Journal of Cleaner Production 88 (2015) 29–42

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental assessment of domestic solar hot water systems: a case study in residential and hotel buildings

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ARTICLE INFO

Article history:
Received 24 November 2013
Received in revised form
10 June 2014
Accepted 11 June 2014
Available online 20 June 2014

Keywords:
Life Cycle Assessment
Environmental impact assessment
Building energy systems
Domestic solar hot water systems
Eco-efficiency
Energy savings

ABSTRACT

Domestic solar hot water systems (SHWS), which are used to reduce domestic energy use, represent one of the most widely known technologies of solar thermal applications. Taking into account the sizing of these systems during its design phase, it is also important to consider the effects on the environment of their use from a life cycle perspective. An evaluation method based on the Life Cycle Assessment (LCA) methodology is used in this paper to analyse the environmental implications of SHWS considering the production, use, maintenance and end-of-life stages. As a case study, 32 different types of SWHS to meet the hot water demand (HWD) of 2 dwellings and 2 hotels, located in the region of Aragón in Spain, are studied. The aim of the case study is to compare the environmental performance of SHWS and to select the best environmentally friendly solution while considering their energy pay-back time (EPBT).

From an environmental point of view, comparing the results obtained in all cases studies, e.g., in terms of kg CO_2 eq, the use of biomass as fuel for the auxiliary system in each SHWS considered provides the greatest environmental benefit in comparison with the other fuels, usually followed by the use of natural gas. However, in terms of the EPBT, because biomass is the fuel with lowest environmental impact and associated embodied energy, the avoided embodied energy due to the solar contribution in SHWS is the lowest in the biomass case, thereby resulting in a higher value of the EPBT.

1. Introduction

At the European level, with the implementation of the directives 2002/91/EC (The European Parliament and the Council of the European Union, 2003) and 2010/31/EU (The European Parliament and the Council of the European Union, 2010) of the European Parliament and of the Council of 16 December 2002 and 19 May 2010, respectively, on the energy performance of buildings, the need for sustainable building energy systems is of a great importance (Koroneos and Nanaki, 2012). In Spain, the Spanish Building Technical Code (CTE) is the basic document that sets the principles to analyse the limitations on buildings energy demand (Ministerio de Vivienda (Ministry of Housing (Spanish Government), 2006). The CTE is currently under review as a result of the recast of the directive 2010/31/EU (Manuel et al., 2013).

These current European regulations and also the CTE in Spain only focus on reducing the direct impact of buildings associated with the final energy consumption during their use phase by implementing several energy efficiency measures. Nevertheless, there are some indirect impacts associated with the other stages of a building's useful life that have greater relative significance; these impacts include the production and transport of its components, the construction process and the final disposal of the building (Zabalza Bribián et al., 2011). Direct energy consumption in the building use phase accounts for 60–70% of the total impact, depending greatly on the type of building, construction solutions and climate, e.g., the indirect consumption accounts for a range of 2–38% for typical buildings and 9–46% for "low energy" buildings (Sartori and Hestnes, 2007).

Several tools and methodologies exist for assessing different aspects of the environmental impact of buildings, such as the procedures for environmental certification LEED (Kubba, 2009), BREEAM, ITACA and VERDE (Macías et al., 2005). However, most of these are just qualitative, only considering some aspects or stages of the building's life cycle, and do not allow for a comparison of the environmental implications of energy systems.

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http://dx.doi.org/10.1016/j.jclepro.2014.06.035
0959-6526/

Nomenclature

β_{ij}	difference between the emitted and avoided CO_2-eq. emissions
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
CTE	Spanish Building Technical Code
E_{g_i}	CO_2-eq emissions generated by n subsystems of the *i-th* building energy system
E_{a_j}	CO_2-eq emissions avoided by m valorisation methods considered by the recovery stage j
EPBT	Energy Pay-back Time
GHG	Greenhouse Gas
HWD	Hot Water Demand
i	building energy system considered
j	scenario considered for the recovery methods at end of life phase
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
QDPV	Quantum Dot Photovoltaic
SHWS	Solar Hot Water Systems
WISARD	Waste Integrated System Assessment for Recovery and Disposal

The Life Cycle Assessment (LCA) methodology provides better decision support when optimising environmentally favourable design solutions that consider the impacts caused during the entire lifetime of the building (Malmqvist et al., 2011). All the new residential, office and services buildings built in the EU from 2020 will be nearly zero-energy buildings, defined as buildings that on an annual basis generate approximately the same amount of energy as they require. This conversion to zero-energy buildings will promote on-site generation from renewable sources and the incorporation of energy efficient equipment in buildings. Addressing building energy demand with renewable energy sources reduces the use of fossil fuel energy systems and the relative amount of Greenhouse Gas (GHG) (Tsilingiridis and Martinopoulos, 2010). Thus, the life cycle thinking can aid decision-making in the selection of the best available technologies to minimise the environmental impact of building energy systems through their entire life cycle.

There are several studies that have focused on the analysis of life cycle impact for some energy systems technologies, such as: i) small wind turbines, e.g., residential off-grid use in comparison with a single-home diesel generator system (Fleck and Huot, 2009) and comparison of two grid connected rooftop wind turbines (300 W vertical axis and 500 W horizontal axis) (Uddin and Kumar, 2014); ii) photovoltaic modules, e.g., environmental comparison of 4.2 kWp stand-alone photovoltaic system with other supply options (García-Valverde et al., 2009) and a comparative LCA of a quantum dot photovoltaic (QDPV) module with other types of PV modules and energy sources (Şengül and Theis, 2011); iii) biomass boilers and combined heat and power (CHP) (Cellura et al., 2014); or iv) solar water heating, e.g., a solar thermal collector with integrated water storage (Battisti and Corrado, 2005), LCA of different types of solar collectors, auxiliary systems and locations of solar water heating systems for the U.S. typical residential buildings (Hang et al., 2012), net energy analysis of installed domestic SHWS in operation and life cycle perspective of its energy use (Hernandez and Kenny, 2012), and the technical and environmental performance from an LCA perspective of a solar water heater (flat-plate collector type) with electricity as auxiliary for domestic use (Koroneos and Nanaki, 2012).

There are even studies that have used to some extent the LCA methodology to compare the exergetic performance with the environmental impacts of building energy technologies (Koroneos and Tsarouhis, 2012), or as part of a broader study to consider the GHG emissions and other social and economic sustainability indicators of energy technologies for the building sector (Huang et al., 2012).

However, no relevant studies in the literature were found that focused specifically on the application of an evaluation method that uses LCA methodology to determine the environmental implications of building energy systems, e.g., solar water heating systems (SWHS), and to allow for a detailed comparison to support the decision making process in selecting such systems. Thus, a methodology for evaluation, based on LCA, was developed in this paper in order to analyse the environmental implications of several alternative building energy systems for use in addressing the demands of electricity, heating, cooling and hot water of a building. To validate the methodology, 32 different types of SWHS to meet the hot water demand (HWD) of 2 dwellings and 2 hotels, located in the region of Aragón in Spain, are studied.

2. Methodology

The evaluation method proposed uses LCA methodology to estimate the environmental implications of building energy systems and support decision making in the selection of the best available technologies to minimize their environmental impact. It is based on the methodology described by Aranda Usón et al. (2012a, b).

Equations (1)–(3) and Table 1 summarise the methodology used in terms of the CO_2-eq emissions, which corresponds to the impact category of global warming or *global warming potential*. Note that the methodology can be replicated in terms of other impact categories, such as acidification (SO_2 eq), eutrophication (PO_4 eq), and ozone layer depletion (CFC-11 eq), among others. Table 1 shows a matrix for general analysis. This matrix represents the difference between the amount of CO_2-eq emissions generated by a building energy system i and the amount of CO_2-eq emissions avoided in a recovery scenario j considered at its end of life treatment disposal. The elements of the matrix that are presented in Table 1, β_{ij}, are calculated as follows:

$$\beta_{ij} = E_{g_i} - E_{a_j} \quad (1)$$

$$E_{g_i} = \sum_{x=1}^{x=n} E_{g_x} \quad (2)$$

$$E_{a_j} = \sum_{y=1}^{y=m} E_{a_y}, \quad (3)$$

where E_{gx} represents the CO_2-eq emissions generated by n subsystems of the *i-th* building energy system and E_{ay} represents the CO_2-eq emissions avoided by m valorisation methods considered by the recovery stage j. Note that a lower positive value in the matrix indicates a higher net profit in terms of CO_2-eq emissions. The amount of CO_2-eq emissions generated (E_{gi}) includes the CO_2-eq

Table 1
Net CO_2-eq emissions – Matrix of the relationship between building energy systems.

Recovery scenario j↓	1	2	3	←Building energy system i
1	β_{11}	β_{12}	β_{13}	
2	β_{21}	β_{22}	β_{23}	