Petrakopoulou, Fontina; Batuecas, Esperanza (2021). Introduction to an exergy-based socioeconomic analysis, *Energy Conversion and Management,* 249: 114853.

DOI: https://doi.org/10.1016/j.enconman.2021.114853

Title: Introduction to an exergy-based socioeconomic analysis

Fontina Petrakopoulou* and Esperanza Batuecas
Universidad Carlos III de Madrid, Avda. de la Universidad 30, 28911 Leganés (Madrid), Spain
**fpetrako@ing.uc3m.es*

Abstract

This study introduces and validates an exergy-based, socioeconomic (ESEC) analysis that couples an economic expression of environmental impacts (external costs) with conventional costs and thermodynamics. The ESEC analysis improves on previous approaches by combining disparate analyses into one framework based on monetary costs, which facilitates robust, multi-criteria optimization of energy-conversion systems. As a proof of concept, it is applied to a combined-cycle power plant (reference plant) and a power plant with chemical looping combustion (CLC plant). The results show good agreement with the results of the individual exergoeconomic and exergoenvironmental analyses. Nevertheless, the analysis shows some bias towards the economic results, which reveals a higher inherent weight of that component of the evaluation. Critically, the consideration of the costs of environmental impacts through the ESEC analysis produces a significant shift in the comparative performance of the plants. The increase in the levelized cost of electricity of the CLC plant relative to the reference plant falls from 23.4% to 7.2% when external costs are included. This reveals a strong effect of the environmental impacts on the overall outcome and shows the potential importance of their inclusion in design evaluations for policy and decision making.

1. Introduction

One of the reasons for governmental intervention in European energy markets is that market prices do not include costs related to environmental damages [1]. The translation of such damages into monetary values establishes the concept of **external costs**[1] (also called externalities). Although external costs are important to be considered along with private costs[2] (social costs), they do not have a known market value a priori and they are associated with high uncertainties. Today, the energy sector is undergoing a rapid transformation that calls for modern tools to facilitate the accurate evaluation and optimization of future energy systems that can satisfy demanding sustainability goals and rapid market shifts. The incorporation of external costs into the evaluation of energy systems will lead to a fairer consideration of the detrimental impacts on human health and the environment of energy processes. To evaluate alternatives and choose the design of energy systems, engineers rely on simulation and optimization techniques. This paper aims to present a new evaluation method that will allow the thermodynamic, economic, and environmental multi-objective (MO) optimization of energy systems at their design stage.

Optimization methods used in the energy sector today are commonly based on private costs, operational efficiency, and environmental performance. To create sustainable designs, however, optimization methods must consider the external costs together with the private costs. Further joint consideration of several criteria like environmental performance and thermodynamic efficiency can only strengthen the capacity of an optimization method. Thermodynamic analyses based on the first law of thermodynamics usually fall short when it

---

[1] External costs (also known as externalities) refer to the economic concept of uncompensated social or environmental effects.

[2] Private costs are the internal costs of a good or a service, including the direct monetized costs for planning, construction, management, maintenance, and disposal.

comes to the evaluation of the efficiency of energy systems [2]. The reason for this is that energy analysis only identifies material streams crossing the thermodynamic boundaries of a given system as thermodynamic inefficiencies [3]. In this way, an evaluation based on exergy and the second law of thermodynamics is more adequate to evaluate and optimize energy systems. The new multi-criteria method presented here will, for the first time, couple the principle of exergy with private costs and externalities.

Various approaches to the valuation of external costs of energy systems and transport exist in the literature, with more work produced in the last two decades. In general, these valuation methods consider costs of damages, or market prices, to reach a specified emission target, or they may be based on mitigation, abatement and/or restoration costs [1]. Approaches based on market prices reflect the current market framework at a given moment, leading to significant variability of value estimations over time and by policy, and therefore they do not offer a robust internalization of externalities. Methods considering costs for abatement or mitigation and restoration are also susceptible to factors like technological advancements, resource scarcity and policies, leading to significant price variability and weaker externality correlations. In contrast, approaches that valuate costs of damages consider all possible societal costs with a long-term perspective, therefore increasing complexity but covering a broader spectrum of external costs.

Approaches that valuate the cost of damages are usually based on the concept of life cycle assessment (LCA), a recognized and useful tool for evaluating the environmental impacts of products, processes, and activities. In an LCA, materials used, and pollutants emitted over the life cycle of a process are converted into environmental impacts. A stand-alone LCA does not provide information about cost, so it needs to be combined with economic tools. The most common economic tools can be classified into cost-benefit analyses (CBA), eco-efficiency (EE) and Life cycle costing (LCC) methods [4]. The most common tool is LCC, which is analogous to life cycle impact assessment (LCIA) but including economic costs instead of environmental impacts. LCC is an environmental cost accounting method [5] that identifies private costs in order to minimize them. Although there is no agreement about the selection of the methods to characterize ecology and economy, there is a more general classification of such approaches [6]: i) methods (mainly graphical) that integrate environmental and economic aspects but do not calculate a composite indicator, ii) methods that divide the environmental indicator by the economic indicator, or vice versa, obtaining a composite indicator, and iii) methods that calculate a composite indicator value by adding the two indicators after appropriate scaling is applied. Approaches that valuate the cost of damages calculate a composite indicator combining environmental impacts with external costs by using characterization factors[3] of a selected LCIA method[4].

The ExternE project series presents a unified methodology for the valuation of the externalities of different power generation technologies [7,8]. By March 2010, the ExternE project series involved over 50 research teams from more than 20 countries, and became a well-recognized source for the estimation of external costs [8,9]. An important recent application of ExternE was an exercise to quantify the external costs of the major electricity generation technologies in 15 European countries, to aggregate these damages for national power systems, and to apply results to policy making issues [10]. Overall, ExternE/CASES/NEEDS and CE Delft Shadow Prices are considered the most extended approaches to estimate the societal cost of finite energy-resource depletion [1,11]. These approaches use LCIA methods to determine characterization factors for impact assessment. ReCiPe is the recommended LCIA method, as it presents the most

---

[3] Characterization factors quantify the environmental and social damages per unit of materials used or substance emitted (e.g., greenhouse gas emitted, material used, etc.).

[4] A method that translates quantities of materials and pollutants into environmental impacts.

accepted and widespread characterization factors for impact assessment. The latest approach to environmental pricing (i.e., external costs), developed by CE Delft in 2017/18, is based on the NEEDS/CASE projects and estimates the damage costs of 2,500 pollutants. In 2019 the method was added to SimaPro, simulation software widely used in the realization of LCA. The incorporation of the approach into SimaPro is realized at the pollutant level (per substance), at the midpoint level (per impact category) and at the endpoint level (per damage category). Except for climate change, all other factors included in the approach, are again based on their coupling with the LCIA ReCiPe 2008 methodology.

The present study uses externalities from the External-E approach [12], that provides a valuation relationship between impacts and damages (based on scientific literature and modelling). The monetisation of the impacts is based on estimates of the damage that will be done in the future by emissions for categories such as climate change. For categories like fossil fuel depletion, the external costs are based on a surplus cost of the production of energy resources. For impacts of particulate matter formation, the monetization is based on direct valuation of the endpoint impacts on human health. In the literature, very little is known about the externalities of energy markets. Although several studies [13,14] take into account the economic implication of environmental impacts by means of LCC, this will be the first study to integrate external costs with thermodynamic analysis for the evaluation and optimization of energy conversion systems. Existing research recognises the critical role of exergy-based MO optimization of exergy, economic and environmental issues but past attempts have not produced a straightforward MO approach for wider use [15–17]. The mathematical optimization approach of environomics developed by Christos Frangopoulos at the beginning of the 1990s was the first attempt to create an exergy-based MO optimization approach including external costs for energy systems [18,19]. The mathematical model proposed included an objective function with the goal of minimizing the overall private and external costs of a complete energy facility. ESEC, the developed method in this paper, belongs to the class of iterative optimization exergy-based methods and it targets the evaluation and improvement at the component-based, as well as overall plant. ESEC aims to reveal trade-offs between the three objectives of external-cost minimization, private-cost minimization, and efficiency maximization and is based on the updated concepts and calculation procedures of life-cycle assessment methods and external costs. The developed method is further applied to a combined cycle power plant, an advanced plant with CO_2 capture and the obtained results will be compared to the conventional exergoeconomic and exergoenvironmental analyses.

Section 2 below presents the steps of the methodological approach to realize an ESEC analysis. Section 3 describes briefly the case studies on which the method was applied, and Section 4 presents and discusses the results, with a comparison to the results obtained from conventional exergy-based methods. Finally, Section 5 presents the conclusions and future outlook.

2. Methods

The realization of an exergy-based socioeconomic (ESEC) analysis, requires the following steps:

1. life cycle assessment (LCA),
2. calculation of external costs,
3. exergetic analysis,
4. economic analysis,
5. ESEC analysis

In this work, the ESEC method is applied to two case studies described in Section 3, a combined-cycle power plant (reference plant) and a similar plant with chemical looping combustion and CO_2 capture. It should be mentioned that in order to facilitate the comparison of the new method with conventional exergy-based analysis and evaluate its results and conclusions, the analysis is realized in two steps. In the first step, the external costs of materials of components are considered and added to the costs of purchase and maintenance (accounting only for the construction phase). In the second step, the externalities of the operational phase are also accounted for including the environmental impact of fossil-fuel use (natural gas). In this way, in the second step both the construction and the operation phases are included.

2.1 LCA

Life-cycle environmental impacts are carried out according to ISO 14040 and ISO 14044 standards [20]. The first step here is to create a life cycle inventory (LCI) of each studied process depicting all input and output flows, based on predefined system boundaries. The calculation of the environmental impacts of the analysis is then realized for both the construction and the operation of the plants. The construction phase involves the calculation of the environmental impacts of all required materials to construct each of the components of the plants, while the operation phase refers to the environmental impacts associated with the generation of 1 kWh in each plant.

To quantify the environmental impacts the LCIA method ReCiPe, the ILCD method and the Ecoinvent 3 database are used. ReCiPe 2016 v1.1 midpoint method, hierarchist version [21], is used to calculate all impact categories except for the photochemical ozone formation (POF) and ionizing radiation HH (IRHH) that are calculated with the ILCD version 1.0.9 (May 2016). The ILCD Midpoint method was created by the European Commission [22], while ReCiPe by Radboud University, the Norwegian University of Science and Technology and PRé Consultants. Both methods are widely recognized by the scientific community.

2.2 Estimation of external costs

The external costs of energy generation are calculated using the ExternE approach [12]. This approach is based on methodologies developed within the projects NEEDS [23] and CASES [24] that use energy and heat production data from EUROSTAT. The method followed can be classified in the category of approaches that define a composite indicator through the multiplication of the value of the economic indicator by that of the environmental indicator, as suggested by Ferran et al. (2018) [6].

The environmental results estimated in Refs. [3,17] and expressed in units of mPts using the EcoIndicator99, are in this work expressed in environmental impacts of midpoints using the LCIAs ReCiPe and ILCD. Table 1 presents the specific monetary values of 17 impact categories expressed in €/unit, as calculated by Alberici et al. (2014). The specific external costs used here are based on the ExternE projects and do not include impacts of employment or the depletion of non-renewable resources. The latter are considered internal, i.e., already included in the prices of the fuels. The chosen specific costs are combined with the LCA environmental impacts calculated above to obtain the total external costs of these 17 impact categories [12]. Specifically, the external costs are estimated by multiplying the specific external costs expressed per unit of midpoint of environmental impact with the environmental impact of midpoint estimated. Subsequently, some necessary modifications are carried out. These modifications are related to national characteristics of energy production, relative efficiency, working hours etc. compared with the reference data. In the present work, the estimated environmental impacts of fine particulate matter formation and mineral resource scarcity in PM2.5 and Cu eq., respectively, have been converted to PM10 and Fe eq. This was realized to be able to use the available specific external costs [12] that were based on PM10 and Fe eq [12]. The appropriate conversion factors used were based on data derived from the World Health Organization and the ReCiPe report [21,25].

2.3 Exergetic and economic analyses

The exergetic and economic analyses of the plants used for comparison and validation in this work are presented in published works [3,17]. The exergetic analysis, realized to calculate the thermodynamic irreversibilities of each individual component of evaluated case studies [26] was realized using a MATLAB programming code that included balance equations stated at the component level and one equation for the overall plant. The economic analysis was performed using the total revenue requirement (TRR) method and it was based on assumptions related to the economic life of the plants, the cost of fuel (natural gas), the average annual cost of money and inflation rates [3]. The new ESEC method will combine the previous exergetic and economic results with external costs to study the effect of the addition of external costs to extract conclusions. Since the new method will be based on the previous analyses and will also be compared against them, it is critical that these basic results of the individual exergy-based analyses remain unchanged.

2.4 ESEC analysis

The developed ESEC method is based on the methodological approach of existing exergy-based methods but aims to advance the state-of-the-art of MO exergy-based optimization analyses with a straightforward procedure. It also combines the concepts of both the exergoeconomic and exergoenvironmental analyses in a unified framework and aims to deliver results as inherently explicit financial expenditures.

The calculated monetary values of external costs in Section 2.2. are converted into costs rates with units of Euro/s and then are added to the cost rates of investment cost, operating and maintenance expenses Z_k calculated in the conventional economic analysis (Section 2.3). The rates of the total costs are then used as input values in the component balances, defined in a similar way as in an exergoeconomic or an exergoenvironmental analysis. Specifically, the ESEC analysis is realized using a system of balances, one for each component as follows:

$$\sum_{i=1}^{i=n} T_{i,k} - \sum_{j=1}^{j=m} T_{i,k} + Z_{s,k} = 0 \qquad (1)$$

where, $\sum_{i=1}^{i=n} T_{i,k}$ and $\sum_{j=1}^{j=m} T_{i,k}$ stand for the sum of the total cost rates of *n* streams entering and *m* streams exiting component *k*, respectively. The rate of total cost of a material stream ($\dot{T}_{i} = \dot{C}_{i} + \dot{C_e}_{,i}$) includes its cost calculated in the economic analysis (C) and its external cost ($\dot{C_e}$) linked to the operation of the plant (for example, the external cost of natural gas use). $Z_{s,k}$ is the total (social, *s*) cost rate of component *k* that includes the external costs ($\dot{EC}_k$) of the component due to the environmental impact of its construction and its cost rate, $\dot{Z}_k$:

$$\dot{Z}_{s,k} = \dot{Z}_k + \dot{EC}_k \qquad (2)$$

Following the methodology of the conventional exergy-based analysis, two parameters are defined to help with the evaluation process in an ESEC analysis and to facilitate assessment. These parameters will also serve to compare the results of the new method with those of the exergoeconomic analysis and evaluate the insight gained with the ESEC method and its relative value in energy system evaluation efforts.

First, the socioeconomic factor, $f_{s,k}$, is calculated for each plant component *k* and the overall plant. This factor shows the impact of the external costs to the total cost of the components that includes the material/maintenance and operation cost and the total cost of irreversibilities ($S_{D,k}$):

$$f_{s,k} = \frac{Z_{s,k}}{S_{D,k}+Z_{s,k}} \quad (3)$$

The cost of irreversibilities of exergy destruction is calculated using the exergy destruction calculated in the exergetic analysis and the total cost of fuel of the component, $s_{F,k}$, as calculated in the ESEC analysis:

$$S_{D,k} = s_{F,k}E_{D,k} \quad (4)$$

For the overall plant, the socioeconomic factor is defined as:

$$f_s = \frac{Z_s}{S_D+Z_s} \quad (5)$$

with Z_s the total cost rate of the plant due to the environmental impact of its construction and $S_D = s_F E_D$. s_F is the total specific cost rate of the total fuel of the plant and E_D is the total exergy destruction of the plant. Since the ESEC analysis accounts for the external costs of the environmental impacts of the fuel used and the construction of components, the total cost of exergy destruction will be higher than the exergy destruction cost calculated in a conventional exergoeconomic analysis.

Second, the ESEC relative social cost difference is calculated as follows:

$$r_{s,k} = \frac{s_{P,k}-s_{F,k}}{s_{F,k}} \quad (6)$$

where, $s_{P,k}$ and $s_{F,k}$ the ESEC cost of the product and fuel of component *k*. The relative cost difference reveals how much more expensive the product of the component would be relative to its fuel due to irreversibilities, costs and external costs associated with the operation of each component *k*. In the case of the total plant, the relative cost difference is based on the ESEC cost of product and fuel of the overall plant, i.e., the s_P and s_F.

3. Case studies

The case studies used to implement the developed method in this work are a combined-cycle power plant (reference) and a chemical looping combustion plant with oxyfuel carbon capture (CLC plant) [3,17]. The reference plant is a natural-gas-fired combined cycle plant with three-pressure level heat-recovery steam generator (HRSG) with a reheating system. The CLC plant includes a similar structure, but it includes a CLC unit coupled with CO_2 capture and a 4-stage compression unit with compressors and intermediate coolers to liquify the captured CO_2. The two plants are used to, first, test and validate the new ESEC method and, second, to provide a basis for the evaluation of the magnitude of the effect accounting for external costs in a typical analysis. The flow diagrams and the results of the conventional exergy-based analyses of the two plants are shown in the Appendix of the paper to support the comparison with the new ESEC method.

4. Results and Discussion

4.1 Life Cycle Inventories

The LCI of the reference case and the CLC plant are presented in Table A1 and Table A2 of the Appendix, respectively. These tables show the breakdown of the plant components according to their materials summarized into steel, cast iron, concrete and PVC. A comparison of the two tables reveals the differences between the number and type of components in the two plants. The reference plant is composed of 24 components while the oxyfuel CLC plant consists of a total of 40 components. This affects the environmental impact of the latter significantly since additional components require additional material.

4.2 LCA results

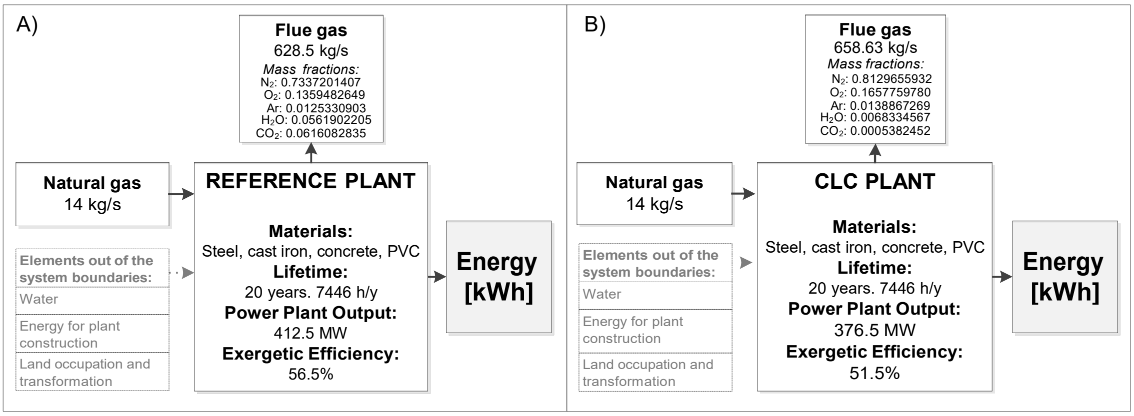

Figure 1. Flowchart of the (A) reference and (B) CLC plants. Processes depicted in light grey boxes are considered out of the system boundaries.

The comparison is initially realized at the component level of the power plants. Initially, the comparative LCA reveals which components are associated with higher environmental impacts (construction phase). The functional unit of the construction phase is the size of the power plants that is approximately 400 MW. The operational phase of these plants is then addressed. The basis of comparison, in the operational case, is the energy generation of 1 kWh (functional unit). The two plants consume the same amount of fuel and generate electricity with different efficiencies. Figure 1 shows the flowchart of energy production in the reference case (A) and the CLC plant (B), highlighting the foreground system i.e., the processes that are included in the LCA system boundaries. The overall system boundaries for the LCA of energy production include as inputs the fuel (natural gas) and the materials used to construct the plants (presented in Tables A1 and A2 of the Appendix). During operation, both plants consume 14 kg/s of natural gas. The plant materials are spread throughout the plant lifetime (20 years with and operation of 7440 h/y). The power plant output of the reference plant is 412.5 MW (with 56.5 % as exergetic efficiency), while that of the CLC plant is 376.5 MW (51.5 % exergetic efficiency) due to the addition of CO_2 capture. The exhausted stream of the plants is the emitted flue gas. The reference plant releases 628.5 kg/s of flue gas with a molar fraction shown in Figure 1A. The molar fraction of the flue gas of the CLC plant is presented in Figure 1B. Using all the above information, it is possible to allocate the inputs/outputs to the functional unit (1 kWh) and calculate the associated environmental impacts.

Figure 1 also presents other elements, like water, energy for the construction of the plant and land occupation and transformation, that are necessary for the operation of the plants and the generation of the required energy. When the environmental impact analysis does not include these elements, the stand-alone results of 1 kWh are underestimated. However, the work here is focused on comparing the results of the ESEC with those of the conventional exergy-based analyses and should include thus the same material streams considered in the initial evaluations. In addition, the additional elements would cancel each other out in a comparative evaluation. As such, the results of the present study are adequate to compare the LCA performance of the two plants with and without CO_2 capture.

Table 1. Environmental impacts and external costs for the CLC and REF plants per 1 kWh.

Environmental impact category	Abbr	CLC PLANT	REF PLANT	REF plant savings per kWh produced	Unit	External cost (€/Unit)	CLC PLANT (€)	REF PLANT (€)	REF plant savings per kWh produced (€)

Global warming potential	GWP	$4.41\cdot10^{7}$	$3.44\cdot10^{7}$	**$-5.69\cdot10^{-1}$**	kg CO_2 eq	0.043	$1.90\cdot10^{6}$	$1.48\cdot10^{6}$	**$-2.45\cdot10^{-2}$**
Stratospheric ozone depletion	OD	3.90	3.17	$2.80\cdot10^{-8}$	kg CFC11 eq	107	$4.17\cdot10^{2}$	$3.39\cdot10^{2}$	$2.99\cdot10^{-6}$
Terrestrial acidification	AC	$1.21\cdot10^{5}$	$9.55\cdot10^{4}$	$5.51\cdot10^{-5}$	kg SO_2 eq	0.2	$2.43\cdot10^{4}$	$1.91\cdot10^{4}$	$1.10\cdot10^{-5}$
Freshwater eutrophication	FWEU	$6.41\cdot10^{2}$	$5.25\cdot10^{2}$	$1.49\cdot10^{-7}$	kg P eq	0.2	$1.28\cdot10^{2}$	$1.05\cdot10^{2}$	$2.98\cdot10^{-8}$
Marine eutrophication	MEU	68.90	53.90	$1.33\cdot10^{-8}$	kg N eq	1.8	$1.24\cdot10^{2}$	$9.70\cdot10^{1}$	$2.40\cdot10^{-8}$
Human carcinogenic toxicity	HCT	$1.19\cdot10^{6}$	$9.71\cdot10^{5}$	$9.78\cdot10^{-5}$	kg 1.4-DCB	0.04	$4.78\cdot10^{4}$	$3.89\cdot10^{4}$	$3.91\cdot10^{-6}$
Human non-carcinogenic toxicity	HNCT	$3.00\cdot10^{6}$	$2.53\cdot10^{6}$	$5.23\cdot10^{-4}$	kg 1.4-DCB	0.04	$1.20\cdot10^{5}$	$1.01\cdot10^{5}$	$2.09\cdot10^{-5}$
Photochemical ozone formation	POF	$1.29\cdot10^{5}$	$1.01\cdot10^{5}$	$7.82\cdot10^{-5}$	kg NMVOC eq	0.0023	$2.97\cdot10^{2}$	$2.32\cdot10^{2}$	$1.80\cdot10^{-7}$
Fine particulate matter formation	FPMF	$4.00\cdot10^{4}$	$3.22\cdot10^{4}$	$1.88\cdot10^{-5}$	kg PM10 eq	15	$5.99\cdot10^{5}$	$4.84\cdot10^{5}$	$2.82\cdot10^{-4}$
Terrestrial ecotoxicity	TE	$1.49\cdot10^{-3}$	$1.27\cdot10^{-3}$	$7.10\cdot10^{-3}$	species.yr	$1.04\cdot10^{-9}$	$1.55\cdot10^{-12}$	$1.32\cdot10^{-12}$	$7.39\cdot10^{-12}$
Freshwater ecotoxicity	FWET	$1.44\cdot10^{-5}$	$1.11\cdot10^{-5}$	$3.93\cdot10^{-6}$	species.yr	$2.95\cdot10^{-12}$	$4.26\cdot10^{-17}$	$3.27\cdot10^{-17}$	$1.16\cdot10^{-17}$
Marine ecotoxicity	MET	$9.97\cdot10^{-6}$	$8.23\cdot10^{-6}$	$2.65\cdot10^{-4}$	species.yr	$5.68\cdot10^{-17}$	$5.66\cdot10^{-22}$	$4.67\cdot10^{-22}$	$1.50\cdot10^{-20}$
Ionizing radiation HH	IRHH	$3.98\cdot10^{5}$	$3.20\cdot10^{5}$	$8.22\cdot10^{-4}$	kBq U^{235} eq	0.001	$3.98\cdot10^{2}$	$3.20\cdot10^{2}$	$8.22\cdot10^{-7}$
Land use	LU	$3.46\cdot10^{5}$	$2.84\cdot10^{5}$	$4.95\cdot10^{-5}$	m^2_acrop eq	0.09	$3.11\cdot10^{4}$	$2.56\cdot10^{4}$	$4.46\cdot10^{-6}$
Water consumption	WRD	$5.38\cdot10^{5}$	$4.15\cdot10^{5}$	$2.17\cdot10^{-5}$	m^3	0.2	$1.08\cdot10^{5}$	$8.29\cdot10^{4}$	$4.33\cdot10^{-6}$
Mineral resource scarcity	MRS	$4.03\cdot10^{4}$	$3.51\cdot10^{4}$	$3.86\cdot10^{-5}$	kg Fe eq	0.07	$2.82\cdot10^{3}$	$2.46\cdot10^{3}$	$2.70\cdot10^{-6}$
Fossil resource scarcity	FRS	$1.65\cdot10^{7}$	$1.28\cdot10^{7}$	$5.55\cdot10^{-2}$	kg oil eq	0.05	$8.26\cdot10^{5}$	$6.38\cdot10^{5}$	$2.78\cdot10^{-3}$

Table 1 presents the environmental impacts and external costs for the CLC and REF plants per 1 kWh. The environmental impact categories are abbreviated as follows: Global warming potential (GWP), stratospheric ozone depletion (OD), terrestrial acidification (AC), freshwater eutrophication (FWEU), marine eutrophication (MEU), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), photochemical ozone formation (POF), fine particulate matter formation (FPMF), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FWET), marine ecotoxicity (MET), ionizing radiation HH (IRHH), land use (LU), water consumption (WRD), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). As seen, there is a significant difference between the two plants in all impact categories, with GWP as a primary example. Table 1 reveals that the CLC plant results in a much worse environmental behaviour with higher environmental impacts in all impact categories, when compared to the reference plant. This is mainly due to the extra construction materials required for the additional components that make the CLC plant more material intensive. Specifically, this is due to the components used in the oxy-fuel combustion and the capture of the generated CO_2 (four CO_2 compressors, five CO_2 coolers, and the oxy-fuel reactors) that are not used in the reference plant that does not include CO_2 capture (see Table A2 in Appendix). Additionally, it is seen that 0.0217 l of water per kWh produced are saved with the reference plant relative to the CLC case. The electricity generated in the CLC plant also results in higher ecotoxicity (freshwater, terrestrial and marine) estimated in species.year (species disappearing during one year). When looking at the ozone-related indicators, i.e., OD, POF, FPMF, it is found that $2.80\cdot10^{-8}$ kg of CFC11, $1.88\cdot10^{-5}$ kg of PM10 and $7.82\cdot10^{-5}$ kg of non-metallic VOCs can be avoided, respectively, when generating electricity in the reference plant instead of the CLC. The carcinogenic indicators also show that the reference case performs better than the CLC, while the eutrophication and acidification of the reference plant is approximately 20% lower than those of the CLC. Nevertheless, the most important difference between the two plants is the much lower GWP of the CLC plant, mainly related to the reduced CO_2 emissions in this case.

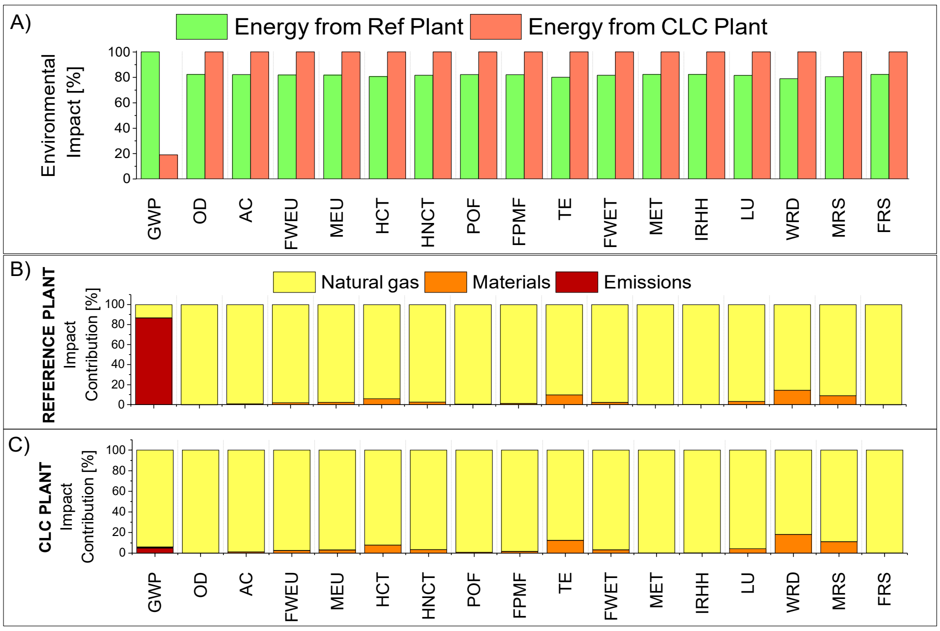

Figure 2. A. Comparative LCA for the generation of 1 kWh. B. Environmental contributions of the reference plant. C. Environmental contributions of the CLC plant.

Figure 2 presents the savings of environmental impact in the operational phase of the two plants. The results are presented in a comparative way to reveal the influence of fuel consumption and the emissions in the two plants and to show how the impact of the plants' materials are distributed over their lifespan. Figure 2A shows the results for the operational phase (i.e., when 1 kWh is produced). It is seen that power generated in the CLC plant has an approximately 20% higher environmental impact in 17 out to the 18 impact categories, when compared to the reference plant. A more detailed picture of the impacts is shown in Figures 2B and 2C. These figures demonstrate the high impact of the emissions on the GWP of the plants. More than 80% of the GWP in the reference plant comes from the emissions (see Figure 2B), when the lower emissions in the CLC plant (particularly the CO_2 emissions) decrease its carbon footprint by more than 80%. The contribution of the use of natural gas to the environmental impacts of the operational phase for the reference and CLC plants is shown in Figures 2B and 2C, respectively. Categories like OD, POF, MET, IRHH or FRS are heavily dominated by the contribution of the natural gas (99%). Figures 2B and 2C also show that the impact of the plant materials used in the construction phase are almost negligible when accounting for the operational phase of the plants in several impact categories (GWP, OD, AC, FWEU, MEU, HTNC, POF, FPMF, FWET, MET, IRHH) or they result in contributions not higher than 17% (HCT, TE, WRD, MRS). This result is consistent with previous studies, as for example that of Wang et al. who found that only 0.25% of the GWP was due to the construction phase in an LCA conducted for hydrogen production via chemical looping combustion [27]. A more detailed presentation of the component-level environmental impact of the two studied plants is presented in the Appendix of the paper.

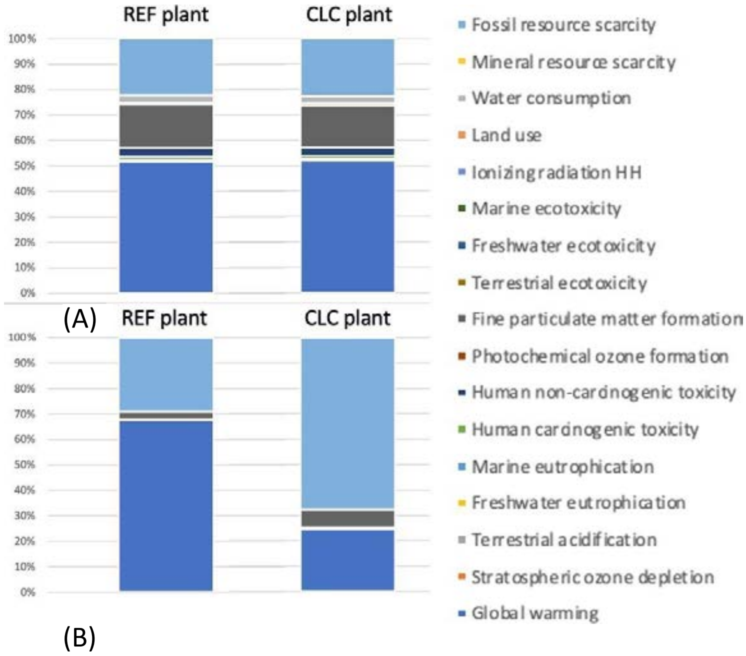

Figure 3: Contribution of the different environmental impact categories to the external costs of (a) construction and (b) operation of the reference and CLC plants.

The external costs of the environmental impacts, presented in Table 1, are shown in a relative perspective in Figure 3 [12]. Figure 3A reveals that the percentage-wise contribution to construction costs of the different environmental impacts is very similar in the two plants. More than 50% of the cost is associated with the GWP, followed by the fuel resource scarcity (22-23%) and the fine particulate matter formation (17-18%). However, the percentage-wise operational cost contribution differs significantly between the two cases (Figure 3B). The external cost of GWP is reduced from 68% of the total external cost in the reference plant down to a contribution of 24% in the CLC plant. The primary external cost contribution (equal to 68%) is associated with fossil resource scarcity in the CLC case.

Overall, the economic results reflect the environmental impacts. When looking at the use of construction materials, for example, it is seen that the environmental impacts of the CLC are higher than those of the reference plant (Table 1). For example, the carbon footprint, i.e., the GWP, of the CLC plant is 1.90 M€, while that of the reference case is 1.48 M€. However, when looking at the operational phase, the lower GWP of the CLC plant results in saving of 2.45 € cents per kWh when compared to the reference case. Nevertheless, the evaluation of the operational phase shows savings in 16 other environmental indicators when the reference plant is used instead of the CLC plant.

4.3 ESEC results and comparison with conventional analysis

Tables 2 and 3 present the results of the ESEC analysis for selected components of the reference and CLC plant, respectively. Two sub-tables are seen in each case. The first sub-table (a) presents the results of the ESEC when only the external costs of the construction phase are accounted for, while the second sub-table (b) presents the results of the complete ESEC analysis that includes the external costs of both the construction and operational phases. Complete tables with all the components of the plants, including the results of the exergoeconomic analysis, can be found in the Appendix of the paper. Table 4 shows the relative differences between the exergoeconomic and the ESEC analyses including both construction and operational phases.

Table 2: Selected results of the ESEC analysis of the reference plant without CO_2 capture. Sub-table (a) shows the results of the ESEC accounting only for the construction phase, and sub-table (b) shows the complete results of the ESEC analysis including construction and operation.

	a) External costs of construction							**b) External costs of construction and operation**						
Component	s_F **(cent/MJ)**	s_P **(cent/MJ)**	S_D **(cent/sec)**	Z_s **(cent/sec)**	S_D+Z_s **(cent/sec)**	f_s **(%)**	r_s **(%)**	s_F **(cent/MJ)**	s_P **(cent/MJ)**	S_D **(cent/sec)**	Z_s **(cent/sec)**	S_D+Z_s **(cent/sec)**	f_s **(%)**	r_s **(%)**
Compressor	1.69	1.95	19.26	39.72	58.98	67.34	15.06	2.31	2.59	26.26	39.72	65.98	60.20	12.36
Combustor	0.92	1.37	202.12	28.39	230.51	12.32	49.51	1.31	1.94	289.77	28.39	318.16	8.92	47.67
Expander	1.55	1.69	31.68	45.61	77.29	59.01	9.41	2.14	2.31	43.80	45.61	89.41	51.01	7.87
RH	1.55	1.98	3.99	3.39	7.38	46.00	27.75	2.14	2.66	5.51	3.39	8.90	38.12	24.35
HPSH	1.55	1.98	5.18	4.84	10.02	48.28	28.04	2.14	2.66	7.16	4.84	12.00	40.30	24.47
HPEvap	1.55	1.93	5.77	5.28	11.04	47.78	24.63	2.14	2.60	7.97	5.28	13.25	39.82	21.52
HPEcon	1.55	2.08	6.19	2.57	8.77	29.36	34.36	2.14	2.81	8.56	2.57	11.14	23.11	31.23
IPSH	1.55	3.66	0.09	0.11	0.20	56.79	136.40	2.14	4.63	0.12	0.11	0.23	48.74	116.48
IPEvap	1.55	2.08	0.67	1.86	2.53	73.56	34.34	2.14	2.74	0.92	1.86	2.78	66.81	27.86
IPEcon	1.55	2.28	0.29	0.15	0.44	33.94	47.55	2.14	3.06	0.40	0.15	0.55	27.10	42.83
LPSH	1.55	3.05	0.59	0.55	1.14	48.30	96.96	2.14	3.95	0.82	0.55	1.37	40.32	84.61
LPEvap	1.55	2.48	5.49	4.97	10.45	47.50	60.22	2.14	3.27	7.59	4.97	12.56	39.55	52.65
LPEcon	1.55	3.21	5.86	2.70	8.55	31.52	107.19	2.14	4.22	8.10	2.70	10.79	24.98	97.02
HPST	2.08	2.48	4.38	5.15	9.54	54.02	19.65	2.78	3.26	5.88	5.15	11.03	46.70	17.17
IPST	2.07	2.53	4.52	9.26	13.77	67.22	22.25	2.77	3.29	6.05	9.26	15.31	60.48	18.75
LPST	2.19	3.06	21.11	21.41	42.52	50.35	39.69	2.92	3.94	28.14	21.41	49.55	43.21	35.09
CondPump	2.02	8.52	0.02	0.20	0.22	91.20	321.15	2.70	9.45	0.03	0.20	0.22	88.59	249.77
HPP	2.02	3.74	0.33	1.12	1.46	77.11	84.91	2.70	4.58	0.45	1.12	1.57	71.61	69.55
IPP	2.02	14.89	0.02	0.22	0.24	91.26	636.31	2.70	16.07	0.03	0.22	0.24	88.66	494.76
LPP	2.02	40.83	0.00	0.07	0.07	97.42	1918.62	2.70	41.96	0.00	0.07	0.07	96.58	1453.33
Total	**0.92**	**2.08**	**274.91**	**181.20**	**456.11**	**39.73**	**127.66**	**1.31**	**2.79**	**394.13**	**181.20**	**575.33**	**31.49**	**112.29**
LCOE (€/MWh)					**75.00**							**100.27**		

Table 3: Selected results of the ESEC analysis of the CLC plant with CO_2 capture. Sub-table (a) shows the results of the ESEC accounting only for the construction phase, and sub-table (b) shows the complete results of the ESEC analysis including construction and operation.

	a) External costs of construction							**b) External costs of construction and operation**						
Component	s_F **(cent/MJ)**	s_P **(cent/MJ)**	S_D **(cent/sec)**	Z_s **(cent/sec)**	S_D+Z_s **(cent/sec)**	f_s **(%)**	r_s **(%)**	s_F **(cent/MJ)**	s_P **(cent/MJ)**	S_D **(cent/sec)**	Z_s **(cent/sec)**	S_D+Z_s **(cent/sec)**	f_s **(%)**	r_s **(%)**
Compressor	1.94	2.13	25.58	26.93	52.51	51.29	10.10	2.27	2.49	30.03	26.93	56.97	47.28	9.33
Reactors	0.91	1.55	177.52	139.11	316.63	43.94	69.13	1.13	1.84	218.83	139.11	357.94	38.86	63.40
Expander	1.81	1.94	35.55	30.96	66.51	46.55	7.05	2.13	2.27	41.93	30.96	72.89	42.47	6.55
GT2	1.18	1.36	3.31	6.07	9.37	64.72	15.49	1.41	1.60	3.95	6.07	10.01	60.59	13.86
HXNG	1.18	6.93	6.13	0.29	6.42	4.53	487.68	1.41	8.22	7.32	0.29	7.61	3.82	484.10
RH	1.81	2.38	4.06	1.66	5.72	29.04	31.68	2.13	2.78	4.78	1.66	6.44	25.76	30.25
HPSH	1.81	2.26	3.61	3.29	6.90	47.71	24.72	2.13	2.63	4.26	3.29	7.55	43.62	23.07
HPEvap	1.81	2.18	5.01	4.01	9.02	44.45	20.32	2.13	2.54	5.91	4.01	9.92	40.42	19.05
HPEcon	1.81	2.41	6.63	1.64	8.27	19.80	33.24	2.13	2.82	7.83	1.64	9.46	17.30	32.05
IPSH	1.81	3.09	0.25	0.22	0.47	47.18	70.57	2.13	3.54	0.29	0.22	0.52	43.09	65.92
IPEvap	1.81	2.30	1.76	2.60	4.36	59.59	27.36	2.13	2.67	2.08	2.60	4.67	55.56	25.12
IPEcon	1.81	2.53	0.60	0.25	0.85	29.00	39.69	2.13	2.94	0.71	0.25	0.96	25.73	37.89
LPSH	1.81	3.43	0.57	0.39	0.96	40.40	89.70	2.13	3.94	0.67	0.39	1.06	36.49	84.52
LPEvap	1.81	2.72	5.49	3.88	9.37	41.40	50.43	2.13	3.15	6.48	3.88	10.35	37.45	47.46
LPEcon	1.81	3.56	6.81	2.11	8.92	23.68	96.58	2.13	4.11	8.03	2.11	10.14	20.82	92.74
HPST	2.33	2.73	4.03	2.94	6.97	42.20	17.05	2.72	3.15	4.70	2.94	7.64	38.53	16.12
IPST	2.37	2.79	3.33	4.21	7.54	55.83	17.85	2.76	3.21	3.88	4.21	8.09	52.06	16.58
LPST	2.51	3.34	16.62	10.89	27.51	39.58	33.03	2.91	3.83	19.30	10.89	30.18	36.07	31.37
ST4	2.36	3.77	11.96	4.42	16.38	26.97	59.60	2.75	4.33	13.92	4.42	18.33	24.10	57.39
CondPump	2.11	7.60	0.02	0.16	0.18	88.92	260.04	2.46	8.08	0.02	0.16	0.18	87.31	228.37
HPP	2.11	3.63	0.30	0.80	1.11	72.51	71.99	2.46	4.07	0.36	0.80	1.16	69.34	65.16
IPP	2.11	9.97	0.03	0.23	0.27	87.81	372.58	2.46	10.53	0.04	0.23	0.27	86.06	327.93
LPP	2.11	36.13	0.00	0.06	0.06	96.82	1611.68	2.46	36.72	0.00	0.06	0.06	96.31	1391.87
CO2_compr1	3.77	17.77	2.30	8.78	11.08	79.21	371.16	4.33	20.01	2.64	8.78	11.42	76.86	362.54
CO2_compr2	3.77	7.82	2.43	8.99	11.42	78.75	107.50	4.33	8.55	2.78	8.99	11.77	76.36	97.67
CO2_compr3	3.77	8.08	2.43	8.86	11.28	78.50	114.17	4.33	8.83	2.78	8.86	11.64	76.09	104.06
CO2_compr4	3.77	8.17	2.52	8.91	11.42	77.96	116.76	4.33	8.93	2.89	8.91	11.79	75.52	106.47
Cooler1	1.18		26.50	1.92	28.42	6.76	0.00	1.41		31.63	1.92	33.55	5.72	0.00
TOTAL	**0.92**	**2.58**	**281.32**	**288.56**	**569.88**	**50.64**	**181.50**	**1.13**	**2.99**	**346.43**	**288.56**	**634.99**	**45.44**	**165.06**
LCOE (€/MWh)						**92.74**							**107.53**	

Table 4: Relative differences between the ESEC analysis (including construction and operational phases) and the exergoeconomic analysis of the reference (left side) and CLC plants (right side).

	s_F	s_P	S_D	Z_s	S_D+Z_s	f_s	r_s		s_F	s_P	S_D	Z_s	S_D+Z_s	f_s	r_s
Component	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**Component**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**

Compressor	36.48	33.31	36.48	0.45	12.25	-10.51	-17.76	Compressor	17.62	16.82	17.62	0.54	8.87	-7.66	-7.44
Combustor	43.37	41.63	43.37	0.52	38.11	-27.22	-3.66	Reactors	23.27	19.23	23.27	0.67	13.38	-11.21	-8.02
Expander	38.36	36.48	38.36	0.94	16.36	-13.25	-15.90	Expander	18.14	17.62	18.14	1.12	10.26	-8.29	-6.67
RH	38.36	37.22	38.36	9.90	25.93	-12.73	-4.09	GT2	19.49	17.92	19.49	1.22	7.71	-6.03	-9.86
HPSH	38.36	37.11	38.36	10.42	25.56	-12.06	-4.44	HXNG	19.49	18.86	19.49	2.29	18.73	-13.85	-0.64
HPEvap	38.36	36.61	38.36	2.67	21.54	-15.52	-6.75	RH	18.14	18.91	18.14	11.46	16.34	-4.20	2.88
HPEcon	38.36	37.74	38.36	3.85	28.49	-19.18	-1.86	HPSH	18.14	18.49	18.14	12.65	15.68	-2.62	1.61
IPSH	38.36	30.91	38.36	2.10	17.95	-13.44	-9.57	HPEvap	18.14	17.95	18.14	3.30	11.66	-7.48	-0.98
IPEvap	38.36	33.22	38.36	2.27	11.96	-8.66	-15.04	HPEcon	18.14	18.91	18.14	4.64	15.56	-9.45	2.74
IPEcon	38.36	37.00	38.36	2.53	26.39	-18.88	-3.21	IPSH	18.14	17.41	18.14	2.96	11.08	-7.31	-1.54
LPSH	38.36	33.81	38.36	2.63	21.33	-15.41	-6.91	IPEvap	18.14	17.25	18.14	3.06	9.26	-5.67	-3.66
LPEvap	38.36	35.03	38.36	2.65	21.62	-15.60	-6.68	IPEcon	18.14	18.58	18.14	3.49	13.99	-9.21	1.36
LPEcon	38.36	36.75	38.36	3.88	27.77	-18.70	-2.34	LPSH	18.14	17.94	18.14	3.21	12.22	-8.02	-0.37
HPST	36.82	34.78	36.82	2.08	18.06	-13.54	-9.36	LPEvap	18.14	17.95	18.14	3.29	12.10	-7.86	-0.50
IPST	36.67	33.33	36.67	1.31	12.85	-10.22	-13.68	LPEcon	18.14	19.43	18.14	4.81	15.09	-8.93	2.30
LPST	36.28	32.96	36.28	0.88	18.33	-14.75	-8.76	HPST	18.39	18.12	18.39	3.06	11.98	-7.96	-1.65
CondPump	35.23	12.19	35.23	0.08	3.14	-2.97	-22.33	IPST	18.37	17.61	18.37	2.07	9.29	-6.60	-4.36
HPP	35.23	24.72	35.23	0.01	8.00	-7.39	-17.03	LPST	18.28	17.72	18.28	1.28	11.53	-9.19	-1.97
IPP	35.23	9.04	35.23	0.01	3.05	-2.95	-22.41	ST4	18.21	18.36	18.21	1.61	13.74	-10.66	0.35
LPP	35.23	3.23	35.23	0.09	0.98	-0.89	-24.89	CondPump	17.70	7.51	17.70	0.09	2.03	-1.90	-12.00
Total	**43.37**	**35.37**	**43.37**	**1.57**	**26.92**	**-19.97**	**-10.04**	HPP	17.70	13.74	17.70	0.01	4.84	-4.61	-8.12
LCOE (%)	**+35.4**							IPP	17.70	6.79	17.70	0.01	2.15	-2.09	-11.77
								LPP	17.70	2.09	17.70	0.09	0.65	-0.55	-14.08
								CO2_compr1	18.36	20.70	18.36	0.72	4.32	-3.45	2.53
								CO2_compr2	18.36	12.00	18.36	0.29	4.04	-3.61	-10.32
								CO2_compr3	18.36	11.95	18.36	0.14	3.97	-3.68	-10.11
								CO2_compr4	18.36	11.86	18.36	0.21	4.12	-3.76	-10.14
								TOTAL	**23.14**	**17.59**	**23.14**	**1.10**	**12.04**	**-9.77**	**-7.05**
								LCOE (%)	**+17.6**						

Since the ESEC analysis is founded on the conventional exergoeconomic analysis, the comparison of their respective results reveals the direct impact of including external costs in the evaluation. Such a comparison can be realized using the results presented in Tables 2, 3 and 4. It is seen that the addition of the external costs leads to an increase in the total costs in comparison to the exergoeconomic analysis that does not account for externalities. There is, however, a significant difference between the case where only the construction phase is included and the case where both the construction and the operational phase are accounted for. The increase of the total cost $(S_{D,k} + \dot{Z}_{s,k})$ relative to the initial exergoeconomic analysis is on the order of 0.5-0.6% when only the construction phase is considered. When both the construction and operational phase are included, on the other hand, the total cost increases up to 20% in the reference case and up to 40% in the CLC plant for most of the components.

The socioeconomic factor of the ESEC analysis that shows the contribution of the construction costs (external and financial) on the total cost is always higher than the exergoeconomic factor, when only the construction phase is included. This is due to the increase of the numerator of the socioeconomic factor from the addition of the external cost of the construction materials. Nevertheless, this increase is small and less than 1%. When the operational phase is included as well, however, the socioeconomic factor becomes lower than the exergoeconomic factor, since the external costs of exergy destruction increase (denominator of the socioeconomic factor). This shows that the impact of the construction phase gets less important when the complete external costs are included, with the impact of the operation dominating the results. With approximately 32% and 45% of the total costs stemming from the construction of the reference and CLC plants, respectively, 68% and 55% of the costs of the plants is due to their operational phase (costs of exergy destruction). The reduction in the socioeconomic factor relative to the exergoeconomic factor is on the order of 20% in the reference plant and 10% in the CLC plant. The higher relative reduction in the reference plant shows the important impact of the external costs of the CO_2 emissions in this case since the plant emits more CO_2 when compared to the CLC plant. A large part of the potential external costs of the CLC plant, on the other hand, is avoided due to the capture of a large portion of the CO_2 emissions. A similar effect of the external cost inclusion is seen on the relative cost-difference factor. The relative socioeconomic cost difference (r_s) for the reference and CLC plants, however, is higher by 10% and 7%, respectively, in the ESEC analysis relative to the exergoeconomic analysis.

The LCOE of electricity of the reference and CLC plants in the exergoeconomic analysis was calculated 74.1 and 91.5 €/MWh, respectively (see Appendix). The inclusion of the external costs of construction results in a modest increase in the LCOE of 1.26% and 1.41% in the reference and CLC cases, respectively. However, when the operational phase is accounted for as well, the results change drastically (Table 6). Specifically, increases of 35.4% and 17.6% relative to the conventional exergoeconomic analysis are found for the reference and CLC plants, respectively. This is again associated with the strong environmental impact of the operational cost and specifically with the use of natural gas throughout the lifespan of the plant that is translated into large external costs. The approximately double percentage-wise increase in the case of the reference plant is associated with the higher CO_2 emissions of the plant relative to the CLC case or, in other words, the reduction of the potential external costs of the CLC plant due to the high amount of CO_2 captured. When looking thus at the LCOE of the two plants, we see that although the CLC plant with CO_2 capture was 23% more expensive when only the conventional economics are included, it is only 7% more expensive when the external costs are accounted for. This reveals the potential power of the inclusion of external costs in energy-generation systems and opens the door to making, otherwise seemingly more expensive alternatives, financially attractive.

Comparison and validation with conventional analyses

The ESEC analysis combines financial data with environmental impacts and its overall indications should thus agree with those obtained in the individual exergoenvironmental and exergoeconomic analyses. In the exergy-based analyses, the primary indication used in the evaluation and optimization process of energy conversion systems is the total cost. For the ESEC method to be adequate to represent both the environmental and the economic criteria, the final indications of the total scores of the new analysis should lie somewhere between those of the individual analyses. This procedure also helps to evaluate the overall impact of more subjective considerations of external costs in a more objective manner and to bring the analysis closer to the indications of widely accepted environmental methods.

To validate the results of the ESEC analysis, we calculate the percentage-wise cost contribution of the different components that show us the components with the highest priority for improvement. First, the component contributions to the investment cost and the cost of exergy destruction calculated in the exergoeconomic analysis are compared to the construction costs and the cost of exergy destruction calculated in the ESEC analysis. These comparisons for the reference and CLC plants are presented in the panels (a) and (b) of Figures 3 and 4.

The percentage-wise contributions of the individual components are seen to be very similar in the two analyses. The improvement suggestions based on the results of the two analyses are thus interchangeable. However, when comparing the results of the three analyses, i.e.., ESEC, exergoeconomic and exergoenvironmental analyses, we expect to see that the final indications of the ESEC analysis for all the different components are indeed found to lie percentagewise between the indications of the economic and the environmental results. When looking at the total costs of the exergoeconomic analysis (costs exergy destruction plus the investment costs), the total costs of the ESEC analysis (social costs of exergy destruction plus the investment costs) and the total costs of the exergoenvironmental analysis, however, it is seen that the final indication is closer to the results of the exergoeconomic analysis. This shows that the economic criteria are weighted more than the environmental criteria. The reason for that bias towards the economic side are the weight of the external costs (associated with the environmental impacts) relative to the weight of the private costs. As shown in Tables 4-6, the increase of the cost due to the external cost of construction is lower than 4% for most of the components. The impact of the addition of external costs of construction and operation in the ESEC analysis on the cost of exergy destruction (Table 6), however, is much higher. Specifically, the cost of exergy destruction in the ESEC analysis increases by approximately 20% in the CLC plant and 40% in the reference case. Even so, most of the costs are associated with the initial costs and not with the external costs (environmental impacts). This shows, again, the much stronger effect of the economic calculations on the results of the ESEC analysis.

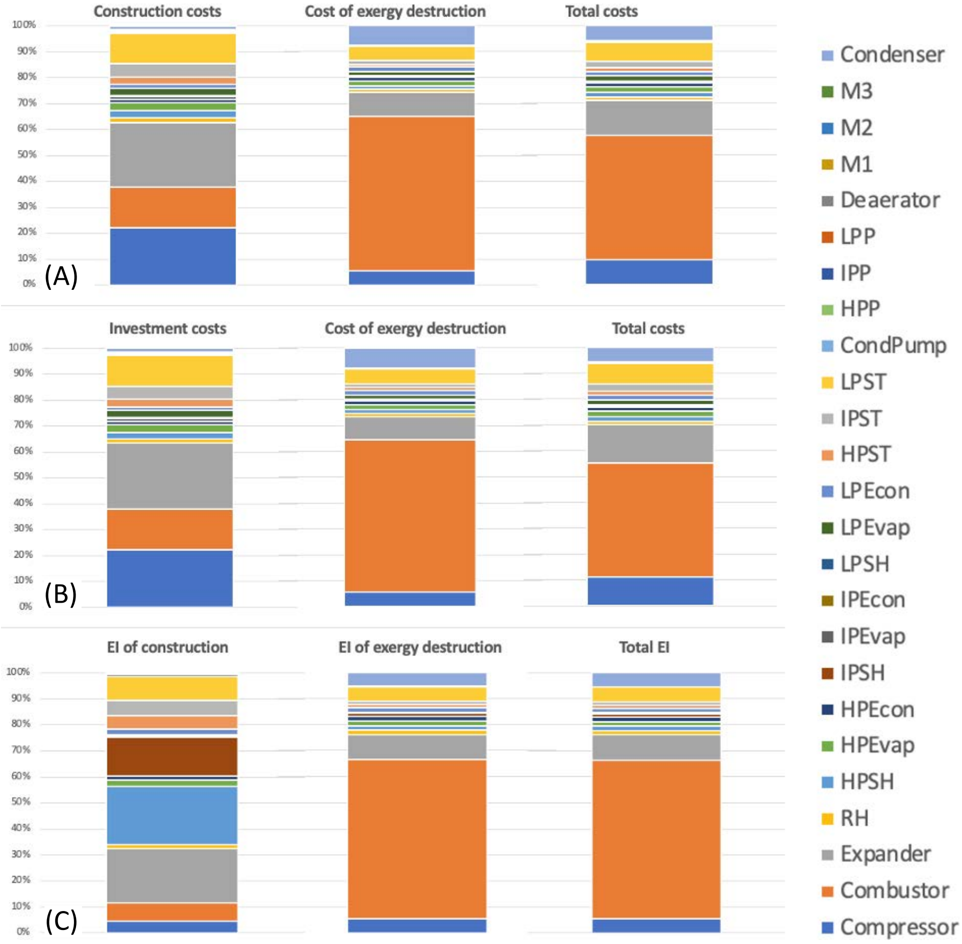

Figure 4. Component contribution in (a) the ESEC analysis, (b) the exergoeconomic analysis, and (c) the exergoenvironmental analysis for the reference plant. The improvement suggestions of the ExEc, ExEn, and ESEC analysis are driven by the percentage-wise contribution of the individual compoentnes to the total costs (column "Total costs/Total EI"). It is seen that the results of the ESEC analysis fall between the results of the ExEc and ExEn analyses with some justified bias towards the economic criterion.

The relative results of the exergoenvironmental analysis are presented in panels (c) of Figures 4 and 5. Complete tables can be found in the Appendix of the paper. If we compare the cost of exergy destruction calculated in the exergoenvironmental analysis to the cost of exergy destruction calculated in the ESEC analysis, we find some small differences. It is seen that the priority ranking based on the cost of exergy destruction from the ESEC analysis is identical to that obtained from the exergoenvironmental analysis for the three most important components. The results show a different component in the fourth ranking position, revealing, again, more agreement with the economic criteria (same ranking as in the exergoeconomic analysis). To further test whether the obtained results from the ESEC agree with those of the exergoenvironmental analysis we can also look at the impact of the construction phase on the overall environmental performance. The exergoenvironmental factor (f_b) that shows the impact of the environmental impact of the construction on the overall impact of the overall structure was found to be 0.46% and 0.59% for the reference and CLC plants, respectively [17]. The impact of the construction in the case of the ESEC analysis can be found by dividing the increase in the construction costs with the final total costs. For the reference plant, for example, it is calculated as: (181.2-178.4)/ 575.3, resulting in a value of 0.485%. A similar value (0.495%) is calculated for the CLC plant. This small effect of the external costs of the construction phase thus agrees with the results of the exergoenvironmental analysis, also validating the order of magnitude of the external costs used.

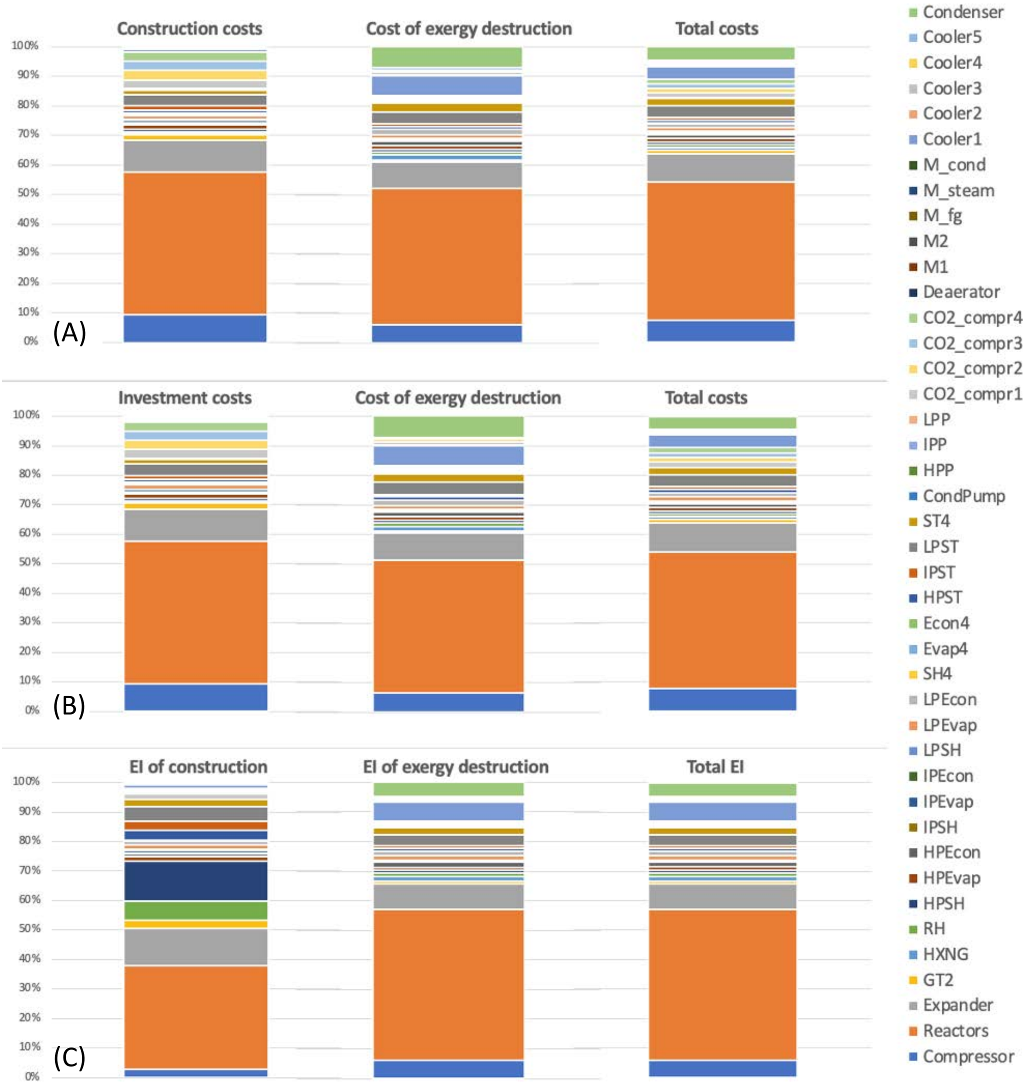

Figure 5. Component contribution in (a) the ESEC analysis, (b) the exergoeconomic analysis, and (c) the exergoenvironmental analysis for the CLC plant. As in the case of the reference plant, the results of the ESEC analysis of the CLC plant also fall between the results of the ExEc and ExEn analyses with some justified bias towards the economic criterion.

5. Conclusions

Currently, energy markets do not include externalities. The incorporation of external costs in the evaluation of energy systems can provide an insight into the environmental impacts of energy generation on society and support an implicit understanding by linking environmental impacts to costs. This study introduced and validated an exergy-based socioeconomic analysis (ESEC) method that can be used to evaluate energy systems at their design stage under thermodynamic, economic, and environmental criteria. The environmental performance is evaluated with a life-cycle assessment and the environmental impacts calculated are converted into costs. These external costs are combined with those of a conventional economic analysis and the resulting total costs are coupled with an exergetic analysis to realize the component-level ESEC evaluation.

The ESEC method has been developed as a trade-off analysis tool that can offer insight into both economic and environmental aspects simultaneously. As a multi-objective integrated tool incorporating economic and environmental impacts, its results should provide similar indications to those of the individual exergoeconomic and exergoenvironmental analyses. However, the ESEC method allows the simultaneous optimization of thermodynamic, economic, and environmental criteria. To test and validate the results of the developed method it was applied to two case studies and its results were compared to those of conventional exergoeconomic and exergoenvironmental analyses.

Overall, it was seen that the indications of the new analysis fell within expected limits and within the range of those from the exergoeconomic and exergoenvironmental methods. Some bias favoring the indications of the economic analysis was found, showing that the weight of the environmental criterion in the overall analysis is somewhat smaller. This bias may be driven by two main factors. First, the relatively small environmental importance of the construction phase in energy systems, when compared to the economic contribution of the construction phase and, second, the used specific external costs that could be further tuned to provide a more balanced weighting between the economic and environmental sides.

The two power plants used to in the study were a conventional combined cycle power plant (reference plant) and a plant with similar structure including chemical looping combustion (CLC) for CO_2 capture. The selection of these specific cases was intended to test the effect of the externalities on the evaluation of plants with CO_2 capture and evaluate their potential importance in similar occasions.

The two case studies were compared on 17 different environmental impacts. It was seen that the plant with CO_2 capture performed better only in the category of global warming potential because of the CO_2 captured relative to the reference plant. The same result was found when the external costs were accounted for: the reference plant performed better in all other 16 environmental categories. As expected, the environmental implications of the construction phase (i.e., construction materials needed in a plant) were much less significant when compared to the operational phase (i.e., the fuel consumption). The inclusion of the external costs of the construction phase led to in a small increase in the levelized cost of electricity. However, if the operational phase is included, the LCOE increases strongly by 35.4% and 17.6% in the reference and CLC cases, respectively. The inclusion of the external costs significantly reduced the difference between the cost of electricity of the two plants. Specifically, the exergoeconomic analysis shows that the LCOE of the CO_2 capture plant was 23.5% higher than that of the reference case. The ESEC analysis, on the other hand, shows that the LCOE of the carbon capture plant is only 7.2% higher than that of the case without CO_2 capture. This shows that the inclusion of external costs may play a decisive role in the decision making of environmental policies. The adaptation of methods like the ESEC analysis in energy-system evaluations can offer a more representative picture of the operational implications of energy systems and may bring about potential important shifts in future practices.

NOMENCLATURE

C_e	External cost rate of a material stream (€/sec)
f_s	Socioeconomic factor (%)
$r_{s,k}$	Relative social cost difference (%)
S_D	Social cost rate of irreversibilities (cent/sec)
T_i	Total cost of material stream *i* (cent/sec)
Z_s	Total cost rate of a component (cent/sec)

Abbreviations

AC	Terrestrial acidification
CBA	cost-benefit analyses
CLC	Chemical looping combustion
EC	External cost
EE	eco-efficiency
ESEC	exergy-based, socioeconomic analysis
FPMF	Fine particulate matter formation
FRS	Fossil resource scarcity
FWET	Freshwater ecotoxicity
FWEU	Freshwater eutrophication
GWP	Global warming potential
HCT	Human carcinogenic toxicity
HNCT	Human non-carcinogenic toxicity
HRSG	Heat-recovery steam generator
IRHH	Ionizing radiation HH
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land use
MET	Marine ecotoxicity
MEU	Marine eutrophication
MO	Multi-objective
MRS	Mineral resource scarcity
OD	Stratospheric ozone depletion
POF	Photochemical ozone formation
REF	reference (plant)
TE	Terrestrial ecotoxicity
TRR	Total revenue requirement
WRD	Water consumption

Subscripts

F	Fuel (exergy)
i, j, m, n	Streams
k	Component
s	Social
e	external
D	Destruction (exergy)
P	Product (exergy)

References

[1] Alberici S, Boeve S, Breevoort P Van, Deng Y, Förster S, Gardiner A, et al. Subsidies and

costs of EU energy - Final report and Annexes 1-3. 2014.
[2] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. Wiley; 1995.
[3] Petrakopoulou F. Comparative Evaluation of Power Plants with CO2 Capture: Thermodynamic, Economic and Environmental Performance. Institut für Energietechnik, 2010.
[4] Jeswani HK, Azapagic A, Schepelmann P, Ritthoff M. Options for broadening and deepening the LCA approaches. J Clean Prod 2010;18:120–7.
[5] Shapiro KG. Incorporating costs in LCA. Int J Life Cycle Assess 2001;6:121–3.
[6] Huguet Ferran P, Heijungs R, Vogtländer JG. Critical Analysis of Methods for Integrating Economic and Environmental Indicators. Ecol Econ 2018;146:549–59.
[7] CIEMAT. ExternE - Externalities of Energy (Vol XX : National Implementation). vol. XX. 2000.
[8] European Commission. ExternE - Externalities of Energy. vol. EUR 21951. Stuttgart: 2005.
[9] Bruyn S De, Korteland M, Markowska A, Davidson M, Jong F de, Bles M, et al. Shadow Prices Handbook Valuation and weighting of emissions and environmental impacts. 2010.
[10] IER - University of Stuttgart. EcoSense Model 2018.
[11] Hunt A, Arnold S. National and EU-Level Estimates of Energy Supply Externalities. Cent Eur Policy Stud 2009:7.
[12] Alberici S, Boeve S, Van Breevoort P, Deng Y, Förster S, Gardiner A, et al. Subsidies and costs of EU energy: final report. Ecofys, by Order Eur Comm 2014.
[13] Yan J, Brown MA, Yu D, Crittenden JC. Policy incentives and social cost of emissions for promoting decentralized energy production: A life cycle cost analysis. J Clean Prod 2021;282:125394.
[14] Al-Breiki M, Bicer Y. Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon. Energy Reports 2020;6:1897–909.
[15] Petrakopoulou F, Tsatsaronis G, Morosuk T, Carassai A. Conventional and advanced exergetic analyses applied to a combined cycle power plant. Energy 2012;41:146–152. https://doi.org/10.1016/j.energy.2011.05.028.
[16] Lara Y, Petrakopoulou F, Morosuk T, Boyano A, Tsatsaronis G. An exergy-based study on the relationship between costs and environmental impacts in power plants. Energy 2017;138:920–8.
[17] Petrakopoulou F, Boyano A, Cabrera M, Tsatsaronis G. Exergoeconomic and exergoenvironmental analyses of a combined cycle power plant with chemical looping technology. Int J Greenh Gas Control 2011;5:475–82.
[18] Spakovsky MR Von, Frangopoulos CA. Analysis and optimization of energy systems with sustainability considerations. EXERGY, ENERGY Syst. Anal. Optim., vol. III, 2001.
[19] Frangopoulos C. Introduction to environomic analysis and optimization of energy-intensive systems. ECOS ’92 Int. Symp., 1992.
[20] ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework. 2006.
[21] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, et al. ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization 2016.
[22] Wolf MA, Chomkhamsri K, Brandao M, Pant R, Ardente F, Pennington DW, et al. ILCD handbook-general guide for life cycle assessment-detailed guidance. Jt Res Cent Eur Comm Ispra, Italy 2010:1–417.
[23] NEEDS – the New Energy Externalities Development for Sustainability project (2005 - 2009) n.d.
[24] CASES – Cost Assessment for Sustainable Energy Systems (2006 - 2009) n.d.

[25] World Health Organization. Burden of disease associated with urban outdoor air pollution for 2008 2008.

[26] Bejan A, Tsatsaronis G, Moran M. Thermal Design and Optimization. Wiley-Interscience; 1995.

[27] Wang Z, Li L, Zhang G. Life cycle greenhouse gas assessment of hydrogen production via chemical looping combustion thermally coupled steam reforming. J Clean Prod 2018;179:335–46. https://doi.org/10.1016/j.jclepro.2018.01.063.

Acknowledgment

Fontina Petrakopoulou would like to thank the Spanish Ministry of Science, Innovation and Universities and the Universidad Carlos III de Madrid (Ramón y Cajal Programme, RYC-2016-20971).