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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.

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 $\mathbf{x}_\mathbf{N}$ (in monetary value) can be expressed as the sum of *intermediate consumptions* $\mathbf{Z}_\mathbf{N}$ and the households' *final demand vector* $\mathbf{f}_\mathbf{N}$, as in relation (1). Moreover, the *exogenous resources vector* $\mathbf{R}_\mathbf{N}$ is assumed to be known and it is composed by the primary non-renewable resources (fossil fuels, in exergy units).

$$\mathbf{x}_\mathbf{N}(n\times 1) = \mathbf{Z}_\mathbf{N}(n\times n)\mathbf{i}(n\times 1) + \mathbf{f}_\mathbf{N}(n\times 1) \quad ; \quad \mathbf{R}_\mathbf{N}(1\times n) \tag{1}$$

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 $\mathbf{e}_\mathbf{N}$ (J/€) refers to the specific embodied exergy per unit of product, while vector $\mathbf{E}_\mathbf{N}$ (J) refers to the exergy embodied in the total production.

$$\left.\begin{array}{l} \mathbf{A}_\mathbf{N}(n\times n) = \mathbf{Z}_\mathbf{N}\hat{\mathbf{x}}_\mathbf{N}^{-1} \\ \mathbf{B}_\mathbf{N}(1\times n) = \mathbf{R}_\mathbf{N}\hat{\mathbf{x}}_\mathbf{N}^{-1} \\ \mathbf{L}_\mathbf{N}(n\times n) = (\mathbf{I}-\mathbf{A}_\mathbf{N})^{-1} \end{array}\right\} \quad \rightarrow \quad \begin{cases} \mathbf{e}_\mathbf{N}(n\times 1) = (\mathbf{B}_\mathbf{N}\mathbf{L}_\mathbf{N})^{\mathrm{T}} \\ \mathbf{E}_\mathbf{N}(n\times 1) = \hat{\mathbf{f}}_\mathbf{N}\,\mathbf{e}_\mathbf{N} \end{cases} \tag{2}$$

In relation (2), elements of Technical coefficients matrix $\mathbf{A}_\mathbf{N}$ and Input coefficients vector $\mathbf{B}_\mathbf{N}$ 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 $\mathbf{L}_\mathbf{N}$ 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.