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Environmental profile of latent energy storage materials applied to industrial systems

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HIGHLIGHTS

- PCM shows the highest contribution to global warming category in TES manufacture.
- HTF has the highest impact in human toxicity during the TES manufacture.
- The disposal of components in the landfill has negative effect on the final results.
- Energy saving compensates environmental impacts associated to the use of a TES.

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ABSTRACT

Industry sector is an intensive-energy consumer and approximately 20–50% of industrial energy consumption is lost as waste heat. Therefore, there is a great potential for reducing energy consumption and, subsequently, decreasing the fossil fuels used if this lost energy can be recovered. Thermal Energy Storage (TES) based on Latent Heat Storage systems (LHS) using Phase Change Materials (PCMs) has become one of the most feasible solutions in achieving energy savings through waste heat recovery, especially when there is a mismatch between the supply and consumption of energy processes. In this paper, a shell and tube heat exchanger incorporating PCMs has been considered to store the excess energy available in an industrial process. Several attempts have been made to design the most appropriate system considering many cost–benefit and technical criteria to maximise the heat recovery. However, the environmental criterion also is an important factor when determining whether this technology is not only energy and cost-efficient but also environmentally friendly, considering the whole life of the system from its manufacture to its disposal.

To this end, this research includes a Life Cycle Assessment (LCA) to determine whether the energy savings of conventional fuels during the operation stage are large enough to balance the environmental impact originated in an industrial TES system including the manufacture, use and disposal phases. Inputs and outputs of each management stage have been defined, and the inventory emissions calculated by SIMAPRO v7.3.2. A midpoint and endpoint approaches have been carried out using two methods, CML 2001 and Eco-indicator 99, respectively. As a preliminary result, a promising reduction in the overall impacts was obtained by the use of this technology. From the environmental impact results, a matrix of possible technical solutions is displayed, to improve the environmental performance.

1. Introduction

Thermal energy storage (TES) is an attractive technology for different industrial applications from a technical, economic and environmental point of view (Dincer and Rosen, 2001). In fact, this technology can reduce the size, the operational failures, the environmental impact, and the manufacturing and operating costs of several industrial systems which cannot manage the waste heat generated during their operation. TES can be designed to keep both the hot and cold media in contact or to separate them by using a heat exchanger. Then, the cold medium storage involves two well-known mechanisms for storing waste heat, namely latent heat (LH) or sensible heat (SH).

Several authors have studied both mechanisms in order to design systems capable of storing waste heat or excess heat from an industrial system with the purpose of using it in other systems or heat itself when its operation is required (Dinçer and Rosen, 2002). Most of these studies are focused on TES which have been developed and based on experimental (Al-Abidi et al., 2013; Delgado et al., 2012; ElGhnam et al., 2012; Mawire and McPherson, 2009; Regin et al., 2006; Tay et al., 2012a, 2012b; Trp, 2005; Tyagi et al., 2012) and numerical (Banaszek et al., 2000; Guo and Zhang, 2008; Guo et al., 2013; Mawire and

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Nomenclature

DALY	disability adjusted life years
DPO	diphenyl oxide
ES	energy storage
ETAP	Environmental Technologies Action Plan
GHG	greenhouse gases
HTF	heat transfer fluid
LCA	Life Cycle Assessment
LCI	life cycle inventory
LH	latent heat
NZEIT	Net Zero Environmental Impact Times
PCM	phase change material
PDF*m2yr	potentially disappeared fraction times area times year
SH	sensible heat
TES	thermal energy storage
H_f	latent heat
T_f	melting temperature
n	number of years
m	mass
E_m	energy consumption
E_{saved}	total thermal storage energy

McPherson, 2009; Oró et al., 2013; Regin et al., 2006; Tay et al., 2012b; Trp, 2005) research. They are mainly focused on the technical design of these storage systems. All these studies have encouraged several authors to publish different original reviews based on them (Al-Abidi et al., 2012; Gil et al., 2010; Kenisarin, 2010; Oró et al., 2012; Pinel et al., 2011; Regin et al., 2008; Rismanchi et al., 2012; Sharma et al., 2009; Soares et al., 2013; Zalba et al., 2003; Zhou et al., 2012). However, there is a significant lack of knowledge on the environmental implications to quantify the environmental benefits associated to the use of this technology.

Saving of fossil fuel consumption and, therefore, CO_2 eq. emissions generated by using them is one of the most important characteristics of these systems. Then, the continuous increase in the level of greenhouse gas (GHG) emissions and rising fossil fuel prices are the main techno-economic characteristics that promote efforts for using various sources of waste or excess heat recovered (Sharma et al., 2009; Vanneste et al., 2011; Wagner and Rubin, 2014). The first study that addressed the analysis of the environmental implications of TES systems was carried out by Beggs (Beggs, 1994) almost 20 years ago. However, the environmental impact analysis should be performed considering a broader perspective of the product or service's life stages. This perspective should include direct and indirect “cradle-to-grave” environmental impacts.

Then, researchers (Castell et al., 2013; Denholm and Kulcinski, 2004) introduced the Life Cycle Assessment (LCA) methodology as a tool to estimate the environmental impact of TES, particularly in solar power plants (Battisti and Corrado, 2005; Oró et al., 2012; Piemonte et al., 2011). These authors suggested that incorporating of PCM substantially reduces the overall environmental impact under the experimental conditions studied.

Nevertheless, despite the fact that LCA has been applied to different scenarios, a limited number of studies have been published using this methodology to assess environmental aspects such as the overall TES environmental performance throughout its operational life cycle. In addition, in most of the above-mentioned researches which have analysed the environmental implications of TES systems, LCA was evaluated using Eco-indicator method to model the approach of characterisation of an impact indicator. However, a characterisation at midpoint level has not been found. In this study, based on the authors' knowledge, for the first time the impact of substances involved in a new TES design on the environment changing natural environmental aspects (level midpoint) is carried out by means LCA methodology using the CML method.

Then, besides the midpoint approach and following the trend of recently published works, this study uses LCA methodology and also Eco-indicator 99 in order to determine whether energy savings of conventional fuels during the operation stage are large enough to balance the environmental impact caused in an industrial TES system. The manufacture, use and disposal phases are included along this analysis.

2. Methodology

2.1. Scope of the analysis

As mentioned above, the environmental analysis proposed in this work is based on the LCA methodology to determine whether energy savings are large enough to balance the environmental impact caused during the manufacture, use and disposal stage of a TES system.

LCA methodology has been reported for analysing direct and indirect “cradle-to-grave” environmental impacts of products, services or processes (Aranda-Usón et al., 2012; Gironi and Piemonte, 2011; Hunt et al., 1996). On the other hand, this has already been fully technically and scientifically proven (Rebitzer et al., 2004; Society of Environmental Toxicology and Chemistry (SETAC), 1993; UNEP/SETAC Life Cycle Initiative, 2011). Additionally, this methodology is strongly encouraged by the European Union policies and regulations, i.e. the Environmental Technologies Action Plan (ETAP) on Sustainable Consumption and Production and Sustainable Industrial Policy (COM-2008 397) or the ETAP action Plan (COM-2004 38 final).

The most up-to-date structure of the LCA is proposed by the standard ISO 14040 (Guinee et al., 2001) which mentions that LCA has four main phases. All of them are well described in Aranda et al. (Aranda-Usón et al., 2013) and can be summarised as an iterative process which may be repeated if a need for further information emerges during its implementation (Rebitzer et al., 2004; Tukker, 2000; Udo de Haes and Heijungs, 2007). Thus, in this study the LCA methodology attempts to associate emissions and extractions of life cycle inventory (LCI) on the basis of impact pathways to their potential environmental damages. These impact pathways refer to environmental processes and they show the causal chain of subsequent effects originating from an emission or extraction.

In order to study the inventory stage, via impact assessment, two approaches (midpoint and endpoint) frequently used in LCA are performed in this work. Midpoints are considered points in the cause–effect chain (environmental mechanism) of a particular impact category somewhere between stressor and endpoints (Guinee et al., 2001). Whereas, endpoint approach evaluates those elements at the end of an environmental mechanism being themselves of value to society e.g. damage to Human Health or to Ecosystem diversity.

Midpoint and endpoint approach assessments were carried out by two methods commonly used in a scientific LCA research, namely CML 2001 and Eco-indicator 99 (Chen et al., 2012; Tiruta-Barna et al., 2007; Wäger et al., 2011). The CML method uses multiple indicators at midpoint level (Guinée, 2002). This involves the impact categories into two groups: Obligatory impact categories, base line impact categories, which are described in detail by several authors (Amores et al., 2013; Renó et al., 2011; Zaman, 2010), and additional impact categories which are operational impact categories that are dependent on the study requirements.

In this work, the considered base line impact categories of the CML method are as follows: Abiotic depletion, Acidification, Eutrophication, Global warming, Ozone layer depletion, Human toxicity, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity and Photochemical oxidation.