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Exergy Life Cycle Assessment of a Waste-to-Energy plant

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Abstract

In this paper, thermodynamic performances of a Waste-to-Energy power plant are evaluated by means of Exergy Life Cycle Assessment (ELCA). Environmentally Extended Input-Output Analysis is proposed as the computational structure of ELCA, allowing to account for the embodied exergy of electricity production and for the Exergy Return on (non-renewable Exergy) Investment (ExROI). Results of the analysis reveal that non-renewable resources requirement of the WtE plant is not negligible. Nonetheless, the plant is able to produce a net amount of electricity that pays back such resources requirements about a hundred times.

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Keywords: Exergy Analysis; Exergy Life Cycle Assessment; Waste-to-Energy, Input-Output analysis.

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1. Introduction

Over the last decades, environmental concerns related to the depletion of non-renewable fossil resources pushed research efforts in developing innovative methodologies to account for fossils embodiment in goods and services [1]. articular attention has been devoted so far to the joint application of Exergy analysis and Life Cycle Assessment (LCA) to evaluate the overall thermodynamic performances of energy conversion systems [2].

Traditionally, boundaries of Exergy Analysis encompasses the physical layout of energy systems, quantifying the thermodynamic irreversibilities during their operative phase [3], and thus neglecting the primary resources indirectly invoked for the production of goods and services required by the systems during its whole life cycle [4]. According to the literature, any design improvement proposed by Exergy Analysis should be verified in a Life Cycle perspective, since a reduction of the internal irreversibilities within a given system may not always be accompanied by a reduction of its primary non-renewable resources requirement. This is particularly relevant for renewable energy systems, the penetration of which in national electric sectors is continuously increasing [5,6].

Many indicators based on *Exergy Life Cycle Assessment* (ELCA) have been defined to account for the exergy embodied in goods and services: *Cumulative Exergy Consumption* (CExC) [7], *Thermo-Ecological Cost* (TEC) [8], *Cumulative Exergy Extraction from Natural Environment* (CEENE) [9] and *Extended Exergy Accounting* (EEA) [10–13] are some telling examples. A comprehensive and critical reviews of ELCA have been performed by Liao et al. [14], Dewulf et al. [15], Rocco et al. [16] and Bakshi et al. [17].

1.1. Objective of the work

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In this paper, Exergy Life Cycle Assessment (ELCA) is applied to account for the *non-renewable primary exergy embodied* in the electricity produced by a Waste-to-Energy (WtE) power plant currently operating in the Italian context. In this study, *Environmentally Extended Input-Output analysis* (IOA) is proposed as the computational structure of ELCA. Suited indicators are defined to account for the overall thermodynamic performances of energy systems based on the proposed approach. The adopted approach presents many advantages and potential benefits with respect to the current literature: first, Input-Output analysis is widely recognized as the computational structure of Life Cycle Assessment, allowing to model national supply chains in a standardized, comprehensive and reproducible way, relying only on freely available national accountings. Secondly, the application of Input-Output analysis requires less amount of data with respect to conventional process-based LCA techniques, allowing to perform LCA in a simpler and cheaper way. Moreover, the use of ELCA method is particularly relevant for the analysis of Waste-to-Energy technology (and renewables in general): indeed, resources consumption of these kind of systems takes place largely in the supply chains that sustain their life cycle, and such effects cannot be quantified through conventional thermodynamic analyses.

2. Methodology: ELCA based on Environmentally Extended Input-Output analysis

So far, only isolated attempts have been made to perform ELCA accountings based in Input-Output mathematics [18]. In the following, *Environmentally Extended Input-Output analysis* is briefly introduced to provide a proper computational structure for ELCA.

Environmentally Extended Input-Output analysis (IOA in the following) allows to quantify the amount of primary resources embodied in goods and services produced by national economies. IOA relies on *Monetary Input-Output Tables* of national economies (MIOTs) as the reference data to model national supply chains: these tables collect the amount of products exchanged among national productive sectors by means of their monetary values. Once the amount of primary fossil fuels directly absorbed by each sector of the considered economy is known, it is possible to account for the direct and direct (i.e. the embodied) amount of such resources devoted to the production of specific goods and services invoked by the households for final uses.

Let us consider the generic national economy N as composed by *n* productive sectors: the *total production* of all the sectors $\mathbf{x_N}$ (in monetary value) can be expressed as the sum of *intermediate consumptions* $\mathbf{Z_N}$ and the households' *final demand vector* $\mathbf{f_N}$, as in relation (1). Moreover, the *exogenous resources vector* $\mathbf{R_N}$ is assumed to be known and it is composed by the primary non-renewable resources (fossil fuels, in exergy units).

$$\mathbf{x_N}(n\times 1)=\mathbf{Z_N}(n\times n)\mathbf{i}(n\times 1)+\mathbf{f_N}(n\times 1)\quad ;\quad \mathbf{R_N}(1\times n) \tag{1}$$

Based on these values (freely available from national economic department and *International Energy Agency* databases), Input-Output analysis can be applied as in relation (2), evaluating the embodied exergy in products of national economy. Notice that vector $\mathbf{e_N}$ (J/€) refers to the specific embodied exergy per unit of product, while vector $\mathbf{E_N}$ (J) refers to the exergy embodied in the total production.

$$\left.\begin{aligned}\mathbf{A_N}(n\times n)&=\mathbf{Z_N}\hat{\mathbf{x}}_\mathbf{N}^{-1}\\ \mathbf{B_N}(1\times n)&=\mathbf{R_N}\hat{\mathbf{x}}_\mathbf{N}^{-1}\\ \mathbf{L_N}(n\times n)&=(\mathbf{I}-\mathbf{A_N})^{-1}\end{aligned}\right\}\quad\rightarrow\quad\left\{\begin{aligned}\mathbf{e_N}(n\times 1)&=(\mathbf{B_N}\mathbf{L_N})^{\mathrm{T}}\\ \mathbf{E_N}(n\times 1)&=\hat{\mathbf{f}}_\mathbf{N}\,\mathbf{e_N}\end{aligned}\right. \tag{2}$$

In relation (2), elements of Technical coefficients matrix $\mathbf{A_N}$ and Input coefficients vector $\mathbf{B_N}$ respectively represent the direct requirements of products or resources invoked by each sector to produce one unit of product. On the other hand, each element of Leontief Inverse matrix $\mathbf{L_N}$ represent the direct and indirect amount of product required to deliver one unit of good or service.

National MIOTs aggregate different economic activities in larger sectors, so that relation (2) returns the exergy embodied in the *average* products of the considered national sector. As an instance, Input-Output analysis allows to account for the exergy embodied in products out of the *"Electricity, Gas and Water supply"* sector, thus the electricity produced by very different energy conversion systems operating inside that sector results in the same values of embodied exergy. To account for the primary exergy embodied of in products of one specific energy system, literature proposes the *Hybrid Input-Output* analysis [19]. According to this approach, the detailed energy system under investigation is numerically extracted from the national economy in which its life cycle takes place: the national production balance (1) can be thus rewritten as the hybrid (subscript H) production balance of relation (3) (the hybrid system is graphically presented in figure 1). In balance (3), terms with subscript N refers to the national economy, while the subscript S defines the exergy produced by the plant for intermediate consumptions and for final demand.

The *upstream cutoff vector* $\mathbf{C_{NS}}$ is the core of the ELCA model: it collects the *inventory* of goods and services that flow from specific sectors of the economy N to specific processes of the energy system S in one defined period (usually one year). Its definition requires a detailed evaluation of all the inputs that the system receives from the nation, expressed by means of their economic values evaluated through detailed economic analysis of the considered energy system. Similarly, each element of the *downstream cutoff matrix* $\mathbf{C_{SN}}$ represents the amount of products flowing from the system to each sector of the economy (quantified by means of their exergy equivalents).

$$\mathbf{x_H} = \mathbf{Z_H}\mathbf{i}+\mathbf{f_H} \qquad \rightarrow \qquad \begin{bmatrix}\mathbf{x_N}\\ x_S\end{bmatrix} = \begin{bmatrix}\mathbf{Z_N} & \mathbf{C_{NS}}\\ \mathbf{C_{SN}} & Z_S\end{bmatrix}\cdot\mathbf{i}+\begin{bmatrix}\mathbf{f_N}\\ f_S\end{bmatrix} \tag{3}$$

Once the Hybrid Technical coefficients matrix $\mathbf{A_H}$, the Hybrid Input coefficients vector $\mathbf{B_H}$ and the Hybrid Leontief inverse matrix $\mathbf{L_H}$ have been calculated as in relation (2), the embodied exergy of both the products of nation N and system S are calculated through relation (4). Notice that the total embodied exergy in the products can be decomposed, assessing the contribution of each single input absorbed from the national economy.

$$\mathbf{e_H}\left[(n+1)\times 1\right] = \left(\mathbf{B_H}\mathbf{L_H}\right)^{\mathrm{T}} \quad \rightarrow \quad \begin{cases}\mathbf{E_H}\left[(n+1)\times 1\right] = \hat{\mathbf{f}}_{\mathbf{H}}\,\mathbf{e_H}\\ \mathbf{E_{NS}} = diag\left[\mathbf{C_{NS}}\cdot\mathbf{i}\right]\cdot\mathbf{e}_{\mathbf{H},l=1:n}\left(n\times 1\right)\end{cases} \tag{4}$$

$$ExROI = \left|E_{H,Net}\right| / E_{H,Construction} \tag{5}$$

To account for *all* the primary exergy requirements of the considered energy system, boundaries of the hybrid model should cover all the life cycle phases of the system. If a phase lasts more than one year (usually the operation phase), the analyst should carefully split the evaluation and use different MIOTs (if available) in order to properly characterize national supply chains. Finally, the *Exergy Return on (Exergy) Investment* (ExROI) can be defined by relation (5), as the ratio between the net exergy produced by the system and the embodied non-renewable exergy required to build the system.

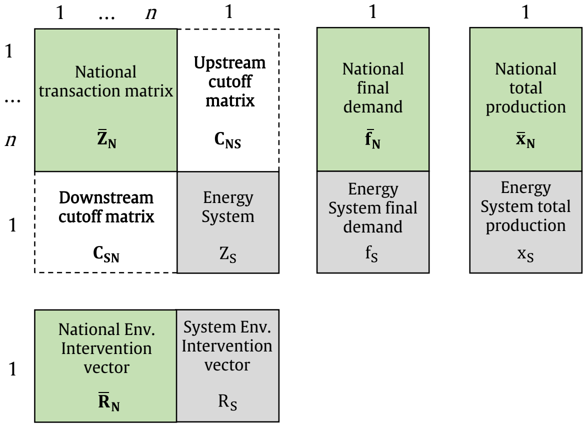

Fig. 1. Outline of the Hybrid Input-Output table. Boundaries of the analysed energy system (in grey) are extended to include its national supply chains (in green).

3. Application of ELCA analysis to a Waste to Energy power plant

In this section, ELCA is applied to a Waste-to-Energy power plant operating in northern Italy. Detailed economic cost assessment required for the application of ELCA has been performed, and embodied exergy of electricity production have been evaluated according to the above-introduced Input-Output model.

Plant layout is depicted in figure 2: the facility is endowed with two waste treatment lines, comprising an air-cooled downward reverse-reciprocating grate (Martin grate) with a counter-flow combustion chamber. The furnace works with an Exhaust Gas Recirculation (EGR) ratio of 15%. Both lines produce superheated steam which is expanded in a single Rankine steam cycle, with about 10 MW net electric power production at nominal conditions. The Flue Gases Treatment (FGT) section includes a Dry Process, featuring a Selective Catalytic Reactor (SCR) with NH3-solution, an Electrostatic Precipitator (ESP), a NaHCO3/Lime and Activated Carbon reacting section, and a Fabric Filter (FF). The plant is designed to treat 120 kt/year of waste, mainly Municipal Solid Waste (MSW, with LHV of 10.8 MJ/kg and chemical exergy of 12.9 MJ/kg [20]). The plant average availability factor results of 0.91, corresponding to about 8000 hours per year of operation at nominal conditions. The boiler produces super-heated steam at 390°C and 40 bar: subsequent expansion in the turbine proceeds to the conditions of 53.5 °C and 0.147 bar. Bleedings at intermediate pressures are designed to provide the necessary heat input to the combustion air pre-heaters, the sludge indirect dryer, and the regenerator.

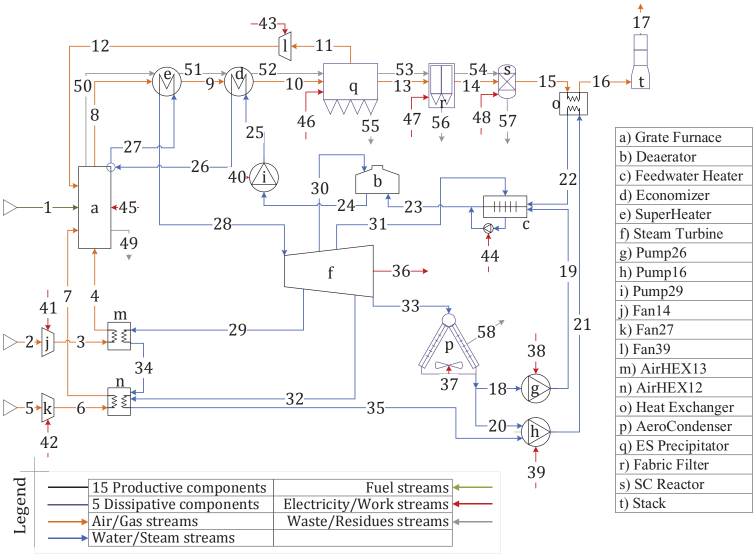

Fig. 2. Physical layout of Tecnoborgo Waste-to-Energy power plant.

ELCA is applied to the WtE plant according to the following fundamental hypotheses. First, the whole construction phase of the WtE plant takes place overnight, in 2010. Secondly, the prospected operative lifetime of the plant is 25 years at nominal operative conditions. Due to a lack of reliable economic data and to the related large uncertainties, disposal phase of the plant life cycle has been finally neglected.

For both construction and operation phase, the Italian MIOT referred to year 2010 is adopted. Italian economy is schematized with 63 productive sectors, classified according to *ISIC Rev.4* standard. Transactions of goods and services are expressed in M€ at basic prices according to 2010 exchange rates, including imports from other countries. Construction phase of the plant is classified within the economic sector "*Construction - Civil engineering*" (code F-42), which includes the construction of power plants and waste-treatment facilities, while system operation is classified within the sector "*Electricity, gas, steam and air conditioning supply*" (code D-35). Values of primary energy production in Italy are derived from the International Energy Agency database (IEA) and properly converted in exergy. This amount of exergy enters the Italian economy through the ISIC sector *Mining and quarrying* (code B). Notice that during both construction and operation phases, the plant does not absorb non-renewable resources directly from the environment. Upstream Cutoff matrix $\mathbf{C}_{NS}$ collects capital and operative economic costs of the plant, calculated from specific economic analysis, while Downstream Cutoff matrix $\mathbf{C}_{SN}$ results as an empty vector.

4. Results of ELCA analysis

Once the Hybrid system presented in figure 1 has been completely characterized, specific and total embodied exergy of electricity can be obtained through the application of relations (4). Results are reported in table 1, while disaggregated contributions of all the exergy embodied in inputs required for plant Construction and Operation have been evaluated thanks to relation (4) and reported respectively in tables 2 and 3.

Results confirm the strong potential of Waste-to-Energy technology with respect to primary fossil fuel savings from a life cycle perspective. The primary non-renewable exergy required for constructing and operating the system equals the yearly total primary exergy supply of about nine hundred Italian citizens in 2010, assuming about 2.8 toe pro-capita in 2010. Not surprisingly, value of ExROI of the WtE plant reveals that it produces an overall amount of electricity exceeding about one hundred times the primary non-renewable resources required along its construction and operation phases.

Table 1. Results of the ELCA analysis.

Parameter	**Parameter**	**Unit**	**Value**
Embodied exergy of Construction phase	$E_{H,Construction}$	toe	1745.9
Embodied exergy of Operation phase (1 year)	$E_{H,Operation}$	toe/y	61.3
Yearly electricity production	Ex_P	toe/y	7062.5
Total Embodied exergy in the life cycle	E_H	toe	3278.3
Exergy Return on (exergy) Investment	ExROI	-	99.25

Table 2. Embodied exergy breakdown: construction phase.

National sector	**Code**	**E_{NS} [toe]**	**E_{NS} [%]**
Manufacture of basic metals	C 24	121,1	6,9%
Manufacture of electrical equipment	C 27	231,1	13,2%
Manufacture of machinery and equipment n.e.c.	C 28	605,4	34,7%
Repair and installation of machinery and equipment	C 33	127,1	7,3%
Electricity, gas, steam, and air conditioning supply	D 35	17,7	1,0%
Construction	F 41-43	474,6	27,2%
Land transport and transport via pipelines	H 49	30,3	1,7%
Real estate activities	L 68	2,6	0,1%
Legal and accounting activities; management consultancy activities	M 69-70	8,8	0,5%
Architectural and engineering activities; technical testing and analysis	M 71	127,1	7,3%
Total for Construction phase	E_{NS},Const.	1745,9	100,0%

Table 3. Embodied exergy breakdown: operation phase.

National sector	**Code**	**E_{NS} [toe/y]**	**E_{NS} [%]**
Mining and quarrying	B 05-09	3.9	6.4%
Manufacture of coke and refined petroleum product	C 19	0.2	0.3%
Manufacture of chemicals and chemical products	C 20	16.4	26.7%
Repair and installation of machinery and equipment	C 33	16.0	26.1%
Electricity, gas, steam, and air conditioning supply	D 35	0.1	0.2%
Water collection, treatment and supply	E 36	2.4	3.9%
Sewerage; waste collection, treatment and disposal activities; …	E 37-39	1.5	2.5%
Construction	F 41-43	9.2	15.1%
Insurance, reinsurance and pension funding, except compulsory …	K 65	11.6	18.9%
Total for Operation phase	E_{NS},Oper.	61.3	100.0%

Embodied exergy breakdown of construction and operation phases are shown in tables 2 and 3. For the construction phase, manufacture of machinery and equipment and construction of buildings represent more than 60% of the total primary resources consumption. Surprisingly, more than 7% of the primary embodied exergy is devoted to non-material services (engineering and supervision), which are usually neglected in standard process-based LCA. The largest fraction of the primary exergy cost of the operation phase (more than 50%) is caused by raw materials supply and equipment maintenance. As above, non-material services play a non-negligible role, affecting primary exergy requirements for slightly less than 20%.

5. Concluding remarks

In this paper, Hybrid Input-Output analysis has been proposed as an appropriate mathematical structure for the practical application of Exergy Life Cycle Assessment. The proposed approach has been formalized and applied to a

Waste-to-Energy power plant currently operating in the Italian context. The adopted Input-Output model makes the application of ELCA to energy systems simple and reproducible. Moreover, results of ELCA reveal that the Waste-to-Energy power plant operating in the Italian context has a strong potential in the perspective of primary non-renewable resource displacement.

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Biography

Matteo V. Rocco (1986) achieved the MSc degree in Energy Engineering in 2011 and the PhD in Energy Science and Technology in 2015 at the Energy Department, Politecnico di Milano. His research activities lies in the fields of Thermodynamic analyses of energy systems and Industrial Ecology, focusing on Life Cycle Assessment and Input-Output analysis.