MILP Model for Energy Supply Design to overcome the Cannibalization of Solar Thermal Plants and large-scale Heat Pumps in Urban District Heating Systems

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1 ABSTRACT

Urban infrastructure is accountable for a large share of carbon emissions, especially energy supply to meet the demand for thermal heat and domestic water. Regarding the climate agreements these systems have to be decarbonized. In urban neighbourhoods, district heating systems (DHS) are efficient solutions to supply heat and favoured by locally or regionally operating municipal utilities. To integrate renewable heat from solar thermal plants or waste heat from lakes or rivers by using heat pumps, DHS in highly densed agglomerations face major problems. On the one hand the availability of land respectively free space is limited. On the other hand operating times of solar thermal plants and large-scale heat pumps are similar considering a long-term planning horizon. In this contribution a mixed integer linear programming (MILP) model is developed to determine the implementation of both options solar thermal plants as well as large-scale heat pumps in DHS with adjustable generation plants in an optimal way. The model computes minimal investment costs and related emission savings for different alternatives integrating heat of renewable sources. The results can support the decision-making regarding the feasibility. Furthermore, good combinations of different renewable energy sources and their integration into a DHS can be identified even though the sources are distributed over the DHS. Main decision variables are the choice of possible plant sizes under consideration of the (existing) DHS-network layout and available space in highly densed urban districts. The network topology as well as energetic and ecological constraints (e.g. maximum flow capacity in pipes or operating times of heat pumps due to boundary conditions of heat sources) lead to a selection of plant combinations which represent the optimal solution to lower the emissions at acceptable investment costs. The developed model is applied to a case study for an DHS in a newly built neighbourhood with several available heat sources for heat pumps and free areas for solar thermal collectors. The results proof the function of the model and illustrate that an energetic improvement of the DHS is possible by integrating solar thermal plants and large-scale heat pumps at economically acceptable conditions.

Keywords: District Heating Systems, Heat Pump, Mixed Integer Linear Programming, Solar Thermal, Urban Energy Supply

2 INTRODUCTION

The necessity of reducing anthropogenic greenhouse gas (GHG) emissions to decelerate climate change is incontestable. Various infrastructure in urban neighbourhoods such as residential zones are responsible for a large part of the GHG emissions, especially because heating and domestic hot water is often provided individually by fossil-fueled energy supply systems. Thus, urban built district energy systems must be decarbonized. (IPCC, 2018; REN21, 2019)

Current policy measures of the European Union and several countries aim at upgrading buildings which underlie a fossil-fired energy supply (e.g. KfW, 2020). In contrast to individual heat supply, district heating systems (DHS) offer the possibility of absorbing (waste) heat from miscellaneous (renewable) energy sources, transporting it over (long) distances and providing it elsewhere in various buildings for (space) heating and domestic hot water (preparation). This fundamental idea of DHS is shown in Fig. 1. It is essential for the success of the energy transition that a mix of local energy sources and various technologies fulfil the DHS supply task in urban agglomerations and neighbourhoods and contribute in the long term to a sustainable and preferably emission-free energy supply including an improved energy efficiency.

Traditionally, excess heat resources have their origin in other energy sectors, i.e. combined heat and power (CHP) plants for electricity generation or industrial processes. Today, there is an additional interest in the use of renewable heat in DHS. A combination of providing recycled and renewable heat is the focus for future DHS. As a result primary energy supply for heat demands will be substituted and lower environmental impact will be achieved. Some potential renewable energy technologies in DHS are solar thermal collectors and heat pumps. Both have better economic and environmental costs and benefits at a (large) district scale compared to an individual building scale. For this reason, their application in DHS makes particular sense. In the future, they will be of great importance, as fossil-fired DHS supply possibly needs to be replaced over time as far as possible. (Frederiksen and Werner, 2013; Wiltshire, 2016; Werner, 2017)

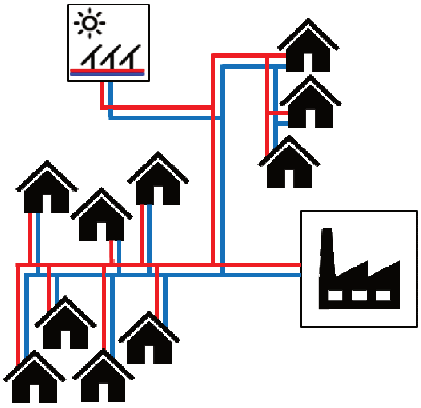

Fig. 1: Schematic overview showing the basic parts of a DHS according to its fundamental idea.

In general, DHS are unique, e.g. regarding their use of resources or network size. Some of the biggest cities in Germany (e.g. Hamburg) respectively agglomerations (e.g. the Ruhr area) rely on DHS to provide space heating and domestic hot water. DHS in-feed is mainly based on CHP, because the plant operation can be optimized by producing at times with attractive power market in-feed tariffs (cf. Fang and Lahdelma, 2016). However, the operation of CHP plants is controllable, so it is possible to achieve a beneficial in-feed for both, DHS and the power grid. In 2018, heat from CHP plants accounted for 80 % of DHS supply in Germany. In the future the combination of (de-) centralized CHP plants and DHS in urban areas is reasonable, since there is a link between the residual power load and the heat load. Especially in times without wind and sunshine CHP plants can meet delivery obligations for DHS as well as flexibility requirements for the power grid with a high efficiency. However, to achieve sustainable (district) energy systems deep energy savings are required and also the integration of renewable energy sources must be pushed forward both in the electricity market and the heating market. (Connolly et al., 2014; Werner, 2017; AGFW, 2019; Thommessen et al., 2019)

2.1 Integration of renewable heat into district heating systems

Locally or regionally operating DHS business utilities often face a number of problems when upgrading the DHS performance or considering renewable energy supply possibilities for their existing infrastructure. Basically, technical and operational parameters of several generation technologies are the former constraints in the decision-making during all stages from (economic) planning, through construction until operation, especially for generation plants that generate heat from renewable energy sources. In addition, a major problem in many high dense urban cases is the availability of space or the competition in the use of (free) land. Ongoing (sub-) urbanisation results in cities with high energy demands but scarce land for an efficient (district) energy supply and distribution, especially in DHS. Such initial conditions make the integration of renewable heat more difficult since a specific amount of space is required. (Miglani, 2018)

Moreover DHS operation temperatures are crucial to the overall system efficiency. Current DHS research focuses inter alia on optimizing supply and return temperatures. Hereby, the development of better piping technology is ongoing. Improvements are needed in order to become a reliable, cost-efficient basis of novel DHS schemes with lower temperatures and a larger share of renewable energy sources. Furthermore, the mature technology of surveillance systems, sophisticated controls and heat meters needs to evolve to make DHS smart in the sense of digitalization. Several studies show that DHS operation temperatures will decrease, so that heat loss reduction and an efficient heat generation become crucial. (Wiltshire, 2016; Werner, 2017)

In Germany, the integration of e.g. large-scale heat pumps or solar thermal plants is becoming increasingly important which is apparent from the fact that the last call for bids to fund innovative CHP systems was oversubscribed for the first time in December 2019. Innovative CHP systems are defined as selected and modern systems with a high energy efficiency and low-GHG emissions. As a requirement the cogeneration plants need to be operated in flexible combination with other technologies, i.e. to achieve a high portion of heat supply from renewable energy. Therefore, an innovative CHP system consists at least of three components, i.e. the CHP plant itself, a component for the provision of renewable heat (e.g. solar thermal) and a electric heat generator (e.g. direct electric boilers). As a constraint the production of cogenerated electricity and heat is intendet to be useful for both the power grid and DHS and thus, must accord to demand or loads, respectively. Additionally, the individual components of innovative CHP systems must be jointly regulated and controlled. (BAFA, 2020; BNETZA, 2020; cf. KWKG, 2020)

2.2 Cannibalization effect and financial issues

To achieve higher shares of renewable energy in DHS the integration of solar thermal energy and heat pumps makes particular sense. However, operation times of those technologies cannibalize each other since solar radiation and the required temperature from other renewable heat sources are mainly reached in the summer and transitional periods of a year. Thermal storages can bridge the time between supply and consumption, but require additional free space and imply higher costs for investment and operation. Fig. 2 comprehenses the common cannibalization effect of solar thermal plants and heat pumps in urban DHS in a graphical way.

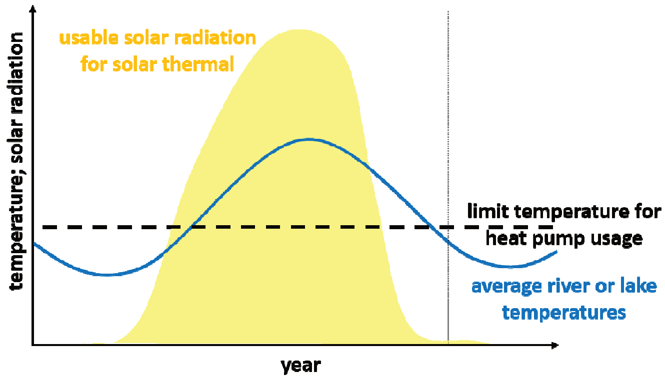

Fig. 2: Cannibalization of operation times for solar thermal plants and heat pumps by means of solar radiation and the temperatures of predestined heat sources.

Next to technical operation parameters financial issues always play a great role in the choice of energy supply source in DHS. Regarding the technologies in focus in this contribution, various advantages and disadvantages can easily be identified, which are related to the long-term economic operation of the energy supply plants.

Depending on the targeted energy yield, a solar thermal plant requires a certain amount of free space, which is (as described before) usually very limited in urban agglomerations. These systems can be mounted on roofs, which in turn places new static requirements on buildings. For planning reasons, it is generally easier to install solar thermal collectors on new buildings than to retrofit it on existing buildings. As shown in Fig. 2, the operating times are relatively easy to predict during the summertime of a year. This means that other operating parameters (e.g. thermal storage, DHS pipe dimensioning) can be easily determined with the aid of suitable calculation tools. Depending on the potential location of a solar thermal plant and the required operating conditions, the investment costs can be determined. Operating costs of solar thermal plants for e.g. pumps or maintenance are usually the minor expense and are usually subordinated when considering the entire lifetime of a solar thermal plant. (cf. Mangold, 2020)

The feed-in of environmentally sustainable heat by using heat pumps makes sense in DHS, especially since this technology can be achieved in a cross-sectoral manner to serve the power network as well. For large DHS, there are special requirements for the heat source of the heat pump, which is correspondingly of a large-scale. In order to achieve high feed-in capacities, high volume flows from a heat source are necessary,

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which should also have a certain temperature level. Usually lakes or rivers are suitable for this purpose, but their temperature fluctuates over a year. It follows the outside temperature (very) phase-shifted and with (strongly) attenuated peaks, which depends on the size of a lake or river. However, in certain seasons of the year, operation often has to be discontinued in order not to cool down the public waters too much, e.g. for reasons of species protection. Heat pumps which take advantage of the ground temperature that rises with depth, operate at relatively constant source temperatures. But the costs of drilling are for most European countries not yet in a reasonable proportion to the energy yield. Generally, a large-scale heat pump that is well designed in accordance with the existing conditions of the heat source requires little space in comparison to a solar thermal plant, although (also for reasons of operational control) a separate operating building must usually still be erected at the selected heat pump location. However, financial issues regarding heat pumps in Germany do not depent on technical operation. Current research shows that the integration of large-scale heat pumps into DHS are not cost competitive with (existing) fossil-fired units because of the regulatory and economic framework. (cf. Popovski et al., 2019)

2.3 Aim of this contribution

All in all DHS technology is improving and business actors react to political efforts to ensure a sustainable energy supply for society. In high-dense urban cities DHS imply low heating costs due to the ability to (re-) use a range of (locally available) heat sources, especially heat from CHP plants and waste heat from industrial processes, as well as renewable heat from solar thermal plants or (large-scale) heat pumps. However, limited space and technological as well as environmental requirements lead to challenges regarding a sensitive DHS network and supply design for a secure energy supply. Considering the number of DHS supply possibilities in current issues, e.g. arising from legislative framework (cf. BAFA, 2020), optimization modeling can be a tool for an improved design of DHS in urban districts or neighbourhoods.

The main goal of this contribution is the development of a computational method in order to determine the optimal design of renewable energy supply for urban districts with DHS. There are several tools available, e.g. to determine excess heat potentials (cf. PETA4, 2020), but decision-making regarding improving DHS supply actually focusses on solar thermal plants and large-scale heat pumps for legislative reasons, e.g. in Germany as mentioned above. Since the operation of those technologies cannibalizes each other, finding an optimal energy supply design considering those renewables as integration into existing DHS can be complex. Mixed integer linear programming (MILP) is chosen to develop a model with the implementation of both options solar thermal plants as well as large-scale heat pumps in DHS. This contribution attempts to address the challenges associated with the modeling of optimal DHS supply design and operation of solar thermal plants and large-scale heat pumps in the long-term.

3 METHODOLOGY AND MATHEMATICAL MODEL FOR IMPROVED ENERGY SUPPLY

The optimization approach developed within this contribution minimizes the total investment costs and considers GHG emissions (in carbon dioxide equivalents) of an energy system. It includes a formulation which allows the analysis of the impact of large-scale heat pump operation on the temperature of several heat sources (ground and river water) with respect to the fluctuating performance due to external factors (as measured by the coefficient of performance, COP). The mathematical model for an improved renewable energy supply design in urban neighbourhoods was developed to overcome the problems arising from the cannibalization of solar thermal and heat pumps mentioned before. With the MILP-model combinations of different renewable energy sources and their integration into a DHS can be identiefied as start values for further steps, i.e. detailed planning and economic calculation for a supply concepts lifetime. The general purpose of the model is shown as a graphic in Fig. 3.

For the general MILP-model some indices, parameters and (decision) variables are being introduced for time steps, heat pumps, solar thermal and transport pipes (in order of appearance):

$$t = 1, \dots, T$$
$$hp = 1, \dots, HP$$
$$st = 1, \dots, ST$$
$$tp = 1, \dots, TP$$

The mathematical model computes minimal total investment costs (TC) with the objective function and related emission savings (TE) for different alternatives integrating heat of renewable sources with a second function:

$$min\ TC = \sum_{hp=1}^{HP} C_{hp} + \sum_{st=1}^{ST} C_{st} + \sum_{tp=1}^{TP} C_{tp}$$

$$TE = \sum_{t=1}^{T} \frac{e_{ref} \cdot D_t}{\eta_{ref}} - \sum_{hp=1}^{HP} E_{hp} - \sum_{st=1}^{ST} E_{st} - \sum_{tp=1}^{TP} E_{tp}$$

$$S_{hp,t} + S_{st,t} + S_{tp,t} = D_t \quad \forall t$$

For the calculation of emissions (E) and the related savings (TE) an energy supply reference (ref) is to be assumed (i.e. often individual supply by heat boilers on a building-scale). The main calculation of the economic variables depends on the selected technology mix, which ensures the energy supply of the neighbourhood for the selected period (e.g. usually one year). This is represented by the third equation above, whereas the demand (D) represents the heat load as well as the energetic DHS losses. In this context, different energy equations must be considered for several supply (S) possibilities:

$$S_{st,t} = \tau_{stm} \cdot SR_t \cdot A_{st} \cdot (1 - \rho_{stm}) - \left(k_{0,stm} \cdot A_{st} \cdot (T_{st,t} - T_{a,t}) + k_{1,stm} \cdot A_{st} \cdot (T_{st,t} - T_{a,t})^2\right) \quad \forall st, t$$

$$S_{hp,t} = COP_{hp,t} \cdot P_{hp} \quad \forall hp, t$$

$$COP_{hp,t} = f(K_{hp}; T_{source,t}; T_{supply,t}) \quad \forall hp, t$$

$$S_{tp,t} = \dot{m}_{tp,t} \cdot c_p \cdot (T_{DHS,supply,t} - T_{DHS,return,t}) \quad \forall tp, t$$

$$\dot{m}_{tp,t} = \frac{\pi}{4} \cdot d_{tp}{}^2 \cdot \rho \cdot v_{tp,t} \quad \forall tp, t$$

As shown in detail for solar thermal plants, there are many parameters that influence the calculations depend on system properties (stm). This also applies to heat pumps and to the necessary transport pipes. Therefore, this documentation is limited to the essential influencing factors. All formulas regardig energetic conversion and supply are based on literature, where further and more detailed (e.g. time stepwise) calculations can be found, too (cf. Witte-Humperdinck, 2019; Wesselak, 2017; Cube and Steimle, 1978; Doering et al., 2016). Other current feasibility studies can be used for comparison in terms of energy calculation and evaluation (e.g. Bücken et al., 2017).

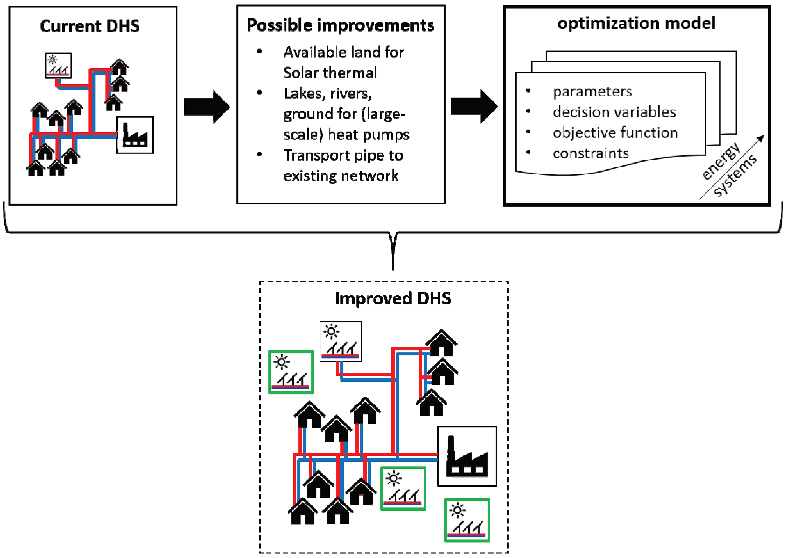

Fig. 3: Schematic overview of the optimization model for DHS supply design considering solar thermal plants and heat pumps.

In the case of solar thermal systems, the main factors for energy supply are the collector surface area (A), location based parameters such as solar radiation (SR), orientation or angle of inclination, as well as (solar thermal and DHS) system temperatures and ambient temperatures (T). In the case of heat pump operation, the COP is the most important variable. It depends on the capacity (K) of the heat pump and its specific

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system properties (e.g. refrigerant), and the temperatures of the heat sink (i.e. DHS supply) and heat source, which are possibly weather-dependent. In the case of transport pipes, the DHS temperatures and the maximum transport capacities (m), which can be determined on the basis of the pipe geometry, are decisive for reliable operation. Constraints referring the (existing) network layout are considered in pipe diameters (d) and its maximum flow capacity (v) (cf. ÖKL, 2016).

However, for cost calculation the main decision variables are the choice of possible plant sizes (K for heat pumps and A for solar thermal) and transport pipe parameters (d for the diameter and l for the length):

$$C_{hp} = C(K_{hp})$$

$$C_{st} = C(A_{st})$$

$$C_{tp} = C(d_{tp}; l_{tp})$$

For programming and solving this MILP-model, special software is needed. A common solver is CPLEX. While solving this optimization problem, DHS topology and the defined energetic and ecological constraints above lead to a selection of plant combinations which represent the optimal solution to lower the emissions regarding the investment costs. In parallel to the underlying heat network design, the potentially possible supply concepts play a decisive role (e.g. connection to existing networks, construction of new generation plants).

However, in general the MILP-model developed considers distributed locations and sources in existing or new-built DHS in urban neighbourhoods. As the available space in high dense urban districts limit the amount of possible solutions drastically regarding solar thermal plants, the main focus is often on local optimal solutions for (large-scale) heat pumps or transport pipes, which connect DHS. Hereby, maximum pipe flow and operating times of heat pumps due to boundary conditions of heat sources are considered. In cases where a solar thermal plant is combined with a large-scale heat pump, the challenge is to overcome the cannibalization effect. Sometimes a combination of transport piping, solar thermal plant and heat pump is the best solution, because new transport pipes can transport renewable (excess) heat from both, solar thermal and heat pump operation in other networks which would otherwise be fossil-fired during times in which the cannibalization effect would be felt.

4 MODEL APPLICATION TO A CASE STUDY

In this section the mathematical model developed is applied to a case study in the German Ruhr area. After the second world war DHS were introduced in this area since there is a high dense population which implies high heat demands. Nevertheless, some parts in the Ruhr area rely on individual heating systems on building-scale. Improved DHS energy supply needs to be considered today and the MILP-model can support the decision-making. In order to illustrate this, at first the investigated neighbourhood is introduced.

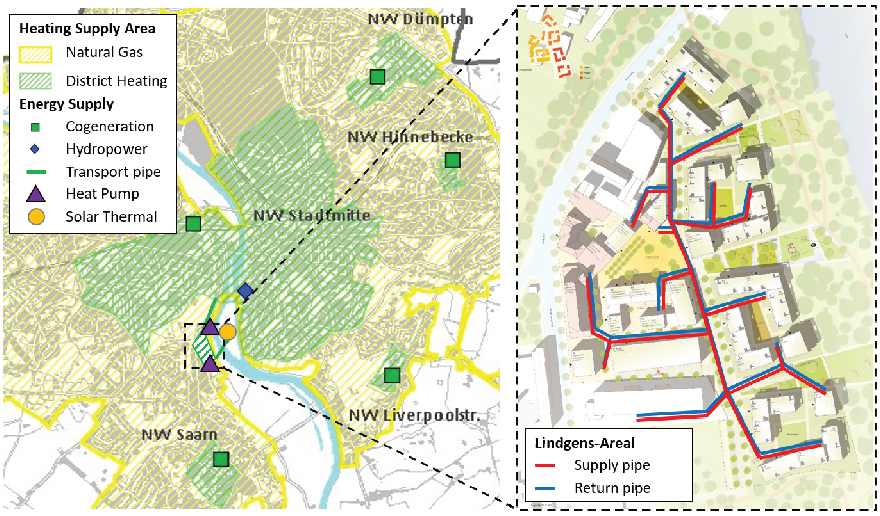

Fig. 4: District heating and gas supply areas in Mülheim (Ruhr), Germany, and localisation of the investigated neighbourhood (Lindgens-Areal) in the urban area. Existing energy generation plants and possible places for new heat pumps and solar thermal collectors assumed are included as well as a possible DHS route in the neighbourhood. (Modified from Marx, 2019; Rödel and Urbanski, 2020; cf. RHA, 2020)

The planned neighbourhood is located in the city of Mülheim (Ruhr) on the western side of the Ruhr river between the districts Broich and Saarn. It covers a total area of approximately 42 ha and is an urban development project of the former Lindgens leather factory. In the published urban development draft a scarcity of space and a resulting competition in terms of land use can be illustrated by the delimitation of the project development area. Fig. 4 shows the planned neighbourhood and the surrounding heat supply with all relevant energy generation facilities of a locally operating municipal utility. For the planned neighbourhood a new DHS with heat supply from a solar thermal plant and large-scale heat pumps is considered, too.

Due to its location several energy supply possibilites can be identified. There is an island in the Ruhr, located east of the neighbourhood. This area comes into question for the use of solar thermal energy, especially because of its size about 60 ha. Solar thermal collectors on the roofs of (new-built) objects in the neighbourhood are also sensitive. Furthermore, two types of large-scale heat pumps are considered, which differ in their heat source. The first uses river water and the second uses energy from the ground in the south of the neighbourhood, which can technically be implemented by e.g. borehole heat exchangers. Finally, a network connection to the existing DHS in the north must also be considered. The route of a transport pipe can be oriented along the course of the main road. Any connection pipes for correspondingly large energy supply systems are also taken into account.

4.1 Extract of data and relevant calculations of the model

Basic weather-related influences that apply to every possible energy supply design concept has to be determined carefully. For the MILP-model typical data is used for this purpose, which is called "Test Reference Years" (DWD, 2020). The outside temperatures and solar radiation are of particular interest. In the following Fig. 5 average values per month are representated at the location of the new neighbourhood.

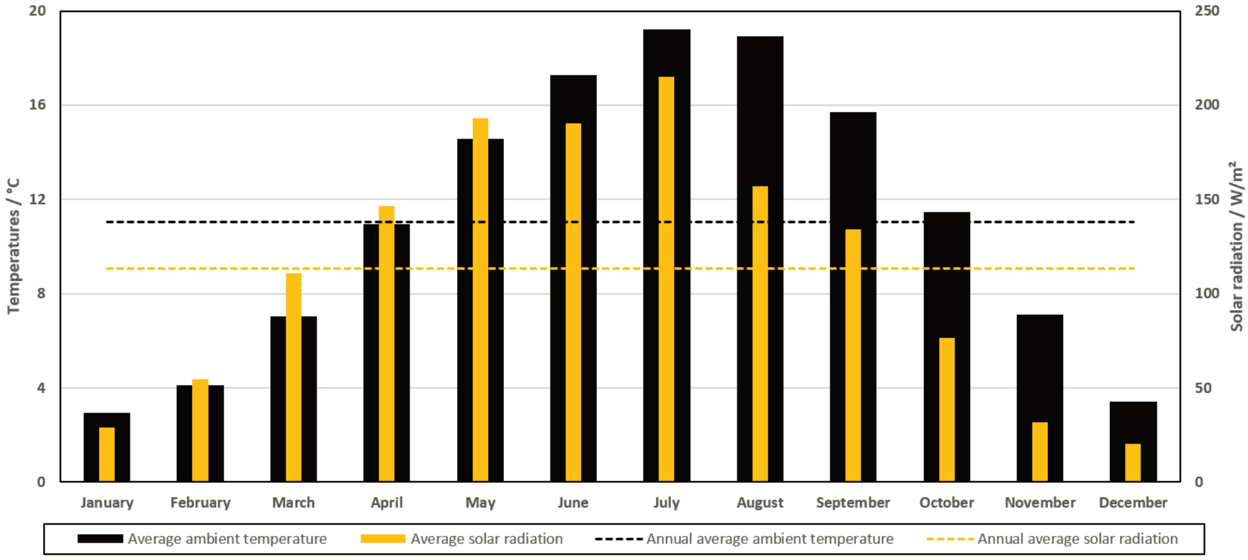

Fig. 5: Average ambient temperatures and solar radiation for the case study.

It is noticeable that the curves are similar. Of course, this was to be expected, as these curves can be understood as the cause of the cannibalization effect described at the beginning. Note in this figure that the values for solar radiation are somewhat distorted by the hourly resolution of the data set. During the day, obviously, higher values can be expected, especially in the summer period. The peak in the data set used is 918 W/m². An average annual temperature of around 11 °C can be determined.

However, all further calculations are based on the hourly values of the data set. This approach plays a particularly important role in all calculations for solar thermal plants. Various collector types from different manufacturers are also included in these calculations. These can be taken from another data set, e.g. (SKN, 2020). Within the framework of MILP-model development, a separate database was created with the typical solar thermal collectors from known large-scale projects in Germany. In order to calculate the two heat pumps considered in the model, different data must be collected for the Ruhr river water temperature and ground temperature, respectively. In the first mentioned case (LANUV, 2020) is a very helpful source of information. There is a collection of historical river water data (e.g. temperatures) and related details about

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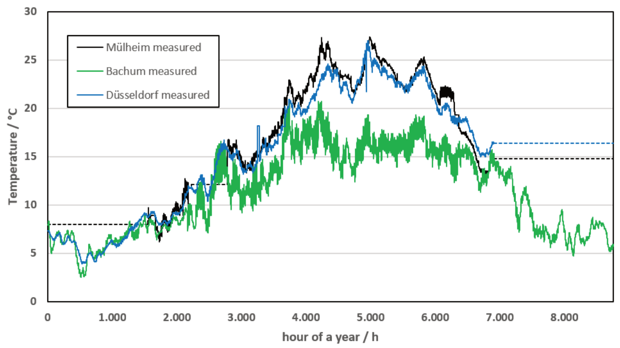
the geographical information of the metering stations in the German state of North Rhine-Westphalia. A station suitable for the area under investigation is located in the immediate vicinity of the hydropower plant (see Fig. 4). For the present MILP-model calculation water data of the past year are used. In general, it can be noted that the course of the water temperature follows the course of the ambient temperature with a slight time lag.

As Fig. 6 shows, there were gaps in the recording of the water temperature in some places. In the figure measured data is represented by completed lines and missing time periods are represented by dashed lines. The gaps may be related to malfunctions of the measuring devices. For this reason the temperatures were first compared with the temperatures of the next available measuring point upstream the Ruhr river. The location of this measurement is Bachum. It is noticeable that especially in summer significantly lower water temperatures of the Ruhr are present at this measuring location. It can be assumed that this is related to the industry located along the Ruhr river. Water from rivers is often used as a refrigerant in production processes or for (fossil-fired) electricity generation. Especially during summer it heats up. As many industries have traditionally settled in the Ruhr area, an increased use of river water as a refrigerant is to be expected and therefore, the variance of the measurements can be explained. In order to set reasonable values in the MILP-model calculation, the water temperature of the (spatially) next metering station was also compared. It is located in Düsseldorf on the Rhine river. Here, a similar course of the water temperature can be observed. From all available water data, the model calculates a representative annual course, which corresponds best to the data of the Mülheim metering station, if possible. Deviations are corrected in a meaningful way based on the measured values of the other two metering stations. Fig. 7 shows the calculated river water temperature for furhter system analysis within the MILP-model.



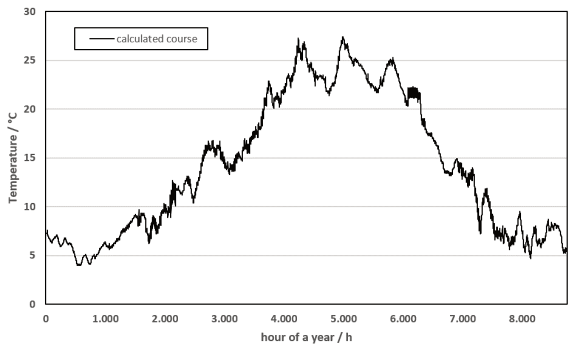


Fig. 6 (left): Water temperatures of relevant rivers for the case study calculation. Fig. 7 (right): Representative annual course of the river water temperature available for the operation of a heat pump.

Furthermore, different ground temperatures must be determined. For this calculation, the approach according to (Thommessen et al., 2018) is used, which is based on the ambient temperature data from (DWD, 2020). At a certain depth, the ground temperature responds very inertly or time-delayed to the ambient temperature and with very damped peaks. A baseload heat pump can make use of this for DHS supply, but the achievable temperature and energy yield must be in a reasonable relationship to the drilling depth and the costs related for boreholes. In the model a usual depth of 8 m was assumed. Additionally, the ground temperature at a common depth of 1.2 m for DHS pipes was determined to calculate the DHS heat losses in the neighbourhood according to (Thommessen et al., 2018). Fig. 8 above summarizes these results.

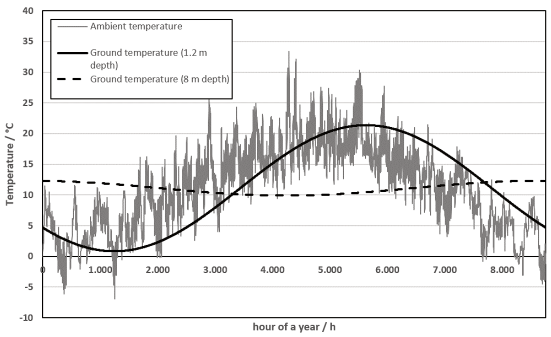


Fig. 8: Ground temperatures calculated from the ambient temperature.

In addition to solar thermal collectors, databases of heat pumps (and their essential system properties, e.g. refrigerant) and common pipelines were implemented. An exemplary approach for DHS route selection is presented in (Résimont, 2019). It was adapted for the purpose of this contribution to determine the routing of transport pipes which connect the investigated neighbourhood with existing DHS nearby. Basically, just one transport pipe to the existing DHS called "Stadtmitte" makes particular sense (cf. Marx, 2019).

Finally, the calculated DHS heat losses are included in the total energy demand of the neighbourhood. As described in the MILP-model a chosen energy supply design must cover the total demand at all times. In order to determine an annual energy balance in the neighbourhood a heat load curve is generated, as described in (Witte et al., 2019), which results in a required total heat demand of 2.1 GWh/a (heat demand of the buildings and heat losses of the DHS). Hereby, a sliding flow temperature control depending on the ambient temperature is assumed with DHS supply temperatures of 110 °C in winter and 70 °C in summer. The value of the DHS return temperature is assumed to constantly be 55 °C. The determined value for the total heat demand is consistent with the results calculated from other approaches (cf. PETA4, 2020; Möller et al., 2018), where e.g. an average DHS efficiency of 0.8 has been assessed at 100 % DHS share for the location of the investigated neighbourhood. Fig. 9 represents the heat load curve or the required heat supply, respectively.

Within the MILP-model, the economic calculations of possible energy supply solutions are based on established average values from literature. The investment costs of each possible solution is calculated depending on the main influencing factors of a supply option described in section 3. Specific average costs for solar thermal energy are estimated at 350 €/m². For heat pumps 2,000 €/kW are assumed. Regarding transport pipes, general costs of 1,000 €/m are considered. Additionally, individual costs (e.g. for civil construction) are assumed and added depending on the route of a transport pipe.

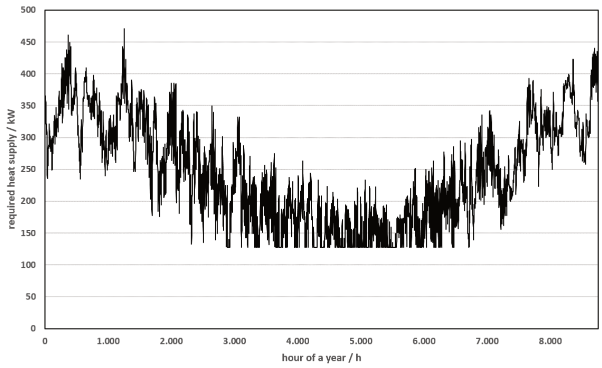


Fig. 9: Required DHS supply for the neighbourhood, calculated on an hourly basis.

4.2 Results

In this section the results of the energy system analysis performed with the developed MILP-model are presented. The approach differs from other current literature (cf. Witte-Humperdinck, 2019). However, similar approaches can be observed for energy system analysis as well (cf. Miglani, 2018). For an improved energy supply of the new neighbourhood an optimal concept consists of a river water heat pump and an additional transport pipe. The chosen heat pump operates with ammonia as refrigerant and a associated connection pipe from the river to the district is considered. The transport pipe is of size DN 300 and connects the DHS of the new neighbourhood with the existing network "Stadtmitte". The route follows the course of the main road over a length of about 1 km. The chosen concept implies total investment costs of 1.54 million € (in addition to the costs incurred in any case for the construction of the new DHS). The savings of GHG emissions calculated by implementing this district energy supply solution amount to 388,478 t carbon dioxide equivalent. The presumption that biomethane-fired CHP plants are operated in the existing DHS plays an important role in this assessment.

The heat pump selected can be operated through the year and therefore, it has many hours of operation. In winter full-load operation is not possible because the river water is cold and a minimum cooling down to 2 °C is set as a boundary constraint in the MILP-model. Nevertheless, a temperature control by pre-heating from the DHS with higher temperatures can be considered as an additional improvement, since a connection pipe for the heat pump from the river to the neighbourhood would have to be built in any case. However, the river water reaches high temperatures in summer, so that the energy conversion process of the heat pump works particularly efficiently. This can be seen from the course of the COP for the river water heat pump operation over one year. This is shown in Fig. 10 for the heat pump selected. The average annual COP amounts to 2.74. However, for the continuous operation shown, maintenance and service intervals would also have to be considered. Obviously, a heat pump cannot be operated during these periods.

No heat pump is selected that uses the ground temperature as a heat source due to the usable ground temperatures and the temperature of the DHS to be provided. During the course of the year, the required temperature rise to supply ground source energy into the DHS is often higher than the temperture rise of a river water heat pump. So the efficiency of the heat pump is finally worse. The cost of drilling also plays a major role. Furthermore, associated drilling costs are added to the costs for connection pipes. Although the ground source heat pump is located closer to the neighbourhood, additional costs for drilling are not justified. This result was to be expected. The fact that the developed MILP-model excludes such a supply possibility illustrates its suitability as a decision aid with regard to the feasibility of improved (and renewable) energy supply concepts.

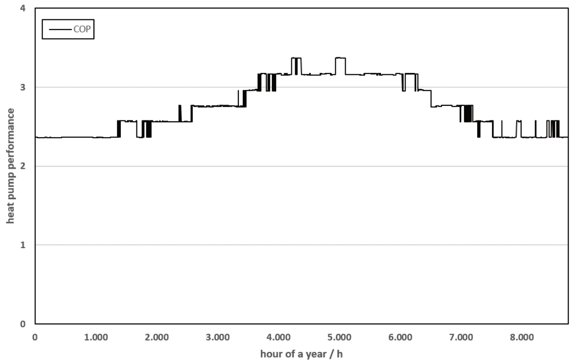


Fig. 10: Performance of chosen river water heat pump.

No solar thermal plant is part of the solution given by the model. One reason is that the year-round operation of the chosen river water heat pump can ensure a base-load supply on its own. Due to the free capacities in the existing network and the selected transport pipe, the energy needed to cover the demand beyond the supply of the heat pump is obtained. Moreover, the costs for connecting a solar thermal plant on the island in the river are extremely high. It would be imperative to build a culvert. In this context, further actions must be taken to ensure that the underground construction and related works are successful. Of course, such costs plays a role in the decision, too. Nevertheless, the MILP-model could have chosen solar thermal collectors on the roofs of the buildings in the neighbourhood, but the costs involved could have been avoided since the predictable operating time of such solar thermal plants makes no sense due to the DHS supply potential of the river water heat pump and, especially, to avoid the cannibalization effect.

However, if a thermal storage tank is integrated into the energy supply concept, the final result could look different again. Depending on the long-term strategy of the utility company (e.g. DHS expansion towards the south or connection of new customers along the transport pipe towards the north) it may make sense, if not even necessary. Of course, in such cases the total thermal energy demand increases. With the additional possibility of interim storage, more renewable energy from a solar thermal plant or a ground source heat pump could be fed into the DHS and via the transport pipe also into the existing DHS. However, energy supply from a new CHP plant should also be examined in further investigations. As shown in Fig. 4 above, various DHS in the overall urban area are supplied by a CHP plant.

The optimal supply concept chosen by the MILP-model meets the total annual heat demand of 2.1 GWh and, additionally, environment-friendly energy is fed into the existing DHS during the summer months. The energy balance for the neighbourhood shown in the Fig. 11 illustrates these relationships. The river water heat pump feeds a total of 1,317.7 MWh of thermal energy. About 12.5 MWh are transported into the DHS “Stadtmitte” in summer, while 839.8 MWh are drawn from it during the rest of the year.

In general, just over 60 % of the total annual demand is covered by the river water heat pump. On the one hand, this is due to the base-load operation of the heat pump and, on the other hand, to relatively low demand peaks in the winter and in the transitional periods. This is because a high standard of the buildings (e.g.

insulation) is expected as most buildings will be newly constructed in the investigated neighbourhood. The selected supply transport pipe covers the remaining heat load peaks.

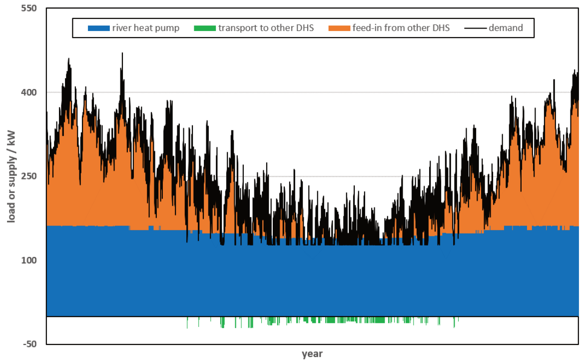


Fig. 11: Energy balance of chosen concept.

The energetic results determined support the decision-making process when examining the feasibility of improved DHS energy supply concepts. However, the results are based on many assumptions and variable parameters, so the calculations do not replace a detailed energy system design or final dimensioning (e.g. plant sizes or pipe diameters). In particular, the economic calculation of energy supply concepts should not be limited to the investment costs alone. In subsequent work also operating costs should be taken into account and should be discounted over the lifetime of the plants chosen for an optimal solution. In Germany, e.g., there is an awkward regulatory framework, so that the operation of heat pumps is not cost-competitive compared to other (fossil-fired) energy supply systems (cf. Popovski et al., 2019). However, the MILP-model created is an approach that can be further developed in any direction and take other influencing variables into account.

5 CONCLUSION AND OUTLOOK

There are many requirements for energy supply systems in urban districts. Especially in the heating sector the challenge of ensuring an improved energy supply for society and, e.g., the integration of more renewable energy (sources) is becoming apparent. Urban planning has to meet the expectations of various disciplines and business actors in order to implement energy efficient supply solutions both in new neighbourhoods as well as in existing urban districts. DHS can provide energy for space heating and domestic hot water in a particularly efficient and environment-friendly way. In order to encompass several sectors (i.e. electricity and heating) DHS is increasingly seen as an integral part of the overall energy system, e.g. to enable the usage of increasing and fluctuating renewable electricity.

In the context of this contibution, a MILP-model was developed, with whose it is possible to improve DHS energy supply concepts by examining various (renewable) energy supply options. The main focus was on solar thermal plants and large-scale heat pumps because their operating times are similar. In order to avoid this cannibalization effect, the model computes with annual data in high temporal resolution. Specifically, a mathematical optimization based on hourly data was carried out to investigate whether the construction of new plants is worthwhile. The final investment costs were used as a decision parameter. They vary depending on the energy supply source associated actions, e.g. civil constuction.

The functionality of the model was demonstrated using a current case study from the Ruhr area. Key findings are that, from an energy point of view, (existing) neighbourhoods, as well as (regenerative) energy supply possibilities, are individual and depend on many external impacts that can hardly be influenced or even not at all (e.g. solar radiation for solar thermal plants due to a geographical location). The boundary constraints implemented to calculate the case study mainly influence the result. However, by applying the MILP-model an energetically reasonable concept could be determined, which is associated with acceptable additional investment costs and a high saving of GHG emissions.

Furthermore, worthwhile approaches for further investigations or further development of the model were identified. The consideration of other technical systems, e.g. thermal storages, may be useful. Moreover, the consideration of operating costs as well as plant lifetimes is recommendable against the background of current political and legal conditions. Finally, the adaptation of the MILP-model to other use cases is also of

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interest in order to identify further improvement possibilities and to implement appropriate solutions for improved energy supply design in urban DHS.

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