Life cycle assessment of a solar PV/T concentrator system

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Abstract The paper shows the energy and environmental analysis of a solar low Concentrating Photovoltaic-Thermal (CPVT) system, installed on the roof of the Energy Department building at University of Palermo (Italy). LCA methodology was applied to assess the whole life-cycle of the selected Functional Unit. Data survey from the producing company regarding the consumption of energy sources and of materials were developed. The assessment allowed to identify the steps and the system components addressing the highest energy and environmental impacts. Energy and environmental benefits and drawbacks related to the CPVT system. The research was developed within the National Relevant Research Programme (PRIN 2008) ‘‘Definition of innovative criteria for the environmental oriented design and production of Energy Using Products in the civil sector”.

1 Introduction

The Directive 2009/125/EC provides coherent wide rules for the eco-design of the Energy related Products (ErP), and defines conditions and criteria for setting, through subsequent implementing measures, requirements regarding environmentally relevant product characteristics and allows them to be improved quickly and efficiently to be allowed into the EU-trade [1]. One of the priority sectors defined by the European Commission, to which focus first, is the sector of heat generators for space heating and the hot water production, which involves a contribution of about 60% in the energy balance of a EU building [2]. The development of high efficiency technologies could reduce both building energy consumption and the related environmental impacts significantly. Relevant advances in this direction are given by the introduction of innovative high-efficiency technologies in renewable energy based systems.

In the solar energy systems a particular attention must be given to the hybrid Photovoltaic and Thermal technologies (PVT), which integrate the photovoltaic cells (PV) with the solar thermal collectors (T) to jointly generate electricity and heat. These innovative micro-cogenerative devices achieve a higher energy conversion rate of the absorbed solar radiation. Traditional PV collectors convert not more than 20% of the incoming solar radiation into electricity, depending on the type of solar cells in use and the working conditions, the remaining is converted as heat (after deducting the reflected rate). This may lead to an extreme cell working temperature, involving an undesiderable drop in cell efficiency (typically 0.4% per °C rise for c-Si cells) [3]. Typically, PVT systems are constituted by flat collectors, where the PV cells works also as thermal collectors; an internal refrigeration system allows to control the cell temperature. In fact the PV cells are very sensible to the working temperature: decreasing their temperature it is increased their efficiency and their electricity yield [4]. Heat extraction can be achieved by water or air circulation systems. This allows the recovery of the heat for different applications, as space heating, hot water generation, industrial processes [5-8].

In a PVT collector the presence of a glazed cover at the top of the collector can increase the thermal efficiency, but reduces the electric efficiency by increasing both optical losses and temperature of PV cells. One of the most important solution to this problem is the concentration of the radiation by means of mirrors and reflecting surfaces. In particular the parabolic mirrors are specially designed to concentrate the sunlight into a focal point where the PV collector is positioned. This solution allows also to minimize the employed surface of PV cells, to which the highest energy and environmental impacts have to be attributed in the photovoltaic technology [9].

The concentrating optics are most efficient when they are directly facing sunlight, hence tracker systems are required to ensure direct exposure to the sun. A tracker system modifies the collectors tilt angles, both optimizing the solar inputs and working as a safety system. In fact, when the refrigeration system is inadequate, the solar tracking redirect the collectors to a shut-down position, shielding the solar radiation and avoiding over-heating problems [10].

The following sections present the case study of a more extensive experimental research performed within the framework of the Italian financed Project ‘‘Definition of innovative criteria for the environmental oriented design and production of Energy Using Products in the civil sector”. In particular, using a life-cycle approach, the authors assessed the energy and environmental performance of a Concentrating Photovoltaic and Thermal (CPVT) equipment. The assessment of the energy and environmental benefits was carried out estimating the saved primary energy resources and the related avoided CO2eq emissions associated to the system under study. Further energy and GWP payback indices were calculated.

2 Case Study: LCA of a solar CPVT system

2.1 Goal and scope definition

LCA methodology was applied to assess the energy and environmental performance of a CPVT equipment during its life-cycle, installed on the roof of the Energy Department building at University of Palermo. The analysis was performed in compliance with the international standards of the ISO 14040 series [11,12]. The main goals of the study were the following:

1) To assess mass and energy inputs and outputs in the life-cycle of the system, including environmental impacts related to energy source generation, water and raw materials production, end-of-life of the CPVT system.
2) To evaluate the saved primary energy resources and the related avoided GWP. In particular, Energy Payback Time (EBT) and GWP Payback Time (GPT) were determined with regard to the reference study.

The following study refers to solar parabolic concentrators which are produced in Sweden.

2.1.1 Definition of the functional unit

The phase of the goal and scope definition includes an important step: the clear statement of the functional unit (FU). According to the UNI EN ISO 14040 standard, FU is defined as the reference unit through which the performance of a product system is quantified in a LCA [13]. The FU is important as basis for data collection and for the comparability of different studies referred to the same product category. In the examined case study the entire CPVT equipment was selected as FU, to which are related all the energy and environmental impacts of the system.

In detail, the studied FU is the CPVT system characterised by the following components:

1) Five solar parabolic concentrators, that are interconnected and have a whole active surface of 10 m2. Each one has an aluminium frame and a reflecting surface made of multiple layers of polymer (polyethylene) covered by a pure silver film to provide high specular reflectance while protecting against UV radiation and moisture. Inside each concentrator there are two parallel adjacent steel pipes for the water flow (hot and cool, respectively), positioned on the focal direction. Each pipe has a whole length of 10 m (2 m for each concentrator) and their external surface is covered by PV cells, in crystalline silicon (c-Si), positioned looking at the concentrator side. Totally, there are 150 PV cells (30 c-Si cells for each concentrator). At the top of each concentrator a glass cover, with a solar transmittance of 90%, allows to rise the system operating temperature. The reflectance is near to zero, thus avoiding the solar radiation reflection. Two side coverings in steel and polycarbonate are also present in each concentrators. There are three external support frames made of steel and aluminium and a tracking system with three aluminium and steel rails. The equipment is fastened to the roof by means of a concrete foundation.
2) Water primary circuit, constituted by
3) copper pipes, valves, a water filter and an expansion tank. Heat recovery unit, which included the boiler and the heat exchanger.

In detail, Table 1 summarises the technical data concerning the components of the reference system, while Figure 1 shows the CPVT equipment.

Tab.1: Technical data of components in the reference CPVT system

Technical data	
Geometric features	
Length (m)	10
Width (m)	1
Weight (kg)	315
Number of legs	3
Thermal properties	
Water fluid (litres)	6.7
Recommended water flow (litre/min)	8
Electric data at standardized condition (PV cells at 25°C and radiation of 1000W/m2	
Electrical Power (W)	1000
Shortcut current (A)	13
Voltage (V)	91
Voltage drop (V)	0.4

Fig.1: CPVT equipment on the roof of the Energy Department (University of Palermo)

2.1.2 System boundaries

This section describes the authors' assumptions on the system boundaries. The following phases were investigated: raw materials and energy supply, manufacturing process of the CPVT equipment, end-of-life, and transports occurring during each step. With regard to the installation phase the authors accounted for the transport of the FU from the producing company to the user place. Maintenance step was neglected, since the company had provided no information. Further, electricity consumption of the tracker system was not accounted.

2.2 Data quality in Life cycle inventory (LCI)

According to the general framework provided by ISO14040, the inventory analysis was carried out to quantify the environmentally significant inputs and outputs of the studied FU, by means of a mass and energy balance. The authors collected the following data from the field, by means of a questionnaire to the Swedish producing company and of direct measurements on the installation site:

1) Mass and material of each component in the reference system.
2) Distances and transport modes for the raw material supply.
3) Electricity and thermal energy consumption during the manufacturing process.

Secondary data were taken from international databases [14]. In particular these were utilized to calculate the ecoinventories of raw materials, energy sources (biomass and electricity), transport, and waste disposal.

Fuel consumption and air emissions from transportation were estimated, depending on the transport mode and the distance between sites. In detail, diesel trucks were assumed for all the transportation steps. It has been assumed that every transport occurs by means of trucks.

With regard to the end-of-life, it should be pointed out that this is probably the most difficult part of a LCA study, as it is necessary to forecast several years (or decades) in advance, what reasonable sequence of activities would be for disposing or recycling wastes. In this study no information is available, since the reference system is a new technology, and no comparative data on the end-of-life exist. Therefore the recycling was neglected and it was supposed that all the materials would be collected and disposed to the nearest landfill by truck, except for iron and plastics. It was assumed to address the former to a recovery facility and the latter to thermal incineration. Disposal of the silver film in the concentrator and the butyl layer in the expansion tank was not taken into account for lack of information. However their masses are lower than 1 kg.

Table 2 summarises, for each component, type and amount of the materials used, while Table 3 shows the direct energy consumption involved in the FU life-cycle: electricity and biomass used for the production process.

Tab.2: Material and component mass in the CPVT system

System components	Sub-component	Material	Amount (kg)
CPVT concentrators	PV cells (including cell contacts)	Crystalline silicon	8.12
	Reflector	Aluminium Silver film Polyethylene film	0.03 1
	Glazed coverings	Low iron glass	105
	Absorber pipe	Steel	31.4
	Side covering	Steel Polycarbonate	2.4 0.1
	Support frame	Steel Aluminium	82 36
	Tracking System	Steel Aluminium	3 3
	Foundation	Concrete	7600
Pipe circuit	Pipes Valves Expansion tank	Copper Brass and plastics Steel and butyl	4.4 4.8 and 0.1 1.9 and 1.1
Heat recovery unit	Boiler	Steel Exp. polyurethane Polystyrene Copper	46 7 8.5 24

Tab. 3: Direct energy consumption

Energy source	Amount
Electricity	20 kWh
Biomass	100 kWh

3 Life cycle impact assessment

The energy and the environmental impacts have been assessed on the basis of declaration scheme and characterization factors utilised in the EPD system [15]. Results are showed in Table 4.With regard to the primary energy consumption in the assessed FU life-cycle, Global Energy Requirement (GER) was calculated.

Figure 2 shows the contribution of each CPVT component to the GER. To be noted is that the highest share arises from the concrete foundation production (55 GJ), followed by the steel support frame and by the boiler (MJ). Figure 3 shows the incidence of each life-cycle step to GER.

Tab.4: Energy and environmental impacts

Indices	Amount
Global Energy Requirement - GER	25.6 GJ
Global Warming Potential - GWP	2,281 kg CO2eq
Ozone Layer Depletion - ODP	1.6E-03 kg CFC-11eq
Photochemical oxidation - POCP	1.6 kg C2H4eq
Acidification Potential - AP	10 kg SO2eq
Eutrophication Potential - EP	7.4 kg PO4---eq

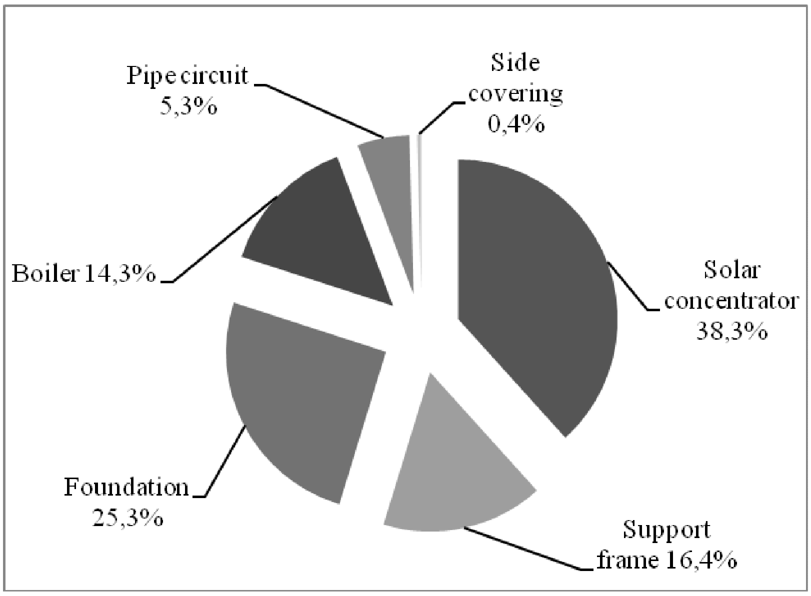

Fig.2: **Incidence of each CPVT component to GER**

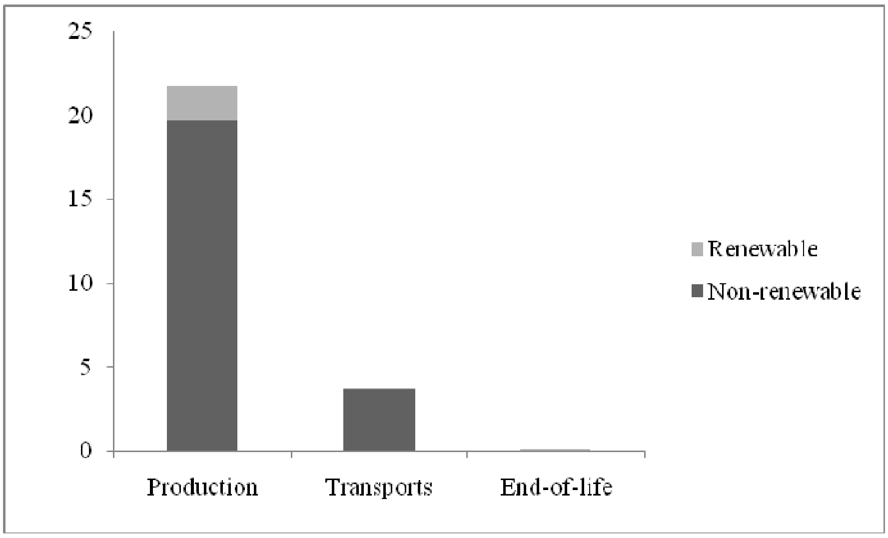

Fig.3: **Primary energy consumption related to each life-cycle step (GJ)**

4 Energy and environmental benefits related to the CPVT system

Starting from the above LCA study, the authors performed a comparison between the life-cycle impacts of the reference system, as GER and GWP, and the saved primary energy and the related avoided CO2eq emissions.

The outcomes are presented in Table 5. Since no information was provided by the manufacturing company, the authors supposed a life-span of 20 years for the CPVT equipment.

From these results the indices of energy payback time (EPT) and GWP payback time (GPT) were calculated. In detail, energy payback time can be defined as the time necessary for a solar equipment to collect the energy (valued as primary) equivalent to that used to produce and to disposal it. It was calculated using the following equation:

$$EPT = \frac{GER}{E_{saved}} \tag{1}$$

where GER is the primary energy demand during the life-cycle of the system (19 GJ), Esaved is the yearly useful energy produced by the system (GJ/y). Esaved was calculated, taking into account a yearly thermal energy output of 5,466 kWh and a yearly electricity yield of 1,366 kWh. It is about 75 GJ/year.

The energy saving was calculated taking into account data estimated from the manufacturing company for a site with average temperatures and solar radiation similar to the city of Palermo [16].

GWP payback time (GPT) index represents the time necessary for the CPVT equipment to avoid the GWP equivalent to that one generated during its life-cycle. It was calculated as follows:

$$GPT = \frac{GWP}{GWP_{avoided}} \tag{2}$$

where GWP is related to the system life- cycle (1.8 kgeqCO2), GWPavoided is the yearly avoided GWP (kgCO2/y) related to the yearly useful energy produced Esaved. GWPuse arises from the use of the systems (kgCO2/y).

Tab.5: Energy and environmental benefits related to the CPVT equipment

Indices	Amount
Esaved (GJ/year)	36
GWPavoided (CO2eq/year)	2,126
EPT (year)	0.7
GPT (year)	1

5 Main results and conclusions

With regard to the innovative technologies in the field of renewable energy based systems, the authors focused on the CPVT devices. The paper starts from a more extended research aimed at supporting the adoption of eco-design criteria for the improvement of energy and environmental performances of ErP.

In detail, the results of a LCA study performed on a solar CPVT equipment, installed at University of Palermo, are showed. Mass and energy balance in the life-cycle of the reference system was carried out, including environmental impacts related to energy source generation, water and raw materials production, end-of-life of the CPVT system. Further the saved primary energy and the related avoided CO2eq emissions associated to the system were assessed like energy and environmental benefits.

The installation has not been completed yet, thus installation, use and maintenance steps were not accounted. For this reason, the authors estimated the yearly output of electricity and of thermal energy with regard to the data provided by the manufacturing company.

Regarding the examined FU, a GER of 25.6 GJ was estimated. It is possible to point out that 91.6% of GER is due to non-renewable sources, while 8.4% is represented by renewable sources, mostly related to the use of biomass in the thermal processes of the manufacturing company. The main contribution to GER is provided by the production step (85%), while transportation and end-of-life scenario account for 14.6% and 0.5%, respectively.

In conclusion, the EPT and the GPT of the systems were calculated, which resulted very low. The outcomes showed that the primary energy saving and the related avoided GWP overcome in a large extent the life-cycle GER and GWP. Therefore this reveals significant energy and environmental advantages in the use of the CPVT technology, making it attractive for a wider application of photovoltaics.

6 References

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