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Life cycle assessment and energy-CO_2-economic payback analyses of renewable domestic hot water systems with unglazed and glazed solar thermal panels ☆

Gabriele Comodi *, Maurizio Bevilacqua, Flavio Caresana, Claudia Paciarotti, Leonardo Pelagalli, Paola Venella

Dipartimento di ingegneria industriale e scienze matematiche (DIISM), Università Politecnica delle Marche, Via Brecce Bianche 60131, Ancona, Italy

HIGHLIGHTS

- LCA (Eco-Indicator 99) study of two DSHWSs with glazed and unglazed panels.
- The impact of DSHWS with glazed panels is much higher than that with unglazed ones.
- The glazed panel impacts more, in term of EI99, than the storage tank.
- The Energy and CO_2 payback times of both DSHWSs are much shorter than their useful lives.
- The cost of competitive commodities highly influences the economic payback times.

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ABSTRACT

The paper presents a cradle-to-grave life cycle assessment for two domestic solar hot water systems. The first consists of polypropylene unglazed solar panels coupled with a 300-l storage tank; the second one consists of a traditional system with glazed solar panels coupled with a thermal storage of the same volume. Life cycle assessment was conducted according to the Eco-Indicator 99 methodology, Egalitarian Approach, yielding 49.7 and 18.3 eco-indicator points for the glazed and unglazed panels systems, respectively. In addition, for each domestic solar hot water system, the energy, CO_2 and economic payback times were calculated. In order to take into account the influence of local climate on the solar panels yield evaluate, the systems performance was simulated for three different locations: Rome, Madrid and Munich. The payback times were evaluated with respect to both natural gas and electrical boilers. The Energy Payback Time of the unglazed panel system ranges between 2 and 5 months, that of the glazed panel between 5 and 12 months. The CO_2 Payback Time of the unglazed panel system ranges between 1 and 2 months, that of the glazed panel between 12 and 30 months.

The economic payback time, if compared with natural gas boiler, is in the range 9–11 years/8–13 years for the system with unglazed/glazed panels, respectively; if compared with the electrical boiler, it is in the range of 3–4 years for the system with unglazed panels and 4 years for that with glazed panels. The different national costs of natural gas and/or electricity play an important role in the economic payback times. Indeed, in Munich, the smaller energy savings achieved with the renewable systems are offset by the higher costs of these commodities.

1. Introduction

Renewable energy is a major worldwide issue since it involves scientific [1,2] and business communities [3,4] together with energy policy [5,6]. In this context, solar thermal technologies significantly contribute to hot water production in several countries with varying solar-resource levels, and also have the potential to be part of systems that are currently under consideration for

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* Corresponding author. Tel.: +39 071 220 4761; fax: +39 071 220 4770.
E-mail address: g.comodi@univpm.it (G. Comodi).

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solar-thermal power generation over a range of scales, including small-scale and distributed applications (such as in the domestic sector) [7–11]. The global solar hot water installed capacity at the end of 2011 was estimated in 232 GW_{th} with an increase in the last year of 44.3 GW_{th} of which 42.4 GW_{th} due to glazed systems and the rest due to unglazed systems, mainly applied to swimming pool heating [3]. The low penetration of unglazed panels in the worldwide market has different explanations. First of all, the market potential of unglazed panels is not yet fully exploited. In fact, according to Mauthner and Weiss [12] the 88.7% share of the total installed solar thermal capacity worldwide is located in China (64.9%), Europe (16.7%) and United States/Canada (7.1%), all temperate climate Countries, where glazed panels are preferred thanks to their higher performance in winter. On the contrary, in hot climate regions, where unglazed panels would be competitive, the solar thermal technologies are extremely underexploited with respect to their high potentialities accounting just the 9.2% (MENA Region, 2%; Sub-Sahara Africa, 0.4%; Asia apart from China, 4.1%) of worldwide market. This limited market penetration is mainly due to economic issues of the hot climate Countries with developing economies. Secondly, scale economy has reduced the cost of glazed panels increasing their profitability and leaving to unglazed panels a market only where glazed ones are clearly unprofitable, such as seasonal applications. Even though the solar energy is usually defined as a clean energy, it is necessary not to neglect the environmental consequences connected with the production, utilization and disposal of the components of the solar plant. A recognized methodology to model environmental impact throughout the whole life cycle of an item is life cycle assessment (LCA). According to Guinée [13], LCA can be applied in relation to "products" [14,15] (assessment of existing and new products, green procurement, eco-labeling and eco-design) and to "wider applications" [15–20] (assessment of services, of implementation and use of technologies). The international standard ISO 14040 [21,22] provides a comprehensive systematization of principles, framework and methodological requirements for conducting LCA studies. The present analysis was developed in compliance with such standards.

Many LCA analyses have been performed on solar energy sources [23–28]. In particular, Lamnatou et al. [23] present a comprehensive review of LCA studies applied to solar thermal systems highlighting that there are few studies in the field of solar thermal panels. Other works on LCA and environmental impact of solar thermal systems are presented by Tsilingiridis et al. [29,30], De Laborderie et al. [31], Martinopoulos et al. [32] and Koroneos et al. [33]. All authors agree that solar thermal systems are an optimal solution to reduce the environmental impact of domestic hot water production and they should be employed whenever possible. Some authors such as Battisti and Corrado [34] and Kalogirou [35] also evaluated the environmental payback times. In particular, Battisti and Corrado [34] noticed that the environmental payback times (from 5 to 19 months) are remarkably lower than the expected lifespan of the systems (15–20 years); Kalogirou [35] found that the payback time with respect to the energy spent for the system manufacture and installation is about 13 months; the payback time with respect to emissions produced from the embodied energy required for the system, the manufacture and installation, varies from few months to 3.2 years. Furthermore, literature review highlighted the lack of LCA analyses on unglazed solar plants, the small interest probably reflecting the minor market penetration.

This work presents the life cycle assessment of two typologies of DSHWS using: (i) polypropylene unglazed panels, mainly recommended for hot climates and seasonal uses; and (ii) glazed panels, which are suitable for all-over-the-year use [36].

The main originality of the paper consists in presenting both LCA and payback time analyses for a DSHWS with polypropylene unglazed solar thermal panel; in addition, the same analyses were also performed for a DSHWS equipped with traditional glazed solar thermal panels. Even if the latter system was already addressed, with respect to existing literature the paper presents elements of novelty; in particular: (i) it reports Energy, Economic and CO_2 payback times for three European locations which differ for both climate (and consequently energy yield) and energy markets (and consequently price of commodities); (ii) it updates the LCA of glazed solar thermal panels with 2013 data. The two LCA studies were carried out according to the Eco-Indicator 99 (EI99) methodology, Egalitarian Approach (EI99-EE) [37]. The result of the methodology is a dimensionless figure, the Eco-Indicator Point (EIP): the higher the score, the greater the potential environmental impact. LCA was performed using Gabi software [38]. For each DSHWS, the "use phase" of the life cycle analysis was evaluated considering the useful thermal energy collected by each typology of solar plant in order to meet the hot water demand profile of an apartment of four occupants. The influence of climate on the energy performance of the panels was evidenced considering three different European locations: Rome, Madrid and Munich.

The paper is organized as follows: after the Introduction, Section 2 describes the two solar thermal panel technologies addressed in the study; Section 3 details the LCA methodology applied to DSHWSs; Section 4 describes the life cycle inventory (LCI); Section 5 presents the results of the life cycle impact assessment (LCIA); in Section 6 the payback times in terms of energy, CO_2 and economic point of view are presented; finally, the conclusions are reported in Section 7.

2. System description – domestic solar hot water system

The main components of DSHWS are the solar panels and the thermal storage tank. This section summarizes the main differences between DSHWS with glazed and unglazed panels and presents the two types of panels considered in the study.

The glazed panel (Fig. 1) consists of an external case in aluminum which contains two sheets of rockwool insulation, a sheet of absorber in copper and a serpentine pipe in copper alloy; the case is hermetically sealed with a 4 mm-solar-glass by means of an EPDM (Ethylene-Propylene Diene Monomer) gasket. Table 1 shows the main characteristics of a solar panel.

The unglazed solar panel considered in this study is a strip of polypropylene 7 mm thick, 313 mm in width and variable in length so that the plant can have a modular structure. Along the strip there are 37 channels with an inner diameter of 5.5 mm (Fig. 2). Two header manifolds, having inner diameter of 38 mm, are welded at the extremities of the strip; their function is to distribute and collect the water flowing through the channels and to allow the connection with other panels in a modular structure (Fig. 3).

Table 2 reports the collecting area, the weight and the water capacity, depending on panel length.

The glazed panels can produce hot water all over the year (also in winter season) thanks to the glass which both keeps radiation

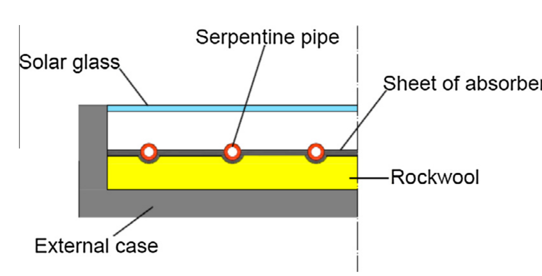

Fig. 1. Cross section of a solar glazed panel.

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