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Life Cycle Assessment of solar energy systems: Comparison of photovoltaic and water thermal heater at domestic scale

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ABSTRACT

This study is concerned with the results of a Life Cycle Assessment comparison between photovoltaic – silicon based modules and thin film modules – and solar thermal systems, as technologies which are usually installed for partially covering household energy demand.

Several studies focused on energy and environmental performances of photovoltaic and solar thermal collectors, however they have been always analysed separately. This study proposes the comparison of different systems to exploit the solar energy, producing different energy types. The comparison was done referring to one square meter of roof surface occupied by the equipment.

The environmental burdens were calculated according to the indicators proposed by Eco-indicator'95 method. The results showed that the system based on thermal solar collector obtained the major number of more favourable indicators: eight out of ten, in the case of no-recycling of materials after dismantling phase, and six out of ten in the case of recycling of materials after dismantling phase. The thin film modules and solar thermal collector showed the lowest values of energy payback time and CO_{2eq} payback time.

Results clearly show that photovoltaic and solar thermal collector can effectively provide comparable environmental and energy benefits as regard to domestic scale installation.

1. Introduction

The renewable technologies are strategic for CO_2 emissions reduction and for improving the security of energy supply. Renewable and resource-efficient areas are considered new promising industrial fields and drivers of growth, which could help in surpassing the current economic crisis [1–4].

Several efforts were addressed to investigate the environmental and energy benefits which green technologies could produce [5]; at the same time the technological reliability and the cost-competitiveness of the renewable power generation technologies are key factors for further diffusion. Relevant results were already reached; for example a relevant cost declining and high learning rates are registered for wind, solar photovoltaic and some biomass technologies [6].

Nevertheless their diffusion still remains dependent on resource availability, reference market and national incentive schemes [6].

Alongside an overall increase of market competitiveness, the national subsidies played an important role in the renewable technologies spread, as regard both to residential and industrial levels. The enormous growth of PV (photovoltaic) installations is a good example of such phenomenon. Thanks to the specific incentive for PV installation and technology costs decrease, in Italy these systems reached a total installed power fourfold higher in one year – 3483 MWp in 2010 and 12,673 MWp in 2011, then 16,431 MWp in 2012 [7,8]. Also in other European countries the PV installations registered the most considerable increase among renewable technologies. In Germany the total installed power doubled between 2010 and 2011, gaining the first position in Europe with 32,698 MWp in 2012, followed by Italy and Spain [7,8].

On the contrary, despite a strong and well-experienced ST (solar thermal) industrial sector, in Italy this sector registered a relevant market decline and installation contraction since 2010 [7]. This could be ascribed to a less generous and less attractive rebate, rather than an effective technological reliability. This fact produced also the perception of more difficulties in this investment choice than PV one [9]. Overall, in the European countries, the ST market suffered the current economic crisis and can be found quite dependent on political support programmes.

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As a consequence, a competing relationship has been produced between the solar energy technologies, and the rational for the exploitation of such resource appeared to be regulated more by economic factors – subsidies, investment costs, specific energy cost – rather than resources availability, technological reliability and effective environmental benefits. This can be observed also out from European boundary [10].

Within this contest, the present study focuses on the solar energy technologies and aims at providing additional elements which could help in the evaluation of advantages and disadvantages they could generate, in reference to a specific geographical area. In particular, by applying the LCA (Life Cycle Assessment) methodology, this work aims to compare environmental and energy performances of PV and ST at residential scale in the Italian territory. This is an innovative comparative analysis whose outcomes may be taken into account as drivers in the planning of subsidies along with costs dynamics of technologies, in favour of mixed resources and technologies energy plan.

It is widely demonstrated that LCA is a very useful tool to evaluate the environmental performances of products and services bringing powerful insights about all the technologies life cycle steps, from cradle to grave, measuring environmental, energy and resource sustainability. In the field of the technologies for renewable energy exploitation, the LCA allows appraising environmental burdens and benefits in comparison with the fossil energy sources. Only turning the attention from the limited analysis of the functioning phase (direct emissions) to a wider analysis including also the construction and disposal steps, it is possible to analyse and demonstrate the advantages from an environmental point of view [12].

Many authors deeply investigated the benefits related to the employment of renewable technologies, in particular solar ones, by means of LCA. Comparative analyses involved both different ST collectors [11,13,14] and different PV cells typologies [15–17] with reference to the produced energy unit. An interesting comparative investigation between PV and ST systems was developed by Wei et al. (2014), nevertheless it concerned a cost-benefit evaluation based on the current economic parameters (i.e. investment cost and government incentive) characterizing such technologies [10].

During the last years such technologies registered a continuous development – also thanks to experimental tests [18,19] – regarding energy performances increase and environmental burdens reduction by reducing materials in production phase, increasing energy efficiency, using recycled materials and taking care of the end-of-life [20–22].

It is largely demonstrated that the PV and ST technologies provide consistent environmental advantages – energy and climate change perspective - compared with the fossil fuel based technology for the electrical and thermal energy production [5,22–26]. In order to develop a comprehensive analysis, detailed materials and energy flows lists are necessary for all the life cycle steps. Some studies tried to detail the production phase as the most delicate one [27], some others enlarged the systems boundaries of the analysis including also the transports, installation and maintenance steps [28,29].

Nevertheless, some hot-spots still remain to be evaluated more in detail. For example the management of the end-of-life and the localization of the production and assembly phases are investigated only in few studies [30–32].

2. Materials and method

2.1. LCA – goal and scope definition

The goal of this work is to compare the energy and environmental performances of two types of solar energy systems – PV and ST as the most widespread renewable technologies at residential scale in the European area along with wood [7,8] – over their whole life cycle by applying the LCA, according to ISO 14040 series. Four types of PV modules – mono-Si (silicon monocrystalline), multi-Si (silicon polycrystalline), CdTe (cadmium telluride) and CIS (copper indium diselenide) – were analysed, whereas only one typology of solar collector was investigated, in particular the FPC (flat plate collector), for sanitary hot water production. Several types of collectors are available on the market, including unglazed, evacuated tube and concentrating, nevertheless the FPC were found to be the most suitable regarding domestic hot water and space heating [13,20].

The domestic scale makes reference to an average family of three-four persons with an energy demand of about 8 kWh day^{-1} of electricity [21] and 50 l day^{-1} $person^{-1}$ of hot water, as a common reference value. The analysis involved energy systems made up of single technological unit, such as one PV module and one ST collector, which are expected to satisfy around 10% of the electricity and 50% of the thermal energy for hot water, respectively. Usually 2–3 m^2 of FPC (flat plate collector) surface and 150 l of storage tank are necessary to cover requirement of a family of four persons [20], whereas 20 m^2 of PV module can meet an average family electricity demand [21], with reference to the average radiation value of the Mediterranean area.

In order to compare the two technologies, the impact results calculated in reference to the single technological unit – PV module or thermal collector – were divided by the roof surface covered by the equipment thus referring to a FU (functional unit) of 1 square meter of roof.

The intent is to answer the following question: “If a given surface of domestic roof is available, which is the best option – in term of energy and environmental impacts – for solar energy exploitation?”.

Of course when a thermal collector is placed in the available surface a given amount of thermal energy is produced and primary energy is saved. Alternatively, if a PV panel is installed, electricity is produced, but also in this case, it is possible to account for the saving in primary energy, according to the selected electric mix.

As said above, the assumed installed units are able to cover only partially the household energy demand (electric or thermal alternatively). So it is assumed that all the produced energy can be used and effectively can substitute conventionally produced energy. This is of course an assumption of this study, which is aimed at evaluating the potential environmental benefits achievable exploiting all the produced energy. As a matter of fact, the assumption seems rather correct in reference to electric energy that during the time of absence of household demand, can be delivered to the grid. When talking about thermal energy, however, the system is always provided by a storage tank able to store, at least in part, the thermal energy which is not instantaneously used in the house. For a more detailed study, however, an hourly analysis along the hours of the year would be required and would be able to account for the effective use of the produced energy. However this is out of the scope of this study, which aims at potential evaluation.

The LCA boundary includes all the life cycle phases as raw material extraction, manufacturing processes, transport, installation, operation, maintenance and end-of-life (dismantling, recycling and final disposal).

The most of the past studies did not include the end-of-life phase of PV and ST technologies [26,27] since few cases, both at industry and at legislator levels, were experienced. Nevertheless, during the last years, the first recycling processes were investigated and developed [31,33,34] and the management of PV and ST disposal is gaining more and more interest. For this reason the end-of-life step of such technologies was included in this study as an