POTENTIAL OF SOURCE-SIDE THERMAL ENERGY STORAGES IN GEOTHERMAL AND SOLAR THERMAL SUPPLIED HEAT PUMP SYSTEMS

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ABSTRACT

Until today the German building stock is still mainly supplied by fossil fuels to provide heating and domestic hot water. Supply solutions are needed to establish a high share of renewable energies in existing buildings and thus contribute to the overall transition of the heating sector. The combination of geothermal and solar thermal energy in electric driven heat pump systems have proven to be an efficient solution for existing buildings despite the higher supply temperatures on the demand side compared to new buildings. This work examines the potential of an additional source-side thermal energy storage on the economic and efficient operation of integrated heat pump systems supplied by solar and geothermal sources. The aim is to investigate whether this system configuration is suitable for achieving an increase in the system efficiency compared to an equal system that is not equipped with an additional source-side storage and to quantify the additional costs that are incurred for the application. The system is modeled in the simulation environment of Polysun, where parameter studies are conducted for different storage sizes and number of collectors under consideration of real measured data from an existing building with moderate level of refurbishment. The results in our recent simulation set up show that geothermal and solar thermal supplied heat pump systems are slightly benefitting only in a few cases from an application of an additional source-side storage regarding the overall system-efficiency. Further studies are necessary to optimize and investigate the control behavior of the system and to further quantify the potential of source-side thermal energy storages in geo- and solar thermal supplied heat pump systems.

1 INTRODUCTION

According to the Federal Environment Agency (UBA) (2024), the building sector, consisting of private households and properties in the trade, commerce and services sector, were accountable for 15% of the total greenhouse gas emissions that have been emitted in Germany in 2022. One reason for this is that 78% of the German building stock is still supplied with fossil fuels such as heating oil or natural gas to provide space heating and domestic hot water (Deutsche Energie Agentur, 2024). Since the beginning of 2024, the current amendments to the Building Energy Act provide for stricter energy requirements for new and existing buildings in Germany in order to reduce the energy demand of the building sector and to increase the share of renewable energies in the heat supply.

1.1 Integration of geothermal and solar thermal energy in current heat pump systems

Electric heat pumps will play a decisive role in the future heat supply of buildings. In addition to the coupling of the electricity and the heat sector, the main advantage of this technology is the ability to efficiently provide several shares of heat with one share of electrical energy. In the future electricity system that is based on volatile renewable energies, the sector-coupled and forecast-based operation of heat pumps will help to flexibly react to the fluctuating electricity generation and thus contribute to overall system stability (Born et al., 2022). The efficiency of heat pump systems depends on the selected environmental heat sources and the required system temperatures in the building. Especially in the German building stock, of which 60% were built before 1978 according to the Deutsche Energie Agentur (2024), geothermal supplied heat pump systems can achieve good efficiency despite higher supply temperatures (Born et al., 2022). A field study conducted by Günther et al. (2020)

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showed that geothermal supplied heat pump systems in existing buildings with different degrees of refurbishment achieve a mean seasonal performance factor (SPF_{HP}) of 3.88. The majority of the buildings in this study are supplied by radiators with heating temperatures between 30 and 45 °C. Additionally domestic hot water is also supplied in each building with a mean supply temperature of 48.9 °C.

Integrating solar energy through solar thermal collectors to geothermal supplied heat pump systems has been applied in the past to increase the overall system efficiency. Frank et al. (2010) divides these systems into the categories parallel, serial and regeneration

In a parallel integration of solar and geothermal heat, the solar collector and the heat pump are independently supplying useful heat for heating and domestic hot water. This system configuration does not utilize the solar collector as an additional source for the heat pump. In contrast, with a serial system integration, the solar energy is mainly used as an additional low-temperature source, which is directly or indirectly supplied to the heat pump. An investigation by Bertram et al. (2011) showed that the serial integration of solar thermal collectors into geothermal supplied heat pump systems can cover a significant fraction of the requested source energy, especially in the transition periods of spring and autumn. This increases the efficiency of the heat pump and relieves the borehole heat exchanger (BHE). Utilizing the heat from solar collectors to regenerate the underground is the third option for integrating solar energy into geothermally supplied heat pump systems. As stated by (Sparber et al., 2011) these categories are not exclusive, therefore a system can be parallel, serial and regenerate the underground. Those systems are categorized as "integrated", where the solar heat is used for the direct supply of heating and domestic hot water, as source energy for the heat pump or for passive regeneration of the BHE (Sparber et al., 2011). Miara et al. (2011) assessed a seasonal system performance factor, as defined in Equation (1) according to Sparber et al. (2011), between 4.9 and 6 for an operating integrated geothermal and solar thermal supplied heat pump system..

$$SPF_{HP} = \frac{\sum(Q_{HP,tot})}{\sum(E_{HP,tot})} \quad , \quad SPF_{Sys} = \frac{\sum\left(Q_{HP,tot} + Q_{Sol,tot}\right)}{\sum\left(E_{HP,tot} + E_{CP,BHE} + E_{CP,sol}\right)} \tag{1}$$

Further detailed information on the building age and the state of refurbishment of the buildings, the energy system is operating in, were not given. So far only few studies included buildings with a moderate level of refurbishment and higher supply temperatures that operate with this kind of energy system (Sparber et al., 2011). Furthermore the systems do not provide storage capacity on the source side of the heat pump. An additional source side thermal energy storage could help to store low temperature heat from the collector for later use.

1.2 Aim of this paper

In this work we analyze the potential of the application of an additional source-side thermal energy storage in an integrated geothermal and solar thermal heat pump system by comparing the system performance as well as the economic viability to an equivalent system where no source-side storage is applied. This investigations are intended to show whether the provision of an additional thermal energy storage on the primary side of the heat pump leads to an increased efficiency of geothermal and solar thermal supplied heat pump systems that are operating in existing buildings with a moderate state of refurbishment. The economic viability calculation is intended to show whether the use of an additional storage provides cost benefits compared to a system without source-side storage and is performed according to the (VDI 2067-1, 2012). This paper first models an appropriate system within the simulation environment of Polysun, then the system performance is evaluated with real measured data from an existing building by performing parameter studies with different system configurations.

2 METHODOLOGY

In this section the model of the geothermal and solar thermal coupled heat pump system is developed. First, the overall building properties are described, the provided heat demand data is analyzed and prepared for later use in the simulation. Then the overall building energy system is described and developed within Polysun and the different components are sized according to the analyzed data. Finally the input parameters for the calculation of the economic viability of the system according to

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VDI 2067-1 (2012) are presented and the upcoming investigations regarding the number of collectors and the volume of the source- and sink storages are described.

2.1 Building performance analysis

The apartment block, on which the investigations are based, is shown in Figure 1. It is part of LEG's building stock and is located in Castrop-Rauxel (Germany). The apartment block consists of four buildings with a total of sixteen residential units, which are currently supplied with heat and domestic hot water via a central gas boiler. LEG Immobilien SE is a German real estate company whose property structures include many existing and moderately refurbished buildings of this type. Many of these buildings will soon or in the near future require new heating supply systems. Investigations into efficiency and cost-effectiveness of integrated geothermal and solar thermal heat pump systems are promising, as it would be possible to widely apply these systems. A data set with heat consumption measurements of the building block were provided by LEG with further information on the current heating system. Table 1 contains overall informations on the building and the heating system, that are used in the following investigations.

Figure 1: Digital building model of the analyzed apartment block

The measured energy consumption for heating and domestic hot water matches quite well with literature data for existing buildings of this type. According to Loga et al. (2016) and the TABULA Webtool (2016) the specific heat consumption for German multifamily buildings of this age (1958 to 1968) with moderate level of refurbishment are approximately 67.2 kWh/m^2 only for the supply of heating. Further information on the state of occupancy and the occupant behavior were not given.

Table 1: Informations on the analyzed building

Heated floor area [m^2]	830
Roof area [m^2] and orientation	341; North-west
Roof area [m^2] and orientation	341; South-east
Roof tilt (from horizontal plane) [degrees]	39
Central DHW supply [-]	Yes
Total annual energy consumption for heating and DHW in 2022 [kWh]	65,444
Specific total energy consumption in 2022 [kWh/m^2]	78.8
Daily operating time of energy system [h]	17
Supply temperatures (Heating and DHW) [°C]	70/50

2.2 Heat load calculation with measured data

The measured data from the energy-plant of the apartment block were analyzed according to the specifications stated in the national appendix of the DIN EN 12831-1 (2017) and have initially been cleared of any non-weather-dependent demand-data (e.g. domestic hot water) and outliers. The average plant load was then calculated considering the daily operating time and the daily amount of heat supplied by the plant according to Equation (2) as stated in DIN EN 12831-1 (2017) by considering the informations in Table 1. The DIN EN 12831-1 (2017) is a German standard that is used to calculate the standard heat load of a building for a given location.

$$\Phi_{h,outg,d} = \frac{Q_{h,outg,d}}{\Delta t_d} \tag{2}$$

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Where

- $\phi_{h,outg,d}$ is the daily mean plant load in kW
- $Q_{h,outg,d}$ is the daily heat supply of the energy plant in kWh
- Δt_d is the daily operating time of the energy plant in h

The average load of the energy plant was then intersected with outdoor temperature data obtained from Deutscher Wetterdienst Climate Data Center (2024) to calculate the heat loss coefficient of the building using linear regression. The heat loss coefficient of the building takes into account the heat losses by transmission and ventilation and corresponds to the slope of the regression line. Additionally the heating limit temperature of the building can be determined through the intersection of the regression line and the x-axis. Figure 2 shows the results of the conducted regression. The load at -8 °C determines the maximum heat load of the building and can be obtained from Table 2. Steady-state heat load calculations have also been added to Table 2. Compared to the analyzed data, the results of the steady state calculations are higher due to internal gains and set-back-temperatures that are not considered in the calculation according to (DIN EN 12831-1, 2017).

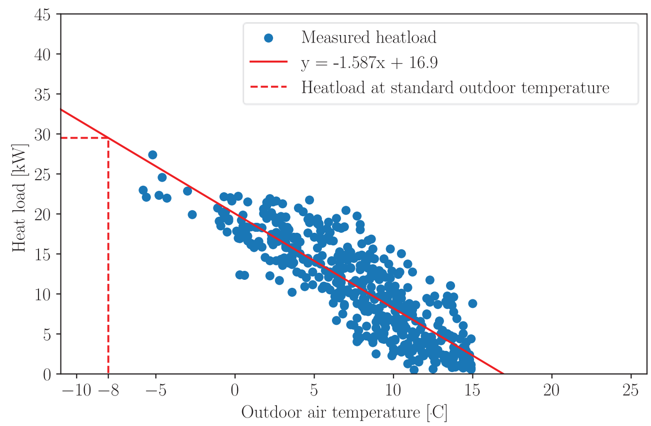

Figure 2: Linear regression for the measured heat load of the apartment block

Table 2: Analyzed heat loads for the building

Measured-data	
Total heat load [kW]	29.7
Specific heat load [W/m^2]	36.6
Steady-state calculation	
Total heat load [kW]	38.7
Specific heat load [W/m^2]	46.6

2.3 Heat demand for room heating

The results of the linear regression were then used to derive an hourly load profile for use in the Polysun simulation. In accordance with the specifications of DIN EN 12831-1 (2017) an hourly weather data set for Castrop-Rauxel was used, where the outdoor temperature was inserted into the linear regression function to determine the hourly plant load. The regression function is given in Figure 2. Figure 3 shows the hourly heat load profile of the apartment block and the outdoor temperature profile for the given location. The annual energy demand for supplying heat is calculated to 40,088 kWh. The heating supply temperatures used in the simulation are described in section 2.5

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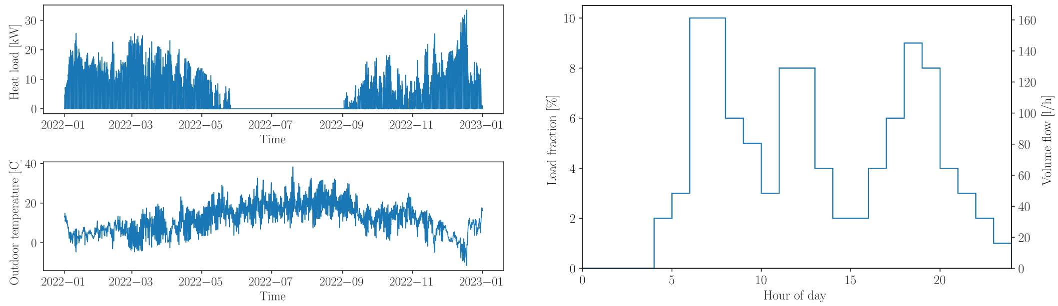

Figure 3: Calculated heat load profile for given outdoor temperature of 2022 (left) and DHW load profile (right)

2.4 Heat demand for domestic hot water

The average load for the provision of domestic hot water was calculated by averaging the system load in the summer months, where no heating demand from the building was evident. The calculated results are shown in Table 3. Due to occupant behavior or heat losses in the featured circulation network for preventing legionella, the measured heat demand for the supply of domestic hot water is higher compared to literature data. For comparison, calculations from the DIN V 18599-10 (2018) result in an energy demand of 17,280 kWh/a for the supply of DHW. The DIN V 18599-10 (2018) is a German standard for calculating and evaluating the energy performance of buildings.

Table 3: Results of analyzed demand data for DHW supply

Average plant load for DHW supply [kW]	3.8
Total annual energy demand for DWH supply [kWh/a]	23,890
Total annual energy demand for DWH (DIN V 18599-10) [kWh/a]	17,280

The load profile that was implemented in Polysun under consideration of the measured and analyzed data can be seen in Figure 3.

2.5 System layout

The layout of the modeled integrated geothermal and solar thermal heat pump system in Polysun can be seen in Figure 4.

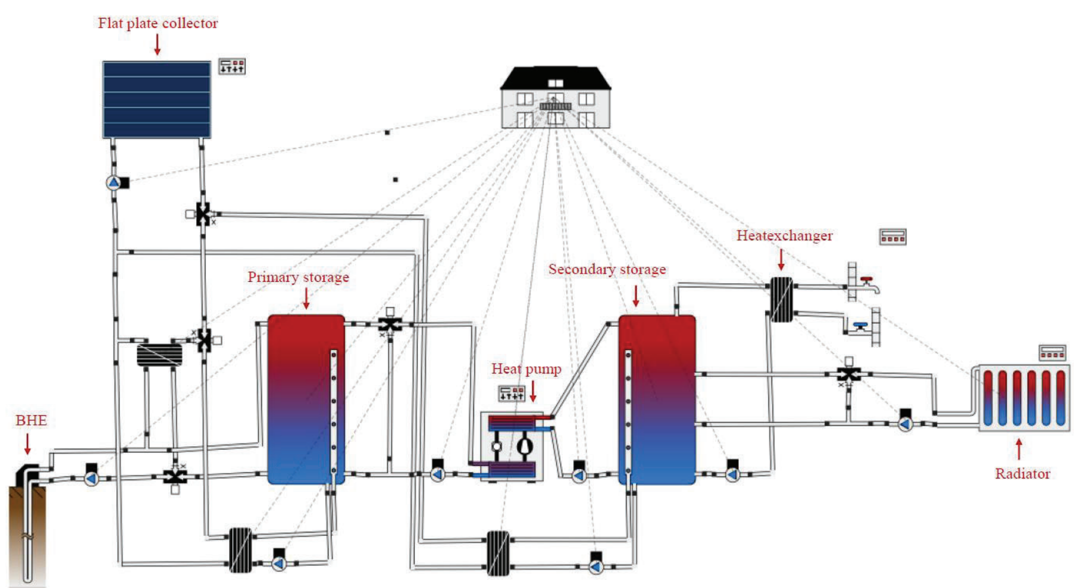

Figure 4: Modelled integrated geothermal and solar thermal heat pump system with primary and secondary storage in Polysun

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The flat plate collectors in the solar loop can individually be switched between the source- and sink-side storage and the BHE loop through the applied three way valves. To prevent mixing of the different working fluids the solar loop is decoupled through plate heat exchangers. The solar loop handles a water-propylene-glycol mixture with a propylene fraction of 38%. Both storage tanks have a stratified lance that enables the solar energy to be fed into the correct layer with a suitable temperature. Due to the direct coupling of the BHE loop the source storage handles a water-ethylene-glycol mixture with 25% glycol to prevent freezing. The mixing valve between the source side storage and the heat pump ensures an appropriate inlet temperature within the operating limits of the heat pump. On the sink side the storage is filled with water that directly supplies the radiators in the heating loop with supply- and return temperatures of 50/40 °C. In contrast domestic hot water is indirectly supplied through plate heat exchangers to the consumers with a freshwater temperature of 10 °C and a supply temperature of 45 °C. The source-side storage has a set temperature of 25°C and the sink-side storage has a set temperature of 55 °C but can additionally be overheated by the solar collectors to 80 °C if possible. The maximum outlet temperature of the solar collectors for the regeneration of the BHE's is considered to be 30 °C.

2.6 Heat pump

The brine-water heat pump was dimensioned and selected according to the maximum heat output of 33.6 kW required for the provision of domestic hot water and heating. As the next largest heat pump model from the polysun database is only available with a heating output of 42 kW, the heat pump was dimensioned slightly larger. The system parameters of the heat pump can be found in Table 4. Polysun models the heat output and the electricity demand of the heat pump by interpolating support points measured in the laboratory (Vela Solaris, 2024). Polysun models a cycling heat pump behavior.

Table 4: System parameters of the selected brine/water heat pump

Parameters	
Nominal heat output (B0/W35 with COP of 4.8) [kW]	42.4
Nominal electrical power [kW]	8.7
Min/Max temperature (Source) [°C]	-10/25
Nominal volume flow (Source) [l/h]	10,500
Max temperature (Sink) [°C]	68
Nominal volume flow (Sink) [l/h]	7,000

2.7 Borehole heat exchanger

Geological data from the Geological Service NRW (2024) were used to estimate the subsurface properties of the given site. This data was then used to calculate the number of boreholes according to the regulations in the VDI 4640-2 (2019) by estimating a mean heat extraction rate of each BHE considering the thermal conductivity of the underground and the annual full load hours of the heat pump. The full load hours of the heat pump have been assumed to 1800 hours. Due to higher legal authorization requirements, the length of the individual BHE was limited to 100 m. Although this calculation method is only valid for systems with a heating output of less than 30 kW, it is still used to estimate the number of BHE's for this building. The number of BHE's is integrated into Polysun, where the thermal simulation is done by approximating Fourier's heat equation with finite-differences and a finite line source model (Huber & Schuler, 1996) (Vela Solaris, 2024). The BHE's are precalculated for five years. Table 5 includes the used parameters and the results of the borehole sizing. For the later investigation regarding the number of collectors and the storage size the number of boreholes is set to a constant value. Due to the fact that it is not possible to dynamically size the BHE within the simulation environment of Polysun to take into account the amount of energy from the solar thermal collector in each iteration step. With increasing solar yield the number of BHE's could be lowered. Additionally solar regeneration will be considered in the simulation.

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Table 5: Subsurface properties and heat pump parameters for the sizing of the BHE's

Subsurface properties and parameters for the calculation	
Heat pump evaporator capacity [kW]	31.7
Required seasonal performance factor [-]	4.0
Heat conductivity of the underground [W/m·K] (Geologischer Dienst NRW, 2024)	2.0
Annual full load hours [h]	1800
Minimal outlet temperature of BHE at maximum load [°C]	-5
Heat extraction rate [W/m]	35
Number of boreholes [-]	10

2.8 Solar thermal collector

As already mentioned in section 2.5 standard flat plate collectors are used in the energy system. The thermal design properties of the collectors can be obtained from Table 6 and are supplied by the Polysun database. The operating strategy for supplying heat to the sink-side storage is considered as high-flow with a constant volume flow. This allows more energy to be drawn from the collectors during periods of high solar radiation. In comparison the operating strategy for the supply of the source-side storage is considered to be low-flow. In periods with low solar radiation higher outlet temperatures can be achieved. The orientation of the collectors is chosen to be the south-east facing roof with an available roof area of 300 m^2 for the installation. Previous investigations showed that a maximum number of 50 collectors (100 m^2 gross area) can be applied to the roof without oversizing the solar system.

Table 6: Properties of flat plate collectors (Vela Solaris, 2024)

Collector properties	
Aperture/Gross area [m^2]	1.8 / 2.0
Optical efficiency ($\boldsymbol{\eta_0}$) [-]	0.8
Linear heat loss coefficient ($\boldsymbol{k_1}$) [W/m^2 · K]	3.3
Quadratic heat loss coefficient ($\boldsymbol{k_2}$) [W/m^2 · K^2]	0.01
Specific volume flow (High flow)[l/(h·m^2)] (Duffie et al., 2020)	60
Specific volume flow (Low flow) [l/(h·m^2)] (Duffie et al., 2020)	10

2.9 Control strategy of solar loop

The control strategy of the solar loop is divided into four operating states which are queried in each simulation step. Associated system components will be activated when all conditions for the given operating state are fulfilled. The next state is checked if a condition for the system state being validated is false. The flow chart of the control strategy of the solar loop can be seen in Figure 5.

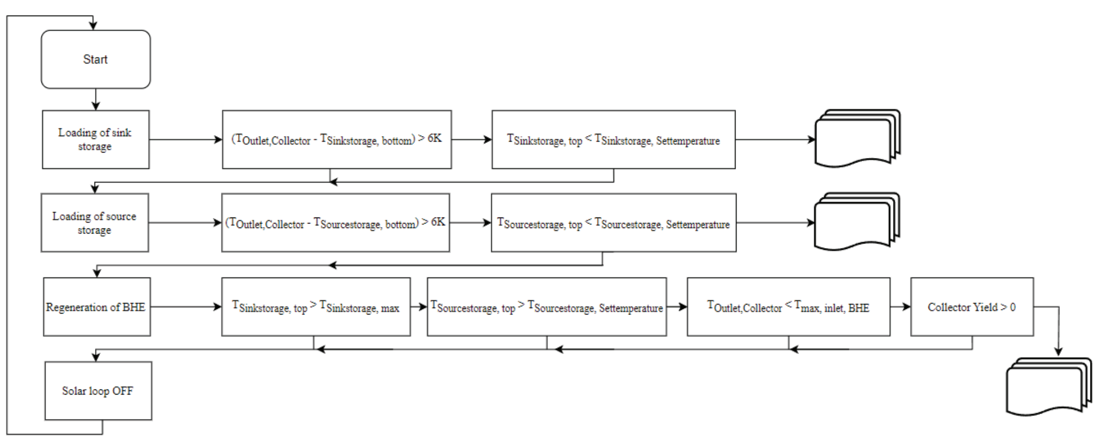

Figure 5: Control strategy of the solar loop

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2.10 Economic efficiency

As stated previously the economic efficiency was calculated with the annuity method of the (VDI 2067-1, 2012). This method estimates the annuity of total annual payments by considering the capital-related, demand-related, and operation-related costs of the building energy system. The parameters used for the calculation are shown in Table 7 and can be found in the VDI 2067-1 (2012). Table 8 contains the used cost functions for the components. The cost functions for the BHE are empirical values from project work while the functions for the heat pump, the storage tank and the circulation pump have been derived from manufacturer prices and catalogs. State subsidies are not included in the calculation.

Table 7: Parameters used for the annuity method (VDI 2067-1, 2012)

Calculation parameters	
Observation period [a]	20
Annuity factor [-]	0.0802
Accrual factor [-]	1.05
Demand related electricity cost [€/kWh]	0.337
Annual base price electricity [€]	142.80

Table 8: Cost functions of system components

Components	
Heat pump	
Investment cost (per nominal electrical power) [€/P_{el}]	$27{,}108.86 \cdot P_{el}^{0.305}$
Assembly cost (per nominal heat output) [€/ $\dot{Q}_{NHO}$]	$380 \cdot \dot{Q}_{NHO}$
BHE [€/m]	$2000 + 125 \cdot l_{BHE,total}$
Flat plate collectors (Jagnow et al., 2019) [€/m²]	$662.67 \cdot A_{Gross,flat\ plate\ collector}$
Thermal storages [€/m³]	$27.04 \cdot V_{Storage}^{0.6017}$
Plate heat exchanger (Österreichische Energieagentur, 2015) [€/W]	$0.0034 \cdot \dot{Q}_{Heatexchanger}$
Circulation pump [€/W]	$9.20 \cdot P_{el}$

2.11 System investigations

The system performance and economic efficiency is analyzed for different storage volumes from 1 to 5 m^3. The volume of the source-side and sink-side storages are equal for all simulations. For every storage volume the number of collectors is varying from 5 to 50 flat plate collectors with a step size of 5 collectors. The results are then compared to an equal system configuration with no thermal storage on the source-side. This system is equipped with one thermal storage on the secondary side of the heat pump that is also sampled from 1 to 5 m^3 in the investigations. All other components are identical to the system with source-side storage as well as the control strategy. As previously stated in section 2.7 the number of BHE will be held constant for each simulation.

3 RESULTS AND DISCUSSION

In this section the simulation results for the different collector numbers and storage volumes are introduced and discussed by comparing the system- and heat pump efficiency of the energy system with and without the source-storage. Additionally the results for the economic viability of both systems are presented.

3.1 Results on efficiency for different collector numbers and storage volumes

Figure 6 shows the difference for the seasonal performance factor of the overall system (SPF_{Sys}) and for the heat pump (SPF_{HP}) between the system with the source-side and secondary storage and the equal system without the source-storage and one secondary storage. A negative difference shows that the system with the primary storage is less efficient than the system without additional storage while positive differences represent a more efficient operation of the system with primary storage. It can be seen that the difference in the overall efficiency between both systems increases with a negative difference as the storage volume increases. In comparison the increasing number of collectors is

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leading to a decrease in the difference of system-efficiency between both systems for smaller storage sizes. For greater storage sizes the increasing number of collectors is leading to an increase in the difference of system-performance. Therefore applying an additional storage to the source-side of the heat pump for storing low-temperature heat does not lead to a higher efficiency of the overall system compared to an equal system with just a secondary storage. It was observed that the operating hours as well as the electricity consumption of the heat pump are slightly increased for the system with the primary storage. This indicates that the system is not running optimally and may be caused by the control strategy and the cycling heat pump model. However, it can be seen in Figure 6 that the efficiency of the heat pump is slightly better for the system with source storage, when smaller storage sizes are applied. The seasonal performance factor of the overall system with the additional source storage varies between 3.8 and 5.2 as depicted in Figure 7.

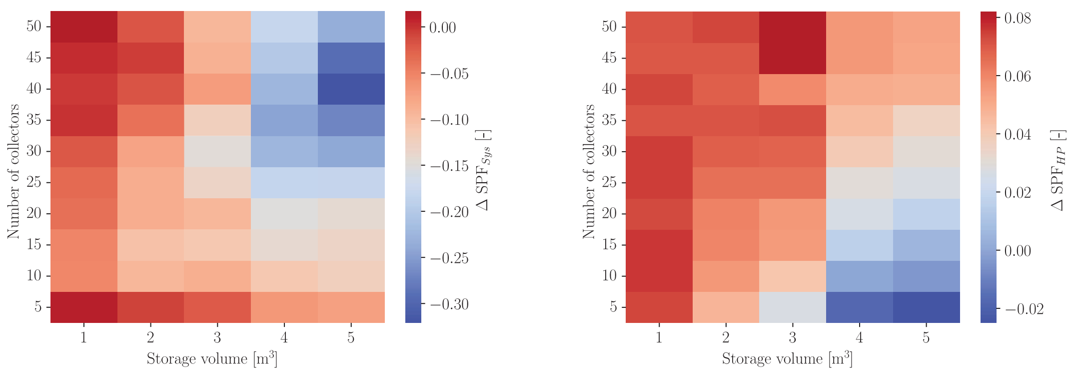

Figure 6: Difference in efficiency between system with and without source-storage for the overall system (left) and the heat pump (right). $\Delta\ SPF > 0$ states that the system with primary storage is more efficient than the system without primary storage.

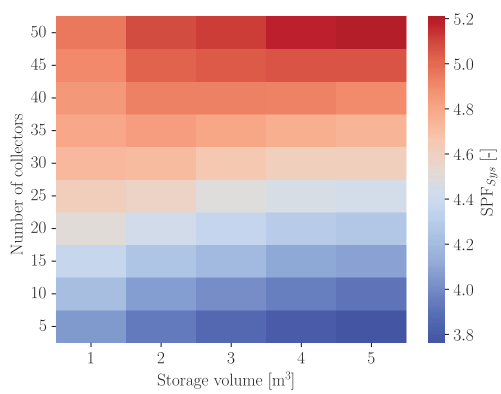

Figure 7: Seasonal system performance factor of the system with additional source-side storage

Figure 8 shows the energy shares for both systems and the mean monthly outlet temperatures of the BHE's. It can be seen that both systems operate almost the same throughout the year. In winter there is no visible difference apparent in the various energy shares. In summer on the other hand the amount of solar energy that is injected into the BHE is slightly larger for the system without additional storage. The effect of the thermal regeneration of the BHE's can be seen in Figure 8 due to the seasonal increase of the mean monthly outlet temperature of the BHE's.

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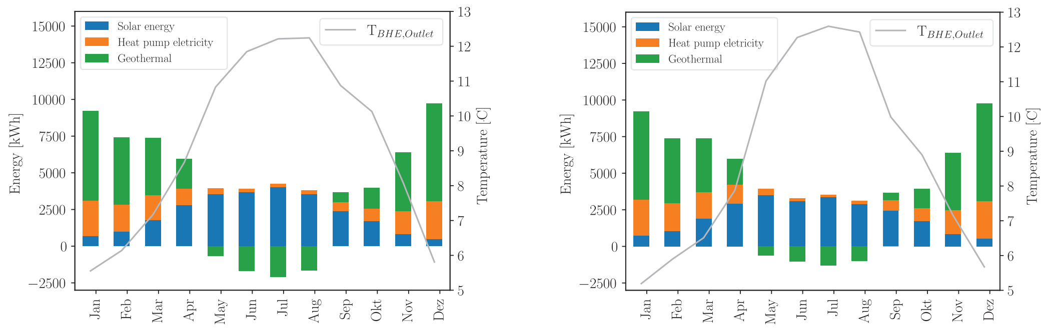

Figure 8: Energy shares and mean monthly outlet temperatures of the BHE's for the system without (left) and with source-storage (right) for 20 collectors and a primary and secondary storage volume of 3 m^3

3.2 Results on economic-viability for different collector number and storage volume

The calculated results for the levelized cost of heat (LCOH) are displayed in Figure 9 for both systems. The results show that the solar thermal collectors account for the majority of the levelized cost of heat in both systems. The additional costs for the source-side storage, heat exchangers and pumps only lead to a minimal increase of 1ct/kWh for all variants. The decreased efficiency of the variant with 5 m^3 source-storage lead to an increase of 2 ct/kWh. The lowest number of collectors with the smallest storage results the lowest levelized cost of heat with 34 ct/kWh for the system with source-side storage. In comparison the highest number of collectors with the biggest storage results in 43 ct/kWh. Compared to conventional gas condensing boilers, which have according to the International Energy Agency (2021) LCOH between 9 and 15 ct/kWh, these systems are still too expensive to be an cost-efficient alternative. As previously stated, the parameter studies do not take into account a change in the number of BHE's in both systems. These account for a large proportion of the levelized cost of heat.

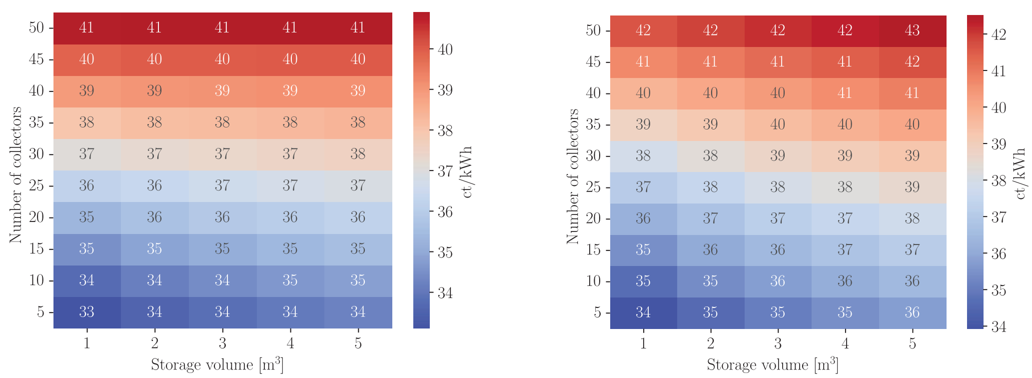

Figure 9: Levelized cost of heat (LCOH) for the system without (left) and with (right) source-side storage

In order to obtain an initial indication of the influence of a reduced number of BHE's on the levelized cost of heat, the economic viability for three different system configurations were recalculated in the next section. The number of boreholes was reduced to the point where the energy demand of the building was still satisfied and the minimal outlet temperature of the BHE was still above -5 °C.

3.3 Results with reduced number of BHE's

The parameters and the results on the system efficiency and the economic-viability of the system with the source-storage and the reduced number of BHE's are presented in Table 9. Looking at the overall system efficiency it can be seen, that the SPF_{Sys} is changing between the different variants. This can be explained by the fact that the system efficiency is mainly influenced by the amount of heat absorbed by the flat plate collectors. The SPF_{Sys} for variant one is the lowest due to the dominant heat extraction from the BHE's. Comparing the LCOH of the presented variants with the reduced number of BHE's with the previous results, a slight reduction of the costs could be achieved without lowering the overall performance of the system, except for variant 1. Nonetheless, the investment costs could be further reduced by taking government subsidies into account in the economic calculations.

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Table 9: Results with reduced number of BHE's for different variants for the system with primary storage

System efficiency	**Variant 1**	**Variant 2**	**Variant 3**
SPF_{Sys} [-]	3.8	4.4	4.9
Components			
Number of BHE's / Collectors [-]	6 / 20	5 / 30	4 / 50
Primary/secondary storage volume [m^3]	3 / 3	3 / 3	3 / 3
Economic parameters			
Total invest [€]	160,965	174,972	188,979
Total Annuity [€/a]	20,441	21,416	22,890
LCOH [ct/kWh]	31.2	32,73	35.0
Specific CO_2 [g/kWh]	143	121	111
Demand related costs per heated floor area [€/m^2]	7.30	6.24	5.77

4 CONCLUSIONS AND OUTLOOK

The present work investigated the potential of the application of an additional source-side thermal energy storage compared to an equal system configuration with only a secondary storage on the efficiency and the economic-viability in integrated geothermal and solar thermal supplied heat pump systems. With the help of simulation studies for different collector numbers and storage sizes it was demonstrated that these systems can efficiently be operated in existing buildings with a moderate state of refurbishment with seasonal system performance factors from 3.8 to 5.2 . These are in agreement with seasonal performance factors published in existing literature (Miara et al., 2011). The results also show that the application of an additional source-side storage does not increase the overall system performance then compared to an equal system without source-side storage and one secondary storage. For greater storage sizes and increasing number of collectors the system performance even decreases. The slightly increased operating hours and electricity consumption indicate that this is caused by the implemented control strategy that needs to be addressed in future investigations. The calculations on the economic viability of the integrated geothermal and solar thermal heat pump system also show that the LCOH of 33 to 41 ct/kWh are still too expensive, compared to conventional condensing gas boilers with LCOH between 9 and 15 ct/kWh, to be an economic viable solution that can widely be applied to existing buildings in the German building stock (International Energy Agency, 2021). Investigations with a reduced number of BHE's suggest that the levelized cost of heat can be further reduced without decreasing the system performance. Nonetheless, applying an additional storage to the source-side increases the levelized cost of heat while decreasing the system efficiency when compared to an equal system without source storage. The results show that the recent model of the geothermal and solar thermal supplied heat pump system is only slightly benefitting in a few cases from the application of an additional source-storage regarding the overall system efficiency. Further investigations are needed to quantify the amount of solar energy within the simulation studies to guarantee an optimal sizing of the BHE's. Future work regarding the CO_2 avoidance costs are also needed to quantify the environmental impact of these systems compared to systems supplied by conventional energy sources.

NOMENCLATURE

BHE	borehole heat exchanger	(-)
SPF_{Sys}	seasonal system performance factor	(-)
SPF_{HP}	seasonal heat pump performance factor	(-)
$Q_{HP,tot}$	total heating energy of heat pump	(kWh)
$Q_{sol,tot}$	total solar energy	(kWh)
$E_{HP,tot}$	total electricity consumption of heat pump	(kWh)
$E_{CP,BHE}$	electricity consumption of BHE circulation pump	(kWh)
$E_{CP,sol}$	electricity consumption of solar circulation pump	(kWh)
LCOH	levelized cost of heat	(ct/kWh)
LEG	Landesentwicklungsgesellschaft	(-)
UBA	Umweltbundesamt	(-)

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