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Comparative analysis of concentrating solar power and photovoltaic technologies: Technical and environmental evaluations

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HIGHLIGHTS

- ▶ Life cycle was assessed for both concentrated solar power and photovoltaic systems.
- ▶ The PV plant has a higher environmental impact than the CSP plant.
- ▶ The Global Warming Potential is lower for the CSP than for the PV plant.
- ▶ The energy payback time is lower for the CSP than for the PV plant.

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ABSTRACT

Solar energy is an important alternative energy source to fossil fuels and theoretically the most available energy source on the earth. Solar energy can be converted into electric energy by using two different processes: by means of thermodynamic cycles and the photovoltaic conversion.

Solar thermal technologies, sometimes called thermodynamic solar technologies, operating at medium (about 500 °C) and high temperatures (about 1000 °C), have recently attracted a renewed interest and have become one of the most promising alternatives in the field of solar energy utilization.

Photovoltaic conversion is very interesting, although still quite expensive, because of the absence of moving components and the reduced operating and management costs.

The main objectives of the present work are:

- to carry out comparative technical evaluations on the amount of electricity produced by two hypothetical plants, located on the same site, for which a preliminary design was made: a solar thermal power plant with parabolic trough collectors and a photovoltaic plant with a single-axis tracking system;
- to carry out a comparative analysis of the environmental impact derived from the processes of electricity generation during the whole life cycle of the two hypothetical power plants.

First a technical comparison between the two plants was made assuming that they have the same nominal electric power and then the same total covered surface.

The methodology chosen to evaluate the environmental impact associated with the power plants is the Life Cycle Assessment (LCA). It allows to analyze all the phases of the life cycle of the plants, from the extraction of raw materials until their disposal, following the "from cradle to grave" perspective. The environmental impact of the two power plants was simulated by using the software SimaPro 7.1, elaborated by PRé Consultants and using the Eco-Indicator 99 methodology.

Finally, the results of the analysis of the environmental impact are used to calculate the following parameters associated to the power plants: EPBT (Energy Pay-Back Time), CO_2 emissions and GWP100 (Global Warming Potential over a 100 year time horizon).

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Nomenclature

a-Si	amorphous silicon
°C	degree centigrade
CdTe	cadmium telluride
CIGS	copper–indium–gallium diselenide
CIS	copper–indium diselenide
CSP	concentrating solar power
DALYs	Disability Adjusted Life Years
DNI	Direct Normal Irradiation
DSC	dye sensitized cell
EERE	energy efficiency and renewable energy
ENEA	Italian national agency for new technologies, energy and sustainable economic development
EPBT	Energy Pay-Back Time
EQ	Ecosystem Quality
GWP100	Global Warming Potential (100 years)
HH	Human Health
IGDG	Italian Climatic Data Collection "Gianni de Giorgio"
kW h/kWp	kilowatt hour per kilowatt peak rating
kW h/m^2 y	kilowatt hour per square meter per year
LCA	Life Cycle Assessment
LCI	Life cycle inventory
LCIA	Life Cycle Impact Assessment
MW_e	megawatt electrical
PDF	Potentially Disappeared Fraction of plant species
Pt	points
PV	photovoltaic
R	resources
Rggmm	monthly average daily global solar radiation
SETAC	society of environmental toxicology and chemistry
Si	silicon
T	temperature
W_i	average direct solar radiation
W/m^2	watt per square meter
η_{coll}	solar field efficiency
μc-Si	microcrystalline silicon

1. Introduction

The continuous increase in the energy demand is driving to an increased attention to the efficiency and the environmental compatibility of power plants, which is now also devoted to renewable systems and not only to conventional fossil fired power plants.

Solar energy has always been a source, which has attracted the interest of scientists and engineers due to its availability in every point on the earth and to being unlimited as an overall amount.

These considerations, combined with the awareness of the consequences of climate change caused by the emissions of fossil fired power plants, have renewed, worldwide, the interest in solar energy after the last two decades of the past century, when oil prices were so low that no alternative was economically interesting and viable.

There are two different technologies, which convert solar into electric energy: solar thermal technologies where a thermodynamic cycle is used, and photovoltaic systems, where the sunlight is directly converted into electric energy.

Both types of plant have emerged as the most efficient solutions to use solar energy, and even if those technologies are quite different, it is interesting to make a comparison based in their performance and environmental compatibility.

This paper aims at offering a comprehensive evaluation of solar thermal and photovoltaic power plants taking into account the conversion efficiency and performance and the environmental impact by using the Life Cycle Assessment methodology.

The results of this analysis will make it possible to show the critical subsystems and indicate potential solutions to improve them.

For both systems, the state of the art plants were studied in order to update former studies on both solar thermal and photovoltaic system, that were presented in the past. A number of concentrated solar power plants were built in the 1970s in the United States but research and development was discontinued until a few years ago, when new concepts in energy storage, new materials for reflecting mirrors and a general improvement of components' efficiency has driven to the construction of several new power plants in Spain and in other countries and a strong support from governments and the EU. Photovoltaic systems have been strongly supported with quite high feed-in tariffs and thousands of MWp were installed worldwide in the last decade [1].

It is now quite important to make a comparison when the developers of solar thermal or photovoltaic power plants are asking to have them authorized, built and commissioned. Photovoltaic systems are winning, when they deal with domestic or micro power plants, because they are much easier to maintain and they generate electricity completely unattended, but when the size is larger than a few MW, an overall evaluation is necessary, which must necessarily include the environmental aspects.

2. Solar thermal technologies

The commonest applications of solar thermal energy operate with a low maximum temperature (generally lower than 120 °C), by means of solar flat collectors, mainly used for sanitary hot water production, for swimming pools or room heating.

To be used in electric power generation, solar thermal technologies have to operate either at medium (about 400–500 °C) or high temperatures (about 1000 °C). To reach such high temperatures, solar energy has to be concentrated on smaller surfaces by means of reflecting mirrors, which may have different shapes. This type of plants are called Concentrated Solar Power Plants (CSPs) because they use mirrors to reflect the sun's radiation on special receivers.

The main characteristics of concentrating solar power systems are summarized below:

- They can reach high efficiencies because they use thermodynamic cycles with high temperature heat input.
- They are able to use only the direct component of solar radiation, but this implies the loss of the diffused and reflected components.
- This technology requires high levels of Direct Normal Irradiation (DNI).
- They are not suitable for the realization of small plants.

Different receivers can be used to capture concentrated solar radiation:

- Tower systems.
- Parabolic dish systems.
- Parabolic trough collectors.
- Linear Fresnel reflectors.