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Techno-Economic Assessment of Active Latent Heat Thermal Energy Storage Systems with Low-Temperature District Heating

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ABSTRACT

Thermal energy storage (TES) is a set of technologies with the potential to enhance the efficiency and flexibility of the 4th generation of district heating systems. This study presents a comparative techno-economic assessment of active TES systems suited to operate with low-temperature district heating (LTDH) for short-term heat storage applications. Latent heat systems (LH-TES) are compared qualitatively and quantitatively to water-based sensible heat systems (SH-TES). It is concluded that latent heat TES systems are still more expensive than water-based systems regarding energy storage cost (EUR/kWh) ranging from 1.5 to 4 times more, mainly due to the cost of the storage media. However, considering distributed TES systems integrated to LTDH, small-scale active LH-TES systems will become more cost-competitive as storage media costs are expected to decline in the future. This study represents a step forward in the development and improvement of the DH system through the integration of TES which will play a key role in the future smart energy system.

Keywords:

Low-Temperature District Heating (LTDH);
Thermal Energy Storage (TES);
Latent heat;
Sensible heat;
Techno-economic assessment;

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1. Introduction

The present energy system is expected to undergo a radical transformation in order to become sustainable. The further expansion and development of district heating (DH) networks has the potential to play a key role in the future sustainable energy system of Europe and the world [1], among other technologies. Still, the current DH concept faces a significant challenge in terms of its ability to re-design, optimise and further develop itself [2, 3]. The subjects that currently pose more significant challenges for the DH technology include: the use of low-temperature grids to reduce heat losses and increase efficiency; the interaction with low-energy buildings and electricity grids; and the effective management and dispatch of thermal energy sources, such as waste and biomass -based CHP, geothermal and solar-thermal, and industrial surplus heat [3].

Concerning the aspects of supply/demand management, the dispatchability of thermal energy sources, and the integration with electricity networks, thermal energy storage (TES) will be key to the management and optimization of the energy system [4]. TES consist of a substance (storage medium) used to store thermal energy that can later be re-used for heating/cooling applications [5]: it is the temporary "holding" of energy for later use [6].The introduction of TES systems into the DH network results, among other benefits, in an increase in flexibility leading to lower heat production costs. Water typically is the storage medium of choice for DH applications [7] due to several techno-economic factors. In water-based systems the energy is stored by changing the

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Nomenclature

Acronyms

CHP	Combined heat and power
DH	District heating
HEx	Heat exchanger
HTF	Heat transfer fluid
LH	Latent heat
LT	Low-temperature
PCM	Phase change material
SH	Sensible heat
TES	Thermal Energy Storage

Latin Characters

C	cost	[EUR]
c_p	specific heat capacity	[kJ/kg·K]
h	specific enthalpy	[kJ/kg]
h_{pc}	latent heat capacity	[kJ/kg]
P	power	[W]
Q	heat	[kJ, kWh]
T	temperature	[K, °C]
V	volume	[m^3]

Greek symbols

Δ	delta, difference	
^	specific heat conductivity	[W/m·K]
η	efficiency	[-]
ρ	density	[kg/m^3]

Subscripts and superscripts

avg	average
liq	liquid phase
pc	phase change
sol	solid phase

temperature of the medium, using the sensible heat storage capacity of the material; thus they are called sensible heat TES systems (SH-TES).

Coupling TES systems to DH networks has several benefits. For heat generation units, TES serves as a buffer between demand and supply, and help to perform load balancing and peak shaving, avoiding the need to install additional generating capacity. TES systems are also commonly used as supporting equipment for combined heat and power (CHP) plants, used to maximize profits by partially decoupling the electricity and heat generation [6]. Within DH networks, seasonal TES brings improved benefits compared to short-term storage [8], and by using it effectively, TES can decrease the network energy consumption. TES enables a smoother integration of distributed, renewable energy generation technologies, having positive benefits in terms of lower fossil fuel consumption and consequently lower emissions [7]. On the other side, the high investment costs connected to TES are a major drawback. Together with space constraints, complex planning, and the lack of adequate supportive legislation [9], these comprise the set of obstacles to be tackled, among others.

Regarding latent heat (LH-TES) systems some applications for heating and the built environment have already been studied. Latent heat is the heat transfer that occurs when a material changes from one phase to another (gaseous-liquid-solid), and the storage medium used is often referred to as phase change material (PCM). Most of the LH-TES applications exploit the phase change between solid and liquid phases to store/release thermal energy, due to the higher heat storage capacity per volume and low volume difference between these two phases [6]. The main advantage of LH-TES over SH-TES is a higher storage capacity per unit of mass (and volume), resulting in lower space requirements. Also, during a phase change there is only a small temperature difference, and thus temperature swings are reduced to the minimum.

Most LH-TES applications are based on the usage of PCM in passive systems [10]. These applications include, for instance, the integration of PCM within walls, floor or ceiling of buildings for indoor temperature control in order to store larger amounts of solar radiation, internal gains, or waste heat, and so increasing the effective thermal mass of the buildings. Some active LH-TES applications have also been proposed and studied: these systems consist of a vessel where the PCM is stored and a heat transfer fluid (HTF) is pumped through the vessel to/from the load/supply and vice versa. Yet, active LH-TES systems are technologies under development which are slowly reaching a commercialization stage.

The development of LH-TES systems is deeply linked to the specific applications [11]. The operating temperature range and temperature fluctuations are the main parameters to consider for system design. In order to choose a suitable PCM, it is necessary to compare its phase change temperature, the required system operating temperatures, and the temperature range of the specific application.

Current studies focus on the use of TES systems in conventional DH networks, and extensive research has been carried out on integrating TES to the 3rd generation DH. Thus, with the coming 4th generation DH, a gap has emerged since limited research has been developed regarding TES integrated LTDH, and more specifically concerning active LH-TES systems [12]. Moreover, TES technologies other than water storage in DH applications are very rare [13]. Therefore, assessing active LH-TES systems coupled to LTDH networks, focusing on the difference in operating temperature ranges, is an important step in order to expand the knowledge in this field.

This study aims to develop a comparative techno-economic analysis of active LH-TES systems for short-term heat storage in DH applications. Water-based SH-TES systems are used as baseline for comparison. Moreover, this work presents a qualitative and quantitative guide regarding these systems, it explores possible benefits/drawbacks, and identifies some possible configurations for LH-TES and LTDH integration.

2. Methodology

In order to perform this techno-economic assessment, the first step was to determine which LH-TES systems are suitable for LTDH applications in a qualitative and quantitative manner. Then for the technical assessment, the most relevant TES media properties are discussed: operating temperature ranges, phase change temperatures, and volumetric heat storage densities. As benchmark, a water-based SH-TES application is used. The performance of active LH-TES systems is discussed as well as the provisions that should be taken regarding outlet temperature and output power; and so possible piping layouts and system operation are briefly examined. Finally, details on the estimation of active systems costs are given; which were used to compare the most suitable PCMs and the benchmark, in terms of the specific cost of stored energy.

2.1. TES media properties

In order to compare materials and systems, and to address correctly the issue of making a suitable selection for the selected application, it is necessary to determine the properties of the TES media. For this purpose, in [14] the authors recommend several criteria and properties that are important to consider. Among these properties and performance indicators, in this analysis, the specific parameters that are taken as key to assess TES systems for LTDH applications include: volumetric heat storage density, thermal power output, and PCMs phase change temperature. We have also explored certain qualitative characteristics of the materials and systems such as market availability, thermal cycling stability, corrosiveness (compatibility with its containing vessel), hazardousness and ease of handling [5].

The main PCM categories hereby studied include: 1) paraffins; 2) fatty acids; 3) salt-hydrates and 4) metallics. The number of compounds was narrowed according to an initial survey of their characteristics and suitability for LTDH application. Some of the compounds are already used as heat storage media, although not necessarily in active TES systems. The main characteristics of the media, both quantitative and qualitative, were gathered and condensed from several studies [14 – 17]. Table 1 shows a summary of the main characteristics of the materials considered in this study.

Table 1: Classification of PCMs and their main characteristics, included in this study. Based on [15–18]

Paraffins	Organic compounds
	Wide phase change temperature (T_{PC}) range
	Low volume variation during phase change (10%)
	Low thermal conductivity
	Non-corrosive, chemically stable, potentially flammable
	Without subcooling phenomenon
Fatty Acids	Organic compounds
	Wide phase change temperature (T_{PC}) range
	Low thermal conductivity
	Mildly corrosive
Salt-Hydrates	Inorganic compounds
	Wide phase change temperature (T_{PC}) range
	Low volume variation during phase change (10%)
	Higher latent heat of fusion and higher thermal conductivity
	Slightly toxic, corrosive, non-flammable
	May face issues of incongruent melting and super-cooling
Metallics	Inorganic compounds
	High heat of fusion per unit volume
	Higher density (weight penalty)
	Suitable for high working temperature applications (e.g. aerospace)

2.2. Volumetric heat storage density for specific applications

Media with high heat capacity and high density are the most suitable for TES, because of their ability to store a large amount of energy in a relatively small volume. To quantify this capacity the property of volumetric heat storage density is defined as the amount of energy that can be stored per unit volume and within a temperature range. In applications with a defined temperature range, the heat storage capacity can be calculated straightforward from the enthalpy difference [19] as in Eq. (1):

$$\Delta h = h\left(T_{high}\right) - h\left(T_{low}\right) = \int_{T_{low}}^{T_{high}} c_p(T) \cdot dT \qquad (1)$$

For sensible heat storage media, where heat is stored only by changing the temperature of the medium, the amount of energy is proportional to the difference between the initial and final storage temperature. If the difference in its heat capacity coefficient is small enough, it is possible to approximate c_p as constant and develop Eq. (1) into:

$$\Delta h_{SHS} = \int_{T_{low}}^{T_{high}} c_p(T) \cdot dT = c_{p,avg} \cdot \left(T_{high} - T_{low}\right) \qquad (2)$$

Where $c_{p,avg}$ is the average specific heat capacity of the medium [kJ/kg·K], and ΔT is the difference in temperature T_{high} and T_{low} [K]. Thus the *volumetric heat storage density* is approximated as:

$$Q / V_{SHS} = \rho_{avg} \cdot \Delta h_{SHS} = \rho_{avg} \cdot c_{p,avg} \cdot \left(T_{high} - T_{low}\right) \qquad (3)$$

where Q is the total heat stored [kJ], V is the volume [m^3], ρ_{avg} is the average density of the material [kg/m^3] within the temperature range.

For sensible heat storage media, this property is proportional to the *volumetric thermal capacity* ($\rho \cdot c_p$) determined by the specific heat capacity of the material in relation to its volume. In the case of latent heat storage media, for a phase change material (PCM) with an ideal behaviour and thus a constant phase change temperature (T_{pc}), the total heat stored is the addition of three terms shown in Eq. (4):

$$\Delta h_{LHS} = \int_{T_{low}}^{T_{pc}} c_{p,sol}(T) \cdot dT + \int dh \Big|_{Tpc} + \int_{T_{pc}}^{T_{high}} c_{p,lip}(T) \cdot dT \qquad (4)$$

Where the first and last terms represent the sensible heat stored before and after reaching the phase change temperature, and the term in the middle represents the latent heat stored during the phase change process. This equation simplifies for the ideal case and with constant heat capacities to:

$$\Delta h_{LHS} = c_{p,sol} \cdot \left(T_{pc} - T_{low}\right) + \Delta h_{pc} + c_{p,liq} \cdot \left(T_{high} - T_{pc}\right) \qquad (5)$$

Here, T_{pc} is the phase change temperature and the subscripts for the specific heat capacities refer to the averages for the solid ($c_{p,sol}$) and liquid ($c_{p,liq}$) phases of the PCM.

2.3. Active TES systems and LTDH

The integration of active TES systems with the DH network has the potential to bring substantial benefits for the network, both from the economic and environmental points of view. The success of this integration and the extent of its benefits will vary depending on the configuration chosen for the TES, which will depend on other factors, such as the scale of economy, regulations, incentives and space availability.

2.3.1. System characteristics & performance

As this analysis focuses on a comparison of the full TES systems rather than the storage media, the typical TES system considered consists of four main components: a heat storage medium that is heated and cooled, a containment vessel for this medium, a heat transfer fluid (HTF), and a heat exchanger (HEx) surface to transfer the heat between the HTF and the storage medium [6]. If the storage medium and heat transfer fluid are the same, such in the case of some water tanks, then the heat exchanger is not required.

For comparison, the SH-TES system represented by a water tank is used as benchmark. Some of the typical characteristics of water-based systems are the following: water is both storage medium and heat transfer fluid (HTF); they are easily scalable; require thorough insulation to minimize heat losses; pressurization might be needed to avoid evaporation; and stratification is desired in order to maximize the storage efficiency [13]. In terms of thermodynamic performance a lower volumetric heat storage density is a significant disadvantage of SH systems as compared to LH systems; hence a wider temperature range is required to store a given amount of energy [10].

In the case of LH-TES, the active system is represented by a tank filled with a PCM as storage medium. In this analysis, we considered a horizontally oriented cylinder as the storage tank, with a shell and tube HEx in place, such as one previously studied in [20]. In the charging process, the heat is stored by passing water at high temperature through the tank and HEx arrangement until the PCM has fully melted. The discharge process occurs in the opposite way, by flowing water at lower temperature that is heated and then supplied to the load/sink.

Besides the PCM properties, the actual performance of the whole active LH-TES system will determine the suitability for specific applications, and will also be the basis to design strategies to improve this suitability. In the case of TES for DH applications, besides the load and demand, the most stringent limitations are the supply/return temperatures. Therefore, it is necessary to consider the performance of the active LH systems with respect to these parameters. There are some studies that report on the transient performance of LH systems [21–23]. Based on these performance analyses, Figure 1 illustrates the characteristic performance curves of active LH-TES in terms of HTF inlet/outlet temperatures as well as input/output power, assuming a constant HTF flow rate.

During the charging process (see Figure 1a), the HTF temperature curve shows that the temperature of the HTF leaving the storage is equal or higher than the phase change temperature during most of the charging period, before full charge is achieved. It is the consequence of the PCM melting occurring within a narrow temperature range, and it means that the flow leaving the storage at the outlet still contains useful thermal energy for the DH loads/sinks, and so this flow should not go to waste. On the other hand, during the discharge process (**Figure 1b**), the HTF outlet temperature is below the phase change temperature range near the threshold of full discharge, which can be set as a minimum value for thermal power output. Thus, if this flow is to be used for DH supply, when the HTF temperature at the storage outlet drops below the minimum required level, a strategy for boosting the temperature of this flow will be needed.

An alternative strategy to control the HTF output temperature is to vary its flow rate passing through the storage. The flow rate would be decreased during the discharging process to raise the output temperature, yet this action will further limit the power output, and would require more complex control. During the charging process increasing the HTF flow rate as a strategy to reduce the output temperature will be ineffective due to the relatively constant phase change temperature range and the high HTF temperature at the inlet.

Figure 1 also shows that thermal power output/input –the system property to release or store heat per unit time– is not constant: there is a maximum at the beginning of the charging/discharging process and then it decreases continuously until reaching zero. Therefore, a buffer or supporting source would be needed to match a specific load during the discharging process.

Regarding thermal power, LH-TES systems exhibit a lower output compared to water-based SH systems. Therefore, a trade-off between energy and power densities arises. The lower thermal power of LH systems is due to the differences in the heat transfer processes

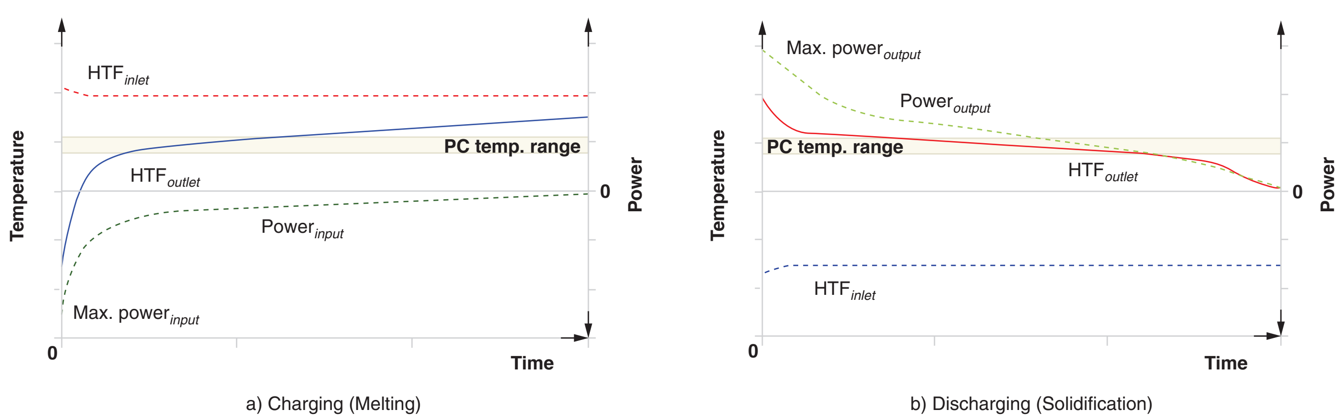

Figure 1: Characteristic temperature and power performance of active LH-TES systems

with respect to SH systems [24]. In water-based systems the heat exchange process is dominated by the convective heat transfer mechanism over conductive heat transfer. However, in LH systems, when phase change takes places, for instance during the discharge process as the PCM solidifies, it is deposited as solid layer over the heat transfer surfaces. Then conduction, instead of convection, becomes dominant. Since PCMs generally have low thermal conductivities, the heat exchange process is hindered and so heat transfer from the LH-TES is sluggish. Another consequence of this process is that melting (charging) occurs faster than discharging and a higher power input can be achieved.

In order to improve the LH systems performance in this aspect, several solutions have been proposed, described and studied in [25, 26]. When considering the full TES system, it is possible to influence this characteristic not only by enriching the storage medium, but also by the design of the vessel and the HEx. These enhancing techniques include, among others: adding materials with higher conductivities into the PCM on a macro scale or composites on a micro scale (e.g. adding graphite to paraffins or salt hydrates), decreasing encapsulation size, or placing the PCM into metallic foams or a graphite matrix.

2.3.2 System Layout & Operation

TES systems can be either located at the heat production facility as a large centralized unit, or at the DH substations in a decentralized manner so that a building or group of buildings have their own TES. In this study we focus on the latter, since for small scale TES, the use of LTDH and PCM could provide a cost-efficient competitive solution. Some configurations have already been explored comparing SH and LH TES coupled to DH, such as in [27] where the storage is placed as an interface between the primary and secondary sides, having the same function as the DH substation and providing hydraulic separation between the primary/secondary networks. However, this configuration would lead to high return temperatures on the primary side, and it requires a bypass system for the tank on the secondary side in order to control the supply temperature.

In the configuration proposed in this study (see Figure 2), the TES system is located in parallel to the substation primary side. The storage temperature is defined to be slightly above the LT supply, and so the required phase change temperature is around 70°C. An advantage of this configuration is that the primary network is used as support especially when the TES approaches full discharge.

The operation of this active LH-TES system intuitively requires two main modes: charging and discharging. During the charging process (Figure 3a), the hot water from the DH primary supply, point (a) is used as HTF input. After exiting the storage, point (c), the cooled HTF is then directed to the primary return. Moreover, as an alternative heat source, when the primary return flow temperature is high enough (>T_{pc}),

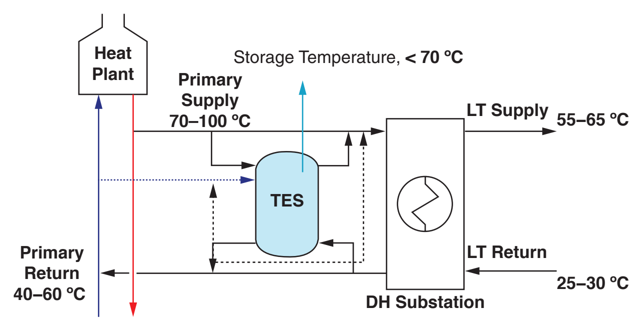

Figure 2: LH-TES system application with LTDH substation

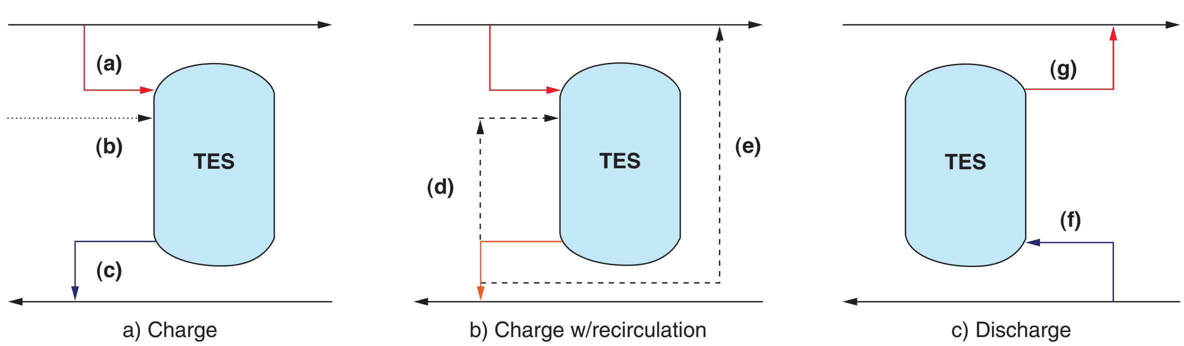

Figure 3: LH-TES system operating modes of the proposed arrangement

this flow could be used to charge the storage, point (b), or either a mixture of both (a) and (b), and thus reuse some of this heat. A drawback of this approach is that the required charging time would be extended.

During the charging process of LH-TES systems, the temperature of the HTF leaving the storage at the outlet is very close and/or exceeds the PC temperature of the medium for a long period of time (see Figure 1b). This temperature could be significantly higher than the network return; therefore, it would not be desirable to channel this flow into the primary return due to the useful heat it contains with respect to the sinks and because of risking of penalties on high return temperatures. In this case, a variation of the charging process operating mode is necessary. This alternative is shown in Figure 3b, where depending on the temperature level of the HTF at the storage outlet, the flow can be recirculated to the TES inlet, point (d), or to the DH substation inlet, point (e). At this point of connection, the flow temperature could be boosted by mixing it with the DH primary supply and so ensure a sufficiently high temperature at the DH substation inlet.

During the discharging process (Figure 3c), the flow at low temperature coming from the substation return is used as HTF input, point (f), to the TES. The heated flow leaving the storage, point (g), is then directed towards the substation supply/inlet. When near the end of the discharge process the storage cannot ensure a sufficiently high outlet temperature, this flow could be mixed with the DH primary supply to boost the temperature level. Notice that for ease of explanation, in figures 2 and 3, the HTF inlet to the tank and HEx, and the HTF outlet are represented with multiple lines, but they are in fact only two points: HTF inlet and outlet; plus additional pipes, and valves and connections not shown for simplicity.

2.4. Active TES systems costs estimation

As this study focuses on the TES system rather than the storage media, the cost analysis is based on the system configuration with three main components: heat transfer fluid, storage medium and heat exchanger. The baseline is represented by a water tank as the benchmark SH-TES system. The cost per kWh of heat stored is estimated based on the costs of already existing systems. The data from the systems used as input are mainly from SH-TES water-based systems located in Germany and Denmark whose characteristics are discussed in [28] and [29].

Table 2: Cost breakdown of active TES systems, from [30]

Item	Water Tank %	PCM Tank %
Containing vessel (and HEx)	45	17
Storage medium	0	43
Operation and Maintenance	3	3
Installation & fixed costs	19	10
Control system	20	24
Occupied volume/space	3	1
Energy (internal)	1	2
	100	100

In order to estimate the total system cost of the LH-TES systems, a costs breakdown is used, proposed in [30], for PCM storage systems. Table 2 shows the cost breakdown which includes: (1) containing vessel (and HEx), (2) storage material/medium, (3) installation & fixed costs (e.g. piping, insulation, and civil works), (4) control system, (5) operation and maintenance. Also (6) internal energy consumption and (7) cost of the occupied volume are approximated. The replacement cost is not taken into consideration at this point. As seen from the cost breakdown, in the case of active LH-TES systems, the PCM cost is the most significant item of the total cost, while in SH systems the tank is the item with the largest share.

PCM prices were gathered from various sources [32, 33, 34] to estimate the total systems costs. Most of the PCM prices correspond to retail prices for the chemical industry (500g or less), thus they have a high cost per kg. Therefore, in order to estimate the wholesale price of PCM, and with the purpose to yield more comparable results, based on the approach proposed in [35] of applying economy of scale, an average divider of 11.79 was used for price reduction, for those materials whose wholesale price is not available.

3. Results & Discussion

The outcomes of the analysis including LH-TES suitability and comparison with the benchmark SH-TES system are shown and discussed. First the cost analysis of water-based systems is presented and discussed with emphasis on the small-scale systems. Then the suitable PCM and their properties are presented. It is followed by the results on total system cost and then they are compared to the benchmark in terms of the specific cost of heat storage from a full TES system perspective.

3.1. Sensible Heat TES Systems

In the first part of this assessment, the baseline for comparison of this study is a SH-TES represented by a water tank. Based on the costs of already existing systems, located in Germany and Denmark, several conclusions are drawn regarding their operating characteristics and cost [28, 29]. Figure 3 shows how SH-TES systems costs benefit from scale of economy: the larger the storage, the lower the cost per volume. Especially water tank applications benefit more from this factor, with significant difference in costs among medium, small and large systems.

Regarding the energy storage cost (EUR/kWh) of SH-TES systems, assuming a DH network operating temperatures of 80/40 °C in the supply/return (ΔT = 40 °C), the average volumetric heat storage density is 50 kWh/m^3, and thus storage costs range from *1 to 10 EUR/kWh* for the water-based systems (*50 to 500 EUR/m^3*): the highest for small-scale water tanks, and the lowest for large-scale boreholes. This cost range is in line with the data found in literature [5] which point out the costs of small-scale water tanks at maximum 10 EUR/kWh. However, during summer, when return temperatures may reach above 50 °C and the supply temperature could be as low as 65 °C, the actual operating cost range may double to *2 to 20 EUR/kWh* (*100 to 1000 EUR/m^3*).

Concerning water tank systems, the most cost-efficient options are found within storage volumes of 1,000 to 10,000 m^3. Having smaller or larger tanks outside this range is not optimal. In the case of small tanks, the fixed costs such as the vessel, installation and control, are relatively constant and independent of the volume; conversely in the case of large volumes, the foundations and other installation costs start to increase exponentially with the size.

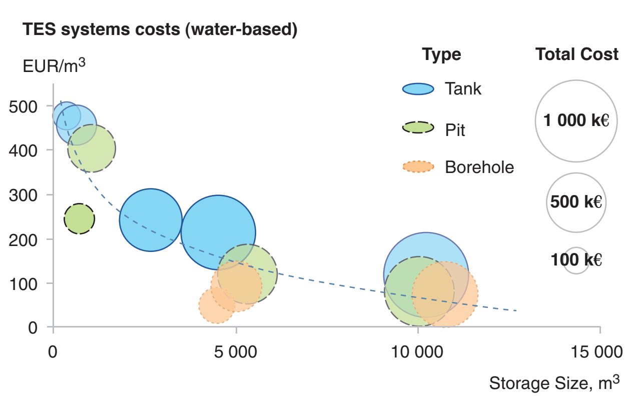

Figure 3: Comparison of water-based TES systems costs

3.2. Latent Heat TES Systems

The working principle of the LH-TES systems is based on the storage medium or PCM. This study evaluates a selected number of PCMs based on their suitability and phase change temperature for LTDH applications. The most relevant thermo-physical properties of the selected PCMs are shown in Table 3. This is the technical data used as input for the analysis. PCMs are sorted according to their T_{pc} suitable for: (1) Low-Temperature DH, (2) Very Low-Temperature DH, and (3) Ultra-Low-Temperature DH.

In general, among PCMs, salt hydrates have a higher *volumetric latent heat capacity* ($\rho \cdot \Delta h_{pc}$) and higher thermal conductivity, with the drawbacks of toxicity and more weight. Organic compounds have lower thermal conductivity which results in lower thermal power output for the TES system, and cannot compete in terms of performance with inorganic PCMs.

As seen from Table 3, with respect to volumetric heat storage density when considering the LTDH applications, PCMs show a better performance than water for the LTDH temperature range: the PCMs storage density is about two to three time that of water. Since PCM storage density is less sensitive to variations in its operating temperature, if this range narrows further and as long as it is still within the T_{pc} range, PCM performance would be even higher in comparison to water-based systems.

The costs of LH-TES systems are considerable higher than water-based systems due to the PCM cost. As seen from Figure 4 and Table 4**,** based on [32-34], the cost per cubic meter of storage for the selected materials starts from 3k EUR/m^3 approximately, which is 6 times higher than a small-scale water-based SH storage application (Figure 3). However, due to the higher volumetric heat storage density, in terms of energy storage cost, the cheapest LH-TES system starts at 45 EUR/kWh, which is 4 times in average the cost of a similar SH-TES application.

The results show that water-based SH-TES systems are considerably cheaper than LH systems. In the case of the cheapest commercially available PCM, a small-scale system is around 3.75 times more expensive, and in the optimal range for SH-TES systems above 1000 m^3 storage size, the water tank could be even 10 times cheaper. Table 5 shows a comparison of estimated costs and volumes of two TES systems. As the heat storage size

Table 3: Thermo-physical properties of the storage media included in this study. Based on [15–18]

PCM	Phase Change Temperature *°C*	Latent Heat Capacity (solid-liquid) *kJ/kg*	Specific heat capacity (solid/liquid) *kJ/kg_K*	Density (solid/liquid) *kg/m³*	Volumetric Storage Density @ ΔT = 40°C *kWh/m³*
$Ba(OH)_2*8\cdot H_2O$	78	265	1.17 / 0.823	2180 / 2076	184.52
Paraffin C-34	75.9	269	2.604 / 2.981	920 / 795	90.66
Paraffin C-33	73.9	268	2.604 / 2.981	920 / 795	90.41
$Al(NO_3)_2*9\cdot H_2O$	72	155	0.336 / 0.496	1400 / 1333	64.49
Stearic Acid	67	195	1.763 / 2.35	1017 / 848	71.09
Paraffin 5838	49	189	2.1 / 2.5	912 / 769	64.07
$MgSO_4*7\cdot H_2O$	49	202	1.76 / 3.31	1152 / 1208	97.50
$Na_2S_2O_3*5\cdot H_2O$	49	210	1.46 / 2.4	1730 / 1620	131.83
Paraffin P116	46.5	210	2.1 / 2.5	817 / 786	69.05
$Zn(NO_3)_2*4\cdot H_2O$	45	110	1.34 / 2.26	2065 / 2024	103.27
Lauric Acid	43	178	2.14 / 2.15	1007 / 870	68.64
Paraffin 6106	43	189	2.1 / 2.5	910 / 765	63.34
Methyil-12	42.5	123	2.01 / 2.05	1049 / 906	55.21
$CaCl_2*6\cdot H_2O$	42	162	1.42 / 1.43	1710 / 1562	85.11
$Na_2HPO_4*12\cdot H_2O$	40	279	1.55 / 3.18	1520 / 1442	156.44
$Zn(NO_3)_2*6\cdot H_2O$	36	134	1.34 / 2.26	2065 / 1967	119.29
Water (H_2O)	(0)*	(334)*	(2.025)* / 4.187	(916.8)* / 998.3	45.9

() Value outside LTDH operating temperature range*

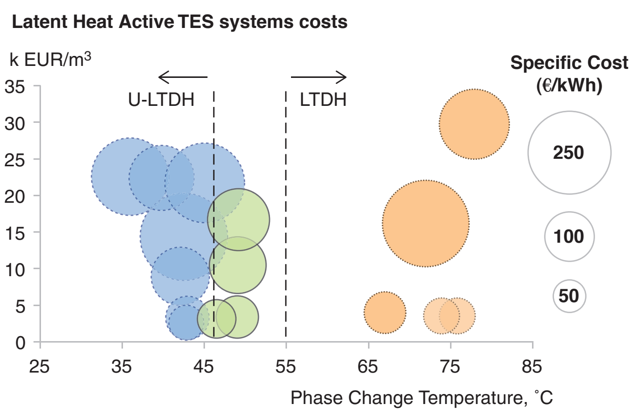

Figure 4. Comparison of Latent Heat TES systems costs (small-scale)

increases, the LH system becomes even more costly in comparison. Still, a LH-TES system occupies half of the volume of a SH system with the same storage capacity. On the other hand, when considering a narrow operating temperature range such as during summer (supply/return temperatures: 65/50 °C) a small-scale LH-TES system would be just 1.5 times more costly than the water-based system.

It is also important to note that within LH-TES systems costs the PCM itself takes the larger share, while in SH systems the tank is the item with the highest cost (see Table 2). This supports the statement that for small-scale distributed TES system applications for LTDH, the balance of cost-efficiency becomes more advantageous for LH solutions when size (occupied volume) and other factors are taken into account, and particularly in the future, when PCM costs are expected to drop.

3.3 Overall Discussion & Recommendations

When choosing a suitable LH-TES system it is necessary to select a PCM whose phase change temperature is adequate to reach full melting/solidification within the application operating temperature range. In this regard, differences due to hysteresis should also be considered by comparing the heating and cooling cycles of the PCM. Moreover, in the case of full TES systems, the temperature range applicable to the storage material is further reduced by the temperature difference necessary for heat exchange [19], and should also be taken into account when selecting the appropriate storage medium.

In DH network applications, SH-TES systems performance is more sensible to variations on the network operating deltaT (supply/return), and so when

Table 4: Comparison of selected LH-TES systems costs (small-scale systems)

PCM	Phase Change Temperature *°C*	Estimated/potential Wholesale Price *USD/kg*	Estimated System Cost *EUR/kWh*	*k EUR/m³*
$Ba(OH)_2*8\cdot H_2O$	78	8.78	179.47	33.1
Paraffin C-34	75.9	1.94	45.58	4.1
Paraffin C-33	73.9	1.94	45.72	4.1
$Al(NO_3)_2*9\cdot H_2O$	72	8.64	281.05	18.1
Stearic Acid	67	1.94	63.95	4.5
Paraffin 5838	49	1.94	63.66	4.1
$MgSO_4*7\cdot H_2O$	49	5.27	122.67	12.0
$Na_2S_2O_3*5\cdot H_2O$	49	5.74	141.50	18.7
Paraffin P116	46.5	1.94	53.46	3.7
$Zn(NO_3)_2*4\cdot H_2O$	45	7.44	235.44	24.3
Lauric Acid	43	1.32	44.88	3.1
Paraffin 6106	43	1.94	64.20	4.1
Methyil-12	42.5	10.44	293.58	16.2
$CaCl_2*6\cdot H_2O$	42	2.97	118.84	10.1
$Na_2HPO_4*12\cdot H_2O$	40	9.13	159.77	25.0
$Zn(NO_3)_2*6\cdot H_2O$	36	7.44	211.13	25.2

Table 5: Performance comparison example of Sensible Heat and Latent Heat systems

Energy stored (kWh)	Volume (m^3) *Paraffin c-33*	*Water*	Cost (k€) *Paraffin c-33*	*Water*
500	6.7	12.1	16.4	4.4
1000	13.0	23.5	32.8	8.8
5000	63.0	114.3	163.0	43.3
10000	122.6	222.2	323.3	85.2

LTDH operation is in place, short-term SH-TES systems risk operating at lower volumetric heat storage densities than that originally designed for. With respect to LTDH, with supply/return temperatures lower than 60 °C/30 °C, latent heat becomes more convenient due to the reduced operating temperature range, compared to SH-TES applications 100 °C/60 °C, and volumetric heat storage density becomes a more relevant indicator.

When comparing the cost-efficiency of the SH and LH systems, still the main disadvantage of LH systems is the PCM cost. In this study we used retail prices of several PCM which are not sold in large quantities and are relatively high and approximated their wholesale prices. It is expected that these prices will drop in the future. Therefore, as this study used a fixed average multiplier, in reality some materials will have a steeper cost reduction than others and it will be beneficial for LH-TES systems cost-efficiency.

In reality the DH operating temperature range varies throughout the year, for instance, supply temperatures are higher during winter and return temperatures are higher during summer. Thus, the actual operating volumetric heat storage density is also variable because it is a function of the operating deltaT (supply/return). Therefore, it is not possible to assume a constant operating volumetric heat storage density, but a variable one. Consequently, the energy storage cost (EUR/kWh) which depends on the volumetric heat storage density, also varies throughout the year, still in this study it was estimated as an annual average value.

4. Concluding Remarks

This study presented a comparative techno-economic analysis of active TES systems operating with DH networks. Latent heat TES systems are compared to water-based sensible heat TES systems used as baseline.

A qualitative and quantitative assessment of these systems was discussed evaluating their suitability for LTDH operation.

The PCMs review showed a set of LH storage materials suitable for LTDH manly based on their phase change temperature among other factors. However, only a small part of these materials is available in wholesale quantities. The rest are sold in retail quantities which have considerably high prices.

Due to the heat transfer mechanisms of PCMs and the performance of full LH-TES systems, there are some provisions to take into account for the design with LTDH applications. Firstly during the discharging process, the limitations in power output might require the use of the primary network as support to match the loads. Secondly, during the charging process the HTF at the system outlet should be directed to a sink/load, and not to the primary return, in order to avoid high return temperatures.

Typical small-scale SH-TES systems such as water tanks operate with an average 50 kWh/m^3 volumetric heat storage density, so their energy storage cost is around 10 EUR/kWh. However when considering a narrow operating temperature range such as during summer (supply/return temperatures: 65/50 °C) the actual operating cost range may reach 20 EUR/kWh.

Regarding volumetric heat storage density, PCMs have overall a better performance than water. However, the costs of LH-TES systems are considerable higher than SH systems due to the PCM cost. Regarding the energy storage cost, active LH-TES systems start at 45 EUR/kWh, which is 4 times the cost of a similar small-scale SH-TES application. On the other hand, within a narrow operating temperature range (supply/return temperatures: 65/50 °C) the LH system would be just 1.5 times more costly than the water-based system.

It is also concluded that although active LH-TES systems are still more expensive than SH-TES, from 1.5 to 4 times more, it is expected that The PCMs costs will decline in the future making them more competitive. In addition, the LH-TES systems occupy half of the required volume by the SH systems. Thus, considering distributed TES systems integrated to LTDH, small-scale active LH-TES systems become more advantageous when size (volume), availability and other factors are taken into account.

In the future, as active LH-TES systems will be more integrated with the 4th generation DH technologies, it will be relevant to analyse the impact of these systems on the main network, as well as the benefits for suppliers and LTDH customers. The technology will have the potential to reduce marginal costs of heat supplied to the LTDH subnets by shifting loads and decreasing peak loads, making it more cost-competitive.

This work explored additional possibilities for enhancing the next generation of DH technologies through active LH-TES, and shows some of the benefits and challenges to enable the creation of smarter, more efficient networks for the future energy system.

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References

[1] H. Lund, B. Möller, B.V. Mathiesen, and A. Dyrelund (2010) The role of district heating in future renewable energy systems. Energy; 35 (3): pp. 1381–1390, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2009.11.023

[2] U. Persson and S. Werner (2011) Heat distribution and the future competitiveness of district heating. Applied Energy; 88 (3): pp. 568–576, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2010.09.020

[3] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J.E. Thorsen, F. Hvelplund, and B. Vad Mathiesen (2014) 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy; 68: pp. 1–11, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2014.02.089

[4] H. Lund, P.A. ∅stergaard, D. Connolly, I. Ridjan, B.V. Mathiesen, F. Hvelplund, and P. Sorknës (2016) Energy Storage and Smart Energy Systems. International Journal of Sustainable Energy Planning and Management; 11: pp. 3–14. ISSN: 2246-2929. http://dx.doi.org/10.5278/ijsepm.2016.11.2

[5] IEA-ETSAP and IRENA. Thermal Energy Storage, Technology Brief E17. 2013. http://www.irena.org/ DocumentDownloads/ Publications/IRENA-ETSAP%20Tech% 20Brief%20E17%20 Thermal%20Energy%20Storage.pdf

[6] T. Nuytten, B. Claessens, K. Paredis, J. Van Bael, and D. Six (2013) Flexibility of a combined heat and power system with thermal energy storage for district heating. Applied Energy; 104: pp. 583–591, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2012.11.029

[7] I. Dinçer and M. Rosen (2001) 3 Thermal Energy Storage Methods. in Thermal Energy, Systems and Applications. John Wiley & Sons; 2001: pp. 83–187, ISBN 0471495735, http://dx.doi.org/10.1002/9780470970751

[8] H. Tanaka, T. Tomita, and M. Okumiya (2000) Feasibility study of a district energy system with seasonal water thermal storage. Solar Energy; 69 (6): pp. 535–547, ISSN 0038-092X, http://dx.doi.org/10.1016/S0038-092X(00)00122-5

[9] M. Martin, and P. Thornley (2012) The potential for thermal storage to reduce the overall carbon emissions from district heating systems. Tyndall Centre for Climate Change Research. http://www.tyndall.ac.uk/publications/tyndall-working-paper/2013/potential-thermal-storage-reduce-overall-carbon-emissions

[10] F. Kuznik, K. Johannes, and D. David (2015) 13 – Integrating phase change materials (PCMs) in thermal energy storage systems for buildings. In: Luisa F. Cabeza, editor. Advances in Thermal Energy Storage Systems. Woodhead Publishing; 2015: pp. 325–353, ISBN 9781782420880, http://dx.doi.org/10.1533/9781782420965.2.325

[11] F. Bruno, M. Belusko, M Liu and N.H.S. Tay (2015) 9 - Using solid-liquid phase change materials (PCMs) in thermal energy storage systems. In: Luisa F. Cabeza, editor. Advances in Thermal Energy Storage Systems. Woodhead Publishing; 2015: 201–246, ISBN 9781782420880, http://dx.doi.org/10.1533/9781782420965.2.201

[12] J.P. da Cunha, and P. Eames (2016) Thermal energy storage for low and medium temperature applications using phase change materials – A review. Applied Energy; 177: pp. 227–238, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2016.05.097

[13] H. Gadd and S. Werner (2015) 18 - Thermal energy storage systems for district heating and cooling. In: Luisa F. Cabeza, editor. Advances in Thermal Energy Storage Systems. Woodhead Publishing; 2015: 467–478, ISBN 9781782420880, http://dx.doi.org/10.1533/9781782420965.4.467

[14] N. Vitorino, J.C.C. Abrantes, and J.R. Frade (2016) Quality criteria for phase change materials selection. Energy Conversion and Management; 124: pp. 598–606, ISSN 0196-8904, http://dx.doi.org/10.1016/j.enconman.2016.07.063

[15] A. Castell and C. Solé (2015) 11 – Design of latent heat storage systems using phase change materials. In: Luisa F. Cabeza, editor. Advances in thermal energy storage, Methods and Applications. Woodhead Publishing; 2015: 285–306. ISBN 9781782420880, http://dx.doi.org/ 10.1533/9781782420965.2.285

[16] A. Solé, H. Neumann, S. Niedermaier, I. Martorell, P. Schossig, and L. F. Cabeza (2014) Stability of sugar alcohols as PCM for thermal energy storage. Solar Energy Materials and Solar Cells; 126: pp. 125–134, ISSN 0927-0248, http://dx.doi.org/10.1016/j.solmat.2014.03.020

[17] A. Sharma, V.V. Tyagi, C.R. Chen, and D. Buddhi (2009) Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews; 13(2): pp. 318–345, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2007.10.005

[18] N. Ukrainczyk, S. Kurajica and J. Šipušic (2010) Thermophysical Comparison of Five Commercial Paraffin Waxes as Latent Heat Storage Materials. Chemical and Biochemical Engineering; 24(2): pp. 129–137, http://hrcak.srce.hr/55015

[19] H. Mehling, S. Hiebler, and E. Günther (2010) New method to evaluate the heat storage density in latent heat storage for arbitrary temperature ranges. Applied Thermal Engineering; 30 (17–18): pp. 2652–2657, ISSN 1359-4311, http://dx.doi.org/10.1016/j.applthermaleng.2010.07.012

[20] J.NW. Chiu, J. Castro Flores, V. Martin, and B. Lacarrière. Industrial surplus heat transportation for use in district heating. Energy 2016; 110: pp. 139–147, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.05.003

[21] M. Deckert, R. Scholz (2014) S. Binder, and A. Hornung. Economic Efficiency of Mobile Latent Heat Storages. Energy Procedia; 46: pp. 171–177, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2014.01.170

[22] N.H.S. Tay, F. Bruno, and M. Belusko (2012) Experimental validation of a CFD model for tubes in a phase change thermal energy storage system. International Journal of Heat and Mass Transfer; 55(4): pp. 574–585, ISSN 0017-9310, http://dx.doi.org/10.1016/j.ijheatmasstransfer.2011.10.054

[23] A. Trp (2005) An experimental and numerical investigation of heat transfer during technical grade paraffin melting and solidification in a shell-and-tube latent thermal energy storage unit. Solar Energy; 79(6): pp. 648–660, ISSN 0038-092X, http://dx.doi.org/10.1016/j.solener.2005.03.006

[24] A. Gupta, R. Mathie & C. N. Markides (2014) An experimental and computational investigation of a thermal storage system based on a phase change material: Heat transfer and performance characterization. Computational Thermal Sciences: An International Journal; 6(4): pp. 341–359. http://dx.doi.org/10.1615/.2014011117

[25] H. Mehling and L.F. Cabeza (2008) 9 – Applications for heating and cooling in buildings. In: Heat and cold storage with PCM. Springer; 2008: 300. ISBN 978-3-540-68556-2, http://dx.doi.org/10.1007/978-3-540-68557-9

[26] J. NW. Chiu, V. Martin, and F. Setterwall (2009) A Review of Thermal Energy Storage Systems with Salt Hydrate Phase Change Materials for Comfort Cooling. In Effstock 2009:

proceedings of the 11th International Conference on Energy Storage; 2009 June 14–17. Stockholm, Sweden. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-26969

[27] F. Colella, A. Sciacovelli, and V. Verda (2012) Numerical analysis of a medium scale latent energy storage unit for district heating systems. Energy; 45(1): pp. 397–406, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2012.03.043

[28] A. Gebremedhin, and H. Zinko (2008) Seasonal heat storages in district heating systems (Säsongvärmelager i kraftvärmesystem). Svensk Fjärrvärme AB; ISBN 978-91-7381-006-7, http://www.svenskfjarrvarme.se/Global/ FJ%C3%84RRSYN/ Rapporter%20och%20resultatblad/ Rapporter%20teknik/2008/S%C3%A4songsv%C3%A4rmelager%20i%20kraftv%C3%A4rmesystem.pdf

[29] H. Kerskes. Seasonal Thermal Storage (2011) State of the Art and Future Aspects. In: RHC Workshop on Thermal Energy Storage; Brussels, Belgium. http://www.rhc-platform.org/fileadmin/Events/4-Kerskes seasonal TES.pdf

[30] J. NW. Chiu, V. Martin, and F. Setterwall (2009) System integration of latent heat thermal energy storage for comfort cooling integrated in district cooling network. In Effstock 2009: proceedings of the 11th International Conference on Energy Storage; 2009 June 14–17. Stockholm, Sweden. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-30636

[31] S.M. Hasnain (1998) Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. Energy Conversion and Management; 39(11): pp. 1127–1138, ISSN 0196-8904, http://dx.doi.org/10.1016/S0196-8904(98)00025-9

[32] OJ. Kosny, N. Shukla and A. Fallahi (2013) Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern U.S. Energy Efficiency & Renewable Energy, Building Technologies Program 2013; U.S. Dept. of Energy. http://www.nrel.gov/docs/fy13osti/55553.pdf

[33] SigmaAldrich Corporation, "Sigma-Aldrich," 2016. [Online]. Available: http://www.sigmaaldrich.com/sweden.html [Accessed 1-20 March 2016].

[34] Molbase, "Molbase.com," April 2013. [Online]. Available: http://www.molbase.com [Accessed 1–31 March 2016].

[35] A. Hasan, S. J. McCormack, M. J. Huang and B. Norton (2014) Energy and Cost Saving of a Photovoltaic-Phase Change Material (PV-PCM) System through Temperature Regulation and Performance Enhancement of Photovoltaic. Energies; 7: pp. 1318–1331. http://dx.doi.org/10.3390/en7031318