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Exergy Life Cycle Assessment of electricity production from Waste-to-Energy technology: A Hybrid Input-Output approach

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HIGHLIGHTS

- Hybrid Input-Output analysis is proposed as the computational structure of ELCA.
- Exergy Analysis and ELCA are applied for the analysis of a Waste-to-Energy plant.
- Thermodynamic optimization has performed based on Exergy Analysis and ELCA.

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ABSTRACT

Exergy Life Cycle Assessment (ELCA) is proposed by literature to account for the exergy embodied in products of energy systems. In order to make results of ELCA comparable, supply chains that support the life cycle of the system should be analyzed through a unified model: this is one of the main concerns related to Life Cycle Assessment and Industrial Ecology disciplines.

In this paper, Hybrid Input-Output analysis is proposed as the computational structure of ELCA: according to this method, national supply chains are modeled through the Monetary Input Output Tables (MIOTs) of national economies, a constantly updated and freely available data source. Then, the adopted national MIOT is expanded to include the detailed model of the considered energy system, hence defining a Hybrid Input-Output model. The (non-renewable) exergy embodied in electricity production and the Exergy Return on Investment (ExROI) are defined as the appropriate performance indicators based on ELCA. The introduced model is here adopted for the analysis of a Waste-to-Energy (WtE) power plant currently operating in the Italian context.

It is found that the primary non-renewable exergy embodied in electricity produced by the analyzed WtE is non-negligible for both the construction (127.1 toe) and the operation phases (11.6 toe/y). Nonetheless, the plant is able to produce a net amount of electricity that pays back such primary non-renewable resources requirements about a hundred times. Finally, the joint application of Exergy Analysis and ELCA lead to improve the overall thermodynamic performances of the WtE system, increasing its exergy efficiency by 1%, and reducing the non-renewable exergy embodied in electricity production by 7938 toe.

1. Introduction

Over the last decades, environmental concerns related to the depletion of non-renewable fossil resources, namely coal, crude oil and natural gas, pushed research efforts in developing methodologies to account for fossil resources embodiment in goods and services [1]. In this perspective, particular attention has been devoted so far to the joint application of Exergy Analysis and Life Cycle Assessment (LCA) to evaluate and to improve the overall thermodynamic performances of energy conversion systems, thus reducing energy-resources depletion [2].

Traditional applications of Exergy Analysis (ExA) are mainly focused on the analysis of the physical layout of energy systems, identifying the main sources of thermodynamic irreversibilities caused by their operative phases, and without distinguishing between irreversibilities caused by renewable and non-renewable resources use [3,4]. However, with the increasing penetration of renewables in national power systems, the importance of analyzing such systems in a life cycle perspective increases, as relatively more non-renewable energy-resource depletion takes place in upstream in supply chains, rather than in the analyzed energy system [5–8]. Therefore, any design improvement proposed by

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Nomenclature

Symbol	Quantity
$\dot{Ex}$, Ex	exergy rate (W), Exergy (J)
n_P, n_D	number of productive/dissipative components in the system (-)
$\mathbf{i}$	summation vector (-)
B, $\mathbf{B}$	input coefficient/matrix (kJ/kJ, kJ/€)
E, $\mathbf{E}$	total embodied exergy, Total embodied exergy vector (toe)
R, $\mathbf{R}$	exogenous resource coefficient/matrix (kJ)
Z, $\mathbf{Z}$	transaction coefficient/matrix (€, kJ)
a, $\mathbf{A}$	technical coefficient/matrix (€/€, kJ/kJ)
e, $\mathbf{e}$	specific embodied exergy, Specific embodied exergy vector (J/J)
f, $\mathbf{f}$	final demand coefficient/vector (€, kJ)
l, $\mathbf{L}$	Leontief inverse coefficient/matrix (€/€, kJ/kJ)
m	total sectors of a national economy (-)
n	total pieces of equipment of the energy system (-)
x, $\mathbf{x}$	total production coefficient/vector (€, kJ)
yr	year (-)
η	efficiency (-)

Acronyms – Subscripts/Superscripts

0	Environment/Reference
CEENE	Cumulative Exergy Extraction from Natural Environment
CExC	Cumulative Exergy Consumption
CExD	Cumulative Exergy Demand
ECT	Exergy Cost Theory
EEA	Extended Exergy Accounting
EEC	Exergo-Environmental Analysis
EGR	Exhaust Gas Recirculation
ELCA	Exergy Life Cycle Assessment
end	Endogenous
ExA	Exergy Analysis
ExROI	Exergy Return on (Non-renewable Exergy) Investment
H	Hybrid
IOA	Input – Output analysis
LC	Life Cycle
LCA	Life Cycle Assessment
MIOT	Monetary Input-Output Table
MSW	Municipal Solid Waste
N	Nation
NS	Nation-to-System
P, R, L, D	Product, Resource, Loss, Destruction
PEC	Purchase Equipment Cost
S	Energy system
SN	System-to-Nation
TCI	Total Capital Investment
TEC	Thermo-Ecological Cost
TPC	Total yearly Production Cost
VAT	Value Added Tax
WtE	Waste to Energy
i, j	components, sectors
r, c	row, column

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 energy-resources requirements. For this reason, in last decades many Authors propose different types of Exergy Life Cycle Assessment (ELCA) methods, with the aim to expand the boundaries of traditional ExA, including the energy-resources depletion caused by supply chains that feed the analyzed energy system [9] (a brief but comprehensive review of ELCA methods is provided in Section 2). However, according to the literature, the application of ELCA is always performed through a *soft-link* between Exergy Analysis and existing LCA software and databases: ExA receives results of LCA as input, but it is not integrated into the LCA model, and therefore one unique computational structure for ELCA method is still missing.

In this paper, the *Environmentally extended Input-Output analysis* is proposed as the computational structure of ELCA, thus defining a mathematical *hard-link* between Exergy Analysis and Life Cycle Assessment methods. Secondly, conventional Exergy Analysis and the defined ELCA model are comparatively applied to a Waste-to-Energy (WtE) power plant currently operating in the Italian context. Thermodynamic performances of WtE plant are comprehensively evaluated in terms of exergy destructions caused by WtE components and in terms of (non-renewable) primary exergy embodied in its electricity production. Finally, the plant design is iteratively optimized based on the results of ExA, and the overall benefits of such optimization process are verified by means of ELCA in terms of non-renewable displacement.

This study adds to and extends existing Exergy Life Cycle Assessment studies in several ways:

- Exergy Analysis and ELCA are integrated for the first time into one single mathematical model by means of Environmentally extended Input-Output analysis, which is assumed by the literature as the proper computational structure of Life Cycle Assessment [10,11]. This approach allows to apply ELCA in a standardized and reproducible way with respect to conventional process-based LCA techniques, without the support of expansive software and databases, but only relying on national economic statistics [12].
- The proposed approach allows to account for the primary energy-resources invoked also for the consumption of immaterial services required by the analyzed energy system, that are usually disregarded in conventional process-based LCA models. Moreover, the proposed approach can be easily extended to account for other kind of environmental impacts, such as pollutant/GHG emissions, land use, and water use [8,13].
- Suited indicators are defined based on ELCA to account for the overall thermodynamic performances of energy systems in a comprehensive and meaningful way. Relying on results of both ExA and ELCA, an iterative design optimization procedure is then proposed to reduce the consumption of primary energy-resources due to the life cycle of the WtE plant.
- Finally, the proposed approach allows to estimate the environmental effects caused by an increasing penetration of new energy technologies on the economic system. This topic is out of the scope of this paper, but it is of paramount importance in the field of Consequential Life Cycle Assessment [14].

2. Exergy Life Cycle Assessment: brief literature review

Starting from early 1970s, many different Thermodynamics-based methods have been proposed to account for the environmental impact caused by production of goods and services [15].

The *Exergy Cost Theory* (ECT) was proposed by Valero as a complete and formalized method aimed at evaluating the exergy costs of the products of energy systems [16,17]. Once all the interactions among components are characterized by means of exergy, the ECT analysis allows to understand the cost formation structure of the products, quantifying the relevance that internal irreversibilities

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