Repeated solar regeneration of a medium-term heat storage for a heat pump

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Abstract. This paper deals with a heat pump system with two heat sources, a medium-term ground collector heat storage and a façade-integrated massive solar-thermal collector. Aiming at affordable system cost, a medium-term heat storage is applied instead of a seasonal heat storage. During milder phases of the heating period, the heat storage is regenerated by the solar absorber to be used as ambient heat source under frosty weather conditions. Preparing for the design of heat pump systems with multiple heat sources, the energy balance of a medium-term underground heat storage has been investigated, based on physical component models. Yearly and seasonal analyses for different absorber sizes from 7.5 to 37.8 m^2 lead to the following statements. In general, even for small absorber sizes solar yields during winter are sufficient for continuous operation of the heating system, with increasing average temperature of the storage for larger sizes of the solar system. Higher ground temperatures result in higher seasonal coefficients of performance of the heat pump, and in higher annual heat losses of the storage. The medium-term character of the storage is shown by the in-season heat gain contributed by the solar absorber. Finally, to assure frost-free operation of the storage the absorber size must be at least 15% of the ground collector size.

Keywords. Heat pump systems, medium-term storage, underground heat storage, solar absorber, regeneration
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1. Introduction

In Germany in 2020, 53 % of the newly built houses have been equipped with a heat pump as the heating device [1]. About 79 % of them use air as ambient heat source [1], motivated by the simple installation and low investment cost. The setback of air source heat pumps is the low efficiency at low outdoor temperatures. In comparison the source temperatures of ground collectors, such as geothermal probes or ground water, are higher in winter months, when most heating power is needed. Higher source temperatures result in higher COP (Coefficient of Performance) and therefore in lower electric power demand. Günther et al. researched the efficiencies of heat pumps in the field [2]. High energetic efficiency is essential for the energy transition towards a completely regenerative energy supply.

Depending on the ground structure and local regulations, the use of geothermal probes or ground water may be restricted in a region or in individual cases. Horizontal earth collectors need large surface areas to collect sufficient heat input for the heat pump. Due to urban redensification and smaller building sites there is often not enough space for an earth collector for the heat supply of a building.

Another approach is to use heat storages to store solar energy for subsequent use. Seasonal heat storages are used, due to the lack of sufficient solar energy in winter. Since a seasonal storage contains the heat for the whole heating season, the construction has a high investment cost. Thus, with one storage cycle per year the amortisation is often too long to be considered profitable as reviewed by Amaya et al. [3].

Regenerating the storage during the heating season allows the reduction of the storage size and its investment cost. The solar yield necessary to regenerate a medium-term storage, serving as ambient heat source for a heat pump system, is investigated in this paper. The storage is regenerated by a façade-integrated massive solar-thermal collector, similar as described by Tanzer et al. [4]. This paper presents a pre-investigation of the models for later validation by the monitoring data of a pilot plant with the goal to design further heat pump system with multiple heat sources. Comparison between different absorber sizes is made to describe the characteristic of the thermal behaviour of the storage and find an optimal absorber size.

This work is organised as follows: After describing the mathematical models of the ground collector storage, the façade-integrated massive solar-thermal collector, and the building, the models are combined in a system simulation. Yearly simulations of the ground collector temperatures, solar yield, and geothermal energies for systems with different absorber sizes lead to the solar fraction of the heat supply during the heating season. The necessity for frost-free operation results in a minimum required absorber size. For this absorber the prerequisites for a frost-free storage are analysed by the energy balance at the top of the storage.

2. Research Methods

The analysis is made with the mathematical software tool EES (Engineering Equation Solver). In the following chapter two models are described, representing the components ground collector storage and solar massive façade absorber. The two models are then combined to represent a heat pump heating system for a residential building.

2.1 ground collector storage

The ground collector storage is modelled by a set of parallel horizontal tubes serving for thermal activation of a cuboid ground volume underneath the building. The collectors size equals the rectangular footprint of the building and is positioned directly underneath the insulation of the base plate of the building. For heat input and output an aqueous brine is circulated through the pipes. A thermal insulation is inserted between the base plate of the building and the storage volume, which is considered ideal. There is no thermal insulation of the storage volume to the surrounding ground.

The heat transport $\dot{Q}_{\mathrm{T}}$ from the brine through the tube wall to the earth outside the tube is described by the heat transfer through a cylinder. Starting from the ground outside the tube, heat is transported deeper into the ground. To describe the heat flow in the ground without a FEM (finite element method) approach using a fine geometric mesh a simplification is made. The depth – 10 m – of the underground collector storage is divided into 40 blocks. The temperatures in each block are calculated with the differentiation method.

A geometric approach based on the from factor, described in the VDI Wärmeatlas (engl.: heat atlas) [5] is chosen to describe the heat flow from the cylindrical outer surface of the tube to the first horizontal block of the storage volume underneath the building. Equation (1) describes the heat flow $\dot{Q}$ transmitted through the earth. λ is the thermal conductivity of the earth, S_{l} the form factor calculated by equation (2), l the length of the tube, $T[1]$ is the temperature of the first block and T_{T} the surface temperature of the tube. d is the distance from tube to the centre layer of the first block, δ is half the tube spacing between two horizontal tubes of the collector and r the tube radius. The ground material is "clay/silt, water-saturated" as defined in the VDI 4640 part 1 [6].

$$\dot{Q} = \lambda \cdot S_l \cdot l \cdot (T[1] - T_{\mathrm{T}}) \qquad (1)$$

$$S_l = \frac{2\pi}{\frac{\pi d}{\delta} + \ln\left(\frac{\delta}{\pi r}\right)} \qquad \text{for: } r \ll d, \delta \qquad (2)$$

In the course of the year, the uninfluenced ground changes its temperatures according to the ambient air temperature and solar yields at the surface. Yet, in 10 m depth a rather constant ground temperature with only marginal seasonal swing around a 10 °C average is found. Therefore, the storage is regarded as 10 m deep with an undisturbed ground temperature of constant 10 °C at its bottom layer. A storage charged with higher temperatures loses heat to the ground underneath the storage. When the storage is cooled to lower temperatures a heat flow towards the storage volume occurs. Heat losses to the sides of the storage are not considered.

2.2 façade-integrated massive solar-thermal collector

The solar massive façade absorber is integrated in the south facing outer wall of a building as a low-tech heat source providing temporarily stable low-grade heat to the heat pump. It consists of a vertical sandwich structure with an outer concrete layer, which includes a tube meander serving as thermal collector. Brine is pumped through the tube to absorb energy from the collector. The back of the absorber is insulated, which eliminates heat transfer to the inside of the building, as an idealistic approximation within the model.

The thermal behaviour of the massive solar absorber is modelled according to equation (3). Heat fluxes conveyed by long $\dot{q}_{\mathrm{rad,lw}}$ and short-wave $\dot{q}_{\mathrm{rad,sw}}$ solar radiation hit the outer concrete surface and heat the bulk of the massive absorber. The heat losses of the absorber to the surroundings consist of long wave radiation $\dot{q}_{\mathrm{loss,lw}}$ and convective losses $\dot{q}_{\mathrm{loss,conv}}$. The heat transfer fluid heats up while flowing through the collector tubes $\dot{q}_{\mathrm{htf}}$ and serves for heat transfer to the thermal storage. Surplus heat stays in the concrete volume $\dot{q}_{\mathrm{MA,stored}}$ of the massive absorber, resulting in a temperature rise of the wall element with increasing heat content. In operation, the temperature of the brine lies in between the temperatures of the massive absorber and the underground thermal storage, governed by the respective heat transfer characteristics of the absorber and the storage.

$$\dot{q}_{\mathrm{rad,lw}} + \dot{q}_{\mathrm{rad,sw}} - \dot{q}_{\mathrm{loss,lw}} - \dot{q}_{\mathrm{loss,conv}} = \dot{q}_{\mathrm{htf}} + \dot{q}_{\mathrm{MA,stored}} \qquad (3)$$

For the weather conditions, ambient temperature, solar radiation, and wind speed are specified by the TRY (test reference year) for Potsdam, Germany.

Condensation of air humidity at the absorber surface occurs when the absorber temperature falls below dew temperature. Although condensation provides additional energy for the absorber, it is not considered in the calculations, because the growth of moss and the formation of frost could damage the surface of the absorber. Further information about the use of solar massive absorbers can be found in Tanzer et. al [4].

As a preliminary investigation, figure 1 shows the potential heat output of a solar massive absorber on the left ordinate. Monthly sums for the specific solar yield $\dot{Q}_{MA}$ are displayed for six different brine inlet temperatures T_{in} from -5 to 20 °C, kept constant throughout the year.

2.3 building

A heat pump uses the underground thermal storage as heat source for the heat supply of a building. The hourly heating demand of the building is determined by the ambient weather conditions, given by the TRY. The building is a single storey building with the same ground area as the ground collector storage. The insulation standard of the building is KfW40 – i.e., the heating demand is limited to 40 % of a standard newly built dwelling – according to EnEV standard (Energieeinsparverordnung – engl.: Energy Saving Ordinance). The single-storey model building with a footprint of 150 m² has an annual heat demand of 5100 kWh with a peak heat load of 4 kW at minimum ambient temperature of -13.4 °C.

The heat pump extracts heat from the earth collector storage. The heat flow to the evaporator of the heat pump is estimated by the COP, according to performance data provided by the manufacturer. Monthly values of the heat source energy $\dot{Q}_{source}$ are shown in figure 1 on the right ordinate.

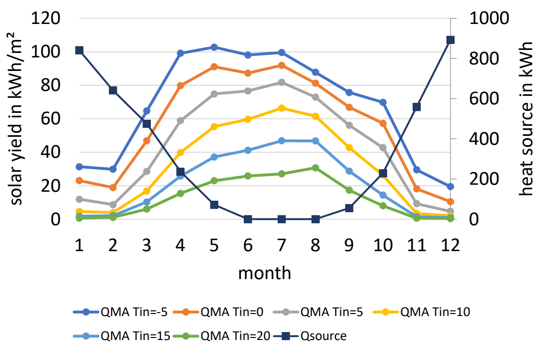

Fig. 1 – solar yield Q_{MA} in dependency of the inlet temperature T_{in}; heat source $\dot{Q}_{source}$.

2.4 storage regeneration

The EES models of the ground collector storage, the massive façade absorber and the building are combined for representation of the entire heating system. The heat pump extracts heat from the storage or the solar absorber according to the heat demand of the building. Surplus heat generated by the solar massive absorber is used for regeneration of the storage whenever possible.

In figure 2 a schematic description of the combined model is given, comprising the three components: solar massive absorber, ground collector storage, and building. $\dot{Q}_{source}$ is the heat source for the heat pump. The heat is extracted from the ground collector. $\dot{Q}_{MA}$ is the collected energy provided by the massive absorber, $\dot{Q}_{net}$ the net heat flow transferred to the heat storage via the ground collector. The heat flows $\dot{Q}[i]$ with $i = 1 \dots 41$ denote the change of the heat content in the respective storage blocks. This results in a change of the related temperatures $T[i]$ of the round layers. The bottom layer is assumed to stay at constant temperature $T[41] = 10$ °C throughout the year. Depending on the temperature profile of the lower cells of the storage, heat loss or heat gain $\dot{Q}_{geo}$ is exchanged with the undisturbed ground underneath the ground heat storage.

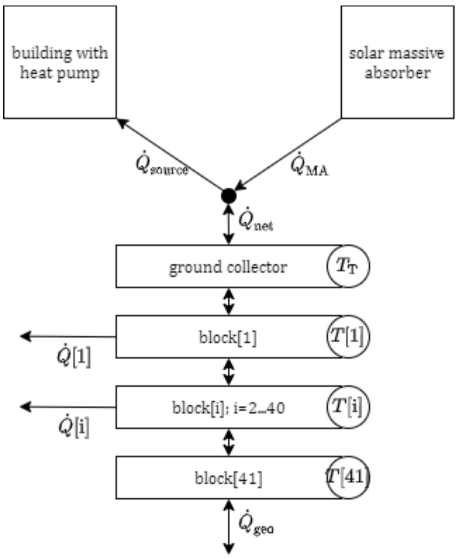

Fig. 2 – EES model of the heating system, comprising the three components: solar massive absorber, ground collector storage, and building.

3. Performance of the heating system

This chapter deals with the analysis of the operation of the described heating system. The system's efficiency and usability are characterised by the temperature curve of the ground storage over a year. Together with the storage temperature the heat transfer fluid's temperature is determined, which is a decisive parameter for the efficiency of the heat pump system. For the system to be financially viable, the seasonal coefficient of performance (SCOP) must be high, resulting in low electrical power consumption and savings in the operating costs.

The following scenario is considered for the analysis. A given one-storey building with a building area of

150 m², as described in section 2.3, is heated by a brine/water heat pump. The COP of the heat pump is taken from nominal design point specified by the manufacturer and is considered constant for a conservative approximation, even though higher source temperatures would result in higher COP values. With this, the required heat input to the heat pump which is to be covered by the heat source is set for the hourly simulation of the heating system. The ground area of the building is identical with the area of the ground collector storage, i.e., the complete footprint of the building is thermally activated by the ground collector. The absorber size is the single variable to influence the performance and usability of the heating system.

The solar massive absorber is varied in size to find the optimal system design for the given situation, defined by the underground heat storage and the building. The size varies from 7.5 m² to 37.8 m² (37.8 m² is the size of a pilot plant, which is not part of this paper). The different solar absorbers equal 5% to 25.2% in relation to the ground collector size.

To obtain a realistic initial state for the modelling of the entire year, the annual calculations have been repeated 10 times until a stable state is reached.

3.1 ground collector storage temperatures

The course of the ground collector storage temperature during the heating period is characteristic for the efficiency of the heating system. The annual temperature profiles of the underground storage are analysed for different absorber sizes. Since the storage is considered a medium-term heat storage, regeneration during the heating season is necessary. A cooled down storage allows for solar yield at low heat transfer fluid temperatures, which enables regeneration during the heating period.

The temperature in the storage is a result of the heat extraction by the heat pump and the regeneration by the solar absorber. The temperature of the first block from the top $T[1]$ changes first depending on the input or output of energy. The temperature difference between two adjacent blocks causes the heat to spread between the blocks. While charging the storage, heat is transferred deeper into the storage. During discharging, lower temperatures at the top cause the heat to travel upward.

Figure 3 shows selected temperatures of blocks in different depths of the storage regenerated by a massive solar absorber with the size of 37.8 m² for one year, starting on January 1st. During the heating period the temperature $T[1]$ is decreasing due to the heat extraction by the heat pump. When the storage is regenerated, $T[1]$ is rising. The temperatures of the deeper blocks follow this trend with a temporal delay as a result from the high thermal capacity of the storage material – earth. The temperature $T[41]$ in 10 m depth is constant since it is defined fixed at 10 °C. If the adjacent block (No. 40) has a higher temperature, the energy exchange between these two blocks is lost to the deep ground. If the temperature of the second last block is lower, heat is gained from the ground underneath the storage volume.

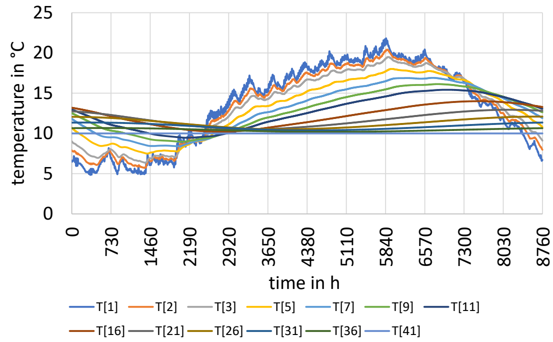

Fig. 3 – temperatures $T[i]$ in different depth of the storage for an absorber size of 37.8 m².

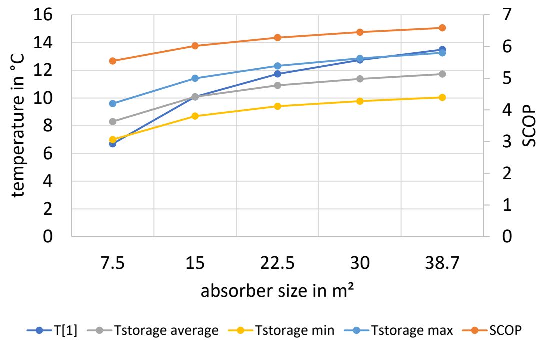

Fig. 4 – yearly average, minimal and maximal temperatures $T_{storage}$ and $T[1]$ (left ord.); SCOP (right ord.) for different absorber sizes.

Regeneration is possible in winter, even if the solar radiation is low. In figure 3 different phases of the operation of the storage can be identified. In fall the temperature in the first block decreases. On a mild day with high ambient temperature and low or no heat extraction this decrease flattens. On a sunny day with more solar yield than heat extraction the temperature is increasing. In addition, the storage temperatures in the upper layers show relaxation. Heat from the lower blocks of the storage flows towards the upper blocks depending on the temperature difference. On days with no heat extraction and no solar yield the temperature in the first block is rising to converge to the temperature of the second block. In winter the temperature decrease of the first block slows down even during high heat extraction and low solar yields, because of the heat flow from the depth of the storage. A ten day long regenerating period until the end of January (500 to 730 h) is shown in figure 3. In this phase, the solar yield surpasses the heat extraction and the temperature in the storage is increasing. The behaviour of the underground heat storage with solar regeneration during the winter months is analysed further in chapter 4. In spring and summer, the solar yield surpasses the heat extraction. Consequently, the temperature in the first block stays above the temperature in the second block. Heat flows from the first block to the depth of the storage and regenerates it.

When the absorber size is decreased, a lower annual mean temperature T_{storage} of the ground storage is found. The minimal, maximal as well as the average temperature as a function of the absorber size is shown in figure 4. Since the ground temperature is decisive for the performance of the heat pump, – primarily the average temperature of the first block $T[1]$ – the value of SCOP is lower for smaller solar massive absorbers and corresponding lower temperatures of the ground collector.

3.2 solar yield and storage regeneration

As shown in the last section, different absorber sizes result in different storage temperatures. In return, the storage temperature is decisive for the solar yield of the absorbers. This interdependency is analysed regarding the energy balance for different absorber sizes. The resulting regeneration behaviour of the underground heat storage is shown in the following section based on the solar yield.

The yearly solar yield of the massive absorbers Q_{MA} is quantified in figure 5. Larger absorbers allow both, higher storage temperatures and increased solar yield, although the demand for heat from the source Q_{source} by the heat pump is set constant. For an absorber size of 7.5 m^2 the solar yield cannot fulfil that heat demand. Additional energy is required to meet the heat demand, which is provided by heat from the depth of the storage Q_{geo}. The solar yield of an absorber with 15 m^2 surface area fulfils the heat demand. For absorber sizes greater than 15 m^2 the heat gain exceeds the heat demand. The surplus heat balances the energy lost in the depth of the storage. These heat losses are higher for higher storage temperatures. Further analysis of the heat losses and gains is made in subsection 3.3.

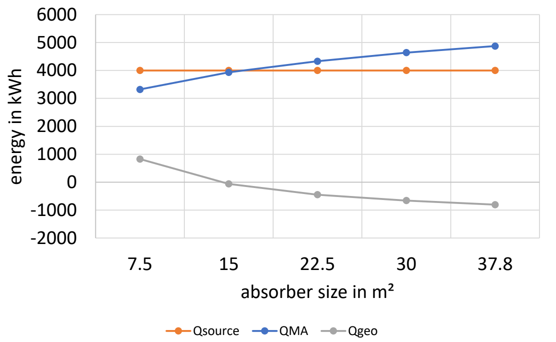

Fig. 5 – annual solar yield Q_{MA}, heat source Q_{source}, and geothermal energy Q_{geo} for different absorber sizes.

For all absorber sizes equation (4) is valid. The source heat flow supplied to the evaporator of the heat pump is covered by the solar yield and the geothermal energy exchanged with the deep ground.

$$Q_{\text{source}} = Q_{\text{MA}} + Q_{\text{geo}} \tag{4}$$

Since the yearly solar yield shows variance for the different absorber sizes, a more detailed analysis is made in monthly intervals, to determine the temporal profile of the solar yield. The monthly solar yield for the absorbers is shown in figure 6. In winter months (November to February – month 11 to 2) the absorbed energy is the same for all absorber sizes. Although the larger absorbers have more absorber surface area to collect the solar energy, their solar yield is the same as for the smaller absorbers. This is due to the higher temperature of the underground heat storage which is achieved by the larger sizing of the solar system. The resulting higher inlet temperatures in the absorber reduce the specific solar yield. During the rest of the year larger absorber sizes result in higher solar yields, due to the larger surface of the solar absorber. Although the highest solar radiation occurs in summer, for larger absorber sizes the maximum solar yield appears already in spring (month 4 and 5). When a large absorber is used, in spring the storage temperature increases at a higher rate, resulting in higher inlet temperatures in the absorber and consequently decreasing solar yields.

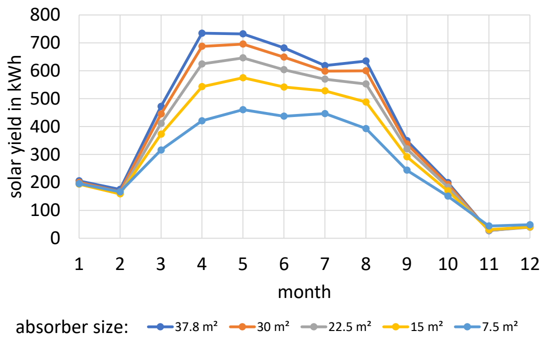

Fig. 6 – monthly solar yield Q_{MA} for different absorber sizes.

3.3 geothermal balance of the storage

Larger absorbers have higher solar yields and allow for higher storage temperatures, resulting in higher efficiencies for the heat pump heating system. Higher storage temperatures also result in higher heat losses to the deep ground underneath the storage volume. The yearly geothermal losses and gains are shown in figure 5. The data are based on a consolidated cyclic situation, which is reached after several years of operation with an identical annual profile to be repeated year by year. To determine the energy balance of the underground heat storage during the year the geothermal energy is investigated in the following section.

The energy balance Q_{balance} of the heat storage, i.e., the change of the heat content of the storage is found by summation of the geothermal energy Q_{geo}, the demand for heat from the source Q_{source} by the heat pump, and the solar yield Q_{MA}, as given in equation (5).

$$Q_{\text{balance}} = Q_{\text{geo}} + Q_{\text{source}} + Q_{\text{MA}} \tag{5}$$

During the year the energy balance is alternating, as shown in figure 7 for the heat pump heating system with solar absorber sizes from 7.5 to 37.8 m². The storage is charged in summer and discharged in winter, resulting in an increasing and decreasing storage balance. For comparison of the heat content of the storage for different absorber sizes, the start is normalised to a heat content of 0 kWh at the beginning of the year. The differences in the graphs are due to the losses and gains of geothermal energy in the depth of the storage.

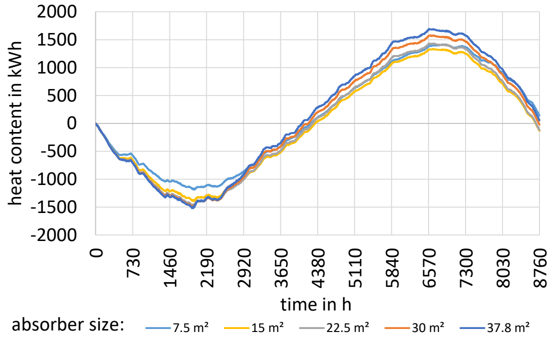

Fig. 7 – heat content of a storage for different absorber sizes over one year.

The geothermal energy is determined by the heat flow from the 40th to the 41st block, as described in equation (6). The 41st block stays at constant temperature of 10 °C throughout the year. When the 40th blocks temperature is above this temperature, energy is lost. Vice versa, energy is gained. The geothermal heat flow depends on the heat transfer coefficient of earth λ, is the thickness of a block d, and the ground collector area A.

$$Q_{\text{geo}} = (T[41] - T[40]) \cdot \frac{\lambda \cdot A}{d} \qquad (6)$$

The geothermal energy is dependent on the temperature profile of the bottom blocks of the storage. Since the temperature of the storage is alternating according to the seasons, the geothermal energy is also fluctuating. Although, the storage temperature is highest in summer, the heat losses and lowest heat gains are found in winter. Energy, which is stored in the summer, heats up the first blocks at the top of the storage. The heat is distributed through the storage and flows into the deeper blocks. The maximum of the temperature of the first block reaches the last block five months later.

Figure 8 shows the summation of the geothermal energy $Q_{\text{geo,sum}}$ during a year for different collector sizes. For smaller solar absorber (7.5 m²) the annual balance is positive. For all other configurations, a heat loss to the deep ground is found. Larger absorbers result in higher losses, due to higher average storage temperatures. When the minimum temperature of the last block is reached in summer the heat losses are the lowest, as can be seen in figure 9 at about 4380 h. For smaller absorber sizes the temperature falls below 10 °C and heat is gained, causing the summation curve to rise. Since the average temperature of the smallest absorber is below 10 °C, there are continuous heat gains throughout the year for this absorber size.

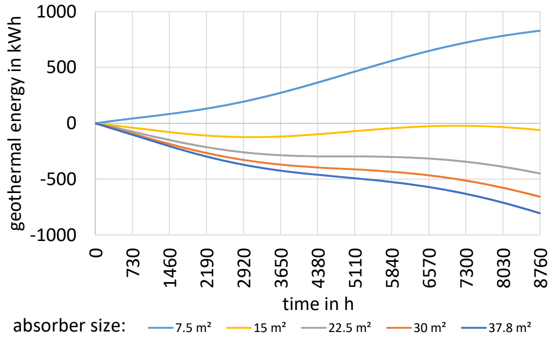

Fig. 8 – summation of the geothermal energy $Q_{\text{geo,sum}}$ for different collector sizes over one year.

3.4 regeneration during the heating season

To reach affordable system cost, a heat storage of limited size shall be sufficient for reliable operation of the heating system. Thus, the storage shall act as a medium-term storage with repeated regeneration within the heating season and not as a seasonal heat storage providing a full seasonal time shift from summer to winter. The additional in-season energy input in the storage is needed to meet the heat demand of the building. In this section the energy input, output, and balance of the storage is analysed for the time period of the heating season. As an example, figure 9 shows these energies for an absorber size of 22.5 m².

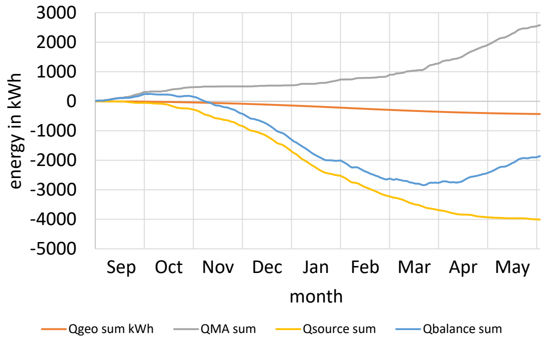

Fig. 9 – summation of the solar yield Q_{MA}, the geothermal energy Q_{geo}, heat source Q_{source}, and energy balance Q_{balance} over the heating season for an absorber size of 22.5 m².

The heating season starts in September, when the heat demand Q_{source} is low and solar radiation still allows for a positive energy balance Q_{balance} of the storage, i.e., heat content. In mid-winter the solar yield Q_{MA} is low, while the heat demand is at its highest, resulting in a decreasing energy balance. The storage temperature decreases and allows for solar yield at low temperatures of the heat transfer fluid in the second half of the heating season. In March the solar yield exceeds the heat demand, and the energy balance increases. At the end of the heating season in May, the energy balance of the storage is still negative. Further regeneration in the summer month is required to fully regenerate the storage reaching a neutral balance of the storage at the beginning of the next heating period in September.

As shown in the example for an absorber size of 22.5 m^2, the regeneration during the winter covers most of the heat demand by the heat pump. The absolute and relative values of the solar contribution for the different absorber sizes are shown in figure 10. With increasing size if the solar absorber, the annual solar yield increases from 3,200 to 4,900 kWh. When considering coverage rate, two ratios are of interest. The first is the rate of solar yield during winter to the total annual solar yield ($Q_{MA}HS/Q_{MA}$). The second is the rate of solar yield during winter to the evaporator heat demand ($Q_{MA}HS/Q_{source}$). The in-season share of the solar yield ($Q_{MA}HS/Q_{MA}$) is about 60% for all absorber sizes. The second rate ($Q_{MA}HS/Q_{source}$) rises with the absorber size, expressing a 51% to 73% coverage of the heat demand. These rates are implicitly influenced by the storage temperatures and geothermal heat. In general, the values found for both rates point out the medium-term character of the storage.

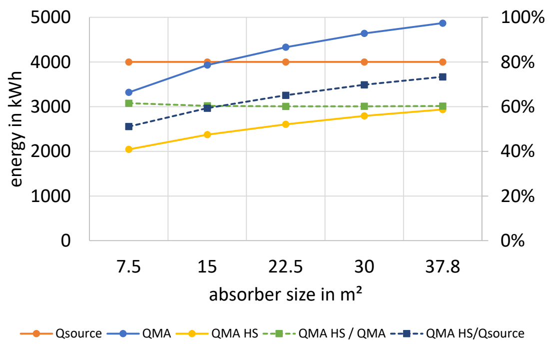

Fig. 10 – solar yield during the heating season $Q_{MA}HS$ and total Q_{MA}, heat source Q_{source} (left ord.); solar rates $Q_{MA}HS/Q_{source}$ and $Q_{MA}HS/Q_{MA}$ (right ord.).

3.5 optimal absorber size

As mentioned earlier, frost in the ground collector storage should be avoided. Therefore, the temperature outside the ground collector tube must stay above 0 °C. Temperatures of the heat transfer fluid slightly below 0 °C are acceptable at the inlet of the ground collector if there is no phase change on the outside of the tube. For this purpose, the heat carrier temperature, and the temperature of the ground in contact with the underground collector has been investigated. Figure 14 shows the minimum values of the fluid inlet temperature T_{in}min and of the temperature of the outer tube wall of the collector $T_T$min occurring in the course of the heating season for different sizes of the solar system. As shown in figure 14 the minimal temperature outside the tube is about 1 K higher than the minimal inlet temperature, independently from the size of the solar absorber. For practical application it must be assessed how often situations with formation of frost occur within the course of the heating season. For a limited duration, such situation can be bridged using an electrical heater. Yet, regarding the desired high energetic efficiency, the use of the electric heater should be avoided.

The grey line in figure 11 shows the annual occurrence of situations with potential formation of frost (T_T<0 °C, in hours per year). According to the result of the system analysis, a size of the massive solar absorber of 7.5 m^2 is insufficient for an efficient operation of the heating system. The solar collector should have a surface area of about 20 m^2 or larger. Therefore, in the following section an absorber size of 22.5 m^2 is chosen.

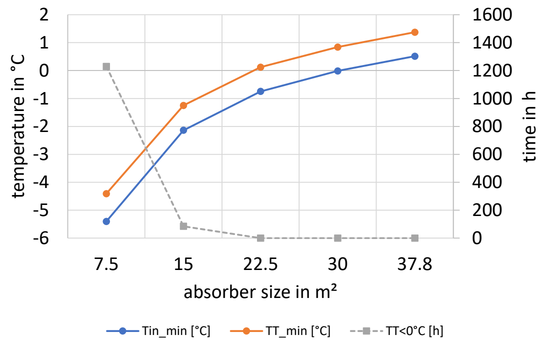

Fig. 11 – minimal temperature at the inlet T_{in}min and outside the tube $T_T$min (left ord.); frost occurrence (right ord.).

4. Balance of the storage in winter

For the selected absorber size frost is avoided in the modelled system configuration. However, this might only be true for the given weather condition of the TRY. In this chapter the characteristics of the storage in the middle of the winter are investigated further, to acquire knowledge about the general prerequisite for a frost-free operation of the storage. The critical time is in January and February during the lowest ground temperatures.

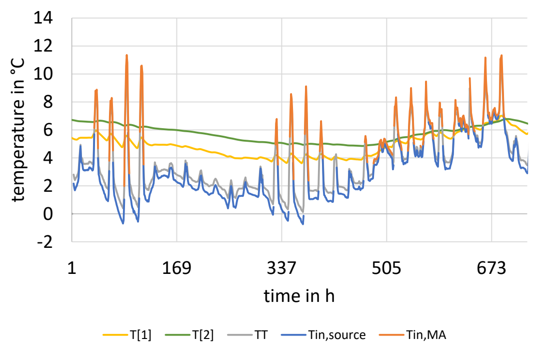

Fig. 12 – temperature in the first $T[1]$ and second $T[2]$ storage block, temperature around the tube T_T, inlet temperatures in the storage from the heat pump $T_{in,source}$ and the massive absorber $T_{in,MA}$ in January.

Frost occurs when water around the ground collector tube cools below 0 °C and freezes. To avoid frost, the earth around the collector tube must stay above freezing temperature. This temperature is influenced by heat extraction from the heat pump, regeneration by the solar massive absorber, and relaxation from the storage below the collector tubes. The influencing inlet temperatures of the heat transfer fluid ($T_{in,source}$ for heat extraction, $T_{in,MA}$ for heat input into the storage) are shown in figure 12.

For relaxation, heat is exchanged between the storage blocks as well as between the first block and the earth around the tube T_{T}, governed by the respective temperature differences. When no heat is extracted or regenerated, the storage relaxes and the temperature around the tube converges to the temperature of the first storage block.

The daily energy balance in the top of the storage is analysed to quantify the energy flows. The temperature around the tube is fluctuating based on the alternating weather condition during the daily cycles. The net energy flow Q_{net} from or to the heat transfer fluid is calculated by equation (7). The daily energy sums of the heat transfer fluid for January and February are shown in figure 13. Although there is solar yield on 41 out of 60 days, the net energy is positive only for 12 days.

$$Q_{\mathrm{net}} = Q_{\mathrm{source}} + Q_{\mathrm{MA}} \quad (7)$$

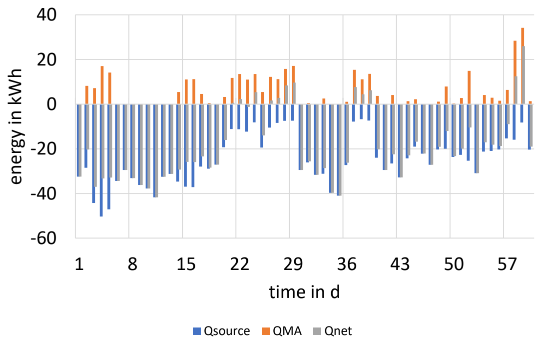

Fig. 13 – solar yield Q_{MA}, heat source Q_{source}, and energy balance Q_{net} in January and February.

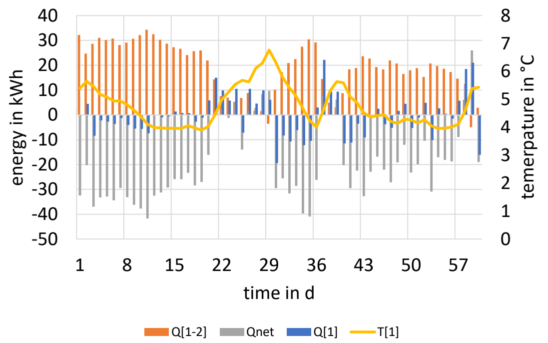

Fig. 14 – daily net energy Q_{net}, heat transfer between the first and second block $Q[1\ 2]$, and energy balance of the first block $Q[1]$ (left ord.); daily average temperature in the first block $T[1]$ (right ord.) in January and February.

Whenever the net energy is negative, the temperature around the tube decreases and heat from the storage flows towards the tube to level out the temperature difference. Therefore, the temperature of the first block is analysed by calculating the energy balance in the first block $Q[1]$ in equation (8). The heat $Q[1]$ supplied to block 1 is obtained by summation of the net energy flow Q_{net} exchanged via the heat collector and the heat transfer between the first and the second block $Q[1\ 2]$, calculated in equation (9), analogously to equation (6). Since the heat flow $Q[1]$ adds or subtracts to the heat content of the first block, the temperature alternates accordingly. The analysis demonstrates that the energy balance of the first block is alternating, but balanced over the two winter months, as expressed by the temperature of block $T[1]$ displayed in figure 14.

$$Q[1] = Q_{\mathrm{net}} + Q[1\ 2] \quad (8)$$

$$Q[1\ 2] = (T[2] - T[1]) \cdot \frac{\lambda}{d} \cdot A \quad (9)$$

5. Conclusion and outlook

In this paper a heat pump system with two building-integrated low-tech heat sources, a massive solar-thermal collector regenerating a medium-term ground collector storage, is analysed theoretically. It is shown that the heat storage can be effectively recharged during the heating season, allowing for reduced size and cost of the storage. It is found that an absorber size equal to 15% of the ground collector is required to operate the heating system, avoiding freezing of the underground heat storage. A small absorber size will allow for minimal investment cost. Whereas larger absorbers result in higher storage temperatures and consequently in higher efficiency of the heat pump heating system.

The medium-term character of the storage is pointed out. The critical months in winter are evaluated regarding the risk of frost and the energy balance at the top of the storage.

Further investigations will include different ground collector storage configurations and the use of ambient air as an additional heat source.

6. References

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Data Statement

The dataset generated is available on demand through direct contact to the author.