Abstract

District heat networks of the 4th generation - development and validation of a calculation tool for the ecological, economical and technical evaluation of innovative heat concepts

Developed as part of a Master's thesis in cooperation with IWN Innovative Wärmenetze GmbH in Berlin

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Summary

Within the scope of the work, a calculation tool for the ecological, economic and technical evaluation of innovative heating networks of the 4.0 generation was developed and validated, taking into account relevant funding programmes. The MS Excel-based calculation tool can be divided into a general feasibility check and the actual concept development. Before the start of preliminary planning, the essential interrelationships of different concept and design variants of a heating network of the 4.0 generation should be consistently mapped, evaluated and compared.

The general feasibility check is a developed model with a significantly reduced complexity, which pursues the goal of a rough evaluation of a suitable energy concept to check the general feasibility. The concept development model, on the other hand, allows for the development and holistic assessment of a wide variety of heating concepts.

The feasibility check and the concept development are validated using simulation results from a reference project in order to prove the suitability of the developed software in relation to its intended use. The validation confirms the functionality of both model approaches. Within the framework in order to check the model validity and functionality, the technical, ecological and economic calculation results of a reference project were compared with an equivalent simulation. Taking into account the correspondingly simplified calculation approaches of both models, compared to a simulation, the deviation of the final results with a maximum of 35% for the feasibility check and a maximum of 11% for the concept development lies within the expected tolerance range. A development and evaluation of suitable energy concepts with the help of the developed calculation tool, in advance of the actual preliminary planning for target-oriented concept development, is therefore recommended.

Introduction

Heating networks are an important pillar of the heat supply in Germany. They are coming under pressure due to higher requirements for CO_2 emissions and the coal phase-out. In order to meet the formulated climate and energy policy goals, a fundamental transformation of the heat supply, which up to now has been based predominantly on fossil fuels, must take place. Low-CO_2 heating networks of the 4.0 generation represent a promising approach to solving the heat transition. In addition to the decarbonisation of the heating market, the realisation of cost-efficient development paths plays a central role here.

The requirements for suitable heating networks of the 4.0 generation, within the framework of the federal funding for efficient heating networks (heating network systems 4.0) of the BAFA, have increased significantly in contrast to conventional systems with the aim of energy efficiency. At the same time, the complexity and thus also the required planning effort of the systems is increasing substantially. The heat supply via heat networks is one of the major municipal levers for a successful heat transition, and the majority of municipal utilities and energy producers have recognised that this potential must be utilised.

It is important to respond to this interest with well-engineered and forward-looking planning tools that enable concrete statements to be made for the basic assessment and preliminary planning, without having to carry out time-consuming and usually costly simulations. The development, or transformation of sustainable heating grids of the 4.0 generation with a high share of more than 50% of renewable energies, represents a central challenge. There must be no prohibitions on thinking within the framework of the planning and transformation process. A system-optimised and feasible concept must be developed from a multitude of possible generation technologies and concepts, taking into account the local conditions (energy potentials).

In the context of this academic paper, a calculation tool for innovative heating networks of the 4.0 generation is developed with consideration of relevant funding programmes and then validated using an equivalent simulation. The MS Excel-based calculation tool can be divided into a general feasibility check and the actual concept development. It enables user-friendly development and subsequent technical, economic and ecological evaluation of a wide range of heating concepts without the need for time-consuming simulation. The aim is to consistently map, evaluate and compare the essential interrelationships of the most diverse concept and design variants of a 4th generation heating network in the run-up to preliminary planning.

Method

The general feasibility assessment is a model with a vastly reduced complexity. The general potential assessment of renewable energies at the site, such as wastewater, geothermal energy or areas for solar energy generation, forms the basis for determining and roughly assessing a suitable energy concept. A technical design and calculation of individual components is deliberately omitted. The aim of the general feasibility study is to be able to assess within the shortest possible time whether the potential project is worth pursuing further and, if so, which heating concepts are suitable for further investigation.

In the process, the general potential assessment is assigned to the respective renewable energy generators. A matrix for evaluating the suitability of renewable energy generation systems represents a correlation between heat density, generation technology, and supply area and influences the respective potential of the renewable generation technology in addition to other influencing parameters, such as the temperature level on the building site. Depending on the individual potential (P), each technology is assigned a theoretical share of the total heat generation, shown in Figure 1, in order to develop a concept from the set of individual technologies, simple conceptual conditions are taken into account. The subsequent rough concept development includes conventional generators in addition to the consideration of renewable technologies. The subsequent prioritisation of the generation technologies for the development of an energy concept is determined and is primarily based on economic criteria, as cost efficiency is decisive for the success of a concept in addition to a regenerative supply.

A rough dimensioning of the system is then carried out to determine the investment costs, based on flat-rate full utilisation hours and the determined heat quantities. For the determination of the ecological parameters afterwards, a CO_2 balance is carried out in addition to the heat balance. Furthermore, an electricity balance is determined with flat-rate characteristic values for the use of combined heat, power plants and heat pumps. In this way, the rights to purchase from the grid and the share of self-consumption for electricity, can be mapped to some extent and the processing in the P&L in the form of costs and incomes. The economic evaluation is mainly based on recognised flat-rate parameters, as is also the case when determining the total investment costs of the proposed heating concept. These are made up of investment costs for energy generation, which are divided into three cost groups according to groups of managed producers. Costs for the heating network depending on the nominal diameter and the route situation (modernisation, new construction in rural areas or new construction in the city) as well as costs for transfer stations depending on the capacity. The result of the feasibility study is summarised in an overview, which highlights challenges and opportunities of the project in addition the developed concept and possible concept alternatives.

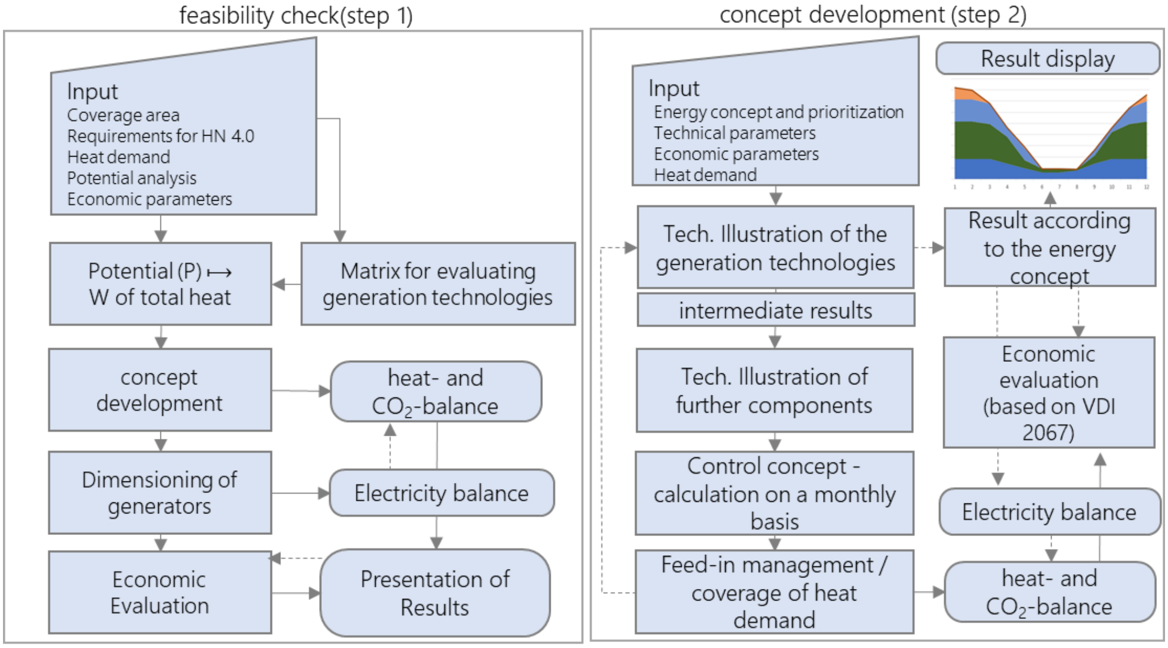

Figure 1: Simplified process flow chart of feasibility assessment (left) and concept development (right)

The concept development in the second step, shown in Figure 1, serves the precise concept development in the run-up to the preliminary planning, with the aim of mapping individual concept variants, without having to carry out a time-consuming and lengthy simulation. This step is a reaction to the requirement of energy suppliers and public utilities to be able to make quick and concrete statements about possible concepts. In order to determine an adequate mathematical model, the essential system interrelationships were first abstracted and then the overall system was broken down into manageable subsystems. The subsystems are constructed in a self-contained manner, so that the functional interrelationships and the results can be checked for each subsystem after completion. In this case, one also speaks of an iterative or agile approach to modelling.

When modelling the concept development, the individual technologies and components are technically mapped. The technical modelling of the generation technologies always follows the same pattern. The technical process of energy generation is mapped with all relevant loss mechanisms, as well as energy flows on an annual basis. More complex generation technologies, such as heat pumps consist of two subsystems, a heat source and the actual heat pump. The design parameters, to be determined by the user for the design of the technologies, depend on the respective generation technology.

In the central overview area of the input screen, an individual energy concept can be intuitively put together by selecting technologies. In addition to the selection of energy generators, the area of application or prioritisation must be defined. In order to be able to map as many different system variants as possible, the following subsystems, shown in Table 1, were both modelled technically and economically. The overall system is divided into energy generation, distribution and storage, as well as transfer. In addition to the generation technologies, the long-term storage facilities, the heat path and the LowEx grid are modelled in detail, both technically and economically, as these subsystems have a significant influence on the overall result. For the other subsystems, quantification is sufficient for the subsequent cost calculation.

Table 1: Representation of all subsystems of the calculation tool considered during concept development

Subsystems - Generation technologies	Subsystems - heat distribution, storage and transfer
Regenerative	**Heat distribution**
Geothermal heat utilisation with heat pumps	Heat train
Wastewater heat utilisation with heat pumps	MSR technology
Boiler biomass	Pumping station
Solar thermal	LowEx network
Waste heat utilisation without/with temp. increase	Energy centre
Photovoltaics	**Storage**
Conventional	Latent long-term memory
CHP	Sensitive long-term memory
Boiler conventional	Power-to-gas
FW connection	**Transfer**
Power-to-Heat	Transfer stations

The development of a heating concept can be divided into two sub-processes. First, the theoretically generated heat quantities of the individual technologies are determined. These quantities are independent of the heating concept. The interface is the feed-in management in the control concept, shown in Figure 1.

In the control concept, an individual annual distribution on a monthly basis with boundary conditions is stored for each technology which divides the annual heat quantity into monthly heat quantities. Then, depending on the defined priority of the generation technology in the feed-in management, a heat demand coverage is carried out. A heat balance is then available, taking into account concept-specific interrelationships. Afterwards, the monthly heat quantities are used as the basis for determining the final energy and CO_2 balance used. Based on the heat balance, the input and output variables are then re-determined for each technology in the technical specifications. A possible deviation from the original design is visualised in the input area so that the design variables can be adjusted if necessary. An electricity balance is then carried out on the basis of the newly determined variables. In addition to the technical design, an economic evaluation is carried out for the developed heating concept.

Furthermore, the technical design, an economic evaluation based on VDI 2067 is carried out for the individual technologies and the developed heating concept. In addition to calculating the heat production costs for each selected technology, the study focuses on a fictitious profit and loss account for the entire system, as well as a dynamic economic analysis in order to be able to adequately assess the relevance of dynamic influences, such as CO_2pricing or energy price developments over the operating period. Technical, economic and ecological studies can then be carried out on the developed model.

The proof of empirical validity and the comparison of the numerical results of the model with empirical data of the real system, is only possible to a limited extent in this research area. For this reason, the results of an exemplary concept development of the developed calculation tool are compared with simulation results. The simulations were carried out with the established software EnergyPro from the company EMD as part of a feasibility study. The feasibility study and the concept development are validated in order to prove the suitability of the software in relation to its intended use.

The unrenovated existing neighbourhood under consideration with a total of 1,100 residential units, distributed over 43 residential properties and an existing heat supply through individual residential solutions with gas floor heating systems, is representative of a large number of applications throughout Germany. A conversion of the existing CO_2-polluted heat supply to a future-oriented, climate-friendly and cost-neutral concept variant requires a well thought-out and reliable concept development. From a multitude of possible concepts and system configurations, a concept was developed which, with the help of heat pumps, uses the local geothermal potential by means of groundwater wells, in combination with a combined heat and power unit, as well as biomass and peak load boilers. The electrification of thermal energy generation is a central component of the future heat supply, because only by making the sectors more flexible and coupling them, energy generation plants can compensate for the fluctuating power feeds from renewable energies in a way that serves the system and is economically optimised.

The technical and economical input parameters are identical for all calculation approaches. The heat demand on the customer side amounts to 9,974 MWh/a, with a living space of 73,000 m² to be supplied. A total of 150 indirect house transfer stations and 2,000 metres of network length are planned to distribute the heat.

In the following Figure 2, the heat demand coverage of the concept development on the left is compared with the monthly heat quantities of the simulation based on hourly generator outputs (see appendix). In the simulation, the heat pump output is divided between two systems. The use of the heat generators follows the same structure in both model approaches although in the simulation, the summer heat demand is somewhat more pronounced.

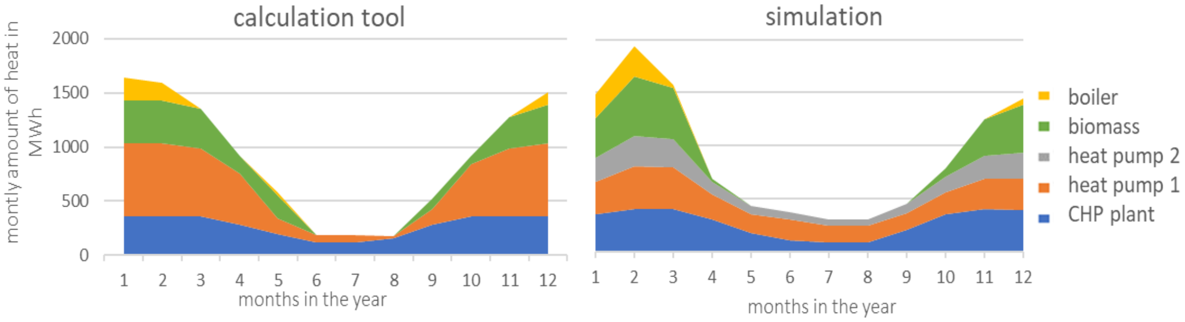

Figure 2: Representation of the heat demand coverage as monthly generated heat quantities according to producers. The hourly outputs of the simulation (see appendix) are shown as monthly heat quantities.

A detailed comparison of the technical and economical results of the subsystems is not provided. Instead, the system-relevant key figures of the three calculation approaches are compared in the following Tables 2 and 3 in order to check the functionality of the overall system as well as aspects of model validity.

The deviations for the feasibility study and concept development results from the comparison with the simulated reference variant. The deviation of the relevant ecological indicators, shown in Table 2, amounts to a maximum of 17% for the feasibility study and 11% for the concept development. Looking at the deviation of the individual producers in the heat supply for the concept development, this is on average 4.9%. Depending on the complexity of the models, the deviations of both model approaches are within the expected permissible range. For both model approaches, the ecological assessment is based on the completed technical design or heat demand coverage. Thus, with the comparison of the generated values, the general structural validity of the models can be assumed. The deviations of the feasibility study are on average higher than those of the concept development. This is due to the, among other things, flat-rate assessment approach followed in contrast to the concept development. The model approach of the concept development shows a slightly lower primary energy factor and lower specific CO_2 emissions. This inaccuracy is due to a deviation in the automated power and efficiency determination of the CHP unit as part of the technical design. With a primary energy factor of less than 0.5 and CO_2 emissions of around 100 g/kWh, the concept variant investigated represents a forward-looking concept, taking into account the low renewable energy potential at the site.

Table 2: Comparison of the ecological key figures of the simulation (reference), feasibility study and concept development for an exemplary energy concept

	Simulation (reference)	Feasibility-audit	Dev.	Concept-development	Dev.
Ecological					
Share of renewable energies	58,3 %	60 %	3 %	58,8 %	1 %
Primary energy factor	0,49	0,48	2 %	0,46	6 %
CO_2 emissions heat	109 g/kWh	128 g/kWh	17 %	98 g/kWh	10 %

The economic evaluation is the final criterion for both model approaches and thus represents the overall system in monetary terms. In the feasibility study, the determination of the total investment costs is based on a flat-rate cost approach, whereas the investment costs, which have a notable influence on the economic viability, are determined in the concept development with the help of cost functions for each technology. As part of the economic analysis, a profit and loss account is carried out for both model approaches. In addition to the sale of heat, the revenues also include payments and reimbursements, which deviate by 4 % in the concept development compared to the reference variant due to the deviating electricity feed-in to the CHP grid. The annual costs consist of energy, operating and C_2 costs. The share of operating costs for maintenance, inspection, repair and insurance of each technology cannot be determined precisely and therefore differs from the guideline values of VDI 2067 according to our own estimates. While the operating costs of the reference variant are slightly more than 62,000 €/a, the concept development has significantly higher operating costs of slightly more than 105,000 €/a. The feasibility study, on the other hand, uses flat-rate operating costs of 1.3 % of the investment costs including subsidies. The key figure profit before taxes (EBT) shows no change in all three model approaches, compared to the profit before interest and taxes (EBIT), as the project is financed 100% from own capital. The deviation in the difference between revenues and costs (EBITDA) is significantly lower in the concept development, as higher costs are offset by higher revenues in contrast to the reference variant. This is due to an increased electricity feed-in of the CHP unit into the grid of 32 % in the concept development.

Table 3: Comparison of the economic key figures of the simulation (reference), feasibility study and concept development for an exemplary energy concept

	Simulation (reference)	Feasibility-audit	Dev.	Concept-development	Dev.
Economic					
Static					
Total investment costs	5,168,790 €	4,626,337 €	10 %	5,366,019 €	4 %
Proceeds	1,109,345 €	1,104,581 €	0 %	1,158,871 €	4 %
Costs	532,144 €	650,248 €	22 %	629,522 €	18 %
EBITDA	577,201 €	454,333 €	21 %	529,349 €	8 %
EBIT	339,612 €	223,016 €	34 %	313,243 €	8 %
EBT	339,612 €	223,016 €	34 %	313,243 €	8 %
Dynamic					
Net present value	1,013,406 €	-	-	74,533 €	-
Return on investment	14.46 %	-	-	18.53 a	
Internal rate of return	8.38 %	-	-	6.16%	-
Heat production costs	68 €/MWh	78 €/MWh	15 %	70 €/MWh	3 %

However, the concept development normally tends towards an increased self-consumption share of the CHP electricity generated, as certain supply situations cannot be mapped due to the monthly, instead of hourly simulation values. Despite the monthly simulation values instead of hourly values, the results of the generated heat and electricity quantities of the individual technologies are satisfactory. For the concept development, a dynamic profitability analysis is carried out in addition to the profit and loss account, as with the simulated reference variant, in order to be able to record and evaluate the investment decision over the entire investment period. In this way, dynamic influences such as the development of energy and material prices or variable CO_2 costs can be depicted. Due to the lower cash flow, the expected return over 20 years is somewhat lower in the concept development than in the reference variant. Taking into account the significantly simplified calculation approach compared to a simulation, a final difference in the internal rate of return of 2.22% and a difference in the heat production costs of only 3% for the concept development and 15% for the feasibility study are within the expected tolerance range.

Conclusion

The results show that a technical, ecological and economical evaluation within the framework of the developed calculation tool delivers valid results. Early development and evaluation of suitable energy concepts with the help of the developed programmes is therefore recommended for targeted concept development.

Prospect

Further development steps such as an implementation of operating and control strategies, an automated optimisation of certain target functions or the development of a web application for feasibility testing are intended.

Based on the study already presented and the development steps outlined in the prospect, one of the topics is briefly presented below. As part of another master's thesis supervised by IWN, the influence of various operating modes and operating and control strategies of large heat pumps in innovative 4th generation heating networks on selected key figures is being investigated and evaluated.

The results from the calculation tool presented are based on the assumption of a heat-led mode of operation for all energy generators. The usual prioritisation of the generators is used for thermal balancing and to cover the heat demand - this procedure is generally used for pre-planning considerations. As many feasibility studies on heat grids 4.0 already show (Kleinertz et al. 2019), (naturstrom AG 2020), (Pehnt 2017) the combination of a heat pump and CHP system forms the basic framework for covering the base and medium load. The CHP plant should achieve high running times with few cycles for economic and efficient operation. For short-term peak loads, gas or biomass boilers are connected. In real operation, however, the running system and switching of the energy generators must be considered more closely under the aspects already mentioned.

The realisation and implementation of 4th generation heating grids not only contributes to achieving the European climate targets through the decarbonisation of the heat supply, but the use of renewable energy systems also offers further opportunities to advance the energy transition through the intelligent coupling of the electricity and heating sectors and to benefit from positive economic effects at the same time. In doing so, the flexibility of one sector is used to support the other. An important pillar of the energy transition is the flexibility of the electricity market in order to compensate for future increases in variable capacities due to wind power and photovoltaic plants (Jansen et al. 2015). At times of high feed-in to the electricity grid (e.g. through photovoltaics), customers must be found who compensate for and use the cheap (surplus) electricity at this time.

A dynamic core element is the integration of large scale heat pumps into heating grids. Heat pump systems offer the possibility to contribute to this compensation via adapted storage systems and the inertia of the grid as well as an optimised grid-managed control strategy. On the one hand, the heat pump can be operated more cost-effectively even at operating points with a less than optimal COP, and on the other hand, the electricity grids are relieved at forecast feed-in peaks. Conversely, the buffered heat from the storage units is first used at critically high loads in the electricity grid before the heat pump system switches on. The limits of the variable operation of a heat pump system are the time availability and the capacity of the heat source. While geothermal and water sources have relatively constant capacity over the year, heat sources from waste water or industrial waste heat, for example, can have a volatile structure over time (Pieper et al. 2019).

This regulatory approach to sector coupling can also be applied to CHP plants. The operating mode of a CHP plant can be divided into heat-led, electricity (market) led and overall optimised led. The latter describes the mode of operation depending on the electricity market and at the same time on the electricity demand (in this case) of the heat pump, taking heat coverage into account (Prognos AG et al. 2019).

In addition to switching on the heat pump (shutting down the CHP plant)when electricity market prices are low - and switching on the CHP plant when electricity market prices are high, however, another regulatory component must be considered - namely the simultaneous operation of the CHP plant and the heat pump. By increasing the degree of self-sufficiency of the heat pump, an improved primary energy factor can be achieved, and the heat production costs reduced. In this context, the coordination of the component's electricity market price, CHP plant and heat pump are one of the most important levers for the optimal operation of the energy producers in a heating network.

Content of the work & methodology

Within the scope of the master's thesis "Operating and control strategies of large scale heat pumps for integration into district heating systems", the electricity market-dependent relationships are examined with a view to selected key figures. One important key figure is the overall primary energy factor, calculated according to AGFW FW 309 Part 1 "Energetic evaluation of district heating - Determination of specific primary energy factors for district heating supply systems". A low primary energy factor makes it easier for developers to comply with legal requirements for building renovations and new buildings, as the energy requirements for the building envelope are reduced. Another important key figure is the ecological footprint: the CO_2 balance in relation to the m² of living space of the area supplied. Due to the introduction of CO_2 pricing from 2021 and the future price increase, minimising CO_2 Emissions is not only desirable for sustainability reasons; economic improvements must also be achieved. Ecological improvements must always be justified by economic viability in real operations. The economic generation of heat is assessed by looking at the variable, operation-dependent heat production costs. An additional full cost calculation based on VDI 2067 is also used to evaluate theoretical variations of system components such as heat storage.

The aim of the study is to develop generalisable operating and control strategies for large heat pumps in heating networks 4.0 with CHP systems. In doing so, the hydraulic integration and its effect on the operating mode is also compiled. A classic heat-led operating mode of the generators without consideration of electricity market signals serves as a reference for the evaluation of the described key figures. The difference between the energy, ecological and economic balances and the reference and the associated findings of the work are intended to be used in a feasibility study of a heating network to make balance sheet adjustments through the optimised operating strategy applied and thus to provide a more reliable result in the preliminary planning. In order to compare and validate the findings with real operation in the future, a measurement concept for recording important parameters and variables is derived as part of the work. In addition, the communication requirements for the heating system to be integrated as a potential virtual power plant, such as VHPready 4.0, are discussed.

A sensitivity analysis is used to test the results by taking a closer look at and varying some parameters and to compare their effects. As already mentioned in the introduction, the flexibilisation of the sectors is an important basic prerequisite for cross-sectoral load shifting. The flexibility of a heating network is defined by the connected heat storage capacity. The question here is which flexibility capacity is economically optimal and economically feasible? Energy prices for electricity and gas, as well as surcharges according to the Combined Heat and Power Act, represent the largest variable part of the demand-related costs and thus have a significant influence on the heat production costs of a producer. The future increase in the price of CO_2 is also an important factor in the prioritisation of connected energy producers. In addition, indirect parameters such as a change in load capacities due to modernisation of the building envelope of the supplied buildings or due to the expansion of the network by new buildings are examined.

Project description

The analysis is based on the example of the residential quarter already mentioned in the main article with 1,100 residential units, distributed over 43 residential properties with a house transfer station. Taking into account a simultaneity factor of 0.77, the peak heat load is 4,500 kW. The base load for the domestic hot water supply varies between 500 kW and 700 kW, also taking into account an appropriate simultaneity factor.

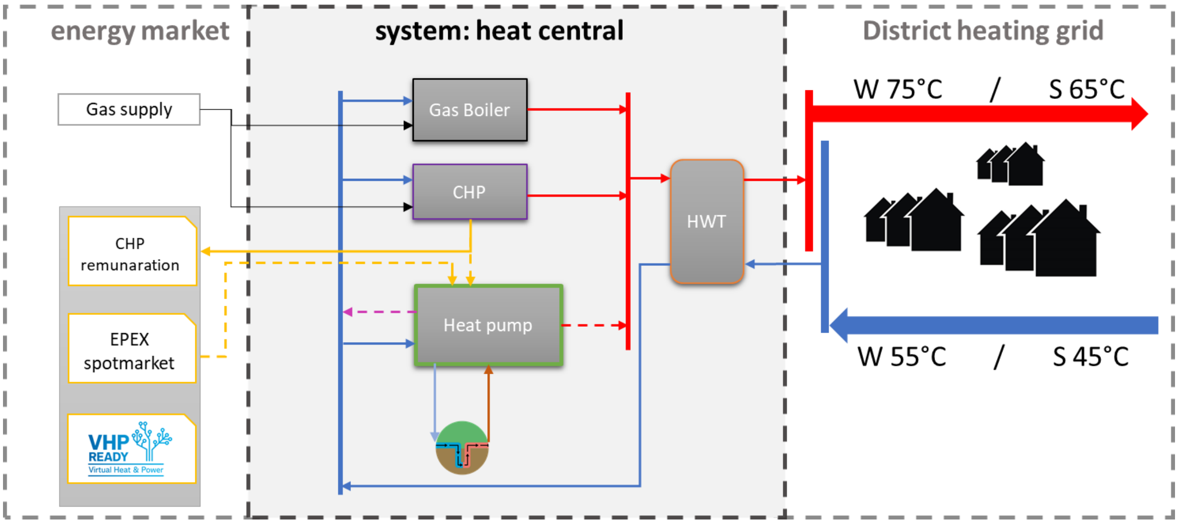

Figure 3- Integration and operation possibilities of heat pumps in district heating networks

As a basis for investigation, 2 system variants (A & B) of the generators are examined. Both variants consist of a gas peak load boiler incl. redundancy (3,000 kW), a CHP plant (360 kW electric) and a water/water heat pump system operated in parallel consisting of two heat pump modules (2 x 570 kW) with a geothermal groundwater source. Variant A and Variant B differ only in the structural design of the CHP plant. In variant A, the CHP system consists of a CHP unit whose electrical output is approximately equal to the electrical power consumption of both heat pump modules at the operating point. In variant B, the same cumulative power of the CHP unit is used (360 kW electric), this time consisting of a small CHP < 100 kW and a larger module. This variant investigates a change in the CHP surcharge and the associated impact on the circuit of the heat pump system.

The core of the analytical investigation is the simulation in energyPRO. energyPRO is often used in the investigation of energetic systems. The software provides a suitable interface between the technical depth, energetic mapping of the system, changeable operating and control levers, and an overall economic framework for evaluating different strategies.

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