Environmental and Climate Technologies
2023, vol. 27, no. 1, pp. 516–531
https://doi.org/10.2478/rtuect-2023-0038
https://content.sciendo.com

Economic Analysis of Mobile Thermal Energy Storages as Complement to District Heating

Alois RESCH[1]*, Harald DEHNER[2]

[1,2]*University of Applied Sciences Upper Austria, School of Engineering, Stelzhamerstrasse 23, A-4600 Wels, Austria*

Received 29.03.2023; accepted 30.06.2023

Abstract **– Urban areas are increasingly supplied by district heating networks (DHN) because this technology is reliable, provides easy handling for the customer and contributes to the required reduction of greenhouse gas emissions if it is operated from renewable sources. Waste heat from the industrial sector can serve as such, however, industrial plants are often not in the meaningful range of DHN, as they are mostly located in the periphery. For this reason, the application of mobile thermal energy storages (M-TES) is investigated by the present research work. M-TES systems are technically capable of exchanging heat between a DHN and heat sources or heat sinks, as previous studies have shown, but economic viability could not be reached with former energy prices. However, geopolitical incidents of 2022 resulted in massive fluctuations on the energy markets and unpredicted price increases. Therefore, this paper provides an updated analysis of M-TES, considering the premises of 2022. An economic model according to VDI2067 was developed for calculating the costs of transported heat for different storage technologies and materials. Moreover, transportation by a Diesel driven truck was compared to an electric driven one. The updated analysis yielded economic feasibility for specific M-TES configurations, achieving minimum heat costs of € 89.5 per MWh. This is equivalent to a reduction of 40.3 % related to the prices of conventional district heating in Austria by end of 2022.**

Keywords **– Economic evaluation; heat transfer network; industrial excess heat; waste heat recovery.**

1. INTRODUCTION

District heating networks (DHN) are an important backbone of today´s heat supply with high potential to contribute to a reduction of greenhouse gas emissions if their heat sources are increasingly transformed into renewable ones [1]–[4]. However, an economically viable application of such networks requires adequate occupancy rates and power density along the lines, because the infrastructure causes significant effort in terms of investment, operation, and maintenance [5]–[7]. This is one of the reasons, why DHN are mostly implemented in urban regions. On the other hand, industrial plants are not always located within the meaningful range of DHN, although they require huge amounts of heat as well as release significant amounts of waste heat, depending on the specific industrial sector [8], [9].

The utilisation of mobile thermal energy storages (M-TES) can be a possibility to close the gap of energy transfer between a DHN and remotely located industry or even directly between two or more industrial plants. The supply of residential heat demand can also be a potential

* Corresponding author.
E-mail address: alois.resch@fh-wels.at

scenario for the application of M-TES. The intention of this approach is to transfer heat by charging a mobile heat storage at the producer and transfer it to the consumer by means of common transport and available infrastructure, e.g. by a truck on the road, as illustrated in Fig. 1.

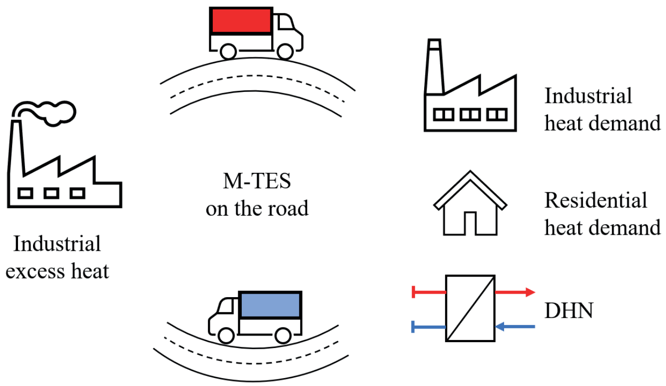

Fig. 1. Schematic illustration of the M-TES concept.

In this way, the M-TES concept could serve as a complementary heat supply technology for regions without DHN or it could even be a competitor to DHN for the case that it might be economically advantageous.

M-TES was already investigated in the past with different approaches and various material configurations, also by experimental implementation, and mostly with a focus on the economic viability of this concept [10]–[12]. An M-TES system working with the phase change material (PCM) Erythritol for providing heat energy for detached houses was investigated by Li *et al.* [13]. One conclusion of their study was that the storage material costs had the highest influence on the total costs of delivered heat, which resulted in $ 30 to $ 60 per MWh in the year 2012. Deckert *et al.* [14] considered another type of PCM for their research on M-TES, which was Sodium Acetate Trihydrate (SAT). Compared to Erythritol, SAT offers a melting point of 59 °C, which meets the requirements for supplying residential heat demand. With a distance of 6 km between a biogas plant as heat source and a small heat network with residential heat sinks, the heat generation costs were calculated to € 50 per MWh, which was a clear benefit compared to the average price of district heat of € 74 per MWh in 2014 in Germany. Although, the profitability of M-TES depends on the transported storage capacity, the number of transportation cycles and the availability of low-cost or even costless waste heat. A comparison of potential storage materials and different types of transportation containers was provided by Guo *et al.* [15], combined with an economic evaluation of different M-TES configurations. This overview shows the wide temperature range of 50 °C to 350 °C that can be addressed by M-TES with available storage materials. Furthermore, the bandwidth of resulting heat costs was calculated by € 20 to € 80 per MWh in 2018, under the premise that the required waste heat is available for free. Guo *et al.* also provided two potential improvement aspects for M-TES. Firstly, not only waste heat should be considered for being transported by mobile solutions, but also any other renewable heat, like solar thermal generated heat, biomass heat, or geothermal heat. Secondly, zero-emission vehicles should be applied in the future for transporting emission-free heat. By contrast to this technical research, Yang *et al.* [16] focussed on the economic performance of M-TES approaches and investigated their dynamic supply chain by numerical modelling. In 2022, Fritz *et al.* [17] presented an economic evaluation of innovative forms of heat transportation, e.g. excess heat distribution through sewer networks or ammonia-water absorption cycle technology. Both grid-bound and grid-free approaches of heat supply were considered and compared to conventional DHN. The calculated levelised costs of transported heat ranged from € 4 to € 260 per MWh, depending on the heat demand and the transportation distance. DHN appears to be the most economical solution for long distances and high amount of heat, whereas M-TES using PCM is favourable for distances below 7 km and transported heat amounts of lower than 700 MWh/a. Guo *et al.* [18] provided an insight into policies and regulations with regard to M-TES in China. PCM were seen as the most promising storage materials, especially Erythritol and SAT, transported by a truck on the road. As Erythritol has a melting point of 118 °C, the charged M-TES is transported with at least this temperature and is therefore subject to the legal regulations of dangerous goods in China. This increases the effort for such M-TES configurations, compared to the utilisation of SAT as storage material with a melting point of 59 °C. Remarkably, M-TES is already supported by national funding schemes of China. By contrast to PCM, Fujii *et al.* [19] worked on the investigation of thermochemical storage materials (TCM) for M-TES, which was Zeolite in this case. A new design of this storage system was provided, containing an amount of 4 t of Zeolite, and assuming a transportation distance of 3 km. The conducted life cycle assessment confirmed that the considered M-TES configuration can reduce greenhouse gas emissions, based on the given assumptions. Practical experience with M-TES could be obtained by the development and operation of a demonstration plant in Germany, as reported by Krönauer *et al.* [20] and Hauer *et al.* [21]. In this case, also Zeolite was used as storage material for transporting heat from a waste incineration plant over a distance of 7 km to an industrial consumer for supporting a drying process. The amount of transported heat was 1092 MWh/a, resulting in total energy costs of € 73 per MWh in 2014. At this time, the M-TES concept competed with low costs of conventional energy of € 36 per MWh, and therefore, the demonstration plant was economically not feasible.

As energy markets had to face unknown fluctuations in 2022, the research work presented by this paper had the aim to analyse the M-TES concept for the current situation. Therefore, a comprehensive economic evaluation was performed, based on VDI2067 [22], for calculating the costs of transported heat (*COTH*) for M-TES. This investigation was done for the three main types of heat storing mechanisms, namely sensible, latent and thermochemical storages. In each category, several material types were considered to meet possible requirements of the specific application, e.g. in terms of temperature demand. This updated analysis of M-TES yielded positive results for thermochemical and latent storage materials, as the *COTH* are significantly lower than the heat costs of DHN in Austria in 2022.

2. METHODS AND METHODOLOGY

Compared to other studies, Krönauer *et al.* [20] presented a realised M-TES system based on Zeolite and monitored its operation over one year. Furthermore, the calculation of the costs of heat is documented in a detailed way, providing the possibility to reproduce the economic evaluation. Due to these reasons, the system of Krönauer *et al.* was chosen as a basis for the present analysis of the M-TES concept for the energy prices in 2022 and for various technical configurations.

2.1. Overview of methodological approach

The detailed methodological process of the performed investigation is depicted in Fig. 2. The economic data of Krönauer *et al.* was used to develop a replication of the heat cost calculation for 2014 according to the annuity method described by VDI2067 [22]. Some details of the economic calculation parameters, e.g. personnel costs of the truck driver, had to be adapted within a loop, until the results of the developed calculation model were equal to the reference results. For transferring the heat costs of 2014 into the year 2022, the customer price indices (CPI) for Austria from 2014 to 2022 [23] were applied to all cost categories affected by inflation. From this point, the developed and updated cost calculation model was used to analyse different configurations of the M-TES concept. On the one hand, thermochemical, latent and sensible storing of heat was considered, and on the other hand, various kinds of storage material were analysed for each storage technology. Furthermore, a comparison between electric and Diesel driven trucks was implemented in the model.

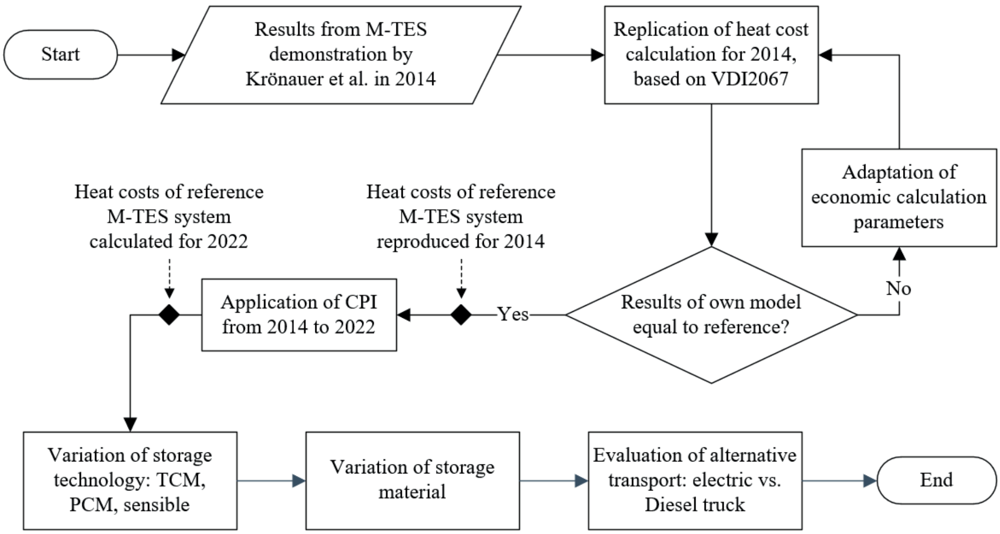

Fig. 2. Visualisation of the applied methodological process.

2.2. Calculation of heat costs

The annuity method described by VDI2067 [22] is the basis for the presented calculation of heat costs caused by M-TES systems, combined with slight adaptations to consider the specific premises of this application.

The total costs for implementing and operating an M-TES system can be split up into three different categories:

- Capital-related costs C_c are investment amounts for the construction of M-TES facilities.
- Demand-related costs C_d are caused by energy demand for operation.
- Operation-related costs C_o cover financial efforts for maintenance and inspection, as well as transportation costs caused by personnel and vehicle.

These cost categories are transformed into annuities by considering an observation period T and a calculative interest rate q. Using these two parameters, the annuity factor a can be calculated as follows in Eq. (1).

$$a = \frac{q-1}{1-q^{-T}} \tag{1}$$

The annuity A_c of the capital-related costs C_c is

$$A_c = C_c \cdot a \tag{2}$$

For the case of ongoing costs, which are C_d and C_o, the price-dynamic cash value factor b has to be introduced. This factor considers discounting of future costs to the initial point in time and takes into account possible increase of energy or personnel costs r in the following years, as displayed in Eq. (3).

$$b = \frac{1-\left(\frac{r}{q}\right)^{T}}{q-r} \tag{3}$$

Therefore, the annuity A_d for the demand-related costs C_d results in

$$A_d = C_d \cdot a \cdot b_d, \tag{4}$$

and the annuity A_o for operation-related costs C_o is calculated by

$$A_o = C_o \cdot a \cdot b_o, \tag{5}$$

where two different kinds of cash value factor are considered for demand-related and operation-related annuity, which are b_d and b_o, respectively. The total annuity A_{tot} adds up the three partial annuities:

$$A_{tot} = A_c + A_d + A_o \tag{6}$$

Dividing A_{tot} by the amount of transported heat Q_{th} between the heat source and the heat sink over a period of one year results in the requested costs of transported heat *COTH:*

$$COTH = \frac{A_{tot}}{Q_{th}} \tag{7}$$

In order to be comparable to other forms of supplying heat, the results of *COTH* are given in €/MWh.

2.3. Boundary conditions

2.3.1. Definitions for the M-TES operation

The following boundary conditions are derived from the reference system of Krönauer *et al.* and are also valid for all investigated M-TES configurations:

- Transported amount of heat: 1092 MWh/a;
- Transportation distance: 7 km;
- Transportation on the road by a semitrailer truck with 40 t gross weight, using two trailers in cyclic operation mode;

– Costs for waste heat: € 5.0 per MWh.

Further applied boundary conditions specific for each case are given in the section "Results" within the corresponding sub-sections.

2.3.2. Customer price index (CPI)

The transformation of the calculated heat costs from 2014 into the year 2022 was done by applying the CPI2010 for Austria [23]. Table 1 in the Appendix lists the CPI2010 for the relevant years from 2014 until 2022 and provides the annual change compared to the previous year. The total change between 2014 and 2022 results in a relative price increase of 21.78 %, which was included in the developed cost model by increasing all relevant cost categories with this factor. In this way, the results of Krönauer *et al.* could be replicated and updated for 2022.

2.3.3. Technical properties and price of storage materials

The technical properties and prices of the investigated TCM, PCM and sensible storage materials were taken from [15], [20], [24]–[28] and are documented in Tables 2 to 4 in the Appendix. As some material costs were given for previous years, they were updated for the year 2022 by applying the CPI2010, accordingly.

2.3.4. Economic parameters for COTH calculation

Similarly to the reference case of Krönauer *et al.*, a value of 5 % was defined for the calculative rate of interest q, and the observation period T was chosen with 15 years, valid for all performed calculations. The detailed assumptions of investment costs are given in Table 5 in the Appendix, required for the calculation of the capital-related costs. Table 6 in the Appendix provides the summary of all demand-related premises and costs, as well as the applied annual increase of waste heat costs. Finally, the operation-related premises and costs for the calculation of *COTH* are condensed by Table 7 in the Appendix.

2.3.5. Boundary conditions for the comparison of Diesel driven and electric driven trucks

The conducted comparison between Diesel driven and electric driven trucks bases on the calculation of the truck operation costs, given in €/km, which are part of the operation-related costs C_o for calculating the total *COTH.* The annuity method described by VDI2067 [22] was used to derive the truck operation costs, based on data of [29], [30]. General boundary conditions were chosen with a truck power of 400 kW, a kilometrage of 100000 km/a, a calculative rate of interest of 5 % and a truck life span of 8 years. The specific capital-related and operation-related premises and costs of both types of drive are given in detail in Tables 8 and 9 in the Appendix.

3. RESULTS

This section provides the resulting *COTH* for different configurations of M-TES systems. The first three sub-sections are dedicated to the specific storing technologies TCM, PCM and sensible storage, each of them considering different kinds of storage materials. The calculated operation-related costs C_o are split up into two segments, which are $C_{o,m+i}$ for maintenance and inspection, and $C_{o,p+t}$ for personnel and transportation, because $C_{o,p+t}$ is varying significantly between the different M-TES configurations. Therefore, its impact becomes more obvious when displayed in a separate cost category. Subsequently, the *COTH* calculation results are summarised and combined with a benchmarking value for conventional district heating networks. Furthermore, an economic comparison between Diesel driven and electric driven trucks yields the impact of fluctuating energy prices on the specific transportation costs.

3.1. Costs of transported heat with TCM

Investigating the M-TES concept with TCM storing technology was done on the one hand for the storage material Zeolite 13X, as it was also used for the demonstrated reference system of 2014 [20]. On the other hand, the *COTH* were also calculated for M-TES using Zeolite 4A, as it is cheaper than Zeolite 13X [24], [25] (see Table 2 in the Appendix).

3.1.1. Replication of the reference system using Zeolite 13X from 2014 and updated calculation for 2022

The verification of the developed cost model for M-TES systems was done by replicating the reference case documented by [20], [21]. The calculated *COTH* resulted in € 73 per MWh, what exactly corresponds to the original investigation of 2014. The segmentation into the single cost categories showed a slight deviation from the results of [20], [21], as the capital-related costs caused 62 % of *COTH* and the costs for personnel and transport were calculated by 23 % of *COTH*. Compared to the replicated results as shown in Fig. 3 (left), this deviation of 1 percentage point each appears to be acceptable.

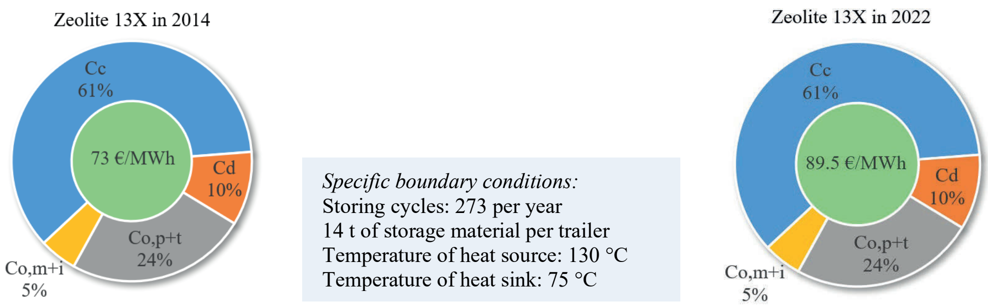

Fig. 3. *COTH* of M-TES using Zeolite 13X and segmentation into cost categories in 2014 (left) and in 2022 (right).

Fig. 3 (right) provides the calculation results of *COTH* for the same M-TES configuration and the same boundary conditions as in the reference system but updated for the year 2022 by including the influence of inflation. In this case, the transported heat had a price of € 89.5 per MWh, while the distribution into cost categories remained unchanged.

3.1.2. M-TES using Zeolite 4A

The use of Zeolite 4A as M-TES material instead of Zeolite 13X reduces the investment costs for the storage material by around 15 %, however, also the energy density decreases from 286 kWh/t for Zeolite 13X to 132 kWh/t for Zeolite 4A [24], [25]. Therefore, this M-TES configuration requires 591 cycles per year for transporting the defined energy amount of 1092 MWh, resulting in *COTH* of € 114.3 per MWh. The financial effort for personnel and transport causes 41 % of the total costs, as illustrated in Fig. 4.

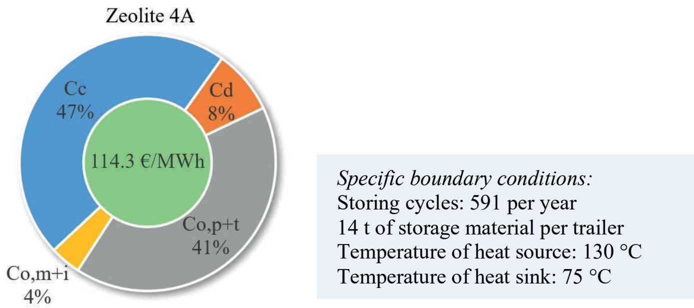

Fig. 4. *COTH* of M-TES using Zeolite 4A and segmentation into cost categories.

3.2. *Costs of transported heat with PCM*

Besides the TCM storing technology, also PCM can be used for realising the M-TES concept. In this study, the materials Erythritol and Sodium Acetate Trihydrate were considered, with melting points of 118 °C and 59 °C, respectively. Compared to TCM, the charging and discharging of PCM storages is done with fluid-based facilities, which were assumed to have reduced investment costs, related to the air-driven charging and discharging stations. Furthermore, heat losses of 5 % by forced convection on the surface of the storage tanks are considered during transportation.

3.2.1. Erythritol as latent storage material

With a melting point of 118 °C, Erythritol could be used for the same application as described in the reference case with TCM, where the heat source supplies 130 °C and the heat sink requires 75 °C. Additionally to the latent heat capacity, also the sensible heat capacity of the phase changing material is covered by the developed model, in the liquid phase between 118 °C and 130 °C and in the solid phase between 75 °C and 118 °C. The investment costs of the charging and discharging stations are considered with a reduction of 15 % compared to TCM. Fig. 5 illustrates the results of the economic calculation with Erythritol, with respect to the given specific boundary conditions. Although 19.5 tons of storage material can be transported per trailer, 492 storing cycles are required per year in order to deliver the defined 1092 MWh. This results in *COTH* of € 105 per MWh.

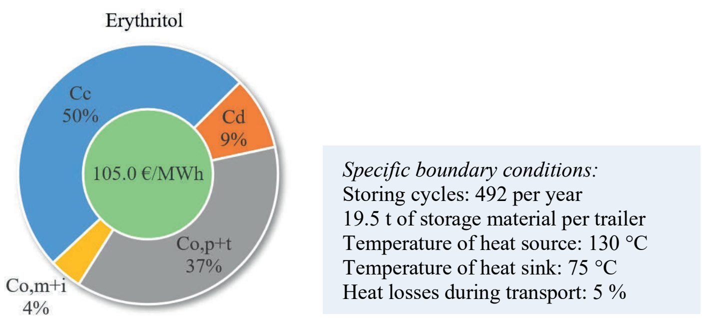

Fig. 5. *COTH* with Erythritol as storage material for M-TES.

3.2.2. Sodium Acetate Trihydrate (SAT) as latent storage material

By contrast to Erythritol, SAT has a melting point of 59 °C, and therefore, it would be suitable for M-TES to supply low-temperature heat sinks, e.g. residential or industrial in-floor heating systems with a flow temperature of 35 °C. The volumetric energy density of SAT is lower than the one of Erythritol, resulting in a higher number of storing cycles per year for transporting the same amount of energy. However, SAT is significantly cheaper, which reduces the *COTH* to € 94.9 per MWh, as displayed in Fig. 6. As the temperatures of heat source and heat sink are below 100 °C, the charging and discharging stations can be driven with water, compared to the M-TES system using Erythritol, and therefore, their investment costs are considered with a reduction of 30 % compared to TCM.

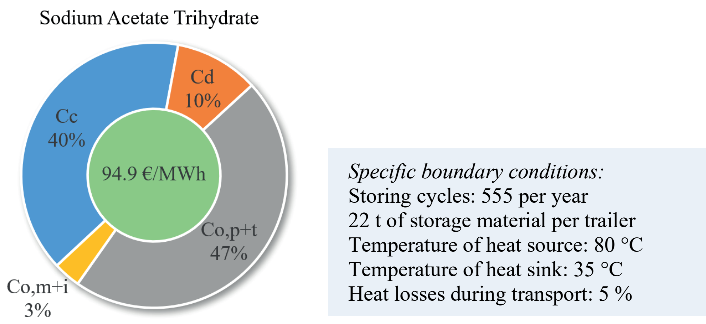

Fig. 6. *COTH* with Sodium Acetate Trihydrate as storage material for M-TES.

3.3. Costs of transported heat with sensible storage

This sub-section summarises the investigation of the M-TES concept with the sensible storing materials water, thermal oil and gravel.

3.3.1. Water as sensible storage material

As water is the most common storage material so far, it can also be considered for mobile heat storages. For the sake of reduced effort, only unpressurised water is investigated for utilisation in M-TES systems, which limits the maximum temperature to 95 °C. Analysing the same low-temperature application for residential or industrial in-floor heating as mentioned above using SAT with a heat source temperature of 80 °C and a heat sink temperature of 35 °C, the *COTH* for M-TES with water results to € 152.7 per MWh. As depicted by the pie chart in Fig. 7, the costs for personnel and transport account for two thirds of the total costs, because the transportation of 1092 MWh per year requires 1284 cycles in this case.

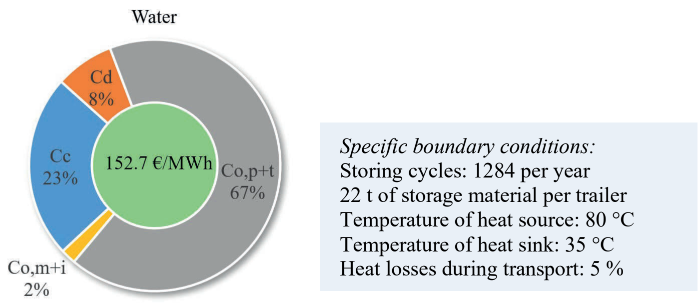

Fig. 7. Calculated *COTH* and distribution of cost categories for M-TES using water.

3.3.2. Thermal oil as sensible storage material

Thermal oil can be a potential storage material for transporting heat with temperatures above 100 °C without pressurisation. The oil considered in this study is a mineral type of the supplier NILS, named Calor 32, with a flash point of 205 °C [27]. Compared to water, its volumetric heat capacity is 50.5 % lower. This requires 2016 storing cycles per year for transporting the defined energy amount of 1092 MWh, if the temperature of the heat source is 130 °C and the heat sink temperature is 75 °C. Besides the increased costs for personnel and transport, also higher investment costs have to be considered due to the price of thermal oil. Fig. 8 displays the *COTH* for this M-TES configuration which results in € 235.2 per MWh for the calculated case.

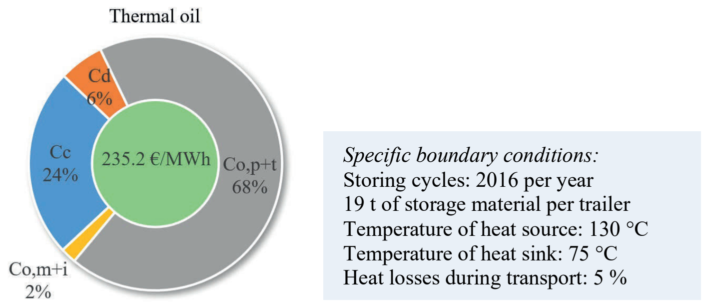

Fig. 8. Calculated *COTH* and distribution of cost categories for M-TES using thermal oil Calor 32.

If this M-TES configuration using thermal oil is considered for a different application with a heat source temperature of 200 °C and a heat sink temperature of 100 °C, the number of required cycles can be reduced to 1008 per year, resulting in *COTH* of € 152.4 per MWh.

3.3.3. Gravel as sensible storage material

Beside the liquid storage materials water and thermal oil, a solid kind of sensible storage was investigated by considering gravel with a diameter of 32 mm. The temperature of the heat source was set to 200 °C, while the heat sink requested 100 °C in this case. Due to the density of gravel, the storage material amount had to be limited to 12.5 m³ per trailer in order to satisfy the gross weight limitation of the semitrailer truck. Moreover, the specific heat capacity is the lowest of all analysed storage materials, and therefore, the number of storing cycles reaches a value of 2689 per year. As illustrated in Fig. 9, the effort for personnel and transport is the main cost driver of this M-TES configuration, leading to total *COTH* of € 276.2 per MWh.

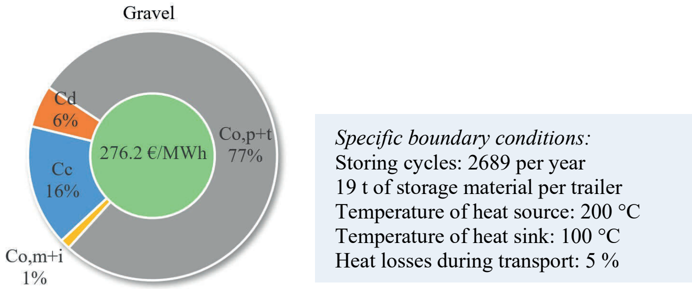

Fig. 9. Calculated *COTH* and distribution of cost categories for M-TES using gravel 32 mm.

3.4. Comparison with COTH of District Heating Networks

Fig. 10 summarises the results of calculating the *COTH* for the seven kinds of investigated storage materials. The colour of the bars indicates the three cases of heat source and heat sink temperatures, whereas the filling pattern categorises the storage technology (TCM, PCM or sensible storing). The very left bar in the chart represents the *COTH* of € 150 per MWh, announced by an Austrian operator of district heating networks by end of 2022, which serves as the benchmark for the analysed M-TES configurations.

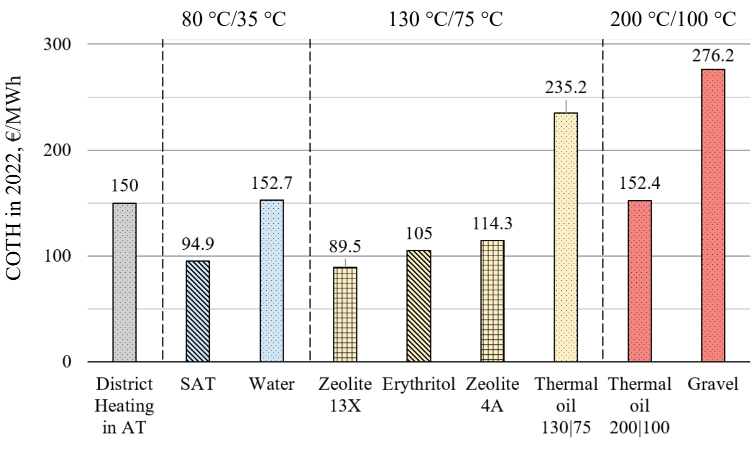

Fig. 10. Calculated *COTH* of M-TES configurations compared to conventional district heating in Austria in 2022.

Among the investigated M-TES technologies, TCM using Zeolite 13X provides the lowest *COTH* of € 89.5 per MWh, related to the given boundary conditions. Both M-TES systems with PCM reveal a reduction of *COTH* of about 33 %, compared to DHN. For the sensible storing technologies, water is competitive in the lower temperature range, whereas thermal oil is only suitable for the highest temperature category. By contrast, M-TES using gravel is economically not viable at all, related to DHN.

3.5. Operation costs for Diesel driven trucks vs. electric trucks

All calculations described above assumed a Diesel driven semitrailer truck for conducting the transportation of the mobile storage. The operation costs for the truck as part of the cost category $C_{o,p+t}$ include fuel costs, truck maintenance, insurance, taxes and tolls. A Diesel price of € 1.6 per liter was taken into account for end of 2022 in Austria, resulting in truck operation costs of € 0.97 per km. For the case of future fluctuations on the fuel market, a sensitivity analysis was carried out, as depicted in Fig. 11. The 100 % basis for the Diesel driven truck was chosen at a Diesel price of € 1.7 per liter, because this is the point where the truck operation costs are equal to an electric driven truck, with a 100 % basis of € 0.25 per kWh of electricity price. If the costs for Diesel and electricity will fall below these base values, the operation of M-TES using Diesel driven trucks is more economic than transporting the heat by an electric driven truck.

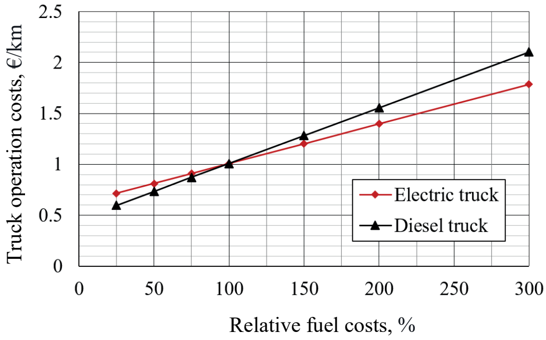

Fig. 11. Impact of fuel and electricity prices on operation costs of electric and Diesel driven trucks.

4. Conclusion

The conducted investigation of M-TES systems in terms of economic competitiveness to conventional district heating yields the conclusion, that the transportation of heat by TCM- and PCM-based storages is realisable for costs between € 89.5 and € 114.3 per MWh. Compared to the heat costs of DHN in Austria in 2022, this would result in cost reductions between 40.3 % and 23.8 %, however, only valid for the considered case with a transportation distance of 7 km and a transported amount of heat of 1092 MWh/a. Even sensible storage systems using water or thermal oil are in the range of being economically competitive to DHN, assumed that they can be applied to a suitable temperature range. Among all parameters involved in the calculations of *COTH*, the storage density shows the highest impact on the economic evaluation, as it directly influences the number of storing cycles which are causing the transportation costs. This is the reason why Zeolite 13X with a mass-related storage density of 286 kWh/t can provide a very cost-effective M-TES system with the lowest *COTH* of all analysed configurations. The utilisation of electric driven trucks is economically only viable, if the energy costs remain at the level of 2022 or increase further on.

By contrast to the outcomes of the study from 2014 [20], M-TES systems in 2022 can deliver heat for lower costs than district heating systems. However, previous studies have already concluded, that M-TES is only meaningful for short transportation distances in the range of 10 km or less. Therefore, mobile thermal energy storages cannot be a replacing alternative to district heating networks, but they can serve as complementary solution for bridging short distances, either between an existing DHN and suitable heat producers or heat consumers, or between heat sources and heat sinks directly. Besides the economic and technical aspects of M-TES investigated by this study, a subsequent analysis of ecologic and environmental parameters in comparison to established heat transfer systems will be targeted for future research work within this field.

ACKNOWLEDGEMENT

The work described in this paper was supported by the research project "Heat Highway" (reference number 880797, funding program "Vorzeigeregion Energie"), financed by the "Klima- und Energiefonds" and the government of Upper Austria.

REFERENCES

[1] Euroheat&Power. DHC Market Outlook. 2023.
[2] Rušeljuk P., Volkova A., Lukić N., Lepiksaar K., Nikolić N., Nešović A., Siirde A. Factors Affecting the Improvement of District Heating. Case Studies of Estonia and Serbia. *Environmental and Climate Technologies* 2021:24(3):521–533. https://doi.org/10.2478/rtuect-2020-0121
[3] Postnikov I. Application of the Methods for Comprehensive Reliability Analysis of District Heating Systems. *Environmental and Climate Technologies* 2021:24(3):145–162. https://doi.org/10.2478/rtuect-2020-0093
[4] Pakere I., Lauka D., Dolge K., Vitolins V., Polikarpova I., Holler S., Blumberga D. Climate Index for District Heating System. *Environmental and Climate Technologies* 2020:24(1):406–418. https://doi.org/10.2478/rtuect-2020-0024
[5] Nussbaumer T., Thalmann S. Influence of system design on heat distribution costs in district heating. *Energy* 2016:101:496–505. https://doi.org/10.1016/j.energy.2016.02.062
[6] Masatin V., Latõšev E., Volkova A. Evaluation Factor for District Heating Network Heat Loss with Respect to Network Geometry. *Energy Procedia* 2016:95:279–285. https://doi.org/10.1016/j.egypro.2016.09.069
[7] Andersen M., Bales C., Dalenbäck J. O. Heat distribution concepts for small solar district heating systems – Techno-economic study for low line heat densities. *Energy Conversion and Management: X* 2022:15:100243. https://doi.org/10.1016/j.ecmx.2022.100243
[8] Kumar L., Ahmed J., El Haj Assad M., Hasanuzzaman M. Prospects and Challenges of Solar Thermal for Process Heating: A Comprehensive Review. *Energies* 2022:15(22):8501. https://doi.org/10.3390/en15228501
[9] HeatRoadmapEurope. Heating and Cooling – facts and figures. Heat Roadmap Europe, 2017.
[10] Miró L., Gasia J., Cabeza L. F. Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review. *Applied Energy* 2016:179:284–301. https://doi.org/10.1016/j.apenergy.2016.06.147
[11] Shehadeh M., Kwok E., Owen J., Bahrami M. Integrating mobile thermal energy storage (M-tes) in the city of surrey's district energy network: A techno-economic analysis. *Applied Sciences (Switzerland)* 2021:11(3):1–12. https://doi.org/10.3390/app11031279
[12] Du K., Calautit J., Eames P., Wu Y. A state-of-the-art review of the application of phase change materials (PCM) in Mobilized-Thermal Energy Storage (M-TES) for recovering low-temperature industrial waste heat (IWH) for distributed heat supply. *Renewable Energy* 2021:168:1040–1057. https://doi.org/10.1016/j.renene.2020.12.057
[13] Li H., Wang W., Yan J., Dahlquist E. Economic assessment of the mobilized thermal energy storage (M-TES) system for distributed heat supply. *Applied Energy* 2013:104:178–186. https://doi.org/10.1016/j.apenergy.2012.11.010
[14] Deckert M., Scholz R., Binder S., Hornung A. Economic efficiency of mobile latent heat storages. *Energy Procedia* 2014:46:171–177. https://doi.org/10.1016/j.egypro.2014.01.170
[15] Guo S., Liu Q., Zhao J., Jin G., Wu W., Yan J., Li H., Jin H. Mobilized thermal energy storage: Materials, containers and economic evaluation. *Energy Conversion and Management* 2018:177:315–329. https://doi.org/10.1016/j.enconman.2018.09.070
[16] Yang J., Zhang Z., Chen J., Hong M., Li H., Li Y., Yang M. Investigating the economic returns of mobile heat storage devices in the multi-stage closed-loop supply chain. *Energy Reports* 2020:6:181–189. https://doi.org/10.1016/j.egyr.2020.06.023
[17] Fritz M., Plötz P., Schebek L. A technical and economical comparison of excess heat transport technologies. *Renewable and Sustainable Energy Reviews* 2022:168:112889. https://doi.org/10.1016/j.rser.2022.112899
[18] Guo S., Zhao J., Bertrand A., Yan J. Mobilized thermal energy storage for clean heating in carbon neutrality era: A perspective on policies in China. *Energy and Buildings* 2022:277:112537. https://doi.org/10.1016/j.enbuild.2022.112537
[19] Fujii S., Nakagaki T., Kanematsu Y., Kikuchi Y. Prospective life cycle assessment for designing mobile thermal energy storage system utilizing zeolite. *Journal of Cleaner Production* 2022:365:132592. https://doi.org/10.1016/j.jclepro.2022.132592
[20] Krönauer A., Lävemann E., Brückner S., Hauer A. Mobile sorption heat storage in industrial waste heat recovery. *Energy Procedia* 2015:73:272–280. https://doi.org/10.1016/j.egypro.2015.07.688

[21] Hauer A., Krönauer A., Lävemann E. Wärmetransport mit Lastkraftwagen. (Heat transport by truck). 2019:1–21. [Online]. [Accessed: 12.03.2023]. Available: https://docplayer.org/126531665-Waermetransport-mit-lastkraftwagen.html (In German).
[22] Verein Deutscher Ingenieure. VDI 2067 – Economic efficiency of building installations 2012:44.
[23] Statistics_Austria. Customer Price Indices 1990 - 2022 in Austria 2023. [Online]. [Accessed: 20.03.2023]. Available: https://www.statistik.at/fileadmin/pages/214/CPI.pdf
[24] Zettl B., Englmair G., Steinmaurer G. Development of a revolving drum reactor for open-sorption heat storage processes. *Applied Thermal Engineering* 2014:70:42–49. https://doi.org/10.1016/j.applthermaleng.2014.04.069
[25] Lizana J, Chacartegui R, Barrios-Padura A, Valverde JM. Advances in thermal energy storage materials and their applications towards zero energy buildings: A critical review. Applied Energy 2017:203:219–239. https://doi.org/10.1016/j.apenergy.2017.06.008
[26] Martin H, editor. VDI-Wärmeatlas. 10th ed. Berlin: Springer-Verlag, 2005.
[27] NILS. Technical datasheet Calor 32 - Spezialöl für Wärmeübertragungsanlagen. 2015. [Online]. [Accessed: 21.01.2015]. https://www.nils.eu/de/prodotti/calor/
[28] Baehr H. D., Stephan K. Wärme- und Stoffübertragung. 5th ed. Berlin: Springer-Verlag, 2006.
[29] Link S., Plötz P., Griener J., Moll C. Lieferverkehr mit Batterie-Lkw: Machbarkeit 2021 Fallbeispiel REWE Group – Region Nordost. Karlsruhe: 2021. (Delivery traffic with battery trucks: Feasibility 2021 case study REWE Group – Northeast region. Karlsruhe: 2021). (In German).
[30] Schwendinger M. Durch emissionsfreie Lkw Klimabilanz verbessern. (Improve the climate balance through emission-free trucks). Fact Sheet 2021:04:8. (In German). [Online]. [Accessed: 25.11.2022]. https://vcoe.at/files/vcoe/uploads/News/VCOe-Factsheets/2021/2021-03%20Emissionsfreie%20Lkw/VC%C3%96-Factsheet%202021-03%20Durch%20emissionsfreie%20Lkw%20Klimabilanz%20verbessern.pdf

ANNEX

TABLE 1. CPI2010 BETWEEN 2014 AND 2022 FOR AUSTRIA [23]

Year	CPI2010	% to previous year
2014	109.7	1.7
2015	110.7	0.9
2016	111.7	0.9
2017	114	2.1
2018	116.3	2
2019	118.1	1.5
2020	119.8	1.4
2021	123.4	2.8
2022	133.6	8.6

TABLE 2. TECHNICAL PROPERTIES AND PRICE OF CONSIDERED TCM

Material type	Density, kg/m³	Volumetric storage density, kWh/m³	Mass-related storage density, kWh/t	Material costs in 2017, €/t	Material costs in 2022, €/t	Ref.
Zeolite 13X	650	186	286	3850	4510	[20], [24], [25]
Zeolite 4A	730	96	132	3290	3850	[24], [25]

TABLE 3. TECHNICAL PROPERTIES AND PRICE OF CONSIDERED PCM

Material type	Density, kg/m³	Specific heat capacity, kJ/kg·K	Latent heat capacity, kWh/t	Melting point, °C	Material costs in 2016, €/t	Material costs in 2022, €/t	Ref.
SAT	1450	1.70 (20 °C) 2.90 (70 °C)	73.33	59	450…800	748	[15]
Erythritol	1300	1.34 (20 °C) 2.87 (140 °C)	94.17	118	3200	3831	[15]

TABLE 4. TECHNICAL PROPERTIES AND PRICE OF CONSIDERED SENSIBLE STORAGE MATERIALS

Material type	Density, kg/m³	Specific heat capacity, kJ/kg·K	Material costs in 2022, €/t	Ref.
Water	975	4.19 (75 °C)	3	[26]
Thermal oil Calor 32	868	2.39 (75 °C)	5000	[27]
Gravel 32 mm	1520	0.9	300	[28]

TABLE 5. CAPITAL-RELATED COSTS FOR THE CALCULATION OF *COTH*

Description	**Value**
Invest for 2 storage tanks TCM (22 m³ each, without storage material)	€ 154 874.0
Invest for 2 storage tanks for SAT and Erythritol (15 m³ each, without storage material)	€ 84 000.0
Invest for 2 storage tanks for water and thermal oil (22 m³ each, without storage material)	€ 96 000.0
Invest for 2 storage tanks for gravel (12.5 m³ each, without storage material)	€ 84 000.0
Invest for air-driven discharging station for TCM and gravel	€ 149 181.0
Invest for water-driven discharging station for SAT and water	€ 104 427.0
Invest for oil-driven discharging station for Erythritol and thermal oil	€ 126 804.0
Invest for air-driven charging station for TCM and gravel	€ 136 394.0
Invest for water-driven charging station for SAT and water	€ 95 476.0
Invest for oil-driven charging station for Erythritol and thermal oil	€ 115 935.0
Invest for 2 trailers	€ 82 810.0

TABLE 6. DEMAND-RELATED PREMISES AND COSTS FOR THE CALCULATION OF *COTH*

Description	Value
Electricity demand for charging	0.02 MWh/cycle
Electricity demand for discharging	0.02 MWh/cycle
Electricity costs for charging and discharging	€ 50.0 per MWh
Costs for waste heat	€ 5.0 per MWh
Annual cost increase for waste heat	5.1 %/a

TABLE 7. OPERATION-RELATED PREMISES AND COSTS FOR THE CALCULATION OF *COTH*

Description	Value
Personnel costs for truck driver	€ 48.7 per h
Annual increase of personnel costs	2 %/a
Transportation distance (one-way)	7 km
Average speed of truck	35 km/h
Time duration for trailer handling	1 h/cycle
Operation costs for Diesel driven truck (including fuel costs)	€ 0.97 per km
Maintenance costs related to total investment costs	0.8 %/a

TABLE 8. CAPITAL-RELATED AND OPERATION-RELATED PREMISES AND COSTS OF DIESEL DRIVEN TRUCKS [29], [30].

Description	Value
Invest for chassis of tractor unit	€ 58 000.0
Invest for engine and gearbox	€ 71.0 per kW
Invest for Diesel tank	€ 2.0 per lt.
Size of Diesel tank	1000 lt.
Invest for after-treatment of exhaust gases	€ 19.8 per kW
Diesel consumption	32.2 lt. per 100 km
Maintenance costs	€ 0.07 per km
Insurance costs	€ 4500.0 per year
CO_2 toll	€ 0.187 per km
Motor vehicle tax	€ 929.0 per year

TABLE 9. CAPITAL-RELATED AND OPERATION-RELATED PREMISES AND COSTS OF ELECTRIC DRIVEN TRUCKS [29], [30].

Description	Value
Invest for chassis of tractor unit	€ 58000.0
Invest for motor	€ 19.8 per kW
Invest for power electronics	€ 29.0 per kW
Invest for battery	€ 261.0 per kWh
Battery capacity	500 kWh
Electricity consumption	1.56 kWh per 100 km
Maintenance costs	€ 0.0595 per km
Insurance costs	€ 4500.0 per year
CO_2 toll	€ 0.187 per km
Motor vehicle tax	€ 373.0 per year