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Design of Heat Pump Systems Considering Operation Dynamics

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Abstract

Decreasing carbon dioxide emissions in heat supply of buildings, heat pump systems (HPS) allow the replacement of conventional technologies that utilize fossil-based energy sources. Increasing HPS market penetration, investment and operational costs need to be reduced significantly.
Recent studies show cost reductions by solving optimization problems and considering operation already in the design process. However, many studies assume systems linear in order to simplify optimization procedures. Therefore, we investigate the applicability of a hybrid approach to design simultaneously heat pump, heating rod, space heating and domestic hot water tank considering their nonlinear interactions introduced by operation. We achieve this by combining dynamic simulation models with a multi-objective genetic algorithm using annualized costs and annual emissions as target functions.
Optimal designed systems reduce annualized costs by installation of smaller heat pumps and larger storage tanks compared to normative design standards. In addition, a reasonable larger heating rod ensures annual reliable supply. Thus, total annualized costs can be reduced by up to 12 %. The design highly depends on heat pump modelling and input weather data though.

Keywords: Heat pump design; design optimization; genetic algorithm; multi-objective optimization

1. Introduction

The building energy sector requires significant ecological improvements to meet political goals until 2050. Within this sector, the main contributor to its emissions is the supply of space heating and domestic hot water. Typically, conventional technologies like gas-fired or oil-fired boilers are used to meet the demand. Exchanging boilers with heat pump systems (HPS) can reduce heat supply related emissions. In general, however, HPS have higher costs than conventional systems. Hence, HPS need a cost reduction.
Costs mainly consist of investments and operating costs. Investment costs relate to system's component sizes whereas operational costs belong to the electricity costs to operate the system. Investments and operational costs are mutually depend and their interdependencies are nonlinear. Nevertheless, conventional design processes do the component design first and regard operation by designing the controller afterwards. Therefore, transient interdependencies of design and operation are neglected. Thus, in order to reduce total costs, there is a potential for advanced design processes that simultaneously take component design and operation into account.

In this study, HPS consists of a heat pump, an electric backup heater and two thermal storages: one for space heating and one for domestic hot water. In the literature, we mainly found two approaches that describe the design processes of these components. On the one hand, there are conventional design processes that design component sizes for steady-state operating points. This procedure is either traditional by applying standardized rules or more advanced by using optimization functions in order to define component sizes. On the other hand, first approaches dealing with simultaneous design of component sizes and controller exist. These use optimization procedures to organize the design process. In order to apply deterministic optimization procedures,

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systems often are linearized. Therefore, nonlinear interactions are neglected as a compensation to determine an optimal solution. However, Dongellini et al. [1] and Naldi et al. [2] show that interactions between component size and control influence considerably each other. In addition, Maier et al. [3] prove that interactions are nonlinear as well. Within this work we, therefore, contribute to the establishment of design procedures that consider nonlinear interactions between components. This design procedure introduces a simulation-based optimization method in order to design component sizes simultaneously including operation:

- In Chapter 2, we give an overview about design methodologies regarding conventional design standards as well as improved procedures.
- Our simulation-based optimization approach is introduced in Chapter 3. We distinguish between three steps. First, we show our data processing procedure to generate the algorithm's input data. Afterwards, we describe our system model and highlight nonlinearities introduced by dynamic simulation models. Lastly, we explain the optimization process.
- We show optimization results in Chapter 4. On the one hand, we compare our results with a German normative design standard. On the other hand, we discuss the influence of different boundary conditions.
- A detailed discussion of all results is done in Chapter 5.
- Finally, in Chapter 6, we conclude our work and give an outlook for further investigations.

2. Literature review

Replacing gas-fired or oil-fired heating systems by HPS, there is an urgent need to reduce heat pump system's costs. Costs depend on component design and operation, which again are mutually dependent.

Common design procedures, however, are either conventional, sequential ones or linearly simplified to ensure optimal solutions.

Within this work, we define a heat pump system as a heat pump, an electric backup heater, a space-heating tank and a domestic hot water tank according to [3]. These components need to be designed and operated related to a building demand.

In Germany, there is a normative design standard DIN EN 15450 that describes the design process of HPS. It uses simple design rules to successively define the component's sizes. Applying these rules, a heat pump system is specified that ensures reliability of supply [4]. On the one hand, this procedure has the advantages of simple application as well as a repeatable methodology. On the other hand, it is obvious that these rules design all sizes very conservative to ensure system's reliability.

Dongellini et al. [1] and Naldi et al. [2] introduce and discuss advanced design procedures, which take interdependencies of components and operational aspects into account. While Dongellini et al. prove in [1] the dependency between heat pump sizing and its consequence on system performance, Naldi et al. show in [2] that system's efficiency is closely linked to considered climate and heat pump type. Therefore, it is promising to apply simulation-based approaches in order to design HPS considering system interdependencies as well as different climate conditions.

Designing HPS using simulation-based approaches is straight forward, respectively. However, if boundary conditions are insufficiently chosen, this approach will not lead to mathematical optimal designs. Therefore, Wolisz et al. [5], Schütz et al. [6] and Bischi et al. [7] introduce mixed integer linear programs (MILP) as deterministic optimization design procedure. This leads to optimal design results for mathematical linearized systems. According to Maier et al. [3], however, some nonlinear interactions exist. Concluding these insights, MILP procedures demonstrate design trends accurately. Deducing conclusions is hardly possible regarding reasonable system dynamics. Therefore, combined approaches, which find optimal solutions considering system dynamics are necessary.

Solving nonlinear problems, a trade-off between solution's optimality and dynamics accuracy leads to further design approaches. Therefore, Nguyen et al. present in [8] a review on simulation-based optimization methods. They suggest genetics algorithms (GA) to optimize the design of building energy systems stochastically. Additionally, they show that multi-objective optimization leads to reasonable designs that take costs and for example thermal comfort into account. Fazlollahi et al. confirm in [9] using combined approaches is promising.

The literature review shows great potential to optimize the design process of HPS by simultaneously considering dynamic operation. A contribution that optimizes component sizes at minimal costs and emissions was not identified, yet. Therefore, we show in Chapter 3 the methodology to apply our simulation-based optimization algorithm in order to minimize total costs and emissions.

3. Simulation-based optimization algorithm

Within this work, we introduce a simulation-based optimization algorithm, which includes a multi-objective genetic algorithm (MO-GA). In order to design heat pump heating systems, we need three calculation procedures according to Fig. 1. These three steps are data processing, simulation and optimization. Executing the data processing step, external inputs of location and building characteristics are necessary. Regarding the optimization part, user settings are additionally required. Developing an efficient optimization procedure, all models need to be both fast and accurate.

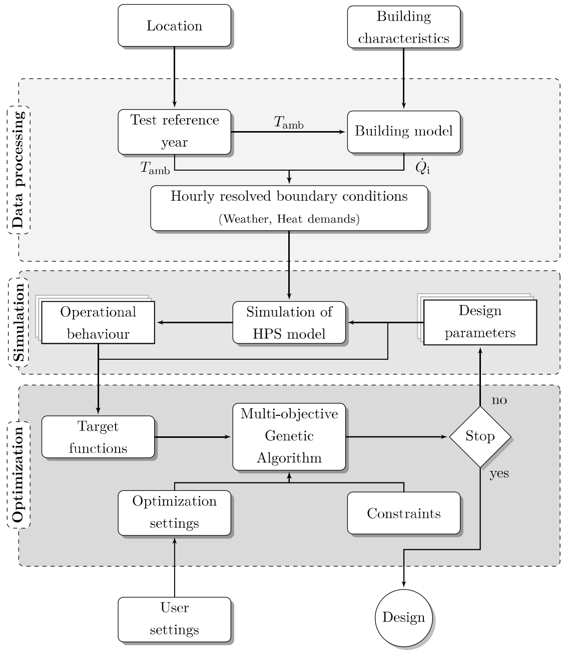

Fig. 1. Superstructure of developed simulation-based optimization algorithm. The algorithm is divided in three parts. Within data processing, the simulation model inputs are prepared. During the simulation, different designs are used to calculate operation behavior. The optimization part improves systems design regarding annual emissions and annualized costs.

3.1. Data processing

Within the data processing, we accumulate few input data in order to estimate the building's energy demand. Based on location, weather data of German weather service (DWD) will be used providing hourly resolved weather conditions in shape of different test reference years (TRY) [11]. Weather data serves as input for thermal building model simulation as well as for HPS model simulation.

Using a high-order building model from the open-source AixLib Library [10], building's demand is calculated hourly resolved. Both time series, weather data and energy demand, are simulation inputs. By taking this step, we neglect the interaction of heat supply system and building's hydraulics in order to increase simulation speed significantly. Simultaneously, we consider hourly resolved system dynamics regarding heat demand, which is reasonable because of large time constants in buildings. For the presented study, we exemplarily use a building located in Aachen, Germany, with a net area of 150 m², year of construction about 1960, insulation standard according to WSchV1984 at normal and cold TRY.

Regarding short time constants, profiles for domestic hot water (DHW) supply are applied according to the German normative standard DIN EN 16147. Within our study, we calculate profile XL, which is common in the heat pump system design process.

In Aachen, normal and cold TRY are summarized in Table 1. In the normal TRY, operating hours below 0 °C arise 313 hours a year, which is only about 4 % of the year. By reducing this temperature by another 2 K, the operating hours decrease to 80 h, which are about 1 %, respectively. The overall mean temperature is 11.48 °C at a lowest temperature of -5.7 °C. This temperature distribution results in a building heat demand of about 63.2 GJ.

In the cold TRY, operating hours below 0 °C are almost doubled with 863 h, which is about 10 % of a year. Operating hours between -2 °C now take 5 % of a year, which means 490 h, respectively. As consequence, the annual mean temperature decreases to 10.66 °C and the lowest temperature is -7.5 °C. With respect to the normal TRY, the building's heat demand increases by about 50 % to 93.4 GJ.

Table 1: Properties of different TRY. Data is proved by DWD. The normal TRY represents the last 20 years best for one region, whereas the cold TRY offers extreme conditions.

Studied year	Hours below 0 °C	Hours below -2 °C	Mean temperature in °C	Coldest temperature in °C	Resulting heat demand in GJ
Normal TRY	313	80	11.48	-5.7	63.2
Cold TRY	863	490	10.66	-7.5	93.4

Comparing both TRYs, the difference of temperatures and heat demands becomes clear. According to Naldi et al. [6], these differences will lead to different system designs as well as system efficiencies and emissions. Both TRYs and hourly resolved building energy demands serve as input for subsequent HPS simulation.

3.2. Heat pump system simulation

As already introduced, HPS consist of a heat pump, a heating rod, which generate heat (Fig. 2). Additionally, there are two storage tanks: one for space heating (Thermal Energy Storage: TES) and one for DHW, which are interconnected by a hydraulic system. These build the distribution system. In combination with a controller, the generation system and the distribution system match the consumer's heat demand.

For the simulation of the HPS, simulation models need to meet different requirements: simulation speed, simulation stability, simulation accuracy. Therefore, we assume reasonable simplifications.

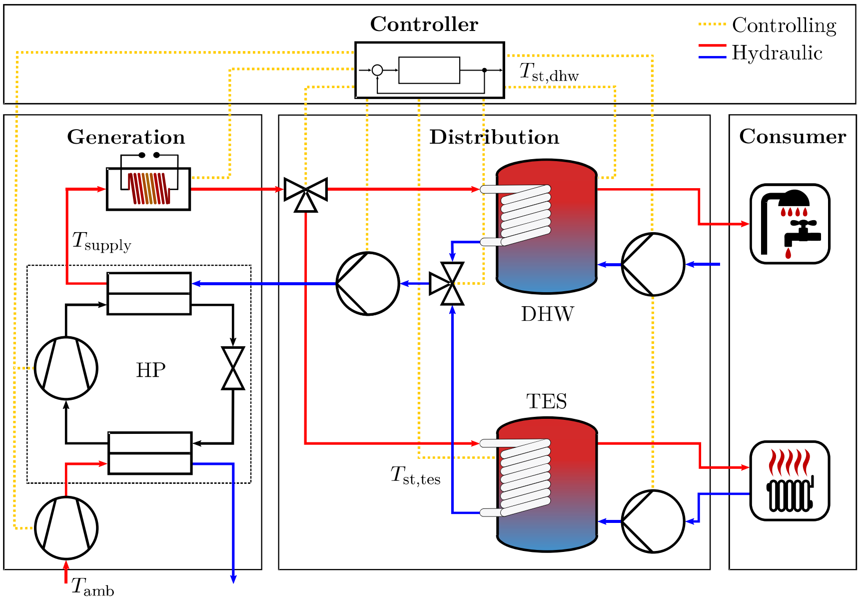

Fig. 2. Schematic structure of used heat pump system models. The system is divided into four subsystems: generation, distribution, consumption and controlling. Generation consists of a heat pump and a heating rod. Within the distribution subsystem storages and the hydraulic system are located. Consumer regard demands for space and hot water heating.

Heat generation:

Instead of using a physical heat pump model with its four components, we summarize its behavior in a characteristic map according to Fig. 3. Using this map, we neglect time delays between two operating points, which means quasi steady-state operation. Therefore, the heat pump is assumed speed controlled between 50 % and 120 % of nominal load according to [12]. We consider start-up losses according to Maier et al. [3] while neglecting defrosting due to missing data. The heating rod has a thermal efficiency of 0.97.

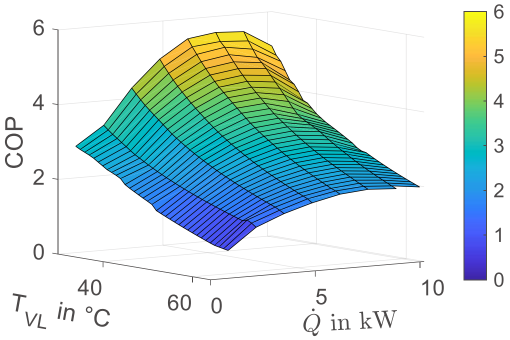

Figure 3: Efficiency map of the heat pump for an ambient air temperature of 0 °C. Within simulations, a three dimensional performance map summarizes dependency of ambient air temperature, supply temperature and condenser heat flow rate.

Distribution system and consumer:

The use of storage tanks is crucial for overall system performance. With respect to implemented models, two target quantities are addressed in the simulation. On the one hand, we define the capacity of a storage by its volume. Both volumes are optimized by the implemented MO-GA. Simplifying the geometry, we assume both storages a cylinder with constant height (h) to diameter (d) ratio of $h/d = 2$. On the other hand, heat losses scale with the surface of the storage tank and heat transition coefficients. Heat transition is calculated assuming free convection on the inner ($\alpha_i = 100\ W/m^2$) and outer side ($\alpha_o = 10\ W/m^2$). In between, heat conduction through insulation is taken into account by $k = 0.045\ W/mK$ and a thickness of $s = 0.12\ m$.

Simple pumps with constant isentropic efficiency are modelled and stratified storages with indirect loading procedure are used in order to match the heat demand of the consumer. As discussed before, the consumer is described by an hourly-resolved data set. Hence, user comfort cannot be measured, yet.

Controller:

Within the scope of this work, we demonstrate that design optimization considering operational dynamics is possible and promising. Therefore, we do not optimize the controller settings for different designs, yet. The controller is a simple heating curve function, which is state of the art. We implement a hysteresis band in order to decrease on/off switches. In addition, DHW has charging priority to increase user's comfort. We do not define a bivalence temperature but use the heating rod, if the lower hysteresis temperature is hurt for more than 20 min. Using this simulation model, the optimization method can be introduced.

3.3. Optimization method

Within this work, we apply a multi-objective genetic algorithm (MO-GA) based on Deb's NSGA-II [13]. In order to adapt it to our design procedure, two further extensions are implemented: The first one is local search in order to improve optimization performance around pareto-optimal solutions [14]; secondly, we use death penalty to deal with constraint hurting solutions [15].

Regarding very extreme demands at normative ambient temperature, thermal power of heat pump and heating rod have to meet normative heat demand according to DIN EN 12831-1, which is 9.7 kW at -12 °C in our use case.

The target functions are annual costs defined by annuity method and annual emissions: costs are defined by the combination of investment costs (according to [3]) investment specific maintenance costs and electric costs (constant specific value of 0.3048 €/kWh in Germany); emissions: specific emissions of German electricity grid (473 g/kWh).

4. Optimal design results

Using the simulation-based optimization approach, we design different systems. In Chapter 4.1 we show the difference between optimized designs compared to normative design standards. Afterwards, we study the effect of different boundary conditions that serve as input for the data processing procedure.

4.1. Comparison of normative and optimized design

When applying the simulation-based optimization algorithm, a pareto front according to annual costs and annual emissions will be calculated. The results are shown in Fig. 4. We discuss three highlighted ones compared to the normative design standard.

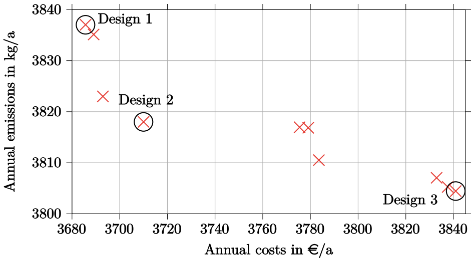

Figure 4: Resulting optimization pareto front using normal TRY. Three designs will be studied more thorough. Design 1 represents the cost optimal solution, design 3 the emission optimal solution and design 2 shows a trade-off between both targets.

Design 1 represents the cost-optimal, design 3 the emission-optimal and design 2 the solution that provides the best trade-off between the two target functions. Table 2 shows the component dimensions of the three optimizations. In addition, the design in accordance with DIN EN 15450 is shown. The corresponding values of the target functions were determined with the aid of an annual simulation in order to allow comparison.

Table 2: Design and performance parameters of optimization and normative designs. Design 1 represents the cost optimal solution, design 3 the emission optimal solution and design shows a trade-off between both targets.

Design label	Heat pump size in kW	Heating rod power in kW	TES volume in l	DHW storage volume in l	Costs in €/a	Emissions in kg/a	SCOP
Cost Optimal	3.95	7.83	578	269	3841	3804	2.76
Cost and Emission	4.03	7.77	412	77	3710	3818	2.74
Emission Optimal	4.18	7.76	257	50	3688	3837	2.72
Normative design	8.25	6.64	193	100	4206	4551	2.39

The three optimised designs show only minor differences in the heat generators' thermal performance. The heat pump thermal power is rated at approximately 4 kW and the heating rod at about 7.8 kW. The cost-optimized solution provides a heat pump's thermal power that is about 5 % greater. In the case of storage tanks, on the other hand, the differences are greater. With a TES of 257 l and a DHW of 50 l, the cost-optimal solution delivers the smallest and the emission-optimal solution the largest storage tanks with 578 l and 269 l, respectively. It is noticeable that the dimensions of the other pareto-dominant optimization solutions for each component lie between the two optimal solutions for a target function. Overall, the different interpretations lead to a difference of 4 % in cost function and about 1 % in annual emissions.

Compared to the normative design, larger differences are identified. This results in a cost savings potential of up to 12 % and a savings potential for emissions of up to 16 %. This is also accompanied by larger differences in the components' sizes. The normative standard designs the heat pump up to 50 % larger. Ensuring reliable supply, the thermal power of the heating rod can be decreased by about 20 %. In addition, an up to three times smaller TES is installed, whereas the dimensioning of the DHW, apart from the emission-optimal solution, lies between the interpretations of the normative standard. Overall, smaller design leads to a reduction in investment costs.

Due to the illustrated design changes, system behaviour varies overall. The efficiency of the system can be illustrated using the seasonal coefficient of performance (*SCOP*). It represents the ratio of the heat provided over the year and the electrical energy required. The *SCOP* of the overall system is 2.39 for the normative design, whereas the *SCOP* varies between 2.72 and 2.76 when using the optimization results. Consequently, *SCOP* can be increased by up to 15 % when using the simulation-based optimized design.

Main contributors to the improved overall efficiency are the changes of TES volume and heat pump capacity. Due to a reduced capacity, the heat pump can be operated more frequently and for longer periods. Therefore, losses related to switching can be decreased by up to 50 % since heat pump starts are reduced. Furthermore, increased full load operation due to larger TES volume is possible, so that efficiency losses in partial load operation are reduced.

In addition, the heating rod provides about 4 % of total heat. Within the scope of reference values according to DIN EN 15450, this result is reasonable, because the use of heating rods should not exceed 5 % of total heat. Hence, it is conspicuous that the heating rod is almost not used during system simulation of normative designed system. The share of the heat supply is below 1 %. Several possible reasons exist for this finding. Either the heat pump is oversized in the normative design or the normal TRY represents a comparatively warm year with a high mean temperature. In order to investigate the influence of different weather data sets, the cold TRY is applied to the algorithm.

4.2. Influences of different weather data sets

We distinguish between optimized design 1 (Opt.1), optimized design 2 (Opt. 2) and normative design (Norm). Case Opt. 1 is the optimized design already presented in Chapter 4.1. Regarding the normal TRY (Fig. 5, red bars), this case shows the optimal solution compared to the other design as expected. In Opt. 2 the design is optimized according to the cold TRY (blue bars). Obviously, Opt. 2 shows the best design compared to the others for both costs and emissions.

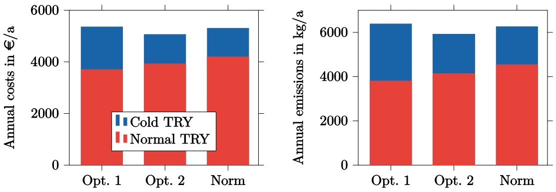

Figure 5: Target functions for the trade-off solutions of optimizations using different TRY as well as the normative design. Opt.1 represent optimization using the normal TRY and Opt.2 represent optimization using cold TRY.

With respect to the normal TRY, normative design rules perform worse. In case of the cold TRY, the normative design procedure nearly obtains the results compared to Opt.1. In Table 3, the component sizes of all design procedures are shown.

Due to the increased heat demand during the cold TRY, the heat pump within Opt. 2 is designed about 60 % larger than in Opt. 1. At the same time, heating rod power can be reduced by around 14 % while satisfying used boundary conditions. In addition, TES is designed at half the volume, whereas the DHW is increased by 10 %. Overall, significantly smaller deviations of the individual components from the normative design procedure can be detected compared to Opt. 1, which reduces potential savings. Nevertheless, the optimized annual costs are about 5 % below the normative design.

Table 3: Optimal designed systems regarding a normal TRY (Opt. 1) and a cold TRY (Opt. 2) compared to a normative designed system. Opt. 2 designs a heat pump with a 60 % higher thermal power and therefore with a reasonable smaller heating rod. Both storage tank volumes are in between Opt. 1 and normative design.

Design label	HP size in kW	HR size in kW	BS volume in l	DHW volume in l	SCOP (standard year)	SCOP (cold year)
Opt. 1 (normal TRY)	4.03	7.77	412	77	2.74	2.24
Opt. 2 (cold TRY)	6.45	6.60	224	93	2.58	2.48
Normative design (Norm)	8.25	6.64	193	100	2.39	2.37

Increasing comparability between the results, operation of all designs is calculated for both weather conditions. For this purpose, annual simulations with both TRYs as boundary conditions are created. Table 3 provides the *SCOP* of the respective simulation and Fig.5 displays each target function.

Opt.1 shows the greatest potential for savings in terms of both costs and emissions compared to normative design. Best results can be observed when using the normal TRY, which leads to a *SCOP* of 2.74. The same design, however, also leads to the lowest *SCOP* during a cold winter. Main reason is the increased operation of the heating rod. When using cold TRY, the heating rod provides about 8 % of the heat demand which requires 20 % of the total primary energy due to its low efficiency. Therefore, both costs and emissions increase significantly.

Opt. 2, on the other hand, provides a lower overall savings potential, but improves target functions by up to 9 % under both TRYs. Consequently, the choice of weather data during the design process has a direct influence on the dimensioning of the components.

Furthermore, Figure 5 shows similar trends for both target functions investigated. This suggests a correlation between the two target functions and can be explained by the predominant influence of operational costs and emissions as a function of power consumption. The operational electricity costs account for between 60 % and 80 % of the total costs. The share of emissions is even higher with up to 90 %. As a result, subsequent work should revise target functions and make it possible to decouple the two goals.

5. Discussion

In contrast to the normative designs, HPS is designed that it ensures just reliable supply when normative heat demand is needed, which reduces heat pump’s thermal power and increases the TES volume for space heating. The ecological optimum of the optimization delivers in each case the design with the smallest heat pump and the largest thermal storage. This coincides with the findings according to [3] where an bigger sized TES leads to a continuous improvement in the final energy consumption which is equivalent to a reduction in indirect emissions.

Due to downsizing heat pump’s capacity, the optimized designs include an increased heating rod power, so the reliability of supply is ensured even at very low ambient temperatures. Accordingly, the heating rod must be operated earlier, whereby the bivalence temperature shifts towards warmer temperatures. Since the bivalence temperature is dependent on the installed heat pump power, it should be optimized in further studies.

The optimized designs highly depend on the boundary conditions and used models. In particular, changing the weather data by using an extreme year instead of an average one with a 50 % increase in heat demand shows large differences in the design. Due to the increased heat demand, heat pump capacity is increased by 60 % compared to other optimization calculations. There are two major reasons for the different heat pump size. Firstly, the general share of total costs accounted by operation increases when using a higher heat demand. Within the normal year, investment costs account for 34 % of the total annual costs, which drops to only 20 % when using the cold TRY. As a result, operational improvements are weighted more strongly than investment costs accompanied by increasing heat pump capacity. Secondly, the inefficient operation of the heating rod is reduced, which improves the overall operation.

When designing HPS under normal weather conditions, the overall efficiency of the system can drop below the efficiency of a system designed using normative design procedure in years with lower mean outdoor temperatures. In contrast, designing for cold boundary conditions shows an economic and ecological improvement compared to normative design at both low and high mean annual temperatures. Consequently, the cold TRY should first be used during the design process. However, further work should investigate to what extent the extreme TRY is necessary when designing HPS and if a trade-off between the two investigated designs can be made. For this purpose, the optimization should be carried out for different locations.

6. Conclusions

In this work, we investigate a simulation-based optimization algorithm to design HPS. The introduced approach improves the component dimensioning of HPS. As a basis for comparison, the design according to the German standard DIN EN 15450 is used. In order to estimate the improvement potential, an optimization algorithm is developed. It consists of a MO-GA, which optimizes HPS models regarding annualized costs and annual emissions. Optimization results are compared with the normative method by using annual system simulation. A potential for improvement regarding the annual costs of up to 12 % and with regard to emissions of up to 16 % is shown. The results of the optimization are influenced by several factors. Among other things, the weather conditions have great influence on the designed system.

If a year with a cold winter is used instead of the normal TRY of the DWD, where heat demand is about 50 % greater, the heat pump capacity increases by up to 60 %. A comparison of system simulations of both designs under different weather conditions shows that the design using the normal TRY is less efficient than the normative design at low annual mean temperatures. Only the cold TRY optimized system guarantees improved operation regardless of weather conditions. Consequently, it must be investigated which weather conditions are required for the design in order to ensure an optimal design. For this purpose, further locations should be included in the comparison in order to validate the statements.

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