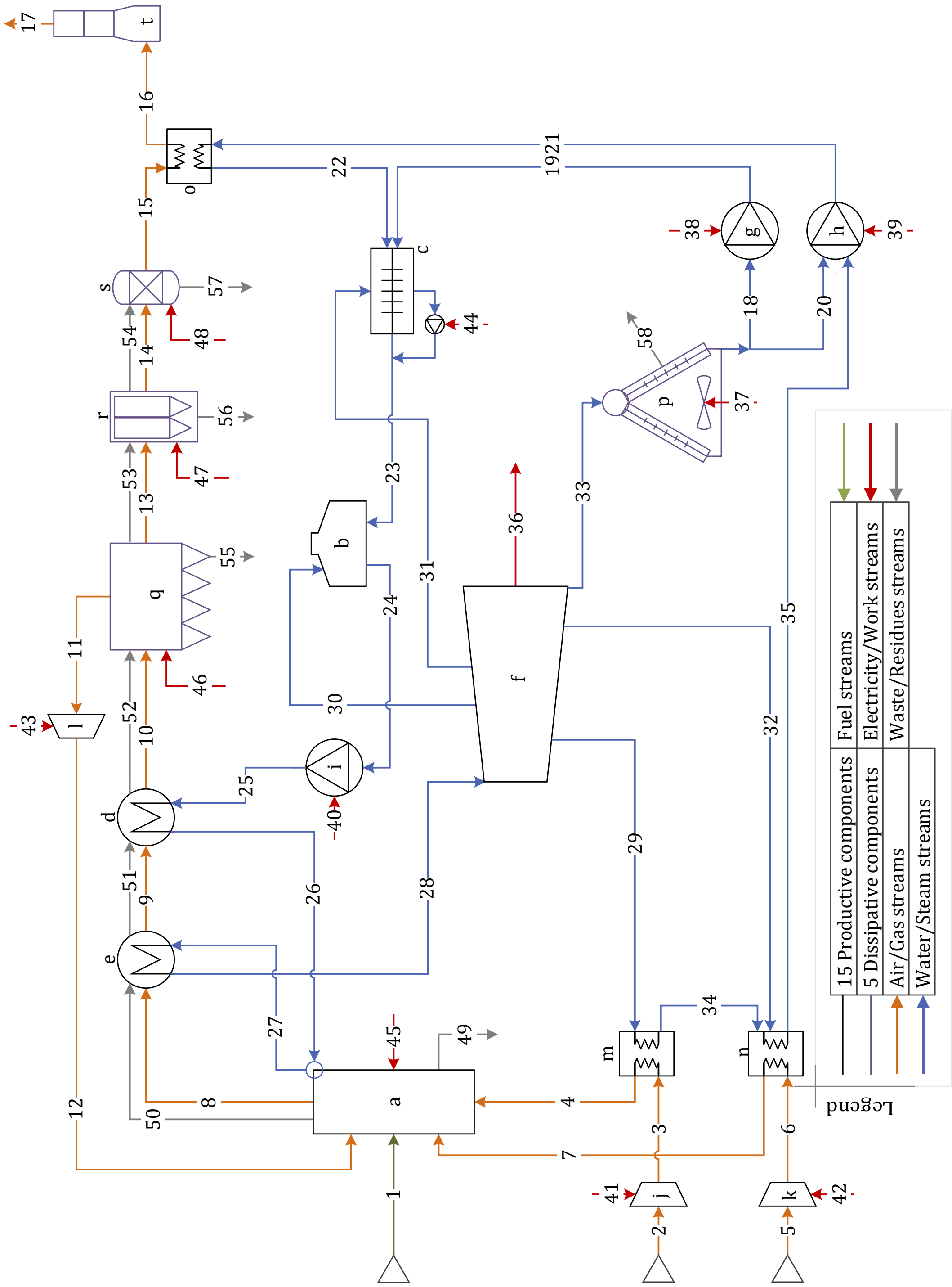


Figure 5.2. Productive structure of the system.

Notice that exogenous resources input consists only in the exergy of the waste, while useful products consists in electric energy and bottom ashes. All the other outputs are classified as dissipations, such as rejected heat, dusts and fly-ashes, and chemical residues.

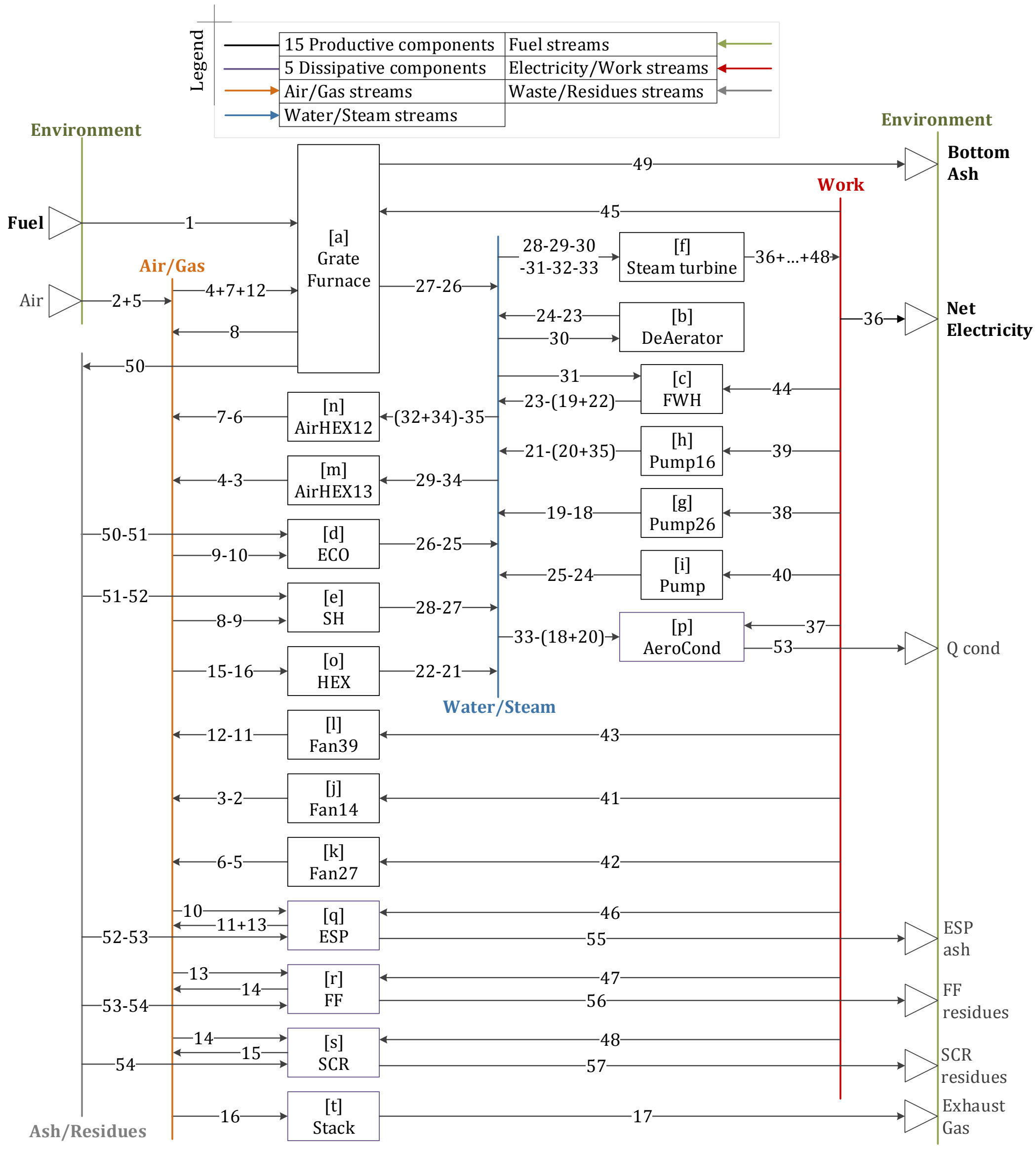


Figure 5.3. Rational Resource-Product diagram of the WtE plant.

It is now upfront to determine exergy destructions, efficiencies and unit exergy consumptions applying the definitions given by eq. (2.32), (2.33) and (2.34).

5.1.1 Resource–Product Table

To accomplish computation of the physical Transaction matrix of the system it is necessary to identify origin and destination of every exergy flow, highlighting where the resource and product of each component are respectively produced and utilized. This task is accomplished with the visual aid of the functional diagram shown in Figure 5.4, which displays connections that have a functional meaning, instead of physical.

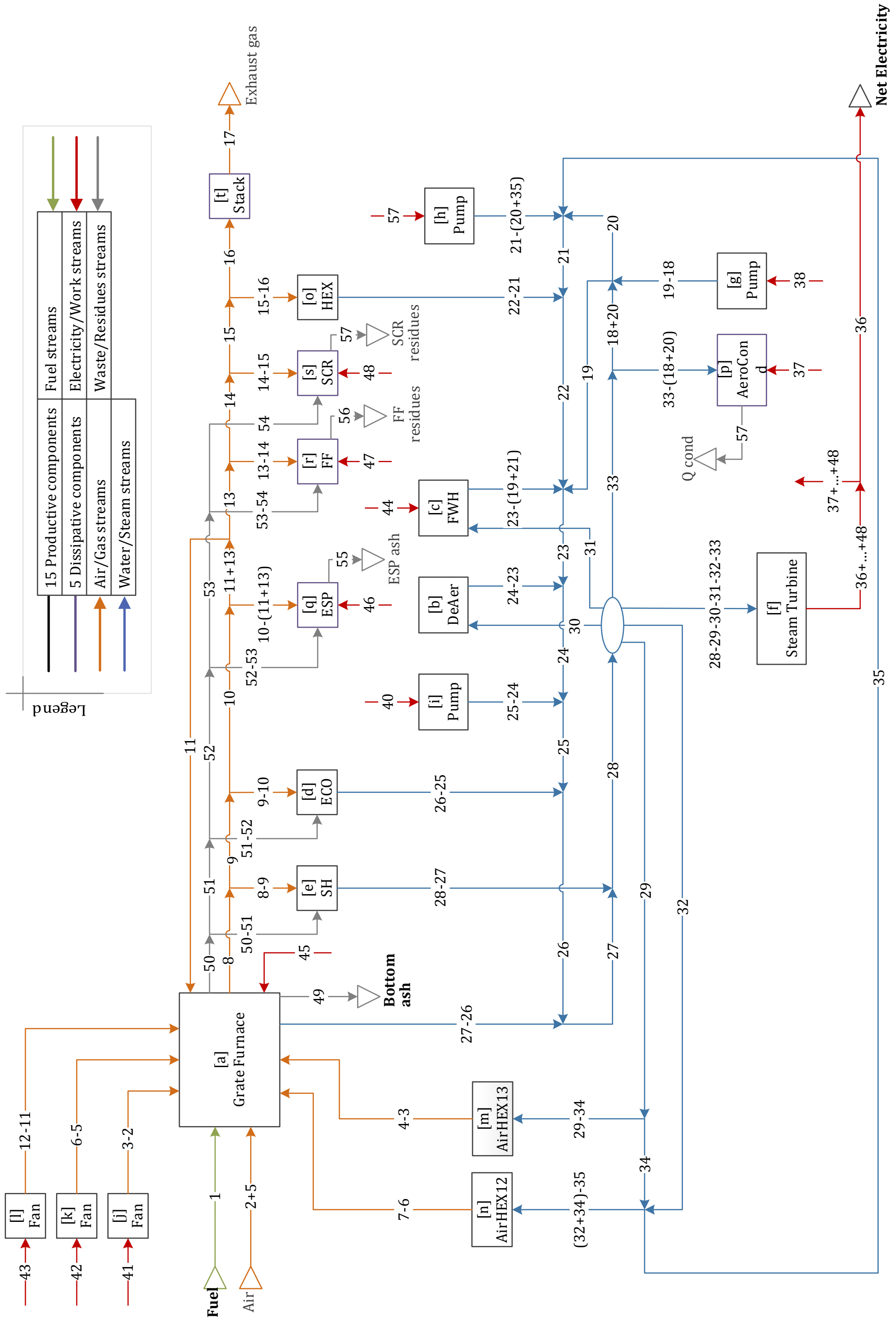


Figure 5.4. Functional Resource–Product diagram of the WtE plant.

For instance, useful effects, in terms of exergy increase, provided to under-fire and over-fire air by fans (j) and (k) as well as air pre-heaters (m) and (n) is assigned entirely to the grate furnace (a), which is the recipient of such exergy. An important feature of this diagram is related to the allocation problem when the product of multiple components is used simultaneously as resource by multiple other components. The junction detailed in Figure 5.5 is representative of this situation.

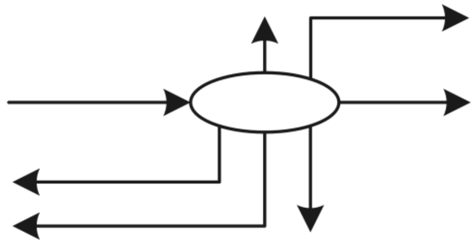


Figure 5.5. Detail of an exergy junction requiring a reallocation pattern.

In this case, the increase in exergy content of the water/steam occurring in the grate furnace as well as all the pumps, heat exchangers, deaerator, and feed-water heater, is added up and subsequently redistributed to all the user components (steam turbine, air pre-heaters, feed-water heater, and aerocondenser). This task is accomplished with the aid of coefficients named *junction ratios* r, which provide the pattern to allocate the product of the junction to each user component. This allocation is performed proportionally to the exergy that each user component receives as resource from the junction, as it is reported in Table 5.2. According to this definition, it is straightforward to demonstrate that the junction ratios must add up to one for each junction:

$$\sum_i r_i = 1 \tag{5.1}$$

Table 5.2. Junction ratios determination.

Component		Resource (from junction)	
b	Deaerator	r_b	30
c	Feed-water heater	r_c	31
f	Steam Turbine	r_f	28–29–30–31–32–33
m	Air HEX [12]	r_m	29–34
n	Air HEX [13]	r_n	32+34–35
p	Aerocondenser	r_p	33–(18+20)

Following this procedure, the physical Transaction matrix of the system can be generally outlined from Figure 5.4, resulting as shown in Table 5.3.

Table 5.3. General layout of the Transaction Matrix of the system.

Component		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
	Ref	R_a	R_b	R_c	R_d	R_e	R_f	R_g	R_h	R_i	R_j	R_k	R_l	R_m	R_n	R_o	R_p	R_q	R_r	R_s	R_t
a	P_a	11	r_b(27-26)	r_c(27-26)	9-10	8-9	r_f(27-26)	-	-	-	-	-	-	r_m(27-26)	r_n(27-26)	15-16	r_p(27-26)	10-11-13+52-53	13-14+53-54	14-15+54	16
b	P_b	-	r_bP_b	r_cP_b	-	-	r_fP_b	-	-	-	-	-	-	r_mP_b	r_nP_b	-	r_pP_b	-	-	-	-
c	P_c	-	r_bP_c	r_cP_c	-	-	r_fP_c	-	-	-	-	-	-	r_mP_c	r_nP_c	-	r_pP_c	-	-	-	-
d	P_d	-	r_bP_d	r_cP_d	-	-	r_fP_d	-	-	-	-	-	-	r_mP_d	r_nP_d	-	r_pP_d	-	-	-	-
e	P_e	-	r_bP_e	r_cP_e	-	-	r_fP_e	-	-	-	-	-	-	r_mP_e	r_nP_e	-	r_pP_e	-	-	-	-
f	P_f	45	-	44	-	-	-	38	39	40	41	42	43	-	-	-	37	46	47	48	-
g	P_g	-	r_bP_g	r_cP_g	-	-	r_fP_g	-	-	-	-	-	-	r_mP_g	r_nP_g	-	r_pP_g	-	-	-	-
h	P_h	-	r_bP_h	r_cP_h	-	-	r_fP_h	-	-	-	-	-	-	r_mP_h	r_nP_h	-	r_pP_h	-	-	-	-
i	P_i	-	r_bP_i	r_cP_i	-	-	r_fP_i	-	-	-	-	-	-	r_mP_i	r_nP_i	-	r_pP_i	-	-	-	-
j	P_j	3-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
k	P_k	6-5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
l	P_l	12-11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
m	P_m	4-3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
n	P_n	7-6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
o	P_o	-	r_bP_o	r_cP_o	-	-	r_fP_o	-	-	-	-	-	-	r_mP_o	r_nP_o	-	r_pP_o	-	-	-	-
p	P_p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
q	P_q	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
r	P_r	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
s	P_s	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
t	P_t	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Subsequent Table 5.4 reports the labels of the streams included in the Final Demand, Residues, and Resources vectors of the system.

Table 5.4. Build-up of Output (Final demand and Residues) and Resource vectors.

Comp	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t
W	49	-	-	-	-	36	-	-	-	-	-	-	-	-	-	58	55	56	57	17
R	1+2+5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

5.2 Exergy and Exergoeconomic Costs

With the Transaction matrix and the vectors just defined, it is possible to perform the standard Thermoeconomic Input–Output Analysis explained in section 2.3, and to compute the standard exergy and thermoeconomic costs of the final demand.

From eq. (2.43), (2.63), (2.67), and (2.68), the method is here summarized:

$$\left.\begin{array}{l}\mathbf{A}=\mathbf{Z}\cdot\hat{\mathbf{x}}^{-1}\\ \mathbf{B}=\mathbf{R}\cdot\hat{\mathbf{x}}^{-1}\end{array}\right\} \quad\rightarrow\quad \mathbf{L_R}=\left(\mathbf{I}-\mathbf{A}-\mathbf{W}\right)^{-1} \quad\rightarrow\quad \mathbf{c}=\left(\mathbf{B}\cdot\mathbf{L}_R\right)^T \qquad (5.2)$$

The same structure applies to the exergoeconomic costs determination, as long as proper redefinition of the Resource vector is performed according to the procedure explained in paragraph 2.3.3.1.

From the Economic Assessment, Purchased Equipment Cost of each component, Total Capital Investment, and Operation and Maintenance yearly costs are computed. With suitable operation hypotheses, fixed and variable costs are summed and converted in monetary units per second, since the Exergy Analysis is carried out in power units (exergy units per second). Afterwards, the total is distributed to each component, proportionally to their PEC. O&M costs comprise: Labor, Operation and Maintenance of Civil and Electromechanical structures, Utilities (water, methane, electricity, and gasoil), Reagents for water treatment, fly-ash inertization, and Flue-Gas Treatment (Sodium Bicarbonate, Activated Carbon, Lime, and Ammonia Solution), and Residues Disposal. While Labor, Operation and Maintenance, and Utilities costs can be assigned to all the components, the other terms must be allocated to the components directly responsible for their consumption. In case of simultaneity, allocation is performed through the PEC share.

Table 5.5 summarizes the variable costs and the corresponding components to which they are assigned.

Table 5.5. Distribution of variable costs to equipment.

		Labor	Utilities	O&M	Reagents for water treatment	Other reagents	Sludge disposal	Residues disposal
a	Grate Furnace	✓	✓	✓	✓	Fly-ash inertization	✓	Bottom ash and fly ash
b	Deaerator	✓	✓	✓	✓		✓	
c	Feedwater Heater	✓	✓	✓	✓		✓	
d	Economizer	✓	✓	✓	✓		✓	
e	SuperHeater	✓	✓	✓	✓		✓	
f	Steam Turbine	✓	✓	✓	✓		✓	
g	Pump26	✓	✓	✓	✓		✓	
h	Pump16	✓	✓	✓	✓		✓	
i	Pump29	✓	✓	✓	✓		✓	
j	Fan14	✓	✓	✓	✓		✓	
k	Fan27	✓	✓	✓	✓		✓	
l	Fan39	✓	✓	✓	✓		✓	
m	AirHEX13	✓	✓	✓	✓		✓	
n	AirHEX12	✓	✓	✓	✓		✓	
o	Heat Exchanger	✓	✓	✓	✓		✓	
p	AeroCondenser	✓	✓	✓	✓		✓	
q	ES Precipitator	✓	✓	✓	✓		✓	
r	Fabric Filter	✓	✓	✓	✓	Dry FGT	✓	Na residues
s	SC Reactor	✓	✓	✓	✓	NH_3 solution	✓	
t	Stack	✓	✓	✓	✓		✓	

Moreover, an additional cost is assigned to the Grate Furnace, to account for fuel consumption; since this term is, actually, a revenue, it is accounted as a negative cost, determined as the gate fee converted in monetary units per second. From Table 4.10, the “cost” of the fuel can be determined as follows:

$$c_f = -\frac{100\frac{€}{t}\cdot 120'000\frac{t}{year}}{8'000\frac{h}{year}\cdot 3600\frac{s}{h}} = -0,417\frac{€}{s} \qquad (5.3)$$

5.3 Hybrid Thermoeconomic costs

Extension of the Transaction matrix to include the national Monetary Input–Output Table in the Thermoeconomic Analysis is a delicate tasks, especially when the Upstream Cut-off matrix has to be defined, since this last is the linkage between the national economy and the physical system. All the system's inputs are provided as products form other producing sectors, apart from labor, which is part of the value added and is hence discarded. Carefulness is required when allocating each resource to the correct cell $sector \rightarrow component$; indeed, any different decision will affect the resulting costs of final demand, since different sectors show different efficiencies.
In this Life Cycle analysis, only the Construction and Operation phases are considered, due to scarcity of data regarding dismantling and recovery of energy systems.
In this work, 63-sectors Italian MIOT for year 2010, provided by the National Statistics Institute [83] has been used.

5.3.1 Construction phase

To determine the primary exergy cost of constructing an energy system, the Total Capital Investment provides the connection between national economy and the plant. The physical system is accounted as a single component, the final demand for which is equal to 1. The power plant under construction is considered as a new unit, so the national final demand needs no correction.

Table 5.6. Resume of investment costs and respective ISIC segments.

TCI	ISIC Sector	
Purchased Equipment Cost	C 28	Manufacture of machinery and equipment n.e.c.
Purchased Equipment Delivery	H 49	Land transport
Purchased Equipment Istallation	C 33	Repair and installation of machinery and equipment
Piping	C 25	Manufacture of fabricated metal products
Instrumentation & Control; Electrical systems	C 27	Manufacture of electrical equipment
Buildings; Yard Improvements; Construction Expenses; Contingencies	F	Construction
Contractor's Fees	K 64	Financial service activities
Land	L	Real estate activities
Legal expenses	M 69	Legal and accounting activities
Working Capital	D	Electricity, gas, steam and AC supply

Instead, the monetary resources fueling the system must be subtracted, in the respective row of the MIOT, from the cell intercepting the column referring to

ISIC F 42 – "Civil engineering", which includes construction of power plants and waste-treatment facilities.

Table 5.6 reports the main elements of the TCI and the corresponding producing sector.

Since no dissipative components appear in the physical system, which is composed by a single productive unit of "power plant", the standard thermoeconomic procedure, without reallocation of residues, is sufficient to obtain the cost, in terms of primary exergy of fossil fuels, to build the entire energy system.

5.3.2 Operation phase

To estimate the total primary exergy cost of operating the power plant, the economy MIOT and the system's PIOT (Physical Input–Output Table) are appropriately merged as explained in Section ⍰. In this specific case, a difference arise in the system's table definition: namely, the exergy content of the bottom ash recovered from the grate furnace (stream 49), while it was previously part of the system's final demand, is now assigned to the Downstream Cut-off matrix (System to Nation), because it is recovered as building material, fueling ISIC Sector F – "Construction". It is not necessary to include this term in the hybrid final demand, given that it is not the final product of main interest. The system's final demand now includes only electric energy generation.

Terms of the yearly production cost are allocated to the respective producing sector in the Upstream Cut-off matrix, in correspondence to the column of the user component; in case of simultaneous utilization, allocation is performed proportionally to the share of Purchased Equipment Cost, analogously to the procedure followed in Section 2.3.3.1.

Table 5.7 conveys the cost voices, with the respective branches and components. It can be highlighted that recovery of iron scrap must accounted as a negative input cost, since it refers to a by-product revenue.

Moreover, final demand for electrical energy from ISIC Sector D – "Electricity, gas, steam, and AC supply" must be corrected to account for the power plant contribution; therefore, assuming a final customer price of $190\,€/MWh$, physical production can be converted into the monetary equivalent and subtracted from the stated segment.

Table 5.7. Production costs allocation from economic sectors to equipment.

Cost	ISIC Sector		Component
Process water; Process methane; Electricity	D	Electricity, gas, steam, and AC supply	Whole system
Gasoil	C 1920	Manufacture of refined petroleum products	
Reagents for water treatment	C 20	Manufacture of chemicals and chemical products	
Sludge treatment	E 37	Sewerage	
Maintenance	C 33	Repair and installation of machinery and equipment	
Bottom ash and Fly-ash disposal; Iron scrap recovery (-)	E 38	Waste collection, treatment and disposal activities; materials recovery	(a)
Na residues disposal			(r)
Fly-ash inertization reagents	C 20	Manufacture of chemicals and chemical products	(a)
Sodium bicarbonate; Activated Carbon; Lime			(r)
Ammonia Solution			(s)

5.4 Iterative optimization process

A first iterative strategy is inquired, as explained in paragraph 2.3.4. Starting from the base configuration of the power plant, the Hybrid Thermoeconomic Input–Output Analysis has been performed as explained in Figure 5.7. Results are reported in Table 5.8 and plotted in Figure 5.7.
Indications arising from the Thermoeconomic Design Evaluation, which are reported in detail in Appendix, are used to guide the step-by-step optimization process. Each simulation differs from the previous one by the value of a single parameter. The Exergoeconomic Cost Analysis provides monetary cost of the final demand. In particular, the cost of electric energy (*Cost of Energy*, COE, in $€/MWh$) produced by the system is taken as the reference indicator for economic evaluations and optimization procedures, so its value must reduce in each simulation step. The method is refined since results of the optimization procedure are validated in terms of environmental performance (i.e. in terms of primary fossil-fuels consumption) through the hybrid thermoeconomic method and its indicators (C_{PR}, *ExROI*, *LExCOEx*).

Simulation 01. Output of simulation 00 shows that the *grate furnace* is the most impacting component in terms of Γ, and that it has a great potential for improvements, given its high value of γ. The value of φ is slightly over 0,5, suggesting that a benefit could be obtained if the monetary was reduced. Therefore, a first attempt is made by reducing the value of the excess air ε, in order to reduce the size, and hence the investment cost, of the equipment.

Simulation 02. Output of simulation 01 confirms the importance of the grate furnace in increasing the cost of the final demand; nonetheless, in this second step it has been decided to focus on the second component, the *steam turbine*. Value of φ reveals a predominance of the thermodynamic effect. Enhancement of this component is more critical, given its low value of γ; indeed, increasing exergy efficiency of steam turbines is a delicate task, usually requiring important increase in investment costs. In the attempt to achieve this purpose, the steam turbine inlet temperature is increased.

Simulation 03. The grate furnace still remains the most impacting component, with a slightly predominant economic effect instead of thermodynamic. In this simulation, the exhaust gas temperature is decreased, in the attempt to reduce the need for combustion air and hence reduce size and investment cost of the equipment. However, this expedient results in a very low impact on the overall performance.

Simulation 04. As it has been done in simulation 02, this step aims at increasing thermodynamic performance of the steam turbine, and is guided by the same considerations. This is attempted by increasing the steam turbine inlet pressure.

Simulation 05. The third component in order of thermoeconomic importance is the under-fire air pre-heater. It is characterized by a great potential for improvements, and the very low value of φ reveals a strong thermodynamic over economic effect. Hence, the aim is to reduce heat-transfer irreversibilities in order to increase the overall efficiency of the component; to reach this objective, temperature of the hot source ought to be lowered, and this is reached by reducing the steam bleeding pressure.

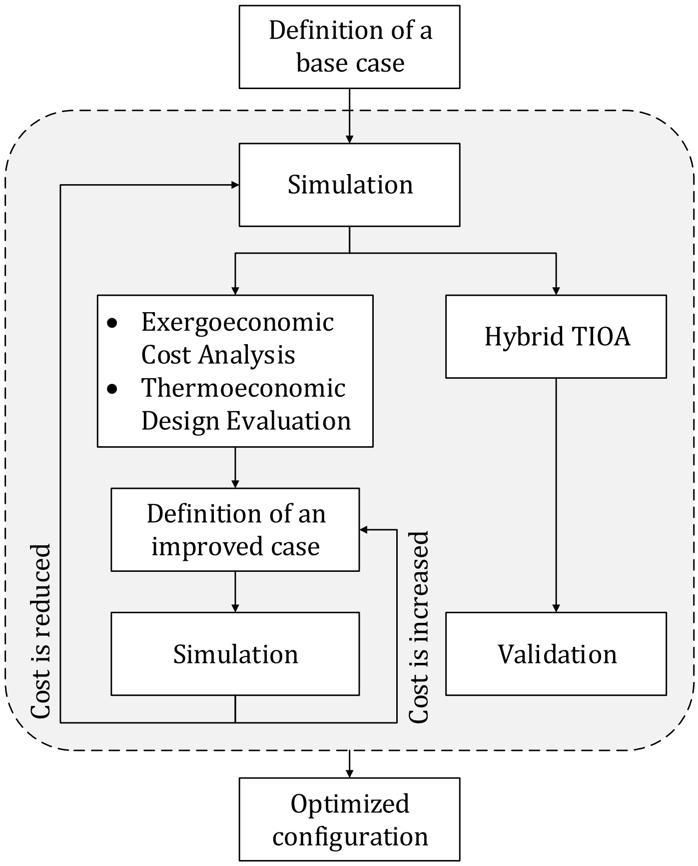


Figure 5.6. Flow diagram for the application of the iterative optimization procedure.

Table 5.8. Iterative optimization process.

Simlation	Changed parameter	Symbol	Unit	From	To	*COE* [€/*MWh*]	*ExROI* [−]	*LExCOEx* [−]
00						87,63	124,02	0,01435
01	Grate furnace excess air	ε	%	40	↘ 30	87,23	124,58	0,01428
02	Steam turbine inlet temperature	T_{28}	$°C$	390	↗ 420	85,12	127,797	0,013925
03	Grate furnace exhaust gas temperature	T_8	$°C$	526,8	↘ 510	85,10	127,805	0,013922
04	Steam turbine inlet pressure	p_{28}	bar	40	↗ 50	83,77	129,98	0,01370
05	Underfire air pre-heater steam pressure	p_{29}	bar	12,56	↘ 11	83,74	130,04	0,01369

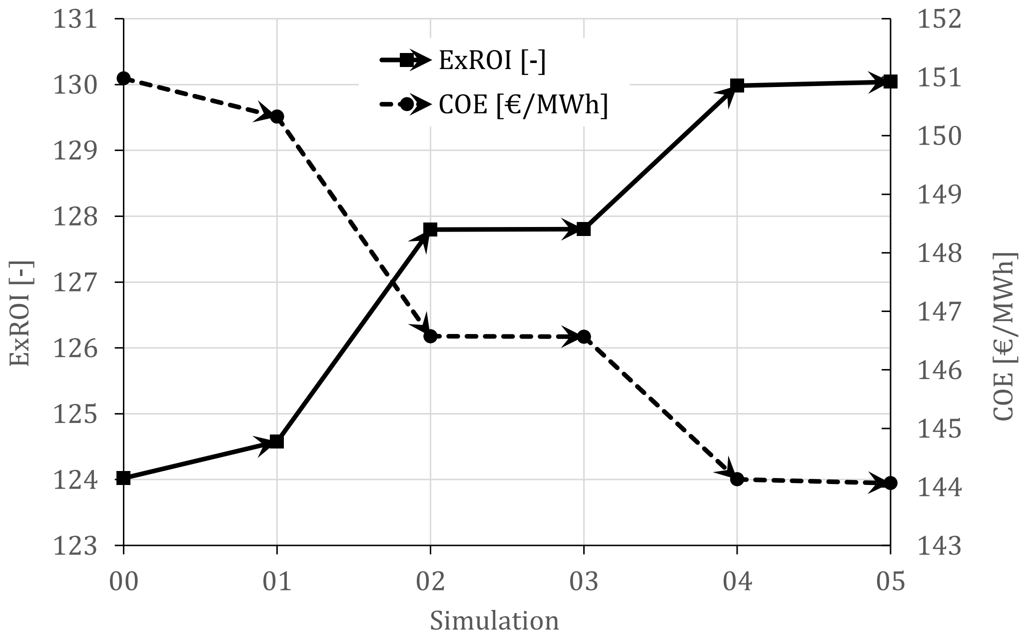


Figure 5.7. Results plot of the iterative optimization process.

It is noteworthy to notice that well-established optimization methods usually perform a numerical minimization/maximization of an objective function. In this work, the iterative optimization procedure has been accomplished with a manual approach, with an arbitrary selection of the parameters to be changed and their respective values, although the choice is guided by the Thermoeconomic Design Evaluation tool. This fact implies that the results of the iterative optimization do not represent *optimum* values in a numerical perspective, just *enhanced* values from a thermoeconomic standpoint. This is related to the constraint given by the software used for thermodynamic simulations, which does not allow to perform numeric optimization procedures, and hence cannot be analytically linked to the thermoeconomic model. Conversely, if the thermodynamic model of the system was freely available in an editable form, it would be possible to set-up a more effective optimization procedure with the best available numerical techniques.

5.5 Stochastic optimization

In this section, a more traditional optimization method is applied to the case study. The aim is to compare the output with the results of the iterative method, based on Thermoeconomic Design Evaluation, proposed as an alternative. It can be revealed in advance that this routine results more demanding from a computational perspective, and provides a weaker solution.

When an energy system is being designed, the amount of variables expected to affect its future performance is overwhelming. In this case, a stochastic procedure is recommended instead of an iterative method. A set of variables is identified, which are expected to have a significant role in affecting the system performance either by existing literature assessment or by professional experience. For each of these parameters, a reasonable range of variation is stated, and a simulation campaign is carried out over this hyper-space of values. A set of proxies is devised as the result of the simulation procedure, and the best simulation could be selected as the optimized configuration. Alternatively, a restricted region of values could be selected, and an iterative optimization procedure could be performed over this reduced domain, resulting in an enhanced optimization routine.

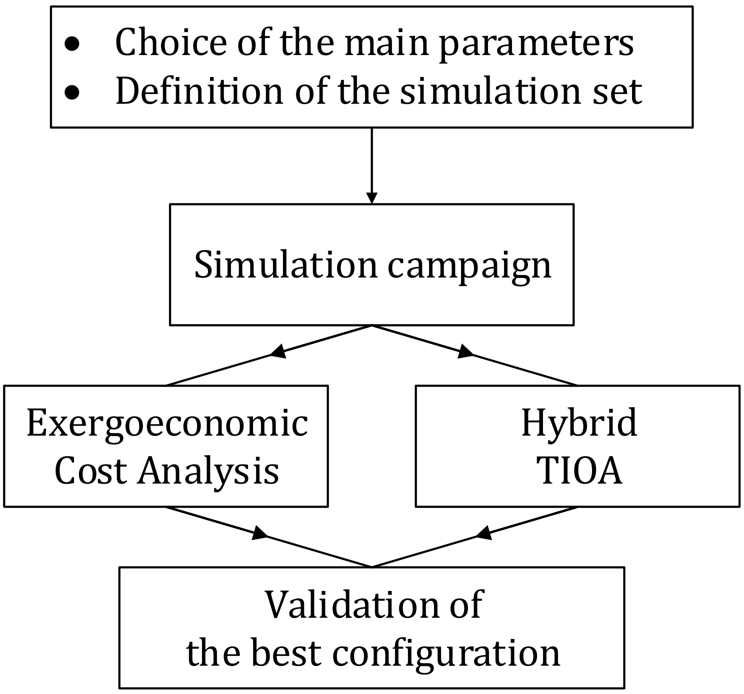


Figure 5.8. Flow diagram for the stochastic optimization procedure.

As explained by Figure 5.8, this optimization strategy starts from the identification of a set of couples for the inquired configuration parameters ($p_{28}; EGR$). For each couple a simulation is performed; Exergoeconomic Cost Analysis returns each value for the COE, and one simulation or a smaller set is expected to raise as optimal. Resulting values of $ExROI$ and $LExCOEx$ provided by Hybrid Thermoeconomic Input–Output Analysis are used to validate the output of this procedure.

For the case study considered in this work, two optimization parameters have been chosen:

- p_{28} $[bar]$, the steam turbine inlet pressure;
- EGR $[-]$, the fraction of Exhaust Gas Recirculation in the furnace.

The range of possible values that has been selected is reported in Table 5.9. Boundaries derive from indications included in [70]. Inside this space, a restricted region is pinpointed, characterized by the best performance in terms of the indicators introduced above.

Table 5.9. Selected range of variation for stochastic optimization parameters.

Variable	Unit	Minimum	Maximum
p_{28}	bar	35	55
EGR	%	5	30

Table 5.10 summarizes the results obtained for each simulation; graphical elaboration is given in Figure 5.11 and Figure 5.12.

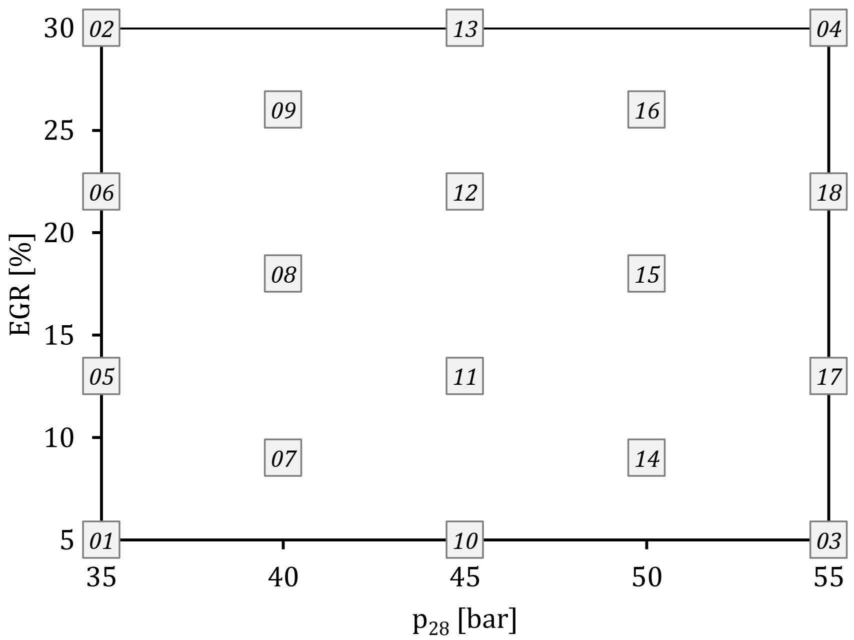


Figure 5.9. Grid of the selected simulations for the stochastic strategy.

Table 5.10. Summary of the stochastic simulation process.

Simulation	p_{28} $[bar]$	EGR [%]	COE [€/MWh]	$ExROI$ [−]	$LExCOEx$ [−]
01	35	5	88,53	122,54	0,01452
02	35	30	92,97	116,55	0,01527
03	**55**	**5**	**85,87**	**126,65**	**0,01407**
04	55	30	87,35	124,57	0,01431
05	35	13	88,68	122,43	0,01453
06	35	22	90,58	119,73	0,01486
07	40	9	87,52	124,11	0,01434
08	40	18	87,70	123,97	0,01436
09	40	26	89,95	120,67	0,01475
10	45	5	86,74	125,25	0,01422
11	45	13	86,88	125,15	0,01423
12	45	22	87,08	125,00	0,01425
13	45	30	89,76	121,00	0,01472
14	50	9	86,40	125,85	0,01415
15	50	18	86,58	125,72	0,01417
16	50	26	87,09	124,93	0,01426
17	55	13	86,00	126,54	0,01408
18	55	22	86,20	126,39	0,01410

It can be seen that the best performance in terms of both $ExROI$ and $LExCOEx$ are reached in simulation 03, which is characterized by higher pressures and lower EGR ratios. For this configuration, Figure 5.10 inquires how performance is affected by the variation of only one of the two selected parameters, while the other one is kept fixed.

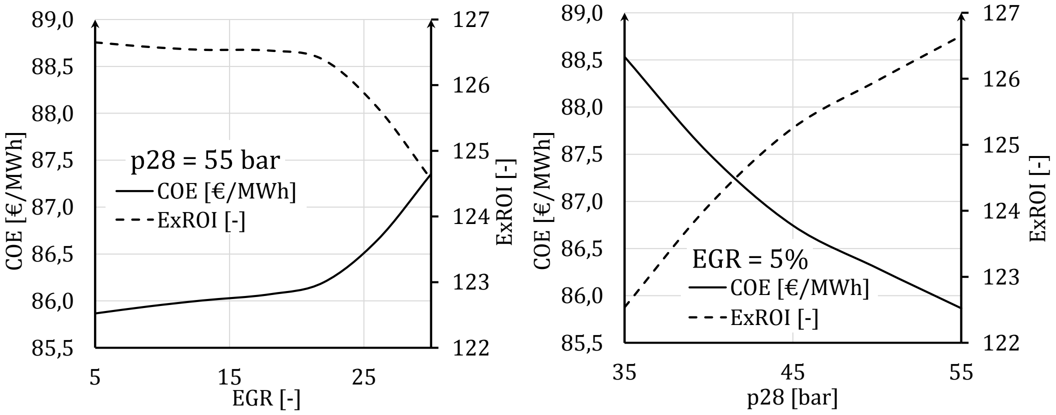


Figure 5.10. Effects of EGR ratio and pressure variation on $ExROI$ and $LExCOEx$ for the best configuration (simulation 03) identified through stochastic process.

It can be noticed that a reduction of the EGR below the value of 20% has a negligible effect on both performance indicators. Conversely, the turbine inlet pressure shows an remarkable impact, since any increase in its value entails a significant benefit on both the $ExROI$ and $LExCOEx$.

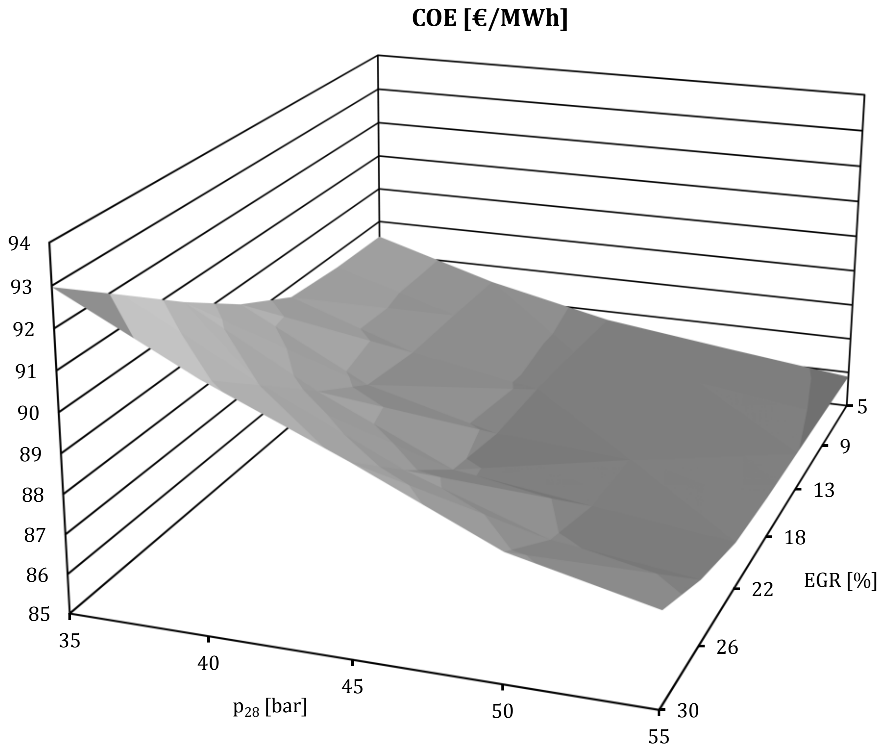


Figure 5.11. Surface interpolation plot of the COE.

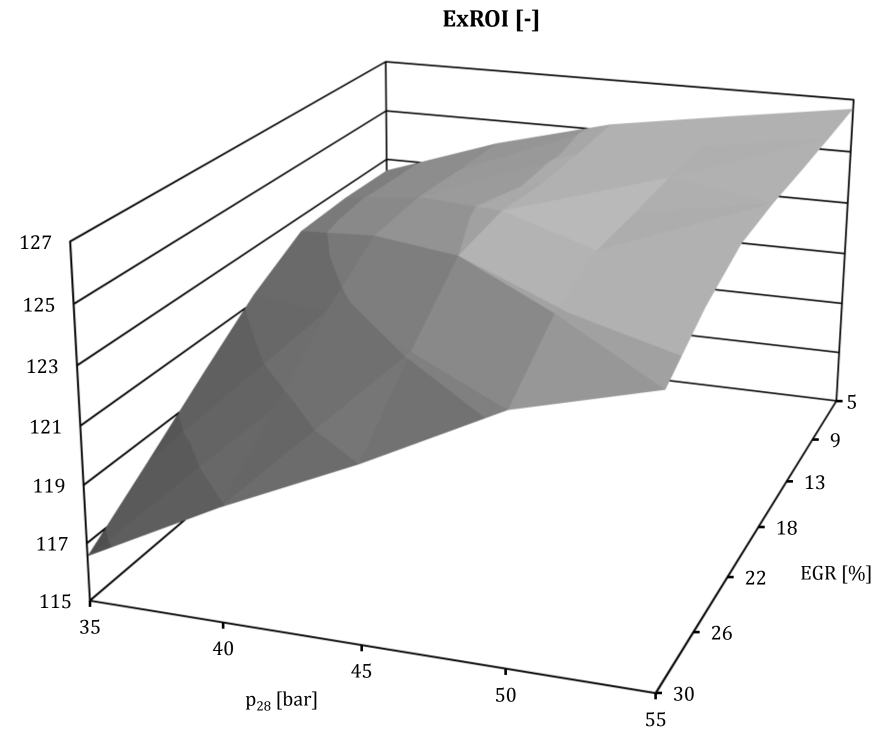


Figure 5.12. Surface interpolation plot of the $ExROI$.

Chapter 6
Conclusions and further developments

In this thesis, Hybrid Thermoeconomic Input–Output Analysis has been presented as an improved procedure based on standard Thermoeconomic Analysis to address the issues presented in Chapter 1. A comparison is performed between this novel method and a more traditional optimization procedure. The main advantages and drawbacks are highlighted, and possibilities for further developments are discussed.

6.1 Theory

In this work, standard Thermoeconomic Analysis with an Input–Output approach has been presented, and it has been extended in the attempt to overcome the main drawbacks arising from literature.

1. *Indirect requirements*. Extension of analytical boundaries to include all the supply chains fueling the system has been accomplished by appropriate combination of the system's Physical Input-Output Table (PIOT) with the national Monetary Input-Output Table (MIOT), hence defining a Hybrid Transaction matrix. This procedure allows the method to be *comprehensive* of the entire supply chain, while simultaneously analyze the system with a suitable level of *detail*. Application of Hybrid Thermoeconomic Input–Output Analysis to Life Cycle Assessment of a physical system requires some specific adjustments for every Life-Cycle phase, which have been discussed.
2. *Reallocation*. The issue of reallocating the cost of residues to the final demand has been faced: the approach introduced by Valero et al. [17] has been adapted to the hybrid model.

This technique is able to provide, as final result, the cost of the final products of the system, in terms of the primary fossil fuels extracted within the selected national economy. Furthermore, some useful indicators have been properly defined to assess the performance of the analyzed system, also providing a coherent basis for eventual comparison with other technologies.

6.2 Practice

Hybrid Thermoeconomic Input–Output Analysis has been applied to the case study of Tecnoborgo Waste-to-Energy power plant. A novel optimization method based on the Exergoeconomic Design Evaluation has been tested and validated with the use of the Hybrid Thermoeconomic indicators defined in this thesis, and a comparison with a more traditional stochastic method is performed in the following.

Table 6.1. Comparison between the best configurations of the system.

Parameter (best configuration)	Unit	Optimization strategy	
		Iterative	Stochastic
Exergy cost of final demand	J/kJ	4'859	4'992
	kJ/s	52'317	52'322
Exergoeconomic cost of final demand	$€/GJ$	23,26	23,85
	$M€/year$	7,21	7,20
Fossil fuel cost of final demand	J/kJ	6,11	6,28
	$toe/year$	45,23	45,29
Construction cost	$ktoe$	1,40	
Operation net benefit	$toe/year$	7'362	7'164
Cost of Energy	$€/MWh$	83,74	85,87
$ExROI$	–	130,04	126,65
$LExCOE$	J/kJ	13,69	14,07
Number of simulation performed	–	6	19

Table 6.1 shows that the *iterative* optimization procedure is able to achieve better results than the respective *stochastic* method. Besides, the number of simulations accomplished is significantly lower, which corresponds to lower needs for time and computational effort. This feature is possibly explained by the fact that the stochastic strategy proceeds with arbitrary attempts, guided only by experience. Conversely, the iterative method progresses considering information arising from previous attempts, thus resulting in a more suitable optimization track.
In conclusion, Hybrid Thermoeconomic Input–Output Analysis applied to the case study outlined in this work confirms, as expected, the great potential of Waste-to-Energy technology in terms of primary resources saving. Since the main thermal input consists in a recovered biomass, the amount of primary exergy required throughout the entire Life Cycle of the power plant is risible in comparison with the amount of useful exergy produced.

6.3 Further developments

Possibilities for further investigations in H–TIOA include the following:

- *Sensitivity Analysis*. The general method discussed in this work has focused on the analysis of a generic energy system with a fixed operating configuration. Nonetheless, a key step in any optimization process is the sensitivity analysis, in order to assess the stability and powerfulness of the option highlighted as the best one.
- *Analysis of uncertainties*. Economic assessment is probably the most delicate task. In general, a high level of accuracy regarding monetary expenses required to construct, operate, and dismantle an energy system is difficult to obtain; for this reason, results are affected by non-negligible and unavoidable uncertainties. In H–TIOA, monetary terms constitute the linkage between the physical system and its economic environment (through compilation of the Upper Cut-off matrix): errors from economic evaluations will be transferred and amplified, and will affect the primary exergy cost determination, as well as all the related performance indicators. This factor, added to the well-known sources of error related to the use of MIOTs (discussed in paragraph 3.1), contribute to the need for an analysis of the uncertainties arising from Hybrid Thermoeconomic Input–Output Analysis, in order to assess the reliability of the method.
- *Audits and Diagnosis*. Thermoeconomics has been enhanced with powerful tools and techniques based on the Second Law of Thermodynamics [38]. The aim is to analyze causes and magnitudes of thermodynamic inefficiencies, as well as their overall economic impact. So far, such techniques have been restricted to standard Thermoeconomic Analysis; application to hybrid methods could represent a fascinating extension and lead to interesting results.
- *Optimization*. Effectiveness of the optimization procedure in this work has been constrained by the thermodynamic simulation through an external software. Enhanced techniques, such as those involving genetic algorithms, could be coupled and exploited to obtain more reliable results. To keep a high detail of the thermodynamics behaviour of the system, an important computational effort would be required.

- *Application*. Fossil-fuel consumption of a WtE power plant has proved very low. More meaningful examples for the application of H–TIOA could be represented by other power-generating technologies based on renewable energy sources, especially in the case of intensive and energy-consuming end-of-life phases (e.g. in the case of solar panels).

Appendix

A.1 Exergy

Exergy is defined as the maximum amount of work that could be obtained through a reversible process that transforms a given system from its initial conditions to the conditions of its reference environment (*dead-state*). Once the environment conditions are fully specified, exergy becomes a property of the system.
Neglecting all other kind of contributions[11], exergy of a system comprises:

- *physical exergy*, due to thermal and/or mechanical imbalance between the system and its environment, that is, differences in temperature and/or pressure (subscript "0" refers to the environment conditions):

$$e^{PH} = (h - h_0) - T_0 \cdot (s - s_0) \tag{A.1}$$

- *chemical exergy*, due to chemical imbalance between the system and its environment, that is, differences in chemical potentials of one or more of the system's components. Analytical computation of these values is more complex, since it requires the modeling of standard chemical reactions for each species in order to express the different composition of the system in terms of the reference composition of the environment. As an example, in case of complete oxidation, the reaction products are reference species, and their exergy results only from the different composition with respect to that of the environment:

$$e^{CH} = T_0 \cdot R \cdot \sum_i \left[x_i \cdot \boldsymbol{ln}\left(\frac{x_i}{x_{i,0}} \right) \right] \tag{A.2}$$

  where $R = 8{,}414472 \frac{J}{mol \cdot K}$ is the molar gas constant [84], and x_i is the molar fraction of the i-th component. Further and more exhaustive details can be retrieved in literature [6, 85].

[11] Other types of exergy, such as kinetic (due to system velocity relative to the environment) or potential (due to vertical height relative to the environment) are usually negligible for process analysis purposes.

Usually, chemical exergy is negligible when compared to physical exergy, except for the case of fuels, whose exergy content is essentially chemical. Standard[12] chemical exergy of fuels can be determined through approximate relations based on chemical composition, such as that suggested by [60] for solid and liquid fuels:

$$e^{CH}\left[\frac{kJ}{kg}\right]=363{,}439C+1075{,}633H-86{,}308O+4{,}147N+190{,}798S-21{,}1A \quad \text{(A.3)}$$

where C, H, O, N, S and A represent the weight fractions of, respectively, Carbon, Hydrogen, Oxygen, Nitrogen, Sulphur and Ash content of the considered fuel.

Table A.1. Chemical exergy of various fuels valued with the approximate correlation suggested by [60] and reported in eq. (A.3); composition data are taken from [61].

Fuel	Composition on dry basis [$\%wt$]						$e^{CH}\left[\frac{MJ}{kg}\right]$
	C	H	O	N	S	Ash	
Coefficients	*363,439*	*1075,633*	*-86,308*	*4,147*	*190,798*	*-21,1*	
Methane	74,85	25,15	-	-	-	-	54,26
Propane	81,70	18,30	-	-	-	-	49,38
Anthracite coal	86,78	1,63	1,96	0,65	0,92	8,06	33,13
Coke	89,13	0,43	0,98	0,85	1,00	7,61	32,81
Charcoal	92,04	2,45	2,96	0,53	1,00	1,02	36,00
Wood-tar	63,03	5,31	12,06	1,76	-	17,84	27,21
MSW	47,60	6,00	32,90	1,20	0,30	12,00	20,72

[12] The adjective *standard* refers to standard conditions: $T = 298{,}15K$ and $p = 101'325Pa$.

A.2 Economic Analysis

In this work, the procedure for the economic evaluation of the system under study follows closely the guidelines depicted in [30]. It is based on the estimation of the *Purchased Equipment Cost* (PEC), which represents the cornerstone for the determination of the *Total Capital Investment* (TCI). A minimum and a maximum value have been identified for each term of the economic analysis, and the average value has been used for the Thermoeconomic Analysis.

A.2.1 Purchased Equipment Cost

Purchased Equipment Cost includes the costs of all the processing equipment, as well as raw materials and finished-products handling and storage facilities. When direct, detailed information are difficult or impossible to obtain, these terms can be determined resorting to approximate methods:

- *cost-capacity plots*, often supplied directly by manufacturers

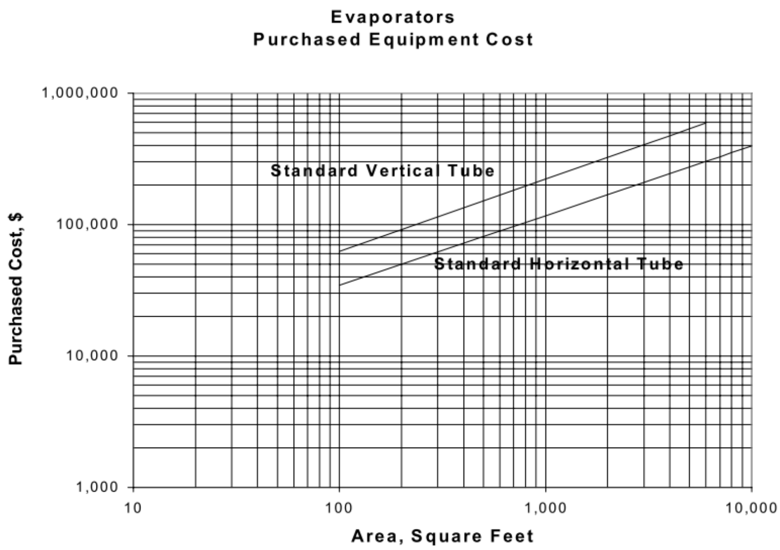


Figure A.1. Example of a cost-capacity diagram [86].

- *exponential methods* express the cost-capacity relation in the form:

$$C = C_0 \cdot \left(\frac{P}{P_0} \right)^n \tag{A.4}$$

where the subscript 0 refers to a known couple taken as reference, and the *size exponent n* is a factor that assumes, for different types of equipment, typical ranges of values determined statistically from published sources. In the absence of any data, the *six-tenths rule* can be applied, assuming $n = 0{,}6$ with a good level of approximation that holds for many cases. This value arises from an average on observed entries, as it can be comprehended from the non-exhaustive example summarized in Table A.2.

Table A.2. Examples of size exponents [87].

Equipment	Unit	Size exponent
Air compressor, single stage	cfm	0,67
Air dryer	cfm	0,56
Boiler, industrial, all sizes	lb/h	0,50
Dust collector, cyclone	cfm	0,80
Fan	Hp	0,66
Heat exchanger, fixed tube	sf	0,62
Pump, centrifugal, carbon steel	Hp	0,67

- *cost indexes* allow the analyst to convert costs of given goods between different years in the following way:

$$C_1 = C_0 \cdot \frac{index_1}{index_0} \tag{A.5}$$

A reference year is taken as basis, and indexes referring to different years are determined to reflect inflation/deflation and general market prices variation rates. Many sources publish different collections of cost indexes; famous examples are the Marshall & Swift (M&S), the Chemical Engineering (CE) and the Nelson-Farrar (NF) indexes, exemplified in Table A.3.

Table A.3. Selection of cost indexes [88].

Year	M&S	CE	NF
Base	1926 = 100	1957-1959 = 100	1946 = 100
1990	915,1	357,6	1225,7
1992	943,1	358,2	1277,3
1994	946,2	368,1	1349,7
1996	1039,1	381,7	1418,9
1998	1061,9	389,5	1477,6
2000	1089,0	394,1	1542,7
2001	1093,9	394,3	1579,7
2002	1104,2	395,6	1642,2
2003	1123,6	402,0	1710,4

What follows is a list of the plant's components and their respective PECs[13]. Data are based on Tecnoborgo power plant layout (Figure 4.1).

a) *Grate furnace* including post-combustion chamber and evaporative section

- Min: linear interpolation from [89] € 12'007'387,53
- Max: linear interpolation from [90, p. 121] € 15'400'000,00

b) *Deaerator*, from [91] with size exponent from [62]

- Min: single correction on nominal power € 14'373,49
- Max: double correction on nominal power and pressure € 23'522,81

c) *Feedwater heater* with pump, different cost-capacity relations:

- Pump: from [92] $Z = 705{,}48 \frac{\$}{kW^{0,71}} \cdot P^{0,71} \cdot \left(1 + \frac{0{,}2}{1-\eta_P}\right)$

  P and η_P are, respectively, the nominal power and the isoentropic efficiency of the pump.

- Heater: from [39 Table 2] with $a = 6$ $Z = \frac{66 \frac{\$}{...} \cdot Q \cdot \left(\frac{1}{T_{TTD} + a}\right)^{0,1}}{\left(\Delta p_w\right)^{0,08} \cdot \left(\Delta p_s\right)^{0,04}}$

  Q is the thermal power transferred; is the terminal temperature difference; are the pressure drops on the water and the steam sides.

d,e,m,n,o) *Heat exchangers*: economizer, superheater, air pre-heaters and regenerator. Calculation is based on the heat exchanging surface, and different values for the heat transfer coefficient have been selected, as shown in Table A.4.

$$Q = \dot{m} \cdot \Delta h \quad \rightarrow \quad A = \frac{Q}{U \cdot \Delta T} \quad \rightarrow \quad Z = c \cdot A$$

Table A.4. Selected heat transfer coefficients and cost per surface of heat exchangers [93].

Component	$U\left[\frac{W}{m^2K}\right]$	$c\left[\frac{\$}{m^2}\right]$
Economizer	42,6	45,70
Superheater	50,0	96,20
Air pre-heaters and general HEx	40,0 (from [41])	45,70

[13] Costs are expressed in referenced currency and have been converted and actualized in the proceeding of the analysis.

f) *Steam turbine* including three-phase generator. From [92].

$$Z = 3'880{,}5\tfrac{\$}{kW^{0,71}} \cdot P_T^{\;0,71} \cdot \left[1+\left(\frac{0{,}05}{1-\eta_T}\right)^3\right] \cdot \left[1+5\cdot \boldsymbol{exp}\left(\frac{T_{in}-866K}{10{,}42K}\right)\right]$$

P_T and η_T are the turbine's power and isoentropic efficiency; T_{in} is the admission temperature of the steam.

g,h,i) *Pumps* on water circuit, centrifugal, including mechanical drive. Expressed as a function of flow capacity. From [39].

$$Z = 378\tfrac{\$}{kW^{0,71}} \cdot \dot{E}_P^{0,71} \cdot \left[1+\left(\frac{1-0{,}808}{1-\eta_P}\right)^3\right]$$

- $\dot{E}_P$ and η_P are, respectively, the exergy of the product and the isoentropic efficiency of the pump.

j,k,l) *Fans*, underfire and overfire air fans and EGR fan, including mechanical drive. Expressed as a function of flow capacity, from [86, p. 40].

$$Z = 1'082{,}925 + 12'079{,}121 \cdot q + 675{,}795 \cdot q^2 - 43{,}189 \cdot q^3$$

$q[m^3/s]$ is the volumetric flow rate, averaged between inlet and outlet.

p) *Air-cooled condenser*, three cells. Expressed as a function of heat exchanging surface, from [86, p. 21].

$$Z = 21'074{,}785 + 210{,}384 \cdot S$$

$S[m^2]$ is the heat exchanging surface of the aero-condenser cells.

q) *ElectroStatic Precipitator*, 15 kV, in number of 2
- Min: linear interpolation from [89] € 1'301'519,74
- Max: linear interpolation from [90, p. 131], as $2 \times 60\ kt/year$ € 3'520'000,00

r) *Fabric Filter*, in number of 2
- Min: linear interpolation from [89] € 2'602'299,43
- Max: linear interpolation from [90, p. 132], as $2 \times 60\ kt/year$ € 3'850'000,00

s) *Selective Cathalytic Reactor*, in number of 2
- Min: linear interpolation from [89] € 2'603'070,32
- Max: from , with size exponent from € 4'492'074,31

t) *Stacks*, in number of 2, linear interpolation from [89] € 3'051'766,56

A.2.2 Other equipment

- Discharge and storage facilities
  - Min: linear interpolation from [89] € 4’251’059,92
  - Max: linear interpolation from [90, p. 120] € 5’212’000,00
- Bottom ash extraction system, unique for both lines
  - Linear interpolation from [89] € 1’139’08853
- Ferrous material removal system, unique for both lines
  - Min: linear interpolation from [89] € 199’371,49
  - Max: from [94] € 245’019,68
- Fly ash and dust extraction system, unique for both lines
  - Min: linear interpolation from [89] € 677’900,93
  - Max: from [62] € 866’407,00
- Fly ash and dust inertization system, linear interpolation from [89] € 832’407,00
- Waste water treatment system, linear interpolation from [89] € 2’377’158,41
- Weather station, independent on plant size, from [89] € 15’493,71
- FTIR analyzer for continuous flue-gas screening, from [89] € 258’228,45
- Distribute Control System (DCS) and Electronic Instrumentation
  - Linear interpolation from [89] € 8’497’476,76
- Sales taxes and freights, from [95] 3+5 % of PEC

Table A.5. Eur/Dollar Exchange Rate

Ref. year	$/€	€/$	Ref. year	$/€	€/$
2014	1,3743	0,7276	2004	1,2596	0,7939
2013	1,3203	0,7574	2003	1,0488	0,9535
2012	1,2959	0,7717	2002	0,8863	1,1283
2011	1,3391	0,7468	2001	0,9414	1,0622
2010	1,4334	0,6977	2000	1,0053	0,9947
2009	1,3973	0,7157	1999	1,1685	0,8558
2008	1,4591	0,6854	1998	1,0995	0,9095
2007	1,3197	0,7578	1997	1,2538	0,7976
2006	1,1841	0,8445	1996	1,2813	0,7805
2005	1,3536	0,7388	1995	1,3030	0,7674

A.3 Thermoeconomic Design Evaluation

This section reports the detailed output of the Exergoeconomic Cost Analysis procedure that is analyzed in order to proceed with the iterative optimization procedure described in paragraph 5.4.

Table A.6. Simulation 00 - Thermoeconomic Design Evaluation.

Simulation 00	π [€/kJ]	Π [€/s]	Π_d [€/s]	$\dot{Z}$ [€/s]	Γ [€/s]	Rank Γ	γ [%]	φ [%]
a) Grate Furnace	9,6E-06	0,0046	2,6E-01	2,8E-01	5,4E-01	1	96,98	51,70
b) Deaerator	1,6E-05	-	9,8E-04	3,0E-04	1,3E-03	11	9,93	23,57
c) Feedwater Heater	1,7E-05	-	8,8E-04	1,4E-04	1,0E-03	12	17,19	13,63
d) Economizer	1,5E-05	-	8,3E-03	3,0E-03	1,1E-02	3	18,96	26,85
e) SuperHeater	1,4E-05	-	9,1E-03	1,9E-04	9,3E-03	5	19,53	2,10
f) Steam Turbine	2,4E-05	0,2499	7,3E-02	5,1E-02	1,2E-01	2	27,74	41,07
g) Pump26	6,3E-05	-	1,2E-04	4,0E-05	1,5E-04	14	71,79	25,60
h) Pump16	6,2E-05	-	-	4,2E-05	-	15	-	-
i) Pump29	4,8E-05	-	1,8E-03	5,9E-04	2,4E-03	7	48,63	24,53
j) Fan14	5,7E-05	-	9,7E-04	1,0E-03	2,0E-03	9	34,85	50,83
k) Fan27	5,9E-05	-	7,0E-04	7,5E-04	1,5E-03	10	35,83	51,55
l) Fan39	1,1E-04	-	2,5E-04	4,9E-04	7,4E-04	13	31,41	66,11
m) AirHEX13	2,6E-05	-	9,1E-03	5,8E-04	9,7E-03	4	105,51	6,00
n) AirHEX12	2,9E-05	-	2,3E-03	3,2E-04	2,6E-03	6	103,41	12,35
o) Heat Exchanger	2,4E-05	-	2,1E-03	9,2E-05	2,2E-03	8	111,01	4,18

Table A.7. Simulation 01 - Thermoeconomic Design Evaluation.

Simulation 01	π [€/kJ]	Π [€/s]	Π_d [€/s]	$\dot{Z}$ [€/s]	Γ [€/s]	Rank Γ	γ [%]	φ [%]
a) Grate Furnace	9,6E-06	0,0046	2,6E-01	2,8E-01	5,4E-01	1	100,20	51,35
b) Deaerator	1,6E-05	-	9,8E-04	3,0E-04	1,3E-03	11	9,96	23,69
c) Feedwater Heater	1,7E-05	-	8,9E-04	1,4E-04	1,0E-03	12	17,20	13,71
d) Economizer	1,6E-05	-	7,7E-03	2,7E-03	1,0E-02	3	19,79	26,31
e) SuperHeater	1,4E-05	-	8,7E-03	1,8E-04	8,9E-03	5	18,82	2,04
f) Steam Turbine	2,4E-05	0,2498	7,3E-02	5,1E-02	1,2E-01	2	27,74	41,17
g) Pump26	6,3E-05	-	1,2E-04	4,0E-05	1,5E-04	14	71,95	25,62
h) Pump16	6,1E-05	-	-	4,2E-05	-	15	-	-
i) Pump29	4,8E-05	-	1,8E-03	5,9E-04	2,4E-03	7	48,63	24,60
j) Fan14	5,8E-05	-	9,3E-04	1,0E-03	1,9E-03	9	34,92	51,86
k) Fan27	5,9E-05	-	6,5E-04	6,9E-04	1,3E-03	10	35,83	51,57
l) Fan39	1,1E-04	-	2,4E-04	4,5E-04	7,0E-04	13	32,55	65,20
m) AirHEX13	2,6E-05	-	8,4E-03	5,4E-04	8,9E-03	4	105,31	6,07
n) AirHEX12	2,8E-05	-	2,1E-03	3,0E-04	2,4E-03	6	103,47	12,43
o) Heat Exchanger	2,5E-05	-	2,0E-03	8,6E-05	2,1E-03	8	112,44	4,09

Table A.8. Simulation 02 - Thermoeconomic Design Evaluation.

Simulation 02	π $[€/kJ]$	Π $[€/s]$	Π_d $[€/s]$	$\dot{Z}$ $[€/s]$	Γ $[€/s]$	Rank Γ	γ [%]	φ [%]
a) Grate Furnace	9,5E-06	0,0045	2,6E-01	2,8E-01	5,4E-01	1	100,40	51,54
b) Deaerator	1,6E-05	-	9,4E-04	3,0E-04	1,2E-03	11	10,08	24,32
c) Feedwater Heater	1,7E-05	-	8,5E-04	1,4E-04	9,9E-04	12	17,35	13,87
d) Economizer	1,5E-05	-	5,9E-03	2,7E-03	8,5E-03	4	18,15	31,26
e) SuperHeater	1,4E-05	-	7,4E-03	1,8E-04	7,5E-03	5	14,21	2,40
f) Steam Turbine	2,4E-05	0,2502	6,9E-02	5,2E-02	1,2E-01	2	26,42	42,78
g) Pump26	6,2E-05	-	1,1E-04	3,9E-05	1,5E-04	14	72,17	25,97
h) Pump16	6,1E-05	-	-	4,1E-05	-	15	-	-
i) Pump29	4,7E-05	-	1,7E-03	5,8E-04	2,3E-03	7	48,64	25,09
j) Fan14	5,7E-05	-	9,2E-04	1,0E-03	1,9E-03	9	34,92	52,19
k) Fan27	5,8E-05	-	6,4E-04	6,9E-04	1,3E-03	10	35,83	51,90
l) Fan39	1,1E-04	-	2,4E-04	4,5E-04	6,9E-04	13	32,55	65,35
m) AirHEX13	2,5E-05	-	8,4E-03	5,4E-04	8,9E-03	3	106,63	6,06
n) AirHEX12	2,8E-05	-	2,1E-03	3,0E-04	2,4E-03	6	103,42	12,60
o) Heat Exchanger	2,4E-05	-	2,0E-03	8,6E-05	2,1E-03	8	111,91	4,16

Table A.9. Simulation 03 - Thermoeconomic Design Evaluation.

Simulation 03	π $[€/kJ]$	Π $[€/s]$	Π_d $[€/s]$	$\dot{Z}$ $[€/s]$	Γ $[€/s]$	Rank Γ	γ [%]	φ [%]
a) Grate Furnace	9,6E-06	0,0046	2,6E-01	2,8E-01	5,4E-01	1	101,42	51,16
b) Deaerator	1,6E-05	-	9,4E-04	3,0E-04	1,2E-03	11	10,08	24,33
c) Feedwater Heater	1,7E-05	-	8,5E-04	1,4E-04	9,9E-04	12	17,35	13,87
d) Economizer	1,6E-05	-	5,0E-03	2,6E-03	7,6E-03	4	17,34	34,07
e) SuperHeater	1,4E-05	-	6,2E-03	1,8E-04	6,4E-03	5	12,08	2,83
f) Steam Turbine	2,4E-05	0,2501	6,9E-02	5,2E-02	1,2E-01	2	26,42	42,78
g) Pump26	6,2E-05	-	1,1E-04	3,9E-05	1,5E-04	14	72,17	25,98
h) Pump16	6,1E-05	-	-	4,1E-05	-	15	-	-
i) Pump29	4,7E-05	-	1,7E-03	5,8E-04	2,3E-03	7	48,64	25,09
j) Fan14	5,7E-05	-	9,2E-04	1,0E-03	1,9E-03	9	34,92	52,20
k) Fan27	5,8E-05	-	6,4E-04	6,9E-04	1,3E-03	10	35,83	51,90
l) Fan39	1,1E-04	-	2,4E-04	4,5E-04	6,9E-04	13	32,55	65,36
m) AirHEX13	2,5E-05	-	8,4E-03	5,4E-04	8,9E-03	3	106,63	6,07
n) AirHEX12	2,8E-05	-	2,1E-03	3,0E-04	2,4E-03	6	103,48	12,60
o) Heat Exchanger	2,4E-05	-	2,0E-03	8,6E-05	2,1E-03	8	111,91	4,13

Table A.10. Simulation 04 - Thermoeconomic Design Evaluation.

Simulation 04	π $[€/kJ]$	Π $[€/s]$	Π_d $[€/s]$	$\dot{Z}$ $[€/s]$	Γ $[€/s]$	Rank Γ	γ [%]	φ [%]
a) Grate Furnace	9,3E-06	0,0044	2,5E-01	2,8E-01	5,3E-01	1	98,65	52,19
b) Deaerator	1,5E-05	-	9,0E-04	3,0E-04	1,2E-03	11	9,88	25,20
c) Feedwater Heater	1,6E-05	-	8,2E-04	1,4E-04	9,6E-04	12	17,22	14,38
d) Economizer	1,5E-05	-	5,0E-03	2,6E-03	7,6E-03	4	17,48	34,15
e) SuperHeater	1,3E-05	-	5,4E-03	1,8E-04	5,6E-03	5	11,00	3,29
f) Steam Turbine	2,3E-05	0,2505	7,4E-02	5,2E-02	1,3E-01	2	28,21	41,35
g) Pump26	6,1E-05	-	1,1E-04	3,9E-05	1,5E-04	14	71,33	26,49
h) Pump16	6,0E-05	-	-	4,1E-05	-	15	-	-
i) Pump29	4,5E-05	-	2,1E-03	6,9E-04	2,8E-03	6	48,12	24,50
j) Fan14	5,7E-05	-	9,1E-04	1,0E-03	1,9E-03	9	34,92	52,40
k) Fan27	5,8E-05	-	6,4E-04	6,9E-04	1,3E-03	10	35,83	52,10
l) Fan39	1,1E-04	-	2,4E-04	4,5E-04	6,9E-04	13	32,48	65,51
m) AirHEX13	2,5E-05	-	8,0E-03	5,4E-04	8,6E-03	3	105,55	6,31
n) AirHEX12	2,7E-05	-	2,0E-03	3,0E-04	2,3E-03	7	103,79	12,83
o) Heat Exchanger	2,4E-05	-	1,9E-03	8,8E-05	2,0E-03	8	110,87	4,30

Table A.11. Simulation 05 - Thermoeconomic Design Evaluation.

Simulation 05	π [€/kJ]	Π [€/s]	Π_d [€/s]	$\dot{Z}$ [€/s]	Γ [€/s]	Rank Γ	γ [%]	φ [%]
a) Grate Furnace	9,3E-06	0,0044	2,5E-01	2,8E-01	5,3E-01	1	98,65	52,22
b) Deaerator	1,5E-05	-	8,9E-04	3,0E-04	1,2E-03	11	9,77	25,42
c) Feedwater Heater	1,6E-05	-	8,3E-04	1,4E-04	9,7E-04	12	17,42	14,24
d) Economizer	1,5E-05	-	5,0E-03	2,6E-03	7,6E-03	4	17,48	34,16
e) SuperHeater	1,3E-05	-	5,4E-03	1,8E-04	5,6E-03	5	11,00	3,29
f) Steam Turbine	2,3E-05	0,2505	7,4E-02	5,2E-02	1,3E-01	2	28,26	41,31
g) Pump26	6,1E-05	-	1,1E-04	3,9E-05	1,5E-04	14	71,30	26,50
h) Pump16	6,1E-05	-	-3,0E-05	4,1E-05	1,1E-05	15	74,17	362,60
i) Pump29	4,5E-05	-	2,1E-03	6,9E-04	2,8E-03	6	48,12	24,50
j) Fan14	5,7E-05	-	9,1E-04	1,0E-03	1,9E-03	9	34,92	52,41
k) Fan27	5,8E-05	-	6,3E-04	6,9E-04	1,3E-03	10	35,83	52,11
l) Fan39	1,1E-04	-	2,4E-04	4,5E-04	6,9E-04	13	32,48	65,51
m) AirHEX13	2,4E-05	-	7,5E-03	5,4E-04	8,1E-03	3	101,08	6,70
n) AirHEX12	2,7E-05	-	2,0E-03	3,0E-04	2,3E-03	7	103,93	12,81
o) Heat Exchanger	2,4E-05	-	1,9E-03	8,8E-05	2,0E-03	8	110,62	4,31

Nomenclature

Symbols

$\dot{E}$ $[kW]$	Exergy flow
c, $\mathbf{c}$ $[J/J]$	Unit exergy cost and cost vector
C, $\mathbf{C}$ $[kW]$	Exergy cost and cost vector
P, R, W	Product, Resource, Waste
η $[-]$	Exergy efficiency
k $[-]$	Unit exergy consumption
$\mathbb{P}, \mathbb{D}$	Set of Productive and Dissipative components
$\mathbf{Z}, \mathbf{A}$	Transaction and Technical Coefficients matrices
$\mathbf{R}, \mathbf{B}$	Resources and Input (or Intervention) matrices/vectors
$\mathbf{f}, \mathbf{g}, \mathbf{w}$	Final Demand, Residues, and Output vectors
$\mathbf{x}$	Production vector
$\mathbf{L}, \mathbf{L}_{\boldsymbol{R}}$	Leontief Inverse and Modified Leontief Inverse matrices
ψ	Residues cost distribution ratio
$\rho, \mathbf{W}$	Residues production coefficient and Residues Coefficients matrix
$\pi, \boldsymbol{\pi}$ $[€/J]$	Unit exergoeconomic cost and cost vector
$\Pi, \boldsymbol{\Pi}$ $[€/s]$	Exergoeconomic cost and cost vector
$\mathbf{R}_{\boldsymbol{m}}, \mathbf{B}_{\boldsymbol{m}}$	Monetary Resources and Input vectors
m $[-]$	Unit cost of capital (depreciation rate)
f_I, f_V $[-]$	Capital Recovery and Variable Costs factors
A_{eq}	Equivalent Annualized investment cost
p	Share of PEC
$\dot{Z}$ $[€/s]$	Monetary cost flow
H_{eq} $\left[\frac{h}{year}\right]$	Full-time equivalent hours
r $[-]$	Relative Cost Difference or Exergy junction ratios
Γ, γ	Absolute and Relative Cost Increase
φ	Exergoeconomic Factor
$\mathbb{S}$	Set of economic sectors
HHV, LHV $\left[\frac{MJ}{kg}\right]$	Higher and Lower Heating Value
β $[-]$	LHV-to-E^{CH} ratio
$\mathbf{E}_{NS}$	Upstream Cut-off matrix (Nation-to-System)
$\mathbf{E}_{SN}$	Downstream Cut-off matrix (System-to-Nation)

C_{PR} $[toe]$	Primary Resource Cost
$ExROI$ $[-]$	Exergy Return On (exergy) Investment
$ExPBT$	Exergy Pay-Back Time, in years
$LExCOEx$	Levelized Exergy Cost of Exergy

Acronyms

EA	Exergy Analysis
TA	Thermoeconomic Analysis
ExCA	Exergy Cost Analysis
EeCA	Exergoeconomic Cost Analysis
RP	Resource–Product
LCA	Life-Cycle Assessment
IOA	Input–Output Analysis
LQM	Leontief Quantity Model
LCM	Leontief Cost Model
IOT	Input–Output Table
MIOT	Monetary IOT
HIOT	Hybrid IOT
TIOA	Thermoeconomic Input–Output Analysis
H–TIOA	Hybrid TIOA
WtE	Waste to Energy
MSW	Municipal Solid Waste
SNCR/SCR	Selective (Non-)Catalytic Reduction
ESP	Electro-Static Precipitator
FF	Fabric Filter
CW	Clinical Waste
SS	Sewage Sludge
FGT	Flue-Gas Treatment
EGR	Exhaust Gas Recirculation
WACC	Weighted Average Cost of Capital
LT	Prospected Life-Time of the project, in years
PEC	Purchased Equipment Cost
TCI	Total Capital Investment
FC, VC	Fixed and Variable Costs
EoL	End of Life

Sub-scripts, super-scripts

P, R, W	Product, Resource, Residues
N	National economy
H	Hybrid system
d	Exergy destruction
CH	Chemical (Exergy)
C, O, D	Construction, Operation, Disposal

Notation

$\widehat{\mathbf{A}}$	Adjusted matrix
$\mathbf{A}^{-1}$	Inverse matrix
$\hat{\mathbf{a}}$	Diagonal matrix obtained from vector $\mathbf{a}$
$\mathbf{A}^{T}$	Transposed matrix
$\dot{x}$	Flow of quantity x per unit of time

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