Environmental impacts of latent heat thermal energy storage systems

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Abstract

Latent thermal energy storage integrated into energy systems can be a solution to the intermittency of renewable energies. The objective of this work is to investigate how operational parameters and phase change material properties influence the environmental impacts of thermal energy storage systems through a proposed mathematical correlation, thereby enabling informed decisions in the thermal energy storage sector.

Introduction

Latent heat thermal energy storage (LHTES) has garnered attention due to its potential to aid actions against global warming, since it allows renewable energy to be stored in a phase change material (PCM), which is used when the renewable source does not produce energy [1]. Bio-based PCMs have also received significant focus in various applications like heating and cooling, photovoltaic panels cooling, building, and electronic devices cooling [2]. Despite the considerable number of studies, the environmental impacts of bio-based materials have not been well discussed. Thus, the objective of this study is to investigate the environmental impacts of selected PCMs during their production and use in a 10-kWh TES system through life cycle assessment (LCA). As a result, the main operational parameters of a TES are correlated with the environmental impacts through a proposed mathematical correlation, allowing for the identification of which parameters contribute the most to the impacts and how they can help select the right materials and operational parameters.

Methodology

The environmental assessment study followed the ISO 14040 [3] guidelines and included the analysis of seven different phase change materials for a wide range of temperature applications. Stearic acid (SA), xylitol (XY), and adipic acid (AA). For these materials, the melting temperatures are 69˚C, 92.55˚C, and 153.5˚C, respectively. The environmental assessment aimed to identify the impacts of producing 1 kg (FU) of each PCM at the factory gate, or cradle-to-gate analysis. For this, SimaPro 10.2, Ecoinvent 3.11, and ReCiPe 2016 have been used to obtain the GWP (kg CO_2e). Then, the TES system and the environmental impacts are analyzed based on Figure 1.

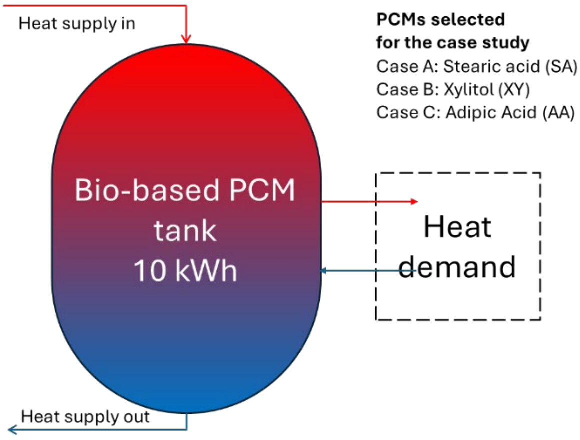

Figure 1. Schematics of the 10-kWh$_t$ TES used for this study.

Initially, the environmental impact is calculated for 1 kg of each PCM, which is crucial to integrate this value into a mathematical correlation that is briefly explained. To simplify, as the thermal storage is the object analyzed itself, it is assumed that the working PCM working temperature range is $\Delta T = T_{max} - T_{min}$, and it is set to 15˚C for all cases. This means that the melting temperature T_{pc} is adjusted to be the mean value in the working temperature range (ΔT). The energy provided by the PCM in this working range (E) and the total impact indicator (Y_{ST}) can be obtained through Equations (1), (2), and (3).

$$E = m_{PCM} c_{sol} (T_{pc} - T_{min}) + m_{PCM} h_L + m_{PCM} c_{liq} (T_{max} - T_{pc}) \quad (1)$$

$$Y_{ST} = m_{PCM} X_{FU} \quad (2)$$

$$Y_{ST} = \left(\frac{E}{c_{sol}(T_{pc} - T_{min}) + h_L + c_{liq}(T_{max} - T_{pc})} \right) X_{FU} \quad (3)$$

Where m_{pcm} refers to the mass of the PCM (kg), T_{pc}, $c_{sol,}$ and c_{liq} are the phase change temperature (K), specific heat at constant pressure in the solid phase (kJ.kg^{-1}.K^{-1}), and specific heat at constant pressure for the liquid phase (kJ.kg^{-1}.K^{-1}), all of them considered constant. The latent heat of fusion is h_L in kJ.kg^{-1}. T_{max} and T_{min} refer to the charging and discharging temperatures of the system (K), which are intrinsic to the heat source and heat sink, respectively, and to the application.

Results

Among the total number of indicators obtained with the applied methodology, Global Warming Potential (GWP) has been selected to simplify and provide a better explanation. The GWP obtained per kg of SA, XY, and AA were 7.00 kg CO_2e, 9.22 kg CO_2e, and 13.00 kg CO_2e. In the case of SA, the highest contribution comes from the farming sector, followed by the manufacturing sector. While manufacturing is responsible for the highest contribution to XY and AA.

Analyzing the impacts based on the energy provided by the PCM during the melting phase, in this case, the amount of 10-kWh$_t$, the results are presented in Figure 3. The results show two ranges of working temperature obtained with Equation (3), ΔT=15˚C and ΔT=20˚C. From both ranges of working temperature, among the three materials, a TES system containing AA has the highest GWP, followed by XY, while SA is associated with the lowest amount. When the working temperature range for the PCM is increased from 15˚C to 20˚C, the environmental impact reduces by 5% for the AA and nearly 3.5% for XY and AA.

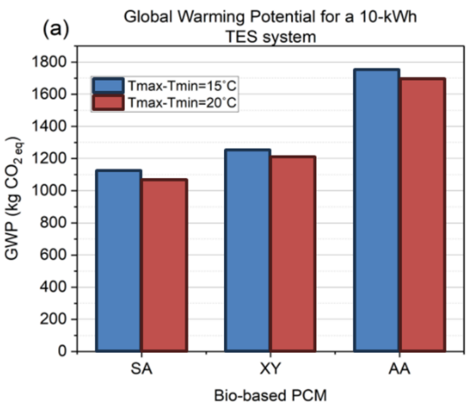

Figure 2. Environmental impact using the tree PCMs material with different temperature ranges.

Based on the correlation presented in Equation 3, the impact associated with a TES system is directly proportional to E and X_{FU}, and inversely proportional

to h_L, T_{max}, T_{min}, T_{pc}, c_{sol}, c_{liq}. Which means that decisions regarding the environmental impact of a TES system can be assessed based on these parameters. However, to understand the intensity of the contribution of these parameters, a local sensitivity analysis varying each one in the range ±10% was conducted. Theresults are shown in Figure 3. T_{max}, h_L, and T_{min} were revealed to be the parameters influencing the most the environmental impact in a TES system.

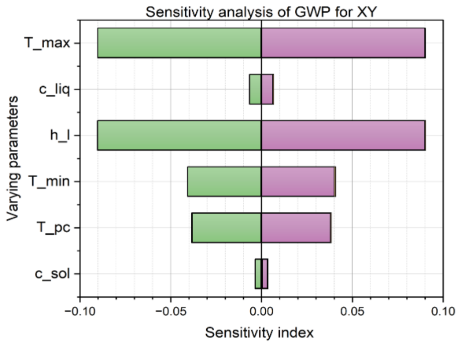

Figure 3. Local sensitivity analysis of the parameters.

Conclusions

Improvements in the manufacturing sector can be a key to reducing the GWP of XY and AA, while for SA, attention should be more toward the agricultural practices.

The higher the thermal energy of the TES, the higher the environmental impact. However, selecting a higher latent heat PCM and proper operating temperatures can lead to lower environmental impacts of a system.

References

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