

Article

Techno-Economic Assessment of a Condenser-Side Phase Change Material Buffer Integrated with an Air-to-Water Heat Pump

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Abstract

Heat pumps are increasingly used for low-temperature heating applications. But their operation can create electricity demand peaks during periods of high thermal load. This paper presents a concept and calculation study for integrating phase change materials (PCMs) with air-to-water heat pump (AWHP) systems as a condenser-side thermal buffer for residential buildings. The analyzed retrofit-oriented storage unit is a 200 L tank containing 30% PCM by volume, corresponding to 60 L of paraffin PCM and 140 L of water. The sizing calculation gives 3.08 kWh of PCM thermal storage, 0.81 kWh of sensible storage in the remaining water over the 55–60 °C interval, and almost 3.89 kWh of total short-term thermal reserve for the PCM-plus-water tank. A 200 L water tank over the same 5 °C interval would store approximately 1.16 kWh. At the nominal 14 kW heat pump output, the PCM buffer corresponds to about 13.2 min of operation. At representative part load it corresponds to about 53 min at 25% load and 26 min at 50% load. The PCM sizing model predicts storage capacity, buffer time and possible cycling relevance, but it does not by itself predict a seasonal COP increase. Therefore, annual electricity and economic effects are evaluated only as COP-uplift sensitivity cases, including 0%, 3%, 4%, 5%, 8%, 15% and 28.6%. Given the assumptions in this study, the PCM add-on reaches positive net present value at approximately 11% COP uplift when the initial marginal investment and discounted year 10 replacement cost are considered. Approximately 14.1% is reached if the replacement cost is added upfront as a simplified lifecycle basis. The results indicate that the condenser-side PCM buffer may be technically useful for short-term thermal buffering and possible on-off cycle reduction, but its annual energy and economic benefit requires dynamic simulation or experimental validation. Moreover, peak-demand reduction, demand shifting and renewable electricity utilization are discussed as potential applications of the buffer concept.

Keywords: phase change materials; thermal energy storage; air-to-water heat pump; condenser-side buffer; on-off cycling; techno-economic assessment



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1. Introduction

Energy communities are expected to play an important role in the transition to low-carbon and decentralized energy systems. In these systems, building heating technologies may become relevant for coordinated operation. In this case a community-level flexibility assessment requires renewable generation profiles, several connected consumers, monitored demand profiles and control strategies. This perspective is used only as future application context. The quantitative analysis is restricted to a single residential building.

Air-to-water heat pumps are suitable for residential heating, but their seasonal performance depends strongly on outdoor air temperature, supply water temperature, compressor control and part-load operation. When the water-side temperature is increased, the condensing temperature generally increases, and the instantaneous COP may decrease. For this reason, adding a PCM storage unit cannot directly be assumed to increase seasonal COP. The potential benefit of PCM must be linked to a specific operational mechanism, like stabilizing water-side temperature, lengthening compressor cycles, reducing start-stop events or giving more favorable operating periods.

Phase-change materials have been studied for heat transfer enhancement and latent thermal energy storage [1,2]. The integration of PCMs with heat pump systems has been investigated in several configurations, including condenser-side storage, refrigerant-to-PCM heat exchangers, domestic hot water desuperheaters, building-integrated storage and water tank storage [3–17]. Lin et al. [13] studied a condensing heat storage unit and reported a storage capacity of 31.83 kWh and a COP improvement of approximately 4.01% for a three-stage PCM arrangement. The reviewed literature shows that PCM storage can be useful in heat pump systems. It can support thermal buffering and may improve operation in some cases. However, the COP improvement is not the same for all systems. It depends on the storage design, operating temperature, heat transfer conditions and control strategy. Therefore, in this study, the COP increase is treated as a sensitivity assumption, not as a direct result predicted by the PCM sizing calculation.

Literature still has a gap between experimental or numerical studies and simple retrofit-oriented decision frameworks. Many published studies focus on PCM material properties, heat transfer enhancement, or experimental charging and discharging behavior. These studies are usually carried out under specific operating conditions. However, fewer studies show how a small condenser-side PCM buffer can be evaluated at the building level in a simple and reproducible way. The present study addresses this gap by separating the storage capacity, part-load buffering effect, possible reduction in start-stop cycling, and economic performance under different COP-uplift assumptions. This gap is particularly relevant for already existing residential buildings. In this case, modification of the heat pump, condenser or building envelope is usually undesirable.

The present paper focuses on the use of PCM-based thermal storage as a condenser-side buffer between an AWHP and the building thermal demand. The proposed approach is designed for practical residential applications. It does not require changes to the refrigeration circuit of the heat pump. For this reason, the study should not be interpreted as a dynamic prediction of seasonal heat pump performance. Instead, it is a sizing and sensitivity analysis. The calculation clearly separates two aspects. First, the PCM storage model gives the stored energy, the contribution of the water volume, the buffer time and the estimated operating duration. Second, the seasonal COP improvement is treated only as an assumption. Based on this, the annual electricity reduction and the economic benefit are also scenario-dependent results, not direct outputs of the PCM storage model. The specific objective of the paper is to quantify the short-term storage capacity and operational relevance of a small 200 L condenser-side PCM buffer and to determine the COP uplift that would be required for this retrofit measure to become economically attractive.

The contribution of the study is threefold. First, it provides a reproducible calculation method for a compact 200 L condenser-side PCM buffer, including both PCM and water storage contributions. Second, it adds an analysis, based on equivalent full cycles, possible delayed compressor starts and part-load autonomy on a design day. Third, it replaces a single imposed COP value with a sensitivity-based techno-economic assessment, including the no-uplift case and the literature-aligned 4% COP-uplift case.

The new element of this study is not the PCM concept itself, nor the proposal of a new heat pump component. These topics are already well established in the literature. The novelty is instead at the framework level. The proposed framework combines several practical elements that are usually treated separately. These are: storage sizing, water versus PCM energy accounting, simplified operational-cycle estimates, COP-uplift sensitivity and marginal economic indicators. The framework includes the sizing of a small PCM storage tank, the comparison between water storage and PCM storage, a simplified estimate of operating cycles, a COP-uplift sensitivity analysis, and marginal economic indicators. These elements are applied to a representative 14 kW residential air-to-water heat pump system.

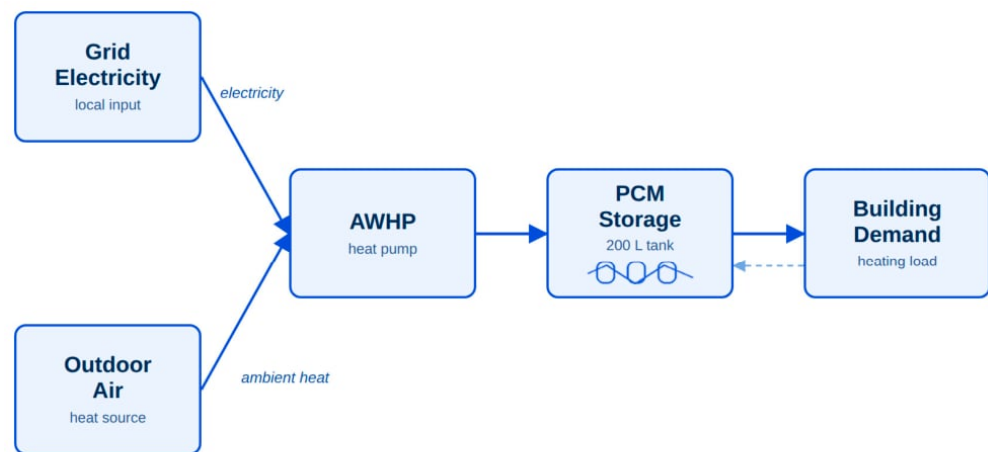
The selected configuration is deliberately smaller and simpler than many published PCM-assisted heat pump stores. For example, the ASHP-LTES system reported in [13] stored 31.83 kWh and released heat at an average power of 4.73 kW, while the present 200 L retrofit tank stores 3.08 kWh in the PCM and approximately 3.89 kWh when the remaining water contribution is included. This places the present unit in the category of short operational buffers rather than long thermal stores. The 13.2 min full-load PCM buffer is studied because of the simple design. The PCM is placed in replaceable tubes inside a standard water tank, without redesigning the heat pump or the building envelope. Its value is therefore associated with smoothing short demand spikes and reducing short cycling, not with seasonal storage.

The paper is structured as follows. First, the PCM-AWHP integration concept is presented and related to previous studies. Then, the calculation method is described, including the storage sizing equations and the economic indicators. The residential case study and the main assumptions for the reference AWHP are introduced next. The results section then discusses the storage capacity, operational estimates, economic results and sensitivity analyses. Finally, the main limitations and future research directions are summarized.

2. Phase Change Materials and Heat Pump Integration

In buildings, the electricity demand of a heat pump depends on the useful heat demand and on the coefficient of performance (COP). A higher COP reduces the electricity needed to deliver the same amount of useful heat. In the present configuration, the PCM buffer is not assumed to directly increase the thermodynamic efficiency of the heat pump. Its role is to act as a water-side thermal reserve, storing a limited amount of heat and releasing it later when the building requires heating. This may help the compressor operate for longer and more stable periods, with fewer start-stops and reduced operation. At the same time, the selected 55 °C PCM and the assumed 60 °C tank water temperature correspond to a relatively high condenser-side temperature for an AWHP, which may reduce the instantaneous COP. Therefore, any seasonal COP improvement is treated as a separate hypothesis and is evaluated through sensitivity analysis, rather than being considered a direct result of the PCM storage calculation.

During favorable operating periods, the heat pump can charge the PCM storage tank. Later, the stored heat can be discharged to the building, reducing the immediate need for compressor work on short intervals. The PCM tank therefore acts primarily as a condenser-side thermal buffer. The schematic representation of the AWHP coupled with a condenser PCM storage tank is illustrated in Figure 1. Three technical aspects are considered: the stored thermal energy, the equivalent buffer time and the potential operational effect on the compressor. A complete demonstration of demand shifting at the energy-community level would require hourly load profiles, dynamic tariffs, photovoltaic generation profiles and a control strategy, which are outside the scope of the present paper.



Charging during favourable electricity periods; discharging during thermal-demand peaks.

Figure 1. Schematic representation of the AWHP coupled with a condenser PCM storage tank.

The quantitative study in this paper is limited to building-level storage sizing, buffer duration and techno-economic sensitivity. The possible contribution to energy community flexibility is discussed only as a future application perspective. It is not presented as a demonstrated result of the present annual balance model. For the same reason, peak demand reduction, demand shifting and increased renewable energy utilization are not reported as quantified results. They are considered potential operational benefits. Their quantification would require hourly demand profiles, time-dependent electricity prices, photovoltaic generation data and a validated control strategy, as previously mentioned.

3. Methodology

3.1. Calculation Procedure and PCM Storage Sizing

The methodology is organized as a calculation procedure applicable to a residential thermal consumer. The quantitative analysis is performed for a single building, while the relevance for energy communities is discussed as a possible aggregation of similar buildings. The detailed building description is presented separately in Section 4.

Two system configurations are evaluated: an air-to-water heat pump (AWHP) and an AWHP coupled with a condenser PCM storage tank. The boundary of the analysis includes building heating and cooling energy use, heat pump electricity consumption, PCM storage sizing, buffer time estimation and investment evaluation. The analyzed configurations and main assumptions are presented in Table 1. The PCM storage unit is evaluated only for heating operation, because it is installed on the condenser side and uses a paraffin PCM with a melting temperature of approximately 55 °C. This temperature level is compatible with hot water production and space heating, but not with chilled water storage for cooling. Therefore, the cooling demand is included in the annual energy balance of the heat pump system, but the PCM unit is not assumed to reduce cooling electricity consumption. A cooling PCM configuration would require a different melting temperature range and a different integration solution.

Table 1. Analyzed system configurations and main assumptions.

Parameter	AWHP Nominal Case	AWHP + PCM Modeled Effective Case
Design heating load	14 kW	14 kW
Design cooling load	9.8 kW	9.8 kW
Selected heat pump nominal capacity	14 kW	14 kW
Nominal heating COP	3.5	3.5
Modeled effective COP range for sensitivity analysis	-	3.50–4.50, corresponding to 0–28.6% uplift; COP = 3.64 is included as a literature-justified 4% uplift case
Energy efficiency ratio (EER) for cooling	3.6	3.6
Thermal storage	Not included	200 L tank with PCM tubes on the condenser side
PCM volume fraction	-	30% of tank volume
Purpose in the analysis	Efficient heat generation	Condenser-side thermal buffering, temperature stabilization and possible reduction in on-off cycling
Heat-pump representation	Generic reference 14 kW AWHP; COP = 3.5 and EER = 3.6 used as annual-balance inputs	Same generic 14 kW AWHP; PCM effect analyzed only through storage sizing and COP-uplift sensitivity

The design heating and cooling loads are calculated from the useful floor area and from the specific thermal load values adopted for the case study. A specific heating load of 100 W/m² and a specific cooling load of 70 W/m² are taken from the building energy performance documentation used for the case study dwelling. These values are therefore treated as case study inputs rather than general design recommendations. The selected heat pump nominal capacity is 14 kW because the design heating load is 14 kW, while the design cooling load is 9.8 kW. Thus, the 14 kW value in Table 1 refers to the selected equipment size, whereas 9.8 kW represents the calculated cooling requirement of the analyzed area. The factors of 1000 in Equations (1) and (2) explicitly convert W into kW, because q_h and q_c are expressed in W/m².

$$P_h = \frac{A \cdot q_h}{1000} \quad (1)$$

$$P_c = \frac{A \cdot q_c}{1000} \quad (2)$$

$$E_{el,h} = \frac{Q_{h,ann}}{COP} \quad (3)$$

$$E_{el,c} = \frac{Q_{c,ann}}{EER} \quad (4)$$

where P_h and P_c are the design heating and cooling loads [kW], A is the analyzed floor area [m²], q_h and q_c are the specific heating and cooling loads [W/m²], $E_{el,h}$ and $E_{el,c}$ are the annual electricity consumptions for heating and cooling [kWh/year], $Q_{h,ann}$ and $Q_{c,ann}$ are the annual useful heating and cooling demands [kWh/year], COP is the heating coefficient of performance [-], and EER is the energy efficiency ratio used for cooling [-]. The factor 1000 in Equations (1) and (2) converts W to kW.

The PCM storage unit is sized as a 200 L tank with cylindrical tubes filled with PCM. The selected configuration uses a 30% PCM volume fraction. This fraction is selected as a compromise between thermal storage capacity and the available water volume in the

tank. The PCM tube volume is calculated from the cylinder geometry. The number of tubes is obtained from the ratio between the selected PCM volume and the volume of one tube. The stored thermal energy includes the latent heat of fusion and the sensible heat corresponding to the temperature difference between the tank water temperature and the PCM melting temperature. The buffer time is calculated by comparing the total stored energy with the nominal heat pump thermal power, according to Equations (5)–(8).

$$V_{tube} = \pi \left(\frac{D_{tube}}{2} \right)^2 L_{tube} \quad (5)$$

$$N_{tube} = \frac{V_{PCM}}{V_{tube}} \quad (6)$$

$$Q_{PCM} = \frac{\rho_{PCM} V_{PCM} [h_f + c_{PCM} (T_w - T_m)]}{3600} \quad (7)$$

$$t_{buffer} = \frac{Q_{PCM}}{P_{HP}} \cdot 60 \quad (8)$$

where V_{tube} is the volume of one cylindrical PCM tube [m^3], D_{tube} and L_{tube} are the tube diameter and length [m], N_{tube} is the number of PCM tubes [-], V_{PCM} is the total PCM volume introduced into the tank [m^3], Q_{PCM} is the total stored thermal energy [kWh], ρ_{PCM} is the PCM density [kg/m^3], h_f is the latent heat of fusion [kJ/kg], c_{PCM} is the PCM specific heat used for the sensible storage term [kJ/kgK], T_w is the tank water temperature [$^{\circ}C$], T_m is the PCM melting temperature [$^{\circ}C$], t_{buffer} is the equivalent buffer time [min], and P_{HP} is the nominal thermal output of the heat pump [kW]. The denominator 3600 in Equation (7) converts kJ into kWh. The symbol Q_{PCM} is used consistently for the total stored thermal energy. The PCM storage sizing inputs are listed in Table 2.

Table 2. PCM storage sizing inputs used in the methodology.

Input Parameter	Value
Tank volume	200 L
PCM volume fraction selected for the case study	30%
PCM volume	60 L
Water volume remaining in the tank	140 L
Tube diameter	0.06 m
Tube length	0.5 m
PCM density	880 kg/m^3
Latent heat of fusion	200 kJ/kg
PCM specific heat used for the sensible term	2 kJ/kgK
PCM melting temperature	55 C
Assumed tank water temperature	60 C

3.2. Technical Flexibility Indicators and Economic Assessment

The technical study uses indicators that describe both energy efficiency and short-term buffering potential. Energy efficiency is represented by AWHP electricity consumption and COP, while buffering potential is represented by stored thermal energy, buffer time and equivalent shifted electricity per complete storage charge. The baseline COP of 3.5 and the cooling EER of 3.6 are adopted from the nominal performance data of the selected 14 kW AWHP used in the case study. The effective COP improvement produced by a

condenser-side PCM buffer is uncertain and depends on the detailed heat-exchanger design, water temperature, control strategy and cycling behavior. Literature reports modest COP improvements of about 3.1% for an ASHP with integrated PCM storage used as a desuperheater, with potential values up to 9.4% under improved low feed water conditions [11]. Review studies also show that thermal energy storage can improve heat-pump operation, but the reported performance strongly depends on configuration and control strategy [12]. Lin et al. reported a COP improvement of about 4.01% for an ASHP system with latent heat thermal energy storage [13], while higher values, around 22% in heating mode, have been reported for different hybrid PCM-air-conditioning layouts and climate assumptions [14]. Therefore, the present paper does not assert a fixed COP increase. Instead, COP-uplift values of 3%, 5%, 8%, 15% and 28.6% are analyzed. The 28.6% case corresponds to an effective COP of approximately 4.5 and is treated only as a high theoretical sensitivity case, not as a validated operating value.

The use of a constant nominal COP in the annual balance is a simplification adopted for transparency and reproducibility. In real operation, AHP performance varies with outdoor air temperature, supply water temperature, part-load ratio, defrosting events and the control sequence of the storage tank. Therefore, the annual electricity values are scenario-based estimates and not predictions of seasonal performance obtained from a dynamic heat-pump model.

$$C_{gas} = \frac{Q_{h,ann}}{\eta_b \cdot 1000} \cdot p_{gas} \quad (9)$$

$$C_{el} = \frac{E_{el}}{1000} \cdot p_{el} \quad (10)$$

$$S = C_{ref} - C_{option} \quad (11)$$

$$SPB = \frac{I_0}{S} \quad (12)$$

$$NPV = -I_0 + \sum_{t=1}^n \frac{S_t - C_{rep,t}}{(1+r)^t} \quad (13)$$

$$DPB = \min \left\{ N : \sum_{t=1}^N \frac{S_t - C_{rep,t}}{(1+r)^t} \geq I_0 \right\} \quad (14)$$

$$0 = -I_0 + \sum_{t=1}^n \frac{S_t - C_{rep,t}}{(1+IRR)^t} \quad (15)$$

where C_{gas} is the annual heating cost of the reference gas boiler [EUR/year], η_b is the boiler efficiency [-], p_{gas} is the natural gas price [EUR/MWh], C_{el} is the annual electricity cost [EUR/year], E_{el} is the annual electricity consumption [kWh/year], p_{el} is the electricity price [EUR/MWh], C_{ref} is the annual operating cost of the reference system [EUR/year], C_{option} is the annual operating cost of the analyzed option [EUR/year], S is the annual saving [EUR/year], SPB is the simple payback period [years], I_0 is the initial investment cost [EUR], NPV is the net present value [EUR], S_t is the saving in year t [EUR/year], r is the discount rate [-], n is the analysis period [years], $C_{rep,t}$ is the replacement cost in year t [EUR], DPB is the discounted payback period [years], N is the first year in which the cumulative discounted savings recover the investment [-], and IRR is the internal rate of return [%]. Since $Q_{h,ann}$, $Q_{c,ann}$ and E_{el} are expressed in kWh/year, the factor 1000 in Equations (9) and (10) converts kWh into MWh, consistent with energy prices expressed in EUR/MWh. The economic assumptions included in the calculation framework are presented in Table 3.

Table 3. Economic assumptions included in the calculation framework.

Economic Parameter	Air-to-Water Heat Pump	Air-to-Water Heat Pump + PCM
Initial investment considered	6120 EUR	6976 EUR
Capital repair/PCM replacement	-	356 EUR in year 10
Total cost considered over the analysis period	6120 EUR	7333 EUR
Analysis period	20 years	20 years
Discount rate	12%	12%
Electricity price used in the assessment	200 EUR/MWh	200 EUR/MWh
Natural gas price used for reference comparison	80 EUR/MWh	80 EUR/MWh

4. The Case Study

Residential Building and Useful Energy Demand

The case study is focused on a residential building used as a representative thermal consumer. The analyzed dwelling is in Țițești, Argeș County, Romania, corresponding to climatic zone II. It has a total built area of approximately 172 m². For the present study, only the area requiring heating and cooling is included in the calculations, resulting in an analyzed floor area of 140 m². The existing thermal solution consists of a gas condensing boiler used for space heating and domestic hot water and split air-conditioning units used for cooling. The paper compares two new configurations: an AWHP and the same AWHP coupled with a PCM thermal storage unit. The annual useful demand values used in the technical assessment are 23,000 kWh/year for heating and 8000 kWh/year for cooling. These values define the energy service that must be covered by both analyzed heat pump configurations. All input data for the calculations are presented in Table 4.

Table 4. Case study data used for the calculations.

Parameter	Value	Comment
Building type	Single-family residential building	Ground floor + one upper floor
Location	Țițești, Argeș County, Romania	Climatic zone II
Total built area	172 m ²	Building-level description
Heated and cooled area used in the calculation	140 m ²	Area included in the technical model
Specific heating load	100 W/m ²	Building-specific energy performance documentation
Specific cooling load	70 W/m ²	Building-specific energy performance documentation
Design heating load	14 kW	Sizing condition for the heat pump
Design cooling load	9.8 kW	Cooling requirement of the analyzed area
Annual useful heating demand	23,000 kWh/year	Useful thermal demand supplied to the building
Annual useful cooling demand	8000 kWh/year	Useful cooling demand supplied to the building
Reference AWHP used in calculation	Generic 14 kW AWHP	Representative unit; no manufacturer-specific control map used

The first analyzed configuration consists of a 14 kW AWHP selected to cover the calculated design heating load. Although the calculated design cooling load is 9.8 kW, the same 14 kW selected unit is considered for cooling because the equipment sizing is governed by the heating requirement. For the annual calculation, the AWHP is characterized by a baseline heating COP of 3.5 and a cooling EER of 3.6, in accordance with the nominal performance data used for the selected equipment. The second configuration keeps the same 14 kW AWHP and adds a PCM thermal storage unit on the condenser side. Three filling ratios are examined, 20%, 30% and 40% of the tank volume. The 30% configuration is selected for the detailed comparison because it provides an intermediate storage capacity while preserving a sufficient water volume in the tank.

For reproducibility, the heat-pump unit is represented as a generic commercially available 14 kW air-to-water heat pump used as a reference calculation unit. The model inputs retained for the annual balance are the nominal heating capacity of 14 kW, a nominal heating COP of 3.5, and a cooling EER of 3.6. No proprietary manufacturer control map is used. The case study should be interpreted as a representative AWHP calculation rather than a manufacturer performance simulation.

The effective COP value used for the PCM configuration is therefore not presented as a manufacturer-rated or experimentally validated performance value. It is treated as a variable sensitivity parameter that shows possible benefits of smoother operation and reduced on-off cycling. These are balanced against the possible COP penalty associated with maintaining condenser water close to 60 °C. Experimental validation or dynamic simulation would be required before assigning a definitive seasonal COP to the PCM configuration.

5. Results and Discussions

5.1. Annual Electricity Consumption

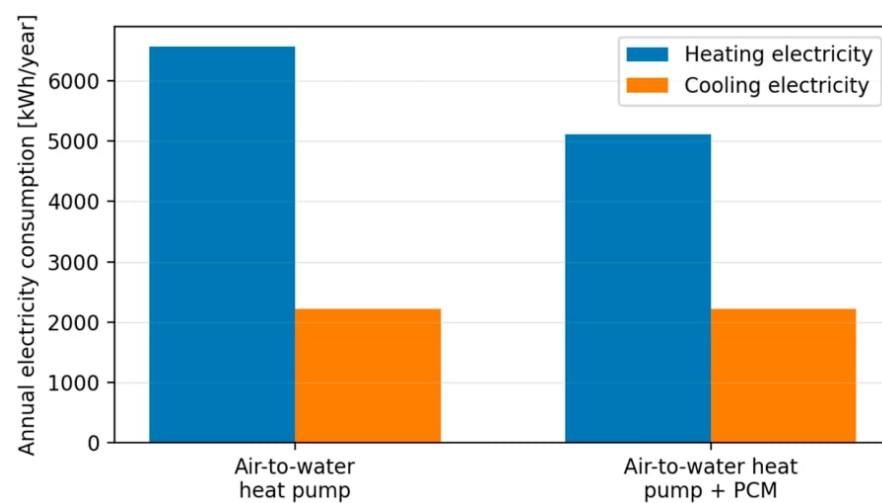
The annual electricity consumption is calculated by applying the useful heating and cooling demand values to the performance indicators of each configuration. For the heat pump without PCM, the useful heating demand of 23,000 kWh/year and the nominal COP of 3.5 result in an annual heating electricity consumption of 6571 kWh/year. The cooling electricity consumption is 2222 kWh/year, considering the useful cooling demand of 8000 kWh/year and an EER of 3.6. For the PCM configuration, the cooling demand and cooling efficiency remain unchanged. The PCM storage capacity calculation does not predict the annual heating electricity reduction. It establishes only the short-term storage capacity and buffer time. Annual savings can only be calculated after assuming an effective COP uplift, which is why they are treated as sensitivity cases.

For illustration, the high sensitivity case corresponding to a 28.6% COP uplift uses an effective COP of approximately 4.5. In this case, the annual heating electricity consumption decreases to 5111 kWh/year, because 23,000 kWh/year divided by 4.5 gives 5111 kWh/year. The resulting reduction of 1460 kWh/year is therefore mathematically imposed by the assumed COP uplift and is not a direct output of the PCM storage model. This distinction is central to the interpretation of Table 5 and of the economic results.

The values in Table 5 should therefore be interpreted as a high COP-uplift sensitivity case. The PCM model itself supports the storage and buffering results reported in Section 5.2; it does not independently demonstrate that the seasonal COP increases from 3.5 to 4.5. The corresponding electricity consumption is illustrated in Figure 2.

Table 5. Annual electricity consumption for the baseline AWHP and the high COP-uplift sensitivity case.

Indicator	Air-to-Water Heat Pump	Air-to-Water Heat Pump + PCM (28.6% COP-Uplift Sensitivity Case)	Variation
Heating electricity consumption	6571 kWh/year	5111 kWh/year	−1460 kWh/year (−22.2%)
Cooling electricity consumption	2222 kWh/year	2222 kWh/year	0 kWh/year
Total annual electricity consumption	8794 kWh/year	7333 kWh/year	−1460 kWh/year (−16.6%)
Nominal electrical input for heating	4.00 kW	3.11 kW	−0.89 kW

**Figure 2.** Annual electricity consumption of the two analyzed heat pump configurations.

5.2. PCM Storage Capacity and Buffer Operation

The role of the PCM is evaluated through the amount of heat stored in the tank and the equivalent buffer time at nominal heat pump output. The stored thermal energy reported for the PCM corresponds to the sum of latent heat and the sensible heat stored in the PCM between the melting temperature and the assumed tank water temperature. Each PCM tube has a diameter of 0.06 m and a length of 0.5 m, corresponding to an approximate PCM volume of 1.413 L per tube. For the selected 30% filling ratio, 43 tubes are required to reach a PCM volume of approximately 60 L. Using Equations (7) and (8), the selected configuration stores approximately 3.08 kWh in the PCM and provides a PCM-only buffer period of 13.2 min at 14 kW. The remaining 140 L of water also stores sensible energy over the same temperature interval and is reported separately.

The selected 55 °C PCM melting temperature and 60 °C tank water temperature leave only a 5 °C temperature difference for heat transfer. This choice is conservative from the perspective of AWHP efficiency because increasing the tank water temperature to 65 °C would increase the thermal driving temperature difference but would also increase the required condensing temperature and could reduce COP. The present lumped calculation does not compute heat transfer coefficients and therefore does not predict a numerical condensing temperature reduction. No specific °C decrease in condensing temperature is claimed. The possible COP benefit is instead linked to fewer start-stop events and more stable operating periods, and this remains a hypothesis requiring dynamic simulation or

experimental validation. The present calculation does not solve a transient heat-transfer model for the PCM tubes. Charging and discharging times are therefore estimated from energy-to-power ratios. Heat transfer coefficients, internal temperature gradients, tank stratification and standing thermal losses are left for future dynamic or experimental work. This limitation is stated explicitly so that the calculated buffer time is not interpreted as a validated charging/discharging rate. The effect of the PCM filling ratio on storage capacity and buffer time is summarized in Table 6.

Table 6. PCM filling ratio sensitivity for the 200 L storage tank.

PCM Filling Ratio	PCM Volume	Remaining Water Volume	Number of Tubes	Stored Thermal Energy (Latent + Sensible)	Buffer Period
20%	40 L	160 L	29	2.05 kWh	8.8 min
30%	60 L	140 L	43	3.08 kWh	13.2 min
40%	80 L	120 L	57	4.11 kWh	17.6 min

The 20% case maintains a larger water volume but provides limited buffer capacity. The 40% case increases the stored heat and buffer period, but it reduces the water volume to 120 L, which can be restrictive for residential use. The 30% case is therefore used as a balanced scenario for the analyzed building. It combines 3.08 kWh of stored thermal energy with 140 L of remaining water volume in the tank. The selected PCM configuration is summarized in Table 7.

Table 7. Selected PCM storage configuration used in the comparison.

Indicator	Value
Storage tank volume	200 L
Selected PCM filling ratio	30%
PCM volume	60 L
Remaining water volume	140 L
PCM tube diameter	0.06 m
PCM tube length	0.5 m
PCM volume per tube	1.413 L
Number of PCM tubes	43
Stored thermal energy, latent + sensible [kWh]	3.08
Buffer time at 14 kW thermal output	13.2 min
Equivalent electricity shifted per full storage charge [kWh]	0.68, only for the high COP = 4.5 sensitivity scenario

The 30% ratio is therefore not presented as a mathematical optimum over a continuous design space. Three ratios were investigated in this paper. This case was selected as the most balanced one. Additional water-storage and first-order thermal estimates are summarized in Table 8.

The table shows that the PCM addition primarily increases short-term thermal reserve. The annual thermal throughput depends on how many complete charge/discharge events the control strategy actually uses during the heating season. It is therefore reported as an operating estimate, not as a direct annual electricity saving.

Table 8. Additional water-storage and first-order transient estimates for the 200 L PCM tank.

Question Addressed	Assumption	Result	Comment
Sensible energy in remaining water	140 L water, 55–60 °C, cp = 4.18 kJ/kgK	0.81 kWhth	This is additional to the 3.08 kWh stored in the PCM
Water-only reference tank	200 L water, 55–60 °C	1.16 kWhth	Reference storage if the same tank contained only water
Total short-term reserve in PCM-plus-water tank	3.08 kWh PCM + 0.81 kWh water	3.89 kWhth	About 3.35 times the 200 L water-only reserve over the same interval
Additional reserve vs. water-only tank	3.89–1.16 kWh	2.73 kWhth	Represents the additional storage contribution obtained by adding PCM tubes
Annual PCM thermal throughput	180–360 equivalent full cycles per heating season	554–1109 kWhth/year	Thermal energy buffered, not electricity saved
Complete PCM melting time	Average net charging power of 1.5/3/5/7 kW	123/62/37/26 min	First-order estimate based on 3.08 kWh; not a heat-transfer simulation
Complete PCM solidification time	Building load of 3.5/7/10.5/14 kW	53/26/18/13 min	Equivalent discharge time under part-load to full-load conditions
Condensing-temperature change	Static water-side storage sizing	Not predicted	The model does not calculate a °C reduction in condensing temperature

5.3. Operational Buffering and Simplified Transient Estimate

The results show that the PCM tank can modify the operating logic of the heat pump by adding limited short-term thermal storage between heat generation and building demand. In the simple heat pump configuration, the compressor must operate whenever the building requires heat and no other thermal reserve is available. In the PCM configuration, part of the heat can be produced earlier and stored in the tank, then released when building demand appears. The simplified transient interpretation is based on equivalent full cycles. One complete PCM charge/discharge event corresponds to 3.08 kWhth stored and later released by the PCM, while the total PCM plus water reserve is approximately 3.89 kWhth over the 55–60 °C interval. The seasonal operating-count estimate is summarized in Table 9, while the part-load autonomy is presented in Table 10.

Under these assumptions, the PCM buffer does not provide seasonal storage and it is not large enough to cover several hours of peak heating demand. Its role is instead to delay or avoid short compressor starts and to smooth short demand spikes. Complete solidification time is load-dependent: about 53 min at 3.5 kW, 26 min at 7 kW, 18 min at 10.5 kW and 13 min at 14 kW. Complete melting time is charging-power-dependent: about 123 min at 1.5 kW net charging power, 62 min at 3 kW, 37 min at 5 kW and 26 min at 7 kW. These values are first-order estimates and do not replace a transient heat transfer model.

The technical results also highlight the limits of this concept. The PCM unit does not replace proper heat pump sizing, and it does not provide seasonal storage. Moreover, without hourly load profiles, time-of-use tariffs, photovoltaic generation data and a dispatch strategy, the euro value of flexibility cannot be quantified. Thus, the proposed configuration should be viewed as a building-level condenser-side buffer with possible future relevance for residential energy communities, not as a demonstrated energy community flexibility asset. So, any reference to flexibility in this manuscript is limited to short-term buffering potential as stored heat, possible delayed compressor starts and part-load auton-

omy. The paper does not quantify demand shifting in euros, peak load reduction at the community level, or PV self-consumption gains, because these require hourly profiles and a control strategy.

Table 9. Simplified seasonal operating-count estimate for the 3.08 kWh PCM buffer.

Assumption	Equivalent Full Cycles per Heating Season	Seasonal Heat Buffered [kWhth/year]	Potential Delayed/Avoided Compressor Starts
1 full charge/discharge per heating day over 180 days	180	554	up to 180 events/year
2 full charge/discharge events per heating day over 180 days	360	1109	up to 360 events/year
Interpretation	First-order estimate	No measured hourly operation	Actual reduction depends on control logic and thermostat deadband

Table 10. Match between 3.08 kWh PCM capacity and representative part-load heating demand.

Operating Point	Building Heat Demand [kW]	Autonomy of 3.08 kWh Buffer [Min]	Interpretation
25% of design load	3.5	52.8	Relevant for low-load hours and cycling reduction
50% of design load	7.0	26.4	Short interval buffering at moderate load
75% of design load	10.5	17.6	Limited but useful delay of compressor operation
100% of design load	14.0	13.2	Full-load buffer value reported in storage sizing

5.4. Economic Results

The annual operating costs are presented in Table 11. For the existing system, the heating cost is calculated using the annual useful heating demand, the gas boiler efficiency of 90% and the natural gas price of 80 EUR/MWh. The cooling cost of the existing system is calculated using the annual cooling demand of 8000 kWh/year, an EER of 2 for the existing air-conditioning units and an electricity price of 200 EUR/MWh. For the AWHP, the total annual operating cost is 1759 EUR/year, corresponding to a saving of 1086 EUR/year compared with the existing system.

Table 11. Annual operating cost comparison.

Configuration	Heating Cost [EUR/Year]	Cooling Cost [EUR/Year]	Total Cost [EUR/Year]	Annual Saving vs. Existing [EUR/Year]
Existing system	2044	800	2844	-
Air-to-water heat pump	1314	444	1759	1086
Air-to-water heat pump + PCM	1022	444	1467	1378

In the high 28.6% COP-uplift sensitivity case, the annual operating cost of the AWHP + PCM configuration decreases to 1467 EUR/year. This corresponds to an additional annual saving of approximately 292 EUR/year compared with the heat pump

alone. This saving is not predicted directly by the PCM storage model. It is the consequence of the effective COP assumed in this sensitivity case.

The decrease in heating electricity consumption has a direct impact on operating cost only when a COP uplift is assumed. The storage model supports the buffer capacity result. The economic benefit depends on the real seasonal performance change produced by the PCM buffer in operation. For this reason, the marginal economic indicators are interpreted together with the COP-uplift sensitivity analysis. The annual operating costs are also compared in Figure 3.

The investment and economic indicators are summarized in Table 12 for the high COP-uplift sensitivity case, corresponding to an effective COP of approximately 4.5. The table separates the initial investment from the lifecycle replacement cost. The AWHP configuration requires an initial investment of 6120 EUR. The AWHP + PCM configuration requires an initial investment of 6976 EUR and includes an additional 356 EUR PCM replacement cost in year 10, leading to a lifecycle cost basis of 7333 EUR. The economic indicators considered are the simple payback period (SPB), the discounted payback period (DPB), the net present value (NPV) and the internal rate of return (IRR). Marginal PCM add-on values are reported separately in Table 13 on both initial-investment and lifecycle bases.

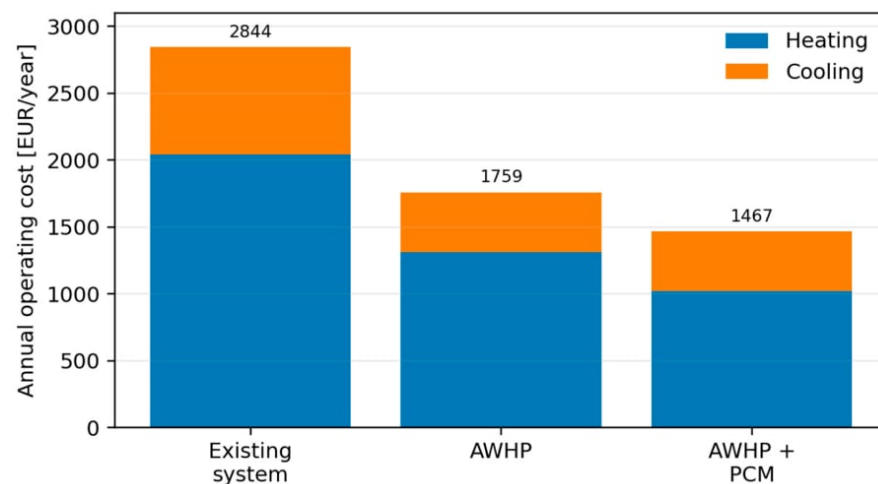


Figure 3. Annual operating cost comparison for the reference system and the two heat pump configurations.

Table 12. Investment components and economic indicators of the analyzed heat pump configurations.

Configuration	Initial Investment [EUR]	Lifecycle Replacement Cost [EUR]	Total Lifecycle Cost Basis [EUR]	SPB [Years]	DPB [Years]	NPV [EUR]	IRR [%]
Air-to-water heat pump	6120	-	6120	5.6	10.0	1777	17
AWHP + PCM, 28.6% uplift case	6976	356 in year 10	7333	5.3	9.0	2642	18

In the 28.6% COP-uplift sensitivity case, the economic result of PCM integration is positive. The marginal initial investment of the PCM add-on is 856 EUR, calculated as 6976 EUR minus 6120 EUR. When the lifecycle PCM replacement cost is also included, the marginal lifecycle cost basis is 1212 EUR. The additional annual saving is approximately 292 EUR/year compared with the heat pump alone. On the initial-investment basis, the marginal SPB is approximately 2.9 years and the marginal IRR is approximately 33.2%,

considering the 356 EUR replacement in year 10. On the simplified lifecycle-cost basis, the marginal SPB is approximately 4.2 years.

Table 13. Marginal economic assessment of the PCM add-on.

Basis	$\Delta I0$ [EUR]	Replacement	ΔS [EUR/y]	SPBadd [y]	IRRadd [%]	NPVadd [EUR]
Initial-investment basis	856	356 EUR in year 10	292	2.9	33.2	1213
Lifecycle-cost basis	1212	856 + 356 EUR	292	4.2	-	971

The sensitivity analysis in Table 14 shows that the economic attractiveness of the PCM add-on is strongly dependent on the effective COP uplift. The zero-uplift row at COP = 3.5 represents the true no-improvement reference. The 4% uplift row, corresponding to COP = 3.64, was added as a literature-aligned value close to the experimental COP improvement reported for ASHP-LTES systems. Under the assumptions used in this study, the incremental PCM add-on reaches positive NPV at approximately 11.0% COP uplift when the 856 EUR initial marginal investment and the discounted year 10 replacement cost are considered. If the replacement cost is added upfront as a simplified lifecycle-cost basis, the break-even uplift is approximately 14.1%. The 28.6% uplift case is therefore retained only as a high sensitivity case, not as a validated central performance assumption.

Table 14. Incremental PCM economics for assumed COP-uplift scenarios.

COP Uplift	COPeff	Eh [kWh/y]	ΔS [EUR/y]	SPBadd [y]	NPVadd Init [EUR]	NPVadd Life [EUR]
0%	3.50	6571	0	-	−971	−1212
3.0%	3.60	6380	38	22.4	−685	−926
4.0%	3.64	6319	51	16.9	−593	−834
5.0%	3.68	6259	63	13.7	−503	−745
8.0%	3.78	6085	97	8.8	−243	−485
15.0%	4.02	5714	171	5.0	310	68
28.6%	4.50	5110	292	2.9	1213	971

Savings are noticed only when a seasonal effective COP uplift is assumed. They are not attributed directly to the 3.08 kWh storage capacity. The uncertainty of this assumption is addressed through the COP-uplift sensitivity table, break-even thresholds, marginal payback and marginal NPV indicators. The effect of electricity price on the additional PCM benefit is summarized in Table 15.

Table 15. Sensitivity of the additional PCM benefit to the electricity price.

Electricity Price [EUR/MWh]	Additional Annual Saving from PCM [EUR/Year]	Simple Payback of PCM Addition [Years]
150	219	5.5
200	292	4.2
250	365	3.3

The base case uses fixed energy prices. Dynamic electricity tariffs, photovoltaic self-consumption and peak tariffs are not included in this calculation. Therefore, no real

EUR/kWh flexibility value is reported. This limitation is stated explicitly; community scheduling is treated as future work not as a demonstrated result of the present study.

5.5. General Discussions

The results show that PCM thermal storage can act as a short-term condenser-side buffer for an air-to-water heat pump. In a conventional heat pump configuration, electricity consumption follows the direct thermal demand of the building. The PCM configuration introduces a limited thermal reserve between heat generation and demand. This can support smoother operation and may reduce start-stop cycles, but the present annual-balance model does not quantify peak shaving or demand shifting under time-dependent tariffs.

The results also show that the PCM mainly acts as an operational buffer in this configuration. It should not be presented as a fully demonstrated energy-flexibility solution. The PCM is placed in tubes inside a water storage tank. This makes the system easier to install in existing residential buildings. It also makes maintenance and future replacement of the PCM modules simpler. This solution is therefore more practical than integrating PCM directly into the condenser or into the building envelope.

The real performance benefit depends on the operating conditions. Reduced cycling and temperature stabilization may improve the effective operation of the heat pump. However, the relatively high condenser-side temperature may also reduce the instantaneous COP.

Therefore, the quantitative results of this study are limited to storage capacity, seasonal thermal throughput, part-load autonomy and economic sensitivity. A full dynamic proof of flexibility value, peak-load reduction or renewable-electricity utilization is outside the scope of this study. As a simple aggregation thought experiment, if 50 similar dwellings used the same 3.08 kWh PCM buffer, the aggregate short-term thermal reserve would be approximately 154 kWhth. At an effective COP of 3.64–4.50, this corresponds to roughly 34–42 kWh of heat pump electricity that could be delayed during one complete coordinated discharge event. This is not a simulated flexibility value, and it is not converted into EUR/kWh in the present paper. It only shows why small buffers may become relevant when many similar residential systems are coordinated.

From a practical perspective, the proposed PCM buffer should be seen as a small operational support component. It is not intended for large-scale energy storage. Its main value is its simplicity. It can be integrated into existing water-side installations. It can also be replaced more easily than PCM solutions integrated directly into the heat pump or the building envelope. The calculated PCM storage capacity is 3.08 kWh. This value is limited. However, it can still be useful during short part-load periods, when compressor cycling may occur.

Therefore, the engineering significance of the solution is related to short-term buffering and retrofit feasibility. It should not be interpreted as a demonstrated seasonal performance improvement because this solution presents important limitations. The improvement of the heat pump performance is not experimentally measured; it is analyzed through COP-uplift sensitivity cases. The 60 °C tank-water temperature used in the sizing procedure is relatively high for an AWHP condenser and may reduce instantaneous COP. The analysis also uses annual energy balances and fixed energy prices. No dynamic electricity tariffs, hourly load profiles, PV self-consumption case or control algorithm is included. Future research should therefore include experimental validation, transient simulations, time-of-use tariffs, photovoltaic profiles and coordinated operation strategies if the system is to be evaluated as an energy-community flexibility asset.

6. Conclusions

This paper analyzed the use of phase change materials as a condenser-side thermal buffer for an air-to-water heat pump in a residential building. Two configurations were compared: a standard AWHF and a configuration including a PCM thermal storage unit on the condenser side.

The results showed that the integration of PCM in a 200 L storage tank, with 30% of the tank volume occupied by PCM tubes, provides approximately 3.08 kWh of stored thermal energy and an estimated buffer period of about 13 min. Based on the storage-sizing comparison, the 30% PCM filling ratio was retained as a balanced scenario for the analyzed tank volume.

The economic results indicate that the conventional AWHF reduces annual operating cost compared with the existing natural gas boiler and air-conditioning system, from 2844 EUR/year to 1759 EUR/year. For the PCM configuration, further cost reduction is not treated as a direct prediction of the storage model. Instead, it is reported through COP-uplift sensitivity. In the high 28.6% uplift case, the operating cost would decrease to 1467 EUR/year and the annual saving would increase from 1086 EUR/year to 1378 EUR/year.

The economic benefit of PCM integration is therefore conditional. The zero-uplift case shows no annual electricity saving from the PCM buffer alone, while the 4% literature-aligned uplift gives only a modest improvement. Under the assumptions used in this study, the PCM add-on reaches positive NPV only above approximately 11.0% COP uplift when the initial marginal investment and discounted year 10 replacement cost are considered, or approximately 14.1% if the replacement cost is added upfront as a simplified lifecycle basis.

The main contribution of the study is a transparent sizing and sensitivity evaluation of a small condenser PCM buffer. The proposed solution is intended for retrofit applications. A simple operational estimate was also included. If the tank completes one charge/discharge event per heating day, this corresponds to about 180 equivalent full cycles over a 180-day heating season. If two events occur per day, the value increases to about 360 equivalent full cycles. These events could delay a similar number of compressor starts, depending on the control strategy.

The selected PCM capacity is 3.08 kWh. This corresponds to about 53 min of operation at 25% of the design load. It corresponds to about 26 min at 50% of the design load. At full design load, it corresponds to about 13 min.

The conclusions are therefore limited to what the model can support. The calculated results include storage capacity, water contribution, buffer time, first-order cycle estimates and marginal economic sensitivity. The scenario-based results include COP uplift, annual electricity reduction and payback. No experimentally validated performance improvement is claimed for the proposed configuration.

Overall, the manuscript should be read as a pre-design and uncertainty assessment. It is not a completed dynamic flexibility study. Quantified energy-flexibility indicators require future transient simulations or experimental monitoring.

Future work should include dynamic simulations and experimental validation of charging and discharging. It should also include quantified start-stop cycle reduction, time-of-use tariff analysis, photovoltaic self-consumption and aggregation of multiple dwellings. Therefore, the community-level application is kept as a future research direction, not as a quantified result of the present study.

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Nomenclature

Symbol	Definition	Unit
A	Analyzed floor area	m ²
COP	Coefficient of performance	-
EER	Energy efficiency ratio	-
Eel _h	Annual electricity consumption for heating	kWh/year
Eel _c	Annual electricity consumption for cooling	kWh/year
Q _{h,ann}	Annual useful heating demand	kWh/year
Q _{c,ann}	Annual useful cooling demand	kWh/year
Q _{PCM}	Total stored thermal energy in the PCM buffer	kWh
V _{PCM}	PCM volume introduced in the tank	m ³
ρ _{PCM}	PCM density	kg/m ³
c _{PCM}	PCM specific heat	kJ/kgK
h _f	Latent heat of fusion	kJ/kg
η _b	Boiler efficiency	-
C _{rep,t}	Replacement cost in year t	EUR
I ₀	Initial investment	EUR
r	Discount rate	-
n	Analysis period	years
S	Annual saving	EUR/year
SPB	Simple payback period	years
DPB	Discounted payback period	years
NPV	Net present value	EUR
IRR	Internal rate of return	%

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