High-temperature heat pumps in local heating networks: With the right system configuration to economic efficiency

Stefan Adldinger[(1)], Lothar Behringer[(2)]

[(1)]Zentrum für gekoppelte intelligente Energiesysteme, Munich School of Engineering, Technische Universität München, Lichtenbergstr. 4a, 85748 Garching, +49 (0)89 289 10486, stefan.adldinger@stadtwerke-neuburg.de, www.mse.tum.de/coses/

[(2)]Stadtwerke Neuburg a. d. Donau, Heinrichsheimstr. 2, 86633 Neuburg a. d. Donau, +49 (0)8431/509-106, lothar.behringer@stadtwerke-neuburg.de, www.stw-nd.de/

Abstract:

This study analyses whether monetary savings can be achieved by optimizing the system configuration in terms of adapting the heat demand to the high-temperature heat pump, the selection of the PV system power and the size of the thermal energy storage system, compared to fossil-fuelled heat energy generators. The basis for the hypothesis presented here is the collection and analysis of measured data from an innovative cascade air-to-water heat pump with 60 kW_{th}, which can generate flow temperatures of up to 75 °C. The results are presented in the following. The simulations carried out show that the high-temperature heat pump, presented in this study, is a practicable heat generation technology that is able to guarantee an inexpensive, efficient, regenerative and CO_2-saving heat supply on the basis of environmental heat, and this under economic conditions. By using the high-temperature heat pump, almost 50 % of the heat demand of the heating network can be provided with environmental heat. In the summer months, this coverage percentage is even increased to 99 % of the required heat demand, so that no combustion of fossil or biogenic fuels is necessary during this time. The entire heat pump operation is independent of price fluctuations in the fuel market and thus represents a price-secure and calculable alternative for the pipeline-based heat energy supply over the entire service life.

Keywords: High-temperature heat pump, power-to-heat, district heating, environmental and low-temperature waste heat, CO_2 neutral, economic efficiency, heat production costs, heat grid

1 Introduction

In mid-2021, the German government tightened a key target of its climate protection policy by raising the 2030 greenhouse gas reduction from minus 55 % to minus 65 % compared with 1990 [1]. The targets have also become stricter in the building sector [1]. Currently, the target is still a greenhouse gas reduction of 66 % to 67 % by 2030 compared to 1990 [2]. However, the renovation rate has been stagnating at one percent for years [3], which means that it can be assumed that the desired goal of a nearly climate-neutral building stock by 2050 cannot be achieved through thermal energy savings alone.

This gives rise to the need to focus more on the pipeline-based heat energy supply in the form of local and district heating networks in the course of decarbonizing the heat supply. Especially here there is the possibility to reach a large number of buildings together as well as to supply them efficiently and climate neutrally with renewable energies. Initially, this does not have to be based on the renovation of the buildings. In addition to the direct use of renewable energies, such as solar thermal energy, the focus is on an electrification of the heat supply. Heat pump technology is an important link with which environmental and low-temperature waste heat can be harnessed and efficiently and intelligently integrated into heating networks. Using green electricity from solar, wind and hydropower, it contributes significantly to the sustainable generation of thermal energy. Therefore, the heat pump plays a key role in the future pipeline-based heat energy supply.

2 Tasks and goals

The hypothesis of this study is that by optimizing the system configuration in terms of power consumption of the high-temperature heat pump, peak power of the PV system and the size of the thermal energy storage system, monetary savings can be leveraged compared to fossil-fired thermal energy generators. The reason for this solution approach goes back to a result from the publication for the 16th Symposium on Energy Innovation at Graz University of Technology in 2020 (EnInnov 2020). It shows that the flow temperatures of a heating network, even with an extreme heating network design of 100 K spread, can be lowered to 65 °C in the transition and summer months [4]. In conjunction with this, an innovative high-temperature heat pump with flow temperatures of up to 75 °C has been in test operation at Stadtwerke Neuburg a. d. Donau (hereinafter referred to as "project partner") since mid-2020. From this application, the central question of this study arises for an economic system configuration of a high-temperature heat pump incl. storage in combination with a PV system, with which a wide range of supply scenarios can be covered. In the future, it should be possible to supply not only inner-city areas but also rural regions sustainably and as climate-neutrally as possible with grid-based heat. Based on the above-mentioned components, a system is being developed that eliminates the need to burn fossil fuels for large parts of the year.

3 Methodical approach

The basis for the hypothesis presented here is the collection and evaluation of measurement data from a heat pump field test. By using statistical modeling of the real data, the operation of the heat pump is mapped, the generated energy quantities are characterized in relation to the ambient temperature over the course of the year, and heat supply scenarios are derived. With the help of mathematical optimization, an overall energy system is simulated, which is optimally matched in terms of system size and configuration. It is investigated whether a high share of own electricity use from the PV system also represents the most economical operation. The influence of the PV system size and its orientation on the economic efficiency is also examined.

In addition, the flexibility potentials available through the use of a sufficiently dimensioned heat storage system with regard to load management in the power grid are investigated, so that the contribution to sector coupling can also be included in the monetary evaluation. As a reference value, the heat production costs of the overall system are calculated and compared with the variable production costs of a gas condensing boiler and a woodchip boiler. Both firing technologies represent currently common technologies used in the field of pipeline-based heat supply in a local heating network.

3.1 Model structure and system boundaries

In comparison to the IEWT 2019 [5] and EnInnov 2020 [4], the focus of the scientific investigations in this study is not on the side of heat consumption or heat distribution, but is expanded to include the heat generation side. The heat generation model, used as a basis, represents an initial alternative system with which renewable heat can be provided in the transition and summer months both in heat networks with high temperature fluctuations and in heat networks with constant flow temperatures.

The system boundary is selected from the point of view of power plant operation (cf. Figure 1), i.e. for the further considerations only the costs and efforts for heat generation are considered for the calculation of the heat production costs. The separation from the heat network is illustrated before the network pumps, so that only the heat losses from the heat network are included, since these must also be provided by the heat generators. Within the heat generation, the electricity side is significantly more important due to the combination of heat pump and PV system. Both the electricity fed into and the electricity consumed from the public grid are taken into account. The consumed electricity quantities of the heat pump are based on performance curves, but these do not represent the coefficient of performance (COP), but rather a system performance indicator, since the electricity consumption of the peripheral components is also taken into account here.

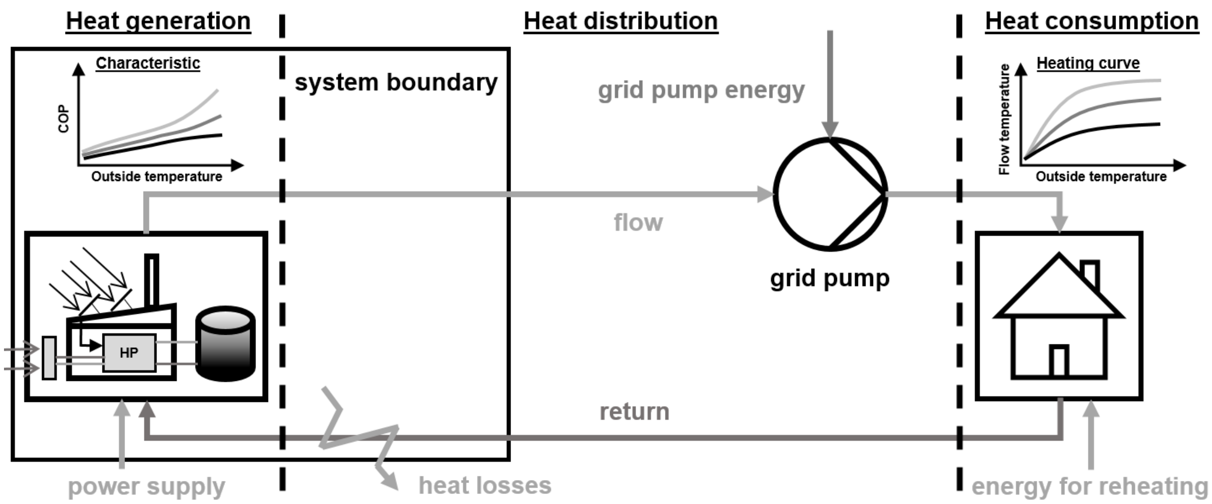

Figure 1: *System boundary of the heat network calculations for evaluating the economic efficiency of a high-temperature heat pump (own representation)*

3.2 Economic efficiency and basis of calculation

The annuity method [6] is used as the basis for calculating the economic efficiency of different heat generation systems in this study. In order to ensure the comparability of the results from the different heat generation technologies, the specific heat production costs are defined below as a comparative value. These result from the heat production costs per year related to the heat transferred to the heating network (cf. formula 1). The parameters of the heat production costs are defined as the capital, operating and consumption costs as well as the revenue from the surplus electricity of the PV system.

$$k_{\mathrm{HPC}} = \frac{K_{\mathrm{HPC}}}{\dot{Q}_{th} \cdot \tau} \cdot \left(100\ \frac{ct}{€}\right) = \frac{K_{\mathrm{Cap}} + K_{\mathrm{Op}} + K_{\mathrm{Con}} - E_{\mathrm{PV}}}{\dot{Q}_{th} \cdot \tau} \cdot \left(100\ \frac{ct}{€}\right) \qquad \text{f. (1)}$$

with	k_{HPC}	specific heat production costs in [ct/kWh],
	K_{HPC}	heat production costs per year in [€],
	K_{Cap}	capital costs per year in [€],
	K_{Op}	operating costs per year pro Jahr in [€],
	K_{Con}	consumption costs per year in [€],
	E_{PV}	profits for PV electricity per year in [€],
	$\dot{Q}_{th}$	thermal pover of the heat pump in [kW],
	τ	Full operating hours of the heat pump in [h/a].

The capital costs are calculated by multiplying the investment costs for the entire system by the annuity factor, which determines the capital costs taking into account the imputed interest rate and the calculation period for one year (cf. formula 2). The total investment costs consist of the investment costs of the heat pump, the photovoltaic system and the periphery. The costs of the periphery include the material costs of the piping, the costs of the measurement, control and regulation technology as well as the acquisition and installation costs of the heat storage tank.

$$K_{\mathrm{Cap}} = I_{\mathrm{ES}} \cdot a = (I_{\mathrm{HP}} + I_{\mathrm{PV}} + I_{\mathrm{PE}}) \cdot \frac{i \cdot (1+1)^n}{i \cdot (1+1)^n - 1} \qquad \text{f. (2)}$$

with	I_{ES}	investment costs for the entire system in [€],
	I_{HP}	investment costs fort he heat pump in [€],
	I_{PV}	investment costs for the PV system in [€],
	I_{PE}	investment costs for the periphery in [€],
	a	annuity factor in [1/a],
	i	imputed interest rate in [1/a],
	n	calculation period in [a].

In this study, the operating costs can only be equated with the costs for maintenance and service of the heat pump (cf. formula 3). Therefore, they have only a very small influence on the calculation of the specific heat production costs.

$$K_{\mathrm{Op}} = K_{\mathrm{M}} \qquad \text{f. (3)}$$

with	K_{M}	Maintenance and service costs of the heat pump in [€].

In this model, the consumption costs are the same as the costs that arise from the purchase of electricity from the public grid (cf. formula 4). The electricity consumption occurs in times when there is too little PV electricity available, but the heat pump is still to be operated. However, due to the taxes, levies and charges included in the electricity price, these electricity quantities should be kept low, as their influence on the level of the specific heat production costs is very high.

$$K_{\mathrm{Con}} = K_{\mathrm{ECon}} = \frac{W_{\mathrm{ECon}} \cdot p_{\mathrm{S}}}{\left(100\ \frac{ct}{€}\right)} \qquad \text{f. (4)}$$

Mit K_{ECon} costs of consuming electricity from the grid per year in [€],

W_{ECon} electricity consumption from the public grid per year in [kWh],

p_{S} electricity price in [ct/kWh],

4 Description of the high-temperature heat pump

The central component in this study is an innovative high-temperature air-to-water heat pump, which was developed as a demonstrator in the course of the InnoNEX research project [7]. The heat pump was set up in 2020 and is currently still being maintained and operated by the project partner of this study, Stadtwerke Neuburg a. d. Donau. The heat pump covers a power range of 40 - 60 kW_{th}. The innovation of the heat pump is its cascade design, where two cooling circuits are connected in series. The first stage is used to absorb heat from the ambient air. It is operated with R32 refrigerant. The R32 can efficiently absorb heat even at low outdoor temperatures. The special feature is that the condenser section of the first stage is also the evaporator of the second stage. The second stage is operated with the refrigerant R1234ze. In summary, both refrigerants are particularly suitable for providing higher temperatures in the condenser. The heat pump cascade is therefore capable of generating flow temperatures of at least 70 °C [7].

In the course of the test operation, the theoretical targets of the research project were confirmed. Due to the cascade design, i.e. the series connection of two smaller compressors, the heat pump is able to generate heat at a high temperature level more efficiently than a heat pump with a single-stage compressor of the same power rating. Energetically, this means that the processes of the two refrigeration circuits are correspondingly efficient, that 2 times the power consumption is less than the single effort of the single-stage heat pump. Another advantage of the cascade heat pump has been shown to be that a constant heating capacity can be maintained over a very wide source temperature range. Based on this, it has also been possible with the heat pump to maintain a constant supply temperature level of up to 75 °C down to an outside temperature of about 7 °C before defrost cycles restrict continuous heat pump operation. It is therefore possible to provide an almost year-round heat supply with the cascade heat pump [7]. Chapter 5.1 describes the system parameters in more detail.

5 Data basis

The core aspect of the economic considerations given in this study is based on the measured data analysis and characterization of the high temperature heat pump described in chapter 4. The data analysis is described below. In addition, this chapter presents all other basic data that are included in the economic feasibility considerations.

5.1 Data analysis and energetic key figures

Data recording and measurement of the demonstrator heat pump already started in spring 2020. For this study, it was therefore possible to access a broad collection of real data of heat pump operation over all four seasons. In particular, the data analysis examined the energy parameters, such as system efficiency, electricity consumption and generated heat quantities. As already presented in chapter 3.2, energy quantities are primarily used for the calculations of economic efficiency. Therefore, characteristic system curves were formed on the basis of the real data, which in turn were incorporated into the simulation of the system configuration (cf. Figure 2).

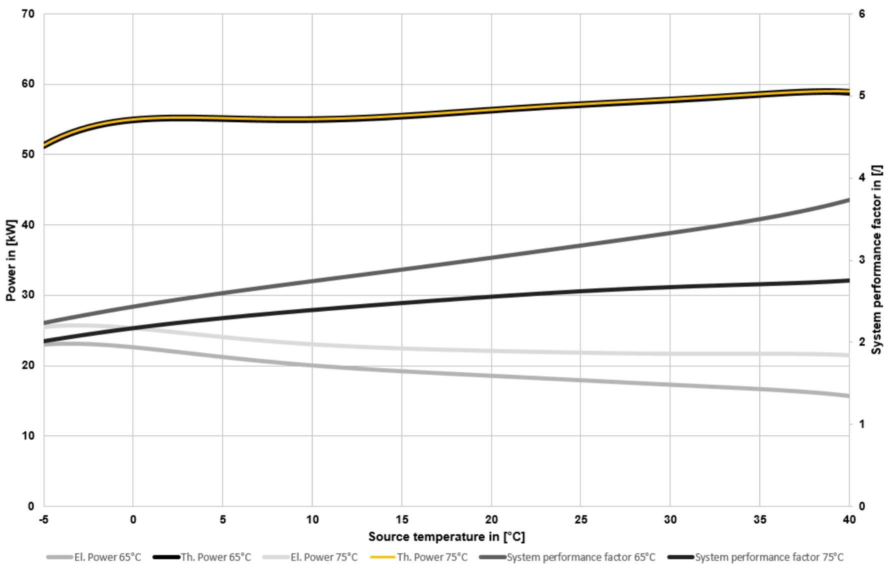

Figure 2: *Characteristic system curves of the high-temperature heat pump (own representation)*

Figure 2 shows the three most important system characteristics from an energy point of view, including the system efficiency, the electrical power and the thermal power of the heat pump. These curves correspond to the averaged real system parameters, which in turn represent the characteristic performance indicators. The system efficiency is not to be compared with the Coefficient of Performance (COP), but corresponds to an efficiency of the entire system, since in addition to the compressor, the entire peripheral power consumers, such as pumps, valves, fans and the I&C technology are also taken into account. When providing supply temperatures of 75 °C, the heat pump still has an efficiency of 2.0 to 2.8 and this in a source temperature range of the ambient air of -5 °C to 40 °C. At the same time, it delivers a thermal output of 52 kW to 58 kW almost constantly. Accordingly, power consumption ranges from 26 kW, at low outdoor temperatures, to 21 kW, at very high outdoor temperatures. The results described in the following chapters from the determination of the optimal system configuration and the resulting economic considerations are based on a heat pump simulation in which the system characteristics for the provision of a supply temperature level of 65 °C are specified. In the simulations, it is also specified that defrosting starts at an outdoor temperature of 5 °C. Depending on the weather the heat pump must be switched off and must go into the defrost cycle for 15 - 30 min. every hour before it can resume heat generation.

5.2 Economic operating conditions

The data on which the calculations in this study are based are provided by the project partner and correspond to the reference values currently used in practice. To calculate the most economical system configuration, the investment costs of the heat pump, which already include the costs of the electrical and hydraulic integration, are set at 55,000 €. It is assumed that the heat pump concept under consideration will be funded by one of the possible public funding programs, e.g. the Heat Networks 4.0 funding program of the German Federal Office of Economics and Export Control. Therefore, a financing rate of 40 % of the investment costs is assumed [8]. The useful life is assumed to be 30 years and the imputed interest rate is set at 2 %. The maintenance and repair costs are assumed to be 550 € per year. An electricity production cost of 5 ct/kWh is assumed for the electricity provided by the PV system. In addition, there is a markup of 40 % of the EEG surcharge, which currently amounts to 6 ct/kWh, for self-consumed electricity from a renewable energy system. Electricity purchased from the public supply grid is valued at 19.23 ct/kWh.

On July 16, 2021, the German Federal Ministry of Economics and Technology presented a draft of the "Richtlinie für die Bundesförderung für effiziente Wärmenetze - BEW". This shows that in the future heat pumps can be supported via a systemic funding in the form of operating cost subsidies. These amount to maximum of 3 ct/kWh for heat generated from renewable electricity, depending on the system's energy efficiency factor [9]. For the system solution considered in this study, an operating cost subsidy of 2.7 ct/kWh of generated heat is therefore assumed.

For the comparison of the heat production costs of the heat pump system with those of the gas boiler and the wood chip boiler, an energy price for gas of 2.266 ct/kWh is assumed. The gas boiler has an efficiency of 87.5 %. The fuel costs for wood chips are assumed to be 17.86 €/m^3, with the wood chip boiler having an annual efficiency of 72.1 %.

6 Economic efficiency of the high-temperature heat pump

In the following chapters, the best possible coordinated system configuration is determined on the basis of economic specifications. The goal is that the determined system configuration also represents the most economical system solution. First, the size of the heat demand load profile as well as the heat storage tank and the PV system are determined.

6.1 Differentiation of the PV system orientation

The economic considerations for the high-temperature heat pump were calculated for all scenarios both with a PV system with south orientation and with a PV system whose half of the peak power is oriented toward the east and the other half toward the west. It has been shown that the east-west system can only show its advantages when the heat pump operation is designed for a long runtime. This is the case when large heat demands are to be generated and, accordingly, the output of the PV system is large enough to provide the heat pump with sufficient power from the early morning hours. In an operating simulation with simple storage loading and unloading and low heat grid demand load profiles, the heat generation of a heat pump fed with electricity from an east-west PV system is lower than that of a south oriented PV system. In addition, the position of the sun in the intermediate and winter months, assuming the plant location is in the mid-latitudes, significantly affects the PV electricity generation from an east-west plant compared to a south oriented plant. For the simulations, the location Neuburg a. d. Donau is assumed.

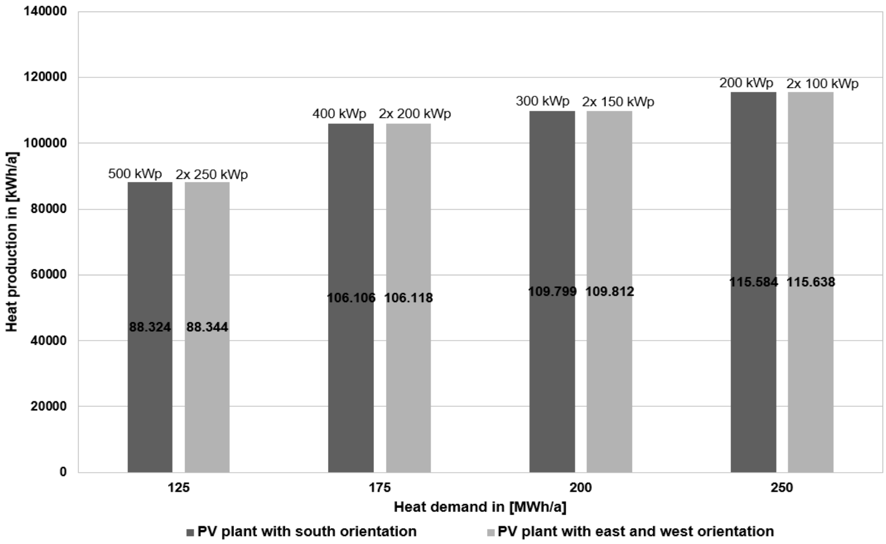

Figure 3: *Comparison of heat generation amounts based on the availability of electricity from PV systems with south or east-west orientation (own representation)*

Figure 3 shows the critical load profile and PV system sizes at which the heat pump generates more heat based on the power supply from a PV system with east-west orientation than via a PV system with south orientation. The larger the peak power of the respective PV system, the lower the heat demand of the heat grid may be, until the combination of heat pump with PV system in east-west orientation generates more heat than a heat pump combined with a PV system of the same power size and south orientation. Assuming that the geographic location, the peak power level, the size of the heat storage tank, and the operating mode and control concept used for the heat pump are identical, a high-temperature heat pump powered by electricity from a PV system with 100 kWp panels each facing east and west will not generate more heat than a heat pump powered by a PV system facing south until the heat demand reaches 250 MWh plus 15 % grid losses (see Figure 3). As described in more detail in the following chapter 6.2, the results of the simulation show that the heat demand load profiles for the output size of the underlying high-temperature heat pump are significantly lower than 250 MWh. However, since the generated thermal energy quantities have a significant influence on the economic efficiency of the overall system, this turns out to be worse for the system configuration with PV system in east-west orientation than that with PV system in south orientation. For the reasons mentioned above, only the economic efficiency of the simulations with PV system in south orientation are presented in the results section of this study.

As a final summary on the subject of PV system orientation, however, it can be said that if roof areas are available in practice for the installation of a possible PV system in an east-west orientation, then this variant can also be selected. This is because, in combination with a high-temperature heat pump, this variant can still be economically better than the alternative forms of heat generation that are operated with fossil fuels. The results of the following chapters can therefore be generalized in principle, but must be recalculated for the respective plant location in the case of concrete project planning.

6.2 Identification of the heat grid feed-in load curve

When calculating the most economical system configuration consisting of heat pump, PV system and heat storage, the heat grid load profile has rather little influence. This is because, although the size of the load profile influences the running time of the heat pump, the larger the load profile becomes, the more residual heat demand must be covered by another form of generation. The resulting price change effect is relatively small (see Figure 4). It is assumed for the simulations that the residual heat demand is provided by a natural gas boiler. The heat network feed-in load curve indicates how much heat must be provided to the network by the respective form of generation. It is made up of the heat demand of the consumers connected to the heating network and the network losses. For the execution of a simulation, a variable heat network feed-in load curve can be generated based on the specification of heat demands and a fixed share of 15 % of heat losses. By changing the peak power of the PV system and varying the heat demands in the range of 50 - 350 MWh, the minimum specific heat production costs of the overall system could be determined. Figure 4 shows the determined characteristic curves. The comparison of the specific heat generation costs shows that for the PV system size of 100 - 400 kWp, the heat grid feed-in load curve with heat demands of 150 MWh/a is the one where the high temperature heat pump has the most economical operation. Henceforth, a heat demand of 150 MWh/a is chosen to determine the PV and storage size.

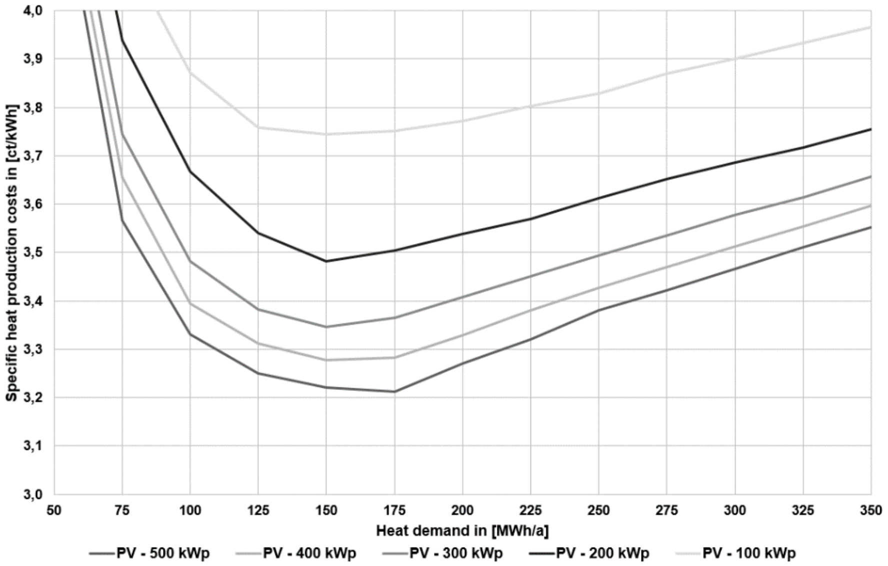

Figure 4: *Comparison of the specific heat production costs for the selection of the load profile size (own representation)*

6.3 Identification of the heat storage size

To determine the storage size, the peak power of the PV system is changed between 100 and 500 kWp in the simulations to determine the most economical system configuration, similar to the determination of the load profile size. However, the calculated load profile size of 150 MWh is kept and the storage size is varied between 5 and 120 m^3. It can be seen that for the entire power spectrum of PV system size, the specific heat production costs decrease rapidly up to a storage size of 20 m^3 and are subject to very little change from then on. These small changes in the spec. heat production costs do not outweigh an additional investment in a larger heat storage tank. Therefore, a storage size of 20 m^3 is used to determine the PV system size.

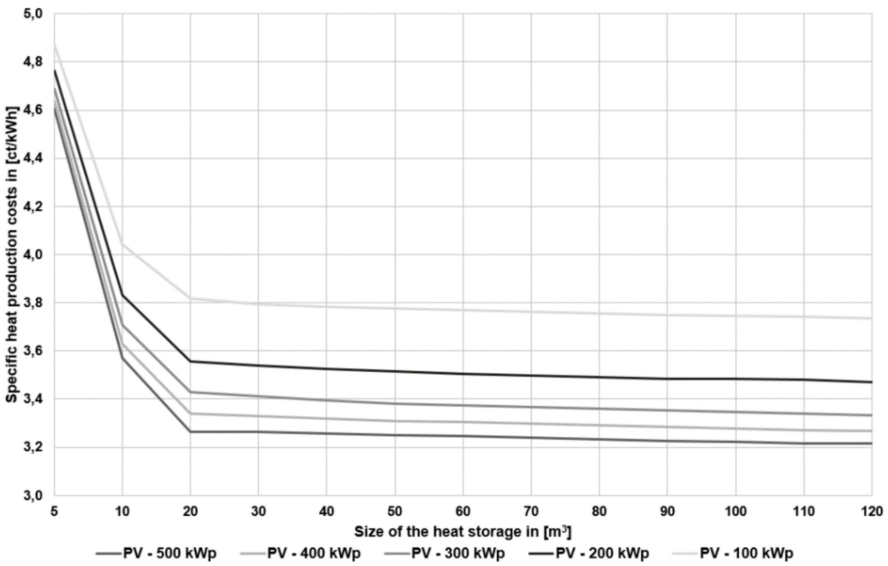

Figure 5: *Comparison of the specific heat production costs for the selection of the storage size (own representation)*

6.4 Identification of the photovoltaic system size

The simulations for the calculation of the PV system size also proceed identically to the previous chapters. The difference is, however, that the size of the PV system has a significantly higher influence factor in finding the most economical system configuration. This is due to the fact that the heat pump is given more runtime by larger peak powers. The heat demand, however, remains the same and thus an increase in the PV system size reduces the residual heat demand and therefore also the heat production costs. In the simulations, the already known parameters of the heat grid load profile and storage tank size are fixed at 150 MWh/a and 20 m^3 and only the PV system capacity is varied. The calculations are performed with a resolution of the power size between 50 and 170 kWp. Figure 6 shows that the spec. heat production cost of the heat pump decreases with increasing peak power. Compared to the simulations for load profile and storage size, no optimum can be seen here. This is due to the fact that only a fixed power generation contribution of 5 ct/kWh is included in the calculations for the PV system. The larger the PV system output, the longer the running times of the heat pump and the more heat it can generate, which in turn reduces the heat generation costs. For a more precise resolution and evaluation of the effects of the variation of the PV system size on the economic efficiency of the overall system, a price scale of the investment costs for the PV system size should have been stored. In Figure 6, it can be seen that the heat production cost of the overall system is lower than the heat production cost of a gas boiler even for very small PV system sizes. For the selection of the optimal PV system size, two further specifications are included in the calculations. The size is determined at which 50 % of the total heat demand and almost 100 % of the summer load case can be covered by the heat generation of the heat pump. With a PV system size of 100 kWp, it is possible to cover 45 % of the total heat and 99 % of the summer load in heat pump operation. Therefore, the PV system size is set at 100 kWp.

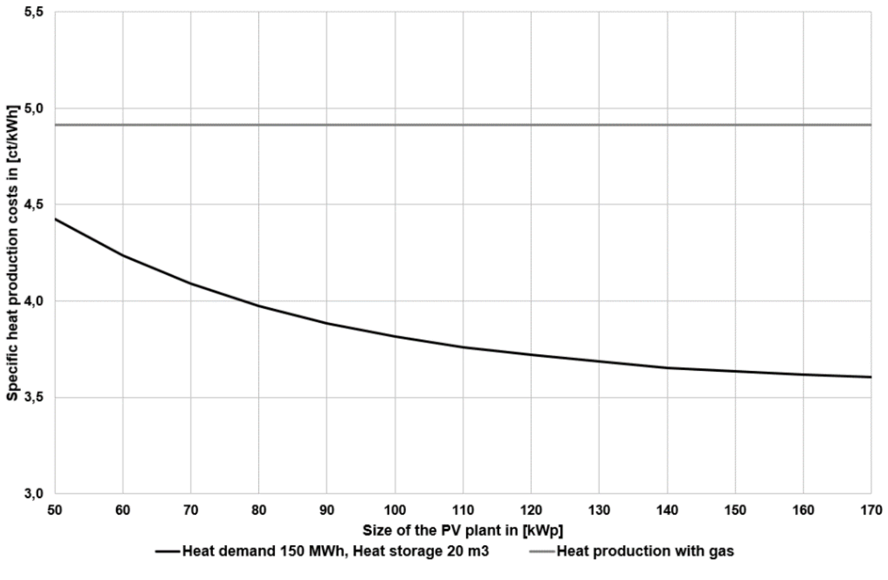

Figure 6: *Comparison of the specific heat production costs for the selection of the PV system size (own representation)*

6.5 Identified most economical plant configuration

For the assumptions and basic data described in the previous chapters, a combination of a high-temperature heat pump with a thermal output of approx. 60 kW, a PV system with a peak output of 100 kW and a storage tank with a volume of 20 m^3 (with a spread of 20 K) represents the most economical system configuration. It should be noted that the overall system is designed for a heat demand of 150 MWh/a.

The following figures show the determined energy amounts from the simulations for the most economical plant configuration and describe the mode of operation in more detail. Figure 7 shows the heat network feed-in load curve over a period of one year. Including the network losses, this shows a heat energy amount of 172.5 MWh/a. In addition, it can be seen how the load profile is structured on the basis of the heat generation from the heat pump, the heat amounts from the storage tank and the residual heat demand. Of the 172.5 MWh, the heat pump directly supplies 25.7 MWh. An additional 52.2 MWh is provided via the heat storage tank. Thus, a proportion of 45 % of the heat grid feed-in is covered by the heat pump's heat generation. A residual heat demand of 94.6 MWh remains.

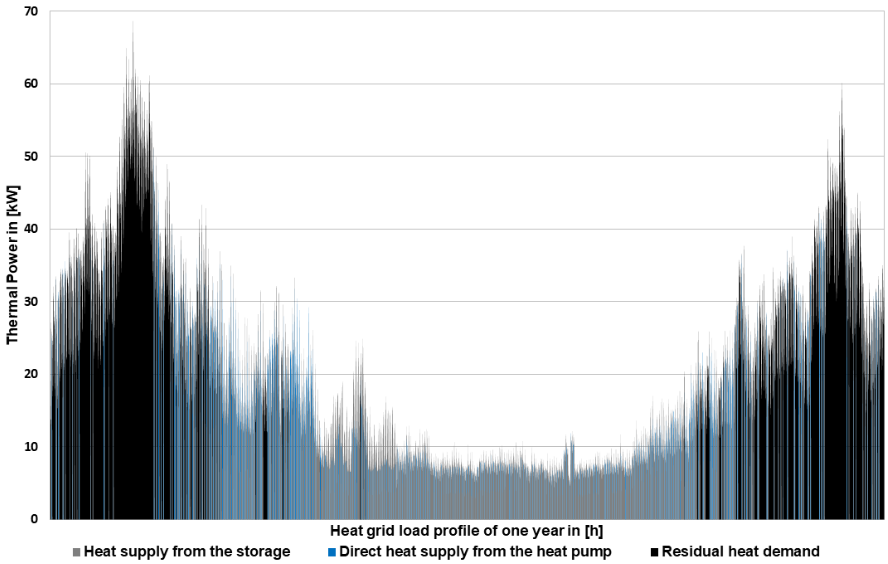

Figure 7: *Heat supply by the high-temperature heat pump over the course of the year (own representation)*

Figure 7 also clearly shows that during the entire summer period and also in the transition periods, heat is provided almost exclusively via the heat pump or temporarily via the heat storage tank. Thus, the criteria of almost 100 % coverage of the summer load via the heat pump is also fulfilled. The operation of the peak load boiler becomes most noticeable in the winter months, here the output of the heat pump is no longer sufficient to cover the daytime heat demand and, in addition, still provide sufficient heat for the shutdown times at night.

The power generation load curve of the PV system with south orientation is shown in Figure 8. In addition, the electricity consumption of the high-temperature heat pump, i.e. both the electricity grid consumption and the direct electricity consumption of the PV system, is shown. The electricity consumption load curve over the course of the year shown here is the equivalent of the heat generation load curve shown in Figure 7. From the electricity consumption load curve, it can be seen very clearly that the electricity consumption in the summer months is lower than in the winter months due to the higher outdoor temperatures. In the simulation described here, the high-temperature heat pump has a total electricity consumption of 29.4 MWh, of which 541 kWh is drawn from the public utility grid. The PV system generates a total of 109.4 MWh of electricity. Of this, 80.5 MWh is fed into the power grid and the remaining 28.9 MWh is provided directly to the heat pump as its own power consumption. The annual performance factor, as the ratio of the amount of heat generated to the amount of electricity consumed, is 2.65 for the high-temperature heat pump in the simulation.

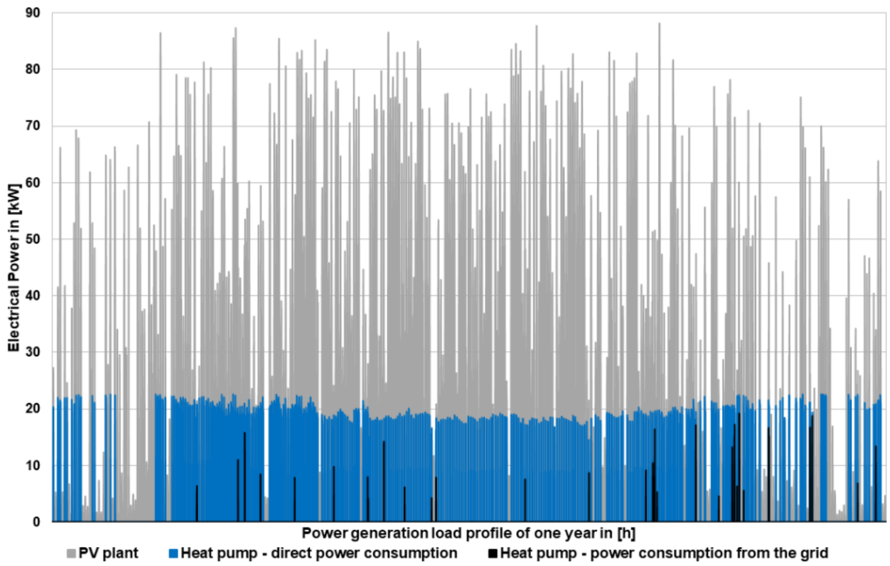

Figure 8: *PV generation load curve and electricity consumption of the high-temperature heat pump over the course of the year (own representation)*

In addition to the generation and electricity consumption load curve over the course of the year, the heat pump mode of operation is discussed in more detail below. For this purpose, the heat generation load curve is broken down more finely in order to be able to better represent the timing of the heat pump as well as the composition of the heat grid feed-in load curve. A week from April, as a characteristic week for the transition period, is compared with a week in July, as an example of a typical week in summer. Figure 9 shows the transition week in April. It is noticeable that on some days the heat production of the heat pump is sufficient to cover also the heat demand of the night. On days with low power generation from the PV system, the peak load boiler must provide the missing heat after the heat storage tank has been emptied. In order to be able to estimate the timing of the heat pump within the power generation times of the PV system, the power generation load curve is also drawn in Figure 9. In the transitional periods, the heat pump uses the entire generation period specified by the PV system to be able to generate as much heat as possible. The running time is only limited by the filling level of the heat storage tank.

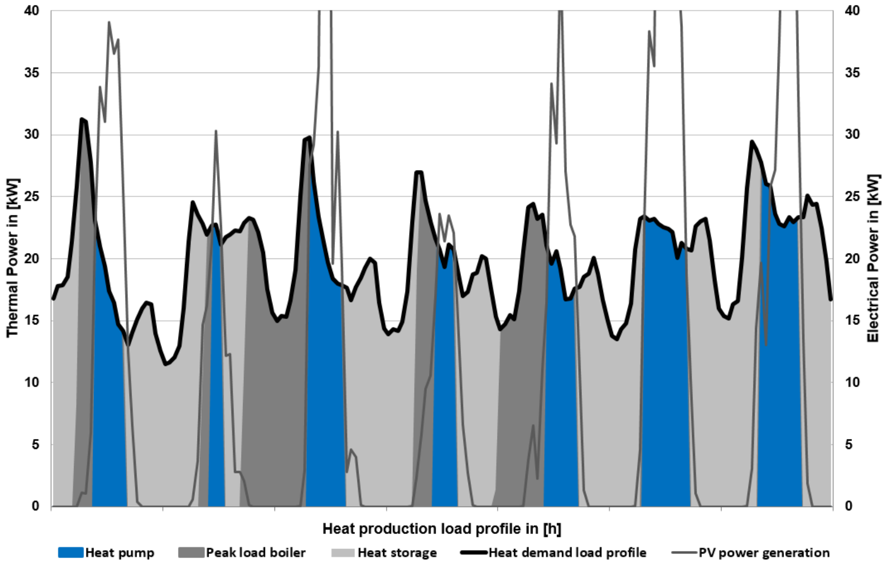

Figure 9: *Composition of the heat grid feed-in load profile based on a week in April (own representation)*

Compared to figure 9, figure 10 shows that the entire heat demand is covered by the heat generation of the heat pump and the discharge from the heat storage. The running times of the heat pump in the summer months, in relation to the respective day, are significantly reduced compared to the running times in the transitional period. This is due to the fact that the heat pump is controlled in such a way that it may only be switched on to fill the storage tank completely if the heat consumption of the night and the early morning hours of the next day can be covered by the heat generation. This shows that the heat pump can vary in the range of the generation period of the PV system. Mostly, however, the heat generation takes place in the afternoon hours, after the heat storage has been largely emptied by the consumption peak and allows a longer runtime of the heat pump (cf. Figure 10).

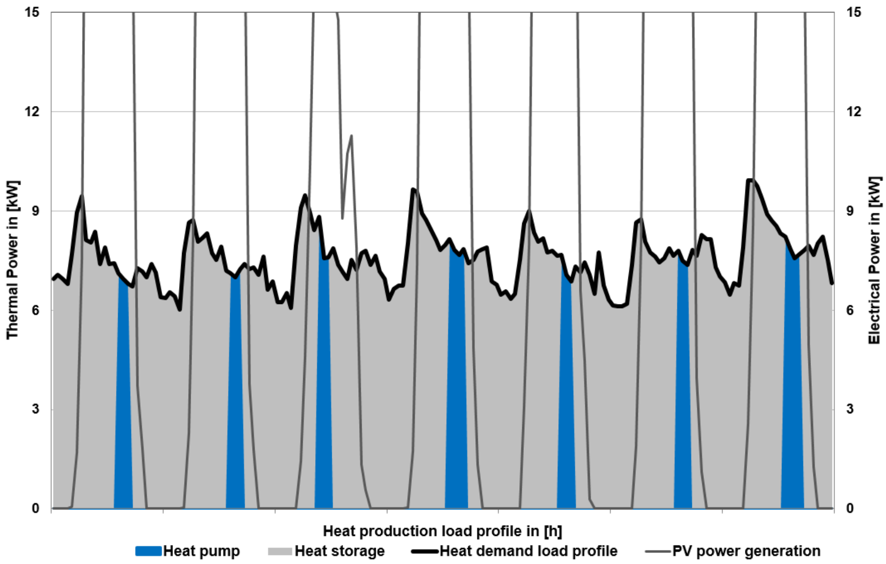

Figure 10: *Composition of the heat grid feed-in load profile based on a week in July (own representation)*

7 Comparison of the specific heat generation costs

In order to be able to classify the specific heat production costs of the most economical plant configuration, these are compared with the heat production costs of a natural gas boiler and a wood chip boiler. Only the variable costs are used to calculate the heat production costs for gas and woodchip boilers. The investment costs of the two boiler designs are not considered because they are on both sides of the equation in the comparative calculations and thus cancel each other out. This in turn requires the assumption that all simulations are consistent and identical in their calculations. It is assumed for the simulations, as is also common in practice, that the entire heat demand of the heat grid feed-in load must be covered. The heat pump system is therefore combined with a peak load boiler in all simulations to ensure comparability. The specific heat production costs of this combination therefore represent a mixed price of the two individual solutions.

Figure 11 below shows the specific heat production costs of the individual and combined forms of generation in a trend over 10 years. The specific heat production costs are also compared in each individual year. The development of the cost price of the natural gas boiler is based on a CO_2 price development from 25 €/t in 2021 to 55 €/t from 2025. This results in an increase in the cost price of 0.7 ct/kWh for this period. A further price development for the raw material costs of gas and wood chips is not deposited in the simulation, since the proportionality of the price differences is well recognizable even without a raw material price development.

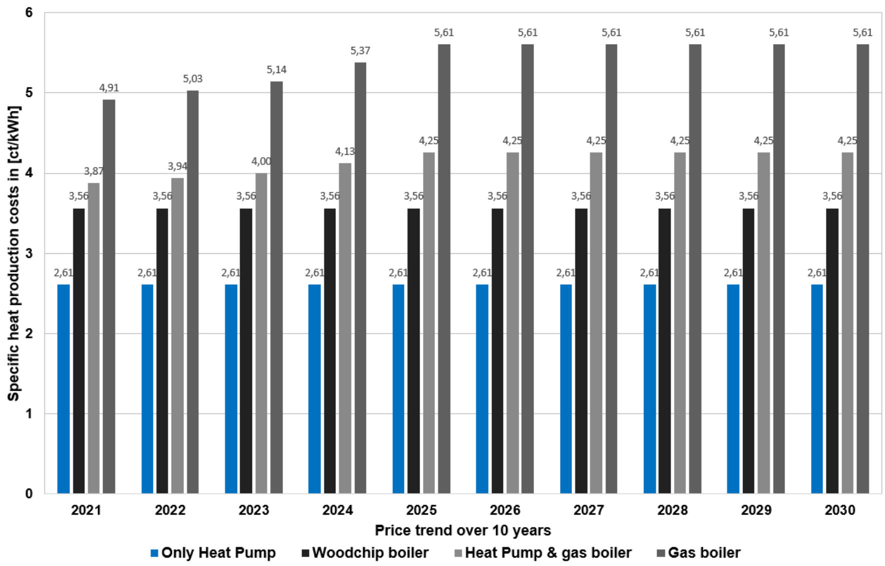

Figure 11: *Comparison of the specific heat production costs of different forms of heat generation (own representation)*

If the forms of generation are considered in detail, it can be seen from the spec. heat production costs shown in Figure 11 that heat production via the simulated heat pump system at 2.61 ct/kWh is significantly cheaper than the production costs of gas and wood chip boilers at 4.91 and 3.56 ct/kWh in the year under consideration 2021. As already mentioned, however, the heat pump system must be considered in combination with a peak load boiler. The specific heat production costs from the combination of heat pump and gas boiler amount to 3.87 ct/kWh in 2021 and are therefore between the production costs of the individual solutions.

Due to the low prime costs of the heat pump, the prime costs of the combined solution also remain lower than the individual solution. Accordingly, a major advantage of the heat pump system can already be mentioned. By the combination of gas or wood chip boiler with the heat pump the spec. heat production costs of the total system are always smaller than those of the single solution. This in turn means that an addition of the system configuration described in this study, consisting of heat pump, PV system and heat storage, to a gas or wood chip boiler, is profitable in any case.

8 Sector coupling and flexibility

The principle of the system configuration described in this study is that the heat pump, using the electricity provided by the PV system, supplies as much heat as possible to the heating network at very favorable production costs. The operating mode of the system solution is therefore primarily heat-led. The heat pump technology used provides the heating sector with efficient, environmentally friendly and CO_2-reducing thermal energy using renewable electricity from the PV system and existing environmental heat, thus realizing true sector coupling.

Due to the connection to the public power grid, in addition to the heat-led mode of operation, there is also the possibility of using the resulting flexibility of the heat generation, especially in the summer months, in order to operate load management in the power grid, for example. In this case, however, the PV system would have to be switched off and the electricity demand would have to be drawn specifically from the public power grid. In addition, it would be conceivable to operate the heat pump with electricity from the public grid, especially in times of negative electricity prices, and also to specifically shut off the PV system for this purpose. In order to be able to extend the system runtime during these periods, it would also be conceivable to dimension the storage system larger. For the applications mentioned, however, the power purchase costs from the power grid must be lower than the power generation costs of the PV system installed specifically for the heat pump. However, due to the low power purchase capacity of the system configuration considered, initial estimates indicate that the incentives to use the available flexibility are too low to be able to use it profitably. In order to meet the objective of this study, it must be said that the existing flexibility in the heat generation of the heat pump cannot be attributed any positive monetary effects on the profitability of the system configuration under consideration.

9 Conclusions

The central question of this study described at the beginning aims at an economic system configuration consisting of a high-temperature heat pump, heat storage and PV system. Following on from this question, it can be stated that an economic system configuration has been found on the basis of the results from the simulations. This shows that the high-temperature heat pump can provide its heat most economically when it is combined with a 100 kWp PV system and the heat storage tank has a size of 20 m^3 (20 K spread). The system parameters that result from the simulations are, however, extremely interesting. The heat pump has a heat load factor of 2.65, even though a flow temperature level of 65 °C is provided and all peripheral power consumers, including defrost cycles, are included in the calculation of the heat load factor. By comparing the specific heat production costs of heat pump, gas boiler and wood chip boiler, it could be shown that the system solution of heat pump, PV system and heat storage has such low production costs that the addition of the said system solution to an existing peak load boiler has in any case a positive influence on the overall economic efficiency. In addition, the heat pump provides almost 50 % of the heat network demand from environmental heat. This is credited to the heat network with a primary energy factor of 0, which is extremely positive. In addition, during the entire summer operation, the heat is provided exclusively from renewable energies by means of PV electricity, which means that no more combustion of fossil or biogenic energy sources is necessary. This in turn has a very positive effect on the CO_2 balance of the overall system.

Another positive effect, which emphasizes the practicality of the investigated system configuration, is that heat generation by means of heat pumps is not subject to price fluctuations of fuels. Thus, this system solution is a price-secure and, above all, calculable heat supply alternative over the entire service life. In summary, the investigated system configuration represents an extremely practical, efficient and CO_2-saving form of heat generation, which should not only be used in inner-city existing heating networks. The investigated system configuration can also be used in rural areas for the supply of smaller stand-alone networks without any problems and guarantees an economical and environmentally friendly heat supply.

10 Outlook

Building on the simulations carried out so far, a series of simulations for the provision of even higher flow temperatures up to 75 °C is to be carried out on the basis of the measured value analysis already performed. The aim is to investigate whether economical plant operation is also possible at this temperature level. In addition, the simulation environment and the calculation tool used are to be further expanded so that future heating projects can be mapped with it. For this purpose, among other things, investment costs must be stored with a price increase for the respective storage tank size and PV system size. In order to be able to map the range of relevant heat pump sizes, a scalability of the heat pump performance is aimed at. In the future, the scope of application should extend to system sizes of 400 kW_{th}.

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