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Integration of environmental indicators in the optimization of industrial energy management using phase change materials

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ABSTRACT

This work addresses the potential environmental effects of thermal energy storage using the life cycle assessment to perform an optimal system framework. The study assesses the recovery of waste thermal energy at medium temperatures through the application of phase change materials and the recovered heat use in other industrial processes avoiding the heat production from fossil fuel. To this end, twenty different situations were analysed in terms of energy and environmentally combining four thermal energy storage systems varying the type of phase change material incorporated (potassium nitrate, potassium hydroxide, potassium carbonate/sodium carbonate/lithium carbonate and lithium hydroxide/potassium hydroxide) which were defined as cases and five scenarios were the heat can be released based on the type of fossil fuel consumed (coal, heavy fuel, light fuel, lignite and natural gas). Moreover, a net zero environmental metric time parameter was calculated to assess the time period in which the environmental impacts associated to the thermal energy system were equal to the avoided impacts by the use of the heat recovered. Values that were lower than the thermal energy system lifetime were obtained in more than 40% of the total study situations. Finally, an additional analysis was performed to identify the most significant parameters for the further development of a mathematical model to predict the net zero environmental metric time.

1. Introduction

There are a large number of industrial processes in which thermal energy is lost every day, especially those processes running at low and medium temperatures. In addition to the reduction in the amount of excess energy released by production processes, several options are available for the use of industrial excess energy, including heat harvesting, heat storage, heat utilization and heat conversion technologies [1]. This energy is commonly called waste heat, and its optimal use represents a significant opportunity to establish advanced Thermal Energy Storage (TES) technologies [2]. As studied by different models [3], TES can store waste heat and then release it to different industrial applications [4]. Concretely, Kere et al. [5] studied the applicability of a TES system in the ceramic sector. Thereby, the consumption of other energy resources for heat production is avoided [6].

Previous studies have been focused on advanced TES development using Phase Change Materials (PCMs) [7], which are able to use their latent heat as a way to store heat. In this sense, Fernandes et al. [8] developed a comparison of different possibilities available for energy storage and specially for high temperature thermal energy storage they highlighted the suitability of metal foams as PCM to improve the metal thermo-mechanical properties.

The heat storage is a capacity very useful, especially regarding those systems which involve heat exchange [9], so different techniques are been analysed in order to improve the heat transfer. One option is the use of fins inside the thermal management systems, as is was used reported by Al-Abidi et al. [10] containing sixty panels divided into nine internal horizontal fins acting as a heat exchanger. On the other hand, there are other methods that enhance the heat transfer by means of tubes as was reported by Tay et al. [11] who studied experimentally a TES system based on tubes inside a PCM filled cylindrical tank. By properly selecting the PCM, this technology can be used in the temperature range of 300–400 °C [12]. $NaNO_3$ is a typical inorganic salt example used in the mentioned above temperature range [13] and even a combination of a deformable copper shell filled with a nitrate mix of KNO_3–$NaNO_3$ can be used as example of encapsulated PCM [14]. Although required materials for encapsulation (refractory steel, extruded ceramics) are recognised to be expensive [15], their long lifetime upon charging–discharging cycles reduces the financial impact.

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Nomenclature

GHGs	Greenhouse Gases	n	number of years
HTF	Heat Transfer Fluid	NZEMT	Net Zero Environmental Metric Times
IC	Impact Category	m	mass
LCA	Life Cycle Assessment	PCM	Phase Change Material
LCI	Life Cycle Inventory	TES	Thermal Energy Storage
LH	Latent Heat	H_f	latent heat
LHS	Latent Heat Storage	T_f	melting temperature
NG	Natural Gas	1,4-DB-eq	1,4 Dichlorobenzene equivalent

Consequently, Latent Heat Storage (LHS) is a promising alternative that can reduce the size, operational failures, environmental impact, and manufacturing and operating costs of several industrial systems that cannot manage the waste heat generated during their operation. On the other hand, heat exchangers are widely used in most industrial processes for efficient heat transfer from one medium to another. In fact, innovate designs can be used as an integral heat exchanger, which can combine an evaporator, a condenser and a recuperator into a single heat exchanger.

In essence, the combination of heat exchangers with LHS applications results in an attractive way to store a large amount of waste heat generated during short operating peaks and to dissipate the heat during steady state operations [16]. In this case, when PCM is used in a heat exchanger , the selection of the suitable material is a key aspect and it must be based on the working temperature conditions as is was reported by Iten and Liu [17]. In addition, other PCM properties are also important for the heat flux behaviour such as the thermal conductivity [18]. Furthermore, Kaizawa et al. [19] reported the relevance of the PCM density and highlighted that it should be taken into account in order to optimize the volume and mass of the system. So, all of them are highly relevant due to their influence in the heat exchange rate.

In general, these types of systems aim to save energy and, therefore, they can help avoid impacts associated with extractive industries and with energy generation, transformation, distribution and consumption. Nevertheless, an overall environmental assessment of this TES–PCM technology is very important for granting the environmental sustainability of these systems [20]. In the past, several researchers had already studied the environmental impact of other system types with PCM. For instance, in a brick construction system [21], as a representative application in the building and construction sector. Regarding the energy generation, the performance of solar power plants can be enhanced by means of PCM application [22]. Another example is the performance improvement for water storage due to a transparent insulating material layer as additional covering for the collector [23]. In these studies, the Life Cycle Assessment (LCA) was used and the main conclusions suggested that incorporating PCMs substantially reduced the overall environmental impact under the experimental or theoretical conditions studied, although further developments must be carried out regarding this young technology [24]. However, there are few works regarding an integrated study of the PCM system at low temperatures [25] (excluding environmental assessment) to store energy to be released in other process, avoiding the use of conventional fuels. Neither is the case of PCM systems with medium temperatures [26] nor their environmental implications.

Environmental metrics are powerful tools for tracking the environmental assessment [27]. They can be related to concepts such as measurements of a product's environmental impact, implications for market access, market share and production standards. In addition, environmental metrics can help to identify problems, define priorities, drive police development, compare different process and monitor progress over time in reaching goals. This work focused on the impacts associated with a PCM system, considering the context of natural resources, human health and ecological health and considering environmental metrics such as potentials, potency factors, equivalent factors, or characterisations factors [28] for five categories, namely, the acidification, eutrophication, carbon footprint, human toxicity and terrestrial ecotoxicity.

The LCA is known as one framework for holistically evaluating the inputs and emissions associated with the stages in a productś life cycle from cradle to cradle (raw material acquisition, manufacturing, use and disposal) [29]. Based on the LCA stages [30], the system boundaries and scope were established and the assessment was performed by associating a data sheet (inventory analysis) using environmental metrics for converting energy, materials, resources and emissions in environmental impacts.

To this end, the CML 2001 (baseline) method was used to characterise (at midpoint level) the five categories, which are presented in this method according to the Handbook on Life Cycle Assessment [31]. Thus, the inventory analysis results are assigned to the impact categories, and then the calculation of category indicators is performed using the associated characterisation factors (comparison metrics). For this purpose, several cases were analysed using this method by taking into account different PCMs working in the temperature range of 300–400 °C in a TES system based on a heat exchanger design. This approach allows generating several PCM–TES systems to store waste heat, which can be subsequently released in other processes, thereby minimising the use of conventional fuels.

The entire approach was analysed to demonstrate if the savings of conventional fuels are sufficiently large to balance the environmental impact caused by the manufacturing of the TES systems and to determine the required operational time of the TES system to obtain this balance. This was based on energy savings of conventional fuels during the operation stage, which increased over time along with the subsequent environmental benefits. Thus, a Net Zero Environmental Metric Time (NZEMT), in terms of the environmental metrics grouped in the above mentioned impact categories, was defined as the time when the environmental impact caused by TES manufacture is compensated by the environmental benefits. Finally, this parameter and the PCM latent heat were studied in terms of carbon footprint to identify significant parameters for the further development of mathematical models to predict NZEMT under several conditions.

2. Methods

2.1. Scope and boundaries

The LCA study was focused on TES including PCM to recover waste heat energy that can be used as thermal energy in other processes, avoiding the generation of heat in conventional technologies during a specific time period. Thus, the TES system configuration corresponds to a conventional U-tube bundle heat