Thermal High Performance Storages for use in vehicle applications

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Abstract. To overcome the restrictions on electric vehicles ranges on winter term conditions, due to the heating demand of the interior, the use of a Thermal High Performance Storage with metallic Phase Change Materials is one possible solution. A new storage concept, using a so called Heat Transport System, enabling the heat transfer from the storage to a vehicles cooling fluid by evaporation and condensation of a working fluid within a closed circle, is introduced in this study. The influence of the storage on an electric vehicles range is exemplary shown for DLR´s Urban Modular Vehicle Concept for a motorway cycle by theoretical investigations. An increase of range by 36,3 km resp. 18,4 % for an ambient temperature of -10 °C and 46 km resp. 26,7 % for an ambient temperature of -20 °C could be reached. The energy densities of the designed storages reach values of more than 220 Wh/kg resp. more than 310 Wh/l. The cost estimations for those storage systems are approx. 445 € resp. 660 €. A comparison between the thermal energy storage and a conventional heating system consisting out of a PTC-Heater and a battery show, that the conventional heating system has a mass which is about two thirds higher, a volume which is more than one third higher and a quadrupled price compared to the thermal energy storage.

Keywords: Thermal Energy Storage, metallic Phase Change Material (mPCM), Electric Vehicle, Interior Heating, Thermal Management

1 Introduction

As the electrification of vehicles increases, the thermal management gains in importance. [1] Providing cost and energy efficient thermal energy for heating the interior in winter term conditions is one of the major challenges, resulting from the lack of waste heat due to the missing combustion process of the engine. [2] Until now, the standard concept for this purpose is the use of PTC (Positive Temperature Coefficient) – Elements, powered by electric energy out of the vehicle´s traction battery. [3] However, the vehicle´s range can be cut in half when using such heating systems on cold winter days (see **Fig. 1**) on which thermal outputs for heating the vehicles interior can rise up to 5 kW. In the figure, the relative range, which is the reduced range because of electric users' energy consumption in ratio to the maximum range without electric users in dependence of the wattage of additional electric users (e.g. electric heaters, air conditioning, etc.) is shown. The coherence between the vehicles relative range and the wattage of additional load in this diagram refers to measurements conducted at DLR on a Smart for Two Electric Drive. On an exemplary heating demand of 4 kW, which refers to winter conditions, the range of this vehicle would be reduced by 45 %.

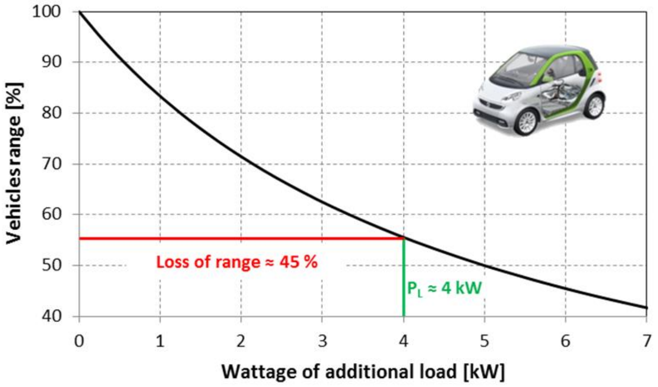

Fig. 1. Range of an Smart for Two Electric Drive in dependence of the wattage of additional load (e.g. electric heaters) [4]

To solve this shortcoming, the use of a Thermal High Performance Storage (THS) with a metallic Phase Change Material (mPCM) was already proposed by DLR in the past. [5] [6] [7] [8] [9] The THS is supposed to be charged simultaneously to the traction battery just before driving. Additionally, recuperation can be used to charge while driving.

In this study, a different base design of a THS for use in electric vehicles, compared to the previous proposals, is shown. Based on this design, dimensions and characteristics of a THS are derived for a specific reference scenario. Also, the maximum range of an electric vehicle for this reference scenario with and without a THS is investigated. At least, the potentials of a THS compared to conventional heating systems, using a PTC-Heater and a battery are shown.

2 Design of a Thermal High Performance Storage

In past publications, a design with an air heat exchanger and the ability to be discharged directly by air was proposed [5], this study introduces a design of the THS which enables the coupling with a vehicles cooling fluid (mixture of water and glycol) circle. By the extension of the variety of the THSs´ designs, the needs of various applications with different architectures of the thermal management system can be served. The new design of the THS is shown in **Fig. 2**.

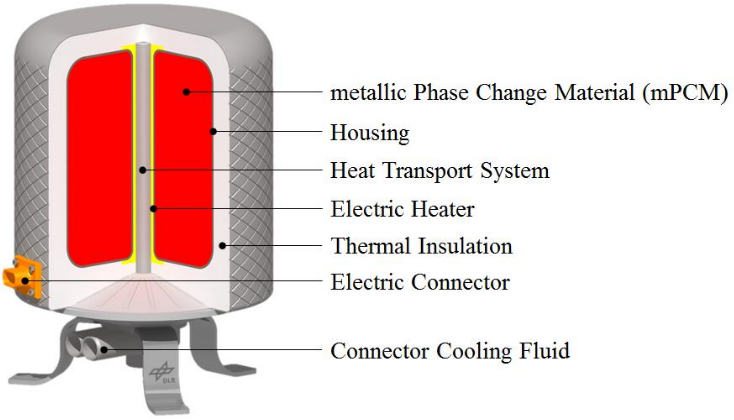

Fig. 2. Three-dimensional CAD view of the design of the THS - Concept, enabling the coupling with a vehicles cooling fluid circle

Basically, the THS consists of seven different parts: the metallic Phase Change Material, its housing, the Heat Transport System, thermal insulation, the electric heater and connectors for electricity and the cooling fluid.

Key component for the coupling with the cooling fluid is the so called Heat Transport System. Since the THS stores thermal energy at temperatures of up to 600 °C, direct discharging of the THS by the cooling fluid would lead to evaporation and dissolution of the cooling fluid. Therefore, a secondary fluid within the Heat Transport System is used, realizing a closed working cycle similar to a heat pipe, using evaporation and condensation of a working fluid (a more detailed description will be given in future publications). By indirect coupling of the working fluid cycle and the cooling fluid cycle, heat can be transferred from the THS into the cooling fluid and further to the vehicles interior.

For charging, an electric cartridge heater in a hollow shape is placed around the Heat Transport system. Besides the charging of the THS, the functionality of a conventional water heater can be realized by this positioning. In use cases of a cold storage and the need of thermal energy, the Heat Transport System can be fed with thermal energy out of the electric heater, which feeds the cooling fluid with thermal energy. An additional PTC-heater within the cooling fluid cycle could be substituted by this solution.

The connector to the cooling fluid consists of an inlet and an outlet port. By the connector for electricity, the needed electric energy can be provided, as well as measurement signals, necessary for controlling and monitoring, be exchanged.

For the results shown in the further chapters, the use of the eutectic alloy $AlSi_{12}$ as mPCM is assumed. As housing material, a stainless steel based solution is considered. As insulation material, microporous insulation is chosen.

The cylindrical shape of the THS is used, since it is beneficial for the ratio of volume to surface area, leading to less thermal losses. However, different shapes, e.g. cuboids are possible as well.

3 Boundary Conditions

3.1 Reference Scenario

The reference scenario, for which the THS is designed, is visualized in **Fig. 3**. The scenario is divided in for different phases, which are further described below. In general, the reference scenario is regarded for two different ambient temperatures: at an ambient temperature of -10 °C and an ambient temperature of -20 °C. The consideration of -10 °C assumes, that over 99 % of all heating scenarios within Germany can be covered by the THS, the consideration of -20 °C allows over 99 % of the heating demands within Northern Europe to be covered [10].

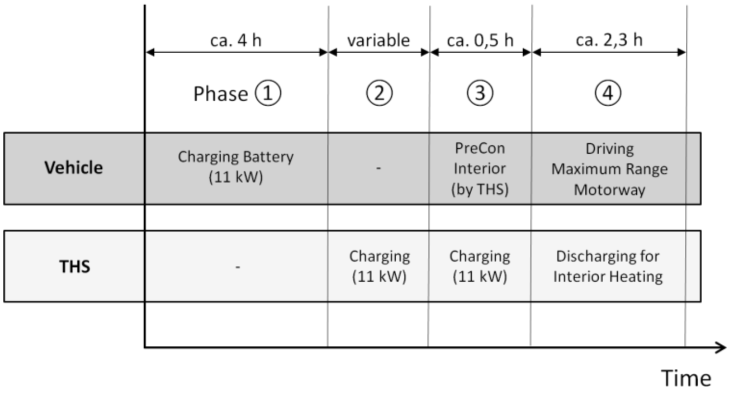

Fig. 3. Reference scenario for the designing of the THS; Phase 1: Charging of the battery; Phase 2: Charging o the THS; Phase 3: Charging of the THS and pre-conditioning of the vehicles interior; Phase 4: Driving of the maximum range on the motorway

Phase 1: The vehicle is parked at a charging station or at the vehicle owner´s home. The battery is charged within a period of about 4 h, which leads to a fully charged battery, even with a SOC of close to zero before charging. For the charging infrastructure, an electric output of 11 kW is assumed.

Phase 2: The vehicle is still parked. In this phase, only the THS is charged with a power of 11 kW. The time of phase 2 is variable, since the capacity of the THS varies dependent on the assumed ambient temperature.

Phase 3: The vehicle still is parked. The THS continues to be charged with a charging power of 11 kW. Meanwhile, thermal energy is transferred from the THS to the vehicles interior by using the THS´s Heat Transport system (compare section 2). By this, the vehicles interior is pre-conditioned. To ensure that the interior is warmed up to a comfortable level, half an hour is designated for this period. At the end of phase 3, the THS is fully charged.

Phase 4: In phase 4, the vehicle is driving. For the driving it is assumed, that the maximum range of the vehicle is traveled on a motorway with an average speed of 102 km/h [11]. Driving on a highway is selected, since long term distances are mostly travelled on highways. At the end of phase 4, the battery is fully discharged. All the heating capacity for interior heating in this phase is provided by the THS.

3.2 Reference Vehicle

DLR´s future Vehicle Concepts

Current research activities at German Aero Space Center´s (DLR) Institute of Vehicle Concepts focus on the development of three different future generation vehicles within the project Next Generation Car (NGC): the Urban Modular Vehicle (UMV), the Interurban Vehicle (IUV) and the Save Light Regional Vehicle (SLRV) (see **Fig. 4**).

The UMV is a fully battery electric vehicle with a modular platform concept, focusing on the needs of increasing urbanization. The introduction of autonomous assistance systems allows an autonomization up to SAE Level 5. The IUV is an upper class Plug In Electric Vehicle (PHEV) with a fuel cell as range extender, allowing ranges of up to 1000 km. Autonomization systems on this vehicle allow autonomous driving up to SAE Level 4. The SLRV is the smallest and most lightweight vehicle within the NGC project. It addresses solutions on safety issues of vehicles of the class L7e. As drivetrain, a hydrogen based fuel-cell concept is introduced. Autonomous driving up to SAE Level 3 is possible on this vehicle.

Since the UMV is the only battery electric vehicle (BEV) developed at DLR, it is considered as the reference vehicle for this study, in particular the version UMV Long, which is a typical electric vehicle for e.g. families. Information in more detail about the different versions of the UMV can be found in past publications. [12] [13] [14]

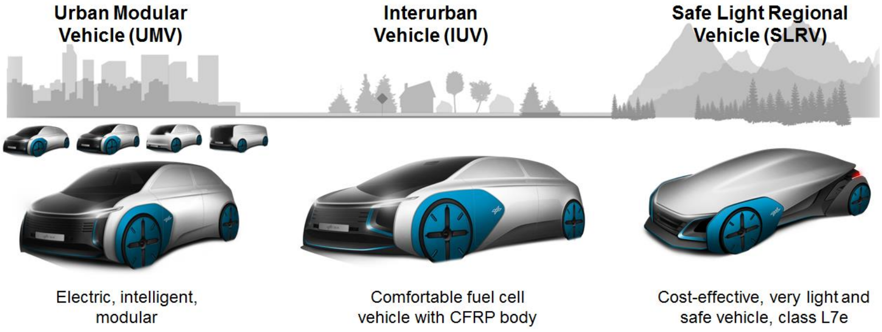

Fig. 4. Future vehicle concepts developed at DLR´s Institute of Vehicle Concepts

Relevant technical properties

For the UMV Long, a battery capacity of 45 kWh is planned. The heating capacities for interior heating had been calculated after the method proposed by Grossmann [4]. Under consideration of general boundary conditions on average interior air temperatures and fresh air rates, as proposed by the standard DIN 1946-3 [15], heating capacities of 3,4 kW for -10 °C and 5,1 kW for -20 °C are the result. Regarding the investigation of the vehicles range (compare section 3.1 and 4.2), values on specific energy consumptions for traction are essential. Since on the current state of development, there are no data available for the UMV, specific energy consumptions of a Mitsubishi i-MieV, which is an electric vehicle of a similar class as the UMV, are considered. Regarding the investigation of the maximum range on a motorway cycle, an energy consumption without heating of 19,3 kWh/100 km for -10 °C and 19,8 kWh/100 km for -20 °C are taken in account [11].

3.3 Integration of the THS into the vehicle

The position, where the THS is intended to be placed within the vehicle, is shown in **Fig. 5**. Since the UMV has the ability to drive autonomous up to a SAE Level 5, the seats can be turned around to enable a face to face seating position. In the version as shown below, the THS is conducted as a table in the interior of the vehicle. Besides the effect that no extra installation space is needed for the THS, heat losses of the THS can directly be used to heat the interior. By this, the overall efficiency of the THS can be increased. Regarding the designing of the THS, the thickness of the thermal insulation has to be chosen in a way, that surface temperatures are limited to 60 °C. By this, the THS becomes a component, suitable for integration into a vehicles interior [16].

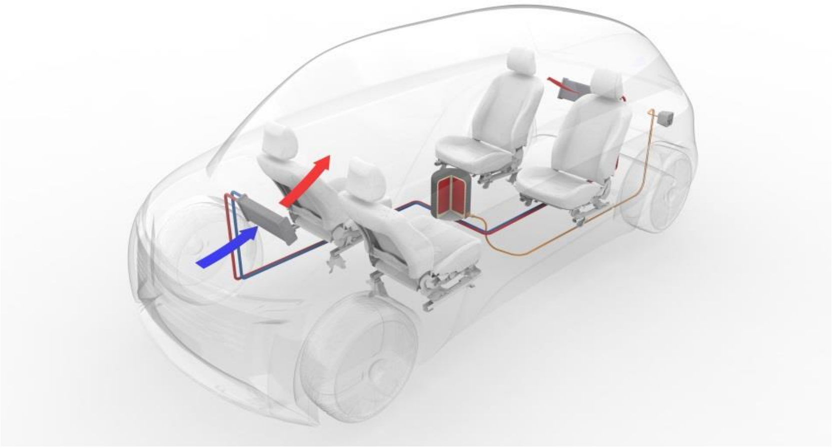

Fig. 5. Position of the THS within the interior of the UMV, to be used as a table

4 Results and Discussion

4.1 Properties of the Thermal High Performance storage

The properties of the THS for both designings are shown in **Table 1**.

Table 1. Properties of the designed THS for ambient temperatures of -10 °C and -20 °C

Property	Design for -10 °C	Design for -20 °C
Capacity	8,9 kWh	13,2 kWh
Installed electric charging power	11 kW	11 kW
Installed Thermal Output	3,4 kW	5,1 kW
Thickness Insulation	32 mm	36 mm
Height / Diameter	317 mm	359 mm
Mass	35 kg	50 kg
Volume	25 l	36 l
Effective grav. Energy Density	222 Wh/kg	227 Wh/kg
Effective vol. Energy Density	311 Wh/l	325 Wh/l
SOC at the end of Cycle	12,3 %	13,8 %
Estimated cost	445 €	660 €

The given capacities of 8,9 kWh and 13,2 kWh both refer to the underlying ambient temperatures (sensible heat capacity is calculated with the ambient temperature as the low reference temperature) and therefore are the theoretic maximum capacities. For -10 °C it is less, since the needed thermal output for heating the interior is less.

The installed electrical charging power is set equal at both designs at 11 kW, since the charging power of the charging station is assumed to be 11 kW.

The installed thermal output with 3,4 kW at -10 °C and 5,1 kW at -20 °C is connected to the demanded heating power of the vehicles interior. Since those are the maximum needed thermal outputs to heat the interior, they are chosen for the designing of the Heat Transport System. Consequently, the Heat Transport System within the THS designed for -10 °C is smaller and has less weight, compared to the Heat Transport System designed for -20 °C.

Since the thermal insulation is designed to allow maximum surface temperatures of 60 °C (compare section 3.3), it´s thickness varies dependent on the average air temperatures within the vehicle cabin. For -10 °C it is 32 mm, for -20 °C it is 36 mm. The different assumed average air temperatures are 25 °C and 28 °C for -10 °C and -20 °C, which is a result of using the guideline given in the underlying standard DIN 1946-3. [15] Different air temperatures within the interior lead to different heat fluxes from the THS to the cabin, demanding a thicker insulation at higher cabin air temperatures.

Height and diameter are set equal since for the concept as shown in section 2, no specific ratio is defined. For -10 °C it is 317 mm, for -20 °C it is 359 mm. Both values refer to the outer height and diameter of the THS.

Overall masses and overall volumes are 35 kg resp. 25 l for -10 °C. For -20 °C they are 50 kg and 36 l.

For the volumetric and gravimetric energy densities, effective values are shown. As effective it is understood, that only the thermal energy, which is really transferred to the interior is taken in account for the calculation of those values. Since the Heat Transport systems working principle is based on the evaporation of a working fluid as described in section 2, a minimum temperature of the mPCM is required to enable the evaporation. In this scenario, this temperature level is at about 110 °C. As conclusion, all the sensible heat stored from ambient temperature up to 110 °C isn´t considered for the calculation of the effective gravimetric and volumetric energy density. However, it could still be used with restrictions to the thermal output of the THS. Since heat transfer coefficients are way higher in case of evaporation compared to convection with liquids, the performance of the Heat Transport system decreases when convection to the liquid working fluid is used instead of evaporation to transfer heat, at temperatures around or below the boiling point of the working fluid. The ratio of energy still left in the storage compared to the overall capacity, is expressed by the State of Charge (SOC) at the end of the cycle. For -10 °C, 12,3 % and for -20 °C, 13,8 % of the overall capacity is still left in the THS. For -20 °C the left capacity is slightly higher, since the reference temperature to calculate the SOC is lower (-20 °C vs. -10 °C).

For -10 °C, effective energy densities are 222 Wh/kg and 311 Wh/l. For -20 °C, they are 227 Wh/kg and 325 Wh/l. As it can be seen, both the gravimetric and volumetric energy densities rise with a rising Capacity of the THS. With the rising capacity, the ratio of mPCM in relation to the overall weight and volume is higher in the THS with the higher capacity, because not all parts of the THS are scaled up. For example housing thickness and the installed electric charging power are constant for both designs. This leads to a scaling effect, allowing higher energy densities on storages with higher heat capacities.

Since the cost of a vehicles component is a very important criterion, a cost estimation regarding production costs is given. For this, the overall capacity of the THS is multiplied with specific costs for 1 kWh storage capacity. The specific cost assumed in this study, resulting out of internal ratings made by DLR for a potential series production, is about 50 €/kWh. Therefore, the estimated cost for a THS for -10°C is 445 € and 660 € for a THS for -20 °C. However, scaling effects could lead to lower specific costs on THS systems with higher capacities, but were not considered in this study.

4.2 Range of the vehicle

The range of the vehicle with and without THS for the different ambient conditions is shown in **Fig. 6**. For -10 °C it is 197,3 km without THS and 233,6 with THS. For -20 °C it is 179,5 km without THS and 227,5 km with THS. For -10 °C, the range is

36,3 km higher, which is a plus of 18,4 %. For -20 °C, it is 48 km higher, resulting in a plus of 26,7 %. The ranges without THS had been calculated, assuming that both the energy for traction and heating are supplied by the traction battery. The ranges with THS were calculated assuming, that the energy for traction is supplied by the battery and the energy for heating is supplied by the additional THS. Effects of the additional mass of a THS on the vehicles energy consumption were not considered, since they can be neglected in this specific scenario, since it is low compared to the vehicles overall mass [17]. The values with THS therefore also represent the range of the vehicle, if no heating would be conducted while driving.

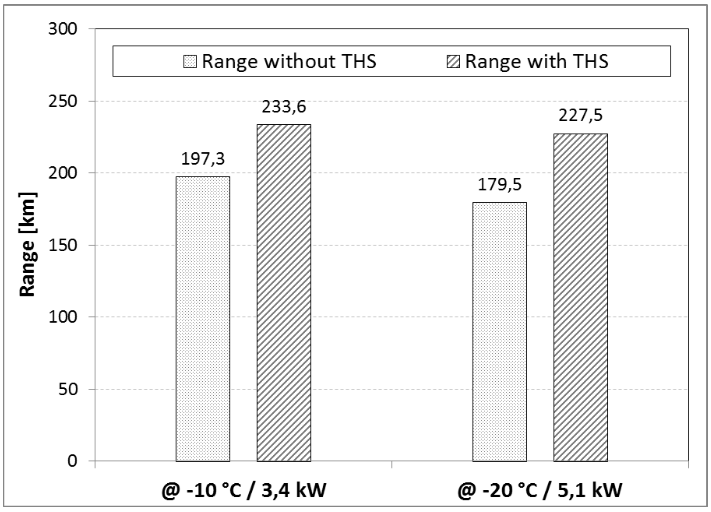

Fig. 6. Ranges of the UMV with and without THS in dependence of the ambient temperature

Compared to potential relative losses of ranges as shown in the introduction (see chapter 1), the relative losses in the investigated scenario are about the half (ca. 25 % loss of range for a heating capacity of 5,1 kW in this study compared to ca. 50 % in the case shown in the introduction for the same heating capacity). This comes out of the effect that the energy consumption for traction on a motorway cycle is higher, compared to driving on a country road or in the city. Therefore, the relative amount of needed energy for interior heating compared to traction is less while driving on a motorway, leading to a lower relative loss of range in this scenario. However, higher relative losses while driving in urban or countryside can easier be accepted, since the total distances travelled in one term in those use cases are less, compared to distances travelled on motorways.

4.3 Comparison of Thermal High Performance Storages to state of the art heating systems

For a comparison to state of the art heating systems used in electric vehicles, PTC – heaters drawing electric energy out of a battery system are considered. Another state of the art system, which might be considered for a comparison, is a heat pump system. However, heat pumps only can work beneficial regarding energy efficiency, if the temperature of the energy source is high enough. For the selected scenarios with ambient temperatures of -10 °C and -20 °C, no automotive heat pump system used in electric vehicles is able to provide the needed thermal capacity. This is due to low COP and glaciation effects on the ambient air heat exchanger at low ambient temperatures [18]. Due to this, heat pumps are not considered for the comparison to state of the art heating systems.

Properties of a PTC/Battery – system

Before drawing a comparison between a THS and a PTC/Battery – system, the assumptions made on the PTC/Battery - systems have to be set. In general, the comparison is conducted regarding mass, volume and the cost of the systems. **Table 2** gives an overview on the assumed properties of a PTC/Battery system, which are necessary to make a declaration for this.

Table 2. Assumed general properties of a PTC/Battery - system

Property	Value	Reference
Grav. Energy Density Battery	150 Wh/kg	[19]
Vol. Energy Density Battery	250 Wh/l	[19]
Usable SOC Battery	100 %	-
Efficiency Battery	95 %	[20], [21]
Efficiency PTC	95 %	[22]
Specific Cost Battery	200 €/kWh	[23], [24]
Cost of PTC-Heater	150 €	[25]

In general, all the shown values come from literature. The only exception is the assumed usable SOC, which is an own assumption. Since the vehicle is preheated on the reference scenario as described in section 3.1 while charging, a preheating of the battery can also be assumed. Therefore, no SOC is lost due to low battery temperatures. Other effects leading to a not usable SOC, like a limited depth of discharge, are not considered in this study. Consequently, the usable SOC is set to 100 %.

Out of the shown general properties of a PTC/Battery – system, the properties of a PTC/battery – system for providing the same heating capacity as the THS for the reference cycle is calculated (see **Table 3**). Therefore, using the PTC/Battery – system for heating the interior leads to the same ranges, as if an additional THS was used for interior heating (compare **Fig. 6**).

The capacity of the battery system was calculated considering the usable SOC of the battery, the efficiency of the battery and the efficiency of the PTC - Heater. Out of this, a battery capacity of 8,63 kWh for -10 °C and 12,6 kWh for -20 °C is the result. The masses and volumes are conducted considering the capacity and the gravimetric resp. the volumetric energy densities. Mass and volume of a PTC - Heater are not considered, since both are low compared to the battery. For -10 °C, the PTC/Battery – system has a mass of 57,5 kg and a volume of 34,5 l. For -20 °C it is 84 kg resp. 50,4 l. For calculating the cost of a PTC / Battery - system, the cost of the battery and the PTC are considered. For batteries, a buying price of 200 €/kWh for OEM´s is assumed. For PTC elements, it is about 150 €. This results in a total cost of 1876 € for the PTC/Battery – system designed for -10 °C and 2670 € for the system designed for -20 °C.

Table 3. Properties of a PTC/Battery – system to realize interior heating for the reference cycle

Property	For -10 °C	For -20 °C
Capacity	8,63 kWh	12,6 kWh
Mass	57,5 kg	84 kg
Volume	34,5 l	50,4 l
Total Cost (Battery+ PTC)	1876 €	2670 €

Comparison between Thermal high performance storage and PTC / Battery – system

The comparison between the THS and the PTC/Battery – system are conducted regarding mass, volume and cost. The comparisons of these values for -10 °C are shown in **Table 4** resp. in **Table 5** for -20 °C.

For -10 °C, the mass of the PTC/Battery – system is 22,5 kg higher, which is a relative difference of 64,3 % compared to the THS. Regarding volume, it is 9,5 l resulting in a relative difference of 38 %. The cost for a PTC/Battery system is 1431 €, resp. 322 % more compared to the THS.

For -20 °C, the mass of the PTC/Battery – system is 34 kg higher, which is a relative difference of 68 % compared to the THS. Regarding volume, it is 14,4 l, resulting in a relative difference of 40 %. The cost for a PTC/Battery - system is 2010 €, resp. 305 % more compared to the THS.

Table 4. Comparison of mass, volume and cost between the PTC/Battery – system and the THS for an ambient temperature of -10 °C

Property	Value Battery/PTC	Value THS	Abs. difference	Rel. difference
Mass	57,5 kg	35 kg	+22,5 kg	+64,3 %
Volume	34,5 l	25 l	+9,5 l	+38 %
Cost	1876 €	445 €	+1431 €	+322 %

Table 5. Comparison of mass, volume and cost between the PTC/Battery – system and the THS for an ambient temperature of -20 °C

Property	Value Battery/PTC	Value THS	Abs. difference	Rel. difference
Mass	84 kg	50 kg	+34 kg	+68 %
Volume	50,4 l	36 l	+14,4 l	+40 %
Cost	2670 €	660 €	+2010 €	+305 %

The comparison for both designings deliver similar statements: a PTC/Battery – system has a mass which is about two thirds higher, a volume which is more than one third higher and costs more than four times as much as a THS. The slightly higher relative difference for mass and volume for -20 °C compared to -10 °C, correspond to the slightly higher energy densities of the THS for -20 °C compared to -10 °C (compare section 4.1). Regarding costs, the relative difference for -20 °C is lower compared to -10 °C. This is a result of the calculation method, which simply multiplies the relative costs with the overall capacity. Since the not usable capacity on the THS for -20 °C is higher compared to the THS for -10 °C (compare section 4.1) but considered for calculating the costs, the cost for the THS designed for -20 °C is overrated compared to the THS designed for -10 °C. As already mentioned in section 4.1, scaling effects resulting in lower specific costs on larger THS might occur, which would counteract the effect seen in this study.

5 Conclusion and Outlook

A new concept of a Thermal Energy Storage, using metallic phase change materials for interior heating of electric vehicles, was shown. The concept offers the possibility to connect the storage to a vehicles cooling fluid by using a so called Heat Transport System. To show the influence of a THS on an electric vehicles range, designings of the THS were done for two different winter ambient conditions, resulting in increasing ranges of the vehicle. For drawing a comparison of the THS to conventional heating systems, a PTC/Battery – system leading to the same increase of range of the vehicle was selected. The comparison outlines the potentials of a THS for use as interior heating system in electric vehicles by having a lower mass, less volume and costing less compared to a PTC/Battery – system.

For future investigations on THS, two different paths should be followed. The first one is the technological development of a THS towards higher energy densities up to two times higher. The use of vacuum insulation panels instead of microporous insulation, as used for the concept in this study, could lead to higher volumetric energy densities. For increasing the gravimetric energy densities, the increase of the maximum temperature of the THS could enable two positive effects: First one is the rise of the storable sensible heat. Second one is the enabling of the use of alternative storage materials to AlSi, having a higher melting temperature, but offering higher melting enthalpies and heat capacities.

Second path is the investigation for different application, additional to the investigation in electric vehicles. One application offering a high potential for the use of THS are electric buses, e.g. used in public transport. Buses have an even higher demand on thermal energy for interior heating, due to the high window areas and heating losses because of opened doors. Also, battery systems for electric buses generally cost 3 to 4 times more than battery systems for electric vehicles [26], leading to an even higher potential of a THS compared to a PTC/Battery – system regarding cost.

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