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Large-Scale Thermal Energy Stores in District Heating Systems – Simulation Based Optimization

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Abstract

Large scale thermal energy storage (TES) will be beneficial regardless of the future composition of the energy system. This paper presents a dynamic finite difference TES model, which is coupled to a 2D finite element model for the simulation of large-scale (underground) TES. With the geometrically flexible model TES can be simulated dynamically in district heating systems considering different types of construction and geometry (cylinder, truncated pyramid/cone, free-standing or buried) with variable distribution of the thermal insulation. The influence of the properties of the ground as well as approximately the influence of ground water on the thermal losses and the stratification can be investigated. In addition, the optimum distribution of the thermal insulation (bottom, wall, cover) can be determined for different applications of the TES (e.g. buffer or long-term). The model is implemented in the MATLAB/Simulink simulation environment. Simulation results for different storage types and geometries are presented.

1. Introduction

Regardless of how the future energy supply is composed (fossil, renewable, with or without nuclear energy or mixed systems) - all scenarios [IER Uni Stuttgart, ITT DLR, Wuppertal Institute, FHG-ISE] show that - waste heat from the electricity production will be so valuable in the future, that large-scale storage of heat will be beneficial (Mangold 2009). Currently the optimization of solar assisted district heating by means of heat pumps is frequently discussed (e.g. German project in Eggenstein or Austrian FFG project store4grid). Usually an increase of the share of renewable energy in the heat supply contradicts an increase of the efficiency of the energy or heat supply, respectively. A detailed investigation of the system by means of simulation is necessary to develop an optimally balanced solution with maximum primary energy savings. The profitability of large-scale TES is currently not given. Seasonal TES will be hardly economically even in future due to the low number of storage cycles. Intelligent multi-functional storage concepts might improve the economic feasibility. The investigation of the technical and economic potential of integrating a heat pump and TES into (solar) district heating systems requires accurate (and sufficiently fast) TES models.

2. LARGE-SCALE TES – REVIEW

Large-scale thermal storage is increasingly used. We have to distinguish in large-scale buffer storage for district heating systems, mostly free-standing steel or concrete tanks, such as for example the thermal energy store with approximately 35 000 m m³ in Linz and in long-term or seasonal thermal energy stores, such as the pit heat store in the solar assisted district heating system in Marstal with 75 000 m³, see Fig. 1.


(source: www.vam.at)

source: Marstal Fjernvarme)

Fig. 1: (left) Buffer TES of the district heating system in Linz. (middle/right) pit heat store in Marstal (sunstore IV)

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In case of buffer storage good stratification is of greater importance than the heat losses through the envelope. To minimize the internal exergy losses a relatively large height to diameter ratio (h/d~3) should be aimed at. For long-term heat storage external losses are more significant. Minimum A/V-ratios and thus h/d-ratios in the range of about 1 should be designed. However experience shows that, usually lower h/d-ratios were realized due to architectural (i.e. optical) restrictions or geophysical boundary conditions, such as groundwater or rock layers. Examples are the underground tank stores in Hamburg (h/d≈0.4), Friedrichshafen (h/d≈0.6) or Hanover (h/d≈0.7), see (Ochs 2013) for further details. And this applies in particular for large pit heat stores such as the 10 000 m³ pit heat store in Wolfsburg, the 30 000 m³ pit heat store in Mannheim and also the pit heat stores that have been realized in recent years in Denmark. All were planned and/or realized with rather flat slopes which leads to low h/d-ratios and correspondingly large surfaces (Tab 1.).

Tab. 1: Volume V, height h, slope angle β and surface A of large-scale pit heat stores, acc. (Ochs 2010), (Sørensen 2014)

Project	**Mannheim§**	**Wolfsburg§**	**Marstal I**	**Marstal II**	**Droninglund**
Volume V / [m³]	30 000	10 000	10 000	75 000	62 000
Slope / [-]	1/1.3	1/2	½	1/2	1/2
Angle β / [°]	38	27	27	27	27
Height h / [m]	15	8	6.5	16	14.5
Surface A/[m²]*)	75x50	51x51	65x42	113x88	92x92
A/V / [1/m] #)	0.31	0.52	0.56	0.27	0.29
h/d / [-] *)	0.35	0.23	0.16	0.23	0.23

§) planed *) of cover #) aspect ratio *) ratio of height (h) to mean diameter $d_m=(d_{top}+d_{bottom})/2$

Such large pit heat stores are frequently realized with a floating cover as self-supporting covers of this size are technically rather complicated and accordingly not economically feasible. A detailed state of the art of large-scale storage can be found in (Ochs 2013a).

3. Optimized construction concepts

A classification will be established first to develop optimized concepts for large (underground) stores. Tank stores (T) can be build free standing, partly buried or underground. Large underground thermal energy stores can be constructed as a pit heat store as a cylinder, or as truncated cone or pyramid. Free-standing tanks can be insulated without problems from the building physics point of view. Moisture accumulation in the insulation can be avoided by means of construction with rear ventilation. Underground thermal energy stores can be built with or without thermal insulation. Avoiding moisture accumulation in the insulation is not trivial in case of underground thermal energy storage: penetrating moisture (during construction or during operation by diffusion or ground water) cannot escape ("wet outside, wet inside").

A special solution is the underground storage with rear ventilation, realized by a container in a pit. Such a solution was chosen for the tank thermal energy storage in Hamburg (see Bauer et al.), which was rebuilt in the pit of the back built old tank store. With this rather complex solution that will likely remain an exception, rear-ventilated insulation is possible and accessibility is guaranteed (maintenance). Generally, free-standing stores are beneficial compared to underground storage. There are no excavation costs on the one hand, and on the other hand the insulation is significantly less problematic. Only for TES with a certain size (> ca. 100 000 m³) the effort to build a free-standing tank becomes too large and pit thermal energy storage is economically advantages. For stores with a volume less than approximately 100 000 m³ there are two reasons to build underground:

- if visibility is not desirable and
- if the area should be usable (trafficable by foot or car), see Fig. 2

Following questions arise:

- Which storage type (size, geometry and thermal insulation standard) is the most appropriate for which type of system (local or district heating, solar with/without heat pump) at a specific location? From energetic and economic point of view.

- Are there benefits of integrating a heat pump in such a system by improving the stratification of the store or enable further discharge of the store (below the level of return flow temperature) and thus increase the solar yield? A primary energy and economic analysis is required.
- What is the equivalent volume of a pit thermal energy store with high A/V- or low h/d-ratio, respectively or how much more compact can an ideal (free-standing) cylindrical thermal energy store with the same efficiency be build?

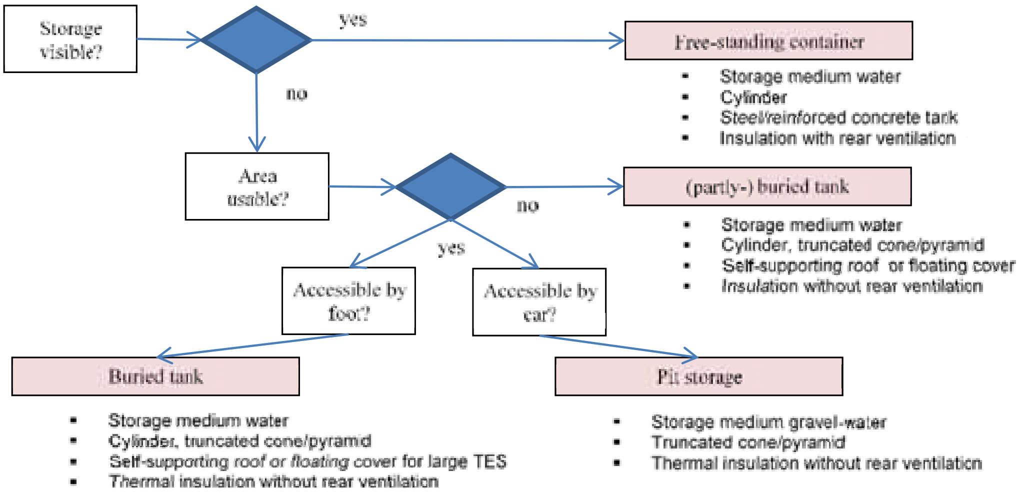

Fig. 2: Schematic of decision-making process for large-scale thermal energy storage

4. Modelling Large-Scale Underground Stores

4.1 General aspects

For the depiction of the thermo hydraulic behavior of TES in principle fine and coarse structure models can be used. Fine-structure or CFD models allow a geometrically precise, finely resolved 2D or 3D depiction of the store structure, as well as a consideration of all heat transport processes occurring in reality. Fine-structure models require the solution of partial differential equations for the relevant physical parameters such as temperature, humidity, pressure and speed. Because of the very large computational effort (multi-) annual system simulations with long-term storage are currently not feasible (and probably also not in the near future). Furthermore, it is disadvantageous that any geometry change is associated with a complex numerical mesh generation.

Coarse structure models use, depending on the present task, simplistic assumptions in geometry, material properties and boundary conditions for the calculation, leading to a significant reduction of the computational effort. Detailed calculations with the aim of optimizing the store geometry and the distribution of the thermal insulation cannot be performed with currently available coarse structure models (e.g. with those available in TRNSYS or MATLAB/Simulink). So far, dynamic storage models, which were usually developed for the depiction of small buffer stores are limited to a sufficiently detailed depiction of the hydraulic behavior while simplifying the geometry (cylinders) and do not take correctly into account thermal losses.

The few available models for large-scale underground thermal energy storage such as the XST or ICEPIT in TRNSYS are suitable for a rough sizing of the store and system optimization but not for an optimization of the store itself. In (Ochs, 2010) the aspects of moist insulation were investigated the influence on the heat loss was determined. However, detailed studies on the optimal geometry and the economically optimal use of thermal insulation were not fully investigated. The integration of a heat pump and aspects related to the geometry and the insulation of the store have not been investigated so far.

4.2 Coupled FD storage and FE ground model

The model presented here allows to dynamically simulate TES of different types and geometry (cylinder, cone, or pyramid stump) with variable distribution of the insulation in a block or district heating system. The geometry can be easily parameterized. The influence of the soil as well as approximate of ground water on the heat loss and the stratification can be investigated. In addition, the optimal distribution of thermal insulation (floor, wall, cover) for various applications and system configurations can be determined. Such a model should enable to determine the (reduction of) losses resulting from the ground coupling as well as predict the performance of more complex geometries, such as a double cone or wall made with the excavation, such as in Marstal and Droninglund with good accuracy. A dynamic finite difference (FD) thermal energy storage model is coupled to a 2D finite element (FE) model which allows the simulation of large-scale underground thermal energy stores with flexible geometry. The model is implemented in the numerical environment Matlab/Simulink using the PDETOOL and so-called level-2-S-functions.

The heat equation – a parabolic partial differential equation (PDE) is transformed into a system of ODEs applying the „Method-of-Lines“, which can be solved with Matlab or Simulink, respectively (see Ochs et al. 2013). Parabolic PDEs of the form

$$d \cdot u' - div\left(c \cdot grad(u)\right) + a \cdot u = f \qquad \text{(eq. 1)}$$

can be solved in Matlab with the PDETOOL (2D). The coefficients d, c, a and f are functions of the position x and time t and are independent from the dependent variable u and their derivative (du/dx). Applied to heat transfer eq. 1 forms to:

$$\rho \cdot c_p \cdot \frac{\partial \vartheta}{\partial t} - div\left(\lambda \cdot grad(\vartheta)\right) = \dot{q} \qquad \text{(eq. 2)}$$

The temperature ϑ is a function of the position x, the time t and the heat source q. The thermal conductivity λ, and the volumetric capacity $\rho \cdot c_p$ can be functions of space and time but not of temperature. With the formulation of the PDE in cylindrical coordinates, 2D radial symmetric problems can be depicted. The formulation of the heat equation reads:

$$r\rho c_p \frac{\partial \vartheta}{\partial t} - \frac{\partial}{\partial r}\left(r\lambda \frac{\partial}{\partial r}\vartheta\right) - \frac{\partial}{\partial z}\left(\lambda \frac{\partial}{\partial z}\vartheta\right) = \dot{q}r \qquad \text{(eq. 3)}$$

Here, r is the radius and z the depth. Using the method of lines, the thermal conductivity λ, and the volumetric capacity ($\rho \cdot c_p$) can be functions of space, time, the temperature and its derivative ($d\vartheta/dx$). The system of ordinary differential equations (ODEs) can be coupled with the ODE system for the storage and thus be solved by Matlab/Simulink. Exemplarily the differential equation is shown for element i (applies for *1< i <N):*

$$\begin{aligned} & V \cdot \rho \cdot c_p \frac{\partial \vartheta}{\partial t} = \dot{m} \cdot c_p \cdot \left(\vartheta_{i-1} - \vartheta_i\right) + \\ & U \cdot A_S \cdot \left(\vartheta_s - \vartheta_i\right) + \\ & \frac{\lambda_{eff}}{h} \cdot A \cdot \left(\vartheta_{i-1} - \vartheta_i + \vartheta_{i+1}\right) + \\ & \dot{m}_{mix} \cdot c_p \cdot \left[\max\left(\vartheta_{i+1} - \vartheta_i, 0\right) + \max\left(-\vartheta_{i-1} - \vartheta_i, 0\right)\right] \end{aligned} \qquad \text{(eq. 4)}$$

Here V is the volume of the segment i, ρ the density and c_p the specific heat capacity of the fluid, m the (dis-) charging mass flow, U the (overall) heat transfer coefficient of the envelope, A_s the mantle area of the segment, λ_{eff} the effective thermal conductivity of the storage medium, h the segment height, A the segment cross section area, and m_{mix} the mass flow in case of inversion. In case of cones the segments are divided such that they possess equal volume (hence the height of the segments is increasing with depth).

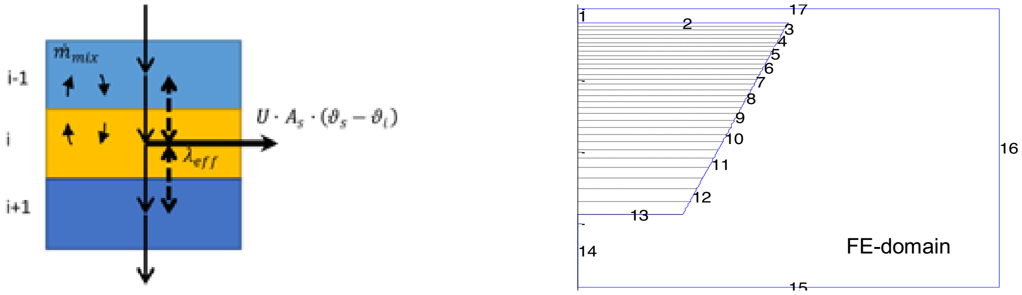

Fig. 3: Schematic representation of three storage segments (i-1, i. i+1) with energy fluxes (left) and FE-domain of a underground pit (truncated pyramid) with 30 segments (right)

The temperature profile in the ground in the surrounding of the store is shown exemplarily for an underground pit heat store (Fig. 4, left) and for a tank with ground coupling, (Fig. 4, right).

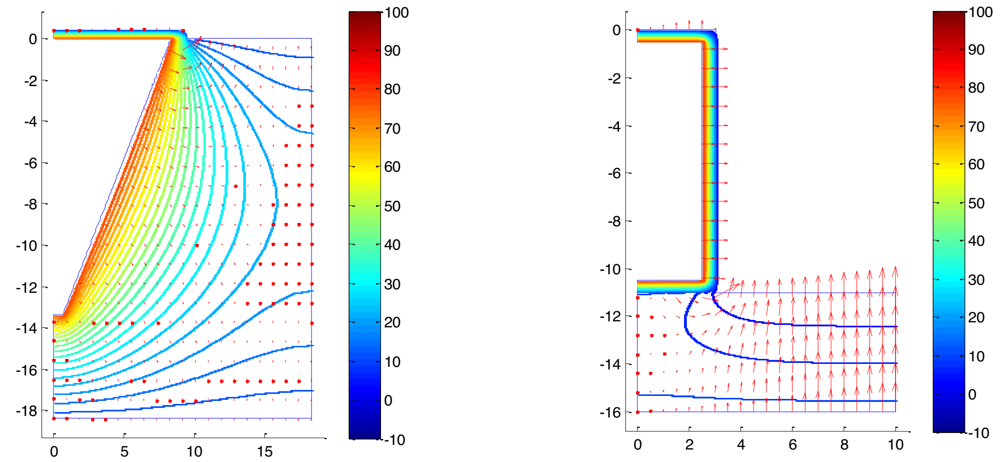

Fig. 4: Temperature profile (in °C, arbitrary point of time, x,y-coordinates in m) in the surrounding ground of (left) a pit heat store and (right) a free-standing tank with ground coupling for ambient and ground temperature of 10 °C

4.3 Validation of the thermal energy storage model

The model developed for the simulation environment Matlab/Simulink is cross-validated by means of comparison with the storage model of the CARNOT Blockset. Good agreement was found with minor deviations resulting from effects of the thermal mass of the insulation which is considered in the new model but disregarded in the CARNOT storage model where massless resistances are considered. Furthermore insignificant deviations can occur due to the use of different numerical solvers. (Note: in earlier works, the CARNOT storage model was validated against measured data (Hafner 2012) and against the TRNSYS type 343 (see Bauer et al. 2013). An additional comparison with the TRNSYS XST will be conducted in future).

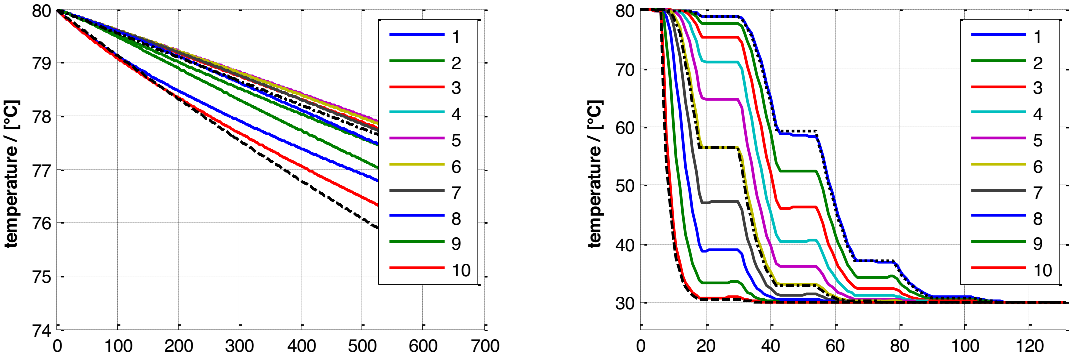

Fig. 5: Comparison of the temperatures in the store simulated with the storage model of the CARNOT toolbox (dashed line) and with the new coupled FD store and FE environment model (solid line); each 10 knots; (left) storage losses starting with 80 °C for 10 °C ambient temperature; (right discharging from initial temperature of 80 °C for 6 days with 12 h/d for a flow temperature of 30 °C; x axis: time in hours

5. Evaluation of the efficiency of large-scale thermal energy stores

The efficiency of a thermal energy store is influenced by many factors. These are (among others):

- operating conditions (system temperature, (dis-) charging cycles)
- site properties (soil properties, boundary conditions, ground water)
- design and type of store construction (geometry A/V- and h/d-ratio, cylinder, cone or truncated pyramid, thermal insulation standard (U-value))

One important characteristic of a TES is the number of (dis-)charging cycles or cycle number (CN)

$$CN = \frac{Q_{out}}{Q_{max}} \qquad \text{(eq. 5)}$$

The maximum charging (or storage) temperature determines the max. heat capacity of the store Q_{max} and depends on the one hand on the used materials (e.g. stainless steel or polymer liner) and on the other hand on the max. pressure (i.e. pressurized tank). Both factors have also significant influence on the economic feasibility. One important evaluation parameter is the storage utilization factor (storage efficiency).

$$\eta = \frac{Q_{out}}{Q_{in}} \qquad \text{(eq. 6)}$$

A detailed assessment can be conducted only coupled to the total system. Eventually, the overall system efficiency must be optimized taking into account the efficiency of all components (in particular the solar thermal system). The utilization factor is determined primarily by the insulation standard. Stratification (and hence the h/d-ratio) has a second-order influence on the utilization factor (but a 1st order influence on the efficiency of the heat generator, i.e. solar thermal collector). The economically optimal storage efficiency thus depends on the number of (dis-)charging cycles. The higher the number of (dis-)charging cycles the less thermal loss play a role. An assessment of the thermal storage without total system represents only a simplified approach, however, is useful to understand basic relationships and trends.

6. Simulation study - storage utilization factor and storage geometry

Three different scenarios are defined in order to investigate and optimize storage geometry and construction type: a) Long-term thermal energy storage b) Buffer-storage c) Heat pump operation; To avoid a complex system simulation first simplified charging, discharging and storage scenarios are defined that allow to assess the storage utilization factor and the stratification of the store. For the long-term thermal energy storage following simplified assumptions were chosen: initial condition 30 ° C, charging with 80 °C and 7.11 kg/s for 2 months (12 h/d), 1, 2 or 3 months, of storage period, discharge over one month with 30 °C and 3.83 kg/s (24 h/d). The ambient temperature and the groundwater temperature are kept constant at 10 °C. The simulations are carried out for a free-standing cylinder with and without consideration of ground coupling and an underground cylinder as well as an underground cone. The following parameters are varied: A/V- or h/d-ratio, slope angle, insulation standard, soil properties. The underground storage has 1 m soil coverage or a floating cover. Here only the results for long-term storage will be presented. (Future work will deal with buffer and heat pump operation (multi-functional storage with combined use of solar and heat pump).

The storage utilization factor has a relatively flat optimum at approximately h/d = 1 regardless of which insulation standard is selected, independently of the volume of the store (at constant flow rate) and also regardless of how long the storage period is. The storage utilization factor is decreasing with decreasing insulation standard and increasing A/V-ratio (for obvious reasons). The storage utilization factor decreases also with increasing duration of the storage period. Storage utilization factors of 75% to 85% can be achieved (for the investigated thermal energy store with 1050 m³) with well insulated (U < 0.1 W / (m² K)) cylinders with optimal h/d-ratio of about 1, see Fig. 6.

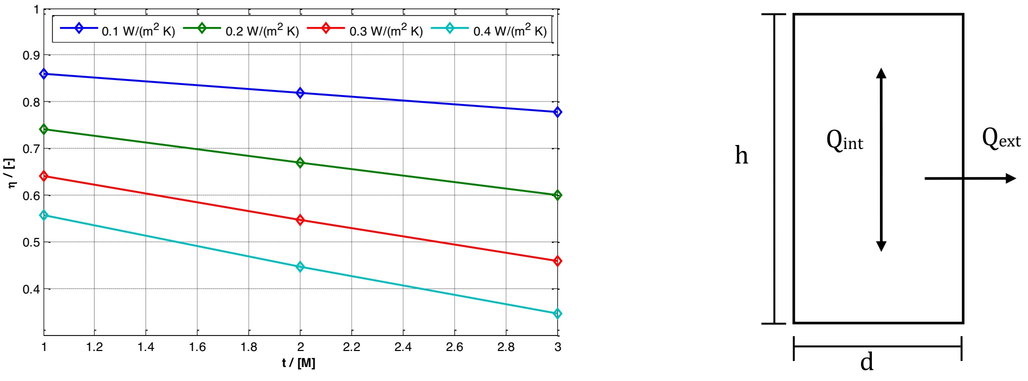

Fig. 6: Storage utilization factor depending in the duration of the storage period (1, 2, 3 months) with the U-value of the cylinder wall as parameter (cylinder with V = 1050 m³; d = 10 m;);

The relations are somewhat more complex in case of underground thermal energy storage. Here, low A/V-ratios should be aimed in principle, too, but the surface ratio insulated/non-insulated area has to be taken into account, too. This applies in particular for TES where only the cover is insulated (here U = 71.4 W W/(m² K)). The lower the U-value the greater is the influence of the geometry and the thermal conductivity of the soil. Without thermal insulation (U = 90.9 W /(m² K)) the storage utilization factor decreases at low A/V-ratios from some 85% to approximately 75 % for low soil thermal conductivity to about 60 % for medium and to about 45 % for high soil thermal conductivity see Fig. 7.

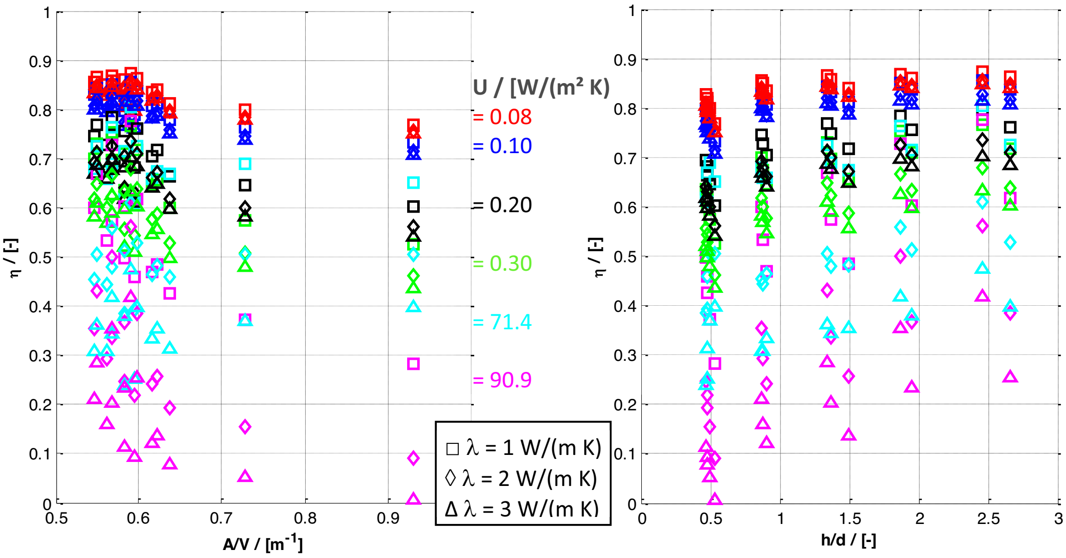

Fig. 7: Storage utilization factor of an underground thermal energy store as a function of the A/V-ratio (left) and h/d-ratio (right) for different U-values and ground thermal properties (V = 1050 m³, slope ß = 90°, 75°, 60°, h = 13.369 m * (1.5, 1.25, 1, 0.75, 0.5), for 2 months storage period

One example of such an underground TES with large surface area is the pit heat store in Marstal (see Table 1). According to (Schmidt et al. 2014) the thermal losses of the 75 000 m³ pit measured in 2013 sum up to some 2600 MWh leading to a storage utilization factor of only 65 % (with a cycle number of CN = 1.4). These very high losses might be explained to some extend by first year operation. Further investigation is needed. The 16 m deep store has a surface area of 18 878 m² (cover only). In case of a cylindrical tank with the same height the cover area would reduce to 4687.5 m². A cylinder with an h/d ratio of 1 would only have 1640.9 m² of cover area and therefore significantly reduced losses. However, it has to be considered that in the latter case the pit would have a depth of 45.7 m! If the storage utilization factor can be increased from 65 % to 85 % the storage volume can be decreased by about 18 000 m³ (but it must be considered that high storage utilization factors are more difficult to achieve for smaller volumes and insulation of bottom and wall would be required). The economic advantage depends on the location and will be part of future work. The influence of the shape (i.e. geometry), the insulation of the cover ($di_{ns)}$) are shown in Fig. 8 for the case of the simplified load profile with a storage period of 3 months. It is not comparable to the measured data but the trend can be derived that losses can be significantly reduced with better aspect ratios. In future work simulations will be performed with measured data as boundary conditions to quantify the effect and to perform an economic analysis.

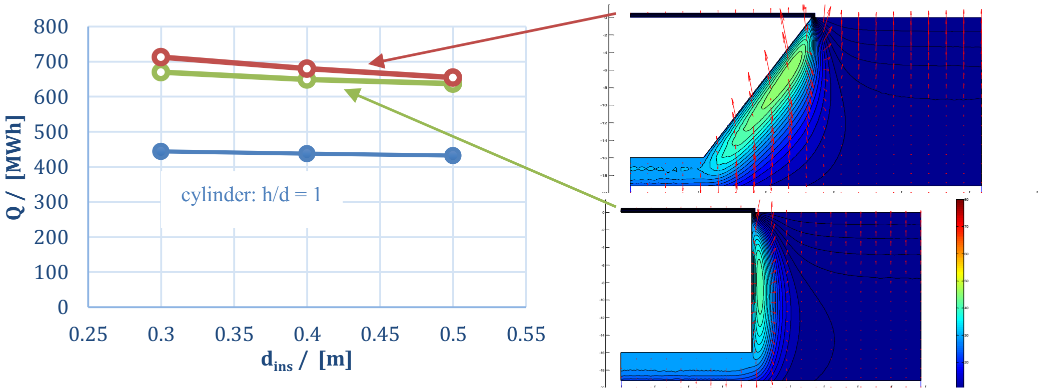

Fig. 8: Storage losses calculated for a three month storage period of a 75000 m³ pit with floating cover such as the store in Marstal, thermal conductivity of the ground 3W/(m K), average ambient temperature 0 °C

7. Conclusions

A coupled finite difference (FD) and finite element (FE) thermal energy storage model has been developed, cross-validated and exemplarily applied to calculate storage losses or storage utilization factors, respectively. With the new model for underground thermal storage both thermal stores of different construction types and designs can be compared and thermal stores can be optimized with regard to their design for a specific application. Future development will focus on a sufficiently fast component model for the MATLAB/Simulink simulation environment using S-functions to enable the simulation of solar assisted block or district heating systems with/without heat pump. It will be investigated whether a heat pump operation in a solar assisted district heating with pit thermal energy store with usually unfavorable h/d- and A/V-ratio will be beneficial. Furthermore, it will be investigated by how much the volume of an optimum free-standing cylinder can be reduced compared to a pit thermal energy storage can be reduced with the aim to improve the economic feasibility. A feasibility study will be carried out. In addition, in the future the possible degradation of the insulation properties due to convection (mainly in the cover) and due to moisture in case of underground stores should be taken into account.

By means of modeling and simulation of district heating systems with different store concepts and designs, strategies will be developed, leading to better response of district heating systems to demand and supply fluctuations, to increase the integration of fluctuating energy sources and to increase the contribution of solar thermal energy (in large scale) in order to achieve maximum primary energy savings under consideration of economic constraints.

8. Acknowledgement

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9. References

Bauer, D., Drück, H., Heidemann, W., Marx, R., Nußbicker-Lux, J., Ochs, F., (2013) Solarthermie 2000plus: Forschungsbericht zum BMU-Vorhaben 0329607P (August 2008 bis September 2012), Stuttgart, 2013.

Feist W., (2014), Passivhaus – das nächste Jahrzehnt, 18. Internationale Passivhaustagung, Aachen, 2014.

Hafner, B. (2012), CARNOT Toolbox für Matlab/ Simulink Ver. 5.2, CARNOT 5.2 Manual. 2012.

Mangold D., (Editor) (2009), DSTTP, Forschungsstrategie AG 3 Saisonale Wärmespeicherung

Matlab®/Simulink® Version R2012b, The Mathworks, Inc, 2012.

Ochs F. (2010), Modelling Large-Scale Thermal Energy Stores, Diss. Universität Suttgart, Shaker Verlag, ISBN 978-3-8322-8834-1 2010.

Ochs F., (2013), Dermentzis G. Feist W., (2013), Investigation of New Concepts of Ground Heat Exchangers and Building Integrated Heat Exchangers for Passive Houses by Means of Dynamic Building and System Simulation, 13th International Conference of the International Building Performance Simulation Association, BS 2013, Chambery 2013.

Ochs F. (2013a), Stand der Technik erdvergrabener Wärmespeicher, Bericht, FFG Projekt store4grid, Innsbruck, 2013

Thomas Schmidt T., Mangold D., Monitoring results from the Sunstore 4 smart district heating plant in Marstal, Denmark, Second Solar District Heating Conference, Hamburg, 2014.

Sørensen P. A. (2014), Per Alex Sørensen, Planenergi, Persönliche Auskunft, April, 2014.

TRNSYS, Klein at al. 2013