The technical and economic feasibility of utilizing phase change materials for thermal storage in district heating networks

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The Technical and Economic Feasibility of Utilising Phase Change Materials for Thermal Storage in District Heating Networks

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Abstract

This study investigates the feasibility of utilizing phase change materials (PCM) for thermal energy storage (TES) within district heating applications (DHN). The increased storage capacity associated with PCM can increase the contribution from LHC technologies and reduce cycling of plant which in turn can increase lifespan and improve the overall system performance. The results suggest that PCM such as Sodium Acetate Trihydrate can be economically and environmentally feasible when utilized for TES in DHN; however, cost reductions of over 50% to approximately £5/kWh are required to provide financial savings over traditional sensible storage solutions such as pressurised hot water tanks. Air pollution and CO2 emissions can be reduced through the increase in heat pump contribution.

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Keywords: Phase Change Material; Thermal Storage; District Heating

1. Introduction

We have investigated the technical and economic feasibility of utilizing phase change materials (PCM) for thermal energy storage (TES) in district heating applications (DHN). We have identified commercially available PCMs and...
suitable for DHN applications. The investigation into methods of integration of PCM into DHNs and a comparison of various PCMs with sensible storage solutions which utilising pressurised hot water stored in insulated vessels has also been conducted. The UK has ambitious targets to reduce carbon emissions by 80% (based on 1990 baseline) by 2050[1]; Scotland go further with targets of reducing greenhouse gases by at least 90% by 2050 [2]. As heating and hot water in UK buildings make up around 40% of our energy consumption and are responsible for 20% of our greenhouse gas emissions, decarbonisation of the heat sector is essential to meet these targets [3]. The UK and Scottish governments recognise DHNs as a key player in decarbonising this sector. DHNs make a good strategic choice as they are technology agnostic, they can be fed by numerous heat sources. DHNs require large capital investment and for these schemes to be economically viable, the operating costs need to be kept to a minimum whilst revenues need to be maximised. DHN typically utilise pressurised liquid water in insulated steel tanks to store energy to support the operation of low zero carbon (LZC) technologies. Thermal stores allow operators to de-couple heat generation from heat demand thus maximising economic performance, for example: minimising cycling, taking advantage of variable tariff structures, and minimising the capacity of peaking plant. The main challenges associated with storing energy in water tanks for DHN applications include:

•Large volumes of water are required to store useful quantities of heat, this is a significant problem for low temperature DHN networks where temperature differences between flow and return fluid are small.

•Thermal stores require a sufficient aspect ratio (typically between 1:2 to 1:3+[4]) to support stratification. As thermal stores tend to be large tall vessels they can provide challenges when trying to locate stores within plant rooms or energy centres. Thermal stores can be installed outside however this can pose a challenge obtaining planning permission as they can be unsightly. To minimise heat losses, the level of insulation will also need to be higher than if they are located internally. Multiple smaller tanks are frequently used however this can significantly increase the required footprint which can be expensive and reduce the footprint of other income generating areas such as retail or commercial areas.

2. Literature review

K. Pielichowska 2014 et al [5] reviewed the present state of PCMs for thermal energy storage and provide an insight into the development of new PCMs with enhanced performance and safety. The study concludes that investigations over the past three decades have given PCMs significant advantages over sensible systems including; lower mass and volume of systems, higher storage densities and lower losses. The study also identifies that inorganic compounds have a higher latent heat per unit volume and higher thermal conductivity than organic compounds. The paper includes data on melting points, heat of fusion, thermal conductivity and density of various PCM. The paper gives a comprehensive overview of various types of PCMs, including advantages and disadvantages of organic, inorganic and eutectic compounds. The paper does however suggest that it is difficult to compare PCM technologies due to a lack of an international technical standard for testing PCMs [5]. Sharma et al [6] has undertaken a review of the available thermal energy storage systems incorporating PCM for use in various applications. The study includes a general overview of the various classifications of PCM. J.Pereira da Cunha et al [7] undertook a review of thermal energy storage for low and medium temperature applications using PCMs. The review suggest that organic compounds and salt hydrates are more suitable for applications below 100°C while eutectic compounds are more suitable for applications between 100-250°C. This review also included the thermophysical properties and cost data for a selected number of compounds. The study also reviewed various storage containers and systems for the integration with various process heating and cooling networks. The study concludes that encapsulated system seems more feasible as there are more suitable to integrate into existing systems and have a lower PCM volume ratio. M.Deckert 2014 et al [8] constructed and tested a mobile test rig to identify the economic and technical feasibility of mobile latent heat stores. The prototype consisted of a 20ft container containing approximately 1.3MWh of latent heat and 0.7MWh of sensible heat. Sodium acetate trihydrate was utilised as the storage medium for this analysis. A storage efficiency of between 90-94% was achieved. The study concluded that the economic feasibility of these systems is heavily dependent on the storage capacity (scale), user behavior (number of cycles per year) as well as low cost of heat. The economic feasibility of heat transportation was shown if very low cost (non-utilised, waste) heat is available to charge the system [8].
3. Methodology

A database was generated and PCM were sorted based on melting temperature and heat of fusion and cost. The PCMs selected must be suitable to be charged from a Low Zero Carbon (LZC) heat sources such as heat pumps, combined heat and power generators or Energy from Waste (EfW) facilities therefore a temperature range of 40-90°C has been selected. This temperature range is also compatible with typical DHN within the UK. A PCM material can only be suitable for thermal storage if it meets the following criteria; safe/non-toxic, low cost, sustainable and has a high energy density. All these parameters must be considered when selecting and comparing suitable PCM for TES. The PCMs identified from the initial literature review include; Sodium Thiosulfate Pentahydrate (H10Na208S2), (SoTP), Sodium Acetate Trihydrate (CH3COONa3H20), (SAT), and Barium Hydroxide Octahydrate (BaH18O10), (BHO). Cost data has been obtained based on bulk quantities (>1000kg) of base PCM from the online marketplace Alibaba [9]. There are various methods of integrating PCM TES into DHN including compact beds, finned heat exchangers, encapsulation etc. The heat exchanger type considered in this study are based on a PCM/Water type arrangement. The most appropriate method identified in this study is utilising finned copper heat exchanger housed in an insulated vessel. Technical data from Sunamp has been used to reverse engineer the Sunamp cube to improve cost estimates of the encapsulation and heat exchanger system for other PCMs [11]. The melting point of these materials make them suitable for networks operating at different temperature regimes as highlighted below in Table1. This study assumes that the PCM is charge by a water source heat pump (WHP) operating above the melting point but a DHN operating with a flow temperature just below to maximise energy storage within the latent phase of the material.

Using the Sunamp Cube data sheets it is estimated that for a 1m³ PCM store containing SAT under the operating temperatures stated above in Table1 contains approximately 435kg of PCM, 313kg of copper (heat exchanger) and 657kg of water. Assuming a storage efficiency of 95% the available stored energy is 54kWh. The mass and energy stored in the vessel material has been excluded as this is negligible. Based on high level budget prices provided by Sunamp of £75-£150/kWh, the base material only equates to 2-5% of the total cost of the storage system. This ratio has been applied to all other PCMs in this study for modelling purposes. These results suggest that the cost variation of the actual material has a very small impact on the overall cost of the system. In order to investigate the impact of scale on the feasibility of PCM thermal storage three network scenarios have been designed, costed and modelled. Each scenario is based on a purpose-built energy centre comprising of heat pumps, gas fired boilers, thermal storage and all associated DHN equipment such as distribution pumps, water treatment pressurisation and expansion equipment. The three scales include; small scale (block of 50 flats), medium scale (10 blocks of 50 flats), and large scale (50 blocks of 50 flats) with a purpose-built energy centre. A two bedroom flat with a floor area of 60m² has been taken as the average property type [12]. The annual domestic hot water (DHW) demand is calculated assuming 80 litres of 40°C hot water per person per day [13]. The peak hot water demand has been diversified as per DS 439 as recommended by the CIBSE CP1 heat network code of practice [14]. The space heating demand is calculated using benchmarks of 30kWh/m²/annum and 60W/m²[13] and diversified using a diversity curve developed by Ramboll. The annual and peak demands for each scenario are included in Table 2. For each scenario the heat pump has been initially sized based on 20% of the peak demand for each scenario in order to achieve over 70% contribution from the heat pump with only 1 hour of storage. Each network has been designed with a maximum pressure of 10 Bar.g. The DHN hydraulic software package System Rorret (SR) has been utilised to design the system. The networks have been laid out in a grid arrangement with EC located in the centre. Each load is equally spaced at 50m intervals. SR produces a pipe schedule which allows the network to be costed. Costs are based on benchmarks for pre-insulated steel pipework from quotations and project specific data. Annual heat losses in the network has been calculated using the Logstor heat loss calculator [15], see Table 2. For SoTP the delivery temperature is not sufficient for generation of domestic hot water (DHW) therefore the assumption is that it’s used to meet the space heat demand but only a portion of the hot water energy requirement. Localised electric boilers are used to boost DHW temperature to 50°C for delivery to outlets.

### Table 1 - PCM DHN Operating Parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting Temp</th>
<th>DHN Flow Temp</th>
<th>DHN Return Temp</th>
<th>Heat Pump Charge Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Thiosulfate Pentahydrate</td>
<td>46(°C)</td>
<td>45(°C)</td>
<td>25(°C)</td>
<td>50(°C)</td>
</tr>
<tr>
<td>Sodium Acetate Trihydrate</td>
<td>58(°C)</td>
<td>55(°C)</td>
<td>35(°C)</td>
<td>60(°C)</td>
</tr>
<tr>
<td>Barium Hydroxide Octahydrate</td>
<td>78(°C)</td>
<td>70(°C)</td>
<td>50(°C)</td>
<td>80(°C)</td>
</tr>
</tbody>
</table>
The energy modelling software EnergyPro was used to generate hourly heat demand data and size and model the contribution of the LZC technology for a typical year using temperature data from Edinburgh for 2017 [16]. EnergyPro was also used to identify the impact of thermal storage on the overall operation of the system. An average diversified hourly profile for a standard week was applied to calculate the hourly heat demand of the network for each scenario. The sensible thermal store is selected in order to provide 1 hour of storage of the heat pump for each network scenario, this is referred to the business-as-usual scenario (BAU). As discussed in M.Deckert 2014 et al [8] storage efficiency of between 90-94% can be achieved. Heat losses in conventional thermal stores can also be very low if suitably insulated therefore the impact of heat losses within the vessels has not been considered within this study as the difference is considered negligible. This could be improved upon in future more detailed energy modelling.

### 3.1. Financial Modelling

Project specific costing data from Ramboll Energy, the Danish Energy Agency and SPONS for conventional thermal storage DHN and Energy Centre components were utilised to undertake a whole lifecycle cost analysis of the system. There are several companies producing PCM for commercial applications such as thermal storage and the automotive industry however many of these companies have patents pending therefore it is challenging obtaining the thermochemical properties of commercially available PCMs. A discounted cashflow model has been generated to compare the various PCM at various scales of network to understand the overall impact of PCM TES can have on the economics of a DHN. The cashflow model includes a sensitivity analysis to investigate the impact of several key variables including; capital costs, heat sales price, cost of electricity and RHI rates. The heat sales price is based on a 10% saving over the alternative cost of heat, in this case individual gas boilers. This cost includes cost of gas, O&M, insurance and the annualised capital cost of boiler. A heat sales price of 10.5p/kWh has been applied to all scenarios. The renewable heat incentive (RHI) is a government subsidy which pays the network operator for every kWh produced from renewable source such as heat pumps. Payment for heat pumps is based on a two tariffs structure where 9.09p is paid for the first 1,314 full load equivalent hours from the heat pump whilst 2.71p is paid on the remaining heat produced by the heat pump [17]. This scheme runs for a 20-year period after which payments stop.

### 4. Results and Discussions

SoTP has been identified as a suitable PCM for thermal storage due to its heat storage capacity and relatively low cost however like SAT supercooling, decomposition and phase segregation limits its practical application [12]. To overcome these issues “MicroPCM” can be utilised which are small “core-shell structure capsules” with a PCM material (salt hydrate) coated by a shell. The advantages of microPCM include; Preventing leakage of the melted PCM during phase change process, increasing heat transfer area, and controlling the volume change of PCM during phase change [12]. The testing carried out by Liu 2017 [12] concluded that the thermal stability of the SoTP can be improved by micro-capsulating the SoTP with a silica shell. The results from the testing identified that after the encapsulation of the SoTP the thermal conductivity can be improved from 0.6035 to 0.7718 W/m°C which represents an increase of 27.9%. The study concludes that that Sodium Thiosulfate/ silica microPCMs have great potential for utilisation in thermal energy storage applications. Further testing is essential to understand the degradation of the material under cycling. No data could be found on the lifespan or long-term performance of this material. No commercially available products that utilise this material have been identified during this study. These issues described will make this material challenging to integrate into a network utilising the proposed heat exchanger arrangement proposed in this study and would need to be overcome if to be widely implement in similar applications.

### Table 2 - Scenario annual and peak DHW and space heating demands

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Annual Space Heating Demand (MWh)</th>
<th>Annual DHW Demand (MWh)</th>
<th>DHN Heat Losses (MWh)</th>
<th>Peak Space Heating Demand (kW)</th>
<th>Peak DHW Demand (kW)</th>
<th>Total Peak Demand (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>189.7</td>
<td>187.24</td>
<td>6.6</td>
<td>113</td>
<td>187</td>
<td>187</td>
</tr>
<tr>
<td>2</td>
<td>1897.3</td>
<td>1872.4</td>
<td>66.7</td>
<td>1117</td>
<td>921</td>
<td>1117</td>
</tr>
<tr>
<td>3</td>
<td>9486.3</td>
<td>9361.9</td>
<td>352.3</td>
<td>5581</td>
<td>3506</td>
<td>5581</td>
</tr>
</tbody>
</table>

The energy modelling software EnergyPro was used to generate hourly heat demand data and size and model the contribution of the LZC technology for a typical year using temperature data from Edinburgh for 2017 [16]. EnergyPro was also used to identify the impact of thermal storage on the overall operation of the system. An average diversified hourly profile for a standard week was applied to calculate the hourly heat demand of the network for each scenario. The sensible thermal store is selected in order to provide 1 hour of storage of the heat pump for each network scenario, this is referred to the business-as-usual scenario (BAU). As discussed in M.Deckert 2014 et al [8] storage efficiency of between 90-94% can be achieved. Heat losses in conventional thermal stores can also be very low if suitably insulated therefore the impact of heat losses within the vessels has not been considered within this study as the difference is considered negligible. This could be improved upon in future more detailed energy modelling.
SAT is an incongruently melting salt hydrate and suffers from phase separation especially over repeated cycling [18]. Dannemand [18] investigated using stable supercooling of SAT which makes it possible to store thermal energy partly loss free. The study suggests that cycling stability phase separation can be avoided by using the thickening agents such as carboxymethyl cellulose or xanthan rubber [18]. The purpose of a thickening agent keeps the segregated salt from settling to the bottom of the container. Supercooling is when a PCM in liquid state cools down below melting point without solidifying, leaving it in a metastable state where the latent heat of fusion is not released. This can be avoided by using a nucleation agent such as Aluminium Nitride Nanoparticles or various salts [18]. The volume of SAT increases by 10% when changing phase between solid and liquid. This needs to be considered when designing a storage vessel [18]. Sunamp use a variant of SAT with both a nucleator and a stability enhancer to prevent phase separation and degradation [11] offering various scales and types thermal store batteries for solar thermal storage including Sunamp Cube with plans to develop a large container scale planned system (1.5-4MWh per container). There patent material PCM-58 has a tested lifespan of >36,000 cycles without degradation. It is this extensive testing and proof of longevity that makes this material the most suitable PCM for TES in DHN applications considered in this study. BHO is the crystalline hydration salt with high latent heat density when compared to other PCM within the temperature regime considered suitable for DHN applications [19]. There are however significant challenges associated with developing BHO PCM for thermal storage applications. Anhydrous barium hydroxide when exposed to air can react with CO2 to form barium carbonate therefore the container must be well sealed [20], barium salt (with solubility) is toxic and can cause severe dermatological and cardiac problems. The melting temperature does increase slightly with the number of cycles but not noticeably. Very little change in thermal properties was witnessed, the testing also concluded that supercooling does not occur. The main disadvantage is the toxicity and corrosiveness of the material however this could be managed with suitable container design and safe methods of work [20]. More testing would however be required with a higher number of thermal cycles to evaluate its suitability for DHN application where the store could cycle daily for up 25-30 years. No commercially available PCM products utilising BHO have been identified. The lack of data and testing along with the issues with corrosiveness make this material less attractive than alternative material considered in this study, in particular SAT. Under scenario 1 the contribution from the heat pump increases by over 8.5% while scenario 2 and 3 increase by approximately 5%. The reason why the largest increase in heat pump contribution occurs in scenario 1 is due to diversity of heat demand. As there are relatively few customers the peak to base load ratio is very high or can be considered “peaky”. In scenario 3 where there are a larger number of customers the diversity on the network is higher therefore the duration curve is less “peaky” This suggests that even though economies of scale do not benefit the financial performance of smaller systems increased levels of thermal storage has a bigger impact on small systems (in terms of %) than in large systems. The impact of PCM would have an even large overall impact in a single dwelling when compared to a network. This increase in contribution leads to reduced gas consumption and increase RHI revenue. The impact of these increases in contribution per annum and over the life time of the project (25 years) are included below in Table 3 for each scenario in terms of net present value (NPV, £k) compared to the BAU. The results in all scenarios show the BAU outperforming the scenarios where PCMs is used for thermal storage. With scenario 1 indicating the least negative impact when compared to the BAU. In Scenario 3 however both the BAU and PCM scenarios generate positive net present values which suggest that these schemes are financially viable based on a discount rate of 3.5% over 25 years.

Table 3 - Financial Results (NPV, £k)

<table>
<thead>
<tr>
<th>Network</th>
<th>SoTP (NPV, £k)</th>
<th>SAT(NPV, £k)</th>
<th>BHO(NPV, £k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 BAU, (NPV, £k)</td>
<td>-£1,256.1</td>
<td>-£1,256.1</td>
<td>-£1,254.7</td>
</tr>
<tr>
<td>Scenario 1 Results, (NPV, £k)</td>
<td>-£1,269.5</td>
<td>-£1,270.3</td>
<td>-£1,264.3</td>
</tr>
<tr>
<td>Scenario 2 BAU, (NPV, £k)</td>
<td>-£2189.5</td>
<td>-£2196.6</td>
<td>-£2155.8</td>
</tr>
<tr>
<td>Scenario 2 Results, (NPV, £k)</td>
<td>-£2487.6</td>
<td>-£2522.8</td>
<td>-£2344.5</td>
</tr>
<tr>
<td>Scenario 3 BAU, (NPV, £k)</td>
<td>£4,821.2</td>
<td>£4,817.2</td>
<td>£4,822.1</td>
</tr>
<tr>
<td>Scenario 3 Results, (NPV, £k)</td>
<td>£4,653.3</td>
<td>£4,632.1</td>
<td>£4,722.2</td>
</tr>
</tbody>
</table>

RHI can have a significant impact over the lifespan of a district heating project; over £250k is generated in revenue in scenario 3. This revenue is essential to ensure a positive cashflow for these systems based on current prices. The
increased utilisation also has a benefit towards CO2 and NOx emissions. The carbon emissions associated with the heat pump is based on long run marginal figures published by BEIS [21]. In scenario 1 approximately 80 tonnes are saved over 25 years. In scenario 2 around 450 tonnes is saved while in scenario 3 over 2,100 tonnes is saved over 25 years. NOx emissions have not been modelled as part of this study however air pollution is currently politically very important in regions such as London and is arguably driving the change away from combustion through gas boiler and gas-fired CHP more so than a reduction in carbon emissions

5. Conclusions

The study has identified that there are various PCM which are suitable for integration into DHN applications for thermal storage however SAT appears to be the most feasible. It has undergone the most vigorous testing and there are commercially available systems utilising the material. It is also safe, non-toxic, non-corrosive, relatively cheap and has been proven to have limited degradation over a high number of cycles essential for DHN applications. In order to compete with conventional thermal storage system which, utilise stored pressurised hot water; the cost of the PCM storage device needs to reduce down to approx. 57£/kWh which would equate to over a 50% reduction. This study concludes that PCM TES can be technically and economically feasible as well as can provide environmental benefits by reducing a schemes CO2 and NOx emissions. The study assumes that the PCM is located centrally however there could be additional benefits by distributing storage throughout the network or at customer connections. The reduction in flow rates could also lead to smaller DHN pipework and customer connections, leading to reduced capital costs and a reduction in heat losses within the distribution network. Variable tariff scenarios have not been considered, LZO can be controlled to operate to maximise these low-tariff periods to further improve the economic performance. This would allow an operator increase heat pump operation during low tariff periods and utilise stored heat during high tariff periods. Utilising different types of PCM layered or in series can mimic stratification which can provide further benefit to the system.

Acknowledgements

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