Life cycle analysis of PCM-enhanced domestic hot water storage

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Abstract: Encapsulated phase change material (PCM) can be used to increase the capacity of domestic hot water (DHW) storages by a factor of 2 to 3. This extra capacity allows for an increase of own-consumption and self-sufficiency of locally produced renewable energy from solar thermal or photovoltaic systems and thus reduces the energy demand taken from the grid or other fuel sources. While the energetic sustainability can already be seen directly from simulations, the environmental benefit in terms of avoided CO2 emissions depends heavily on the life cycle analysis (LCA) of the added PCM capsules compared to the energy saved. This LCA was carried out for a demonstrator PCM-enhanced domestic hot water station and shows a very early break-even point for CO2 emissions. In addition, a comparison was made with a battery system (as an electrical storage system in front of the heat pump, with equivalent heat capacity), which shows that the latent heat storage system with encapsulated PCM leads to ten times fewer emissions per kWh of thermal energy delivered.

Keywords: CO2 emissions, domestic hot water, life cycle analysis, phase change material

1 Introduction

Heat pumps in conjunction with renewable energy sources and thermal energy storage could become one of the major drivers in the decarbonization of our energy system [1]–[3]. By adding storage capacity, the overall performance can be increased while still being cost-efficient [4]. Thermal storage technologies based on encapsulated phase change material (PCM) offer now the possibility to triple the storage capacity of domestic hot water (DHW) storages while neither altering the storage volume nor modifying the system layout. Since the technical, the energetical and the economic feasibility have been proven, the question now arises whether PCM-based DHW storages are able to recover the additional CO emission from adding the PCM during the operational phase on one hand by an increase in own-consumption of locally produced renewable energy [5] on the other hand.

1.1 System description

The evaluated system is shown in Fig. 1 and includes a primary heat supply by a heat pump with an 800 L buffer storage being connected via a distributor to the floor heating and through another heat pump and the 120 L PCM thermal storage to the DHW station.

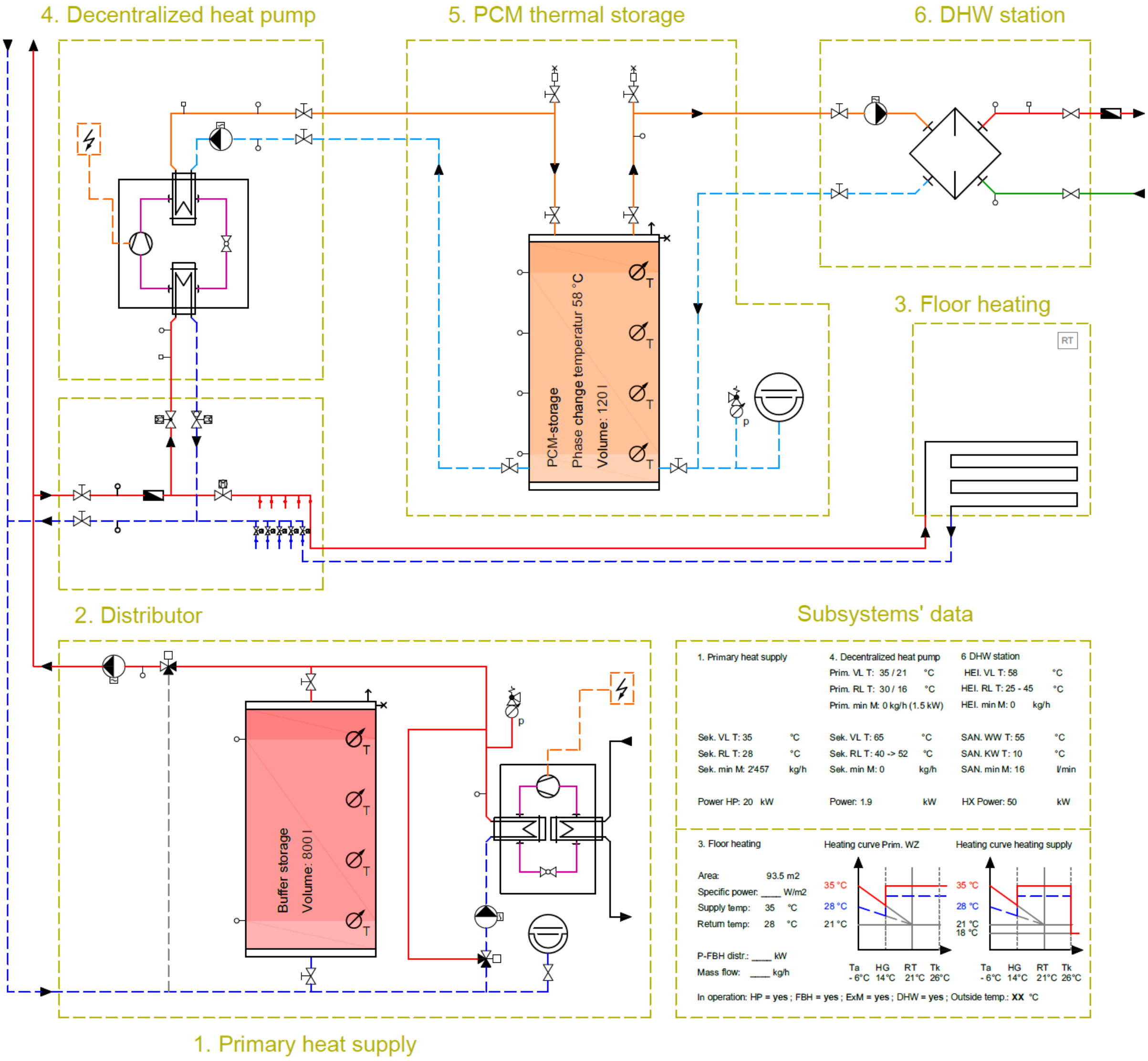

Figure 1: Space heating and DHW station by BMS-Energietechnik AG as evaluated for the LCA

For the LCA, we draw the system boundary around the PCM storage itself, which would otherwise be a sensible buffer storage of the same volume and hull material.

2 Methodology

The evaluation is using the *ecoinvent* database [6]. The proposed PCMs have been modeled as a full system, where the storage unit including the containment has been compared against conventional batteries [7], following a cradle-to-gate approach by the inventory, including transport and processing of all materials. The encapsulated PCM are either metal or high-density polyethylene (HDPE) capsules filled with salt hydrates and additives. The capsules increase the storage capacity of a DHW system [8], thus potentially increasing the own-consumption of locally produced photovoltaic electricity [2], [9]. As such the systems saves CO2-emission related to the electricity mix of the local grid, and the big questions are: a) how long does it take to recover the LCA-costs of the capsules, and b) is the capsule-based solution better than an equivalent battery storage?

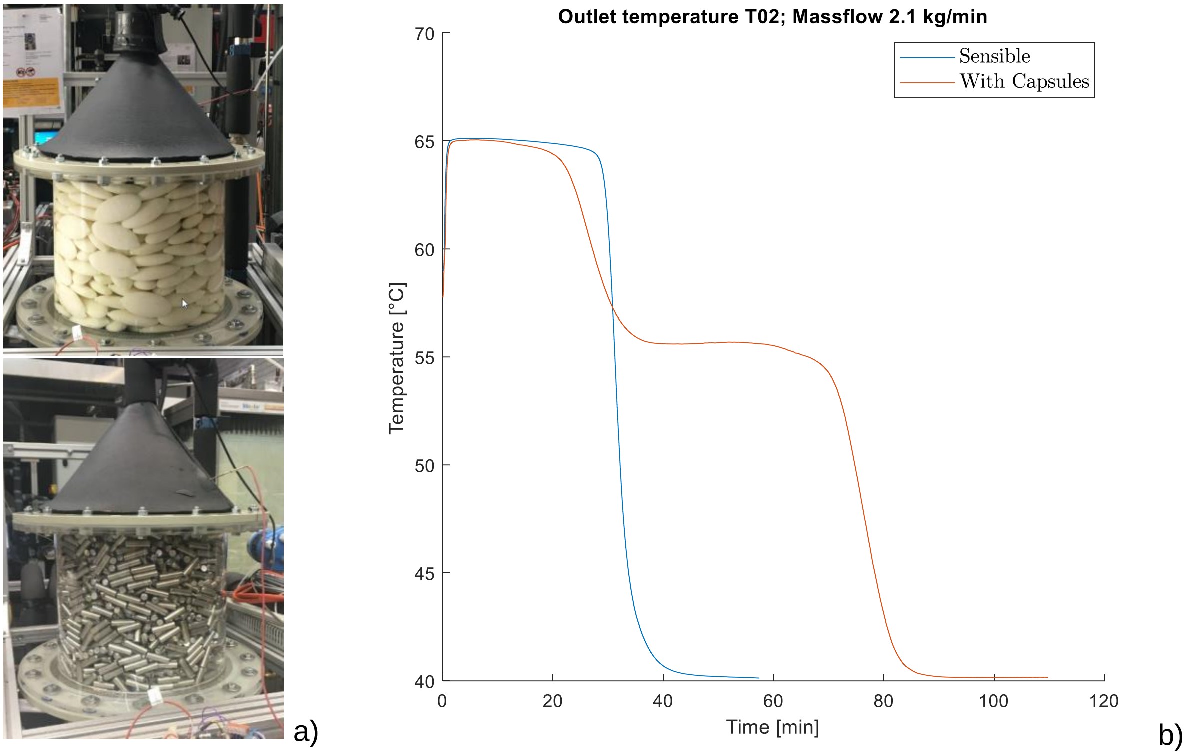

Figure 2: DHW testbed in a) with HDPE capsules (top) and metal capsules (bottom); temperature profile in b) during discharge with metal capsules.

Typical questions about PCM-based storage technologies deal with cycle stability, heat transfer performance and supercooling effects [8]. Therefore, the proposed capsule designs have been evaluated in a testbed as shown in Fig. 2 and modeled in Polysun for the system analysis [4]. In a) the HDPE-capsules are shown in the top, the metal capsules are shown in the bottom. In b) a typical performance curve for the outlet temperature of the thermal storage is plotted, with the characteristic plateau of the PCM during crystallization. The behavior of the PCM and additives mixture has been measured with differential scanning calorimetry (DSC), whereas the performance of the capsules in the system is measured in cycling and aging test with the testbed. Details on the results can't be shown here due to confidentiality restrictions.

Table 1: Design parameters of HDPE and metal capsules

Parameter	HDPE	Metal
Volume PCM [cm^3]	58	6.08
Volume outside [cm^3]	75.33	7.47
Mass [g]	20	5.16

The measurements of both capsule variants are presented in Table 1. General settings for using the *ecoinvent* database, as well as calculation assumptions for the LCA are stated in Table 2. We conducted a comparison between local production of electricity from solar PV where the own-consumption is increased by the added thermal storage capacity versus the otherwise used grid electricity for Switzerland, Germany, and Austria. Obviously, the best return on invest with respect to the CO2 footprint can be expected when the CO2 footprint of the grid is high. The testbed has indicated technical feasibility and the system producer COWA TS AG and BMS-Energietechnik AG expect economic feasibility. Now the environmental benefit and sustainability must be proven. Only if we can reduce the net footprint over the full life cycle, this technology makes sense. Otherwise, one would simply increase the PV area.

Table 2: Assumptions for the life cycle assessment [10], [11], [12]

Parameter	Value	Unit
COP heat pump	2.6	
Latent heat PCM	264	kJ / kg
Sensible heat PCM (ΔT=10K)	28	kJ/kg
GWP grid CH	128	g $CO_{2\ eq}$ / kWh
GWP grid DE	408	g $CO_{2\ eq}$ / kWh
GWP grid AT	100	g $CO_{2\ eq}$ / kWh
GWP solar CH	40	g $CO_{2\ eq}$ / kWh
Liftime of capsule	10000	cycles
Lifetime of battery	1850	cycles
Packing density HDPE	65	%
Packing density metal	58	%
Shipping distance PCM	14000	km
Shipping distance additives	14000	km
Lorry & train distance	1500	km
Ratio lorry vs. train	40	%
Energy input for HDPE filling	35	MJ / 1000 capsules
Energy input for metal filling	3.67	MJ / 1000 capsules

Further important assumptions:

- HDPE is produced in CH (recycled) or ‘rest of world’ (RoW) (0% recycled material)
- The production of HDPE Cowa capsules including the moulding and filling of capsules takes place in Switzerland (best case) or China (worst case)
- The production of metal Cowa capsules including the deep drawing and filling of capsules takes place in Switzerland/RER (best case) or RoW/China (worst case)
- The HDPE electricity input represents the energy needed to heat up the PCM to fill the capsules (≈ 35MJ)
- The metal electricity input represents the energy needed to heat up the PCM to fill the capsules, down scaled linearly from HDPE value (≈ 4.5 MJ)
- All the heat stored in Cowa capsules is from PV, which is assumed to be already there, so the solar energy is considered carbon free
- For the heat storage capacity per capsule calculations only the latent heat of PCM and the sensible heat (ΔT=10K) of PCM and additives are considered
- Disposal / Recycling: PCM and HDPE are both incinerated in CH; metal is being treated for recycling at end of life in CH
- Transportation for disposal is already included as they are all market activities; separation of materials is not included here.

Stoff	Details	Bestellt aus	HDPE Capsule Masse/Kapsel [g]	best case [g CO2 eq]
Sodiumacetat trihydrat	CAS-Nr.: 6131-90-4	Deutschland (bilgram GmbH)	79.89	213.2
Tetrasodiumpyrophosphat decahydrat	CAS-Nr.: 13472-36-1	Österreich (w. ulrich GmbH)	4.25	9.4
Xanthan	CAS-Nr.: 11138-66-2	China (Hefei TNJ Chemical Industry Co.,Ltd)	0.85	
HDPE Production and Blow Moulding	Grade: BB2581	Deutschland (Borealis Group)	20	23.0
Chromium Steel Production & Deep Drawing				
Other (electricity & transport)			Amount	22.7
Electricity [MJ/1000 Capsules]			35.00	0.9
transport, freight, container ship [kg*km]				10.4
transport, freight, train [kg*km]			94.49	5.5
transport, freight, lorry [kg*km]			63.00	5.7
Disposal / Recycling				55.0
Waste treatment PCM				44.4
Waste treatment HDPE				10.5
Waste treatment Metal				
Total				323.5

: LCIA for PCM 58. GLO: Global, RER: Rest of Europe, RoW: Rest of World

Material		HDPE capsule		Metal capsule		Origin	
		best case [g CO2 eq]	worst case [g CO2 eq]	best case [g CO2 eq]	worst case [g CO2 eq]	best case	worst case
PCM & additives		222.69	222.69	23.35	23.35	CN & GLO	
HDPE production & blow moulding		23.06	79.22	–	–	CH & RER	RoW
Metal production & deep drawing		–	–	24.49	25.04	RER	RoW
Electricity & transport		22.75	34.15	2.71	4.31	–	–
Electricity [MJ/1000 Capsules]		0.98	9.10	0.10	0.95	CH	CN
Transport [kg*km]	Vessel	10.46	13.74	1.10	1.84	Global	
	Train	5.58	5.58	0.75	0.75	DE	
	Lorry	5.73	5.73	0.77	0.77	RER	
Disposal & recycling		55.01	55.01	4.68	4.68	–	–
Waste treatment	*PCM*	44.45	44.45	4.66	4.66	CH	
	HDPE	10.56	10.56	–	–	CH	
	Metal	–	–	0.02	0.02	CH	

Total	323.51	391.08	55.23	57.38	–	–

3 Results

The DHW application of PCMs include specific power requirements, which influence the capsule design (see Figure 2) [8]. The material composition of the resulting PCM, additives and shell (HDPE or steel) and their embodied CO2-equivalent have been balanced against the storage capacity increase and savings in grid electricity. This has been carried out for the DACH region, assuming a refurbishment cycle of 50 years with 10’000 cycles, meaning 200 cycles per annum on average. Note that the system could be designed for even more than one charging-discharging cycle per day, which would sum up to over 30’000 cycles and a shorter break-even period. However, more cycles per time have less likelihood to match with the local PV production, therefore not necessarily increasing the own-consumption in a linear fashion.

The following parameters have been calculated:

- Global warming potential (GWP) of PCM-enhanced DHW storages for HDPE and metal capsules as best- and worst-case scenario (*ecoinvent* vers. 3.7, method EF 2.0 midpoint)
- GWP relative to storage capacity (Fig. 4 left) and relative to lifetime thermal energy delivered (Fig. 4 right) for the three systems metal capsules, HDPE capsules and batteries. Data for batteries from [7], [13]
- CO2 payback time in number of cycles according to Swiss, German and Austrian electricity grid’s carbon intensity.

Depending on the national grid’s CO2 intensity, HDPE capsules break even after only 10% of the lifetime (after 1014 cycles) in the case of Switzerland, as shown for HDPE and metal for each country in Fig. 3. For Germany, the break-even happens after around 318 to 528 cycles (best case HDPE and worst case metal, respectively). For Austria, even the worst case has a return within a quarter of the proposed lifetime. In comparison for the encapsulation material, HDPE is performing better than metal.

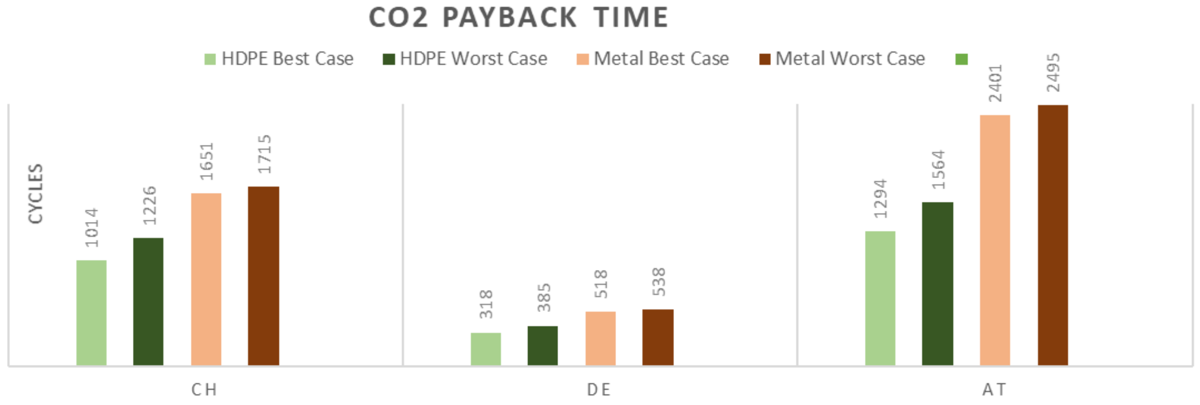

Figure 3: Comparison of CO2 payback time of HDPE and metal capsules for Switzerland, Germany and Austria.

Since the capsules designs have different dimensions, the specific performance per capsule is different for HDPE and metal, as listed in Table 4. The energy demand for producing the capsules is calculated from assumptions and for estimations mass production.

Table 4: Meta calculations and results

Parameter	Formula	HDPE	Metal	Unit
Heat storage capacity of one capsule per cycle	Q_{CAP}	23.29	2.446	$\left[\frac{kJ}{capsule * cycle}\right]$
Electrical energy needed to produce this heat	$\frac{Q_{CAP}}{COP_{HP}}$	8.973	0.941	$\left[\frac{kJ}{capsule * cycle}\right]$
GHG mitigation by using PV electricity instead of CH grid (PV has zero impact)	$\frac{Q_{CAP}}{COP_{HP}} * \frac{GWP_{grid\ CH}}{3600}$	0.319	0.033	$\left[\frac{g\ CO_{2\ eq}}{capsule\ * cycle}\right]$
GHG mitigation by using PV electricity instead of DE grid (PV has zero impact)	$\frac{Q_{CAP}}{COP_{HP}} * \frac{GWP_{grid\ DE}}{3600}$	1.017	0.107	$\left[\frac{g\ CO_{2\ eq}}{capsule\ * cycle}\right]$
GHG mitigation by using PV electricity instead of AT grid (PV has zero impact)	$\frac{Q_{CAP}}{COP_{HP}} * \frac{GWP_{grid\ AT}}{3600}$	0.250	0.026	$\left[\frac{g\ CO_{2\ eq}}{capsule\ * cycle}\right]$
GHG mitigation by using PV electricity instead of CH grid (PV has impact)	$\frac{Q_{CAP}}{COP_{HP}} * \frac{GWP_{Solar}}{3600}$	0.219	0.023	$\left[\frac{g\ CO_{2\ eq}}{capsule\ * cycle}\right]$
Heat storage capacity in Wh of one capsule per cycle	$Q_{CAP,\ kWh}$	6.48	0.68	$\left[\frac{Wh}{capsule * cycle}\right]$
Number of Capsules in 1 m^3 storage	–	8'629	77'696	–

As mentioned, Polysun has been used to simulate the system behavior of DHW and space heating with the buffer storage and the PCM storage for a single family house [4]. Since battery energy storage are more and more used nowdays together with PV systems, we added this setup for the direct comparison between the options for investment. As indicated in Fig. 4, PCM-enhanced DHW storage have a factor between 6 and 8 lower global warming potential (per storage capacity, and over factor 10 per lifetime energy delivered, respectively) compared to battery systems and are therefore an alternative and environmentally friendly solution with respect to decarbonization. Finally, without interfering too much with the confidential data of the PCM mixture, we provide a breakdown of the global warming potential for the capsules based on the component. This is overall influenced by geometry, fill factor and lastly by material. Here one can see the CO2 footprint from the metal in the capsule, even so the metal is easier to recycle. For the best case of HDPE, the hull material is fully recycled, which adds on the cost side, but massively improves the footprint. About 2/3 of the final impact are related directly to the PCM.

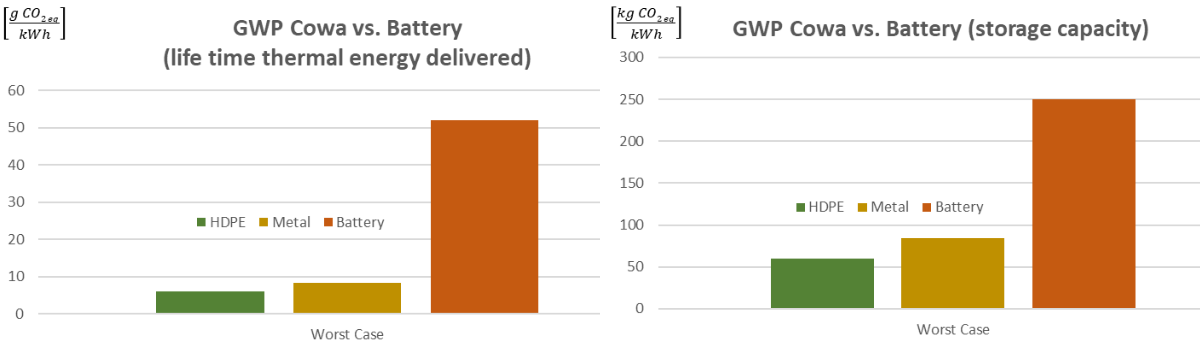

Figure 4: LCA comparison of HDPE and metal capsules with batteries. GWP relative to lifetime thermal energy delivered (left) and relative to storage capacity (right).

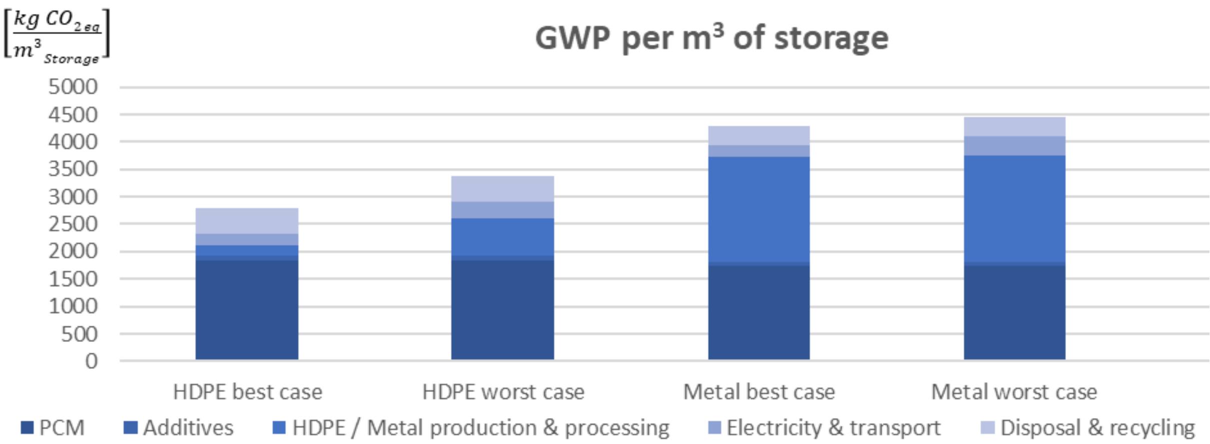

Figure 5: Global warming potential in kg $CO2_{eq}$ per cubic meter of storage.

4 Discussion

Reaching a net gain by introducing encapsulated PCM for DHW is a very promising result. Outperforming state-of-the-art battery storage for the same purpose by at least factor 6 is demonstrating that sectoral coupling can have tremendous benefits while being cost-efficient. Based on the results one wonders why metal capsules have been chosen in the first place, as the high impact could have been expected. This is due to the superior heat transfer performance as well as the simplicity of the manufacturing process. In the end, when judging by a sustainability perspective, there will be a trade-off between costs for adding PCM to the storage and gains in CO2 reduction. By putting a price tag on CO2, this Pareto-optimality can be shifted in one or the other direction.

5 Summary

Electricity provision for heat pumps to facilitate domestic hot water supply are an upcoming challenge to our energy system. To help consuming the locally produced electricity from PV systems on single family homes, adding more storage capacity is one of the decentralized solutions. This paper evaluated encapsulated phase change materials (PCM) for increasing the storage capacity of a hot water tank in comparison to adding conventional battery storage. From a sustainability perspective, this concept is only valid if the net CO2 emissions from the added PCM is lower than the footprint of the avoided grid electricity. For the DACH countries, this benefit and therefore the environmental feasibility has been proven. A substantial reduction of DHW-related CO2 emission can be achieved.

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