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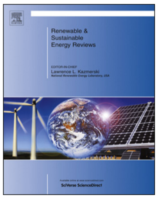

Exergetic and environmental life cycle assessment analysis of concentrated solar power plants

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ABSTRACT

The study addresses an exergetic analysis combined with a Life Cycle Assessment of concentrated solar power (CSP) plants. This work is focused on 50 MW parabolic-trough plants; its main objectives are: 1) to assess the environmental impact and cost, in terms of exergy for the entire life cycle of the plant; 2) to find out the weak points of the process; and 3) to verify whether solar power plants have the potential of reducing environmental pollution and the cost of electricity generation. The economic evaluation is presented through a thermoeconomic analysis conducted using the specific exergy cost (SPECO) approach. The main findings of the study are that the solar field is the component with the most important contribution towards environmental impact (79%). Out of the material used in the construction of the CSP plants, the one with the highest impact is steel followed by molten salt and synthetic oil. The “Human Health” damage category presents the highest impact (69%), followed by “Resource” damage category (24%) and “Ecosystem Quality” damage category (7%). The highest exergy demand lies with the steel manufacturing (47% out of the total demand). The solar field presents the largest value of cost rate, where the boiler is a component with the highest cost rate among the power cycle components followed by the condenser.

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Nomenclature

$\dot{C}_D$	Cost rate associated with exergy destruction
C	Cost per unit exergy
CED	Cumulative Energetic Demand
CExD	Cumulative Exergy Demand
ch	Chemical exergy
d	Coefficient of damage
$\dot{E}_D$	Exergy destruction rate
E_x	Exergy
IMP_j	Impact category
k	Physical exergies
LCI	Life Cycle Inventory
m	Mass
n	Amount of energy
r_{ex}	Relation of exergy to energy

Subscripts

CH	Switzerland (Geographical boundary)
CSP	Concentrate solar power
DALYs	The number of years of life lost and the years of living disabled
DNI	Direct Normal Insolation
ELCA	Exergetic Life Cycle Assessment
EQ	Ecosystem Quality
GLO	Global (Geographical boundary)
HH	Human Health
HTF	Heat-transfer fluid
LCA	Life Cycle Assessment
MJ	surplus refers to energy demand
NGCC	Natural gas combined cycle
OCE	Oceanic (Geographical boundary)
PDF	The loss of species for a specific area and over a particular time span
PTPP	Parabolic trough-CSP plant
R	Resources category
RER	Europe (Geographical boundary)
SEGS	Solar energy generation systems
SPECO	Specific exergy cost
TES	Thermal energy storage

1. Introduction

The south side of the Mediterranean shoreline has a high annual direct normal irradiation (DNI) [1], which makes Libya a privileged potential producer of solar power generation technologies due to its high DNI, small precipitation level and a large amount of free flat land. In fact, Europe is studying the feasibility of building renewable energy projects with particular emphasis on solar thermal power plants along the North African, Middle East shores and North African Sahara, and in this regard the Desertec initiative [2] is particularly relevant. Undoubtedly, the eventual sales of the CSP generated electricity to Europe will be a prime motivation to start these solar power projects. The CSP is composed of rows of mirrors that track and reflect the sun's rays into a receiver when the concentrated sunlight strikes the boiler pipes to heat the water. The steam produced by the heated water is piped from the boiler to a turbine where electricity is generated; CSP in this way becomes adispatchable renewable energy when combined with Thermal Energy Storage (TES). However the use of CSP with TES is not free of technological challenges. Energy storage is a critical factor in the advancement of solar thermal power systems [3], while CSP technologies cover a large array of different options, of which, the most common systems are based on parabolic trough, central receiver, parabolic dish or linear Fresnel. The parabolic trough is the one with a wider usage [4,5] and it was selected in this study. However, the central receiver technology is becoming increasingly important, particularly in the US and Spain. The dish technology has the advantage of having a low requirement in what concerns water consumption for surface cleaning, but the technology still has very high capital costs [6].

Furthermore, CSPs are becoming one of the most promising technologies to produce clean and sustainable energy; therefore, in the future, their use is expected to increase [7]. The main advantage of solar radiation is that allows the conversion of electromagnetic radiation to electricity to occur without environmentally harmful discharges. However, other stages of the fuel cycle contribute to environmental damage, where the environmental performance has become a key issue especially in the conceptual and design stages of a large-scale project; therefore, producers should be investigated and implemented to minimize its impact on the environment. Life Cycle Assessment (LCA) has emerged as one of the preferred tools to assess environmental impact of a selected product or process over its life and it encompasses all stages, including raw materials selection, production, use and disposal. LCA is an objective procedure to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases. To some extent this may help in assessing the impact of both energy and material use and release on the environment to identify and implement opportunities yielding environmental impact minimization.

Two powerful tools – LCA and ELCA are used in the present study to evaluate the CSP plant along its life cycle in terms of environmental impacts and energetic performance. LCA, as already mentioned is a tool which can be used not only to investigate the contribution of each life cycle stage to the total environmental load, but also to enable the identification of environmental hotspots and provide opportunities for process improvement and optimization of either the plant or a specific life cycle stage. On other hand, the use of the exergy balance as a tool to assess industrial processes, it can overcome the limitations of a simple energy analysis; the exergy analysis allows the evaluation of the thermodynamic performance of energy systems and the determination of the energy quality disintegration during energy transfer and conversion [8]. Exergy, which is derived from the second law of thermodynamics, is useful in the identification of the irreversibilities associated with the energy flow and its conversion. The exergy analysis allows the evaluation of the maximum available work in terms of quality and quantity for a critical assessment of the thermodynamic performance of any energy producing system; it has been widely used in the design, simulation and performance evaluation of energy systems.

Recently, Cornelissen [9] proposed a method that involves exergetic considerations into the LCA framework. The integration of the two methodologies within one combined method has large enhancing their respective strengths, while reducing their individual weaknesses. the combination of exergy and LCA, known as exergetic life cycle assessment (ELCA), enables the production of exergy scores for a large number of materials and processes, which, in particular for resource use and resource depletion scores, may prevail over conventional life cycle assessment methods [10]. ELCA analysis is considered to be the most appropriate instrument